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# FLASH FLOODS IN THE NADI WATERSHED, FIJI:
# MORPHOMETRY, PRECIPITATION, HYDROLOGY AND RIVER CHANNEL VARIATION

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## Abstract

Intense precipitation and flash floods has been a problem in Nadi, a town located in the north western part of Viti Levu island, Fiji. The latest flood events occurred in January 2009 and 2012 respectivefully of which the former was reported to be the worst since the 1931 floods (Chandra & Dalton, 2010). The main aim of this research is to understand the characteristics of flash floods in the Nadi watershed by analysing three main research objectives; (i) basin morphometry of the Nadi watershed using geo- spatial technology, (ii) precipitation data for a period of 52 years (1961-2013) by calculating time of concentration, peak discharge for a return period of 10, 50 and 100 years using Giandotti formula for the main basin as well as four sub basins. Also to construct a trendline for maximum monthly rainfall for 50 year period and predicted maximum monthly rainfall for 60- 100 years and (iii) dynamics of river channel changes in the Nadi basin that is caused by a flood event by using satellite images for the years 2005 (pre flood), 2012 (during flood) and 2014 (post flood).

The methodology chosen was done in three parts. Firstly, in order to realise how flash floods occur, there is a need to better understand the basin morphometry of the watershed. These include a linear and areal analysis to obtain drainage density, hydrographic density, compact coefficient, elongation and roundness amongst other parameters. Secondly, using the precipitation data, calculation of time of concentration, peak discharges on a 10, 50, 100 year return period was carried out using Giandotti formula. Finally, using satellite images and ArcGIS to digitize river channels of the main Nadi river in two locations and to compare any changes in its physical aspect as well as the flooded alluvial plain.

The results show that the basin morphometry of the Nadi watershed is such that the total number and length of stream segments is high in first order streams and decreases as the stream order increases.The time of concentration ($t_c$) of **11.8hours** for the main basin is relatively rapid considering the elongated shape of the watershed. Furthermore, the peak discharge of a 10, 50, and 100 year return period also indicates the main basin having a peak discharge of **3762.47 $m^3/s$** for a return period of 10 years and doubles in a 100 year return period with **6165.27 $m^3/s$**, predicting the increase in severity of intense precipitation. This pattern is the same for the four sub basins. Channel variation results also indicate a small yet significant change in its channel formation for a period between 2005-2014, increasing the extent of flooded alluvaial plain, and consequently increasing the boundary of the river channels. These results are intended to assist future researchers in the field of geo- hydrological studies.


**Keywords:** Flash Flood, Basin Morphometry, Hydrology, Channel Variation, Nadi

## Acronyms

CDB- Central Business District

CSD- Commission on Sustainable Development

DEM- Digital Elevation Model

DTM- Digital Terrain Model

EU- European Union

FIBS- Fiji Islands Bureau of Statistics

FJD- Fiji Dollars

FMS- Fiji Meterological Services

GIS- Geographical Information System

JICA- Japan International Cooperation Agency

NOAA- National Oceanic and Atmospheric Administration

PIC- Pacific Island Countries

SOPAC- South Pacific Islands Applied Geoscience Commission

SRTM- Shuttle Radar Topography Mission

UN- United Nations

UNCED- United Nations Conference on Environment and Development

UNDP- United Nations Development Program

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# Chapter 1: Introduction

## 1. Introduction

Flooding as a natural disaster is a severe and costly hazard that many countries face regularly (UNDP, 2004). It is the most common and most spatially distributed natural hazard and according to Dilley et al. (2005) over one third of the earth's land mass is estimated to be prone to flooding.

According to a report published by UNDP (2004) these land masses that are prone to flooding affects an estimated 82% of the entire global population. The report goes on to explain that records of major flood disasters in the world have increased dramatically in the past half century. To illustrate the increasing frequency of flood occurences the report states that there were six major flood disasters in the 1950s; seven in the 1960s; eight in the 1970s; eighteen in the 1980s; and twenty six in the 1990s.

A drastic increase in flood disasters for each passing decade only entails the escalation in the number of people affected which consequently hinders the development of the country economically as floods often cause devasting damages to urban infrastructures.

Additionally, about 196 million people in more than 90 countries are victims of flood disasters with about 170, 000 deaths with floods between 1980 and 2000 (UNDP, 2004). These statistics puts into perspective the severity of floods worldwide and the need for research in order to potentially minimise its impact.

| FLOOD TYPE | DEFINITION/ CHARACTERISTICS |
|---|---|
| **Fluvial floods** | This is a result from rivers breaching or overtopping flood defences and urban areas |
| **Coastal floods** | Result from tidal or storm surges in cities close to the coast or deltas |
| **Flash floods** | Caused by the rapid response of ephemeral streams to heavy rainfall, related, amongst other things, to slopes |
| **Groundwater floods** | Caused by groundwater table rising. This tends to occur in low lying areas, and especially those that are underlined by permeable rocks (to provide aquifiers) after much longer periods of sustained high rainfall. |
| **Pluvial floods** | Due to heavy rainfall directly on urban area such that the runoff exceeds the capacity of the draingage system |
| **Progressive floods** | Caused by prolonged heavy rainfall lasting several weeks |

**Table 1** The five main types of urban floods (Source: Vojinovic & Abott, 2012)

There are several reasons as to why floods occur and ideally can be categorized into man made and natural causes. Some obvious causes of floods are heavy rain, melting snow and ice, and frequent storms within short time duration (Sharifi et al., 2012).

According to Aderogba (2012), there are three school of thoughts about '*the preponderance of floods all over the globe, especially in the tropics'*. Firstly, is the belief that floods are caused by global warming and climate change that is directly and or indirectly increasing the amount of rain and ice melting that is consequently increasing the amount of run off[1].

The second school of thought suggests that there has been an abundant development on the physical environment and that the environment is only responding to the 'abuses' heaped on it. Aderogba suggests that '*these abuses include but not limited to poor planning of the physical environment, poor management of wastes, inadequate drains for the built up areas and others'* (Aderogba, 2012: pp. 551) . The final school of thought however, suggest that floodings is caused by a combination of both global warming and climate change, as well as abuses of man on the environment.

All floods are not alike as Vojinovic & Abott (2012) defines the six main types of urban floods (table 1). Some floods develop slowly over a period of days (progressive floods), and others can develop quickly within minutes (flash floods).

Flash floods often have a high velocity and have been known to approach critical flow conditions carrying rocks, mud, cars, and other obstacles that lie in its path (Sharifi et al., 2012). The focus of this research will be on flash floods in Fiji (figure 1), especially looking at the flash floods in the chosen study area of the Nadi watershed.

[1] **Runoff-** water flow that occurs when the soil is infiltrated to full capacity and excess water from rain, melt water or other sources and flows over the land (Beven, 2004)


**Figure 1** The Fiji islands located east of Australia with the coordinates: 18° S, 179° E).

## 1.2 Objectives

The main focus for this study will be to investigate flash floods in the Nadi watershed by analysing three main research objective; the first being basin morphometry, secondly investigating precipitation data for a period of 52 years (1961-2013) and the third is the change in river channel formation in the Nadi basin, focussing on two different location in the watershed and a segment of the main channel from each location of the Nadi river.

The first research objective is basin morphometry and includes linear and areal analysis to ascertain the basin attributes of the Nadi watershed. Morphometric analysis of the drainage basin and channel networks play an important role in understanding geo-hydrological behaviour of drainage basins (Hajam *et al*, 2013). These include parameters such as stream order, bifurcation ratio, stream length, basin area and length, compact co-efficient, relationship between width and length, index of elongation and roundness, drainage density etc.

The second research objective is based on investigating precipitation data for a period of 52 years to calculate time of concentration, peak discharge for a return period of 10, 50 and 100 years, as well as a trendline of maximum monthly rainfall and its return period. Additionally, an objective from this research point is to try and ascertain the periods of intense precipitation and if it correlates with recorded flood events.

The third and final research objective is channel variation, and its objective is to use satellite images of three different years: 2005, 2012 and 2014, to compare the impact of the 2012 flood event on the Nadi river channel and its alluvial plains. An objective is to digitize these satellite images on ArcGIS, calculate the width of the channels along with digitizing inundated areas, and compare the statistics of these results to find out whether channel variation occurs.

## 1.3 Conceptual Framework

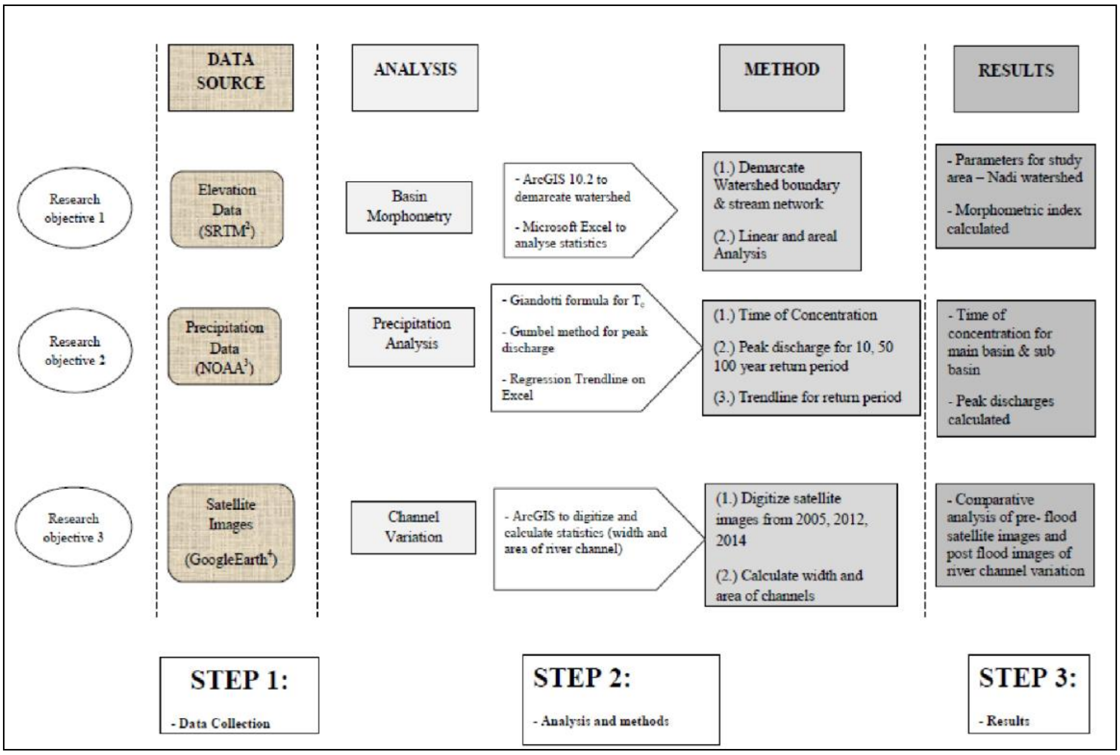



**Figure 2** The proposed scheme for this research consisted of 3 main steps to obtain the main objectives (i) data collection[2][3] [4](ii) processing and analysis of data (iii) result analysis

The thesis research is divided into five chapters. The first chapter, the introduction, presents the project and the study area as well as the reasoning behind the importance of this research. It discusses several literary works that has been already

[2] SRTM- Shuttle Radar Topography Mission. Data acquisition further explained in chapter 2
[3] NOAA- National Oceanic and Atmospheric Administration. Data acquisition further explained in chapter 2
[4] GoogleEarth- GoogleEarth Pro.. Data acquisition further explained in chapter 2

published in the same theme of this particular research. The second chapter discusses the methodology and materials used. In this chapter the reasons as to why a particular method was chosen with contrast to other methods and materials was discussed in addition to the areas where data was collected from.

Furthermore in the third chapter, the watershed attributes of the the Nadi Basin is discussed. This is in terms of basin morphometry and analyses the attributes of the watersheds and its stream network by linear and areal analysis. In addition, the physical characteristics, that is the slope, aspect and geology of Nadi watershed is also discussed.

The fourth chapter discusses hydrological characteristics and river channel variation. In this chapter, analysis of the precipitation data to acquire several outcomes such as time of concentration and peak discharge for 3 return periods (10, 50 and 100 years) was carried out. Additionally, channel variation for three time periods 2005, 2012 and 2014 was also conducted by digitizing satellite images on ArcGIS. In order to compare the changes in channel and floodplain changes, statistics of the width of river channel was calculated and compared for the time periods in question.

The final chapter, conclusion and recommendation provide a summary of the thesis research and its results as well as the challenges in conducting this research and concluding with several recommendations for improving further research in the area.

### 1.4 Study Area: Nadi

Located in the western part of the main island of Viti Levu (figure 3), Nadi boasts the title of Fiji biggest town and third largest metropolitan area of Fiji (Chandra & Dalton, 2010). It hosts the Nadi international airport as well as a slew of hotels, resorts and back packer accommodation and is thus considered a major entry point for tourists. Demographically, Nadi town has a population of 11, 685 and including the peri- urban areas that has a population of 30, 599, a total sum of 42, 284 inhabitants reside in the greater Nadi area (Fiji Bureau of Statistics, 2010).

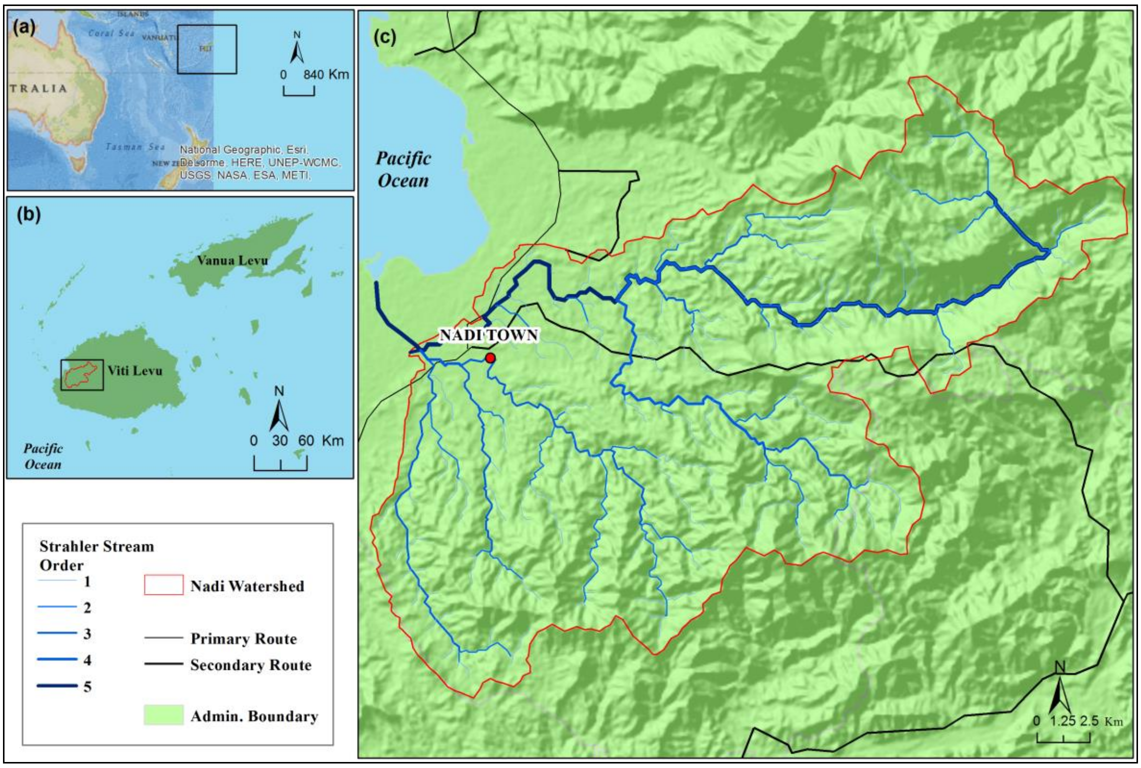



**Figure 3** Location of Nadi town **(a)** The Fiji island group towards the east of Australia **(b)** Nadi watershed is located on the main island of Viti Levu on the western side **(c)** Nadi towns location in the watershed.

The town itself lies along the Nadi river near the lower catchment with the entire Nadi river catchment covering an area of 490 km$^2$ (Terry & Raj, 1999). Furthermore from a hydrological perspective, the Nadi river is considered to be located in an area of low elevation and according to the Pacific Islands Applied Geoscience Commission (2007), a significant part of the town is below 6m mean sea level therefore making it vulnerable to flooding especially in the months that are considered to be ‘cyclone season’ from November to April. During this months there are notable (in terms of recorded flood levels) trends of increasing frequency on the occurrence of flood as illustrated in figure 4.

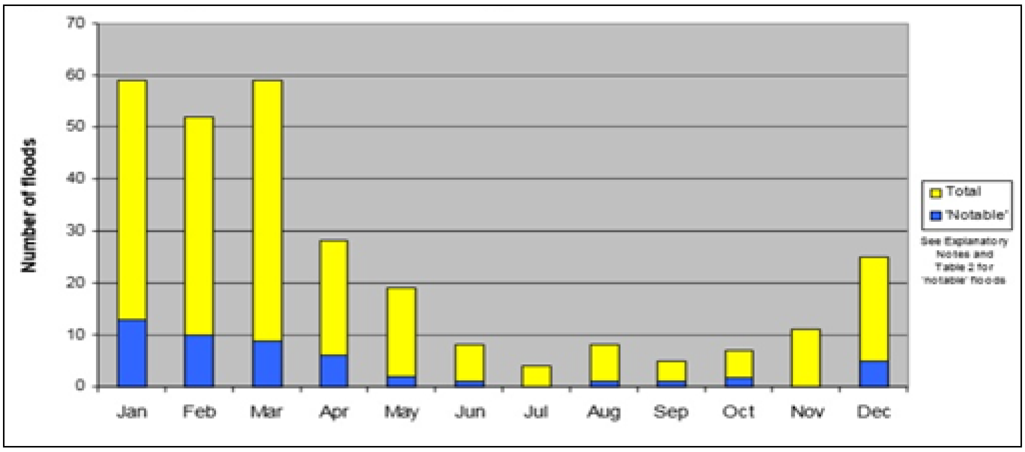
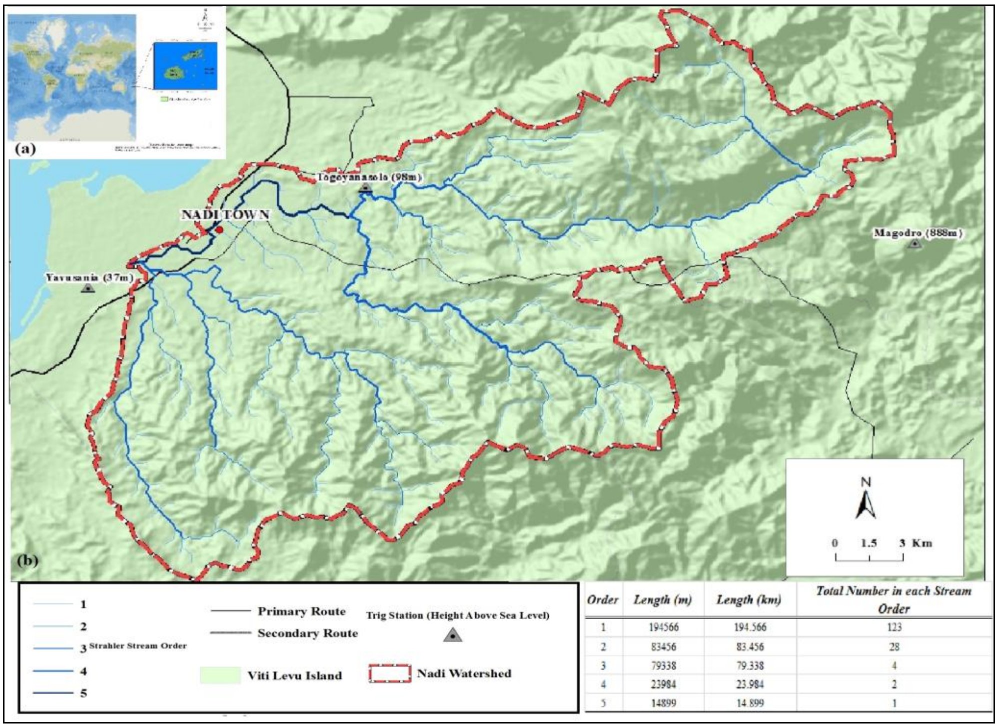



**Figure 4** Cyclone season from November to April tends to produce a significant number of floods. Adopted from 'Flooding in the Fiji Islands between 1840 and 2009 (Source: McGree et al, 2010)

According to JICA (1998), the Nadi river discharges $300m^2/s$ into the sea, and with the onset of cyclone events during the cyclone season, increases river discharge at the mouth of the river. Subsequently, during a flood event in 2007, it is reported that infrastructural damages in Nadi town reached an astounding US$1 million dollars (Government of Fiji, 2009).




| Order | Length (m) | Length (km) | Total Number in each Stream Order |
|---|---|---|---|
| 1 | 194566 | 194.566 | 123 |
| 2 | 83456 | 83.456 | 28 |
| 3 | 79338 | 79.338 | 4 |
| 4 | 23984 | 23.984 | 2 |
| 5 | 14899 | 14.899 | 1 |

**Figure 5** The Nadi basin covers 490 $km^2$ **(a)** Fiji island location in the world- east of Australia **(b)** The chosen study area for this research, the Nadi watershed with Strahler stream order classification

The chosen study area for this research is the Nadi watershed (figure 5b). According to the Strahler classification system the stream network constructed using ArcGIS 10.1, has 123 1st order streams (total length: 194.65km), 28 2nd order streams (total length: 83.45km), 4 3rd order streams (total length: 79.33km), 2 4th order streams (total length: 23.98km), and 1 5th order stream (total length: 14.89km). It also has a total area of 506.69km$^2$, with the highest altitude of 1042m and the lowest of 3m. All basin attributes will be further discussed in the chapters ahead.

## 1.5 Rationale for this research

In January 2009, Fiji experienced a tropical depression which subsequently resulted in intense periods of high precipitation, especially hitting the western part of the main island of Viti Levu, especially the towns of Nadi, Ba and Rakiraki (figure 6). According a report done by Government of Fiji (2009), this was reported as one of the worst loods in Fiji since the 1930s, with most of the low lying areas experiencing lood levels of up to 3–5 metres. The report goes on to state that the impact was greatest in the Western Division with costs estimated at about FJ$ 81 million. Nadi was one of the most affected towns, where businesses suffered a loss of over FJ$ 20 million. Lal et al. (2009) estimate the total economic cost of the January 2009 floods on the sugar industry (infrastructure, losses to growers and millers) to be FJ$ 24 million.

The report stated that with such vast devastation of major townships, visitor arrival numbers declined. The total rehabilitation cost was about FJ$ 73 million, diverting a major portion of government budget. Additionally, humanitarian costs of about FJ$ 5 million were incurred. Most rehabilitation works are still continuing, with assistance from donors and development partners (Government of Fiji, 2009).


**Figure 6** The January 2009 flood caused major infrastructural damage in the western parts of Viti Levu **(a)** An aerial view of a inundated Nadi town **(b)** Main road Nadi town submerged in water **(c)** Villagers located near the Nadi river and tributuaries flooded **(d)** A roundabout on the main road submerged in flood waters **(e)** Flood waters reach waist high in some areas as shown up two men cheering for Fiji **(f)** Shops are forced to shut down businesses when flood waters inundate the town during the 2009 flood. (Source: GoogleImages)

Floods in Fiji are of high significance and according to FMS (2001), over 160 floods from 1840- 2000 have been recorded by the Fiji Meteorological Services (appendix 1) which to be put into perspective, there are floods occuring at an average of 10 per decade.

Furthermore according to Chandra & Dalton (2010), with the increased intensity of floods throughout various parts of the country over the past years as well as future projections, fooding has become a high priority for the Government of Fiji, and thus the need for different type of research concerning floods.

## 1.6 Literature Review

The study of floods in Fiji is not scarce, but at the same time there is not a lot of research that has been done on it. However, several research has been undertaken by both academic researchers as well as organizations to better understand the impacts and the nature of floods, particularly in a developing country like Fiji (Terryand Raj, 2004; Yeo *et al*, 2007;Yeo, 2000; JICA, 1998).

This section will serve as a literature review of a number of published journal articles, books and reports on floods in terms of geo- hydrological characteristics of drainage basins. All journal articles and reports used in this literature review section was obtained form open access databases such as EBSCOhost, ProQuest and Web of Knowledge and SOPAC virtual library which has been summarized and tabulated in table 2.

| No. | Author | Summary |
|---|---|---|
| **1.** | (JICA, 1998) (Chandra & Dalton, 2010) (Terry & Raj, 1999) (Yeo, 2000) (Yeo et al, 2007) | - Several authors that research on flood events in Fiji, the causes, the impacts and recommendations on mitigation activities that can be carried out to minimise the impacts of floods in Fiji.<br>- Includes journal articles and reports. |
| **2.** | (Horton, 1945) (Strahler, 1957) (Strahler, 1964) | - Considered as pioneers in the field of hydrology, Horton researched on the functionality of a watershed and how its attributes are vital in determining variables such as peak discharge, time of concentration and its morphometric parameters with relation to intense precipitation.<br>- Strahler, is well known for classifying streams according to the power of their tributaries.<br>- Published book |
| **3.** | (Hajam, Hamid, & Bhat, 2013) (Rastogi & Sharma, 1976) (Ritter, Kochel, & Miller, 1995) (Wilson, 1990) (McCuen, 2005) (Beven, 2004) (Pilgrim & Cordery, 1993) | - Collectively these 8 authors cover the topics of Hydrographs, Geomorphology, and morphometry.<br>- Discussion on factors such as climatology, land use, geology, meteorology that all contribute to the workings of a watershed and subsequently, the formation of the basin and stream functions.<br>- Includes majority journal articles, and published books |

**Table 2** A brief summary of the literature review, the authors and their research.

## Basin Morphometry & Geomorphology of Watershed

Morphometric studies in the field of hydrology were first initiated by Horton (1940) and Strahler (1945). The morphometric analysis of the drainage basin and channel network play an important role in understanding the geo-hydrological behavior of drainage basin and expresses the prevailing climate, geology, geomorphology, structural antecedents of the catchment (Hajam, Hamid, & Bhat, 2013). Various important hydrologic phenomena can be associated with the physiographic characteristics of drainage basins such as size, shape, slope of drainage area, drainage density, size and length of the contributories etc (Rastogi & Sharma, 1976).

According to Hajam *et al* (2013) analysing drainage basin is important in any hydrological investigation as assessments of relation are important between runoff characteristics, and geographic characteristics of drainage basin systems. Increasingly studies have used the patterns of basin morphometry to predict or describe geomorphic processes (Ritter, Kochel, & Miller, 1995).

| **Linear Morphometry** | |
|---|---|
| Stream number in each order ($N_o$) | $No = R_b^{s-o}$ |
| Total stream numbers in basin ($N$) | $N = \frac{R_b^{s} - 1}{R_b - 1}$ |
| Average stream length | $\bar{L}_o = \bar{L}_1 R_L^{o-1}$ |
| Total stream length | $L_o = \bar{L}_1 R_b^{s-1} \left(\frac{u^s - 1}{u - 1}\right)$ where $u = R_L/R_B$ |
| Bifurcation ratio | $R_b = N_o/N_{o+1}$ |
| Length ratio | $R_L = \bar{L}_o/\bar{L}_{o+1}$ |
| Length of overland flow | $\ell_o = \frac{1}{2D}$ |
| **Areal Morphometry** | |
| Stream areas in each order | $\bar{A}_o = \bar{A}_1 R_a^{o-1}$ |
| Length-area | $L = 1.4A^{0.6}$ |
| Basin shape | $R_F = \frac{A_o}{L_b^2}$ |
| Drainage density | $D = \frac{\Sigma L}{A}$ |
| Stream frequency | $F_s = \frac{N}{A}$ |
| Constant of channel maintenance | $C = \frac{1}{D}$ |

**Figure 7** Linear and areal morphometry formulas used to mathematical calculate basin morphometry (Source: Ritter et al, 1995)

These are made easy with the introduction of geo- spatial techonology such as ArcGIS. Geographical Information System (GIS) techniques are now-a-days in use for assessing various terrain and morphometric parameters of the drainage basins and watersheds, as it provide a flexible environment and an important tool for the manipulation and analysis of spatial information of which can be calculated mathematically using formulas illustrated in figure 7.

The method of studying basin attributes in Fiji using this method of linear and areal morphometry is not widely recognized, and would be vital considering the input needed for calculating these parameters can be easily attained from spatial analysis tool with the ArcGIS.

Horton (1945) introduced geometric processes between number of streams, and corresponding drainage areas which are now known as Hortons Laws. The first important set of values is linked to the morphology of the catchment. For instance the shape of the stream network, determines the discharge time.

Catchment shapes vary greatly and reflect the way in which runoff will be distributed, both in time and space (figure 8). In wide, fan-shaped catchments the response time will be shorter with higher associated peak discharges as opposed to long, narrow catchments. In circular catchments with a homogeneous slope distribution, the runoff from various parts of the catchment reach the outlet more or less simultaneously, while an elliptical catchment equal in area with its outlet at one end of the major axis, would cause the runoff to be more distributed over time, thus resulting in smaller peak discharges compared to that of a circular catchment (McCuen, 2005).

In order to understand the interaction between the different variables influencing the catchment response time and resulting runoff, it is necessary to view all the catchment processes in a conceptual framework, consisting of three parts: (i) the input, (ii) the transfer function, and (iii) the output (McCuen, 2005). Floods are generated in catchment areas in which runoff, resulting from rainfall, drains as streamflow towards a single outlet. Rainfall is the input.

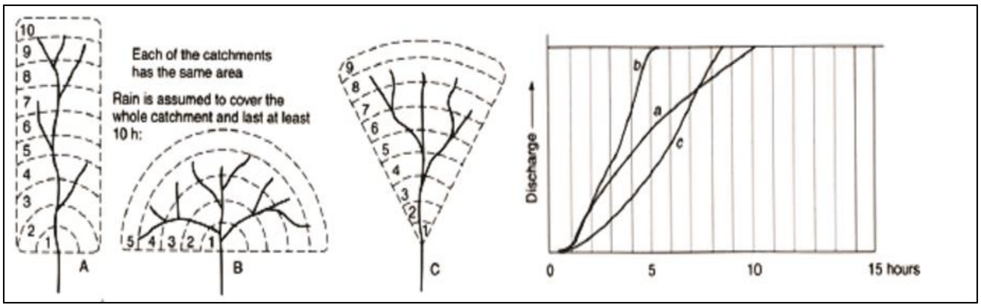



**Figure 8** The shape of stream network affects discharge time. Example: A fan shaped catchment (B) will have a faster stream rise and similarly a faster fall than a dendritic shaped catchment (C) because of shorter travel times (Source: Wilson, 1990).

The catchment characteristics define the nature of the transfer function, since rainfall losses occur as the catchment experiences a change in storage while it absorbs (infiltration), retains or attenuates (surface depressions) and releases some of the rainfall through subsurface flows, groundwater seepage and evaporation.

Furthermore, the effective rainfall exits within the catchment as the streamflow output, i.e. the direct runoff contributing to flood peaks. However, runoff generation in catchments is highly variable both in time and space, depending not only on the amount and intensity of rainfall, but it is also affected by the different physiographical parameters, or combinations thereof, which describe the catchment characteristics (Beven, 2004; Chow, 1988; Pilgrim & Cordery, 1993).

**Hydrographs**

Hydrographs are defined by Sarangi (2007), as '*a graph showing the rate of flow (discharge) versus time past a specific point in a river or channelor conduit carrying flow and is usually expressed in cubic meters or cubic feet per second (cms or cfs)*'. Each depending on the users intent, a hydrograph can be used basically for acquiring run off for a particular time period for events such as floods or storms (figure 9).

In the article, the author attempted to evaluate the models for accurate runoff prediction from ungauged watershed using ArcGIS. This was accomplished by running three types of models namely the (i) exponential distributed geomorphologic instantaneousunity hydrograph (ED-GUIH) model, GIUH based Clark model and spatially distributed unit hydrograph (SDUH) was used to predict the direct runoff hydrograph (DRH) for their study area. Furthermore, the researchers attempted to compare the generated DRH against the observed DRH at the watershed outlet.

The result of Sarangi (2007) research concluded with main point of using ED-GUIH model to predict DRH rather then the other two models because it performed better when predicting the direct runoff hydrograph for short duration storm events (≤6h) with an error margin of 4.6-22.8% for the study watershed.

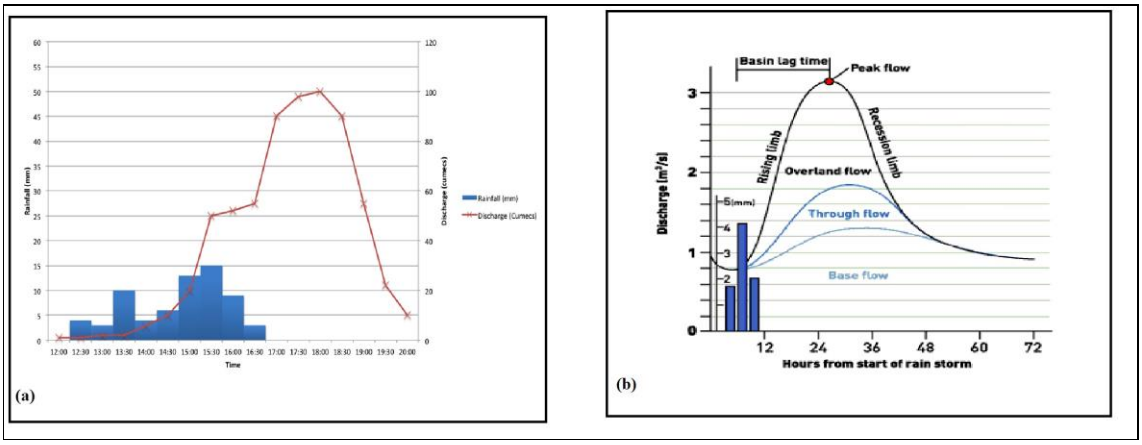



**Figure 9** Different models of hydrographs as adopted from Sarangi (2007) **(a)** A simple flood hydrograph **(b)** A 'hybrid' hydrograph showing flood and storm DRH

# Chapter 2: Methodology & Materials

## 2. Methodology

At this point, one would like to state for the purpose of transperancy, that acquisition of data for this research was somewhat challenging. The primary reason being the distance between researcher and study area that prevented any field work being conducted. However, this does not discourage or discredit the process and outcome of this research, but contributes to the much needed efforts towards scientific research in terms of floods in a developing country such as Fiji.

The methodology of this research was carried out in three major steps as illustrated in figure 2 conceptual framework and all data sources used is summarised in the table 3 below.

The fie first major step is the collection of primary data from online resources. The second major steps following these were its pre-processing in and modification using two major programs namely ArcGIS 10.1 and Microsoft Excel for correlating precipitation data. The final step of downloading satellite images of the Nadi river channel to try and ascertain physical variation of its width before and after the January 2009 flood was also carred out. This was carried out in two different locations within the watershed, the first being near the source of the main Nadi river and the second with proximity to Nadi town.

This chapter will discuss in detail the various methods that were used, as well as the materials analysed.

| DATA | PROPERTIES | SOURCE |
|---|---|---|
| ***(A) Primary Data***<br>i. Elevation | - SRTM based Digital Elevation Model 90m resolution<br>- Raster file (WGS84 datum)<br>- AAI GRID format<br>- Cell size: 0.00083<br>- Columns, Rows: 6001, 6001 | - USGS/NASA SRTM data[5] |
| ii. Precipitation (a) | - Daily precipitation data from station 'NADI AIRPORT FJ'<br>- Period of 52 years (1961- 2013) | - National Oceanic and Atmospheric Administration (NOAA)[6] |
| iii. Precipitation (b) | - Monthly precipitation data<br>- Period of 19 years (1991- 2010) | - Tropical Rainfall Measuring Mission (TRMM)[7] |
| iv. Satellite Images | - Google Images for Nadi area for the years 2005, 2012 and 2014 | - Google Earth v5.1 |
| ***(B) Secondary Data***<br>i. Published Journal Articles, Books | - 40+ journal articles<br>- Journal articles and reports pertaining to river channel morphology, Characterizing Hydrological Basins, Risks of flash floods | - Open access journal databases (i.e. Web of knowledge, EBSCOhost, ScienceDirect, ProQuest) |
| ii. Online Newspaper articles, Online media reports | - Reported flood occurences on F | |

**Table 3** Summary table of data sources used

## 2.1 Primary Data

### 2.1.1 Elevation Data: Shuttle Radar Topography Mission based DEM

The SRTM elevation data is available on request via the USGS website, and DEM data is available in two different resolutions: the ~ 30m resolution is available only under conditions of agreement with US authorities, and the ~ 90m resolution (figure 10) which was used for this study is readily available for researchers, students and any other end users. The downloaded elevation data has the default coordinate system in decimal degrees with datum WGS84 and in AAI GRID format (refer table 3).

5 http://gdex.cr.usgs.gov/gdex/
6 http://www.ncdc.noaa.gov/cdo-web/
7 http://disc2.nascom.nasa.gov/Giovanni/tovas/TRMM_V7.3B42_daily.2.shtml

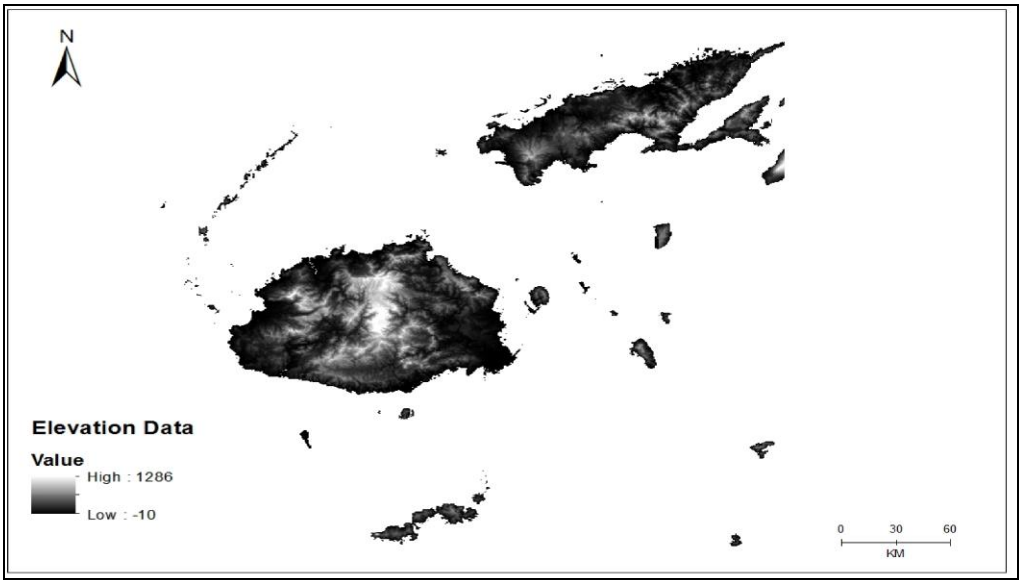



**Figure 10** Processed SRTM elevation data before further geoprocessing steps was undertaken

## Processing of Elevation Data

In order to demarcate the boundaries of the study area that is Nadi town, the elevation data also underwent several geoprocessing steps in ArcGIS 10.1. Firstly, the conversion to GRID format from the default AAIGRID format that the raw data has using the 'Raster to other format' toolset under the 'Conversion' toolbox. Using the downloaded SRTM elevation data as 'input' in the earlier mentioned toolset, the 'output' file was saved as GRID format from the list of options given.

The reason of changing the format to ASCII GRID format is simple. Files that are in ASCII GRID format is both human readable and hardware independent; it is widely supported and easy to import and export from most GIS software, easy to convert with a small script if necessary, and stores data in a reasonably compact raster format when compressed (Kumar, 2006).

Furthermore, the island of Viti Levu was extracted from the 'FJ_Adm' shapefile (downloaded from DIVA- GIS website[8]) by using 'Manual Selection' method, and exporting the selected data as a separate shapefile. This new shapefile of 'Viti Levu' was then used as a mask to extract the Elevation Data for the island using the 'Extract by mask' toolset under the 'Spatial Analyst' toolbox (figure 11).

[8] http://www.diva-gis.org/

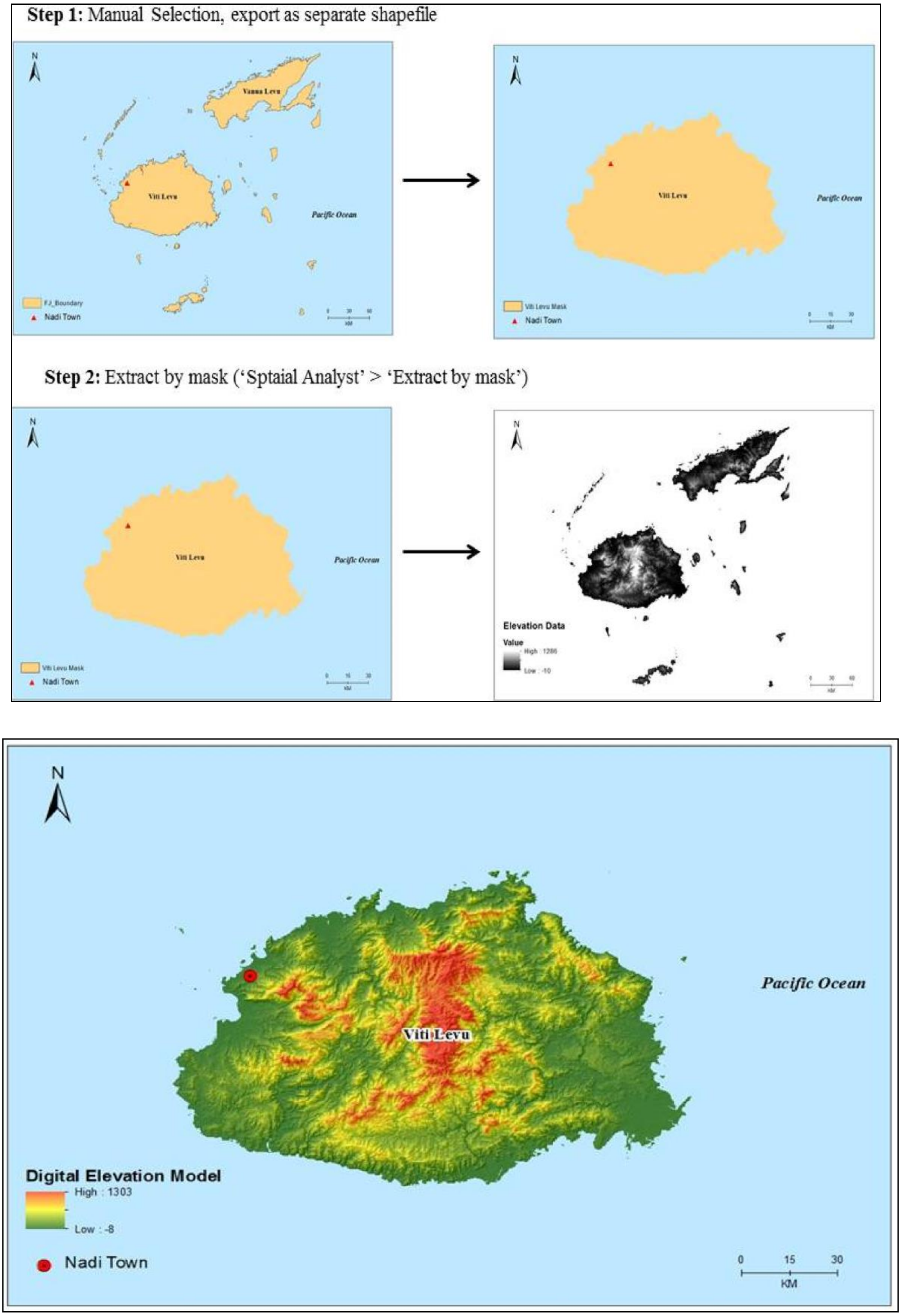



**Figure 11** Step 1: selecting and exporting the island of Viti Levu as a separate shapefile; Step 2: Extract by mask of DEM of Viti Levu. And finally output is illustration showing DTM of Viti Levu

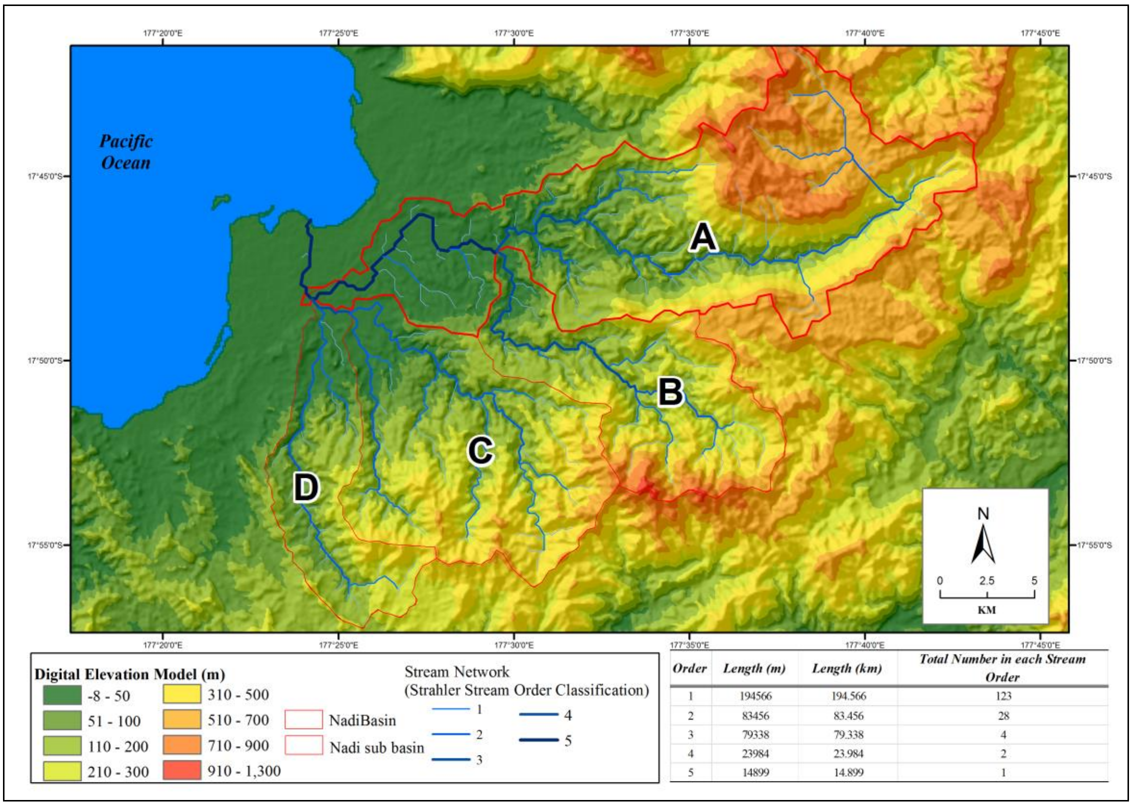
**Nadi Watershed and sub basins**

Moreover, after creating the Digital Elevation Model for the island of Viti Levu, the next step was to delimitate the watershed boundary for Nadi (figure 12). This was carried out in ArcGIS 10.1 and used the 'Hydrology' toolset from the 'Spatial Analyst' toolbox using the DTM as principle input data. The steps carried to delimitate the watershed boundary are as follows:

1. **Fill Sink:** This function fills the sinks in a grid. If cells with higher elevation surround a cell, the water is trapped in that cell and cannot flow. The Fill Sinks function modifies the elevation value to eliminate these problems.
2. **Flow Direction:** This function computes the flow direction for a given grid. The values in the cells of the flow direction grid indicate the direction of the steepest descent from that cell.
3. **Flow Accumulation:** This function computes the flow accumulation grid that contains the accumulated number of cells upstream of a cell, for each cell in the input grid.
4. **Stream Definition:** This function computes a stream grid which contains a value of "1" for all the cells in the input flow accumulation grid that have a value greater than the given threshold. All other cells in the Stream Grid contain no data.
5. **Watershed:** This function computes the watershed boundary by delimiting the stream network based on flow direction and flow accumulation calculated in the previous steps.

These steps constructed the hydrological network as well as demarcated the watershed for the whole island of Viti Levu. In order to extract the intended area of study, Nadi watershed, the watershed raster file (step 5) was converted to polygon shapefiles, and using manual selection to select the Nadi watershed which was exported as a stand alone polygon shapefile. In addition to the main watershed, four sub basins were also created as illustrated in figure 12.

Moreoever, a topography map of Viti Levu, scale 1: 250 000, was then used as an overlay to determine the accuracy of the stream network as compared to ground truth. The major disparity between the two showed the constructed stream network flowing towards a north east direction whereas the stream on the topography map flowing towards a south west direction towards the mouth of the river. Therefore, the researcher decided to eliminate the disparity by editing the main Nadi river as well as the watershed boundary to the point where the disparity begins. This is to allow minimal error as possible when calculating hydrological parameters of the Nadi watershed.




| Order | Length (m) | Length (km) | Total Number in each Stream Order |
|---|---|---|---|
| 1 | 194566 | 194.566 | 123 |
| 2 | 83456 | 83.456 | 28 |
| 3 | 79338 | 79.338 | 4 |
| 4 | 23984 | 23.984 | 2 |
| 5 | 14899 | 14.899 | 1 |

**Figure 12** The main Nadi basin as well as the four sub basin (A,B,C,D) (Source: SRTM and 1: 25000 Topo maps)

### 2.1.2 Precipitation Data

### (a) National Ocean and Atmospheric Administration (NOAA)

A counterpart of the National Oceanic and Atmospheric Administration (NOAA), is the National Climatic Data Centre (NCDC) which is responsible for *'preserving, monitoring, assessing, and providing public access to climatic and historical weather data and information'* (NCDC, 2003). With the use of their massive online database of global climatic data, daily precipitation data for Fiji was downloaded (table 3). Fortunately, a station located in Nadi town (station name: NADI AIRPORT FJ) had a dataset of precipitation from 1944- 2013.

However, it should be noted that data preceding 1961 (as well as from 1971-1973) had extensive amount of data that was missing, hence the desicion to analyse precipitation data from 1961- 2013, a period of 52 years. Moreoever, it should also be noted, that this 52 years of precipitation data also had three years of data missing, from 1971-1973, but was included in the calculation of hydrological dynamics as explained in the following section. Additionally, this precipitation data was analysed to determine long- term average monthly and annual precipitation using Microsoft Excel 2010. Futhermore, this same data was correlated to calculate 'Return Period', 'Time for concentration' and 'Peak discharge for three return periods' for individual sub basins in the Nadi watershed which will be explained in the following chapter. As with all research the need for viable data ensures the researcher with a good foundation to building their research. The principle reason that this data source was chosen is the location of the NOAA station in the study area which contributes to the validity of the data gathered. Additionally, attaining data from Fiji Meteorological Offices in Fiji pertaining to precipitation data dating back to the 1950's was unsuccessful, hence this resource was used.

**(b): Tropical Rainfall Measuring Mission (TRMM)**

The 'Tropical Rainfall Measuring Mission' (TRMM) is a joint space mission between NASA and the Japan Aerospace Exploration Agency (JAXA) designed to study and monitor tropical rainfall on the planet from space. The instruments or sensors used to gather data from the satellite include; Precipitation Radar (PR), TRMM Microwave Imager (TMI), Visible Infrared Scanner (VIRS), Clouds and Earth Radiant Energy System (CERES) and Lighning Imaging Sensor (LIS). However, the main instrument for gathering precipitation is TMI.

Correlating the data from TRMM was carried out in order to try and ascertain peak precipitation periods in Fiji using Microsofts Excel program. Unfortunately, the data from TRMM had values that were not coinciding with that of the precipitation data from NOAA which illustrates a major set back for this dataset. A major limitation when dealing with TRMM precipitation data is its underestimation of precipitation data due to its high latitude, however, analysis of both datasets (NOAA and TRMM) will be explained in the latter sections, to compare the two datasets.

**Calculating Hydrological Dynamics: Time of Concentration, Peak Flow & Return Period**

Using the precipitation data (1961-2013) obtained from NOAA, the hydrological properties (i.e. time of concentration ($t_c$), peak flow (Q) and return period (T)) for the Nadi watershed as well as the four sub basins was calculated. The first parameter that was calculated was the time of concentration ($t_c$) and this was accomplished by using the Giandotti formula given by Grimaldi *et al* (2012) (figure 13):

$$tc = \frac{4\sqrt{A}+1,5L}{0,8\sqrt{H}}$$

*Where:* ***A*** is the area of the watershed (km$^2$),
***L*** is the length of the main river (km)
***H*** is the mean height of the watershed (m)

**Figure 13** Time of concentration Giandotti formula as adopted from Grimaldi et al (2012)

The second parameter to be calculated was 'peak flow' for a return period of 100 years. This was adopted from the Giandotti formula (figure 14) (Giandotti, 1953; Lencastre & Franco, 1984).

$$Qmax = \frac{\lambda . A . h}{tc}$$

*Where:* $\lambda$ is a parameter according to the area of the watershed *A* (km$^2$)
*h* is the height of the maximum precipitation (mm).

**Figure 14** Giandotti formula for calculating peak flow as adopted from Giandotti (1953)

In order to calculate the return period, the 52 years of precipitation data was arranged in descending order of magnitude. This was to allow a frequency analysis to be carried out, after which the Welbull method (figure 15) was applied to get the return period (T):

$$T = (n+1)/m$$

*Where*: ***n*** is the total number of events/records and
***m*** is the order or rank of the event, in this case the annual maximum daily precipitation.

**Figure 15** The formula for calculatting Return Period (T) as adopted from Dawood et al (2012), using the Welbull method

### 2.1.3 Satellite Imagery: Google Earth

Determining channel variation by using satellite images was a method adopted for this research. Several authors have used this simple method to determine channel varioation like (Erskine, 2013) (Friedman & Lee, 2002) (Lyons & Beschta, 1983). Satellite images from the years 2005, 2012 and 2014 were downloaded for selected areas that had the main Nadi channel running through it. This is illustrated in chapter 5, figures 25 and 27.

The main purpose of choosing these specific years was to try and ascertain if the width of the main channel changed before the 2012 flood event. The river channel was digitized in ArcGIS 10.1 and thewidth of respective segments was averaged. Furthermore, it is important to note that by simple observation of the 3 different satellite images, one is able to note the change in river channel formation. This is solidified by the changing width of the river channels.

## 2.2 Secondary Data

As illustrated in table 3, secondary sources of data for this research was largely from open source journal databases such as web of knowledge, ScienceDirect, EBSCOHost and published books as well as online reports.

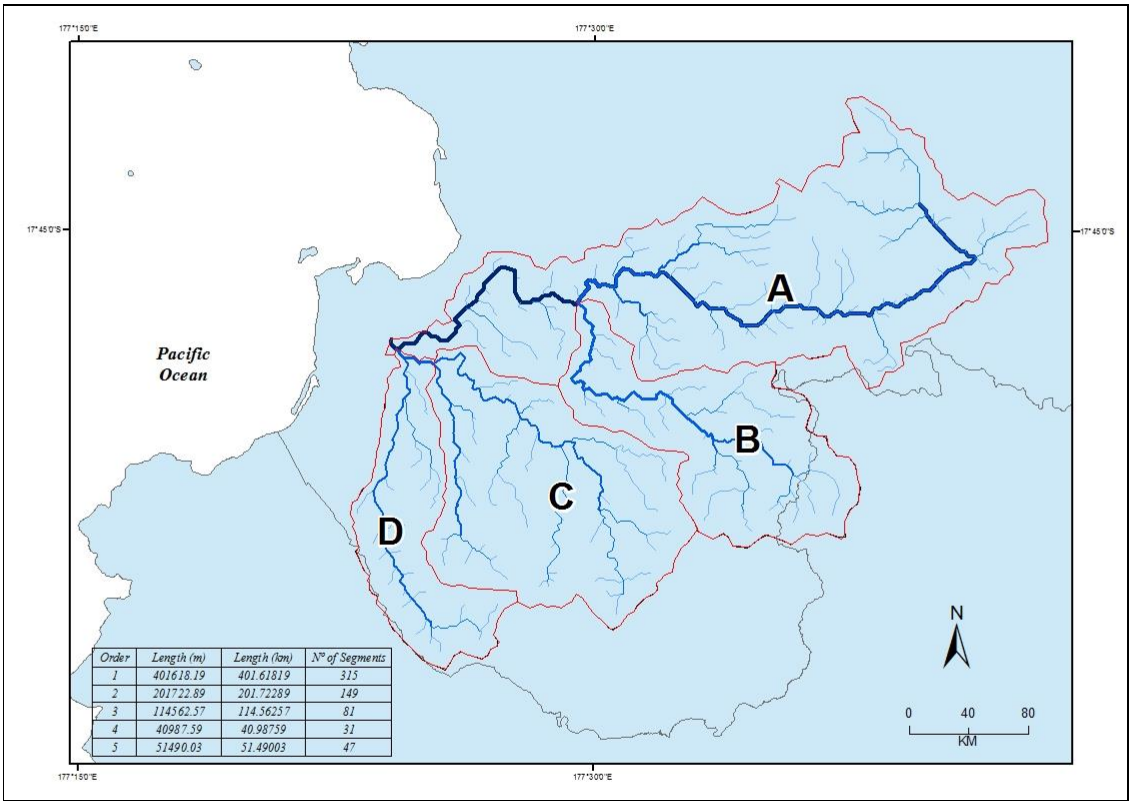
# Chapter 3: Morphometric Analysis and Physical Characteristics of Nadi Basin

## 3. Characteristics of Hydrological Basin for Nadi River

TheNadi river is located on the north- western (NW) side of the main island of Viti Levu. Since the Nadi river is on the lee side of Viti Levu, it experiences long periods of dry spells. The valleys and hills along the Nadi river are rich agriculture lands. Moreover, the monthly average temperature ranges from 24 – 27°C and rainfall ranges from 1440 – 1993 mm/yr. The Nadi district produces the largest volume of sugarcane annually in Fiji, and sugar is the main economic activity, followed by tourism, manufacturing, forestry and fisheries respectively (Ledua *et al*, 1996).

Nadi town is the main business centre of the Nadi district and is located on the western side of the river delta approximately 8 kilometres inland from the coast. The population of Nadi as a province from the last census in 2007 is approximately **231 760,** and Nadi town has a population of **42 284** (Fiji Bureau of Statistics, 2010).

This chapter will discuss the result of the anaylsis carried out on the Nadi watershed based on its hydrological and physical characteristics. Also, precipitation data from NOAA was analysed which was used to try and channel variation which will be discussed in the latter sections.




| Order | Length (m) | Length (km) | N° of Segments |
|---|---|---|---|
| 1 | 401618.19 | 401.61819 | 315 |
| 2 | 201722.89 | 201.72289 | 149 |
| 3 | 114562.57 | 114.56257 | 81 |
| 4 | 40987.59 | 40.98759 | 31 |
| 5 | 51490.03 | 51.49003 | 47 |

**Figure 16:** Hydrological watershed and four sub catchments (A,B,C,D) for Nadi created from SRTM based DEM with a 90m resolution.

## 3.1 Morphometric Analysis of Nadi Basin

A major emphasis in geomorphology over the past several decades has been on the development of quantitative physiographic methods to describe the evolution and behaviour of surface drainage networks (Horton, 1945). All hydrologic and geomorphic processes occur within a watershed and because of these the morphometric features at the watershed level may contain vital information regarding its formation and development (Singh N. , 1990).

For this research, the author has used SRTM[9] based Digital Elevation Models (DEM) with a resolution of 90m and GIS to evaluate linear and areal analysis as discussed in the following sub sections.

### 3.1.1 Linear Analysis:

The hydrological basin for Nadi covers **506.69 km²** with a total of 5 stream orders according to the Strahler Stream Hierarchy Classification system. The length of the main Nadi river under the 3rd, 4th and 5th order sums up to **45.60 km**. The sum of the 1st order stream magnitude, and has a total of 162 segments, with the total length of **194.56 km**. This is tabulated in 'Fluvial Hierarchy of Nadi river' table 3 below:

| STREAM ORDER | LENGTH (M) | LENGTH (KM) | Nº OF SEGMENTS |
|---|---|---|---|
| **1** | 194566 | 194.566 | 162 |
| **2** | 83456 | 83.456 | 64 |
| **3** | 79338 | 79.338 | 65 |
| **4** | 23984 | 23.984 | 18 |
| **5** | 14899 | 14.899 | 12 |

**Table 3** Fluvial hierachy of river channels in the Nadi watershed based on Strahler classification of stream orders

### Bifurcation Ratio (Rb)

The bifurcation ration is defined by Pareta et al. (2012) as '*ratio of the number of stream segments of given order 'Nu' to the number of streams in the next high order'*. Moreover, according to Strahler (1964) the bifurcation ratio is dimensionless property and generally ranges from 3.0- 5.0, whilst the lower values of *Rb* are characteristics of the watersheds which have suffered less structural disturbances and the drainage pattern

[9] Shuttle Radar Topography Mission

has not been distorted because of the structural disturbances (Nag, 1998). In contrast, the higher the *Rb* indicates more structural damages undergone in areas that that the stream order passes through.

| | STREAM ORDER | VALUE |
|---|---|---|
| **BIFURCATION RATION (RB)** $RB = \frac{NU}{NU+1}$ | 1 | 2.531 |
| | 2 | 0.984 |
| | 3 | 3.611 |
| | 4 | 1.5 |
| | 5 | - |

**Table 4** Bifurcation ratio adopted from Horton (1945) for streams in the Nadi watershed

According to the index parameter for bifurcation ratio given by Strahler (1964), and the results in table 4, it can be inferred that the watershed being studied has suffered less structured disturbances.

**Segment Length (LU) and Stream Length Ratio (RL)**

Horton (1945, as cited by Pareta et al., 2012) states that *'length ratio is the ratio of the mean (Lu) of segments of order (So) to mean length of segments of the next order (Lu – 1), which tends to be constant throughout the successive orders of a basin'.* Furthermore, Horton's law of stream length refers to the mean stream lengths of stream segments of each successive orders of a watershed tend to approximate a direct geometric sequence in which the first term (stream length) is the average length of segments in first order (Pareta et al., 2012).

| | STREAM ORDER | VALUE |
|---|---|---|
| **SEGMENT LENGTH** $\overline{LU} = \frac{\Sigma\, LU}{NU}$ | 1 | 1201.02 |
| | 2 | 1304 |
| | 3 | 1220.58 |
| | 4 | 1332.44 |
| | 5 | 1241.58 |

**Table 5** Segment length (LU) and relationship

According to Singh et al. (1997), *change of stream length ratio from one order to another order indicating their late youth stage of geomorphic development.*

| | ORDER OF SEGMENTS | VALUE |
|---|---|---|
| **RELATION TO LENGTH** $RL = \frac{LU}{LU-1}$ | *1* | - |
| | *2* | 1.085739543 |
| | *3* | 0.936031147 |
| | *4* | 1.091644469 |
| | *5* | 0.931808706 |
| | | |

**Table 6** Order of segments and relation to length

The area of the watershed is another important parameter like the length of the stream segment. Schumm (1956) established an interesting relation between the total watershed areas and the total stream lengths, which are supported by the contributing areas. The author has computed the basin area, basin length and basin morphometry parameter for Nadi basin using ArcGIS 10.1 software as displayed in table 7 below and other morphometric parameters for areal anaylsis which is explained in the following sub sections.

| NO. | PARAMETER | FORMULA | DESCRIPTION | REFERENCE | RESULT |
|---|---|---|---|---|---|
| (i) | Basin Area | - | A- Area (km²) | - | 506.69 |
| (ii) | Basin Length | - | L- Length (km) | - | 40.8 |
| (iii) | Basin Perimeter | - | P- Perimeter (km) | - | 134.91 |
| (iv) | Compact Coefficient | $Kc = 0.28(P\sqrt{A})$ | P – Perimeter(Km)<br>A – Area (Km²) | Gravelius (1914) | 1.67 |
| (v) | Relationship between width and length | $RIL = \frac{I}{L}$ | I – Width (Km)<br>L – Length (Km) | - | 0.62 |
| (vi) | Elongation Ratio | $Re = 2 / Lb * (A / \pi)^{0.5}$ | A – Area (Km²)<br>L – Width (Km) | Schumm (1956) | 0.62 |
| (vii) | Circularity Ratio | $Rc = 12.57 * (A / P^2)$ | A – Area (Km²)<br>P – Perimeter (Km) | Miller (1960) | 0.35 |
| (viii) | Relationship between length and area | $Ico = \frac{L}{\sqrt{A}}$ | L – Length(Km)<br>A – Area (Km²) | - | 1.81 |
| (ix) | Drainage Density | $Dd = \frac{C}{A}$ | A – Area (Km²)<br>C – Total length of segments (Km) | Strahler (1957) | 0.78 |
| (x) | Coefficient of Maintenace | $Cm = \frac{1}{Dd}$ | Dd – Drainage Density | - | 1.28 |
| (xi) | Segment density of basin | $Fs = \frac{\Sigma n}{A}$ | $\Sigma$n – Sum of all segments from all stream orders<br>A – Area (Km²) | - | 0.63 |
| (xii) | Hydrographic density or Frequency of Thalweg | $Dh = \frac{N1}{A}$ | N1 – Nº of segments in 1st Order<br>A – Area (Km²) | - | 0.31 |
| (xiii) | Torrentiality Coefficient | $Ct = Dh \times Dd$ | Dh – Hydrological Density<br>Dd – Drainage Density | - | 0.24 |

**Table 7** Important morphometric parameter for basin geometry

### 3.1.2 Areal Analysis

### Compact Coefficient (Cc)

According to Gravelius (1914) compact coefficient of a watershed is the ratio of perimeter of watershed to circumference of circular area, which equals the area of the watershed. The *Cc* is independent of size of watershed and dependent only on the slope.

The calculated *Cc* for Nadi basin is **1.67** that was calculated using the formula provided in table 7 and calculated in a simple Microsoft Excel spreadsheet. The calculated *Cc* suggests an elongated basin as it falls within the range of 1.5 – 1.75 as suggested by Singh (1997).

### Relationship between Width (I) and Length (L)

The parameter calculated for this particular index provides comparative data between the two variables of width and length  (Pareta & Pareta, 2012). Morphometric index for the parameter indicate if the value is close to then width and length are closer to each other.The index calculated as shown in table 7 for the Nadi watershed being studied is **0.62**.

### Elongation Ratio (Re)

According to Schumm (1956) elongation ratio is defined as *the ratio of diameter of a circle of the same area as the basin to the maximum length.* However, Strahler (1957) states that this ratio runs between 0.6 – 0.1 over a wide variety of climatic and geologic types. The varying slopes of watershed can be classified with the help of the index of elongation ratio such as:

| ELONGATION RATIO (RE) | SHAPE |
|---|---|
| 0.9 - 0.10 | Circular |
| 0.8 – 0.9 | Oval |
| 0.7 - 0.8 | Less elongated |
| 0.5 - 0.7 | Elongated |
| < 0.5 | More elongated |

**Table 8** The elongation ratio describes the overall shape of the basin using Strahlers classification for this index

Furthermore, the calculated elongation ratio for Nadi basin is **0.62** calculated by the author using the formula provided in table 7. Subsequently this would deem our basin as elongated according to the classification provided in table 8.

**Circularity Ratio (Rc)**

Circularity Ration or sometimes called Index of roundness is defined by (Singh & Singh, 1997) as *the ratio of watershed area to the area of a circle having the same perimeter to the watershed and its pretentious by the lithological character of the watershed*. Miller et al. (1960) has described the basin of circularity ratios range from 0.4 – 0.7, which indicated strongly elongated and highly permeable homogenous geologic materials.

The *Rc* value for the Nadi watershed is **0.35** (table 7), corroborates the Miller's range, which subsequently indicates the watershed is elongated in shape.

**Relationship between length and area**

The parameter calculated for this particular index provides comparative data between the two variables of width and length. Moreover if the values calculated for this index are close to 0 the basin would be circular. In contrast, if it were close to 1 it would be close to a square and if it were higher than 1 it would be elongated.

The index calculated as shown in table 7 for the watershed being studied is **1.81** which correlates with the elongation ratio.

**Drainage Density ($D_d$)**

Drainage density ($D_d$) is defined by Horton (1945, as cited by Pareta & Pareta, 2012) as *'the ratio of total length of streams in a watershed over the total area covered by the watershed'*. The value that is calculated from $D_d$ follows that increasing drainage density implies increasing flood peaks. Moreover, a long concentration time implies more opportunities for water to infiltrate. Therefore a decreasing $D_d$ generally implies decreasing flood volumes (Pallard *et al*, 2009).

Essentially this index describes the higher the value of $D_d$ the quicker precipitation permeates into streams further increasing the probability of flooding of an area. In contrast, when the $D_d$ index is low, precipitation has to travel by surface run off, throughflow and baseflow permeating into streams in a reduced amount of time as compared to the former. Areas with a low $D_d$ therefore a less likely to experience flooding.

$D_d = \frac{C}{A}$ Where C: Sum of length of all segments

A: Total area covered by basin

For Nadi Basin: 396.243 km / 506.69 km$^2$

$D_d$ = **0.782 km/km²**

**Figure 17** Drainage Density for the watershed of Nadi. Formula was adopted from (Strahler A. , 1957)

For Nadi basin, the drainage density calculated was **0.782** (table 7, figure 17) and according to (Lencastre & Franco, 1987) any index that fell between the range of 0.5 or less is deemed a basin with poor drainage. However, a basin that has the index ranging between 3.5 and above would be considered as one that has good drainage properties. For the Nadi watershed, it can be suggested from this parameter that it has just a degree of proper drainage but one that is not so high as to ensure proper drainage.

There are several factors that contribute to the drainage properties of a basin, some of which was discussed in (Strahler A. , 1957)

- **Geology and soils:** drainage densities are higher on impermeable surfaces because there is less infiltration
- **Land Use:** vegetation increases interception, and reduces drainage density
- **Time:** the number of tributaries and therefore the drainage density tend to reduce overtime
- **Precipitation:** areas of high precipitation tend to have higher drainage densities
- **Relief:** drainage densities are usually higher on steep land because there is less infiltration and often less vegetation (depending on aspect)
-

**Coefficient of Maintenance (Cm)**

This index indicates the minimal area for maintenance of a permanent stream and given that *Cm* of Nadi basin is **1.289** (refer table 7) suggest that it is not under the influence of structural disturbances having high run off and low permeability.

**Segment Density of Basin ($F_s$)**

Segment density is basically illustrating how dispersed each segment of the river is in relation to the area covered by the watershed. As shown in table 7, $F_s$ for Nadi basin is 0.633 indicating there are approximately **0.633** segments per unit of surface.

**Hydrographic Density or Thalweg Frequency ($D_h$)**

It is indicative of the number of $1^{st}$ order streams per square kilometre ($km^2$) of surface of which Nadi basin is **0.319** as shown in table 7.

**Torrentiality Coefficient ($C_t$)**

An important morphometric index when studying the quantitative characteristics of a watershed which describes the network drainage that allows analysts to infer about the response time of watershed to an event of which Nadi basin is 0.248 as depicted in table 7.

## 3.2 Physical Characteristics: Slope and Aspect

In order to determine how a watershed functions in terms of its reactions to flood waters and precipitation, the researcher drew maps to illustrate Nadi watersheds slope, aspect and geology which will be explained in this section.

## Slope

Slope is defined by Black (pp. 287, 1997) as *'the gradient, or vertical difference between two points whose elevation are known divided by the horizontal distance between them'*. According to Karanth (1987), slope has a dominant effect on the contribution of rainfall to stream flow and to the ground water reservoir, as it controls the duration of overland flow, infiltration and subsurface flow. Karanth (1987) explains that slope also indirectly controls the infiltration capacity of soils in the watershed which determines the amount of subsurface flow that infiltrates with the layers of the soils in the watershed.

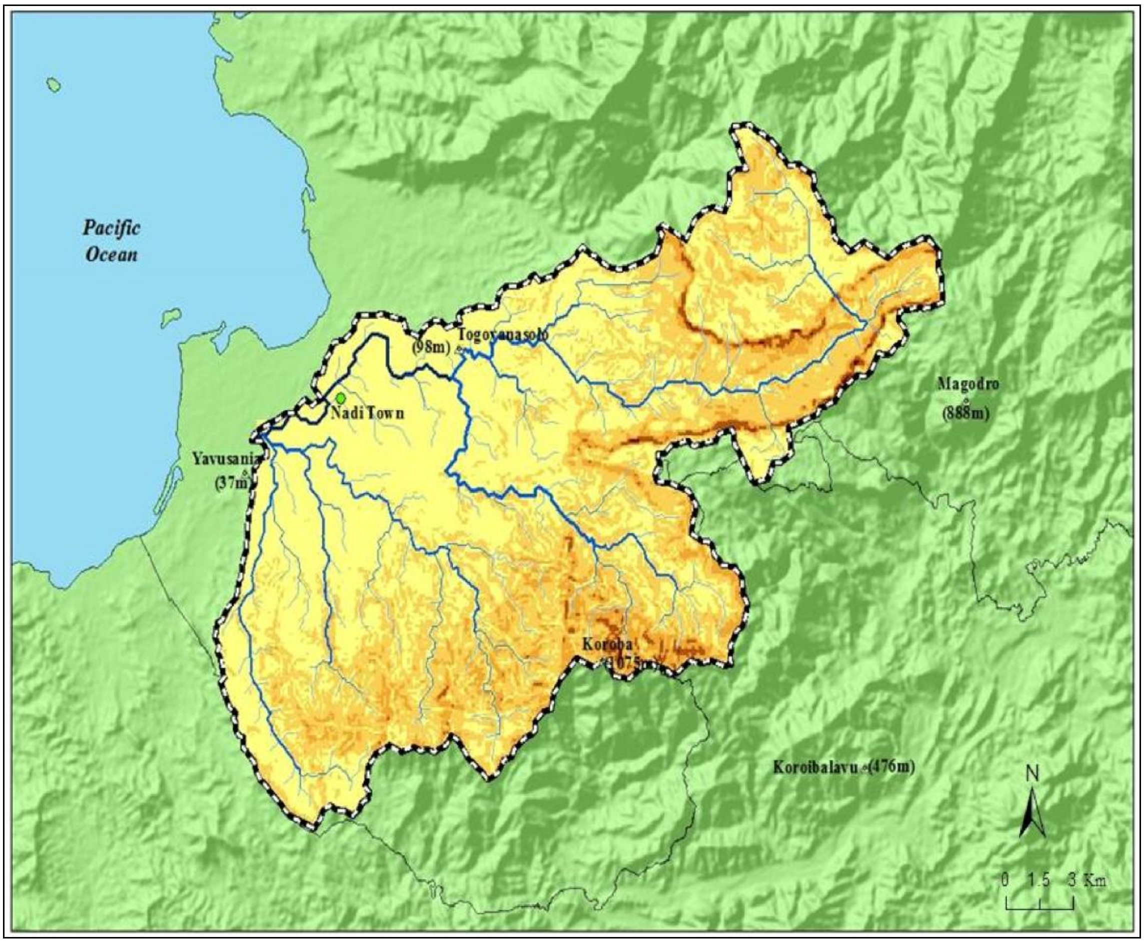



**Figure 18** The slope map of the Nadi watershed with the stream network

For Nadi watershed it can be deduced from the slope map illustrated in figure 18, that an estimated 70% covers a low lying area.Subsequently, the location of Nadi town in a depressed, low lying area of the watershed only means it is vulnerable to flood waters that approach from the steeper areas located further inland. The steepest portion of the watershed has a slope value of >40°, which is located in the periphery of the watershed boundary towards the Nausori highlands and Vaturu dam.

Additionally, it should be noted that slope interacts with other characteristics of the watershed such as microclimate, vegetation, lithology, material source (e.g. *in situ*weathering or loess deposition), and erosion. Steep slopes give rise to coarse textured and permeable materials which are deposited in the form of channel deposits in streambeds (Karanth, 1987).

**Aspect**

This is defined by Black (pp, 290, 1996) as the direction of exposure of a particular portion of the slope, expressed in azimuth (0-360°) or the principal compass points (N, NE, E, SE etc.). It is especially important feature of the watershed in terms of isolation i.e. energy received on a horizontal plane that in effect contributes to evapotranspiration of land masses. Highly insolated facets are likely to have lower average annual runoff than other portions of the watershed (Black, 1996).

In normal circumstances, a 45° south facing aspect watershed at 45°N presents a surface that is parallel with a horizontal surface at the equator and perpendicular to incoming radiation, through the process of insolation (Black, 1996). This inturn meansa general humid to hot climatic conditionsand yield lower annual precipitation and runoff. The aspect map for Nadi watershed (figure 19) determines its isolation properties and given that Nadi is located in the western part of Viti Levu, it receives more isolation as it is exposed to heat more contributing to its evapotranspiration process..

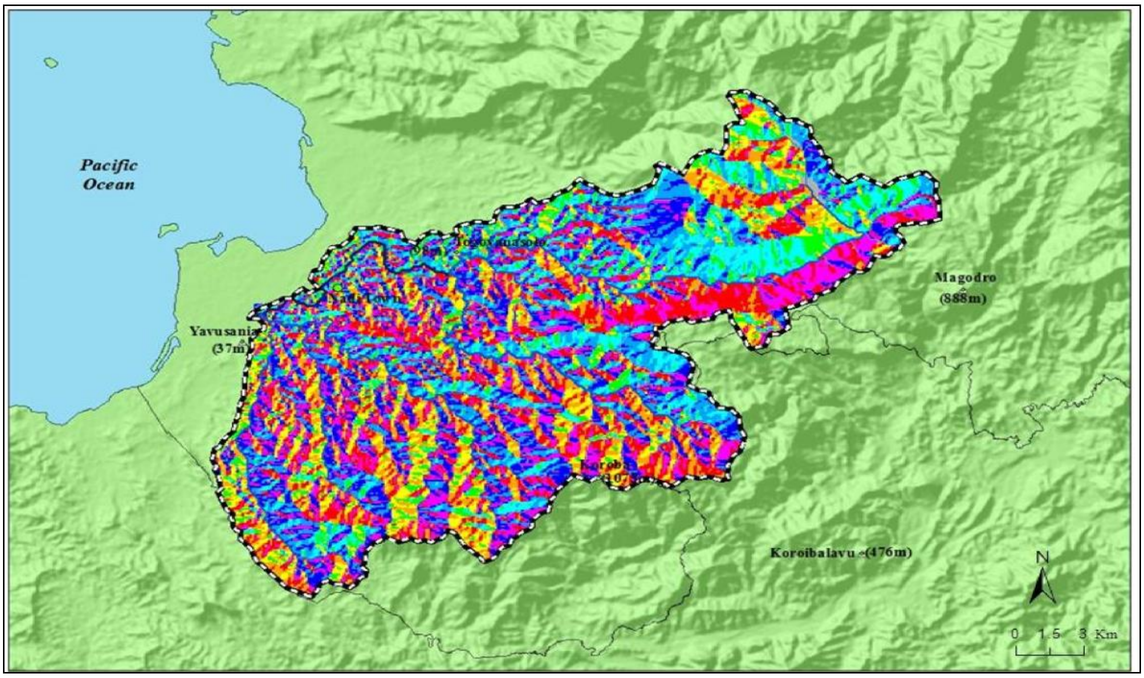



**Figure 19** The aspect map of the Nadi watershed which determines the isolation of the land and contributes to its evapotranspiration

# Chapter 4: Hydrological Characteristics and River Channel Variation

## 4. Hydrology

The recurrence of extreme precipitation anomalies that result in floods or droughts is a normal component of natural climate variability (WMO, 2009). The use of precipitation data to analyse time of concentration, peak discharge for the return period of 10, 50 and 100 years as well as the return period for the Nadi watershed was carried out to better understand the nature of flash floods in the Nadi watershed. It is widely known that floods are more often caused by intense precipitation. In recent years, heavy precipitation events have resulted in several damaging floods in Fiji, the most recent ones being the flood events of January 2009 (figure 21) which was one considered on of the worst flood occurrence.

| Date | Name | Nadi town | | Other | Source | Comment | Rank |
|---|---|---|---|---|---|---|---|
| | | m a.m.s.l. | Source | | | | 1 = highest |
| 1931 Feb | | ? | | Floods reportedly the highest and severest ever experienced in Nadi to that date; 5 ft (1.5m) deep in town, in some instances up to 9 ft deep (2.7m); Nadi River rose 35 ft (10.7m) above normal level | FNA, FTs | Description of river rise sounds too high given other levels. | ? |
| 1939 Jan | | *6.77?* | | 4 ft (1.2m) deep in shops and houses. | FTs | Est. ½ ft (0.15m) lower than Oct 1972 | 6 |
| 1956 Jan | | ? | | Highest flood since 1938-39; higher than 1955 flood; heavy loss of merchandise | FTs | | ? |
| 1964 Mar | | 6.72 | PWD | 18 ft (5.5m) in main street | FTs | Description of depth in main street sounds too high for quoted level | 7 |
| 1965 Feb | | *7.02?* | | Highest flood on record at the time and much higher than Mar 1964 flood | FTs | Est. 0.3m higher than Mar 1964 | 4 |
| 1972 Oct | Bebe | *6.92?* | | 4½ ft (1.4m) deep at ANZ Bank; somewhat lower than 1965; 8 ft (2.4m) in town | Harris, 1972; Blong, 1994 | Est. 0.1m lower than Feb 1965 | 5 |
| 1982 Jan? | Hettie? | 5.86 | PWD | 4 ft (1.2m) at Nadi bus station | Blong, 1994 | | |
| 1983 Mar | Oscar | 6.61 | PWD | 12 ft (3.7m) in the market | Blong, 1994 | | 9 |
| 1984 Mar | Cyril | 5.62 | PWD | 1m at the Nadi bus station | Blong, 1994 | | |
| 1985 Jan | Eric | 4.56 | PWD | | | | |
| 1985 Jan | Nigel | 4.74 | PWD | | | | |
| 1985 Mar | Hina | 5.38 | PWD | 1-2m in town | Blong, 1994 | | |
| 1986 Apr | Martin | 6.53 | PWD | 1.5m at southern end of town | Blong, 1994 | | 10 |
| 1990 Mar | Rae | 5.93 | PWD | | | | |
| 1993 Feb | Poly | 7.06 | PWD | 1.7m in Roshni store | FTs | | 3 |
| 1997 Mar | Gavin | 6.66 | PWD | | | | 8 |
| 1999 Jan | | 7.25 | PWD | 8 inches (0.2m) higher than 1964 | Interview | 1964 probably confused with 1965? | 2 |
| 2009 Jan | | *8.05* | | 0.8m higher than 1999 flood at Jack's of Fiji | Interview | | 1 |

Note: italics represent calculated levels based on the described information; question marks indicate poorly constrained levels.

**Figure 20** Flood events as recorded by Yeo (McGree et al, 2010)

In this chapter, precipitation data for a period of 52 years will be analysed (1961-2013) to calculate several parameters such as time of concentration, peak discharge and return period. Addiotionally, a sketch of a segment of the Nadi river for the years 2004, 2005, 2009, 2013 and 2014 was also done to compare channel changes.

All images used in this analysis was from GoogleEarth pro, and chosen based on period of flood events or heavy precipitation, minimum cloud cover and most importantly availability of images on Historical Imagery tool on GoogleEarth.

### 4.2 Analysing Precipitation Data

The precipitation data from NOAA was graphed according to the daily maximum values recorderd for each year so as to demonstrate the nature of heavy precipitation in Nadi. The day which recorder the maximum amount of rainfall was then graphed as illustrated in figure 21. Additionally this was also done to figure out whether the reported flood event coincided with the value of heavy precipitation from NOAA. In order to to accomplish this, the sum of daily precipitation was summed up and sort according to the days that recorded the highest amount of rainfall and using the Webull method (figure 12) as adopted from Dawood (2012), the return period was calculated.

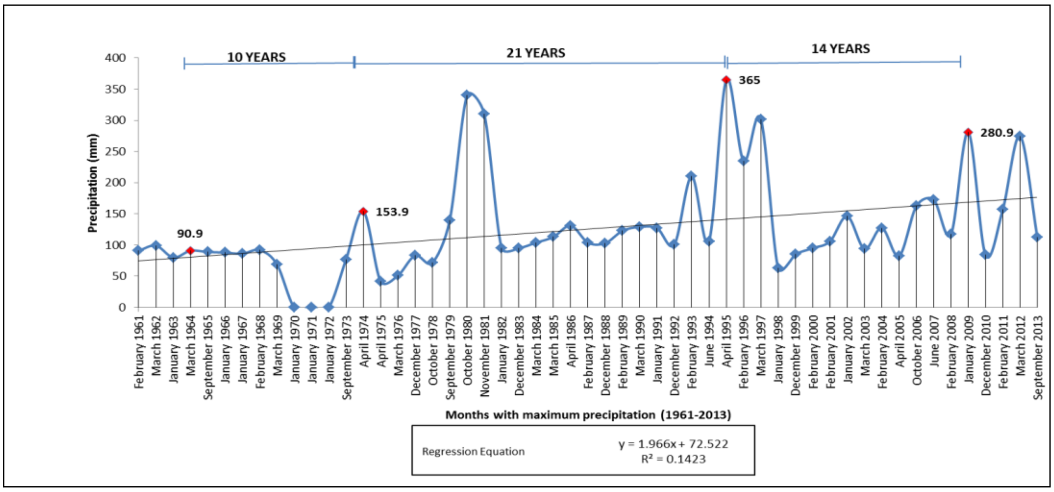



**Figure 21** Precipitation data tabulated and graphed for a period of 52 years (NOTE: Missing data for 1970-1972) (Source: NOAA)

Several studies have examined changes in occurrence of larger scale flooding events under climatic change (Booij, 2005), but little research has been done on changes in small scale flood events. This may be driven by the limited availability of high spatial and temporal resolution precipitation output from climate change models (typically climate model precipitation estimates are daily or monthly values and at spatial scales of 100s of kilometers). For our study area, fortunately

Flash flood occurrence is often associated simply with "heavy precipitation", Doswell et al. (1996). However, Brooks and Stensrud (2000) compared the climatology of heavy precipitation, with the flash flood climatology, and concluded that flash floods occur 17 times less frequently than heavy precipitation. Flash flood occurrence is not driven by heavy precipitation alone but by meteorological, climatic and physiographic influences including precipitation intensity, topography, and soils properties (Georgakakos, 1986).

A trendline as illustrated in figure 22 illustrates a maximum monthly rainfall versus a return period for upto 50 years and further, a predicted value (in red) from 60-100 years using a regression line method on Microsoft excel. Basically, it illustrates that in 100 year return period the maximum rainfall predicted will be 440.32mm, and with the return period of 50years the calculated amount of precipitation received was 365mm.

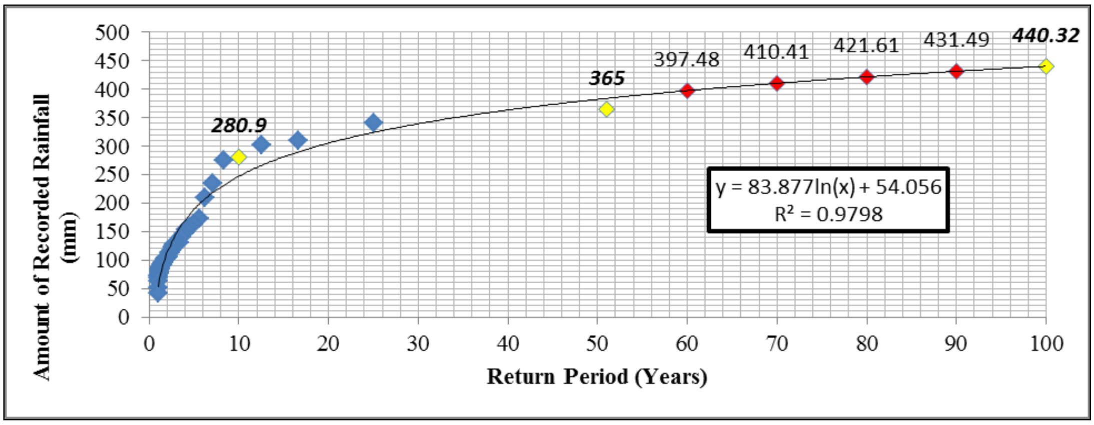



**Figure 22** Trendline for the return period versus recorded maximum rainfall data. Predicted values for precipitation data for 60, 70, 80, 90 and 100 years are in red (Source: NOAA rainfall data)

In hydrograph analysis, time of concentration is the time from the end of excess rainfall to the point on the falling limb of the dimensionless unit hydrograph (point of inflection) where the recession curve begins (Beven, 2004). In the next sub section, the time concentration for Nadi watershed, as well as for the four sub basins was calculated using the methods defined in chapter 2.

### 4.3 Time of Concetration ($t_c$)

Time of concentration represents the hydrologic response time of an urban watershed, is measured in *hours* and is defined by Akan *et* al (2003) as the time required for all parts of a basin to contribute to discharge at the outlet simultaneously.

In simple terms, it is the **time** needed for water to flow from the most remote point in a watershed to the watershed outlet. It can be calculated using several methods, however for this particular research the Gumbel method (Grimaldi *et al*, 2012) was chosen as the formula for obtaining $t_c$.The principle reason for choosing this formula was mainly attributed to the fact that the required input (area, length and height) was easily obtained from the demarcated Nadi watershed carried out in ArcGIS. The main Nadi watershed had a time concentration value of **11.8hrs** as illustrated in table 9 below.

| | | | Sub-Basin | | | |
|---|---|---|---|---|---|---|
| **Parameter** | **Unit** | **Main watershed** | **A** | **B** | **C** | **D** |
| Area | ($km^2$) | 506.7 | 224.6 | 92.6 | 129.3 | 60.2 |
| Length | (km) | 40.8 | 34.5 | 11.2 | 14.7 | 6.5 |
| Height | (m) | 254.8 | 149.7 | 183.3 | 169.6 | 165.2 |
| | | | | | | |
| **$T_c$** | (hrs) | 11.8 | 11.4 | 5.1 | 6.5 | 4.0 |

**Table 9** Time of concentration for Nadi watershed and the four sub basins using the Gumbel method

Considering that the size of the watershed is **506.7 km$^2$**, this illustrates the rapid flow of river water towards the mouth of the river often incurs the quick rise of river water subsequently flooding the areas near the mouth. The same can be deduced from the time of concentration for the four sub basins as well: Sub basin A: area of 224.6 km$^2$ and $t_c$ of 11.4 hrs, Sub basin B: area of 92.6 km$^2$ and $t_c$ of 5.1 hours, sub basin C: area of 129.3 km$^2$ and $t_c$ of 6.5 hoursm sub basin D: area of 60.2 km$^2$ and $t_c$ of 4.0 hours (which exhibit the fast concentration time). These results depict an direct relationship between area of basin and time of concentration i.e. the more the area the more rapid the rain water flows and conctrates towards the mouth.

## Peak Discharge for Return Period of 10, 50 and 100 years

The calculation of the peak discharge for 3 return periods (10, 50, 100 years was made through the application of Giandotti's formula as explained in chapter 2. In the main watershed, the value of peak discharge expected for a return period of 100 years is 6165.27 m$^3$/s (table 10). As shown in table 10, sub basin 'A' for a return period of 10 years the value of the peak discharge is 1702.5 m$^3$/s and these values almost double in 100 years. This can also be highlighted in sub-basin D mainly because it is the smallest sub-basin of the four, with an area of 60.2, and gather great volumes of water in 4hours, for example 1726.96 m$^3$/s in 100 years. In contrast, the sub-basin B is a little larger than D, but the peak discharge is smaller, and takes more time (5h) to achieve the most downstream point of the sub-basin. In quantitative terms, the values reach 815.47 m$^3$/s for a return period of 10 years and 1277.54 m$^3$/s in 100 years.

| **Main basin and Sub-Basin** | **Peak Discharge for Return Period (Years):** | | |
|---|---|---|---|
| | **10** | **50** | **100** |
| **Main Watershed** | 3762.47 | 5462.10 | 6165.27 |
| A | 1,702.51 | 2,469.25 | 2,785.45 |
| B | 1,090.88 | 1,550.72 | 1,726.96 |
| C | 1,336.50 | 1,911.22 | 2,136.56 |
| D | 815.47 | 1,151.85 | 1,277.54 |

**Table 10** Peak discharge for the 4 sub basins in a return period of 10, 50, 100 years

## 4.2. Channel Variation

One of the objectives of this research is to investigate the physical channel changes on the main Nadi river on two areas of the watershed. For this, satellite images of the Nadi river was digitized on ArcGIS, and statistics (width and area) of the channel was calculated to estimate if any physical variation occurred on the river channel for 3 time periods i.e. 2005, 2012 and 2014. These three time periods were chosen to compare if any changes occurred, especially pre- flood event which is 2005, during a flood even-2012, and post flood event, 2014.

The methodology adopted to obtain the width of the digitized river channels was by drawing transects between the two sides of the river. Using ArcGIS, the length of the transects weres calculated to obtain the average length, as well as minimum and maximum length of the width. Furthermore, with these data a comparative analysis was done between the three time periods in the two different location to try and ascertain any channel changes.

**Selected Areas**

The two selected areas were from two two segments of the main channel of the watershed, that is Nadi river. The first near the source or headwaters (L1), and the seond being near the mouth, on the NE end of the watershed (L2) (figure 23). These areas were selected to demonstrate two the impacts of intense flood waters that occurred in 2012 in two different regions of the watershed.

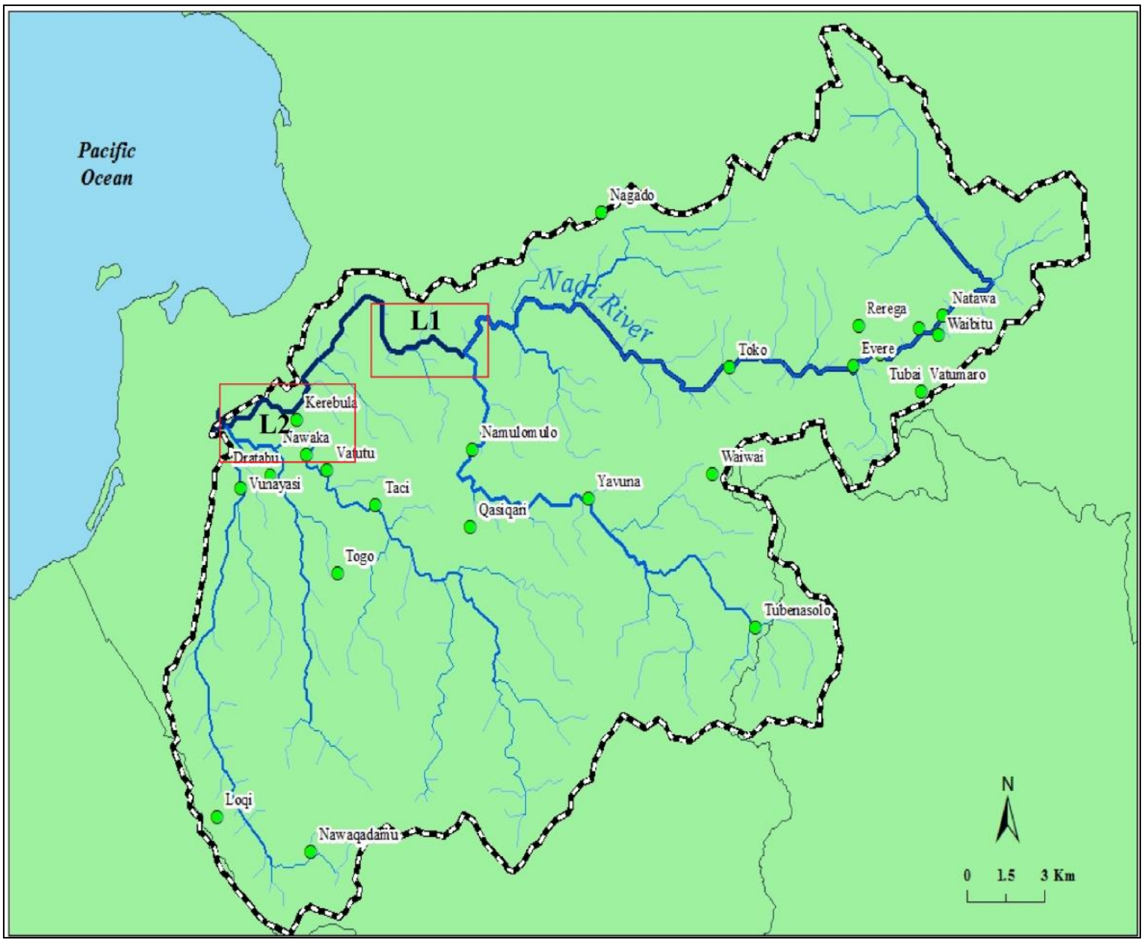



**Figure 23** The two selected areas of study. Location 1 (L1) was towards the headwater and Location 2 near mouth of river (Source: SRTM Elevation Data)

Location 2 contains the Nadi town within its limit as illustrated in figure 25 which is located right next to the Nadi river on an area of low elevation.

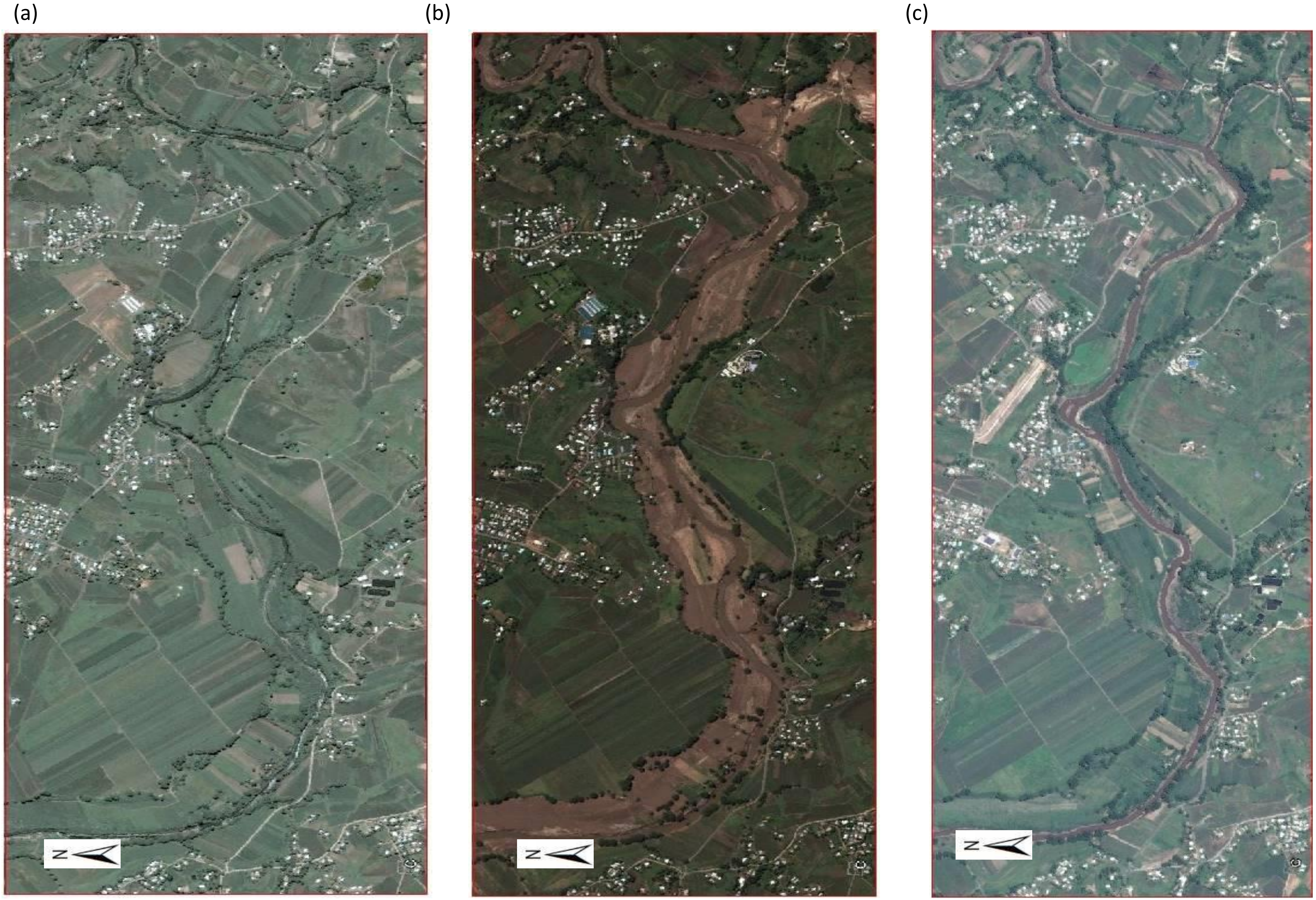



**Figure 24** From the Location 1(a) 2005 satellite image showing the Nadi river pre- flood event(b) 2012 satellite image showing flood event occuring (c) 2014 post flood satellite image (Source: GoogleEarth)

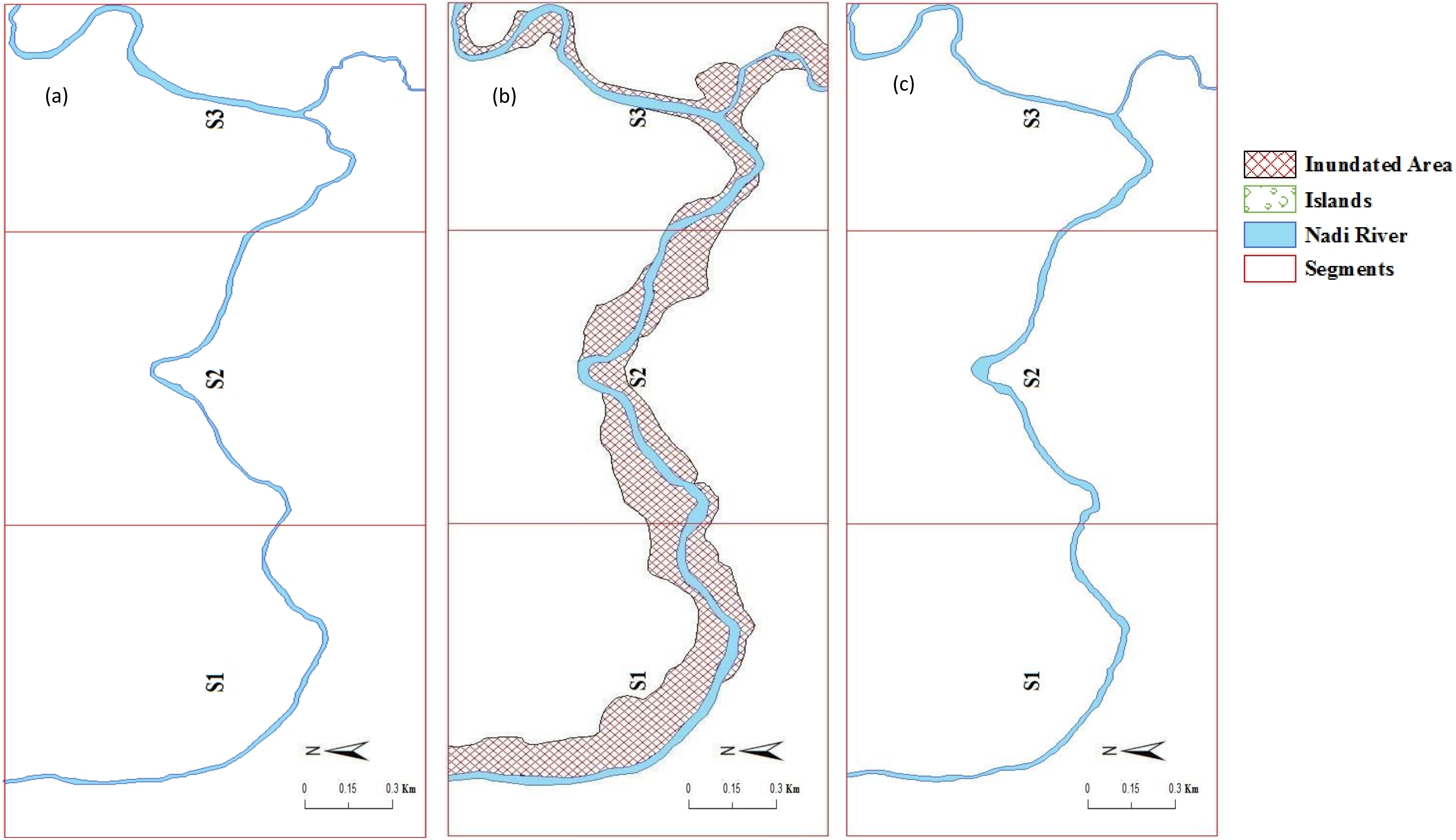



**Figure 25** (a) 2005 channel sketched in ArcGIS showing pre flood event (b) 2012 channel during flood event (c) 2014 channel post flood event.

For the three time periods, 3 segments were delimitated and transects were drawn across from one end of the channel to the other end. The statistical output of the length of the transects enabled the researcher to make deductions on channel change.

As can be seen from merely looking at the satellite images (figure 25) for the three time periods, a slight change in the width of the channel can be noticed. The most significant of which occurs in the levee which can be a result of the overflow of food waters from the river channel, thus extending the width.

In table 11, a slight increase in the average length from the 2005 channel as compared to the 2014 channel further consolidates the that channel variation does indeed occur post flood event. This also can be said for the other parameters that increases such as the area and minimum length of the width of the river channels.

| Year | Area ($m^2$) | Average Length (m) | Minimum Length (m) | MaxLength (m) |
|---|---|---|---|---|
| **2005** | 152214.9 | 19.27 | 12.75 | 45.41 |
| **2012** | 284561.7 | 44.17 | 27.88 | 61.61 |
| **2014** | 187003.9 | 27.66 | 15.25 | 39.96 |

**Table 11** Calculating the average, minimum, maximum length of transects that were drawn on different segments of the river channel in Location 1

It should be noted however that channel changes however, are not soleyly caused by extreme rain events. The impact that humans have on the physical landscape is also a contributing factor. The river channels in question are located near places of residents, and perhaps further study into the impacts of development on river channel formation is warranted.

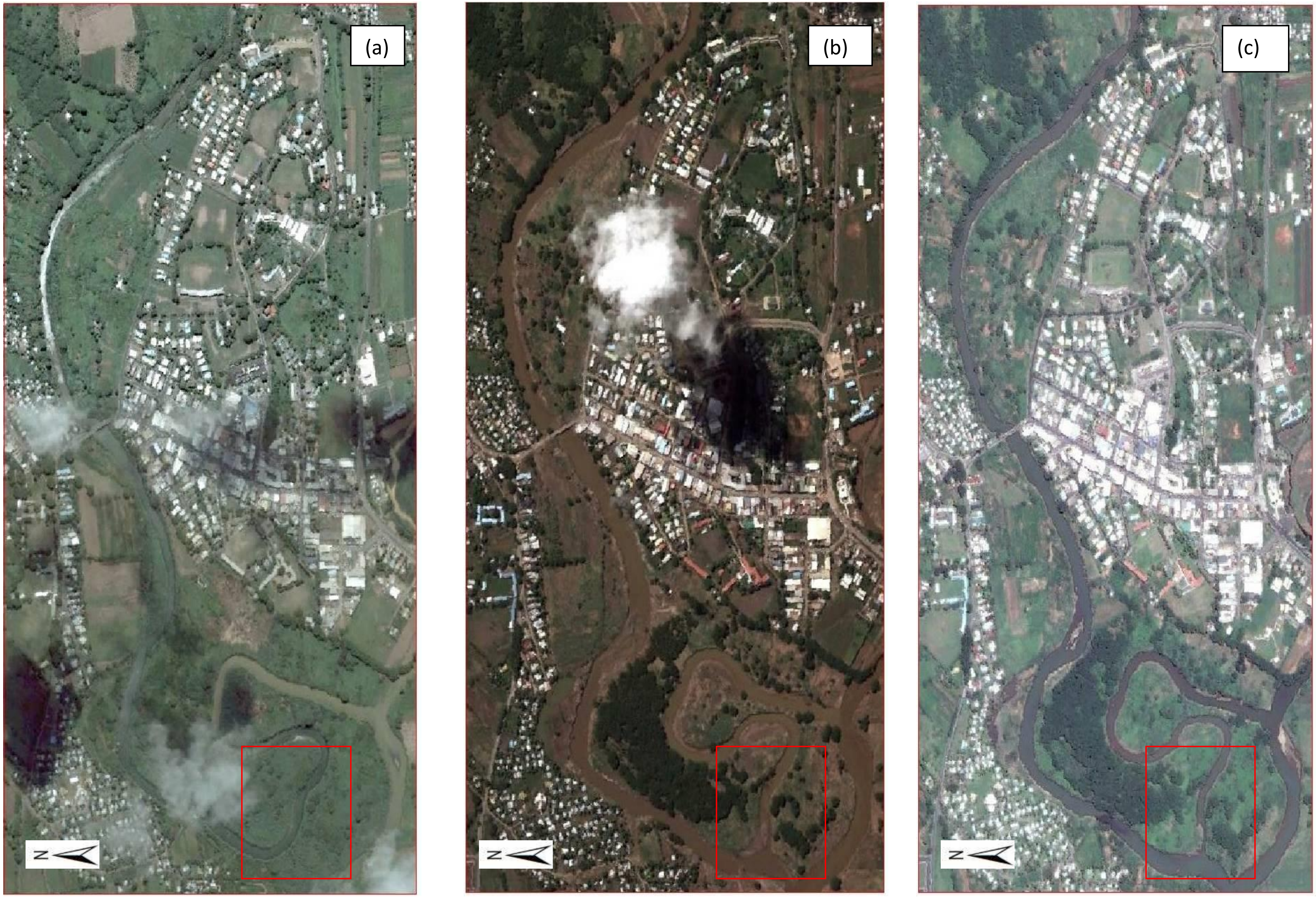



**Figure 26** From Location 2 (a) 2005 satellite image showing the Nadi river pre- flood event(b) 2012 satellite image showing flood event occuring (c) 2014 post flood satellite image. NOTE: The new meander formed post flood event. (Source: GoogleEarth)

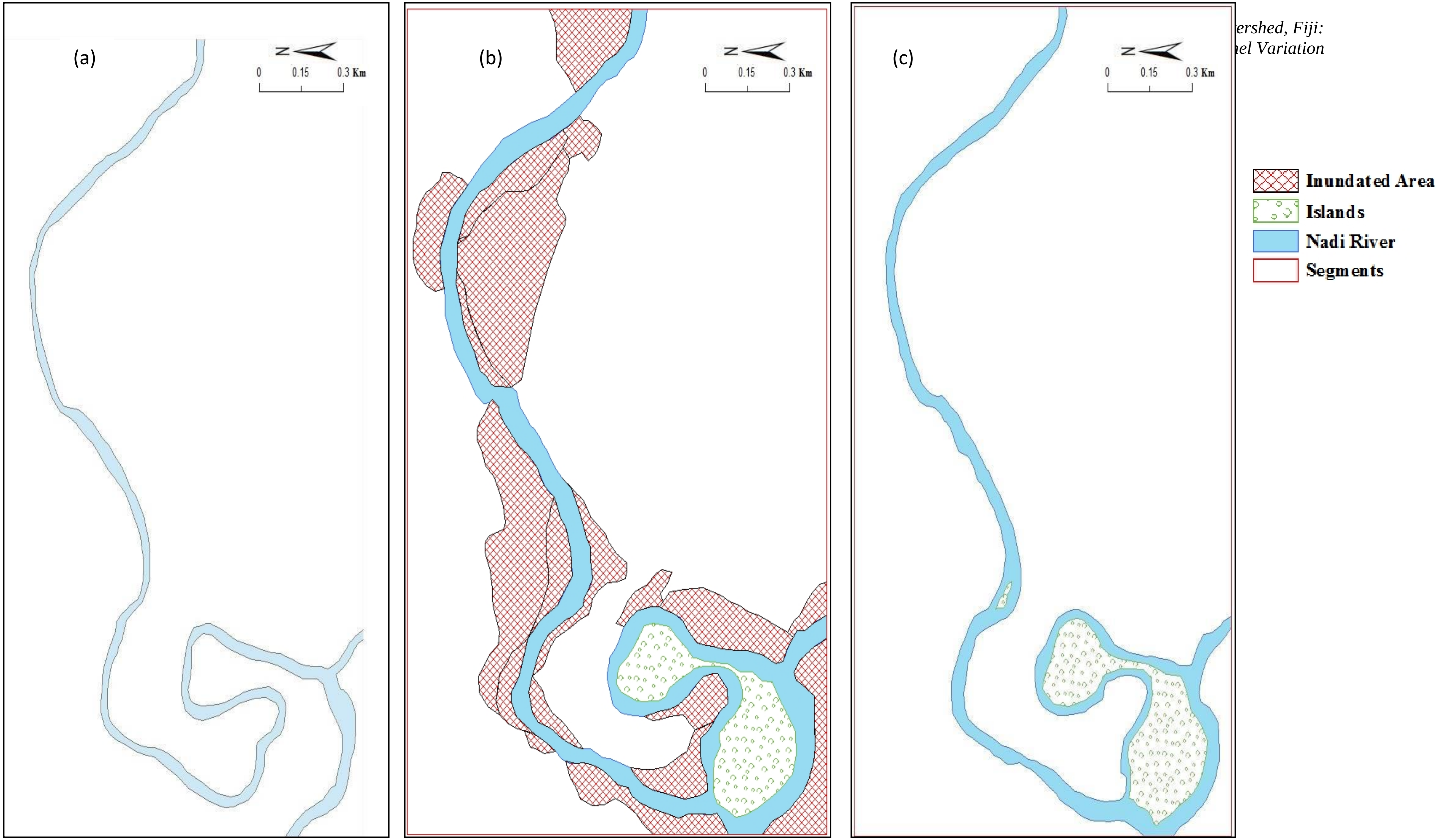



**Figure 27** The segment of the river channel in Location 2 sketched in ArcGIS (a) 2005 pre flood event (b) 2012 during the flood event and inundated area (c) post flood event, 2014

As hypothesised, river channel variation also occur in the second location as illustrated by table 12. The average length of the river channel has a more significant change as compared to location 1. The same can be said for the area of the river channel digitized which doubled in area.

| Year | Area ($m^2$) | Average Length (m) | Minimum Length (m) | Maximum Length (m) |
|---|---|---|---|---|
| **2005** | 165800.9 | 36.36 | 24.26 | 61.29 |
| **2012** | 287547.1 | 56.52 | 34.89 | 69.87 |
| **2014** | 340384.8 | 43.44 | 30.04 | 62.1 |

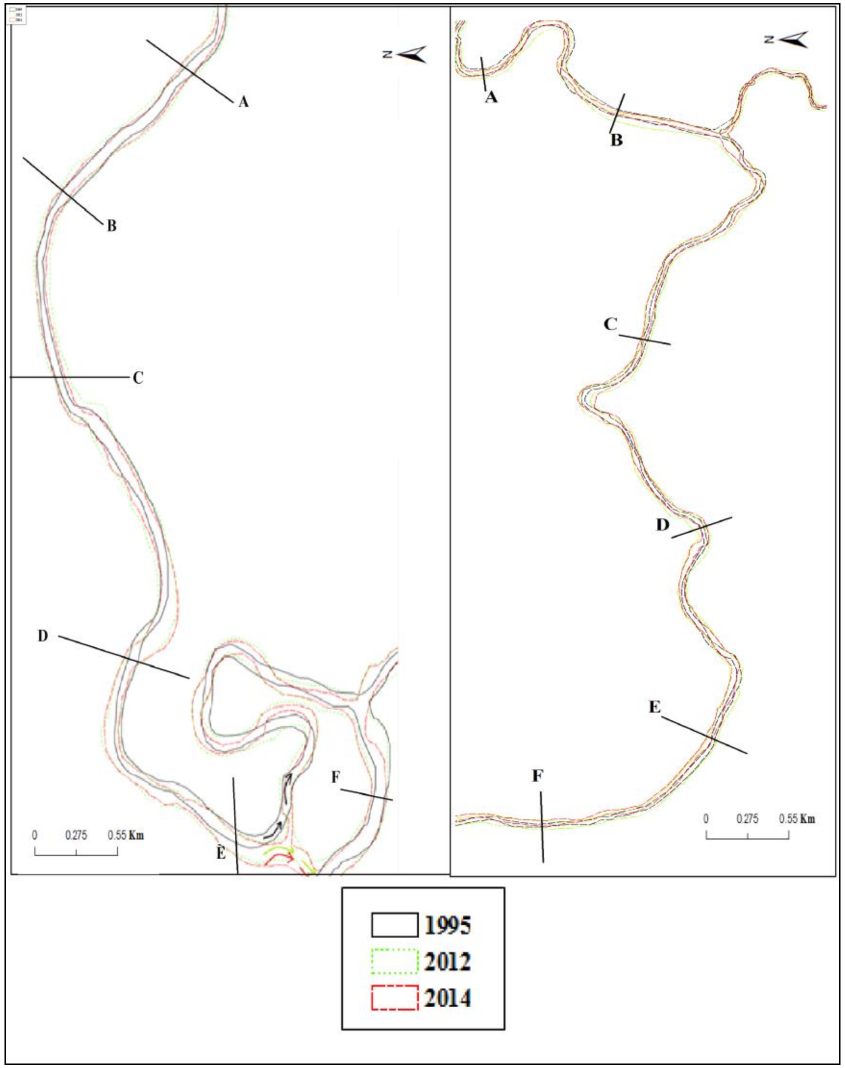
**Table 12** Calculating the average, minimum, maximum length of transects that were drawn on different segments of the river channel in the second location (Location 2)

As compared to location 1, the second location experienced a more severe outcome of the flood event in 2012 which is illustrated by the mass amount of flooded area illustrated in figure 27. The location of Nadi town near the river leaves it vulnerable to this flash flood events, and during intense precipitation, the town can be flooded in a matter of hours.

However, intense precipitation is not the only factor that causes the town to flood. Poor drainage system, and lack of proper planning can also be an attributing factor towards the heavy inundated areas.Additionally, the existence of the bridge also acts as a barrier for free flow of flood waters. This is attributed to the fact that with the barrier in place, it increases upstream flooding by narrowing the width of the channel. Consequently it also increases the channels resistance to free flow.

From the satellite images as well as the sketches done in ArcGIS, a major change that is visible is the creation of a new meander (figure 26). The creation of the new meander changes (illustrated by red limit in figure 26) the channel dynamics and can be deduced that it is the result of the intensity of flood waters. For both the channels digitized and the calculations is summed up below in figure 28 and tables 13 and 14.

**Figure 28** Summary of channel variation analysis carried out by segmenting the river channels to calculate width (a) Location 2 showing the digitized river channels for the years 2005, 20012 and 2014 (b) Location 1 showing the digitized river channels for the year




| Years/ Width Change | Length (m): | | | | | |
|---|---|---|---|---|---|---|
| | A | B | C | D | E | F |
| **2005** | 25.04 | 45.42 | 30.56 | 34.02 | 26.03 | 20.08 |
| **Width (+/-)** | (+) 24.21 | (+) 16.19 | (+) 19.54 | (+) 14.29 | (+) 30.83 | (+) 11.00 |
| **2012** | 49.25 | 61.61 | 50.10 | 48.31 | 56.86 | 31.09 |
| **Width (+/-)** | (-) 23.21 | (-)21.92 | (-) 18.62 | (-) 21.29 | (-) 31.26 | (-) 3.70 |
| **2014** | 26.04 | 39.70 | 31.48 | 27.02 | 25.60 | 27.39 |

**Table 13** In location 1 segments of 6 labelled A-F with the width for the three different years and the changes throughout the years

| Years/ Width Change | Length (m): | | | | | |
|---|---|---|---|---|---|---|
| | A | B | C | D | E | F |
| **2005** | 37.02 | 34.00 | 29.39 | 24.63 | 24.26 | 40.08 |
| **Width (+/-)** | (+) 25.00 | (+) 0.89 | (+) 38.09 | (+) 45.24 | (+) 45.13 | (+) 15.14 |
| **2012** | 62.02 | 34.89 | 67.49 | 69.87 | 69.40 | 55.22 |
| **Width (+/-)** | (-) 12.31 | (-)2.7 | (-) 16.88 | (-) 35.86 | (-) 37.23 | (-) 25.18 |
| **2014** | 49.71 | 32.19 | 50.61 | 34.01 | 32.17 | 30.04 |

**Table 14** In location 2 segments of 6 labelled A-F with the width for the three different years and the changes throughout the years

# Chapter 5: Conclusion

## 5. Conclusion

Flash floods rank high among weather-related natural hazards globally due to the high number of fatalities (UNDP, 2004). However, little research has been done on the climatological aspects of flash flooding on regional scales and on the impacts of projected future changes in precipitation extremes on the occurrence of flash flooding, especially in Fiji, a country constantly plaqued by floods.

Floodplains and flood-prone areas are dynamic land areas that need to be assessed in terms of the risks they pose to existing and proposed development activities. This paper focused on the development of a academic research towards better understanding flash floods in the Nadi watershed that synthesizes elements of morphometric parameters, modeling, hydrology, and channel variation as an integrated approach to address these issues.

The scarcity of research done in the field of hydrology especially in the study of floods has to be improved with developing countries such as Fiji. Flash floods are destructive in nature and given their rapid development during high precipitation events, a proper model should be carried out to try and possibly to map areas that are vulnerable to flooding by constructing a flood model for this particular watershed.

The results show that the basin morphometry of the Nadi watershed is such that the total number and length of stream segments is high in first order streams and decreases as the stream order increases.The time of concentration (tc) of 11.8hours for the main basin is relatively rapid considering the elongated shape of the watershed. Furthermore, the peak discharge of a 10, 50, and 100 year return period also indicates the main basin having a peak discharge of 3762.47 m3/s for a return period of 10 years and doubles in a 100 year return period with 6165.27 m3/s, predicting the increase in severity of intense precipitation. This pattern is the same for the four sub basins.

Channel variation results also indicate a small yet significant change in its channel formation for a period between 2005-2014, increasing the extent of flooded alluvaial plain, and consequently increasing the boundary of the river channels. The main conclusion that can be iinferred after the completion of this research, is given the attributes of the Nadi watershed studied and its location, the area of Nadi is prone to flash flooding and unless proper flood mitigation steps are carried out, this will be a continuing problem.

## 5.1 Recommendation

As a recommendation, the researcher would like to suggest the development of a proper elevation data that would ensure the construction of a Digital Elevation Model efficient enough to delimitate the boundary of the watershed properly.

Secondly, in terms of channel variation and using satellite images to make deductions, more ground work is needed. Collection of data such as channel depth, proper measurements of width, area, identifying human impacts towards channel variation is required and can be furthered more with more research. However, with recommendation, it should also be noted that this is the step in the proper direction for researchers, by input of research work, setting the platform for more to be done in the future.

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# Appendix

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**Information Sheet No. 125**
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## LIST OF FLOODS OCCURING IN THE FIJI ISLANDS BETWEEN 1840 AND 2000

*Issued by Director of Meteorology*

This information sheet provides a listing of reported flooding incidents in Fiji for the period 1840 to 2000. Please note that it is based on information received only from known sources, and as such may not be a complete list. Also, the list may be bias towards the *Ba River*, which was the subject of a detailed survey recently (Yeo, 1998), and towards the last two decades for which information is more readily available.

Floods are regular occurrences in Fiji, happening almost as an annual event. Most major floods are associated with episodes of severe weather phenomena, such as tropical depressions and cyclones that are characterised by high intensity rainfall. Most of the rivers and streams in Fiji are relatively small in size (<1000 $Km^2$) and flow from steep mountainous terrain. High intensity rainfall together with the small size and steep streams and rivers lead to swift rise and fall of water levels. The time between rainfall and floods can be as short as three to four hours. Flash floods are thus pretty common especially during the *Wet Season* (November to April).

The Public Works Department is responsible for issuing warnings on river flooding. Its *Hydrology Section* maintains and operates a systematic flood-forecasting system for the Rewa River while systems for other main rivers are under consideration. The Fiji Meteorological Service (FMS) issues forecasts for heavy rainfall and advises the public on prospects for flooding from extreme weather events like tropical cyclones. It also compiles reports on major flooding incidents, covering primarily the meteorological aspects, and keeps a database of rainfall and other important parameters..

For further information or clarification, please contact the Climate Service Division of FMS.

| Date of Flood Peak | Tropical Cyclone intensity and location or other reason for high rainfall | Flood Description and Areas Affected |
|---|---|---|
| 1840 Feb 25 | (hurricane) Rewa and Northern Viti Levu. | • 'High' flood covering the Rewa flats (Derrick, 1946) |
| | | |
| 1866 Mar 10-12 | (hurricane) Centre passed between Viti Levu and Vanua Levu. | • Cotton plantations along the Rewa flats inundated<br>• Food gardens and coffee plantations buried in silt (Derrick, 1946) |
| | | |
| 1869 Mar | (hurricane) | • Flood at Navua left all the flat land "nearly smooth, and with 12 inches of deposit in some places" (Derrick, 1951) |

| Date of Flood Peak | Tropical Cyclone intensity and location or other reason for high rainfall | Flood Description and Areas Affected |
|---|---|---|
| 1871 Mar 21* | (hurricane) Entire Fiji Group affected. Centre over Western Fiji. | • Several people drowned in the Ba River (Yeo, 1998) |
| | | |
| 1879 Dec 11# | (hurricane) Entire Fiji Group affected especially Northwestern Fiji. | • Storm surge in the Ba area. (Yeo, 1998)<br>• Lautoka town flooded (Blong, 1994) |
| | | |
| 1886 Jan 4-5 | (cyclone) West coast of Fiji. | • Ba River rose considerably, but no damage reported (Yeo, 1998) |
| 1886 Mar 4 | (hurricane) Entire Fiji affected. | • Ba River rose several feet, but no damage reported (Yeo, 1998) |
| | | |
| 1892 Dec 15 | (cyclone) North coast of Vanua Levu and over Yasawas. | • Ba River flood peak recorded as 2.21m below the 1931 peak [A] Rarawai Mill flooded (Yeo, 1998). |
| | | |
| 1901 Mar 8* | | • Ba River flood peak recorded as 2.51m below the 1931 peak [B] Rarawai Mill probably flooded (Yeo, 1998). |
| | | |
| 1904 Jan 11 | | • Ba River flood peak recorded as 4.19m below the 1931 peak [C] (Yeo, 1998) |
| 1904 Jan 21# | (hurricane) Central Fiji. | • Rewa was badly affected by flooding<br>• 1.8m storm surge at Navua (Blong, 1994) |
| 1904 Feb 21-22 | (hurricane) | • Ba River flood peak recorded as 4.42m below the 1931 peak [C] (Yeo, 1998)<br>• Floods in the Rewa River (D'Aubert, 1994) |
| | | |
| 1906 Dec 26 | | • Two people drowned in the Ba River (Yeo, 1998) |
| | | |
| 1907 Jan 25 | | • Ba River flood peak recorded as 4.42m below the 1931 peak [C] (Yeo, 1998) |
| | | |
| 1908 Mar 23 | (hurricane) West and South Viti Levu. | • Two people drowned in the Ba River (Yeo, 1998) |
| 1908 Aug 29 | | • Ba River flood peak recorded as 4.11m below the 1931 peak [B] Rarawai flats flooded (Yeo, 1998) |
| | | |
| 1909 Feb 7 | | • Ba River flood peak recorded as 2.51m below the 1931 peak [A] Rarawai Mill flooded (Yeo, 1998) |
| | | |
| 1910 Mar 5 | | • In the Macuata Province the Qawa River flood peak was 1.07m below the 1929 peak. This flood is ranked 5th for the Qawa River since records began |