From past to present: hydrological and morphological characteristics of Wangi Creek, Northern Territory

Aidan B. Soper

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From past to present: hydrological and morphological characteristics of Wangi Creek, Northern Territory

Abstract
Flooding in the tropical Northern Australia is under researched relative to other regions of the continent yet the entire northern portion of the continent is affected by Australia's most significant climatic phenomena, the Australian Indo Monsoon. This study of Wangi Creek (13° 09’ 49” S, 130° 41’ 07” E) in the Litchfield National Park investigates flood dynamics during the 2013-14 wet season. Wangi Falls cascades off an ungauged catchment on the Tabletop Plateau in the Litchfield National Park. The study reach extends from the plunge pool 3.1 km downstream, a key site investigated in previous paleohydrological studies due to the interpretation of extreme discharges in the Last Glacial Maximum. Using existing high resolution topographic data (LiDAR), plunge pool bathymetry, flood flow stage levels, catchment rainfall and soil moisture, an analysis of wet season rainfall-runoff relationships was undertaken. This was then used for a detailed analysis of inundation patterns and hydraulic characteristics in the study reach. Various scenarios of flow stage conditions were modelled using a 1D steady-state hydraulic model (HEC-RAS), resulting in the quantification of inundation patterns during differing flood stages. Results show that maximum daily rainfall was 201 mm and hourly rainfall 72.6 mm with peak hydrographic responses occurring within 30 minutes of maximum rainfall. Modelled discharge estimates of the ~ 4 m flood flows in 2014 range from 350-500 m$^3$/s, depending on selected roughness parameters. Previous estimates of extreme discharge of 8 m flow depth (3600 m$^3$/s) are examined and the hydraulic model supports such estimates in the upper part of the study reach. However, the presence of a migrating knickpoint (lowering modern levels by up to 2 m) is shown to have a large impact on predicted discharge. Precipitation intensities and unit discharge required to produce such predicted runoff are investigated within the thesis. There have been no observed required precipitation intensities in the Northern Territory to produce the past paleodischarge estimates nor has there been any observed unit discharge values recorded high enough to produce such discharge estimates for a catchment area the size of Wangi Creek. There are however estimates nationally (based on Probable Maximum Precipitation – PMP) that suggest that these rainfall intensities are possible and this is globally verified. Such issues are discussed in the context of previous research on this river which has suggested maximum floods during the Last Glacial Maximum, pointing to a much wetter and extreme climatic period. Beyond this local case study, such an approach provided an improved understanding of flooding dynamics and rainfall-runoff patterns in the seasonally flooded ‘Top End’ and may prove useful in linking past and present flood hydrology.

Degree Type
Thesis

Degree Name
Bachelor of Environmental Science (Honours)

Department
School of Earth & Environmental Sciences

Advisor(s)
Jan-Hendrik May

This thesis is available at Research Online: [https://ro.uow.edu.au/thsci/80](https://ro.uow.edu.au/thsci/80)
Keywords
Surface water hydrology, geomorphology, quaternary environments, landscape evaluation
From past to present: hydrological and morphological characteristics of Wangi Creek, Northern Territory

Aidan B. Soper

A thesis submitted in part fulfilment of the requirements of the Honours degree of Bachelor of Science in the School of Earth and Environmental Sciences, University of Wollongong 2014

Bachelor of Environmental Science (Honours)

October 2014
The information in this thesis is entirely the result of investigations conducted by the author, unless otherwise acknowledged, and has not been submitted in part, or otherwise, for any other degree or qualification.

Aidan Soper
15/10/2014

Cover image: Wangi Falls discharge on the 17/02/2014. Courtesy of Chris Washusen, Litchfield National Park Ranger
ACKNOWLEDGMENTS

This Honours Thesis has been the most enjoyable, challenging and insightful learning experience of my university degree to date. Successfully completing this project could not have been possible without the university and countless hours of assistance from my inspirational supervisors; Dr Jan-Hendrik May and Dr Tim Cohen. Henne, I am honoured to have worked by your side in the field, thank you for, firstly taking me to the Top End, and secondly assisting me with all of my fieldwork. It was hot and arduous at times, but you pushed through, prost! Tim, I cannot say enough about my appreciation for the confidence you had in suggesting to me such a magnificent topic and linking me up with Henne. You provided valuable direction and insight even when you weren’t here so I am grateful. Thankyou both for having patience along this journey and giving me the opportunity to draw upon your knowledge and experience, your constructive and critical review of my thesis was an integral part of successfully completing it to such a standard on time. The devotion and direction from the both of you, at times, half a world away is unmatched.

I would like to acknowledge the traditional owners of the land upon which I carried out my field work, and the Litchfield National Park Rangers; Sam Chris and Adam, for your accommodation as well as permission and assistance to work in some areas of Wangi Falls greatly contributed to my field work being a success. Your experience and knowledge of the Wangi area ensured that I completed my work in the short space of time I had without being a croc snack. Furthermore, I would also like to pay thanks to Dr Annegret Larsen whose insights and assistance in the field added another dimension to my work. Appreciations also go to Chris and Heidi in the SAL lab; your assistance in the early stages of the project was immensely valuable.

My love and gratitude goes to my mother Kathryn, I could write pages on how much you have done for me, but thank you for being understanding and accommodating me throughout my degree, your care and support has helped make this possible. Special mention also goes to Tom, Peter and Sue, as well as countless other friends and family, your encouragement and interest throughout the entire thesis has been amazing.

And finally not enough can be said about the love and energy my beautiful and devoted partner has provided throughout this journey. Jemma you were influential and supportive of my decision to undertake such a full-on project and I cherish the perspective and direction you have given me throughout this journey. I love you and couldn’t do it without you.
ABSTRACT

Flooding in the tropical Northern Australia is under researched relative to other regions of the continent yet the entire northern portion of the continent is affected by Australia’s most significant climatic phenomena, the Australian Indo Monsoon. This study of Wangi Creek (13° 09' 49" S, 130° 41' 07" E) in the Litchfield National Park investigates flood dynamics during the 2013-14 wet season. Wangi Falls cascades off an ungauged catchment on the Tabletop Plateau in the Litchfield National Park. The study reach extends from the plunge pool 3.1 km downstream, a key site investigated in previous paleohydrological studies due to the interpretation of extreme discharges in the Last Glacial Maximum. Using existing high resolution topographic data (LiDAR), plunge pool bathymetry, flood flow stage levels, catchment rainfall and soil moisture, an analysis of wet season rainfall-runoff relationships was undertaken. This was then used for a detailed analysis of inundation patterns and hydraulic characteristics in the study reach. Various scenarios of flow stage conditions were modelled using a 1D steady-state hydraulic model (HEC-RAS), resulting in the quantification of inundation patterns during differing flood stages. Results show that maximum daily rainfall was 201 mm and hourly rainfall 72.6 mm with peak hydrographic responses occurring within 30 minutes of maximum rainfall, Modelled discharge estimates of the ~ 4 m flood flows in 2014 range from 350-500 m$^3$/s, depending on selected roughness parameters. Previous estimates of extreme discharge of 8 m flow depth (3600 m$^3$/s) are examined and the hydraulic model supports such estimates in the upper part of the study reach. However, the presence of a migrating knickpoint (lowering modern levels by up to 2 m) is shown to have a large impact on predicted discharge. Precipitation intensities and unit discharge required to produce such predicted runoff are investigated within the thesis. There have been no observed required precipitation intensities in the Northern Territory to produce the past paleodischarge estimates nor has there been any observed unit discharge values recorded high enough to produce such discharge estimates for a catchment area the size of Wangi Creek. There are however estimates nationally (based on Probable Maximum Precipitation – PMP) that suggest that these rainfall intensities are possible and this is globally verified. Such issues are discussed in the context of previous research on this river which has suggested maximum floods during the Last Glacial Maximum, pointing to a much wetter and extreme climatic period. Beyond this local case study, such an approach provided an improved understanding of flooding dynamics and rainfall-runoff patterns in the seasonally flooded ‘Top End’ and may prove useful in linking past and present flood hydrology.
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<tr>
<td>AEP</td>
<td>Annual exceedence probability</td>
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<tr>
<td>ARI</td>
<td>Annual recurrence interval</td>
</tr>
<tr>
<td>BE</td>
<td>Bare earth</td>
</tr>
<tr>
<td>BoM</td>
<td>Bureau of Meteorology (Australia)</td>
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<tr>
<td>DEM</td>
<td>Digital elevation model</td>
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<tr>
<td>ENSO</td>
<td>El Niño Southern Oscillation</td>
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<td>IFD</td>
<td>Intensity-Frequency-Duration</td>
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<td>LiDAR</td>
<td>Light Detection and Ranging</td>
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<td>LGM</td>
<td>Last Glacial Maximum</td>
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<td>RFFA</td>
<td>Regional flood frequency analysis</td>
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<td>RMSE</td>
<td>Root Mean Square Error</td>
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<tr>
<td>RTK</td>
<td>Real time kinematic</td>
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<tr>
<td>TIN</td>
<td>Triangulated irregular network</td>
</tr>
<tr>
<td>NT</td>
<td>Northern Territory</td>
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<tr>
<td>PCO</td>
<td>Pine Creek Orogen</td>
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<tr>
<td>QBF</td>
<td>Bankfull discharge</td>
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<tr>
<td>Top End</td>
<td>tropical Northern Australia</td>
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<tr>
<td>TDR</td>
<td>Time-depth recorders</td>
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<tr>
<td>DLPE</td>
<td>Department of Lands, Planning and the Environment</td>
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<td>DLRM</td>
<td>Department of Land Resource Management</td>
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1. INTRODUCTION

Monsoonal flooding occurs across the equatorial tropics between the tropic of Capricorn and Cancer, driven by a reversal of the trade winds and associated wet season precipitation. In Australia the monsoon is part of the Indonesian-Australian monsoon system which delivers summer precipitation to the top third of the continent including Queensland (QLD), Western Australia (WA) and the Northern Territory (NT) (Reeves et al. 2013). The flood season falls between the months of November and March and represents 87% of tropical Northern Australia’s (see Figure 1) total rainfall, and accounts for ~26% of Australia’s total annual runoff (based on 30 year average of state rainfall, 1976-2005) (BoM 2014b). Furthermore, the wet tropics of Australia contain a number of important sites that have been used in the past to derive paleoclimatic conditions, including Wangi and Magela Creek, Burdekin Gorge, and the Herbert, East Alligator, Katherine, Finke, Lennard, Margaret, Fitzroy, Piccaninny, and Brooking Rivers (Figure 1) (Baker et al. 1985, Wohl et al. 1994, Nanson et al. 1996, Nott et al. 1996). Very little is known, however, about the relationship between wet season hydrology and channel morphology, and therefore detailed and integrated hydrologic and geomorphic studies are required in order to improve our understanding of both modern and past monsoonal flooding.

Figure 1: Northern Australian study sites used for determining past climatic conditions. Depicted by a yellow polygon is what is referred to as “tropical Northern Australia” or the “Top End”, an area of the Northern Territory that is part of the world’s semi-arid tropics above the latitude of 16°.
1.1 General concept of river floods

Flooding or floods can be interpreted and categorised by perspectives within the following three categories: (1) technical hydrological definitions specified in terms of magnitude and frequency of flow, (2) common sense definitions focused on practical consequences such as damage to property, and (3) environmental science definitions expressed as consequences for biota, the landscape, or other elements of the environment (Baker 1994). Wolman et al. (1960) demonstrated that higher amounts of fluvial sediment transport and consequential landscape modifications often occurred during geomorphic events that were of moderate frequency. Furthermore, this variable discharge that controls river morphology is referred to as the bankfull discharge, and has an occurrence interval of one to two per year (Pickup et al. 1976, Castro et al. 2001). For sediment transport to occur a threshold must be exceeded by the applied stress, for alluvial rivers of sand this is substantially lower than what would be expected in bedrock rivers composed of gravels and boulders (Leopold et al. 1953, Wolman et al. 1960). Therefore, flooding in sandy alluvial rivers can be considered a highly effective process with large potential to induce geomorphic change.

1.2 Monsoon driven floods in the Tropical Northern Australia

It therefore stands to reason that control of channel size and form is attributed to a controlling discharge, or set of discharges and sediment load. The magnitude of these events combined with the frequency, are the overarching factors to river channel morphology and flow dynamics (Wolman et al. 1960). Flood severity (magnitude) and the occurrence of flooding events (frequency) in tropical Northern Australia correlates with El Niño Southern Oscillation (ENSO), (La Niña = wet phases), the influential driver of the monsoon (Nanson et al. 1993, Wasson et al. 2007). Global climatic change is set to increase the magnitude and frequency of these extreme events in Northern Australia compounding the disturbance of current river conditions in the form of increased intense rainfall and tidal surges (Hennessy et al. 2004, Hamilton et al. 2005, Thompson et al. 2013). As this is regarded one of the most dangerous flood hazards and a leading cause of natural disasters (Alcántara-Ayala 2002), the most appropriate geomorphological approach to understanding this process includes the study of paleoflood (past) geomorphology and flood hydrology (Enzel et al. 1993, Baker 1994, Kale et al. 1997), and its calibration the modern hydrology.

When determining the modern hydrology of a river two key parameters exist that need to be evaluated:
1. The coefficient of variation or the ratio of the largest to the mean annual discharge, which is a hydrological indication of the variability in river runoff (Zuming 1982).

2. The flood duration or more importantly peak of threshold for sediment transport. This is the threshold that defines whether channel morphology is altered (Wolman et al. 1960).

River channels are dynamic and hence the geomorphic stability of river systems can also be disrupted by numerous external factors such as river training (anthropogenic), removal or alteration of riparian vegetation (natural or anthropogenic) and the land use in catchments or floodplains associated with developments such as agriculture (Gilvear 1999).

The Northern Australian tropics consist of nine geomorphological river classes which can be tentatively broken into alluvial and bedrock defined systems (Erskine et al. 2005). Bedrock systems in the tropical Northern Australia are characterised by extreme bank and bed resistance which limits the impact of varying conditions upon sediment transport. It has therefore been postulated that the action of rare and large floods dominate in altering these channel morphologies (Baker 1977, Patton et al. 1977). Generally these events have annual exceedance probabilities (AEP) of 1% or 0.1%, and as improbable as 0.001% when considered over annual recurrence intervals (ARI) of 100, 1000 and 100,000 years (Baker et al. 1998). These systems are contrasted by alluvial rivers, whose unconsolidated sediment channels morphologically adjust more easily to streamflow events of intermediate magnitude and frequency (Leopold et al. 1953, Wolman et al. 1960).

Monsoonal rivers flood seasonally and are generally characterised by slow and gradual hydrographs with strong, intermittent pulsations of streamflow (Erskine et al. 2005). For Northern Australia the limited understanding of monsoonal flood processes is attributed to relatively short-term hydrological records from river gauging stations, many of which have no-or an unreliable-rating curve to convert stream height data to discharge data. A number of stations have extensive periods of missing data within the streamflow record, and numerous catchments, particularly those that are relatively small, are ungauged (Weeks et al. 2005, Moliere 2007). During monsoonal rain conditions, floodplains are often inundated by bankfull flows (Tockner et al. 2002, Jakobsen et al. 2005, Wasson et al. 2007). Through the use of paleo-indicators and gauged stage height, these bankfull flows can be modelled in multiple dimensions to determine the hydraulic characteristics of the flow.
1.3 Aims and Objectives

The overarching aim of this study is to determine flow conditions related to flooding in the Wangi Creek catchment, located in the monsoonal tropics of Northern Australia. The degree to which monsoon river channel areas are adjusted to their seasonal discharge is an area of ongoing investigation (Baker et al. 1987, Nanson et al. 1993, Baker et al. 1998, Jansen et al. 2004). To examine such a notion for tropical Northern Australia the thesis sets out to test the following hypothesis: “Channel capacity and floodplain inundation is adjusted to the seasonal monsoonal flooding”. To test such a hypothesis the thesis has the following aims:

1. To characterise rainfall-runoff relationships in a monsoon environment
2. To determine bankfull capacity, inundations patterns and hydraulic characteristics for the modern Wangi Creek

To achieve these aims a greater understanding of paleoflood hydrology both in terms of historical flood analysis (observation) and systematic flood hydrology (measurement) is required (Baker 1987). The project will quantify hydraulic characteristics of the modern flow regime at Wangi Falls using a standard one-dimensional steady-state backwater hydraulic model using 2013 LiDAR and 2013-2014 stage-level data. It will examine the role of seasonal versus extreme events for inundating along Wangi Creek, thus enabling an assessment of past flow conditions (based on existing chrono-stratigraphy).

1.4 Significance

A more complete understanding is needed of the geomorphological processes and controls of flooding (Barredo 2007), particularly in Northern Australia, but is still impeded by a significant lack of data (Marston et al. 1996, Moliere et al. 2009), predominantly both in ungauged and small catchments (Weeks et al. 2005, Weeks 2006). The novel contribution of this project is that it will give us a greater understanding of these floods by acquiring new datasets. This will enable future research into the behaviour of floods, rainfall-runoff characteristics and inundation patterns of small ungauged catchments. The spatial relevance of this is a necessity to any engineering and planning going forward (Gilvear 1999, Alcántara-Ayala 2002). Due to monsoonal rainfall that is characterised by widespread convection and random meso-scale events such as thunderstorms (Story et al. 1976), flooding can take place over an entire region or a single catchment. By determining the rainfall
characteristics of the Wangi Creek catchment, this research will also assist in assessing the rainfall distribution and accuracy for the region.

The modelling technique that will be applied for Wangi Creek will quantify the behaviour of a modern wet season flood, and discuss it in the context of past flooding events. In this context, late Pleistocene and early Holocene paleoclimate reconstruction at Wangi Creek and other nearby sites have suggested that plunge pool flood ridge deposits at the base of waterfalls are evidence of fluctuating water levels, and are representative of periodic but extreme fluctuations in rainfall (Nott et al. 1994, Nott et al. 1996, Nott et al. 1999). This paleohydrological claim declares that flood stages of at least 8 m occurred during the Last Glacial Maximum (LGM) at and immediately before 20 ka. These results, however, represent significant conflict with other published literature advocating that climate in monsoonal Australia was arid during the LGM (Fitzsimmons et al. 2013), and monsoonal flooding was greatly reduced during this period (Reeves et al. 2013). To critically evaluate these contrasting views, gauging and modelling of the modern fluvial regime for Wangi Creek is required (Baker 1987).

1.5 Thesis Outline

This thesis is structured into seven chapters with the following chapter (two) providing a review of the understanding of common river morphology in tropical Northern Australia and the role of modelling in paleohydrological reconstruction in the current literature. Chapter three provides a regional geological, geographical and climatic overview of the study site, and introduces the geomorphic channel characteristics. Chapter four describes the methods used to collect and analyse field data combined with historical data sets for various model analyses and assessments. Chapter five presents the results of the reach scale geomorphic analysis, rainfall-runoff relationship, spatial inundation of channel cross-sections, and hydraulic characteristics of Wangi Creek. This is followed by a discussion of the relevance of these results in relation to the broader literature and their implications (Chapter six), which further provides the limitations of this study and future recommendations emerging from it. Finally, Chapter seven identifies the broader conclusions of this study from a Quaternary paleo-environmental reconstruction perspective.
2. LITERATURE REVIEW

The purpose of this chapter is to briefly review the studies of monsoonal channel morphology in tropical Northern Australia, and establish the relevance of these rivers in the wider context of paleoclimate reconstruction literature. A summary of paleoclimate reconstructive techniques and current interpretations specific to tropical Northern Australia are provided with reference to the approach taken at Wangi plunge pool.

2.1 Floods and channel morphology in monsoonal Australia

2.1.1 Controls on fluvial channel morphology

The effective discharge coupled with its occurrence interval are the overarching factors in determining channel morphology (Wolman et al. 1960). Flooding severity (magnitude) from a hydrological perspective is a combination of catchment variables; geomorphologic setting, hydrological regime, the relative interactions between sediment supply and transport capacity and surface – groundwater relationships (Barredo 2007, Gurnell et al. 2012, Green et al. 2013). For example, the interaction between these variables namely groundwater and sediment supply, are pivotal in determining the ability of a river reach to support riparian vegetation (Green et al. 2013). This as a result may well define whether a channel will be confined, unconfined and laterally stable or unstable. Following on, the occurrence of flooding (frequency) is characterised by time, in that the most catastrophic events will have a longer return interval than smaller magnitude floods (Wolman et al. 1960). This does not, however, automatically imply that larger portions of geomorphic work are done in these low frequency high magnitude events, as in reality moderate floods of higher frequency have been demonstrated to achieve more sediment transport through time than the high magnitude floods (Wolman and Miller, 1960). The question remains whether this is applicable to the seasonal tropics.

River reaches can be classified into three broad dominant substrates; bedrock, alluvium and colluvium (Montgomery et al. 1997). Bedrock channels are characterised by high transport capacities relative to sediment supply and are generally confined by valley walls on steep slopes. Contrasting to this, alluvial channels are more widely variant displaying morphologies that reflect the slope and position within the reach. Alluvial channels exist as either confined or unconfined and with or without a floodplain associated. Although colluvial channels
commonly comprise alluvium, they are typically headwater streams that demonstrate ephemeral flow conditions (Montgomery et al. 1997).

### 2.1.2 Channel morphologies typical of the monsoonal tropics

Tropical rivers globally have been broadly divided based on their geomorphic and geological setting. Specifically these are (I) orogenic mountains belts, (II) sedimentary and basaltic plateau/platforms, (IV) cratonic areas, (V) lowland plains in sedimentary basins and (VI) mixed terrain (Latrubesse et al. 2005). Furthermore, the morphology of these rivers are most effectively described by their sinuosity, symmetry and whether they are single, multi-thread or complex anabranching systems (Latrubesse et al. 2005). As has been mentioned, these channel morphologies are also broadly governed by both the magnitude and frequency of flow events.

In humid temperate zones alluvial channels that are enlarged by extreme flow events revert back to their state of dominant or more common morphology relatively soon after the event (Gupta 1995). The reverse occurs in arid zones with bankfull channel enlargements remaining for long periods after the event (Wolman et al. 1978, Gupta 1995). Unlike rivers in temperate and arid zones, tropical regions influenced by strong seasonal differences in precipitation as typical for monsoonal climate are subject to two dominant and contrasting flow regimes generating a channel-in-channel morphology as illustrated in Figure 2 (Gupta 1995). In this context, the seasonality of flow attributes larger stage height in the wet and low flow in the dry (Gupta 1995), even though this is only a general interpretation and there are other controlling hydrological variables that have been summarised above. These flow conditions are evident in monsoon dominated rivers in India, for example and are illustrated in Figure 2, with dry season flow (red line) confined to a braided channel, and mean wet season flow (blue line) overtopping the braid-bars. A much higher “flood bar” or macro channel is also present indicating the most common flood stage (i.e. average maximum flow) that occurs during the wet season (Gupta 1995).
2.1.3 Channel morphologies in Tropical Australia

Rivers in tropical Northern Australia are generally relatively short in length and receive the majority of their runoff from the more coastal catchments where precipitation tends to be higher than on the extensive sandstone plateaus. The runoff received is seasonal leading to a fluctuating flow regime, with peaks occurring between November and May (Moliere 2007). This seasonal variability is attributed monsoon experienced in this period. Consequently not only discharge, but also sediment transport is significantly higher in these periods (Wohl 1992). The processes behind monsoonal flooding in Northern Australia have received increased attention in the last two decades (Wohl 1992, Wohl et al. 1994, Baker et al. 1998, Wohl 1998), and region has been tectonically stable for an extended period of time (Pietsch et al. 1988) it therefore stands that aside from hydrological variables (see above) underlying lithology is an additional key controlling factor on channel morphology for this region.

The geomorphological setting of Northern Australia is broadly defined by weathering resistant plateaus and lowland plains (Erskine et al. 2005), when the geological setting defined in Latrubesse et al. (2005) is applied. Nine prevailing river typologies have been proposed that are specific to the tropical Northern Australia according to the longitudinal gradient of the channel (steep headwaters to flat lowland plains), (Erskine et al. 2005), as illustrated in Figure 3. The most probable sequence of these observed river types are:

- Resistant Bedrock→Bedrock-confined→Island & Ridge Anabranching→Freshwater Wetlands & Billabongs or
- Resistant Bedrock→Bedrock-confined→Meandering→Floodout→Freshwater Wetlands & Billabongs.
A common variable in the observed river typologies is that bedrock channels and bedrock-confined rivers are almost always present in some part of the catchment.

Table 1 summarises the general characteristics of the river typologies proposed by Erskine et al. (2005) in Figure 3, following a sequence from the higher energy headwaters on the plateaus and escarpments to the coast. Alluvium in tropical Northern Australian Rivers is generally related to the channel flow energy with large gravels occurring in high energy upstream bedrock channels and fine sand and muds in the low energy estuaries and wetlands. The morphology of bedrock channels (Figure 3 and Table 1) changes with relation to flow energy. A shallowly incised channel is associated with gentle gradients where stream power is not suffice to generate erosion, whereas deep gorges form in reaches with sufficient erosive energy to remove bedrock in steeper reaches. The two channel types are often separated by an escarpment along the extensive sandstone plateaus with waterfalls and deep basal plunge
pools. Bedrock confined channels are usually generated when channel widening occurs and lower streamflow energy can lead to the formation of floodplains with small amounts of riparian vegetation. However, this can be stripped during large flood events as described in Nanson (1986).

The large plunge pools described in Erskine et al. (2005) are particularly common in the Kimberly, Kakadu and Litchfield National Park along the prominent sandstone escarpment. Waterfall sites in tropical Northern Australia are subject to strong seasonal changes during a wet season and particularly during floods of extreme magnitude, as water level within the plunge pool rises several meters above pre flood levels. These events are capable of producing sediment ridges or levees adjacent to the plunge pool across a plateau. The process occurs as the result of high energy waves generated from the waterfall carrying sediment, similar to that of slackwater deposits but coarser-grained (Nott et al. 1994, Nott et al. 1996). The importance of these sediments for paleoreconstruction will be discussed below.

Additional to the mentioned bedrock channels, there are six distinct alluvial river types commonly found in the lowland plains in tropical Northern Australia (summarised in Table 1). Avulsive rivers are thought to occur due to blocking of the existing channel by either a sand plug as discussed in Jones et al. (1993), or catastrophic flooding on a millennial scale (Erskine et al. 2005), however, more study is needed to understand the causes and timing of this. Table 1 summarises meandering channels into three main types that correlate with the confining or unconfining nature of the sediment and banks as well as the associated riparian vegetation (Cohen et al. 2000, Erskine et al. 2005). Straight reaches as suggested have low sinuosity and occur in low energy environments attributed to the gentle gradient. Shallow pools and riffles are experienced in these reaches attributed to minimal bed scour and generally eventuate into a wetland or billabong (Schumm et al. 1972). Similarly floodouts, that occur when a channel becomes choked of sediment and flow spills across a floodplain, generally form into a wetland or billabong if the channel becomes terminal. In some cases the channel resumes further downstream. Flow in these reaches is characterised by seasonal variations, with large flow in the wet and low flow in the dry season (Tooth 2000). The final channel reach type that is possible before terminating is an anabranching system. These are characterised by multiple interconnected channels that are separated by large stable alluvial islands, dividing flow up to bankfull (Nanson et al. 1996). This form of channel type in Northern Australia is the most efficient at transportation of sediment in low energy
environments (Jansen et al. 2004). Wetlands and billabongs are most commonly at the termination point of tropical Australian river. They form due to rapid sedimentation of estuarine channels raising the wetland (previous channel) above the level of tidal inundation (Wasson 1992).

<table>
<thead>
<tr>
<th>Type</th>
<th>Topography</th>
<th>Common geomorphic Features</th>
<th>Environment / Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Resistant Bedrock</td>
<td>Plateau Surfaces</td>
<td>Cascade falls and pools</td>
<td>Incision of bedrock is relative to flow energy, with deeper gorges attributed to more extreme flow</td>
</tr>
<tr>
<td>2. Bedrock-confined</td>
<td>Plateau Surfaces</td>
<td>Alluvial floodplains (commonly eroded)</td>
<td>Bedrock resistance is greater than flow energy hence widening cannot occur</td>
</tr>
<tr>
<td>3. Avulsive</td>
<td>Bedrock confined valleys onto a coastal floodplain</td>
<td>Sand plugs and abandoned channels</td>
<td>Occur when an existing channel is blocked</td>
</tr>
<tr>
<td>4. Meandering</td>
<td>Range from bedrock valleys to densely vegetated lowlands</td>
<td>In channel vegetation, log jams and point bars</td>
<td>Classified as confined, laterally migrating unconfined or laterally stable unconfined with the energy relatively high, medium and low respectively</td>
</tr>
<tr>
<td>5. Straight</td>
<td>Gentle gradient terrains</td>
<td>Pools and riffle sequences</td>
<td>Low energy flow environments that generally eventuate in to wetlands or billabongs</td>
</tr>
<tr>
<td>6. Floodout</td>
<td>Low energy alluvial environments with extensive floodplains</td>
<td>Intermediate and terminal floodouts</td>
<td>Areas of rapidly reduced channel stream power that causes localised in-channel deposition of sediment</td>
</tr>
<tr>
<td>7. Island &amp; Ridge Anabranching</td>
<td>Low energy environments</td>
<td>Vegetated alluvial islands, braid bars</td>
<td>Multiple channels with alluvial islands that divide flow up to or near bankfull</td>
</tr>
<tr>
<td>8. Co-existent Mud Braided &amp; Anabranching</td>
<td>More specific to the Lake Eyre Basin.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9. Freshwater Wetlands &amp; Billabongs</td>
<td>Generally at downstream extents of river or directly upstream of an estuary environment</td>
<td>Channel billabongs and backswamps</td>
<td>Formed via intense sedimentation in estuarine channels raising the wetland above the level of tidal inundation</td>
</tr>
</tbody>
</table>

Table 1: General characteristics of tropical Northern Australia specific river typologies, from the headwaters to downstream reaches (Erskine et al. 2005)
2.2 Approaches to paleoflood hydrology

2.2.1 Reconstruction of late Quaternary paleohydrology from sedimentary archives

Paleohydrological reconstruction of the late Quaternary is generally aimed at providing details of flow variability over the past 100 to 10,000 years (Benito et al. 2004). Techniques for this have generally focused on the quantitative analysis of relationships between precipitation, runoff and sediment budget (Gregory et al. 2003). However, modern day paleohydrology has become more comprehensive and encompassed all components of the hydrological cycle; and includes the direct gauging of modern flood stages, use of geological indicators, documented historical data and atmospheric relationship to extreme floods (Gregory et al. 2003).

The use of geological indicators in paleoflood reconstruction has successfully been employed throughout the world and offers greater accuracy when combined with modern flood stages (Benito et al. 2003). These indicators include flood deposits and silt/erosion lines found along a river channel (e.g. bank, wall or terrace) which most often represent the minimum flood stage (Benito et al. 2004). The magnitude and frequency of flooding events are accounted for by documenting a collection of paleodischarges that are greater or smaller than the threshold peak discharge. The use of these techniques varies depending on channel substrates such as bedrock and alluvial, for which the approach for both differs (Benito et al. 2004).

Bedrock dominated channels are thought to be the most suitable for reconstructing paleoflood records as they effectively accumulate flood deposits and preserve flood indicators (e.g. scours) (Baker 1987). In particular the flood (or slackwater) deposits represent an accurate flood stage minimum and have been dated back at least 10,000yr (Baker et al. 1985, Baker et al. 1987). Common dating techniques used are radiocarbon (14C), luminescence methods (thermo- (TL) and optically stimulated (OSL) luminescence). The drawback in using bedrock channels for paleostage indication is in the dating. The dated age of the material may affected by methodological limitations, for example the scarcity of dateable material and residence time of the organics for C-14 (Baker et al. 1985).

As an alternative to this, terraces are often used as the most dominant feature used as an indication of paleostage for alluvial channels (Benito et al. 2004). Preserved surfaces that are
flood modified indicate a period of exceedence whereas undisturbed surfaces represent non-exceedence. This method is carried out by accurately mapping floodplains and lower terraces or benches. A detailed stratigraphic description of the floodplain or terrace is developed and dated, providing details of layers that indicate inundation or not (Benito et al. 2004). There is, however, ambiguity associated with this technique as the water depth above the mapped surface is unclear and completeness of the paleoflood stratigraphy record is never certain (Benito et al. 2004).

2.2.2 Reconstruction of Northern Australian paleoclimate

A variety of techniques have been employed for developing a paleoflood and climate record for the monsoonal north of Australia. These include the use of bedrock channels features used by Baker et al. (1985) at Katherine (Figure 1), and the use of alluvial stratigraphy at Magela Creek in the Kakadu National Park (Nanson et al. 1993). The accuracy and difficulties of these approaches have been mentioned and it is clear that these methods are effective to a period of about 10 ka. An alternative approach has been proposed as outlined in sub-section 2.1.3: levee deposits adjacent to waterfall plunge pools, at least at three separate sites in tropical Northern Australia as identified by Nott et al. (1999), were interpreted to represent paleoflood records that extend at least 30 ka. Preservation of the sediment deposits occurs because flow velocity drops significantly immediately downstream of the waterfall and allows for preservation of sediments. Luminescence dating of levee sediments suggests flooding to at least the levee elevation during the late Pleistocene (LGM) and again during the mid-Holocene (Nott et al. 1999). These findings suggest high magnitude flooding and an active monsoon during the LGM contrary to the notion of dry climatic conditions in the Top End during this time as reflected in most other proxy records (Reeves et al. 2013).

Following on from the above, the plunge pool at Wangi Falls had the potential of reaching 8 m during the LGM and again in the mid-Holocene based on works by Nott et al. (1996). Previous observations and measurements from Nott et al. (1996) of assigned a discharge of 525 to a 2.2 m stage level at Wangi Creek and on proportional outflows from the plunge pool, a discharge of 3600 m$^3$/s would be required to produce a stage capable of over-topping the 7.6 m levee. This derived discharge is justified by a comparison to the Costa (1987) curve adapted in Figure 4, that plots world maximum discharge against catchment area. This assumes, however, that world maximum floods are an appropriate representation of tropical Australian rivers. On the premise that the tropical Northern Australia experiences the same climate as the world floods documented on the curve a discharge of 3600 m$^3$/s would
theoretically be possible for a catchment of 60 km$^2$, but it is more likely that this is not the case as is represented in the Thompson et al. (2013) adaption. This adaption (see Figure 4) identifies that based on floods occurring in several Australian rivers, recorded in the literature, a maximum discharge for catchments of ~60 km$^2$ would be between 100 and 600 m$^3$/s - vastly smaller than the 3600 m$^3$/s proposed by the Costa (1987) curve.

Over the recent years, increasing evidence for late Quaternary paleoclimatic conditions in tropical Australia has emerged from a variety of new proxy datasets, and has been summarised by Reeves et al. (2013). Most of these datasets seem to indicate that at 35 – 32 ka (late Marine Isotope Stage 3) areas in the north of the continent were much wetter than present. These conditions continued to persist in temperate zones through till the onset of LGM (~25 ka) but records from Indonesian vegetation and speleothems suggest that the tropics where dry with no evidence of a strong monsoon penetrating the Australian main land (Reeves et al. 2013). In accordance with Indonesian records dry climate persisted through the LGM with the monsoon absence corresponding to lower lake and river levels in many parts of the interior of the continent (Fitzsimmons et al. 2013). Wetter conditions returned to the north-western part of the continent in the early deglacial period at ~15 ka and by ~14 ka the monsoon had again penetrated tropical Northern Australia bringing warmer and wetter conditions (Reeves et al. 2013). By 9.8 ka glaciers in New Guinea disappeared and the land: sea ratio in the north approached modern conditions (Barrows et al. 2011). Wet conditions in

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*Figure 4: Maximum rainfall-runoff envelope curve adapted from Costa (1987) with Australian flood peaks plotted (Thompson et al. 2013)*
Borneo and Flores throughout the mid Holocene suggest a wetter period for tropical Australia (Partin et al. 2007), but drier conditions were apparent over much of the Australasian region through the late Holocene, attributed to ENSO being strong (McGregor et al. 2004), which led to a decrease in overall fluvial activity.

In summary, the scarce and – in the case of the LGM – conflicting datasets on paleoclimates and landscape evolution in the Top End published in the literature call for additional and more detailed investigations into the paleofloods experienced in tropical Northern Australia, particularly where used for paleoclimate reconstruction such as the waterfall and plunge pool sites (Nott et al. 1999). Despite its importance in paleoclimate studies, there is still a lack of relevant research at the Wangi plunge pool site which is required to clarify the significance of plunge pool and flood levees for the reconstruction of paleo macro-floods during the LGM. In this context, a modelling approach could be adapted to evaluate the flooding potential of sites such as these, and thus to assess the validity of previous interpretations (Benito et al. 2003).

### 2.2.3 Catchment morphometrics, the historical record, and regional flood frequencies

Estimating peak flow and the associated recurrence interval is difficult when stage and discharge records span a shorter return period than of interest, for example estimating the 100 year flood with only 50 years of data. It becomes more complicated when the catchment of interest is ungauged and no flow data exists at all (Zrinji et al. 1994). As previously mentioned in sub-section 2.2.2 this situation can be compensated by applying a statistical method of a RFFA (Zrinji et al. 1994, Aronica et al. 2007). A new method of RFFA for the Northern Territory recently has been summarised in which all stations with records greater than 15 years, and catchment areas less than 1000 km² were analysed for an annual series of flood peak discharges (Weeks et al. 2005, Weeks 2006). Although 15 years is still less than recommended, it ensures that there will be enough stations to create an accurate analysis. The Northern Territory was divided into 4 regions to account for the variation in climate which include the Alice Springs region, the Arid region, the Katherine region, and the Northern region. Design floods were then calculated for each station and from this regression equations were determined for the 5, 10, 20 and 50 year ARI, incorporating catchment area, stream length and catchment slope within the calculations.
2.2.4 Paleoreconstruction using hydrological models

A review of two-dimensional modelling of river flood inundation research by Horritt et al. (2002) confirms that remote sensing, raster-based and finite element approaches can be used to model inundation extent and bulk hydrometric response for river reaches 5–60 km in length. One, two and three-dimensional models can be created using a variety of computer programs. One-dimensional steady flow models require a general geometric representation of the channel, achieved through cross-sectional surveys and use of past flood markers to determine maximum flood levels. These models assume peak instantaneous and simultaneous flooding at all sections of the reach as well as uniform velocity across the cross-section (Carling et al. 2010, Mohammed et al. 2012). To overcome these limitations 2D and 3D models are implemented to simulate the diverse velocity experienced across a channel, done by incorporating digital elevation models (DEM’s) obtained from remote sensing (for example LiDAR) (Carling et al. 2010).

Two-dimensional flow models are the most effective in regards to predicting floodplain inundation during bankfull flows (Horritt et al. 2001). One-dimensional floodplain models are too simplistic and do not incorporate enough flow variables to accurately predict inundation, whereas 3D models are relatively complex and require more calibration and more accurate input data (Horritt et al. 2001, Carling et al. 2010, Mohammed et al. 2012). It is demonstrated in Cook et al. (2009) that in a simulation of steady state 2D modelling, flow velocity is accurately simulated when water passes under a bridge, with velocity increasing under the bridge and then reducing after exiting. This kind of information is required for simulation of sediment transport and the floodplain inundation effects during floods. In this particular study it was demonstrated that the combination of 2D models with high resolution 6 meter digital elevation model (DEM) topographic data decreased the inundation area of a 30 m resolution model by 25%. This alludes to the situation that effective inundation modelling is possible when high resolution DEM’s are available for a study reach.

Tropical Northern Australia is limited in the amount of available hydrologic data for flow modelling. With a fairly limited number of gauging stations, deriving accurate hydrographs for small catchments is not possible. To effectively determine past flood inundation, modelling using a combination of variables is therefore the best alternative. The use of flood markers and flow height can be used effectively to model floodplain inundation and hydraulic characteristics of the flood itself. An example of this is demonstrated at the Lily Pond.
waterfall site on the Katherine River (see Figure 1) where the height of flood debris and sediments are representative of a discharge estimated at 157 m$^3$/s with a mean flow velocity of 2.15 m/s$^{-1}$ (Manning’s n = 0.025, slope = 0.002), occurring during the January 1998 flood (Nott et al. 1999), however, there is no rainfall or quantitative evidence to test the accuracy of this or suggest the exact date of occurrence.

Furthermore, Wohl (1992) presents a situation in which a step-backwater HEC-2 model is used to estimate the discharge values required to reach a paleoflood mark in the Burdekin Gorge (Figure 1). This model approach utilises manually surveyed cross sections and as a result, due to the low relief of floodplains the accuracy of inundation delineation is influenced by the resolution of topographic data. Today, high-resolution DEMs in the form of triangular irregular networks (TIN) can be derived as they generate a more accurate representation of channel and floodplain features (Casas et al. 2006). The reliance on high resolution data determined by Casas et al. (2006) therefore suggests that LIDAR is the optimal remotely sensed dataset for hydraulic modelling, and is enhanced by the use of ground reference points.
3. REGIONAL SETTING

Wangi Creek receives a high percentage of runoff from its 60 km² upper catchment on the Table Top Plateau in the Northern Territory. This northern tributary of the Reynolds River runs ~6 km downstream of Wangi Falls before a major confluence point, the study reach comprising of the first 3.1 km downstream including 200 m of adjacent floodplain either side of the channel. The river reach is characterised by a waterfall that cascades into the low lands of the Table Top Plateau with multiple river forms occurring in the 3.1 km stretch, as presented below and discussed further within the results chapter. The aboriginal heritage site is cited to contain two sedimentary flood levees’ that contain records residing back to ~30 ka (Nott et al. 1996). Wangi Creek is an ungauged catchment and river with the closest rain gauging station at Walker Creek (Figure 5).

Figure 5: Wangi study site extent relative to tropical Northern Australia. The location of gauging devices; climate station (red dot) and time-depth recorders (green dots) are identified. Reach length zones are illustrated relative to the long profile of the river. Drainage is from top right to bottom left
3.1 Regional geology

The Wangi Falls catchment is part of the Pine Creek Orogen (PCO), exposed over an area of 47,500 km² at the northern margin of the Northern Australian Basins. The Litchfield province is one of three major geological provinces located within the PCO (Glass 2011) and covers ~9000 km² (Pietsch et al. 1988). This province is situated on the western third of orogen and is comprised of north-northeast trending poorly exposed Paleoproterozoic metamorphic and igneous rocks with placement ages ranging from approximately 1800 to 2200 Ma (Glass 2011). Wangi Falls overlies the mid- to upper-amphibolite facies Welltree Metamorphics.

Locally the Wangi catchment is dominated by 5 general surface lithologies which can be seen in Figure 6. These are as follows (Hollis et al. 2011):

- **Pfb** - Feldspathic metagreywacke, brown to grey-green, thickly bedded to massive, fine- to coarse-grained, with graded bedding in places and minor lenses of volcanilithic pebble conglomerate; brown to grey, laminated phyllite, slate and mudstone; minor quartz-mica schist; porphyroblastic quartz-mica hornfels, and andalusite schist near granite contact
- **Ptd** - Massive cross-bedded quartz sandstone, commonly ripple marked; quartzite, quartz-pebble conglomerate lenses
- **Czf** - In situ and reworked nodular, concretionary, pisolithic and mottled lateritic duricrust
- **Czs** - Sand: Undivided alluvial and residual
- **Qcl** - Colluvium, sheet-wash deposits: sand, silt, clay
- **Qa** - Quaternary alluvium

The varying flood levee sediments (Qa) discussed in Nott et al. (1996) are most likely the end product of extensive sandstone weathering and downstream deposition during flood events.
3.2 Vegetation in Litchfield

The Litchfield National park contains numerous landscape and vegetation types that can be broadly divided into three landscape units and three correlative vegetation units, as classified by Edwards et al. (2001), (Table 2).

<table>
<thead>
<tr>
<th>Landscape Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lowlands</td>
<td>Slopes &lt; 2°, elevation &lt; 90 m</td>
</tr>
<tr>
<td>Hillslopes and escarpments</td>
<td>Slopes &gt; 2°, elevation 90–160 m</td>
</tr>
<tr>
<td>Plateau</td>
<td>Slopes &lt; 2°, elevation &gt; 160 m</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Vegetation Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low open woodland</td>
<td>Trees 5–10 m; foliage projective cover 1–10 %</td>
</tr>
<tr>
<td>Woodland</td>
<td>Trees 10–30 m; foliage projective cover 10–30%</td>
</tr>
<tr>
<td>Open forest</td>
<td>Trees 10 – 30 m; foliage projective cover 30–70%</td>
</tr>
</tbody>
</table>

Table 2: Summary of the broad landscape and related vegetation units adapted from Edwards et al. (2001)

To further expand on the vegetation units above seasonally inundated floodplains are dominated by grasses and sedges with almost no woody plants present (Griffiths 1997). Both monsoon rainforest and tall open woodlands occur in stream channels and levee units. These groups require permanent fresh water unlike the tall open forest and low open woodlands, generally found on the plateau surface and surrounding steep hill slopes, although some open woodlands are common in the undulating lowlands (Griffiths 1997). Textures in the soils
vary from sand and sandy loams near channels and on the plateau to clays on the floodplains and lowlands (Griffiths 1997).

3.3 Climate

3.3.1 Regional Climate

Annual variation of rainfall in this region is driven by the southward movement of the Intertropical Convergence Zone (ITCZ) illustrated in Figure 8, with the associated onset of monsoon low-pressure troughs and tropical cyclones that generate precipitation in the Australian summer months (Reeves et al. 2013). The decadal and inter-annual variability of rainfall in tropical Northern Australia is influenced by the ENSO (McBride et al. 1983, Nanson et al. 1993). The total annual monsoon rainfall (July to June) for the tropical north varies to a high degree throughout two decades, as is evident in Figure 7. For the three sample stations used, the lowest recorded monsoon total was 1159 mm for Batchelor in the 2002/03 wet season which corresponded with a weak El Niño event. The highest monsoon total was 2959 mm occurred at Darwin Airport in the 2010/11 wet season corresponding with a 20 year high La Niña. This monsoon season and corresponding La Niña resulted in highest total rainfall occurrence for all three stations.

Figure 7: Total annual rainfall received during the wet season since 1993 for Darwin Airport, Batchelor and Walker Creek, relative to the inter-annual variability of ENSO (BoM 2014c)
Local Climate

Wangi Creek does not have a rain gauge in or close to the catchment, with the nearest sites being Walker Creek and Batchelor (see Figure 5) at 9.6 km and 40 km away from the plunge pool respectively. Batchelor offers a more complete record over the past decade but Walker Creek is the closer site of the two, and might therefore offer a more accurate estimate of the rainfall patterns for the Wangi catchment on a sub-annual scale. When sub-annual rainfall averages for Darwin Airport and Walker Creek were compared approximately 87% of rainfall occurred between November and March, and 97% between October and April for the Darwin Airport gauge (74 year average). During the same months 90% and 98%, respectively, of annual rainfall occurs at Walker Creek based on a 22 year average. It is apparent that a high proportion of rainfall and streamflow occurs in the austral summer months with the average monthly rainfall experienced at two sites in tropical Northern Australia summarised in Figure 9. On average Walker Creek receives more rain than Darwin, particularly in the month of February, suggesting this region is slightly wetter.
Figure 9: Average monthly rainfall experienced at Darwin Airport (Station No. 14015) 1941-2014 and Walker Creek (Station No. 14279) 1993-2014, Percentage of the total annual rainfall for Walker Creek is displayed above each month (BoM 2014b)

3.4 Wangi Creek geomorphology

The 60 m high Wangi Falls are located approximately 150 km southwest of Darwin in the Litchfield National Park (Figure 5), and have a watershed that is ~60 km². Founded on 2014 field observations, and the vegetation zones and river typologies summarised in Griffiths (1997) and Erskine et al. (2005), the river reach can be divided into the upstream upper catchment (prior to the waterfall) and following five geomorphic zones downstream of this.

3.4.1 Plunge pool zone (and in this description the upper catchment)

Wangi Creek is shallowly incised within the bedrock directly upstream of the plunge pool (Figure 10). This upland resistant bedrock is similar to that found in the much larger Katherine River catchment (Baker et al. 1987), with the cross-bedded quartz sandstone (see Figure 6) forming a resistant cap-rock, which results in the formation of a prominent escarpment and waterfall. Below the 60 m Wangi waterfall, a basal plunge pool that is ~100 by 50 m and up to 5 m deep has formed, and is confined by dense gallery monsoon rainforest. Adjacent to the plunge pool at intervals of 50 and 200 m away elevated levees occur at ~2 and ~7 m above dry season low-flow levels. Within the pool, alluvium can be separated into sands of varying size through to gravels and cobbles as well as large amounts of organic material. Such variation in bed load material is evidence of the varying bathymetry and flow velocities experienced in the creek.
3.4.2 Vegetation confined billabong zone

Further downstream from the plunge pool the channel becomes relatively straight and forms a series of pools or billabongs, that for the 2013 dry season had a water depth of ~3 m deep and a water surface width of ~10 m (Figure 12). Dry season flow stage in this sub-reach is confined by the dense rainforest type riparian vegetation which extends from the plunge pool zone laterally confines the channel (Erskine et al. 2005). This section of the reach has a much larger macro-channel that is not associated with dry season flow stage and is confined by up to 7 m high flood levees. Sand and fine organic matter have become the dominant alluvium with low flow velocity corresponding to a gentle gradient. The most apparent change in this zone is that it is characterised by both low flow stage channels within a much large macro channel, and billabong sections.
3.4.3 Stable zone

Downstream of the road crossing evident in Figure 5, the reach can be distinctly divided into the stable, knickzone (Figure 14 and Figure 15) and destabilised (Figure 16 and Figure 17) sub-sections. The stable zone is characterised by a small portion of billabongs similar to the upstream subsection (Figure 12) and further downstream a wide macro channel with a large dividing island (Figure 5) of densely vegetated rainforest (Figure 13) similar to that in the plunge pool zone. During the dry season flow is confined to the right of the channel of the observed macro channel, stabilised by dense vegetation as illustrated in Figure 13, with up to ~2 m of peat accumulating in a large proportion of the channel.

3.4.4 Knickzone

This zone is highlighted by two dramatic drops in thalweg elevation due to the presence of knickpoints (Figure 14 and Figure 15). In the 2013 dry season the knickzone was characterised by two knickpoints at ~2500 and ~2700 m downstream of the plunge pool. At the end of the wet season in 2014 it was observed that these knickpoints had migrated further upstream and formed one knickpoint illustrated in Figure 15, hence this zone encompasses both the 2013 and 2014 knickpoint locations. Due to the abrupt change in geomorphic and vegetation characteristics downstream of the knickzone, the knickzone migration along the reach seems to have caused geomorphic change in the form of vegetation alterations and base level lowering. Further evidence of the migrating knickzone within the study reach Wangi Creek and beyond will be discussed further, in the results chapter.
3.4.5 Destabilised zone

The most downstream sub-reach is characterised by strong channel erosion, and the deposition of large bar features within the macro channel that have changed throughout the 2013/14 wet season is evident in Figure 16 and Figure 17. In-channel vegetation has eroded and migrated, forming a large log jam during the 2013/14 wet season, at the downstream extent of the sub-reach (Figure 16 and Figure 17). The alluvium in this section of the reach is dominantly coarse sand with mud clasts deposited in some areas. The in-channel bars evident in Figure 15 are deposited above dry season streamflow which is confined to a width of ~10 m of the channel, emphasising the presence of channel in channel morphology and a two distinct flow regimes. Outside the channel, floodplain vegetation in this sub-reach has progressed into much sparser woodland, which is additionally modified by the modern fire regime, a stark contrast to the upstream gallery forest.
4. METHODS

The methods and approaches of this project were divided into three main sections. Firstly, the field logging and survey tools and techniques are presented, from which fundamental data for both the hydrological and spatial aspects of the project were derived. Secondly, processing and preliminary analysis of the measured data from section 4.1 are presented and illustrated in Figure 5. And thirdly, the hydrological modelling aspect of the data processed is addressed in section 4.2. ArcGIS, LasTools and HEC-RAS software were used throughout the project.

4.1 Field Surveys and Data Collection

Fundamental climatic, hydrological and topographic information was gathered through logging performed by several devices prior, during and following the 2013/14 monsoon season (Figure 5). The data collected was essential to deriving both hydraulic and spatial parameters for the study reach. These devices are discussed in the following.

4.1.1 Hydrological Parameters

A HOBO U30-NRC climate station was installed at 13°9′27.89″S 130°41′24.92″E, on the 20/10/2013 prior to the beginning of the wet season. The station was set to collect rainfall totals (mm), soil moisture (%v/v), barometric pressure (mbar) and device voltage (v) every 5 minutes from the start date to mid-May, 2014. A fence was placed around this station to deter any tampering. The station was halted at 4:40pm on 13/05/14 and data was downloaded from the device.

Secondly, four Sensus Ultra ReefNet, high-resolution time-depth recorders (TDR) (see Table 3) were deployed into the river channel at Wangi Creek (see Figure 5 for relative locations) set with a sampling interval rate of 5 minutes. At the most upstream location two stage loggers where placed in the plunge pool (Table 3). The two submerged plunge pool TDRs where anchored differently, one being tied to a large inundated tree log that had reportedly been present and stable for a significant number of years (Figure 18a), the other attached to a garden brick and placed into a depression within the bank (Figure 18b). The next TDR downstream of the plunge pool was submerged in the billabong to an existing tree branch (Figure 18c). The last in-channel TDR was placed at the most downstream extent of the study reach. The device was attached to a 1.5 m star picket that had been all but 10 cm submerged into the channel bed (Figure 18d). An additional TDR was placed in a store room above the plunge pool to record atmospheric pressure, used to perform stage correction during analysis.
<table>
<thead>
<tr>
<th>Gauge ID</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Distance Downstream of the plunge pool (m)</th>
<th>Submersion method</th>
<th>Launch Date</th>
<th>Collection Date</th>
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<tbody>
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<td>13°9'46.52 &quot;S&quot;</td>
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<tr>
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<td>21/10/2013 2:31pm</td>
<td>17/05/2014 2:58pm</td>
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<tr>
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<td>130°41'4.33 &quot;E&quot;</td>
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<td>~1200</td>
<td>Attached to a submersed tree root</td>
<td>21/10/2013 3:36pm</td>
<td>16/05/2014 7:47pm</td>
</tr>
<tr>
<td>U-10644</td>
<td>13°10'54.9 6&quot;S&quot;</td>
<td>130°39'58.55 &quot;E&quot;</td>
<td>~3100</td>
<td>Attached to a star picket</td>
<td>25/10/2013 12:01pm</td>
<td>15/05/2014 6:36pm</td>
</tr>
</tbody>
</table>

Table 3: Summary of Sensus Ultra ReefNet TDR’s, including locations, launch and collection dates if applicable. Note that the U-10646 was not recovered.

Figure 18: Placement locations (circled in red) of the Sensus Ultra high-resolution TDR’s. a – d in a downstream direction, Device (a) was attached to a stable log, (b) garden brick, (c) stable tree root, (d) submerged star picket
4.1.2 Topographic data collection
A 2013 high-resolution DEM of Wangi Creek was created using LiDAR data collected during the 2013 dry season (11/06/2013) with a resolution of 10 – 20 points/m². Both bare earth (ground) and vegetation was surveyed. A quantitative assessment of the LiDAR elevation data was undertaken by using measurements taken using the Real Time Kinematic (RTK) Trimble R8 (Rover) and Trimble R7 (Base Station) survey equipment. A total of 181 points were taken at the downstream end of the reach, as well as 27 points collected in the upstream reach surrounding the plunge pool. Measurements were collected using the GDA94 MGA Zone 52 coordinate system and the AHD71 height datum. The collection of these points using a base station for real-time corrections allowed for sub-decimetre accuracy. From this error assessment the vertical accuracy relative to the Australian height datum was 0.48 m root mean square error (RMSE) for the upstream point cloud if outliers are disregarded, and 0.11 m RMSE for the downstream point cloud. The large difference may be attributed to poor RTK signal associated with the escarpment in the upstream point collection.

At the time of gauge deployment the plunge pool bathymetry was surveyed using a Ceeducer Pro device with an echosounder. The echosounder was attached to a small boat and submerged approximately 0.5m into the water. The logging was performed by covering the entire plunge pool in a back and forth and left to right motion. Vertical accuracy was to within 1 cm ± 0.1% of depth at a resolution of 1 cm although due to poor GPS signal attributed to the escarpment, horizontal position received through the IALA (International Association of Lighthouse Authorities) beacon receiver was poor.

4.2 Data Processing
4.2.1 Rain Gauge data
Climate loggings were downloaded from the HOBO U30-NRC climate station and exported out of the HOBO software package into excel as a workable spread-sheet. Precipitation and soil moisture logs were summarised into daily time steps tallying the total amount of rainfall occurring over 24 hours with one scenario beginning at 12 am and the other method used by the BoM (2014b) of total rainfall from 9 am. Associated with the collection of precipitation data was the extraction of an intensity – frequency – duration (IFD) table from the BoM (2013) to derive the annual recurrence interval (ARI), the expected periods between the exceedence of a given rainfall total (also interchangeable with annual exceedance
probability), of selected rainfall events for Wangi Falls. An IFD curve was created by extracting the expected 24 hr rainfall in millimetres for each recurrence interval and assigning a logarithmic trend line to the dataset.

4.2.2 Regional Rivers - Gauge data
Gauge records of the entire Northern Territory were supplied by the Department of Lands, Planning and the Environment. There locations were plotted in ArcGIS relative to Wangi Creek in their respective datum. The maximum discharge, length of record and area of stations that reside within 200 km of Wangi Creek, were then derived using the Department of Land Resource Management Water Data Portal. These attributes were plotted in an excel spread-sheet for stations that had the necessary information collected and available, and used to derive regional maximum discharge and discharge per unit area curves. Many of the following steps were automated in the Arc Model-Builder, and the respective work flows are summarised in Appendix A.

4.2.3 Flood stage pressure devices
Sensus Ultra devices measure absolute pressure in millibar (mbar), newton per square meter (N/m²) is the unit of pressure, with 1 mbar being equal to 100 N/m². Combining this with the below formula, the pressure on the given gauge can be derived by subtracting the atmospheric gauged pressure from the absolute submersed pressure (a and b) (Fairman et al. 1996). Following this the derived gauge pressure is divided by both the density of water in kg/m³ and gravitational acceleration in m/s² to derive the height of the water above gauge, in this case dry season flow. Change in water density between temperatures of 20°C and 40°C have a 1–3mm variation in depth calculations. The following calculations were performed for each gauge record, and from this the entire data collection was summarised into daily maximum and daily average stage heights (12 am timestep).

\[ \text{Pressure}_{\text{Absolute}} = \text{Pressure}_{\text{Gauge}} + \text{Pressure}_{\text{Atmosphere}} \]

\[ \text{Pressure}_g = \text{Pressure}_{ab} - \text{Pressure}_{at} \]

i. \[ \text{Pressure}_g = r \times g \times h \]

ii. \[ h = \frac{\text{Pressure}_g}{r \times g} \]

h = height above gauge
r = density of water at given temperature

\[ g = \text{gravitational acceleration at given latitude} \]

4.2.4 Watershed delineation

The Wangi Falls watershed area was delineated to ensure discharge to catchment area calculations produced in the results chapter were accurate. Watershed allocation was completed using SRTM 30 m, and the following approach based on the recommended procedure in Cooley (2010).

By using Fill, small imperfections in the SRTM derived DEM are removed. Direction of flow for each cell is derived using Flow Direction with the numbers in the subsequent layer showing flow direction from each cell to its steepest downslope neighbour. Flow Accumulation calculated the flow into each cell by accumulating the cells that flow into each downslope cell. This layer was then reclassified into Channel & Non-channel Pixel with a channel formation threshold value of 1000. A new empty shapefile to store a pour point was created in ArcCatalog. The pour point was delineated at the downstream extent of the study reach at Wangi Creek using the Editor Toolbar so that everything upstream from the pour point defines the Wangi watershed/catchment. Snap Pour Point was used to ensure that the point was located on the highest flow accumulation cell within the specified radius of 4 cells (~120m radius). This tool converted the pour point into the raster format needed in the next step. In the final step Delineate watershed was used, combining the flow direction and the pour point to derive a watershed raster. To determine the area of the catchment a watershed boundary polygon is created using Raster to Polygon and finally calculate geometry tab in the attribute table of the output polygon.

4.2.5 Plunge pool bathymetry

The plunge pool surveyed by the LiDAR does not reflect the true bathymetry and would produce and inaccurate hydrological model if it was used without correction. A true representation of the plunge pool was achieved by creating a dataset that could be merged with the LiDAR using the following method:

1. The LiDAR X,Y,Z point data was uploaded into global mapper.
2. Plunge pool LiDAR points were deleted manually and the measured XYZ points from the Ceeducer device were merged
3. This section of the study site was clipped from the original LiDAR point cloud, and a shape file of the same area was also extracted.
(4) The new point data from the plunge pool area was saved as a .las file “PlungePoolwithBathymetryinBox”.

4.2.6 DEM creation

The LiDAR described in subsection 4.1.2 was received in .LAZ format and was converted to a bare earth (BE) DEM in the form of a TIN using a combination of ArcGIS Tools in ArcMap (ESRI 2010) and from LAStools (Isenburg et al. 2007). Many of the following steps were automated in the Arc Model-Builder, and the respective work flows are summarised in Appendix B.

The LiDAR data received contained 20 .laz files. For these files to become manageable they were unzipped using laszip .las and combined using lasmerge into a single collection of return points. This entire collection of merged .las files were clipped by a polygon that encompassed the entire plunge pool area that had been surveyed as discussed above. To ensure the DEM was of manageable size the number of return points in the merged .las files were reduced significantly from approximately 266 million to 19 million points using las2las (filter) returning 10 million BE points and 9 million AG (above ground) points. The final dataset used to produce a TIN was created by combing the plunge pool bathymetry .las points with the LiDAR .las points with lasmerge.

To produce a BE DEM the average point spacing of each data point was calculated using point file information. The output of this was used to convert the final .las file of the entire study reach to a multipoint feature class using the TIN class code of 2 for BE. From this a TIN was derived for use in HEC-RAS modelling.

4.3 HEC-RAS Modelling

To determine bankfull capacity, inundation patterns and hydraulic characteristics for the modern Wangi Creek, a standard one-dimensional backwater hydraulic model was used. Based on the approach taken by Roper et al. (2005) there are three major steps to developing a hydraulic model. Firstly, HEC-GeoRAS is integrated in ArcMap and applied to delineate Wangi Creek in the LiDAR TIN layer. Characteristics of the creek that need to be identified include stream centreline, bank lines, bank points, flow path centrelines, and cross-sectional cut lines (see Figure 19). This data was exported into HEC-RAS to test a range of scenarios based on all the gauged data, Manning’s n values based on vegetation density and the RFFA.
data derived by the method proposed in Weeks (2006). Third, was to produce the inundation floodplain model by generating floodplain wetted area polygons, velocity grids and depth grids in ArcMap from the data produced by HEC-RAS. These processes are first summarised in Figure 20.

Figure 19: Feature classes used in the pre-processing the DEM. Stream a. Stream Centreline in light blue, Banks in red, Flowpaths in dark blue, Cross-sectional cut lines in green and vegetation density from 0-1 in brown. Drainage is from top right to bottom left.
Figure 20: Process flow diagram for use of HEC-RAS and HEC-GeoRAS in flood modelling and inundation mapping (Cameron 2012)
4.3.1 HEC RAS file preparation

The following feature classes were produced using the HEC-GeoRAS extension in ArcMaps and overlaid the DEM created in the previous sub-section. These feature classes illustrated in Figure 19 were then processed and exported to HEC-RAS for further editing and hydrological modelling.

   a. Stream Centreline

The stream centreline feature class was derived by manually tracing the approximate centre of flow or in most cases the thalweg, within the main channel from the upstream to downstream extent of the reach. The reach and river were then assigned the name Wangi Creek.

   b. Banks

Banks were selected based on contour line locations for certain sections of the stream. However, this feature class was manually edited in HEC-RAS below so that all bank stations represented the macro channel bank or highest point in the cross-section.

   c. Flowpaths

Flowpath centrelines were added based on estimated general location in the channel, left overbank and right overbank. These lines were only used in determining the distance between cross-sections.

   d. Cross-sectional cut lines

Cross-sectional cut lines were automatically generated at evenly spaced intervals of 10 m over the entire study reach. Any intersecting lines were manually rotated so that centre spacing between each station remained the same and all lines did not intersect another.

   e. Landuse (Manning’s n)

To determine more appropriate Manning’s n values for the channel and surrounding areas, a “vegetation density” raster (Figure 19) was derived using the process highlighted below sourced from Crawford (2009):

1. A multipoint feature class was created for both “Bare Earth” and “Above Ground” (vegetation) using a similar method as highlighted in Section 4.2.6, except the original LiDAR data was not combined with bathymetry.

2. The **Point to Raster** tool was used on the BE and AG points with the COUNT option.
3. Any resulting NoData cells were converted to 0 so that subsequent operations treat zero points in a cell as 0. This was accomplished using the IsNull tool followed by Con.

4. The AG and BE rasters were added together to get a total count per cell using the Plus tool.

5. To get a floating point output from the Divide function (that will be used in step 6), one raster needs to be floating point. This was done by sending the output from step 4 through the Float tool.

6. The Divide tool was applied between the AG count raster and the floating point total count raster. This gave a ratio from 0.0 to 1.0 where 0.0 represents no canopy and 1.0 very dense canopy.

4.3.2 HEC-RAS Analysis

i. Point Thinning

As geometry files in HEC-RAS are required to have less than 500 elevation points the data was thinned using the following process.

1. GeoRAS export data was imported into HEC-RAS as a geometry file.

2. Geometry data points are thinned to \( \leq 500 \) using the programmes point filter (Figure 21).

![Figure 21: Screenshot of the HEC-RAS point filter tool](image)

3. Near point horizontal and vertical tolerance (highlighted) is increased from 0.015 m to 0.45 m in increments of 0.005 m to reduce the points gradually from points < 500 whilst numbers > 500 remain unchanged. Colinear filter remains at default.

ii. Bank Editing

Bank stations were manually adjusted in HEC-RAS to points of probable maximum bank height by using the graphical cross-section editor. To achieve this, each cross-section was manually adjusted to what was previously defined.
iii. Model Parameters

The hydraulic modelling in this thesis has taken three approaches for prescribing the distribution of roughness in the study reach: Variable (V), Left overbank, Channel and Right overbank (LCHR) and Uniform (U) Manning’s n. The most simplistic model was derived by assigning a uniform Manning’s n value of 0.03 over the entire reach. The variable Manning’s n scenario was then simplified by taking the middle Manning’s n value of the left overbank, channel and right overbank to derive the LCHR geometry file. Finally the Variable Manning’s n scenario was derived by determining reach scale roughness attributed to vegetation density.

For each “n” scenario 18 different discharge profiles were produced, ranging from 2 m$^3$/s to 3600 m$^3$/s, or the best guess dry season discharge through to the LGM paleodischarge estimate. Based on the derived overall reach gradient, a normal depth slope (s) of 0.0022 was assigned for both upstream and downstream boundary conditions. A subcritical steady flow analysis was then performed generating the surface profiles cross-section statistics for each specified discharge.

Longitudinal surface inundation profiles were produced by exporting the thalweg elevation and water surface elevation for each profile created into excel, to then be plotted on a line graph. The derived maximum stage levels gauged in the field for the 2013/14 monsoon were then plotted and assessed against the modelled water surface profiles.

Longitudinal shear stress and velocity condition produced by the model were also exported and plotted against water surface width for the “Variable Manning’s n” scenario. From this the influence of valley confinement could be analysed.

4.3.3 Floodplain Inundation Mapping

A select number of profiles for the “Variable Manning’s n” scenario were imported into ArcMap and converted to inundation maps. Only this scenario was mapped as it represents a more accurate model of Wangi Creek as it incorporates added variables. The export dialog in Figure 22 was used in the creation of a workable SDF file for conversion in HEC-GeoRAS.
This SDF file was converted to a workable XML file in HEC-GeoRAS and selected as the RAS GIS Export file. The DEM of Wangi Creek was converted to a grid (raster) file using TintoRaster with a 0.2 m grid size, and selected as the terrain file used in the inundation analysis. Following these steps and the importation of the required feature classes, each profile was converted to a water surface TIN. This TIN was compared to the grid previously created and the elevation difference was computed. Water surface elevation that is greater than the terrain elevation is included and displayed as floodplain inundation.
5. RESULTS

The results are presented in three sections with the fourth section summarising the results presented in Section 5.1 – 5.3. Section 5.1 assesses the reach scale geomorphology with particular reference to sub-reach division and knickpoint migration. Section 5.2 presents the analysis and comparison of real-time hydrological data, whilst Section 5.3 presents the results of hydraulic modelling that assesses the potential discharge scenarios for the creek and the related velocity, shear stress and inundation profiles.

5.1 Reach Scale Geomorphology

The study reach at Wangi Creek is divided into five geomorphic zones (Figure 23) based on channel geometry (Figure 23), vegetation density (Appendix D) and knickpoint location (Figure 24). The plunge pool sub-reach stretches ~ 510 m downstream from the escarpment and is characterised by dense in-channel vegetation and a confining macro-channel that will be discussed below. The billabong sub-reach extends ~800 m (Figure 23) and is highlighted by the presence of a straight and extensive deep pool (billabong) confined by dense riparian vegetation. For ~1,120 m within the stable sub-reach gradient again increases (Figure 23b) and the channel reverts back to dense vegetation, similar to that present in the plunge pool zone. This sub-reach has an apparent division of flow and contains the confluence point of a small tributary stream that correlates with a widened macro-channel. The knickzone sub-reach continues 540 m downstream and is characterised by two relatively dramatic changes in bed gradient between cross section 680 and 460 with two short drops in the alluvial bed indicating the presence of two migrating knickpoints (Figure 23a). The final destabilised sub-reach has been dramatically affected by the migration of the knickzone with bed gradient returning to a similar grade of previous sub-reaches (Figure 23b) but with active bank erosion and bed formation. The width of the macro-channel in this area of the reach is much less than the previous two mentioned.

Ortho-rectified and geo-referenced aerial photographs along with multi-temporal Landsat satellite imagery highlight the presence of a migrating knickpoint at the downstream extent of the study site (Figure 24). This imagery has been used to document the migration of the knickzone over time by analysing the change in vegetation from closed canopy gallery forest to fragmented and destabilised vegetation areas. Examination of these images suggests that the knickpoint or knickzone (destabilising front) initiated geomorphic changes to Wangi
Creek during the late 1980s or early 1990s (Appendix G). This erosional front represents a geomorphic boundary between the more vegetated and stable upstream reach and the heavily eroded downstream reach. Recent locations of the knickpoint (2013 and 2014) were detected by abrupt changes in thalweg elevation from long profiles derived from the LiDAR DEM, direct observation and GPS logging. Figure 24 illustrates that knickpoint migration has been rapid throughout the three decades altering approximately 4 km of river reach. The analysis of Landsat data reveals that the knickpoint formed at the downstream confluence around 1987 with an average retreat rate of 148 m/yr (Figure 24). Based on yearly Landsat data and aerial images the rate of migration has fluctuated between 250 and 90 m/yr since 1987 with the exception of 2012 - 2014. It is illustrated in Figure 23 that there are two knickpoints present when the LiDAR was collected in 2013. The implications of this are that there are two possible retreat rates as demonstrated in Figure 24. Between 2012 and 2014 the rate of knickpoint migration increased to either 195 or 310 m/yr depending on which knickpoint is considered (Figure 24). Because the estimation of these distances and rates are on the basis of vegetation change alone, errors of up to 30 m would be expected as the Landsat satellite imagery has a resolution of 30 m.
Figure 23: Sub-reach locality map for Wangi Creek specifying the observed 2013 and 2014 knickpoint position and gauge locations. Drainage is from (a) top right to bottom left and (b) right to left.
Figure 24: Locality and retreat rates of the knickpoint since 1987 relative to the study reach. Drainage is from to right to bottom left.
5.2 Catchment Hydrology

5.2.1 Wangi Falls 2013/2014 precipitation

Wangi Falls received a total monsoon precipitation of 2163 mm between 21/10/2013 and 13/05/2014, with 63.6% falling in the months of January and February (Figure 25). The highest monthly rainfall event for Wangi Creek occurred in January, which correlated with the strongest La Niña of the season (Figure 25). Rainfall patterns throughout the 2013/2014 wet season consisted of numerous small events that generally lasted 3-4 days at a time but rarely produced daily totals greater than 50 mm (Figure 26). The wettest period of the 2013/14 monsoon is characterised by three much larger events between 13/01/2014 and the 17/02/2014, all of which produced at least one day of rain with more than 75 mm.

Figure 25: Monthly breakdown of rainfall at Wangi Creek, Walker Creek and Batchelor (BoM 2014b) relative to ENSO sub-annual events (BoM 2014c)

The highest 24 hour rainfall experienced in the Wangi Catchment was 201.4 mm occurring on the 17/02/2014. When plotting this on the derived 24 hour Intensity-Frequency-Duration (IFD) curve (Figure 27 – see methods for derivation of this curve) this rainfall event has a 10-year ARI (see methods for definition). When this event is broken down into a sub-daily time steps, the highest rainfall occurring within a 5 min period is 9.8 mm, corresponding to an ARI of less than 1 year (which would be 11.9 mm) (Table 4). The ARI increases as more time is included with 31.2 mm in 20 minutes corresponding to an ARI just less than 2 years (Table 4). The highest ARI for the sub-daily event occurs between 19:25 and 19:50 when 61 mm of rain falls within 40 minutes, which increases the ARI to just less than 10 years (Figure 27 –
Table 4). From these values it is apparent that the sub-daily rainfall events were not intense, but the high frequency of events during the 24 hr period caused the daily event to be of a higher magnitude.

**Wangi Daily Monsoonal Rainfall**

*21/10/13 - 13/05/14*

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<td>25/01/14</td>
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</table>

Figure 26: Rainfall and soil moisture plotted with a daily time step (12am-12am). Inset is a zoomed in subdaily event that occurred on the 17/02/2014. Note; soil moisture is a measure of the total soil water content as a percentage of the soil volume (vol/vol)

The plot of both maximum and average soil moisture recorded in a day returned very similar curves with truncation attributed to events occurring over an extended period of time (see Figure 26). The maximum soil moisture percentage obtained on a day was 33.8% recorded on the 15/01/2014. This does not correlate with the largest daily rainfall event but two

subsequent rainfall events greater than 80 mm/day on the 14/01/2014 and the 15/01/2014 (Figure 26). This maximum soil moisture was retained over a period of 3 days (15/01/2014 - 18/01/2014) before eventually declining with the absence of precipitation (Figure 26). During the period of soil moisture truncation the soil pores are more than likely fully saturated resulting in increased runoff in the form of overland flow.

5.2.2 Wangi Creek Flood Stage for the 2013/14 wet

Three locations along the Wangi Creek study reach were gauged for water levels during the 2013/2014 wet season between the 21/10/2013 and 13/05/2014. Relative to the sub-reaches defined previously, the most upstream gauge was located in the plunge pool zone recording a maximum stage height of 3.7 m above the gauge. The second gauge located in the billabong sub-reach recorded the lowest stage height of 3.3 m in contrast to the furthest downstream gauge in the “post knickpoint” zone recording a maximum stage of 4.9 m (Figure 28a). All three stage recorders gauged the season’s maximum flow stage on the same day (17/02/2014) as well as the season’s highest daily average flow stage (01/02/2014). The peak flow stage
and highest average flow stage both occurred at the downstream extent of the study reach past the knickpoint (Figure 28).

The largest maximum flow event does not correlate with the largest daily average flow event recorded which occurred on the 01/02/2014 with heights of 2.1, 1.8 and 2.9 m occurring relative to the other values previously mentioned (Figure 28b). The cumulative rainfall for the two largest stage flow events and the day leading up to the event was, for the 1\textsuperscript{st} February event 157.6 mm and for the 17\textsuperscript{th} February maximum flood 208.8 mm (Figure 26 and Figure 28). This correlation suggests flood magnitude AND duration relates directly with the duration AND magnitude of the rainfall event. Higher order floods occur when rainfall is of high intensity over a short period of time whilst more prolonged floods occur when rainfall is of medium intensity over an extended period of time.

Neither the highest average or the highest overall stage heights correlate with the maximum soil moisture (Figure 26 and Figure 28). The maximum flow stage at Wangi Creek was achieved with a soil moisture of 27\% on the 17/02/2014, whilst the highest daily average flow stage occurred when soil moisture was at 28\% on the 01/02/2014. This was 4-5\% below the seasons maximum recorded soil moisture that occurred during the third largest event on the 15/01/2014 (Figure 26 and Figure 28).
Figure 28: Flow stage plotted for each TDR throughout the 2013/14 wet season recording period; (a) represents the maximum daily stage height and (b) represents the average daily stage height, recorded for each location.
5.2.3 Max Discharge Analysis

The maximum discharge (m$^3$/s and m$^3$/s/km$^2$) of all gauging stations within a 200 km radius of Wangi Creek that have catchments less than 1000 km$^2$ and gauge records equal to or greater than 15 years in length are represented in Figure 29 (see methods for derivation of results). As a result of this RFFA performed, the maximum discharges of 36 stations have been plotted with an average record length of 37 years. It is illustrated by the linear trend of this logarithmic scatter plot, that an estimation of max discharge for a catchment of Wangi’s size (60 km$^2$) would be ~160 m$^3$/s correlating with a discharge per unit area of 2.6 m$^3$/s/km$^2$.

When all surrounding gauges (69 in total), of all record lengths and size are included the average gauge record length for all stations decreases to 32. Furthermore, the estimated possible maximum discharge decreases to ~125 m$^3$/s correlating with a discharge per unit area of 2.1 m$^3$/s/km$^2$ (Appendix E). From these calculations it is apparent that the maximum discharge area relationship produces a difference of ~35 m$^3$/s and ~0.5 m$^3$/s/km$^2$ dependent on what stations are included in the analysis.
Figure 29: The (a) maximum discharge and (b) maximum discharge per km² recorded, for available stations within a 200km radius; filtered to stations <1000km² and >15 year record length.
A study performed by Weeks (2006) as part of the “ADrail Project” in the Northern Territory derived ARI (see methods for definition) regression equations for four sections of the Northern Territory. For an area equivalent to that of Wangi Creek (60km²) the following discharge estimates were produced as illustrated in Figure 30, based on the equations derived for the ‘Northern Section’ of the Northern Territory; \( Q_5 = 5.55A^{0.740} \), \( Q_{10} = 7.82A^{0.737} \), \( Q_{20} = 10.2A^{0.737} \), \( Q_{50} = 18.5A^{0.667} \). As no equation was derived for a 100 year ARI flood event, a logarithmic regression line was extrapolated to determine an approximate value of 330 m³/s. 

![Discharge ARI's based on ADrail project](image)

Figure 30: Discharge ARI curve for the Northern Region summarised in Weeks (2006); plotted with a extrapolated logarithmic curve to derive a possible 100 year ARI flood discharge

Three maximum discharge estimates and a predicted 100 year ARI discharge for the Wangi Creek catchment size of 60 km² are summarised in Table 5. As previously mentioned the 100 year ARI derived by Weeks (2006) results in a predicted discharge of 330 m³/s. Secondly the RFFA illustrated in Figure 29 specifies the regional maximum discharge (based on a maximum 60 years of gauge records) to be between 125 and 160 m³/s. It is evident that in modern time the maximum discharge potential for a catchment of ~60km² in the Wangi region would range from approximately 125 m³/s to 330 m³/s, founded on the two regional analyses.

The final two discharge values incorporate, for the first instance a global sample space, and for the second paleodischarge value a timescale extending back several thousands of years. The world maximum discharge value for a catchment of 60 km² was derived using the
updated regression equation from Herschy (2002) which takes into account 60 of the world’s maximum floods from varying locations. Secondly the paleo-discharge estimate by Nott et al. (1996) was derived by sedimentary analysis and modern observations. The results of this paper will be discussed further in the following chapter, but the estimates predicted by the regression relationship and the paleo analysis suggest that modern catchments on a global scale are 955 m$^3$/s short of producing the predicted paleoflood. However as already alluded to this is in the order of 10-30 times larger than what the Wangi region is likely to produce for rare events such as the 100 year ARI.

<table>
<thead>
<tr>
<th>Discharge Summary Table</th>
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<tbody>
<tr>
<td>100yr ARI Q$_{100}$=XA$^{0.0000}$ (Weeks 2006)</td>
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<tr>
<td>Q value (m$^3$/s)</td>
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<tr>
<td>Error ±</td>
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</table>

Table 5: Summary of maximum discharges derived from a RFFA and within the literature. Note that an equation for the Weeks (2006) 100 ARI was extrapolated, hence, no regression equation is available

5.3 One-dimensional Hydrological Modelling

5.3.1 Hydraulic Component

Based on the established range of maximum discharge values in section 5.2.3 three model scenarios have been tested using a one dimensional backwater flow model in HEC-RAS. Each scenario represents a different Manning’s n scenario as vegetation density varies longitudinally within the 2013/14 Wangi Creek channel. A total of 18 predicted flow profiles (Appendix F) were derived for each roughness scenario with 8 key profiles illustrated below in Figure 31 to Figure 33. The selected discharge scenarios range between 100 and 500 m$^3$/s and were chosen as incremental discharges to match the 2014 peak flood water surface profile. The values following this were created to give incremental increases up to the 3600 m$^3$/s, the paleoflood scenario suggested by Nott et al. (1996).

5.3.1.1 Uniform Manning’s n values (model 1 and 2)

Changing the Manning’s n roughness coefficient for sections of the channel was used to derive three scenarios of varying discharges along the Wangi Creek study reach. Two uniform scenarios were created based on reach scale simplified Manning’s n values. For the
first scenario the entire study reach had a Manning’s n of 0.03, whilst the second scenario differed in that three values were designated to channel and, left and right over bank areas, which for each cross-section downstream.

The hydraulic model scenario for an entirely uniform Manning’s n value has a stage elevation gradient that remains relatively constant for discharges profiles of 350 m$^3$/s and 500 m$^3$/s (see Figure 31). The knickpoint downstream causes a drop in elevation for flows less than 180 m$^3$/s, but has no effect on water surface elevation for discharges between 180 and 1000 m$^3$/s (Figure 31). At discharges greater than 500 m$^3$/s the water surface profile steepens approximately 670 m downstream of the plunge pool before further steepening at 1000 m (Figure 31). At 1160 m downstream discharges above 500 m$^3$/s level out, until the knickpoint at ~2690 m downstream steepens the water surface for profiles above 1000 m$^3$/s. The largest discharge of 3600 m$^3$/s displays the largest changes in water surface gradient along the reach.

![Discharge Scenarios for Uniform "n"](image)

*Figure 31: Long section of the select modelled water surface profiles for the uniform Manning’s n scenario. Flow is from right to left. TDR maximum recorded height and the observed debris lines are plotted*

Based on the maximum stage recorded for each location in 2013/2014 (Figure 31), the most likely discharge based on the modelled scenario with constant Manning’s n is estimated to be ~500 m$^3$/s, however, the downstream gauge predicts a slightly increased discharge. This
discharge is closer to the 100 year ARI maximum discharge estimated by Weeks (2006) and is substantially lower than both the paleodischarge.

The second scenario (see Figure 32) had a Manning’s n which varied across a given cross-section and which varied downstream, with the same discharge profiles being modelled to the previous model. To derive the Manning’s n value for each of the three cross-section areas the mid-point value for each area was extracted from the variable Manning’s n (outlined below) cross-sections and assigned to the corresponding area. As a result Manning’s n increased in most parts of the reach from 0.03 to values ranging from 0.03-0.1, and flow was generally 0.5 and ~0.25 m higher for the 3600 m$^3$/s and 100 m$^3$/s profiles respectively when compared to the previous modelled uniform Manning’s n scenario. Similarly, the knickpoint had an effect on discharges below 350 m$^3$/s but beyond the water surface profile irregularity was drowned out as stage increased.

**Figure 32:** Long section of the select modelled water surface profiles for the refined left, channel and right bank (LCHR) Manning’s n scenario. Flow is from right to left. TDR maximum recorded height and the observed debris lines are plotted

Flow stage in this model scenario suggests that the 2014 Wangi Creek peak discharge was between 350 m$^3$/s and 500 m$^3$/s. This would relate to a flood ARI of just over 100 years based
on the Weeks (2006) method as summarised in Table 5, however other values within Table 5 are either much larger or much smaller than the modelled peak discharges in Figure 31 and Figure 32

5.3.1.2 Variable Manning’s n value (model 3)

The third and most complex Manning’s n scenario has a up to 20 Manning’s n values for each cross-section derived from the 2013 vegetation density, and is therefore the most spatially realistic roughness scenario for modern Wangi Creek. Results from this scenario suggest similar stage elevation and gradient trends to those modelled and presented in Figure 31 (uniform model scenario).

![Discharge Scenarios for Variable "n"](image)

Figure 33: Long section of the select modelled water surface profiles the Variable Manning’s n scenarios. Flow is from right to left. TDR maximum recorded height and the observed debris lines are plotted.

If incorporating all modelled scenarios (Figure 31 - 31) the maximum paleodischarge proposed by Nott et al. (1996) would be associated with a stage ~8m above the minimum channel height (thalweg), and are contained within the macro-channel in the upper sub-reach (expanded on in following section). The 2013/2014 peak discharge was most likely between
350 m$^3$/s and 500 m$^3$/s based on the three modelled scenarios, but if only the last model is used the peak discharge for Wangi Creek was 400 m$^3$/s.

### 5.3.1.3 Hydraulic characteristics of predicted flows on Wangi Creek

This section presents the predicted hydraulic characteristics for the spatially variable Manning’s $n$ scenario (Model 3). Water surface width is plotted along with predicted shear stress and velocity to determine the influence of valley confinement. As the peak 2013/14 wet season discharge was ~400 m$^3$/s, the closest modelled value of 350 m$^3$/s is plotted to illustrate the approximate hydraulic characteristics for 2014 peak flow stage event. The 3600 m$^3$/s flood is also plotted as it is regarded the maximum paleodischarge prediction within the literature.

In further detail, the predicted shear stress trends for 350 m$^3$/s imitates what occurs during the 3600 m$^3$/s event, except that the peaks around station 2000 and 3050 (see Figure 34) are three times larger than the smaller sub-bankfull flood. Trends between the same modelled profiles for predicted velocity remain relatively equally spaced. The velocity distribution along the reach mimics the predicted shear stress, with peaks and troughs occurring virtually at the same locations.

Following on from this, the predicted shear stress for the 350 m$^3$/s flow is made up of a series of peaks and troughs without very many outlying trends. A point of low shear occurs for a long stretch throughout the billabong zone, attributed to a relatively straight, confined and low gradient part of the channel, before building up to a the series of peaks of 53.7 N/m$^2$ at station 1980 at a point where water surface width has become confined. The lowest shear occurring along the reach is ~9 N/m$^2$ associated with a transition from the knickzone to the destabilised zone and an increased water surface width (this low point is excluding the low shear stress associated with the plunge pool). The modelled shear stress occurring during the largest modelled flow (3500 m$^3$/s) corresponds with those of the 350 m$^3$/s although a second noticeable peak occurs at the exit of the plunge pool.
5.3.2 Morphological Relationship to Floods

5.3.2.1 Bankfull Discharge (QBF) magnitude

For the variable Manning’s n scenario (Figure 33-model 3), five cross-sections from the assigned zones are used to illustrate the varying bankfull discharge (QBF) capacities within each sub-reach (Figure 35). For this to be successful, one cross-section was extracted from each geomorphic zone, and the appropriate water surface profiles were plotted. Each plotted profile is representative of dry season flow, most likely 2014 maximum flood and the cross-sections bankfull capacity.
Figure 35: Various estimated water surfaces for modelled discharges at five cross-sections; (i) 2900, (ii) 2290, (iii) 1590, (iv) 700 and (v) 20 on Wangi Creek. The correlating discharge to the water surface profile is depicted above each profile line. The model was run with a variable Manning’s n and slope of 0.0022, with bankfull defined as the macro-channel overtopping discharge, note; right bank = right and left bank = left. The sixth (vi) profile illustrated is

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\[ Soper, A.B. (2014): Magnificent Monsoonal Floods \]
a long profile summarising the location of the extracted cross-sections relative to the study reach. Note, Flow is from left to right in this instance

The first extracted cross-section illustrated in Figure 35(i) is representative of the cross-section used in Nott et al. (1996). Cross-section 2900 is located 210 m downstream of the waterfall, is ~350 m wide, and located within the plunge pool sub-reach. It illustrates that flow is confined by the macro-channel for all modelled flows, including the modelled paleoflood of 3600 m$^3$/s. The 2 m levee located at ~260 m across and 23.5 m (AHD) on the right bank, as depicted in Nott et al. (1996), is overtopped by any discharge greater than 350 m$^3$/s.

The channel cross-section selected for the billabong sub-reach is characterised by a macro-channel as is illustrated in Figure 35(ii). The macro channel in this section of the reach is ~220 m wide by ~6 m deep and contains all of the predicted flows including the 3600 m$^3$/s. Channel form has altered and is characterised by a single macro-channel, as the smaller levee previously identified in Figure 35(i) has ceased.

The channel within the stable zone, depicted in Figure 35(iii) has a width of ~340 m whilst maximum depth remains at 6 m. All modelled discharges below the 3600 m$^3$/s are contained within the widened macro-channel. Estimated dry season flow is observed to be restricted to the right of the channel.

The cross-section in Figure 35(iv) is located within the knickzone and is ~240 m wide by 4 m deep. This in context to the upstream cross-section is 2 m shallower resulting in QBF becoming any discharge greater than 1000 m$^3$/s as illustrated in Figure 35(iv).

The furthest downstream cross section extracted for the study reach (Figure 35(v)) is located in the destabilised sub-reach. The channel morphology is different in this part of the reach as to be expected with the passing through of the knickpoint. Within the main dry season flow channel there are 2 small levees that are almost symmetrical with a width of ~30 m. Directly above these smaller banks are intermediate banks that have a width of about 60 m. These banks confine flows below ~300 m$^3$/s whilst flows of up to 1000 m$^3$/s are restricted by the macro-channel that has a width of ~250 m.
In summary it is apparent that the channel capacity of Wangi Creek decreases in a downstream direction. The macro-channel from the plunge pool sub-reach (Figure 35(i)) through to the stable sub-reach (Figure 35(iii)) has the ability to contain flood stages produced by any discharge less than or equal to 3600 m$^3$/s. The macro-channel capacity decreases to 1000 m$^3$/s in the knickzone sub reach (Figure 35(iv)), before increasing to 1200 m$^3$/s in the destabilised sub-reach. These patterns of reach inundation will be discussed in further detail below.
5.3.2.2 Inundation Mapping

Figure 36: Spatial inundation of the Wangi Creek reach based on the specified discharges. (a)100 (b)350 (c)3600. Drainage is from top right to bottom left
As alluded to previously, spatial inundation of surrounding floodplains increases with greater discharge (Figure 36). For the 100 (Figure 36a) and 180 m$^3$/s (Appendix Ha) scenarios floodplain inundation remains fairly similar throughout the study reach, although some dividing “islands” are mostly or entirely inundated. At 350 m$^3$/s (Figure 36b) and 500 m$^3$/s (Appendix Hb) inundation patterns in the upstream reach remains fairly similar, but downstream of the road an abandoned or inactive channel becomes an alternate passage of flow (see Figure 36b). Downstream of this, divided flow from the abandoned channel overtops any islands and forms a single channel at ~2200 m$^3$/s (Appendix Hd). At this point significant changes in inundation patterns begin to occur. If the cross-sections and LiDAR were to be extended, a discharge of 3600 m$^3$/s (see Figure 36c) would overtop banks and inundate entire floodplains for sections outlined in red. For sections outlined with a yellow line flow is still confined to the macro-channel.

5.4 Results Summary
Precipitation events correlate with spikes in soil moisture, however maximum rainfall events do not correlate with maximum soil moisture. The largest rainfall event and third highest soil saturation correspond with the highest streamflow stage event for all gauges on the 17/02/2014. When modelled this correlates with a discharge of between 350 m$^3$/s and 500 m$^3$/s, with 400 m$^3$/s the result of the most complex model scenario, correlating with the 100 year ARI (Weeks 2006). If numerous other hypothetical discharges are plotted, total inundation of the downstream floodplain (red outlined in Figure 36) would occur between 1000 m$^3$/s and 2000 m$^3$/s, whilst upstream levees (yellow outline in Figure 36) do not become overtopped with any discharge up to 3600 m$^3$/s.
6. DISCUSSION

For the 2013/2014 wet season, this study has produced temporally and highly resolved data on catchment rainfall, soil moisture, and flood stage. These variables provide a basis for discussing the processes and hydrological significance of flooding along Wangi Creek, and evaluating the implications for the reconstruction of paleofloods. In this context, a paper by Nott et al. (1996) used relict flood levees at Wangi Falls to derive a paleoflood record for Northern Australia extending back to 30 ka. These levees (see Figure 39) were deposited at 50 m and 200 m away from the plunge pool and are 2 m and 7 m higher than the dry season water level (see Figure 39). Thermo luminesence (TL) dating presented in Nott et al. (1996) puts the deposition of the higher levee between ~20 and 30 ka (LGM). Nott et al. (1996) combined field observations and one topographic cross-section to derive a discharge of 525 m$^3$/s that produced a stage capable of over-topping the lower levee of 2.2 m. Furthermore, based on proportional outflows from the plunge pool, the Nott et al. (1996) study assigned a discharge of 3600 m$^3$/s to achieve flood stages greater than 7.6 m. Assuming that discharge values can be up to 20% greater than suggested by paleo-indicators (Baker et al. 1987), these discharges would increase to approximately 630 and 4300 m$^3$/s, respectively. This raises three main questions with regards to the validity and significance of paleoflood reconstruction at Wangi Creek, which will be discussed in the following chapter in the framework of the measured and modelled results of this thesis:

- Are discharges of 3600 m$^3$/s (or even 4300 m$^3$/s) hydrologically realistic at Wangi Falls?
- If they are, what would their geomorphic effect be along the study reach (for example inundation and sediment deposition)?
- And is it valid to assume that the modern geomorphic setting (for example channel bed elevation) is a reliable analogue for paleoflood hydrology?

6.1 Hydrological realities of predicted LGM discharges vs modern extreme events

As discussed in section 2.2.2, the more accepted climate variation over the past 30 ka is that areas in the north of the continent were contrastingly wetter than present, persisting in temperate zones through till ~25 ka (Reeves et al. 2013). However records from Indonesian vegetation and speleothems suggest that the tropics where dry with no evidence of a strong monsoon penetrating the Australian main land in this period (Reeves et al. 2013). In
acCORDANCE with Indonesian records this climate persisted through the Last Glacial Maximum (LGM) with the monsoon absence corresponding with lower lake and river levels (Fitzsimmons et al. 2013). Contradictory to this is the suggestion in Nott et al. (1996) that discharges just less than 3600 m$^3$/s were occurring ~22 ka. To further quantify this, a runoff coefficient of 1.0 (overland flow scenario) was assumed over the entire catchment using the rational method equation. As a result 180 mm/hr of rainfall would be required to produce a peak discharge of this value for a catchment of ~60 km$^2$. Using an alternative approach, 3600 m$^3$/s requires a unit discharge of 60 m$^3$/s/km$^2$ which equates to 216 mm/hr for the duration of time of concentration (Tc estimated for Wangi = 1-2 hours), (BoM 2003).

Furthermore, if the previous LGM rainfall-discharge estimate was accurate then precipitation would need to be two times wetter than the current NT maximum rainfall recorded at Corker Island of 133mm/hr. However the 2014 peak hourly rainfall of 72.6 mm for Wangi Creek would need to be three times larger to produce the required 3600 m$^3$/s of flow. The Northern Territory one hour maximum of 133 mm/hour is 60 mm/hr more than recorded during the 2014 Wangi Falls event that resulted in 72.6 mm/hour (Figure 37) but significantly less than the 180-216 mm/hr required to produce the estimated paleo discharge of 3600 m$^3$/s.

In 2014 the maximum amount of rainfall occurring within 24 hours period for Wangi Creek was 201 mm, which is 344 mm less than the maximum daily rainfall recorded in the NT at Roper Valley Station in 1963 (see Figure 37) (BoM 2014a). Additionally, the daily and sub-daily rainfall values plotted for the NT presented in Figure 37 are three to four times lower than what was plotted for the rest of the world dating back to the 1950s. The highest global daily and sub-daily rainfall events include 1825 mm/day at Foc Foc, La Réunion and 401 mm/hr Shangdi, Nei Monggol, China (see Figure 37). When assessing the world maximum events it becomes more plausible that Wangi Catchment could have experienced rainfall magnitudes greater than 180 mm/hr in a past wetter climate. However modern conditions in tropical Northern Australia do not suggest events of this magnitude are would occur.
On the premise that a catchment of Wangi Creek’s size experienced a flood magnitude of 3600 m$^3$/s during the LGM, it would take ~60 m$^3$/s/km$^2$ for this to be plausible (Figure 38). The maximum 2014 rainfall event experienced was attributed to a 10 year ARI based the regional IFD data (see Figure 25), and it is plausible that the resulting discharge also had 10 year ARI if rainfall was assumed to result in 100% runoff. In the recent wet season the maximum stage event for Wangi Creek was between three and four meters along the study reach and as a result of matching the one-dimensional backwater hydraulic model to the observed maximum TDR stage, a discharge of 400 m$^3$/s is suggested. To produce this event would require 6.6 m$^3$/s/km$^2$ (see Figure 38), which in regards to catchment size relative to Wangi, the closest regional value to producing the estimated paleodischarge is 13.68 m$^3$/s/km$^2$ occurring for a catchment of 50 km$^2$ on the Adelaide River (Figure 38). This is compared to the maximum world value of 38.1 m$^3$/s/km$^2$ for a 56.5 km$^2$ catchment in Nevada (USA) (Figure 38). The maximum local value presented is five time lower than the required discharge per unit area to produce the discussed paleodischarge, although the maximum global value is two-thirds the magnitude that is required.

Furthermore, the only modern analogue globally for a catchment that has recorded a flood of this magnitude per unit area was in Halawa Hawaii, recording 63.5 m$^3$/s/km$^2$ in a 12 km$^2$ catchment, second to this being 46.1 m$^3$/s/km$^2$ recorded in Las Piedras, Puerto Rico (see Figure 38). As illustrated in Figure 38, the maximum discharge per unit area recorded within a 200 radius of Wangi Creek is 26.5 m$^3$/s/km$^2$ at Mitchell Creek with a catchment area of

![Rainfall - Time Curve](image-url)
1km$^2$. This reinforces that globally catchments have the potential reaching floods close to this proportion, but when specific to present tropical Northern Australian conditions, it is highly unlikely.

![World and Northern Territory Envelope Curve](image)

Figure 38: World maximum discharge per unit area envelope curves adapted from Herschy (2002), and Northern Territory maximum discharge per unit area envelope curve for catchments within 200km of Wangi Creek

### 6.2 The probability of mega-flooding

The reach-scale hydraulic model of Wangi Creek presented within this thesis illustrates that the 2.2 m levee is being over topped by predicted discharges of $\sim$300 m$^3$/s (see Figure 39). This corresponds with observations made that the 2.2 m levee has been inundated as recently as the 2013/14 monsoon. This discharge derived to overtop the 2.2 m levee is slightly more than half of what was predicted by Nott et al. (1996). The model discharge for overtopping the levee at $\sim$7.6 m is greater than 3600 m$^3$/s, a value that is approximately 9 times larger than the 2014 Wangi Creek maximum discharge of 400 m$^3$/s. On this premise alone it seems highly unlikely for Wangi Creek to produce floods of this magnitude under present climatic and hydrologic conditions.
Figure 39: Nott cross-section with modelled flood discharges and sedimentary core measured by May (unpublished data). Discharges illustrated are representative of the modern scenario (continuous line), aggradation scenario (dotted line) and degradation scenario (dashed line), with the 350 m$^3$/s represented red lines and the 3600 m$^3$/s denoted by green lines. Red Point identifies the approximate location on the levee that the sediment core was taken as illustrated, with TL dates attributed to the relevant sediment sample depth.

Furthermore, this supports evidence associated to a well-developed soil horizon capping this 7.6 m levee (Figure 39). Dating of the core samples as illustrated in Figure 39, suggests that the levee has not been inundated since ~5 ka. The period of highest activity and deposition of these layers is dated to have occurred during the LGM at ~22 ka with dates closely correlating to newly dated ages (May, unpublished data). If a hypothetical discharge greater
than the 3600 m$^3$/s were to overtop the 7.6 m flood levee, then the grain size should depend strongly on the depositional process (e.g. wave related processes versus fluvial process), as well as water depth and flow velocities. In this context, Figure 39 illustrates that sediments deposited at this high levee are comprised of granules and pebbles, suggesting that stage at some point in time substantially overtopped this levee, or that waterfall related wave pulses are responsible for the coarse nature of the sediment. In either case, the sediment ages within the cores as well as the model produced in this project confirm that sediments must have reached the 7.6 m levee before and during the LGM, and if this is founded upon the modern regime it would take approximately 3600 m$^3$/s of flow to generate this stage height.

6.3 Implications of channel incision for paleodischarge estimates

The scenario presented by Nott et al. (1996) predicts that a flood between 3600 and 4000 m$^3$/s would be required to produce an 8m bankfull stage flow in the plunge pool of Wangi Falls. This calculation was derived by determining the 2 m inundation discharge via a discharge rating curve of the modern flow, and assumes a common bed elevation for the LGM versus the modern Wangi Creek bed. The question is raised, however, as to whether or not bed level elevation around the LGM was identical to the modern elevation or whether elevation could have fluctuated through time.

In this context, the presence of knickpoints and waterfall features along the Wangi Creek study reach are indicators to an actively incising channel (Gardner 1983, Crosby et al. 2006). As this is the case, modelling efforts of progressively increasing the discharge to reach a certain stage height in order to simulate paleodischarge becomes ineffective as this assumes stationary bed level over time. Knickpoint migration rates (148m/yr, Section 5.1) would suggest that the knickzone will migrate upstream to the location of the plunge pool by 2028, which will most likely reduce bed level elevation by 2 m (equivalent to the current knickpoint height), (Figure 40).
To test the hypothesis that the required bankfull discharge changes relative to the channels wetted perimeter, two plausible incision and aggradation scenarios were run through the hydraulic model with a reduced number of cross-sections. An approximate aggradation and degradation of 2 m was applied to reduce or increase the wetted perimeter, and attempt to determine the approximate modelled water surface profile corresponding with a change in absolute bed level throughout the reach.

As hypothesised water surface profiles lowered when the wetted perimeter was increased, and rose when the wetted perimeter was decreased (Figure 39). These scenarios suggest a more plausible bankfull discharge of 3000 m$^3$/s based on a 2 meters bed level increase from the 2013 surveyed elevation (Figure 39). A 2 m reduction in bed level would correlate with a modelled bankfull discharge of ~6000 m$^3$/s (Figure 39). It is illustrated that only a 2 meter change in base level can have as much as a doubling effect on the required bankfull discharge, and as such suggests that the incisional process documented in Wangi Creek have the capacity to greatly influence bankfull discharge estimates.
In summary it is apparent from the hypothetical scenarios presented above that bed-level elevation has a dramatic effect on the magnitude of bankfull/levee-full discharge. The implications of this are twofold. Firstly, the observation of rapidly migrating knickpoint and the associated erosion make it likely that preceding cycles of knickpoint migration might have lowered the creek bed over time since the LGM. Therefore, secondly, the paleodischarge required to explain sediment deposition on the 8 m high LGM flood levee may have been significantly overestimated in the original study by Nott et al. (1996).

6.4 Limitations

A number of limitations must be acknowledged within this project. What would be regarded as the biggest limitation to this study is the fact that Wangi Creek and the catchment are unregulated and ungauged. This introduces error as all the hydraulic modelling is uncalibrated, hence, the model may be under or overestimating Manning’s n. Although this is a significant limitation to the study it is an aspect that hopefully is dealt with by performing 3 various Manning’s n models.

Following on, the availability of a recent LiDAR dataset possesses many benefits to hydraulic modelling as summarised in chapter 2; however this dataset has not been corrected with ground control points, decreasing the horizontal and vertical accuracy. The RTK DGPS field-derived checkpoints could not be used to horizontally correct the dataset as no horizontal reference points were identified in the initial LiDAR survey. Secondly interference from the escarpment caused distortion of the RTK base station signal; hence measured ground points in the upstream section of the reach were inaccurate. Following on from this; the LiDAR dataset was constrained to a small portion of the actual floodplain, which has made it difficult to predict the outcome of higher magnitude discharges that inundate the adjacent floodplain to a greater extent. Because floodplain extent was restricted the use of a 2D model was not possible as the dataset was not accurate enough. For this reason a 1D model was used which means that floodplain inundation for discharges that greater than bankfull have relative inaccuracies (Mohammed et al. 2012).

Furthermore small sub-sections of the LiDAR dataset have elevation discrepancies due to the inability of LiDAR to penetrate water. On a reach scale dry season water depth does not generally exceed more than 0.5 m, however in pool and billabong sections of the reach dry season water depth ranges from 1 to 3 m. Corrections have been made for the plunge pool bathymetry but financial and site access constraints have not permitted acquisition of reach-
scale bathymetry in the pools. The implications of this are not dramatic although thalweg elevations would be lower in parts of the reach with deep standing water however the effect on discharge estimates in the possibly affected areas was not obtainable with existing resources.

It is known that knickzone migration began between the late 1980s and early 1990s although due to the poor resolution of the satellite imagery used it is impossible to prescribe an accurate position of the knickpoint until 2004 when higher resolution imagery for the site is available. This results in the overall migration rate being an estimate for the first decade of analysis.

The regional maximum flood analysis presented in section 5.2.3 requires on long series of hydrological data to ensure that the calculations are an accurate representation of the region. As there were relatively few stations with long term records a compromise was made to include stations with records as short as 15 years, as was the methodology applied in Weeks (2006) to ensure that an adequate number of station were used in the analysis.

6.5 Recommendations

6.5.1 Determining hydrological variations over time
This project has formed the foundation for future investigations into the inundation frequency of floodplains in small ungauged catchments in tropical Northern Australia. Further examination of the monsoonal events at Wangi Creek is required to acquire a sufficient data sample to determine how the catchment hydrology varies over time. As a precipitation-flow stage relationship could be derived using the measured 2013/14 stage it would only be necessary to:

- Gauge monsoonal rainfall conditions over subsequent wet seasons and derive relative flow conditions using a precipitation-flow stage relationship.
- Obtain in-channel bathymetry to develop a more accurate representation of channel morphology and derive more precise discharge values.

6.5.2 Knickzone implications
It is apparent that destabilisation of the Wangi Creek channel is ongoing due to knickzone migration and bed incision occurring in the downstream extent of the study reach. The road
approximately 500 m upstream is likely to be affected by this feature, so it is important for infrastructure and transport to pre-emptively mitigate any damage that may be associated with this. As well as this evidence of downstream destabilisation and vegetation damage suggests that the upstream rainforest regimes are in danger of being altered or destroyed due to change in channel conditions and lowering of the current water table. Further investigation is required to acquire an understanding of the driving factors and conditions to local knickpoint propagation as no immediate indictors such as upstream land use change are apparent.

6.5.3 Wangi as a climate proxy

Lastly, as Wangi Creek is used as climate proxy, sedimentary cores need to be cross-referenced to rebuild the geomorphic history of Wangi Creek, to determine whether or not bed level has fluctuated since the LGM. Waterfall Creek is the second site presented in Nott et al. (1996), that has correlating sedimentary sequences in its flood ridges. The techniques applied in this thesis should be also used to assess this ungauged site and others like it.
7. CONCLUSION
The monitored rainfall and runoff data for Wangi Creek for the 2013/2014 wet season identifies the distinctly seasonal characteristics of the tropical Northern Australia. The creation of a reach-scale DEM for Wangi Creek illustrates a macro-channel that varies in dimension over the entire study reach. This particular morphology (especially in the upper sub-reaches) suggests that the system is adjusted to accommodate both the modern regime and an extreme precipitation event such as the paleodischarge values suggested by Nott et al. (1996).

The hydrological potential derived for Wangi Creek catchment, suggests that the discharge magnitudes experienced are large relative to majority of similar sized catchments within the same region, even though the rainfall patterns and magnitude remain relatively similar. Following on from this the use of HEC-RAS hydraulic modelling results using channel and floodplain roughness assumptions based on reach scale vegetation density, indicates that an the modelled 2013/14 re-produces a similar flood magnitude previously attached to the site in 1996, and predicts a maximum discharge for the 2013/14 monsoon season of 400 m$^3$/s. However water surface elevation is insufficient to fill the macro-channel to bankfull and as a result the floodplains are not inundated. Furthermore it is unclear as to whether or not paleofloods in the LGM achieved such bankfull discharges (an order of magnitude larger than today), as modern channel dynamics point to an actively incising channel.

The presence of a migrating knickpoint today suggests that the system may fluctuate as part of a cut and fill system. If this were the case then bed levels in the LGM (e.g at the time of of coarse bedload deposition in the levee) may have been much higher than today. On a geological time scale this process is important to the estimation of previous flood magnitudes as bed level is crucial to stage height. The use of this site as paleoclimate indicator is reason for ongoing investigation into Wangi Creek and other associated reaches. This project utilised limited time and funding to produce an accurate representation of the modern hydrological regime. Considering this structured approach it would be easy to replicate these methods over a series of wet seasons whilst including multiple sites with similar characteristics.
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Appendix A: Geo-processing of gauge sites in the NT.

Appendix B: Creation of LiDAR in model builder

(1) Unzip all Laz files to Las
(3) Clip entire las by plungepool shp
(4) Reduce number of data points to reduce file size

(5) Combine plunge pool points with clipped entire site data

Appendix C: Vegetation Density Analysis in model builder
Appendix D: Vegetation density map; red = low, blue = high
Appendix E: The (a) maximum discharge and (b) maximum discharge per km\(^2\) recorded, for available stations within a 200km radius; not filtered

(a)

![Discharge per square kilometer for max flood](image1)

(b)

![Max Q vs Area](image2)

\[ y = 9.7142x^{0.6287} \]
Appendix F: All long section water surface profiles for (a) Uniform, (b) LCHR and (c) Variable Manning's n model scenarios. Flow from right to left.

Discharge Scenarios for LCHR "n"

- Thalweg
- Gauges
- Debris line
- 2 m³/s LCHR(n)
- 300 m³/s LCHR(n)
- 800 m³/s LCHR(n)
- 1600 m³/s LCHR(n)
- 350 m³/s LCHR(n)
- 2200 m³/s LCHR(n)
- 100 m³/s LCHR(n)
- 400 m³/s LCHR(n)
- 1200 m³/s LCHR(n)
- 1800 m³/s LCHR(n)
- 500 m³/s LCHR(n)
- 3000 m³/s LCHR(n)

Elevation above AHD (m)

Distance Downstream (m)

Discharge Scenarios for Variable "n"

- Thalweg
- 2 m³/s V(n)
- 300 m³/s V(n)
- 800 m³/s V(n)
- 1600 m³/s V(n)
- 350 m³/s V(n)
- 2200 m³/s V(n)
- Gauges
  - 100 m³/s V(n)
  - 400 m³/s V(n)
  - 1200 m³/s V(n)
  - 1800 m³/s V(n)
  - 500 m³/s V(n)
  - 3000 m³/s V(n)
- Debris line
  - 180 m³/s V(n)
  - 600 m³/s V(n)
  - 1400 m³/s V(n)
  - 2600 m³/s V(n)
  - 1000 m³/s V(n)
  - 500 m³/s V(n)
  - 1000 m³/s V(n)
  - 3600 m³/s V(n)
Appendix G: Landsat Images of Knickpoint location over time, a-f (1987–2010). Flow from top right to bottom left

Legend

- 2014_knickpoint
- 1996_Knickpoint
- 1990_Knickpoint
- 1987_Knickpoint

Downstream E

RGB
- Red: Band_1
- Green: Band_2
- Blue: Band_3

(c)

Legend

- 2014_knickpoint
- 2001_knickpoint
- 1996_knickpoint
- 1992_knickpoint
- 1991_knickpoint

Downstream E

RGB
- Red: Band_1
- Green: Band_2
- Blue: Band_3

(d)

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(e) [Image of satellite map showing flood events from 1987 to 2014]

(f) [Image of satellite map showing flood events from 2010 to 2014]

Legend:
- 2014_knkpnt
- 2010_knkpnt
- 2006_knkpnt
- 2000_knkpnt
- 1996_knkpnt
- 1990_knkpnt
- 1987_knkpnt

Overstorey Extract:

TM_2004_277.jpg

RGB:
- Red: Band_1
- Green: Band_2
- Blue: Band_3

Legend:
- 2014_knkpnt
- 2010_knkpnt
- 2006_knkpnt
- 2000_knkpnt
- 1996_knkpnt
- 1990_knkpnt
- 1987_knkpnt

Overstorey Extract:

TM_2010_293.jpg

RGB:
- Red: Band_1
- Green: Band_2
- Blue: Band_3
Appendix H: Spatial inundation of the Wangi Creek reach based on the specified discharges. (a) 180 (b) 500 (c) 1000 (d) 2200 (e) all. Flow from top right to bottom left. Inundation Maps of Wangi Creek.

(e)