FLOOD RISKS ON ASSETS AND LIVELIHOODS

IN TROPICAL CATCHMENTS WITHIN OIL PALM LANDSCAPES

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Abstract

There are currently more people than before seeking a livelihood through oil palm agriculture around the world – approximately 14 million people with properties vulnerable to flood risks, and more than half of the settlements contain livelihood assets being exposed to seasonal floods. Flood risks cannot be eliminated but they can be effectively analysed and reduced in many oil-palm dominated landscapes. To assist disaster planning, hazard and risk mitigation, tools and models must be used to understand flood characteristics and behaviour, the areas affected, potential flood risks, levels of exposure and loss probabilities of livelihood assets. However, little is known about riverine flood risk to, and vulnerability of, livelihood assets in oil-palm dominated landscapes. This study assessed flood risks on livelihood assets in the Dagi River catchment, PNG.

Fieldwork data and hydrological models were used to determine flood characteristics and behaviour. Water depths, velocity and duration were observed during two wet seasons in 2010 and 2014. Flood discharge in terms of its peak and magnitude were analysed using rainfall data simulated using HEC-HMS. Both Log-Pearson Type III Distribution and Gumbel's extreme value distribution techniques were used to analyse flood frequency. In HEC-HMS program, the millimetre unit of depth is written as MM (USACE, 2013; p.124). Rainfall-runoff simulation results show that upstream reaches have a steep hydrograph with a peak discharge of 1326m^3/s (130.10MM) for 2010 at 13:00pm compared with that of 2014 which peaked at 12:30pm with 729m^3/s (86.96MM). Downstream reach generally showed a broader hydrograph with a peak discharge of 1158.4m^3/s (72.47MM) at 14:00pm in 2014, while in 2010 it was 2424.4m^3/s (109.67MM) that peaked by 14:30pm. Floods in Dagi rise quickly upstream and flow fast downstream and this provides less time for warning and evacuation.

Velocity in all cross-sections decreases towards the banks and in the floodplains as they encounter roughness. The 2014 floods had an average velocity of 4.35m/s in the main channels upstream while downstream average velocity was 2.75m/s. The 2010 floods had an average velocity of 5.38m/s upstream while downstream average velocity was 3.76m/s. The flood duration from upstream in 2014 receded to normal levels in three days (72 hours) but took seven days downstream. In 2010 the flood receded within four days upstream but took 11 days to reach normalcy downstream. Flood height varies for all sites in response to slopes (1-20^0) from 0.01m to as much as 7.5m. The stream power during the 2014 flood increased from 1915.12 watts/m^2 (N/m s - where N is expressed as stream power per unit weight of 1 N and work and energy are metres per second written as one unit - m s) from sub-catchment 1 to as much as 9575.58 N/m s at sub-catchment 4. The flood event of 2010 had a recurrence interval of 11 years (9.09%) while that of 2014 had a recurrence interval of 7.33 years (13.64%). This means floods in Dagi catchment are highly variable and this depends on many factors but primarily rainfall and slope characteristics.

SOBEK 1D2D, HEC-RAS Beta 5.0, HEC-RAS 4.1 and HEC-GeoRAS modelling software were used to model and visualise flood inundation and hazards. Modelling focused on flood velocity and depth in 1D and 2D channels, where inundation and hazards were visualised. The spatial extent of inundation and hazards were determined

by using flood characteristics (velocity and depth) obtained after the 2010 and 2014 flood simulation. Because of the relatively flat topography (1-20^0) with no flood protection in all reaches, high peak discharge breached the bankfull stage and inundated within an average radius of 500m. The 2010 flood event inundated a large area (79.9 ha) compared with the 2014 inundation (55.2 ha), with most inundation occurring in the middle and lower reaches. Results validated using depth and velocity data together with various roughness figures revealed a difference, on average, of 0.40m in the modelled and observed data. The peak difference during the 2014 flood event ranged between 0.24m and 0.55m. On average, the 2010 flood revealed a difference of 0.45m in the modelled and observed results and at peak discharges the difference ranged from 0.32m to 0.54m. Thus, the modelled peaks agreed with those observed. The simulated results with appropriate input data, initial condition, boundary conditions, model assumptions, roughness coefficient values and coarse representation of the grid resolution were able to generate a very good simulated flood inundation extent.

Flood risks were assessed using a risk-based approach by analysing risk comprehensively. It estimated flood hazards using geo-processing tools and hydrodynamic models that represented flood intensity. It estimated vulnerability based on the percentage of livelihood assets damaged, dependent on flood velocity and depth. This study used a combination of qualitative and quantitative risk assessment methods. Focusing on depths of inundation and maps of vulnerable land use, an assessment of risks was performed qualitatively. The level of vulnerability and risk zones were identified based on the assigned land use weights, hazard and vulnerability assessment criteria. Using the weights and criteria and land use curves, raster-based vulnerability and risk maps were drawn in relation to three exceedance probabilities. Quantitative risk assessment involved estimating the total costs of exposed elements (direct tangible) based on the damage functions and classified according to their type. Results showed that houses and buildings incurred the greatest costs (34.3%), leaching of fertilisers (27.2%), deaths (23.7%), subsistence gardens (11.4%), roads (2.6%), damaged oil palm trees (0.8%), non-pick-up of bunches (0.02%) and formal job income loss (0.01%). The total economic costs based on the elements at risk is PGK77,869,451. This is equivalent to US$26,545,696 (23rd September 2015 exchange). The results reveal that the level of damage varies with flood probabilities.

Flood risks have been exacerbated by the increasing population and the need for more people to seek a livelihood. This has increased the extent and impacts of floods through the replacement of vegetation with bare and levelled land surfaces associated with increased oil palm cultivation and subsistence gardening in riparian zones. These land uses have interfered with the water cycle and the stream channel morphology. Prevention plans and mitigations recommended for flood disaster should include the implementation of conventional and unconventional structures.

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Chapter 1.0: Introduction

1.1 Introduction

A riverine flood is the overflow of water over a stream's bankfull stage. It is water accumulating over areas that are not normally submerged (Ayoade, 1988; Kundzewicz et al., 2004; Gupta, 2011). Floods in tropical rivers are mainly caused by rainfall (Ayoade, 1988; Gupta, 2011; Queensland Government, 2011). Rainfall in catchments are either intercepted by land cover, lost through evapotranspiration, become stemflow and throughfall and are absorbed into the soil through infiltration (Queensland Government, 2011; Gupta, 2011). Over time, the soil reaches its field capacity and becomes overland flow into stream channels. The land area drained by rivers and their tributaries (e.g. creeks and lakes, and base flow) that contributes runoff to a point along a channel network (or a depression), based on its topography, is called the catchment (Wagener et al., 2004; Gupta, 2011; Queensland Government, 2011). There can be variations in the amount, intensity, and distribution of rainfall in a catchment and consequently floods vary in frequency and magnitude (e.g. size, extent and duration) (Queensland Government, 2011). Every flood is different. They can occur suddenly and recede quickly, or may take days or even months to build and discharge. A floodplain is a land area accustomed to frequent floods which enrich soil fertility and in response man has settled to farm it (Gupta, 2011; Queensland Government, 2011).

One of the positive impact of flooding is that it replenishes water deficit and helps man and the ecosystem recover after a drought. However, it is a costly natural disaster worldwide because it destroys livelihood assets (e.g. business, health, settlements, infrastructure, and croplands) leaving a bill worth billions of dollars (Geoscience Australia, 2014). Communities are commonly subjected to floods with consequent disruption to their daily activities and means of livelihood, loss of assets and in worst cases, loss of life — virtually all floods result in monetary costs (United Nations International Strategy for Disaster Reduction-UNISDR, 2011; Intergovernmental Panel on Climate Change-IPCC, 2012). Many studies (Jongman et al., 2012; Barredo et al., 2012; UNISDR, 2011; Kreft, 2011; Asian Development Bank Report, 2010; Bouwer et al., 2010; World Bank, 2010; Barredo, 2009), have confirmed that most flood losses worldwide arise when flood barriers are impaired (e.g. dykes), infrastructures (e.g. houses, roads and bridges) are destroyed and when businesses are closed (Jongman et al., 2012). Between 1980 and 2008, flooding directly incurred an average cost of US$13.7 trillion worldwide (Geoscience Australia, 2014; UNISDR, 2011). The type of land use and its location, and flood severity, are some factors that cause variations in flood losses (Geoscience Australia, 2014; UNISDR, 2011).

Floods are a natural process but land use influences them (Queensland Government, 2011). Land use (e.g. vegetation removal for crop cultivation) alters catchment, network and channel characteristics and changes its morphology, which in turn influences flood impact (ibid.). Forest clearance for agricultural developments can exacerbate floods mainly through the removal of the native vegetative cover and replacing it with non-native cash crops. Studies have found that this disturbs the natural hydrological processes of interception, evapotranspiration and infiltration among others, and causes floods (Cammerer and Thieken, 2013; Webb et al., 2010; Germa et al., 2008; Basiron, 2007). Moreover, it was found that vegetation removal alters stream channel morphology and hydraulics, and increases peak discharge and results in floods (Montgomery et al., 2003).

An estimated 1.3 billion people depend on agriculture for their livelihoods worldwide – representing 40% of the global workforce with 500 million workers employed by plantations (World Bank, 2010). In agricultural landscapes, more than half of livelihood assets in settlements are affected by floods (Water, 2013; Environment Agency-EA, 2010). Turner et al. (2001) defined a landscape as a “spatially heterogeneous” area “in at least one factor of interest” (Zinck, 2016: p.77) and in this study, the focus is on oil palm agriculture. The combined term “oil-palm dominated landscape” is used in this study to refer to the area of land that is dominated by oil palm cultivation.

In oil-palm dominated landscapes, many people live on floodplains. Because of good soil fertility and abundance of water, man has settled to farm it in response (Queensland Government, 2011). The Dagi River catchment in PNG, has been cultivated with oil palm as the main source of livelihood. Flood has been an on-going problem due to frequent inundation during the wet season. There are no studies done to understand the hydrodynamics of floods and how they cause hazards and risks to assets and livelihoods (Roundtable on Sustainable Palm Oil-RSPSO, 2014). An understanding of this will enable us to develop mitigation plans, and preparedness for flood hazards within oil-palm dominated landscapes.

1.2 Causes and types of floods

The general causes of flooding in the tropics has been identified as: (i) climatological, (ii) part-climatological, and (ii) others – examples are earthquakes, volcanic eruptions, landslides and dam failures (Ward, 1978; Ayoade, 1988; Gladwell, 1993; Kundzewicz et al., 2004; Kundzewicz et al., 2014; Guo et al., 2014). Most floods result from causes which are wholly or partly climatological in nature (Guo et al., 2014). Rainfall is generally believed to be the dominant precipitation type in the tropics. Floods which are partly climatological in origin include those arising from coastal storm surges or the estuarine interactions between streamflow and tidal conditions in the sea (Ayoade, 1988; Gladwell, 1993). Such floods are limited to coastal areas and the lower reaches and estuaries of rivers draining into the sea (Gladwell, 1993). However, they can be disastrous because such areas are usually densely populated. Other types of floods are due to non-climatological causes such as earthquakes, volcanic eruptions and landslides which disorganise river patterns and often temporarily dam rivers making them flood the surrounding plain (Ayoade, 1988; Gladwell, 1993). Floods also frequently occur because of failure of dams and other control works, but uncommonly. Floods which are climatological in origin are derived from excess of rainfall over evapotranspiration losses when allowance has been made for natural infiltration and surface detention ((Ayoade, 1988; Gladwell, 1993).

The main flood types are, 1. river or fluvial floods due to the breaching of bankfull stage and inundation of floodplain (Water, 2013; Kundzewicz et al., 2004; Armah et al., 2010; Bastola et al., 2011), 2. flash floods as a result of excess rainfall over soil infiltration capacity with high runoff potential that allows water to run downslope in defined flow paths (e.g. valleys) (Water, 2013; Aronica et al., 2012; Atreya et al., 2013; Boelscher et al., 2013), and 3. tides and storm surge floods as a result of weather extremes and high tidal currents in coastal areas (Kreibich et al., 2015; Water, 2013; Brown et al., 2010; Brody et al., 2012; Bachmann et al., 2014). Other flood events have generally resulted from a combination of these types. Two examples are urban and pluvial floods, which are caused by high intensity rainfall when the sewage system and drainage canals do not have the necessary capacity to drain the excess amounts of rain (Jun et al., 2013; Kundzewicz et al., 2014).

1.3 Impacts of floods

Over the past few decades in many countries, damages and losses due to flood exposure have generally increased by more than 50% (e.g. table 1.1, table 1.2, and figure 1.1). For example, the Brisbane and southeast Queensland floods in the 2010-11 wet season affected more than 200,000 people, leaving 100,000 people without power, with an estimated reduction in Australia's GDP of A$40 billion (Chanson, 2011). Van den Honert and McAneney (2011) reported 23 people died in the Lockyer Valley, and one in Brisbane, while inundation destroyed 18,000 properties within the vicinity of Ipswich and metropolitan Brisbane. Economic damage from these floods was estimated at A$2.38 billion, with $A2.55 billion in insurance payouts, and 61 lives were lost in the whole flood. Increased (1) flood height, (2) flood exposure, and (3) poor infrastructure (e.g. embankments), can increase flood incidents, the number of people affected and the monetary costs involved, with worse predicted to come in the 21st century (Scorzini and Frank, 2015; Ali, 2014; Brouwer et al., 2013; Bittencourt et al., 2013; Morand et al., 2012; Angilleri, 2012; Nicholls, 2004).

Table 1.1: Comparative Brisbane River flood damage statistics—Feb. 1893, Jan. 1974 and Jan. 2011 floods.

Flood Damage/Loss	February 1893	January 1974	January 2011
Deaths	35	16	24
Injuries	300	368	750
Persons evacuated/left homeless	5,000	9,000	100,000
Buildings damaged	5,000	7,000	14,700

(EMA Disasters Database and Australian Emergency Management Australia, 2011; van den Honert and McAneney, 2011)

Table 1.2: Human and economic losses worldwide from floods between 1980 and 2008 (UNISDR, 2011).

Flood disasters worldwide from 1980 – 2008	
Overview	
Number of events:	2,887
Number of people killed:	195,843
Average people killed per year:	6,753
Number of people affected:	2,809, 481,489
Average people affected per year:	96,878,672
Economic damage (US$ X 1000):	397,333,885
Economic damage per year (US$ X 1000):	13,701,168

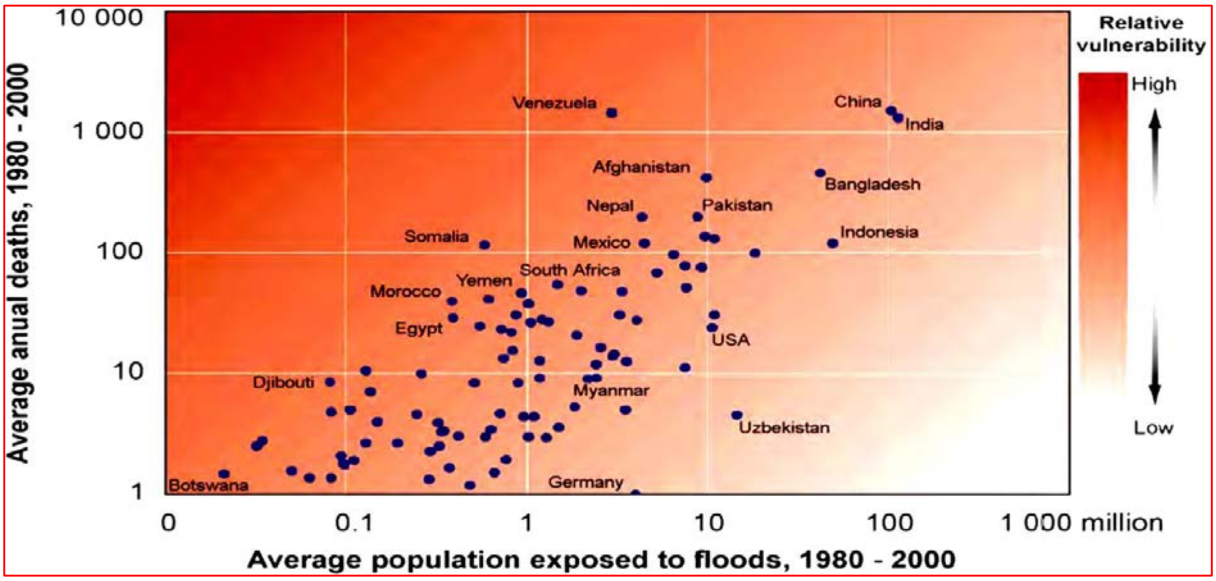

Figure 1.1: Relative vulnerability for flooding related to deaths, 1980–2000 in some countries (EM-DAT OFDA/CRED and UNEP/GRID-Geneva. *In:* UNDP, 2004 by Peduzzi and Herold, 2005).

Some impacts by major river floods may be catastrophic (Cammerer et al., 2013; Ashworth et al., 2012; Battany et al., 2000), while others have had little effect on livelihoods or assets (Nicholson et al., 2013). This variation can depend on the location of the catchment and the rate of population and wealth increase over time (Wilby and Keenan, 2012; Sharma, et al., 2011; Bouwer et al., 2010; Roggema, 2009). Many studies have shown that flood peak discharges of similar magnitudes, frequencies, intensities, timing and duration, depth distributions and their recurrence intervals produce dissimilar impacts, even within the same catchment and at sub-catchment levels (Ashworth et al., 2012; Nicholson et al., 2013; Katimon et al., 2013; Davidson et al., 2013). Given the variety of processes and boundary conditions influencing floods, a spectrum of impacts for a given flood event in any landscape is to be expected and may not be the same elsewhere (e.g. Gupta, 2011; Riley and Rhoads, 2012). This is dependent on the input precipitation, the characteristics and the behaviour of a flood (Battany et al., 2000; Saleh et al., 2013; Kobayashi and Takara, 2013; Guo et al., 2014) and its length and spatial inundation extent (Li et al., 2012). The major characteristics of runoff leaving a catchment are the total volume of discharge and the over-time distribution of the discharge (Lane et al., 2013). Flood peak discharges and magnitude, frequencies, intensities, timing and duration, depth distribution, and their recurrence intervals are useful in assessing hazards to livelihood assets and their vulnerability for different landscapes (Margottini et al., 2013; Brower et al., 2013; Bouwer et al., 2010).

Many studies have assessed flood risks worldwide in response to increasing exposure of assets and livelihoods to this hazard, and the impacts and casualties (e.g. table 1.1, table 1.2 and figure 1.1) have been widely reported in the literature. Most of the studies were done independently and are either linked to physical, or numerical model of flood characteristics and their behaviour (Kusumastuti et al., 2007; Aguillera, 2013; Katimon et al., 2013; Danilov et al., 2014; Roundtable on Sustainable Palm Oil-RSPO, 2014). Studies were also done on flood inundation (Davies, 2011; Aronica et al., 2012; Bernini et al., 2013). Conversely, other studies have focused on the vulnerability of assets and livelihoods (Aubrecht et al., 2011; Aubrecht et al., 2013; Roche et al., 2013; Gray et al., 2014). However, such studies on flood risks are mostly focused in urban areas of the world where the bulk of human populations are concentrated (Meyer et al., 2013; Bouwer et al., 2010; Klijn et al., 2007, Aerts et al., 2008) and little involved landscapes dominated by oil palm. Understanding flood risks on assets and livelihoods in this landscape is important so that flood disaster planning, hazard and risk mitigation measures can be undertaken.

1.4 Flood hazard

"The probability of the occurrence of potentially damaging flood events is called a flood hazard" (UNISDR, 2004: p.3). "Potentially damaging means that there are elements 'exposed' to floods which may be harmed" (ibid.). "Exposure is the nature and degree to which a system experiences physical, environmental, socioeconomic and political stress" from flood hazards (Adger, 2006: p.268). The "characteristics of these stresses include their magnitude, frequency", extent of inundation, depth, velocity and duration of a flood hazard (ibid.: p.269). "Generally these elements are characterised by the probability of a flood event with a certain magnitude", frequency, inundation extent, depth, velocity and duration (ibid., p.270).

The International Training Centre, ITC, (2010: p.11) defined flood hazard as "the potentially damaging physical event, phenomenon or human activity that may cause loss of life or injury, property damage, social and economic disruption or environmental degradation. The flood event has a probability of occurrence within a specific period and within a given area and has a given intensity". "The studies related to analysis of physical aspects and phenomenon through collection of historical records is called hazard assessment" (ibid.). "Flood hazard estimation is based on factors such as the triggering factors causing the hazard, their spatial extent, duration and time of onset, including their frequency and magnitude of occurrence and secondary events influencing the event if any" (ibid.). "Hazard assessment is interrelated to vulnerability of the elements at risk and further assessment of degree of risk" (ibid.).

1.5 Elements at risk and flood vulnerability

According to ITC (2010: p.11), "elements at risk can be defined as the level of exposure with reference to houses and buildings, cash crops, population, economic activities, transport, public services and utilities which can be impacted by flood hazard. Vulnerability is defined as the degree of loss to a given element at risk at a given severity level". Vulnerability has four components that can be influenced by floods: physical, social, economic, and environmental (Cutter, 2003). "Physical" refers to the location and characteristics of the built environment. The social component refers to the people's wellbeing in communities and their demographic characteristics. The economic component is related to the economic status of the individual, community or society. "Environmental" relates to the issues covering the physical, social and economic components that concern sustainable development. The quantification of vulnerability "is determined by conditions or processes that increase the susceptibility of the community (physical, social, economic or environmental)" (ITC, 2010: p.12). Vulnerability is caused by human interaction with the environment as well as with cultural and political settings (UNISDR, 2004). Vulnerability assessment depends on how close communities are to the source of flood hazard, and their social and economic characteristics (Cutter et al., 2000). “Vulnerability of the elements at risk is further related to the degree of flood risk” (ITC, 2010: p.11).

1.6 Flood risk

Flood risk in this study “is defined as the probability of harmful consequences, or expected losses (deaths, injuries, property, livelihoods, economic activity disrupted or environment damaged) resulting from interactions between natural or human-induced flood hazards and flood vulnerable conditions” (Wisner et al., 2012: p.16). This research considers flood “risk as the product of two components”, that is, flood hazard (probability) and flood consequence (vulnerability) (Chan et al., 2014: p.19). It uses this equation: flood risk = flood hazard (probability) x flood vulnerability (consequence) (Smith, 2004). This flood risk concept relates losses in the physical, social, and economic or environment spheres as a consequence of highly probable flood events of certain magnitude (Chan et al., 2014). Kuhlicke (2013: p.62) defined “flood risk as the combination of the probability of a flood event (hazard) and of the potential adverse consequences for human health, the environment, cultural heritage and economic activity associated with a flood event (vulnerability)”. As an input for decision support, flood risk assessments are carried out to determine flood risks on assets and livelihoods before any flood disaster planning (or) measures to mitigate hazards and risks are implemented (Menoni, 2011).

1.7 Flood risk assessment

A flood risk assessment is a process used to make decisions based on the premise that any identified risks in existence can or cannot be tolerated and that restrictive measures are acceptable or unacceptable so that better suggestions can be made for their regulation (ITC, 2010). Furthermore, ITC (2010: p.13) provided an equation to calculate and quantify risks whereby the “vulnerability of the physical elements at risk is related to the intensity of the flood hazard”:

$Risk = P_T*P_L*V*A$ (ibid.)

Hereby: P_T “is the temporal probability of occurrence of a specific flood hazard scenario with a given return period in an area”,

P_L “is the locational or spatial probability of occurrence of a specific flood hazard scenario with a given return period impacting on elements at risks”, “V is the physical vulnerability, specified as the degree of damage to a specific element at risk given the local intensity caused due to occurrence of the flood hazard scenario”, and

“A is the quantification of the specific type of element at risk evaluated” (ibid.).

“Risk assessment can be qualitative, semi-quantitative or quantitative”. This assessment plays an important role in decision support to ensure that flood risks to assets and rural livelihoods are mitigated to ensure a sustainable future. To do so requires use of a “sustainable rural livelihood framework” (Scoones, 1998: p.4).

1.8 Sustainable rural livelihood framework as a concept

The sustainable livelihood framework is a very important tool that can be used to address flood impacts on livelihood assets in rural oil-palm dominated landscapes (ibid.). The sustainable rural livelihood framework (figure 1.2) application and its assessment are on many spatial scales at the level of individual, household, extended family groups, village, region and the nation (ibid.). Livelihoods comprise the capabilities and the assets (what people possess grouped “as natural, physical, human, financial and social capital), the activities, and the access to these (mediated by institutions and social relations) that together determine the living gained by the individual or household” (Ellis and Allison, 2001: p.378). I will use the term “livelihood assets” about flood risks to minimise wordiness throughout this thesis. The five categories of “livelihood assets (natural, physical, human, financial and social)” comprise a vulnerability to flood hazards (ibid.). It is these components that are influenced by floods. A sustainable livelihood outcome occurs when stresses and shocks can be coped with or recovered from, to uphold or increase their abilities and values, and at the same time not eroding the existing asset foundation (Chambers and Conway: 1992).

This thesis incorporates and merges components of two conceptual frameworks: the exposure, risk, and vulnerability framework for flood hazards and the sustainable rural livelihoods framework (figure 1.2) that places communities, their livelihood assets and vulnerabilities, together with the strategy and institutional settings which influence them, at the core of investigation (Mitchell, 2014; Ellis and Allison, 2001). These are shown in figures 1.3 and 1.4.

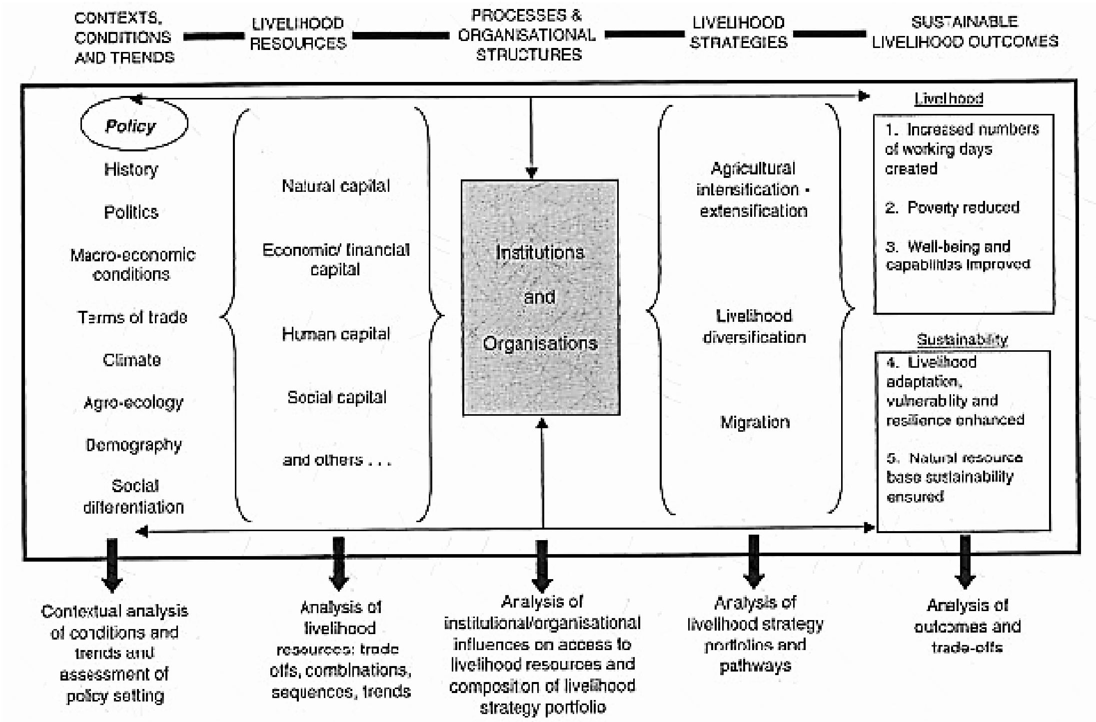

Figure 1.2: Sustainable rural livelihood framework (adapted from Scoones, 1998).

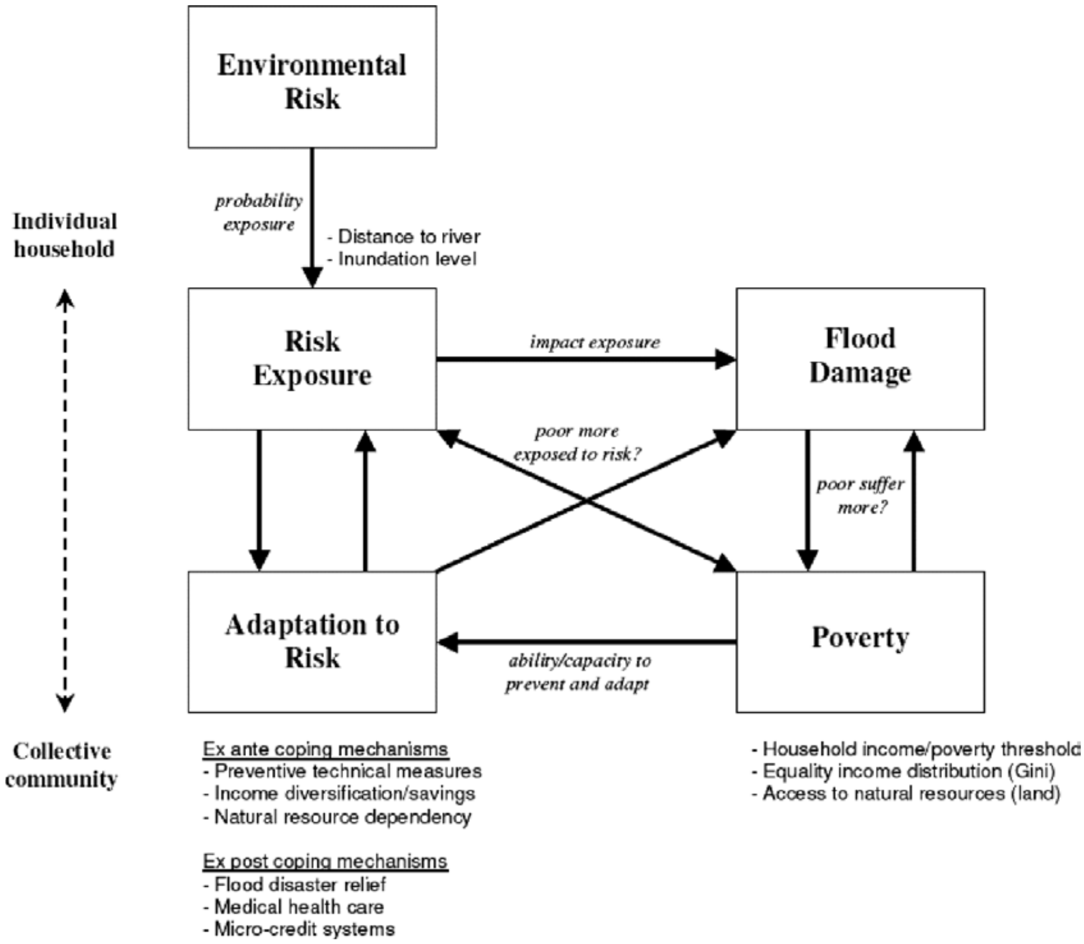

Figure 1.3: Analytical framework underlying the study (adapted from Brouwer et al., 2007).

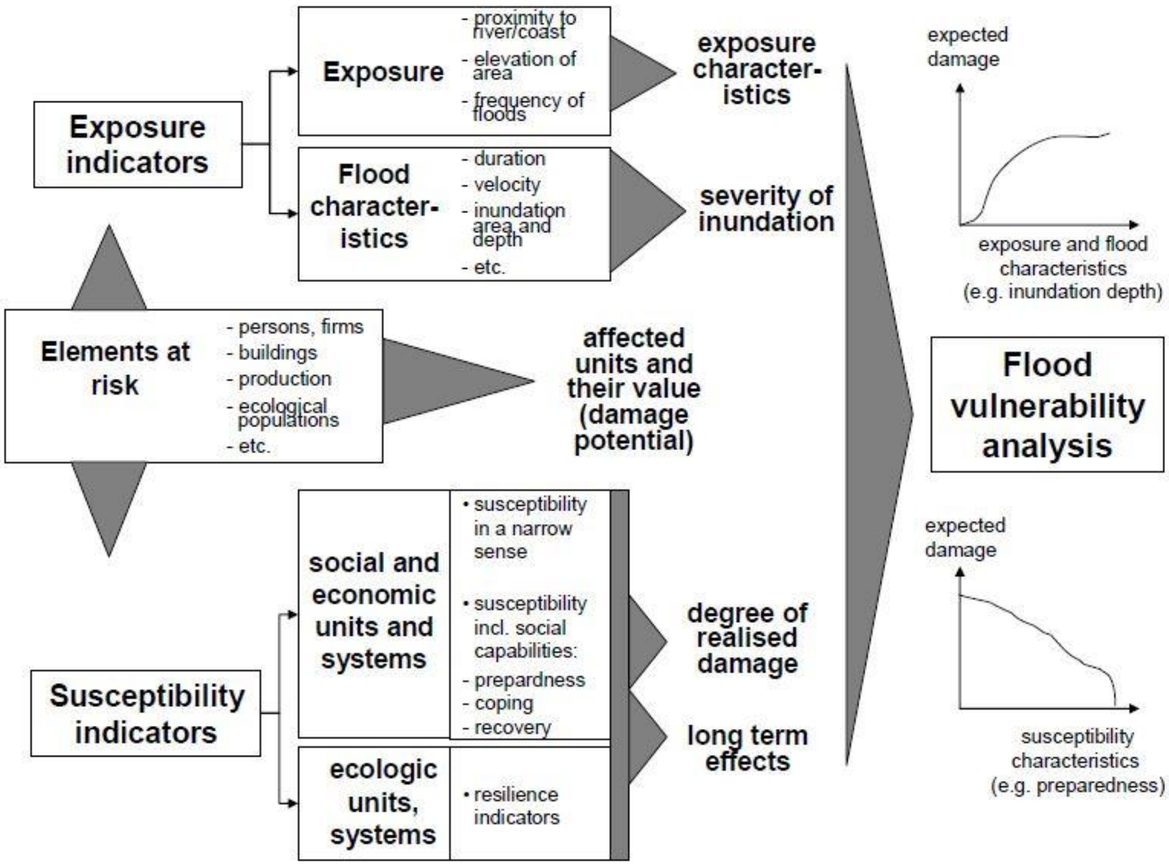

Figure 1.4: Some indicators for flood vulnerability analysis (Messner and Meyer, 2006).

As people seek out their livelihoods in oil palm, forests are cleared to make way for new plantings. These livelihood activities affect the catchment water balance. Deforestation has certain hydrological consequences.

1.9 Deforestation and floods

Several experimental studies have been conducted in the tropics on the hydrological consequences of deforestation or the substitution of forest through crop plantings such as oil palm (RSPO, 2014; Murom et al., 2008; Germer, et al., 2008; Basiron, 2007; Nelson et al., 2006). Forest cover protects the soil against raindrop impact and encourages infiltration so that soil erosion is reduced and the stream flow is regulated, as flood peaks are reduced while dry-period flows may be slightly increased (Nelson et al., 2006; Murom et al., 2008). The opposite happens when vegetative cover is removed and replaced by non-native vegetation, usually with less foliage. An area of land with little vegetative cover would generate more runoff than an area with a good vegetation cover (Nik, 1988). Many studies have shown that land use alteration of land cover influences the interception process , and aids in the development of distinctive flood characteristics and their behaviours in catchments (Fruchtman et al., 2012; Lopez-Vicente et al., 2012; Erskine et al., 2013; Montgomery, 2013), and the spatial extent of inundation (Li et al., 2012). Removal of tree cover also leads to the exclusion of interception loss, stem flow, and through fall components of the interception process and enables free fall of rainfall on exposed surfaces that becomes overland flow into waterways (Zhang et al., 2012; Deshmukh, 2013). When forest is cleared for agriculture there is reduction in evapotranspiration which may steer the rise of the water table. During heavy rainfall, this has led to overland flows and increased stream discharge and caused floods (Nik, 1988; Brown et al., 2005).

There are three ways vegetation removal contributes to flooding: (i) via increasing the channel shape and size, (ii) through increasing the volume of water reaching the channel, and (iii) by reducing the flow resistance (Rutherfurd et al., 2007). Consequently, channel form changes once vegetation (small and large) is removed from streams (ibid.). Gullying, bed-deepening and widening are the main changes. Changes to cross-section morphology and enlargement of the drainage pattern by gullies modify stream hydraulics and hydrology thus increasing peak discharge to breach the bankfull stage and result in floods (ibid.).

1.10 Research problem

Floods benefit the environment by spreading sediments, organic material and nutrients which enrich the soil and its moisture along the floodplain (EA, 2010). Also, water resources are replenished to support breeding, migration and dispersal of seeds for flora and fauna to flourish. It also replenishes surface water, drinking water and groundwater. In contrast, a flood can be an ecological disaster in the short term. It can deposit debris, destroy plants and animals, and cause their extinction (ibid.). It can be severe depending on its natural movement and is affected by land use. Settlements, infrastructure and land clearance can affect natural surface flow of floods in a landscape, and alter its velocity and depth, and cause damage to livelihood assets (ibid.).

Furthermore, the economic effects after a flood can be categorised as immediate, short term, or long term (UNISDR, 2011; IPCC, 2012). Immediate effects include loss of human life and property, damage of infrastructure and utilities, loss of farmland and crops (e.g. oil palm) and communication loss. Short-term effects include homelessness, loss of livelihoods, injuries needing medical treatment, shortage of safe drinking water, food shortage and wage losses. The long-term effects include repair of infrastructure (e.g. bridge), restoration of public services (e.g. transport/roads), reclamation of loss (e.g. replant oil palm), trauma and psychological effect on those affected, mass migration, reduced economic growth and development, and decreased production and purchasing power (UNISDR, 2011; IPCC, 2012).

Two examples of flood losses in oil palm growing areas of Thailand and Malaysia occurred in 2010 during a monsoon season. During the floods, 232 people died in Thailand while four people died in Malaysia and incurred a total cost of US$1.676 billion of damage to property for both countries (*Bangkok Post*, 2010). On December 2014, a plantation along the Terpai River in Malaysia was submerged under 3.7 metres of floodwater and production output fell by 1.36 million tonnes (22% slump) (Yuliani, et al., 2010). This was because heavy rains and floods prevented harvesting when roads and bridges were inundated and damaged. The plantation owner said this had never happened before and he would earn half his monthly income (Bloomberg, 2014).

Flood is currently the second largest hazard in terms of people affected and the levels of economic impacts for many years in PNG (figure 1.5 and table 1.3) and in many parts of the world (e.g. table 1.1, table 1.2 and table 1.4). In terms of economic damage in PNG, the greatest cost is incurred by volcano, followed by flood, and earthquake (figure 1.5 and table 1.3). In addition, flood is the third hazard affecting people in PNG after drought and storm (table 1.3). Compared with other countries in the Asia-Pacific region, flood is a severe hazard in terms of its intensity in PNG together with volcano, earthquake, landslide and tsunami (table 1.4).

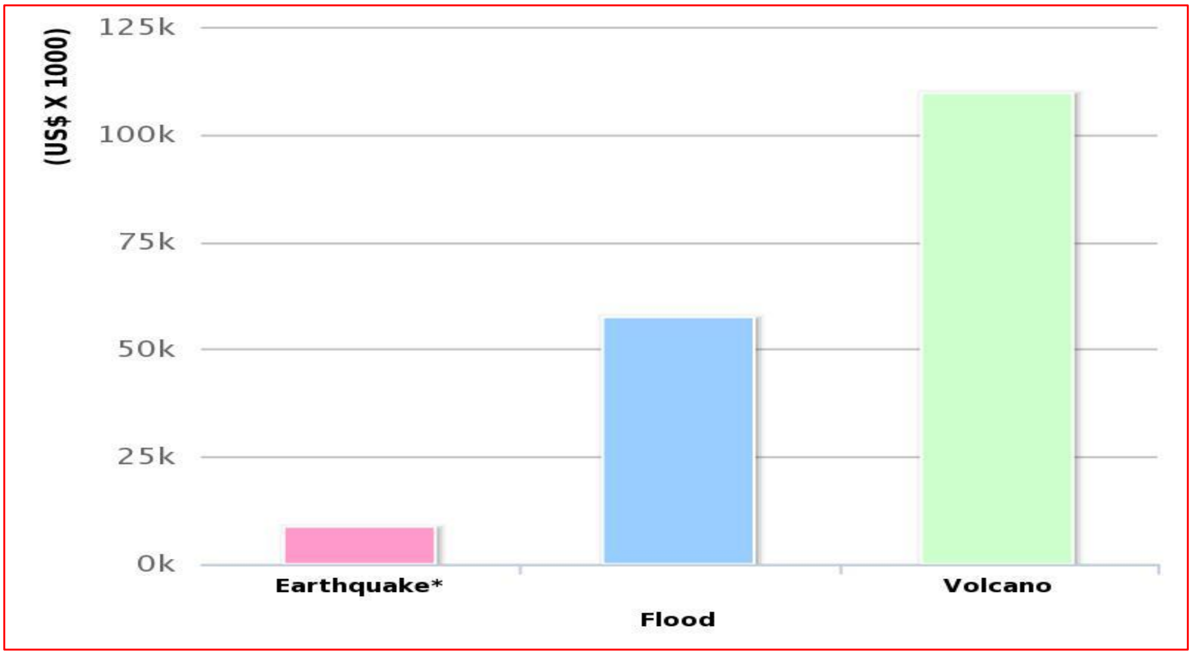

Figure 1.5: Estimated economic damages for PNG reported by main disaster type (US$ X 1,000) between 1980 and 2011 (Guha-Sapir et al., 2012).

Table 1.3: Statistics for affected people and economic damages (US$ X 1,000) per event in PNG between 1980 and 2011 (Guha-Sapir et al., 2012).

Affected People	
Drought:	270,000.00
Earthquake:	3,828.17
Epidemic:	1,571.57
Extreme temperature:	...
Flood:	29,519.30
Insect infestation:	...
Dry mass movement:	500.00
Wet mass movement:	2,012.88
Volcano:	21,973.00
Storm:	69,893.33
Wildfire:	8,000
Economic Damage	
Drought:	...
Earthquake:	760.42
Epidemic:	...
Extreme Temperature:	...
Flood:	5,762.80
Insect infestation:	...
Dry mass movement:	...
Wet mass movement:	...
Volcano:	11,000
Storm:	500.00
Wildfire:	...

Table 1.4: Relative intensity of hazards faced by some countries in Asia and the Pacific.

Country	Typhoon	Flood	Drought	Landslide	Tsunami	Earthquake	Volcano	Civil Strife	Fire	Epidemic	Deforestation	Frost	Accidents
Australia	S	S	S			L			S				
Bangladesh	S	S	S	L	L	L		M	L	M	M		L
China	M	S	S	L	L	S			M	L			L
Cook Islands	M	L	S	L	M	L							L
Fiji	S	S	M	S	S	M					M		
Hong Kong	M	L		M				L	M		M		L
India	M	S	S	L		M		M	M	M	M		M
Indonesia	L	M	M	L	L	S	M		M	L			L
Lao PDR		M	L										
Malaysia	M	S*	S	L	M				L		M		
Myanmar	M	M	M	M		S			S				
Nepal	M	L*	M	L		M			M	M			
Pakistan	M	M	M	L	M	S		L	L	L		L	L
Philippines	S	S	L	S	S	S	M	M	S	L	L		L
PNG	L	S	M	S	S	S	S	L	L	L	L	L	L
Sri Lanka	M	S	S	L				S	L	L	L		
Thailand	M	S*	S	L		L			L		S		M
Vietnam	M	S	L	S	S	L			L	L	L		
Solomon Islands	S	S	L	S	S	S	S		L	L			
Tonga	S	M	M	L	S	S	S						
Vanuatu	S	S	L	S	S	S	S		L	L			M
Western Samoa	L	S	L	S	S	M	L						

Source: **Whitehouse and Burton, 1999 for water related hazards: ADB, 1991 for other hazards, *In: Krige and Pestre (2013).* *Legend:* S = Severe; M = Moderate; L = Low *Note:* * Coastal Flooding**

Similarly, floods can threaten livelihood assets of many people who are mostly rural based and agrarian focused. For example, Cyclone Guba induced flooding in Oro, the second largest oil palm growing province in PNG, caused 149 deaths, the evacuation of 2,000 people, the destruction of roads, bridges and 40 houses, damage to water supplies and electrical infrastructure. Transport was severely disrupted, with road access blocked, and flights suspended. The flood left behind a total damage bill of 200 million kina (US$71.4 million) (PNG National Disaster Centre-NDC, 2014; Wikimedia Foundation Inc., 2016 -http://en.wikipedia.org/wiki/Cyclone_Guba).

Large populations live in oil-palm dominated landscapes where they are vulnerable to riverine flooding (UNISDR, 2011; IPCC, 2012). Besides urban centres, and other diverse environments where the bulk of flood research has been focused, estimates suggest that there are currently more people in settlements seeking a livelihood through oil-palm agriculture around the world – approximately 14 million people with properties vulnerable to flood risks and assets (e.g. oil palm trees) that are exposed to floods (Queensland Government, 2011; EA, 2010; Asian Development Bank and World Bank, 2010).

In addition, the PNG NDC Damage Assessment Report on the 2010 Dagi River flood showed that more than 5,000 people were affected in the Dagi catchment, an area in the largest oil-palm growing area of PNG. During the flood, many access roads to villages and oil palm settlement areas were cut-off by rising water levels from the Dagi River and its tributaries (PNG NDC, 2010). Consequently, the Dagi Bridge was covered by the flood, cutting-off the main highway from Kimbe to Bialla. Two drownings were reported, nine food gardens near the river were inundated leading to loss of food and subsistence income. Also, eight oil palm trees were uprooted and fruit bunches were not harvested for days leading to further loss of income. Residential areas were inundated with three houses destroyed. Also, eight people in formal jobs had cuts to their salaries due to their enforced absences. Finally, the 2010 flood incurred an estimated cost of K4,150,000 (ibid.).

The Dagi River catchment, of WNB Province in PNG is situated "in the largest oil palm growing region of PNG" (Koczberski and Curry, 2005: p.325). It experiences regular wet-season discharges between December and March each year. Generally common in many tropical catchments, information on the flood regime is non-existent. Woodyer (1968: p.114) identified bankfull discharge as a 1.24 to 2.69-year flow event for most rivers in the world. Similar measurements of flow based on gauged rivers in many parts of the world reveal that on average, a bankfull stage has a recurrence interval of 1.5 years (Alexander et al., 1999). This means that there is a 67% chance that a river will overtop its active floodplain. We can say that regular wet-season discharge within its bankfull stage is not a flood in the Dagi catchment unless this is breached and flows on to the floodplain.

The Dagi catchment has an area of 492km^2 with an average annual rainfall of more than 4000mm (PNG NWS, 2014). In their studies, Beven (2011) and FAO (2013) concluded that the characteristics of high intensity and long duration convective rainfall are similar in many tropical areas of the world. In another study that analysed short-term rainfall data, results suggested reasonably stable relationships governing the intensity characteristics of convective rainfall common in the tropics (Battany et al., 2000). By contrast, Botzen and Van Den Bergh (2009), Box (2009), and Steyaert et al. (2011) stated that increases in rainfall in specific areas of the tropics due to climate change would increase flood risks to livelihood assets. Nonetheless, I suggest that variations in the wind patterns due to climate change will vary rainfall frequency and quantity, and create flood generating conditions outside of the established patterns reported by Ayoade (1988), Battany et al., (2000), Beven (2011), and FAO (2013). From recent news reports (e.g. *The National Newspaper* 2010 and 2014; *Post Courier*, 2010 and 2014), the damage from floods in Dagi were caused by high intensity rainfall and duration. However, this relationship remains to be confirmed for this oil-palm dominated landscape.

The Dagi catchment has an annual population growth rate of 3.92%, which is high by PNG standards (PNG National Statistical Office-NSO, 2013). Since 1968 it has been subjected to various types of land use dominated by oil palm cultivation. The decision to develop oil palm and settler blocks led to in-migration and consequent population growth. As a result, nearly 80% of the native vegetation has been replaced with bare and levelled land surfaces associated with increased oil palm cultivation and subsistence gardening in riparian zones upstream and downstream of the catchment. The 2010 NDC report (from WNB NDC Office) for the Dagi catchment identified flooding as the major hazard affecting assets and livelihoods over the past 20 years (NDC, 2010). However, there were no studies conducted to confirm the sources, causes, the characteristics and behaviour of these floods, or to quantify their impacts on assets and livelihoods within this oil-palm dominated landscape.

Forest cover in Dagi catchment protects the soil against raindrop impact and encourages infiltration and regulates stream flow. However, native vegetation cover has been removed over the years (1968-present) by 80% and replaced by predominantly oil palm trees with less foliage. As of 2015, new tracts of native forests upstream of Dagi including its tributaries are being cleared for oil palm cultivation. This is because of population increases as the original settlers' children re-marry and develop new livelihood strategies. There are no data for the Dagi catchment to know the effects of vegetation removal for oil palm cultivation. Usually, oil palm is planted in stages of growth in Dagi. This means younger trees have little foliage and canopy and the leaves are aligned at about 45^0 with small interception allowing for more stem flow and through fall in support of overland flow. In addition, bare ground in newly cleared forest areas upstream allows for raindrop impact that seals off the soil pores hence lowering the infiltration rate. Consequently, more rainwater falls directly on the ground, or reaches field capacity quickly, and increases overland flow into the stream channels. In addition, growth stages of oil palm demand and transpire water at varying amounts depending on their maturity level. As can be expected, small transpiration losses come from areas under young palms, implying more water availability for infiltration and overland flow into stream channels. Generally, this contributes to the problem of floods in the catchment.

The removal of riparian vegetation over the years for settlement, subsistence gardening, gravel extraction and extension of oil palm plots has completely removed the catchment's function as a flood protector for Dagi. In the 1980s and 1990s I observed sufficient riparian vegetation beside the river and streams. The stream shape and size were in a natural form. I re-visited the catchment in 2007 and noticed significant morphological changes to the cross-sections of most reaches of the Dagi channels. In areas where most riparian vegetation was removed, there was little resistance and thus more water flowed directly into stream channels. Flows in channels were freer with little or no resistance from riparian vegetation. The stream shape has become broader in most channels formerly seen as v-shaped and at the same time channel sizes have expanded.

The clearance of riparian vegetation in the Dagi has re-defined the natural bankfull stage through many channel incisions. This has resulted in bed widening and extension of the drainage network by gullying in most parts of the catchment. Consequently, channel storage capacity has decreased as sediments accumulated and large discharge flow easily across most banks. Previously there were large tree trunks in most stream channels of the Dagi but today they are absent. Because of that, I observed several changes in the channel form of the Dagi in 2007. Firstly, the absence of steps in the longitudinal profile, consequently allowing water to flow freely and quickly downstream. Secondly, channel sediment storage and scour has been moderated. Thirdly, formation of bars and benches has been underpinned. Fourthly, bedload transport is regulated. Fifth, there was localised scour. Sixth, more pools were created and there was a decrease in riffles. Finally, there was enhanced overbank deposition of fine sediments, and this appears to be the dominant process on the Dagi floodplains.

The removal of riparian vegetation upstream has not allowed for enough blockage of flow and as a result, velocity has generally increased going downstream. Unlike before, water is readily available for runoff and flow in the Dagi is unrestricted across most stream cross-sections. One obvious feature of the landforms at the lower reaches of the Dagi catchment is the presence of peatlands[1]. Unsuccessful attempts at draining peatlands were made in the lower Dagi by planting oil palm, so that water uptake by the palms would help drain it. The above catchment changes together with those induced by climate change are expected to exacerbate flood stage, cause inundation, and increase the exposure of settlements to flood risks into the future in oil-palm dominated landscapes.

Little is known now on how these catchment changes affect flood characteristics and behaviour, and the exposure of livelihood assets within oil-palm dominated landscapes. There is a need for studies that examine the combined effects of floods on livelihoods assets. Spatial information relating to where flooding is most likely to occur and at what quantity, velocity and depth of inundation, exposure of livelihood assets and its impacts are lacking at present. The interactions between floods and livelihood assets are also not well understood. Furthermore, flood risks cannot be eliminated but they can be effectively analysed and possibly reduced in many oil-palm dominated landscapes. In most cases, this can be achieved by using tools and models to understand flood characteristics such as duration, inundation area and depth (Mouche et al., 2012; Di Crescenzo et al., 2015); and behaviour such as flood velocity and peak (Mouche et al., 2012; Rhoads et al., 2012); potential river flood risks (Bastola et al., 2011), levels of exposure of livelihood assets (Aubrecht et al., 2013), and loss probabilities (Bouwer et al., 2010).

According to a very recent study by Hooijer et al. (2015), oil palm is said to have a limited tolerance to flooding with conditions worsening as climate change progresses. The study detailed the impact of peatland drainage for oil palm cultivation in Sarawak, Malaysia (Hooijer et al., 2015). It quantified the peatland morphology as a result of recent drainage on future land surface lowering and associated flood risk. Because of draining peatland, the study found that between 2000 and 2014, oil palm plantations increased from 6% to 47% and peatland decreased from 56% to less than 16%. The study used an airborne synthetic aperture radar (SAR) to construct a digital elevation model (DEM) by filtering vegetation and canal effects to model floods. In 2009, the model results showed 29% of existing plantations suffered from reduced drainage because of flat topography. Due to climate change as predicted for the Asia-Pacific region, the study projected that 42% of current oil palm plantations in Sarawak and in many oil palm growing areas under peatland would experience more problems as drainage became reduced by 2034, 2059 (56%), and 2109 (82%). For oil palm areas frequently flooded with high water levels, figures corresponded to 18% by 2009, 2034 (27%), 2059

[1] Peatlands are land areas that contains plant humus that have not decomposed properly and have accumulated in an environment saturated with water and lacks oxygen.

(39%) and 2109 (64%). As projected, peatlands will have reductions in productivity due to a decline in groundwater table levels, and experience more floods. Based on these projections, agricultural production will be lost before flooding becomes permanent. A further field survey in that research revealed more flooding in oil palm plantations than that predicted in the reported models and that it would worsen as climate change progressed. Significantly this study on flooding in relation to peatland cultivation of oil palm made several recommendations. One of the key recommendations called for:

> *"All tropical coastal inland areas, including lowland peatlands and its vicinity, and as a matter of urgency, require subsidence and flood analysis to be undertaken as part of land use and economic planning. While carbon emissions linked to climate change have been the focus of recent debates regarding peatland development, the flooding consequences of peatland drainage and oil palm cultivation needed to receive much more attention as they affect direct economic interests and the lives of people living in these regions"* (ibid., p.7).

Contrary to the very recent and relevant study in an oil palm landscape by Hooijer et al. (2015), previous studies conducted in this landscape can be put into five groups. Firstly, studies were done generally on how development of oil palm results in loss of biodiversity, assessments and climate change (Basiron, 2007; Buchanan et al., 2008; Fitzherbert et al., 2008; Turner et al., 2008; Wilcove and Koh, 2010; Yule, 2010; Webb et al., 2010; Azhar et al., 2011; Azhar et al., 2013; Edwards et al., 2013; Jennings et al., 2015; Pardo Vargas et al., 2015). Secondly there were oil palm impact studies relating to carbon budgets from riparian zones (Adachi, et al., 2011; Koh et al., 2011; Pardo Vargas et al., 2015). Thirdly, there were studies on the potential impacts of fresh fruit bunches to the environment (Chan et al., 2007; Rist et al., 2010; Comte et al., 2012). Fourthly, many studies were conducted on soils and land use changes under oil palm and livelihoods (Nik, 1988; Nelson et al., 2004; Dennis and Colfer, 2006; Nelson et al., 2006; Murom et al., 2008; Spiertz and Ewert, 2009; Wicke et al., 2011; Buschman et al., 2012; Cramb and Curry, 2012; Wich et al., 2012; Miyake et al., 2012; Koczberski and Curry, 2005; Koczberski et al., 2009; Webb et al., 2011; Curry and Koczberski, 2012; Li et al., 2012; Sayer et al., 2012; Wakahara et al., 2014). Finally, there were studies on water balance modelling under oil palm (Brown et al., 2005; Billa et al., 2006; Chan et al., 2007; Yusop et al., 2007).

Flood is the most common hazard and third most damaging globally after storms and earthquakes (Lal Narsey et al., 2009). Assessment of flood risks and other hazards are essential to help stakeholders to plan and better prepare for emergencies. However, progress in this area is often hindered by lack of data mostly in developing countries. Consequently, Lal Narsey et al. (2009, p.25) called on developing countries whose economies are mostly agriculture based to:

> *"urgently develop and strengthen specific geo-referenced baseline information related to key hazards, including socioeconomic information, livelihood assets and the costs, with specific reference to Pacific Island Countries and Territories (PICTs)"*.

Anthropogenic climate change is expected to increase flood risks through more frequent heavy rainfall, increased catchment wetness, fluvial erosion, sea level rise and coastal erosion (McCracken et al., 2012). Flooding is already a big problem in many oil palm landscapes and no study has been undertaken to show the relationships between floods and livelihood assets. An understanding of the factors affecting discharge characteristics and the flood behaviour will help us to develop policies to enable communities within oil palm landscapes to be resilient to flood risks.

Obviously as population increases and oil palm development continues throughout the 21st century together with climate change, there is a growing need among authorities with relevant institutions for authentic information on exactly how livelihood assets may be affected by floods (Praskievicz and Chang, 2009; Lal Narsey et al., 2009). This study addresses the second recommendation outlined by Lal Narsey et al., (2009, p.28) and the most recent recommendation by Hooijer et al. (2015, p.7). In the present study, crucial information will be investigated that concerns catchment changes induced by oil palm development on flood characteristics (e.g. duration, inundation area and depth) and behaviour (e.g. flood velocity and peak), potential river flood risks, levels of exposure of livelihood assets and loss probabilities. Importantly, it will increase community (e.g. growers, catchment managers, disaster and emergency officials, decision makers) understanding of vulnerabilities of livelihood assets to flood risks and help them be better prepared to mitigate risks in oil-palm dominated landscapes across the world.

1.11 Objective and aims

Because oil-palm dominated landscapes are vulnerable to flood hazards, a flood risk assessment will be used as a case study in the Dagi River catchment to assess flood risks on assets and livelihoods. The results will provide useful information to both smallholder oil palm growers and company owners and those stakeholders involved in the oil palm industry. Such data should ameliorate severe flooding risks as well as crucially expand collective comprehension of, and develop mitigation plans with preparedness for, flood hazards within oil palm landscapes.

Therefore, the objectives of this research within an oil-palm dominated landscape are to:

1. Determine the hydrological characteristics and behaviour of floods at a catchment and sub-catchment level

2. Determine the spatial extent of inundation, hazards and the stream power available for further damage that will contribute to increasing loss potentials on assets and livelihoods

3. Determine flood risks and vulnerabilities of assets and livelihoods

4. Determine the relative roles of population, land use and livelihood assets in affecting exposure and potential river flood risks, and investigate management options for flood disaster planning, hazard and risk mitigation across sectors

1.12 Research questions

The key science questions to be addressed are:

1. what factors affect the characteristics and behaviour of flood discharge (peak and magnitude), water depths, velocity and duration during wet seasons at a sub-catchment and catchment level in the Dagi River catchment?

2. what is the spatial extent and location of areas subjected to or likely to be subjected to floods and inundation, and how does inundation limit stream power available for further damage in the Dagi River catchment?

3. which assets and livelihoods are at risk and vulnerable to floods in the Dagi River catchment?

4. what relative roles do population, land use and assets play in affecting exposure and potential river flood risk in the Dagi River catchment?
5. what management options are available for flood disaster planning, hazard and risk mitigation in the Dagi River catchment and who should pay for flood damage at the local scale?

1.13 Thesis structure

The thesis comprises seven chapters:

Chapter 1 provides the research background and research problem information that explains why this study is important in understanding flood risks to assets and livelihoods in landscapes dominated by oil palm. It also provides the research objective, aims and questions to be addressed.

Chapter 2 reviews the current state of research into flood characteristics and behaviour, vulnerability of assets and livelihoods, risk assessments and modelling. It is sub-divided into the following subsections: flood dynamics in small tropical catchments, agricultural changes to landscape and their effects on flooding, with focus on oil palm production and tropical agriculture in developing nations. Exposure of rural communities to flood risk is reviewed, as are the impacts of flood events on assets and livelihoods. Theoretical links and research gaps are identified and outlined in the literature.

Chapter 3 describes the location, climate, vegetation, geology, landforms, slopes and soils of the study area. Current information on land use, history, human interactions, modes of oil palm production, and local economy are provided. It ends by outlining the general environmental concerns, flood-risk issues and measures taken so far to address them.

Chapter 4 investigates the hydrological characteristics and behaviour of floods in the case study area. It begins with an introduction and then outlines the specific objectives and aims of the investigation. It explains the available datasets and their sources, software and hardware and purchased and fieldwork datasets needed for the study. The components of floods to be investigated during two wet seasons are peak and magnitude, water depth, velocity and duration, stream power, cross-sections and longitudinal profiles, roughness coefficients, rate and volume of discharge, and specific yield. For each component of flood, a presentation of the results is made at reaches upstream and downstream followed by an explanation at the sub-catchment scale. Results will be presented as hydrographs,

graphs and tables. Factors affecting these flood characteristics and behaviour will be discussed and conclusions drawn.

Chapter 5 investigates the spatial inundation extents and hazards based on the effects of flood volume, depth, velocity, roughness and stream power. It begins with an introduction, and then outlines the specific objective and aims of the investigation. Next, it outlines the available datasets and their sources, software and hardware, datasets purchased and those collected during fieldwork. It will outline and explain the approaches taken to model spatial inundation extents and hazards upstream and downstream based on water depths, velocity and durations. Then it will assess modelling accuracies through calibration by simulated and observed results based on frictional values. This is followed by the presentation of the results and discussion on the spatial inundation extent, hazards and stream power for further flood damage that will contribute to increasing loss potentials on livelihood assets. Study limitations and recommendations conclude the chapter.

Chapter 6 assesses flood risks and vulnerabilities of livelihood assets. It will focus on direct tangible economic costs of exposed land use elements following qualitative and quantitative risk assessment approaches. It begins with an introduction and then outlines the specific objective and aims of the investigation. It will explain the available datasets and their sources, software and hardware, datasets purchased and those collected during fieldwork. The level of hazards, vulnerability and the degree of risk will be determined based on water depth and velocity damage functions. It seeks to derive the average annual risk using risk curves established from the overall monetary loss at dissimilar exceedance probabilities (ITC, 2010). Results will be presented on flood hazards, exposed land use elements, economic price based on elements placed at peril, together with the vulnerability concerning the elements at peril due to water depth, velocity, duration, and stream power based on depth-damage curves (de Moel and Aerts, 2011). This will be followed by a discussion, study limitations and conclusions and recommendations.

Finally, chapter 7 will provide summary discussions, conclusions and recommendations of the whole research. It will be based on an overall methodological framework compiled from each data chapter, and will integrate all findings in the thesis. The findings in this study will be discussed in relation to the overall objective and aims of the research. Each factor involved in affecting the outcome of this research will be compared with other similar research to draw conclusions. The chapter will begin by discussing the climatic, catchment, network and channel factors that affected flood discharge, water depth, velocity, stream power and duration in this study. Secondly, it will go on to discuss the factors that influenced the spatial inundation extent and hazards. Thirdly, it will evaluate the relative roles played by population, land use and livelihood assets in affecting exposure and potential river flood risk. Fourthly, this chapter goes on to investigate management options for flood disaster planning, hazard and risk mitigation and who will pay for flood damage mitigation in oil-palm dominated landscapes and across different sectors. It will end by drawing conclusions from the study, analyse its strengths and weaknesses, and make future research recommendations and actions to be taken by stakeholders involved with oil palm.

Chapter 2.0: Flood-dynamics, impacts, vulnerability, risk management, and their modelling in tropical catchments.

2.1 Introduction

Large volumes of discharge after a high-unit rainfall (e.g. with high intensity and long duration) their over-time distribution, and the geomorphic work they do, comprise a typical regime of a catchment in the tropics (Gupta, 2011; McGregor, 1991). A discharge transport volume of water occurs at a rate measured in cubic metres per second across a stream cross-section (Gupta, 2011; Buchanan and Somers, 1969). After an intense rainfall over a long duration, the water level rises in the stream to reach its peak discharge and breach its bankfull stage. In areas occupied by man, inundation becomes a hazard to livelihood assets. Flood disasters arise where and when man puts himself at risk and consequently causes or intensifies floods by interfering with hydro-geomorphic processes. Man develops and occupies floodplains due to unawareness, or it may be for a cultural and monetary cause (Adebayo and Jegede, 2010). Variability in riverine floods depends on their geographic location, hydro-geomorphic processes, population growth rate, type of development activity, and rate of wealth increase over time (Sharma et al., 2011; Bouwer et al., 2010; Roggema, 2009; Cammerer and Thieken, 2013).

Recently, flood disasters in many countries have claimed thousands of lives and cost billions of dollars in material losses (Cammerer and Thieken, 2013). In response, research was conducted to understand flood risks to reduce the impact of flood disasters (UNISDR, 2002). The Yokohama Strategy was established during the "1994 World Conference on Natural Disaster Reduction" (Twigg, 2004: p.7). It consists of prevention, preparedness and risk mitigation guidelines "by emphasising the risk assessment, disaster prevention and preparedness, vulnerability reduction, early warning" and disaster reduction policies (UNISDR, 2004: p.8). Furthermore, the 2005 World Conference on Natural Disaster established the Hyogo Framework to identify specific gaps and update the Yokohama Strategy. It addresses five areas: "(i) governance frameworks, (ii) risk identification, assessment, monitoring and early warning, (iii) knowledge and education, (iv) risk factor reduction, and (v) preparedness and recovery" (Pharoah et al., 2013: p.17).

Furthermore, "analysis, assessment and reduction" constitute the "flood risk" management process (Schanze, 2006: p.6). The main goal is to quantify the potential causes, exposures of livelihood assets, damage and losses and costs incurred. A flood's a) discharge, b) velocity, c) overbank inundation depth, and d) duration are influenced by catchment processes that in turn increase the vulnerability of livelihood assets. According to McGregor (1991: p.7-8), there are "empirical, statistical, analytical and modelling methods" at hand that could be used as tools for flood risk analysis and assessment. Because of complexities involved with catchment, network and channel characteristics, it is important to understand flood dynamics and their downstream variations and linkages. Impacts from developments on natural processes further add to these complexities. Choosing appropriate flood modelling approaches to integrate physical and human dimensions to floods can help in the assessment of flood risks and vulnerability of livelihood assets.

This review begins by investigating the major components of flood dynamics in tropical catchments and their interactions. It also reviews recent advances in hydrological models used in investigating variations in flood characteristics and behaviour, their upstream-downstream connections and lateral perspectives. Next will be an investigation of the impacts of agricultural developments in the tropics on flood dynamics and how they exacerbate flooding. It also investigates how livelihood assets are vulnerable to flood risks. Finally, the major components of a flood risk management will be reviewed. This review chapter is focused on oil palm cultivation; however, literature will be drawn from other agricultural landscapes. Hence, this review has these sub-headings:

a) flood dynamics in small tropical catchments
b) flood risk modelling approaches
c) agricultural change impacts on flooding in developing countries
d) flood impacts, risks and vulnerabilities of livelihood assets
e) flood risk management

2.2 Flood dynamics in small tropical catchments

2.2.1 General causes of floods in tropical catchments

The general causes of flooding in the tropics are: (i) climatological, (ii) part-climatological, and (ii) others such as earthquakes, volcanic eruptions, landslides and dam failures (Ward, 1978; Ayoade, 1988; Gladwell, 1993; Kundzewicz et al., 2004; Guo et al., 2014). Most floods result from causes which are wholly or partly climatological in nature (Guo et al., 2014). Rainfall is generally believed to be the dominant precipitation type in the tropics except for snow caps in highland peaks of the tropics (e.g. Highlands of West Papua). The rains are monsoonal, or from tropical cyclones, or from a large thunderstorm (Gladwell, 1993). Rain is more abundant in the tropics but decreases towards the subtropical belts, and is more abundant on the windward sides of mountains than on the leeward sides (Ayoade, 1988).

In most parts of PNG, rainfall quantity received is linked with two seasonal monsoons. The northwest monsoon is from December to March and the southeast trade winds from May to October. They bring abundant rainfall with annual average more than 4000mm. Generally coastal plains in PNG receive high rainfall. For example, Kikori located only 600m above sea level (m.a.s.l) has an annual average of 5,700mm. Its mean monthly rainfall is around 300mm between November and February, and 700mm between May and June (PNG National Weather Service–PNGNWS, 2014). In contrast, high altitude and the highlands areas of PNG have low rainfall. For example, at Tari (2167 m.a.s.l), annual average rainfall is 2,560mm with a monthly mean of 120mm consistent with the pattern of the monsoon season. The rainfall decreases in June and July with a mean of 98mm (PNGNWS, 2014). The mountainous terrain of the coastal and highland fringes forces rain bearing clouds to condense and fall as rain leaving behind little moisture to go further inland. On the island of New Britain, rainfall averages more than 4000mm per annum. Variation in the rainfall total between the monsoon seasons is about 1500mm per year. Monthly averages range from 100-200mm per month (Tudhop, et al., 1995: p.577).

Floods which are partly climatological arise from coastal storm surges and estuarine tides (Ayoade, 1988; Gladwell, 1993). These floods are limited to coastal areas and the lower reaches and estuaries of rivers draining into the sea (Gladwell, 1993). They can be disastrous because these areas are densely populated. Non-climatological floods arise from earthquakes, volcanic eruptions and landslides that disorganise river patterns, dam rivers, and soon cause flooding (Ayoade, 1988; Gladwell, 1993). Less common floods are due to dam failure and other control works.

Floods of climatological origin derive from excess rainfall over evapotranspiration losses when allowance has been made for natural infiltration and surface detention (Ayoade, 1988; Gladwell, 1993). Flood characteristics vary from one catchment to another even when the flood generating mechanisms are identical (Ayoade, 1988). Catchment, network and channel characteristics in flood intensifying conditions cause these differences (figure 2.1) (Ward, 1978). They determine how much rainfall will appear as runoff and the speed of movement of water. Human activities modify these characteristics and increase flood risks (Kundzewicz et al., 2004). When these conditions are properly managed, they can ameliorate floods, which is the goal of managing flood risks (Schanze et al., 2006).

2.2.2 Flood intensifying conditions in the tropics

Catchment, network and channel characteristics intensify floods (figure 2.1) (Ward, 1978). They are either stable or variable conditions that interact with and between others to intensify floods. Stable characteristics refer to the conditions of the catchment, network and channel that are not likely to change for a long time (e.g. decades to millennia), whereas variable characteristics refer to those that can change within a short time (e.g. daily, weekly, monthly or annually).

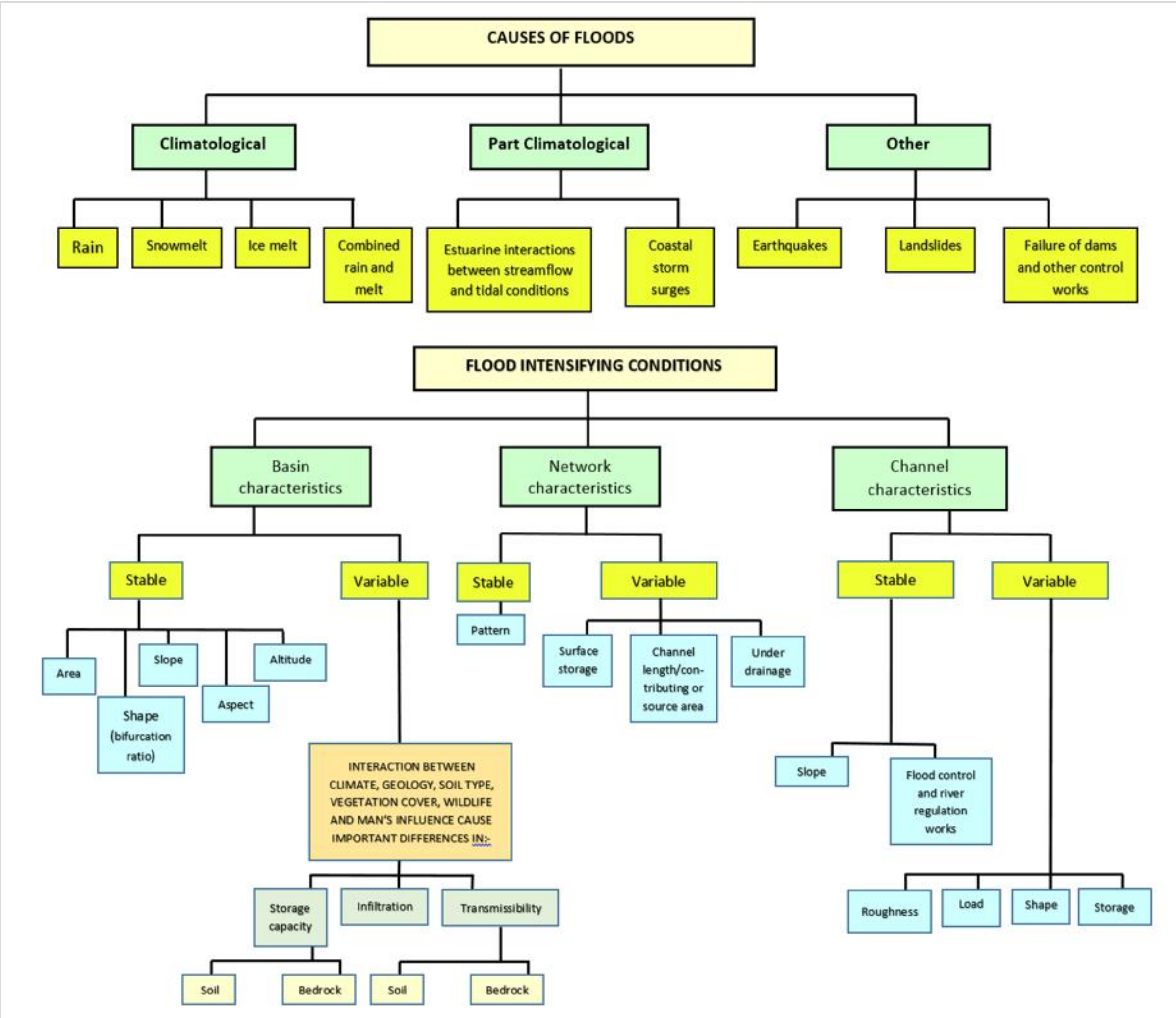

Figure 2.1: Causes and intensifying conditions of riverine floods *(after Ward, 1978)*.

2.2.3 Rainfall-runoff: catchment, network and channel characteristics and flood genesis

An outcome of the 1992 UN Conference on Environment and Development and the 1992 Dublin Conference on Water and the Environment was the recognition of catchments as the fundamental landscape unit for development planning and management (Verdin and Verdin, 1999: p.1). There is improved simulation modelling software available but baseline data to support the research are scarce (Barrow, 1998: p.175). Such data if gathered and made available for use in a geographical information system (GIS) can assist visualisation, modelling, and analysis to make better plans (Verdin and Verdin, 1999: p.1). A GIS is a useful tool for delineating a catchment into sub-catchments using the main tributaries and their topographic controls on drainage and the topology of the network[2] as reference. All reaches at the catchment and sub-catchment level have a unique flow direction ordered in a bifurcated network that needs to be understood in an upstream and downstream direction (ibid., p.3). In this way, the spatial and temporal characteristics and behaviour of runoff processes operating in each sub-catchment can be better studied and understood (ibid.).

The Dagi catchment has an area of 492km^2 and has the main channel with four main tributaries which can be divided into sub-catchments. This catchment area is quite small compared with other large catchments in PNG. In order they are the Sepik with 78,000km^2, the Fly River with 61,000km^2, Purari with 33,670km^2, and Markham with 12,000km^2. Those covering fewer than 5000km^2 are categorised as small catchments in PNG (Food and Agriculture Organisation-FAO, 1999: p.4). The same can be applied at the global scale to large rivers such as the Mississippi (3,220,000km^2) and the Amazon (7.05km^2) (ibid.).

The term hillslope or "slope" used in this study refers to the inclination allocated in degrees to the description of respective landform that occurs between the valley floor and side, drainage divide, lower, middle and upper erosional level and scarps (Schumm, 1967: p.562; Strahler, 1950: p.802). Globally, the value of slope range is between 0-90^0 and in the Dagi catchment, slope values only range between 0-20^{0,} which is low by global standards (Schumm, 1967: p.564). Using this literature, the Dagi catchment and its tributaries can be sub-divided and allocated slope values (see table 2.1). They are: 1. headwater/erosional (15-20^0 referred to as steep), the middle erosional/transport (5-15^0 referred to as gentle/medium), and the lower depositional zone (0-5^0 as low). The slope values relevant to the

[2] Can be based on size and shape of the catchment area, and channel configuration that produce flow at the outlet (Verdin and Verdin, 1999: p.1).

Dagi catchment are used below in the description of the catchment, network and channel characteristics.

2.2.3.1 Catchment characteristics

Discharge in the Dagi is influenced by rainfall patterns, and further intensified into floods by catchment conditions (Ward, 1978). Rainfall with high intensity and frequency, long duration, and quantity received and its distribution within the catchment area influence how much runoff is generated and discharged (Dunne et al., 1970; Dunne, 1983; Jakeman, 1993; Battany et al., 2000; Beven, 2011; FAO, 2013). The proportion of rainfall depth in each duration in mm/hr is called a rainfall intensity (FAO, 2013). High-intensity, short and long duration, convective rainfall is similar in many tropical areas (Battany et al., 2000; Beven, 2011; FAO, 2013). A study in Malaysia showed that 50% of total rainfall happened at intensities greater than 20 mm/hour while 20-30% occurs at intensities greater than 40 mm/hour (Billa et al., 2006).

Falling rain droplets caught by vegetation leaves and stem are referred to as interception storage (Zhu et al., 2015). As it continues, water reaches the ground and enters the soil through infiltration until the rainfall intensity outpaces the soil infiltration capacity (Zhu et al., 2015; FAO, 2013). Thus, surface puddles and ditches develop and are stored as depression storage, and then overland flow is incepted (FAO, 2013; Ayoade, 1988). The soil infiltration capacity of the Dagi catchment depends on texture and structure, as well as on the anterior soil moisture composition (FAO, 2013). The initial capacity is the climax and as rainstorms prolong, it declines to arrive at an unfluctuating estimate called a final infiltration rate (figure 2.2) (FAO, 2013). This runoff generation progresses if the intensity of rainfall outpaces the real soil infiltration capacity and stops when the pace of rainfall lapses under the real pace of infiltration (FAO, 2013; Stone et al., 2008).

A big catchment with an even distribution of these rainfall characteristics relative to its location would receive large amounts of rainwater (figure 2.2). However, a small catchment like the Dagi can also receive large amounts of rainwater if rainfall is evenly distributed. The natural volumes of discharge in Dagi channels are a reflection of a direct relationship with its catchment area (492 km^2). The shape of the Dagi catchment can also influence the shape of the hydrograph (Thorndycraft et al., 2008). These factors collectively influence the recurrence interval of a flood of any given magnitude (Collins et al., 2012). This is because the shape of the catchment determines lag time and the time of rise among other hydrograph parameters (Ashworth and Lewin, 2012). Catchment relief and orientation in the Dagi can affect the amount and rainfall distribution, and the rate of surface runoff (ibid.). In areas where there are steep slopes (>20°), high elevation and geology with impermeable formations, excess water runs off quickly (ibid.). The time of hydrograph rise and lag time is reduced by higher relief while the peak discharge is increased (Thompson, 2008; Ashworth and Lewin, 2012). If rainfall is of high intensity and of longer duration, continuous runoff results in increased peak discharge that has the potential to inundate areas in floodplain in the catchment.

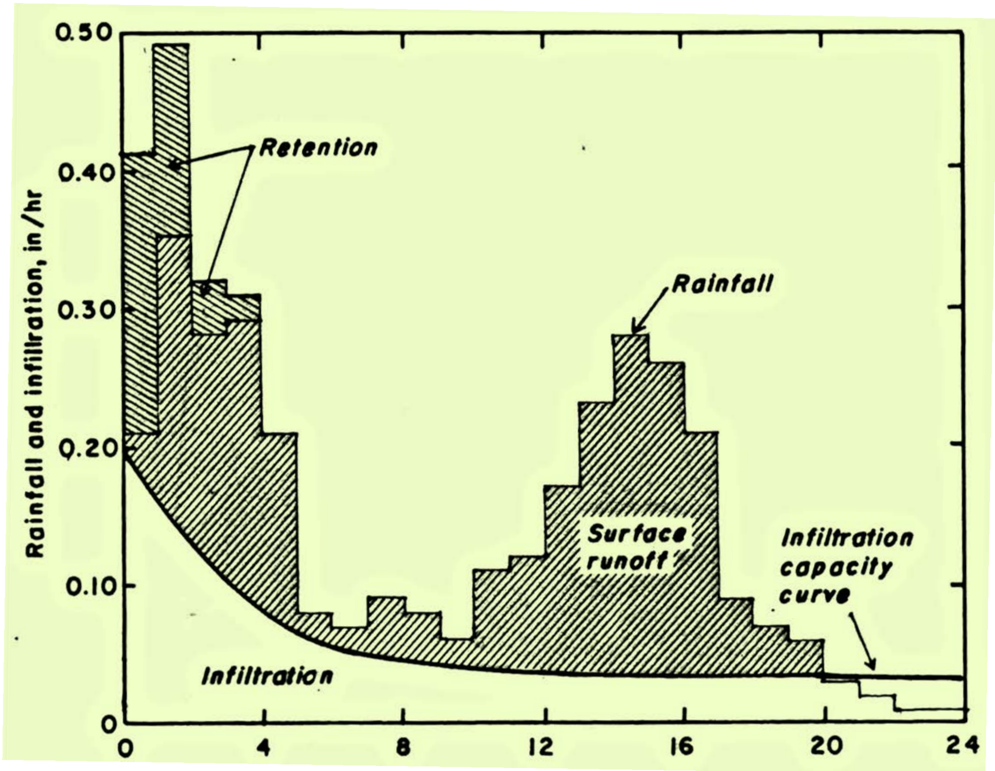

Figure 2.2: The association between rainfall, infiltration and runoff (Linsley et al., 1958).

The amount of runoff generated in the Dagi also depends on slope (0-90^0) and its altitude. Steeper slopes (>20°) at high altitude allow more overland flow into stream channels at high velocity and discharge because rainfall will have insufficient time to infiltrate. High soil moisture storage and infiltration capacity and transmissibility on slopes (15-20°) allows percolation and groundwater recharge and seepage to stream channels. In floodplains where the slopes (<5°) are gentle, rainwater generally accumulates and intensifies inundations.

Furthermore, there are several catchment-precise determinants of the occurrence and volume of runoff in the Dagi (FAO, 2013). Among others, infiltration capacity hinges on soil porosity type in the Dagi which determines the water storage capacity and affects the resistance of water to flow into deeper layers (ibid.). The leading infiltration capacities in the Dagi are noticed in loose, sandy soils at the same time as heavy clay or loamy soils have lesser infiltration capacities prevalent in the catchment (figure 2.3) (Murom et al., 2008; Linsley et al., 1958). Infiltration capacity also depends on the moisture content predominant in a soil at the outbreak of a rainstorm (Murom et al., 2008; Linsley et al., 1958). The antecedent high capacity contracts with duration (in the event rain does not cease) until it attains a fixed amount as the soil profile becomes saturated (figures 2.3) (Murom et al., 2008; Linsley et al., 1958).

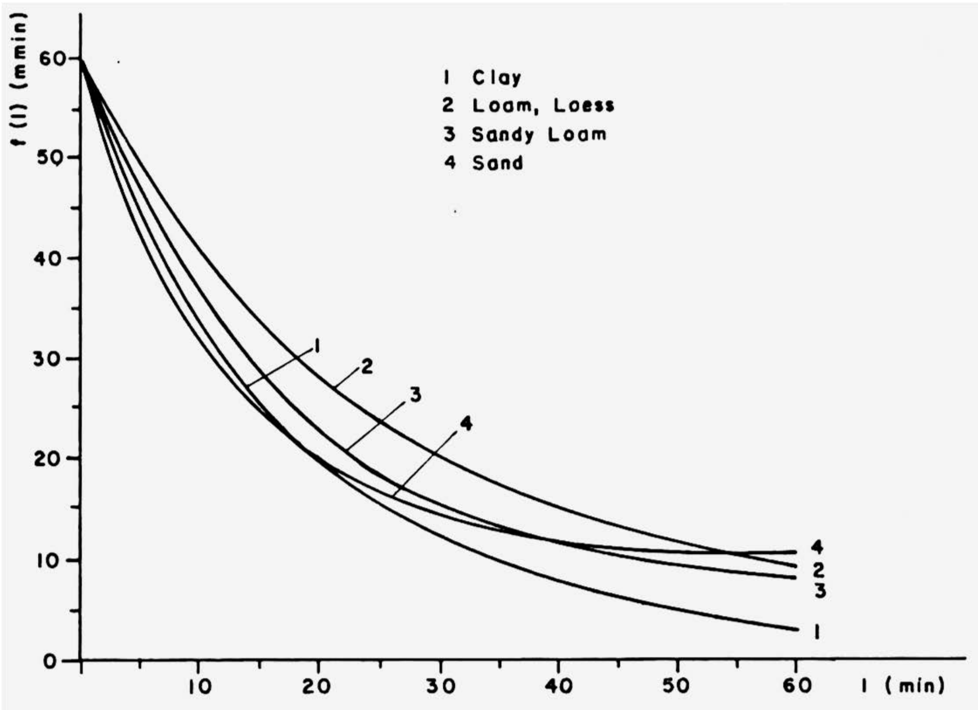

Figure 2.3: Infiltration capacity curves for soil types (Linsley et al., 1958).

The average raindrop sizes grow with rainstorm intensity (Ayoade, 1988). The kinetic energy of raindrops during high intensity rainstorm is considerable when hitting an exposed soil. As a result, this breaks down soil aggregates and disperses fine soil particles into soil pores (ibid.). Consequently, this clogs the pores, framing a light but tight and compressed layer at the exterior and reduces infiltration capacity (ibid.). This is referred to as capping, crusting and sealing (ibid.). When vegetation is removed where high rainfall intensities are frequent, substantial magnitude of overland runoff occurs (Karim et al., 2012; Hajji et al., 2013; Guo et al., 2014; Kotera et al., 2014). Soils sensitive to forming a cap are loess soils with about 20% clay (high clay or loam content) which have subordinate infiltration retention. The effect of capping is minor in coarse sandy soils (Karim et al., 2012).

2.2.3.2 Network characteristics

Network patterns have been widely studied as indicators of the hydrologic and erosional conditions in operation on hillslopes. These studies have typically focused on general network characteristics (Horton, 1945; Strahler, 1957; Shreve, 1974), river channel change (Gurnell, 1997; Winterbottom, 2000), network evolution (Willgoose et al., 1991; Howard, 1994) and the fractal dimensions of river networks (Wilson and Storm, 1993; Tarboton et al., 1998). The Dagi drainage network patterns dip to evolve alongside easily eroded rock types and structures and this gives no clear-cut restraint on flow direction (PNGRIS, 2007). The tributaries connect to bigger channels at critically inclined angles that range between 0 and 20^0. The flow direction is not usually controlled and this causes peak discharge to flow across channels during heavy rainfall. Because of high annual rainfall (>4000mm) in the Dagi catchment and with no structural control, homogeneous lithology and the shape and inclination of the surface ($3\text{-}20^0$) on which they form, the drainage network pattern is dendritic (Wilson and Storm, 1993, Ayoade, 1988; Strahler and Strahler 2001, p. 185).

The Dagi River is of the 4^{th} Stream Order[3] according to the Strahler Stream Order Classification System (Strahler, 1957: pp.913-920; Horton, 1952: p. 312). Based on this hierarchy, the Dagi catchment was divided into sub-catchments based on tributaries where all 1^{st}, 2^{nd}, 3^{rd} and 4^{th} orders were grouped to derive five sub-catchments. The Dagi is a small tropical catchment and its water storage is defined by its network compared with other catchments (e.g. the Sepik with much larger drainage network) with much large storage. With no hydrological data for the Dagi catchment, it can be assumed that the channel water storage to an extent depends on its slope ($0\text{-}20^0$), dendritic drainage pattern, and its estimated 70km channel length, with contribution from ground water in sub-catchments and from two upstream lakes. Straight channels (e.g. 800m) can vary due to a lack of geological control on flow direction. On steep slopes ($15\text{-}20^0$) it was observed that after floods, straight channels in the Dagi often change direction before the next bend. This does not happen in areas with low slope ($0\text{-}5^0$) characterised by pools and riffles, where storage is higher. Further towards the confluence, meandering channels are short and broad where storage can be high for this catchment.

[3] It is a method developed by Strahler, A.N. (1957) and Horton, R.E. (1952) and is used to define stream size using the hierarchy of tributaries.

2.2.3.3 Channel characteristics

Channel shape, slope (0-20^0) and roughness affect stream velocity and discharge and cause floods (Bhatt and Ahmed, 2014). A channel shape is the ratio between the length of wetted perimeter and cross-section of a river channel (Gupta, 2011). Dagi River width that defines its wetted perimeter varies from 250-350m at the mouth to as low as 130m further upstream (PNGRIS, 2007). A channel slope (0-20^0) is the difference between the upstream channel elevation and the downstream channel elevation (Gupta, 2011; Strahler, 2001). Compared with other parts of PNG, slopes along the Dagi floodplain are generally between 0-20^O with channel gradients ranging from 0.0027^0 at the river mouth to 0.0296^0 upstream (see table 2.1). Consequently, the extension of land clearing for oil palm development on to steep slopes (15-20^o) in the catchment affects the velocity and discharge, and increases subsidence (Cramb and Curry, 2012). The velocity of a river is the speed at which the water is travelling generally measured in metres per second (Strahler, 2001, p.134). River velocity is conversely linked to waterway roughness yet surges at a degree relative to the square root of the waterway slope (Krige and Pestre, 2013; Davidson et al., 2013; Duek, 2013). This interaction is not quantified in many oil-palm dominated landscapes. Along the Dagi River, velocity is influenced by channel shape and roughness which in turn impact the wetted perimeter, efficiency and its cross profile.

As channel shape, slope (0-20^0) and roughness all affect velocity and hence discharge, they are normally linked in hydrologic analysis by Manning's equation (Manning, 1891); $Q = AR^{2/3} S^{1/2}/n$. Q[4] is discharge and is the amount of water flowing through a particular point of the river and is measured in cubic metres per second (m^3/s), *A* is the channel cross-sectional area in m^2 derived by: b x d; where b is the channel bottom width in metres, and d is the channel flow depth in metres (Gupta, 2011; Manning, 1891). The hydraulic radius is denoted by *R*, which is the area of flow in the stream channel divided by the wetted perimeter (Gupta, 2011; Manning, 1891). It is the part of the channel that meets water and slows down water velocity by friction. It is derived when the flow area is divided by the wetted perimeter. The wetted perimeter is calculated using this formula: $b + 2d$ (Gupta, 2011; Manning, 1891). *S* is the slope (0-20^0) of the channel, which is calculated by dividing the valley slope (0-20^0) by sinuosity. Valley slope (0-20^0) is derived by multiplying the channel slope (0-90^0) with sinuosity, which is the ratio of valley slope (0-20^0) to channel slope (0-20^0) (Gupta, 2011; Manning,

[4] "Discharge varies directly with cross-sectional area of the channel and the average stream velocity at bankfull flow" (Davidson et al., 2013: p.27; Diez-Herrero et al., 2013: p.38). "The shape and size of the cross-sectional area of the channel can also be expected to be indicative of the amount of stream discharge" (Davidson et al., 2013: p.28; Montgomery, 2013: p.85).

1891). Manning's *n* is referred to as the roughness coefficient[5] of the channel bottom and sides. Roughness coefficients are derived from frictional values assigned to surfaces such as vegetation type and characteristics, type of land surface and the general land use (Gupta, 2011; Manning, 1891).

Table 2.1: Geomorphic characteristics of cross-sections upstream-downstream of Dagi catchment.

Sub-catchment/Reach/ Sub-zone	**Elev. (m)**	**Spatial Ref.**	**Stream type***	**Roughness Coefficient (n)****	**Slope**	**Description*****
Dagi R/ Upstream/ Mountain torrent	65	150.15059, 5.66564	B2	0.065	0.0296	Moderately entrenched, moderate gradient, stable banks & profile, riffle dominated, occasional pools, some boulders, many gravels & cobbles.
Ru Ck/Ru/ Mountain stream	47	150.20145, 5.64979	B3	0.055	0.0176	Moderately entrenched, moderate gradient, stable banks & profile, riffle dominated, occasional pools, some boulders, many gravels & cobbles.

[5] Roughness coefficient is a term used to express the resistance to water flow by a stream surface such as boulders and gravels, land use or vegetation (Gupta, 2011; Rutherford et al., 2007). Its selection for use in computing flow conditions can affect results. Manning's n values are either taken from tables, field calculations or from land use and cover classifications where relevant values are looked up in Manning's table (Gupta, 2011; Rutherford et al., 2007).

Dagi R/ Middle/ Middle lowlands	36	150.19621, 5.63042	C6	0.029	0.0105	Low gradient, meandering alluvial, riffle-pool, channels with point bar, broad well defined floodplains, broad valley with terraces, alluvial soils, well defined meanders, riffle/pool bed morphology.
Dagi R/ Middle/ Middle lowlands	30	150.21382, 5.60754	C6	0.029	0.0100	Low gradient, meandering alluvial, riffle-pool, channels with point bar, broad well defined floodplains, broad valley with terraces, alluvial soils, well defined meanders, riffle/pool bed morphology.
Lamegi R/ Lamegi/ Middle lowlands	28	150.22534, 5.6022	E5	0.031	0.0110	Low gradient, meandering alluvial, riffle-pool, channels with point bar, broad well defined floodplains, broad valley with terraces, alluvial

						soils, well defined meanders, riffle/pool bed morphology.
Dagi R/ Down-Stream/ Lowlands	14	150.23267, 5.57963	C6	0.029	0.0058	Low gradient, meandering alluvial, riffle-pool, channels with point bar, broad well defined floodplains, broad valley with terraces, alluvial soils, well defined meanders, riffle/pool bed morphology.
Dagi R/ Down-Stream/ Lowlands	5	150.21904, 5.55184	C6	0.029	0.0027	Low gradient, meandering alluvial, riffle-pool, channels with point bar, broad well defined floodplains, broad valley with terraces, alluvial soils, well defined meanders, riffle/pool bed morphology.

** Based on Rosgen's (1994) classification of river/stream type from headwaters to lowlands with sub-types being assigned numbers corresponding to the observed median particle diameters of channel materials: A – Headwater, B – intermediate, C & E – meandering, D – braided, F – entrenched, G – gully., 1 – bedrock, 2 – boulder, 3 – cobble, 4 – gravel, 5 –sand, 6 – silt/clay.** Roughness Coefficient: Bankfull stage roughness coefficient based on stream type for bankfull conditions only as adopted from Hicks and Mason (1991). ***These descriptions are for natural channels prior to oil palm development in Dagi catchment.*

2.3 Surface flow and flood risk modelling approaches

2.3.1 Definition and categories of hydrological models

The term "*model*" can be used as a noun to mean "*representation*", as an adjective to mean "*degree of perfection*" or as a verb to mean "*demonstrate*" or "*show what something is like*" *(*Atreya, 2013, p.8; Ayoade, 1988, pp.169-174). Models are primarily used in hydrology to simplify, generalise and conceptualise the various representation of the complexities involved in hydrological processes (figure 2.4) (Ayoade, 1988). There are three main types of hydrological models. They are physical (representative or experimental), analogue (electrical or mechanical), and digital (deterministic, parametric and stochastic) (Ayoade, 1988; Balica et al., 2013). The most relevant hydrological model widely used today is the digital model. Digital models are commonly used because of improvements in computer technology and developments in compatible modelling programs.

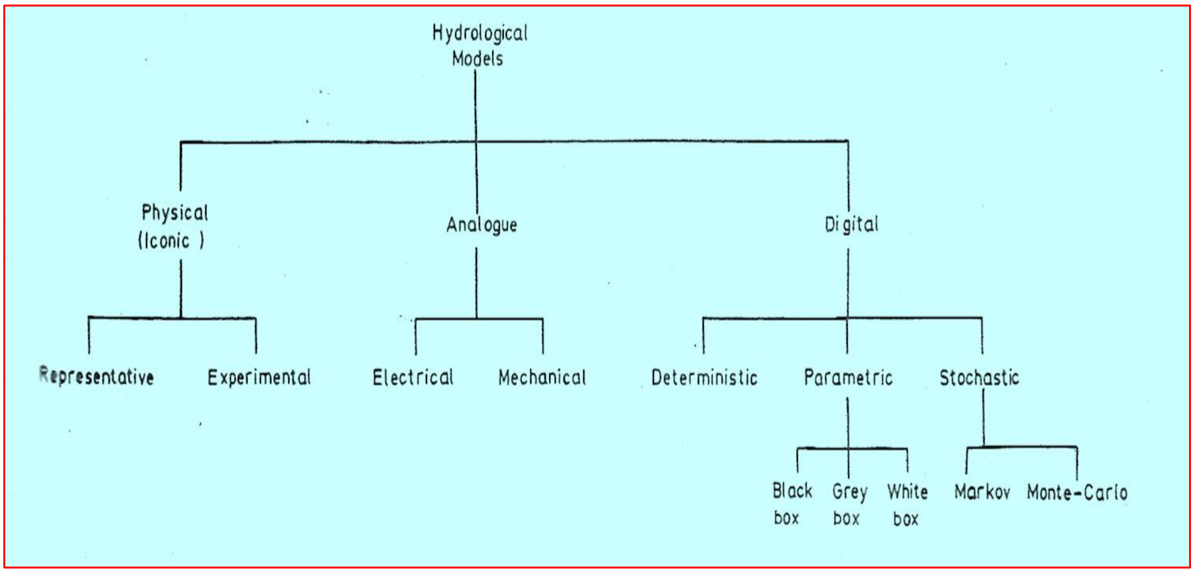

Figure 2.4: Typology of hydrological models (Ayoade, 1988).

2.3.2 Surface water flow modelling approaches

Recent advances in hydrological representations tend to follow a universal methodology to grasp the behaviour of hydrological processes to craft enhanced predictions for water related hazards (Bora and Bera, 2004; Gupta, 2011; Balica et al., 2013). While the objectives of hydrological representation can cover the complete hydrological sequence and exactly how it influences existence on this planet, only surface discharge is reviewed in reference to flood genesis (Gupta, 2011). Hydrologic system processes are complicated beyond many environmental spaces, characterised by stable and exceedingly alterable factors. Modelling empowers anyone to elucidate tangible statistics and enables one to ask a broad question such as: What effect does a catchment, network and channel characteristic(s) have on flood characteristics and behaviour? Irrespective of the realities being represented, the principle always remains the same. Thus, surface water modelling can follow one of the two methods:

(1) Engineer the representation derived out of the physical laws governing the system by describing the relationship amid uncertainty, wherever vicissitudes in the above-mentioned variables connote vagaries in the orderly process. The precision of the representation is then verified by assessing its projections with the surveyed behaviour of the real structure (ibid.), or
(2) Approach the problem using mathematical equations by deducing the systemic actions from the noticed orderliness in it (ibid.).

2.3.3 Rainfall-runoff modelling

For overland flows leading to floods, only rainfall and drainage are represented (ibid.). To estimate discharge, simple lumped-parameter models are used or the runoff hydrograph. The various drainage representations differ in approaches used to propagate runoff and to convey it throughout a catchment. Furthermore, they deviate in the limiting choices on hand, data manipulation and manipulator network, but these disagreements have virtually no consequence on exactly how a representation calculates drainage (ibid.). According to Gupta (2011: p.12), the various models compute runoff by following any one of:

(1) “SCS curve number method; or
(2) Horton’s equation; or
(3) continuous soil moisture balance”.

The SCS curve number method is extensively utilised because it is simple to use, it delineates the catchment storage area, and is measured for a catchment or a sub-catchment primarily from soil types, vegetation canopy and land-use features (Gupta, 2011; SCS, 1986). The equation[6] given by Horton (1939) ascertains that the exponential decrease in soil infiltration rate is an outcome of

[6] fp = fc + (fo – fc) exp (-kt) where; fp is the “infiltration capacity in inches per hour, at time t in hours from the beginning of the rain” (Beven, 2004: p.3349), “fo is the initial infiltration capacity, fc is the minimum constant infiltration capacity and k is a constant” (Begum et al., 2007: p.168).

duration accounted from the initiation of a storm. A few representations take into consideration soil-moisture storage and infiltration by applying either the Green-Ampt or Phillips equation, or a variation thereof (Gupta, 2011). A few prominent features normally used in rainfall-runoff representations are shown in table 2.2.

After estimating the excess rainfall, surface runoff is computed for overland and channel flow using either: (1) unit hydrograph, (2) SCS unit hydrograph, or (3) by solving equations of flow (Gupta, 2011). A hydrography is derived using the unit hydrograph procedure with an assumption that a precise outline portrays land use, soil and geometric feature of a catchment. A unit hydrograph can be derived from rainfall-runoff data using several techniques. One is an estimation of the non-linear runoff distribution by the SCS unit hydrograph that is assumed to be constant. There are also existing methods to solve flow equations. For channel routing, the Muskingum method is used by determining block-shaped channel storage relative to inflow and outflow of volume (Gupta, 2011). A few representations can execute surface flow and channel routing by kinematic waves, diffusive waves or by answering the flow continuity equation (Gupta, 2011; Miller, 1984). A two-dimensional kinematic wave is a cascade method that approximates routing overland flow (Julian et al., 1995). Flood flow modelling focuses on peak discharge (maximum flow) for a particular event with specific exceedance probability. An exceedance probability is chosen by the model designer based on perceived risk to livelihood assets if the magnitude of the event is exceeded (Gupta, 2011).

Given these points, the likely modelling option applicable in this study would be through a combination of SOBEK 1D2D (Deltares, 2015), HEC-GeoRAS (USACE, 2009), HEC-HMS (USACE, 2013) and HEC-RAS (USACE, 2010) modelling software. Each modelling program can perform certain tasks and create results that can be used as an input for another. Based on the available data for the Dagi catchment, the Green and Ampt Loss, SCS unit hydrograph transform, recession base flow methods, and Muskingum Routing Method are the most relevant options to compute upstream and downstream discharges at catchment and sub-catchment scale. Furthermore, the HEC-GeoRAS and HEC-RAS modelling software can be used to create cross-sections and longitudinal profiles and velocity distributions for each discharge measuring points. They can also generate stream hydraulics data (e.g. water surface elevation and wetted perimeter) using a combined Steady Flow (subcritical) and Unsteady Flows (supercritical).

Table 2.2: Some features normally exploited in rainfall-runoff model (Gupta, 2011).

Method	Simulation Type	Runoff Generation	Overland Flow	Channel Flow	Watershed Representation
CASC2D[1]	Event	Soil moisture accounting	Cascade	Diffusive wave	Distributed
CUHP[2]	Event	Horton	Unit hydrograph	Unit hydrograph	Lumped
CUHP/SWMM[3]	Event	Horton	Unit hydrograph	Unit hydrograph	Distributed
DR3M[4]		Soil moisture accounting	Kinematic wave	Kinematic wave	Distributed
HEC-1[5]	Event	SCS Curve no.	Unit hydrograph	Muskingum	Distributed
HSPF[6]	Continuous	Soil moisture accounting	Kinematic wave	Kinematic wave	Distributed
PSRM[7]	Quasi-continuous	Soil moisture accounting and Soil moisture	Cascade	Kinematic wave	Distributed
SWMM[8]	Event	Horton	Kinematic wave	Kinematic wave	Distributed
TR-20[9]	Event	SCS Curve no.	SCS Unit hydrograph		Lumped

[1]CASC2D Cascade two-dimensional (Julien and Saghafian, 1991)

[2]CUHP Colorado Unit Hydrograph Procedure (UDPCD, 1984)

[3]CUHP/SWMM Sub-basin application of CUHP linked to SWMM.

[4]DR3M Distributed Rainfall Routing Runoff Model (Alley and Smith, 1982)

[5]HEC-1 Hydrologic Engineering Centre (USACE, HEC-1, 1990)

[6]HSPF Hydrologic Simulation Program Fortran (Bicknell et al., 1993)

[7]PSRM Perm State Runoff Model (Aron et al., 1996)

[8]SWMM Storm Water Management Model (Hubert and Dickson, 1988)

[9]TR20 Technical Release No. 20 (USDA - SCS, 1983)

NB: A few models possess multiple options to generate runoff and route flow.

2.3.4 Inundation modelling

Inundation modelling approaches are separated into methods and applications characterised by their different dimensionalities (table 2.3). The 1D, 1D+, 2D- and 2D methods are of great interest because most modelling techniques include them to assist in the execution of flood risk-management strategies (Asselman et al., 2009. p.3-6). The 2D methods include hydrodynamic models which were established using two-dimensional shallow water equations. Asselman et al., (2009, p.7) stated that, "the 2D shallow water equations (2D St-Venant equations) can be derived by integrating the Reynolds-averaged Navier-Stokes equations over the flow depth". In this unification procedure, there is an assumption for the distribution of hydrostatic pressure (Hervouet, 2007). Asselman et al., (2009: p.3-10) further outlined "a number of numerical methods (e.g. finite difference, element or volume) that provides solution to these equations and different numerical grids can be used (e.g. Cartesian or boundary fitted, structured or unstructured). However, he argues that all have advantages and disadvantages in the context of floodplain modelling."

One-dimensional models are based on some form of the one-dimensional St-Venant equations[7] (de Saint-Venant, 1871) (see equations 2.1, 2.2 and 2.3) obtained by combining the Navier-Stokes equations[8] (see figure 2.5) above the flow cross-sectional surface. The inference used in the extraction of the Saint-Venant equations restrict their use to pointing the alignment of water flow direction to the river channel centre line (Hervouet, 2007; Gerbeau and Perthame, 2000: p.365). The Saint-Venant equations are limited to 1D flows revealing only hydrostatic pressure distribution, inclination of small beds, and thickness of steady water (Asselman et al., 2009. p.4; Chanson, 2004: pp.307). Hence, resistance to flow are believed to be constant and stable for the identical depth and velocity (Asselman et al., 2009. p.4; Chanson, 2004: p.309). The use of this equation is only confined and restricted to 1D flow channel. It disregards sediment transport, 2D and 3D unsteady supercritical flows in floodplains characterised by discontinuities (Hervouet, 2007; Chanson, 2004: pp.305-313).

[7] "1D Saint Venant equations were developed by Adhemer Jean Claude Barre Saint-Venant and are used to model flows in open channel and surface runoff" (Sleigh and Goodwill, 2000; p.48). "It is a simplified equation derived from the Navier-Stokes equations where the horizontal length scale is much greater than the vertical scale" (ibid, p.53).

[8] "Navier-Stokes equations were named after Claude-Lousis Navier and George Gabriel Stokes and are used to describe the motion of fluid's resistance due to stress based on their viscosity. Stress in fluid is assumed to be proportional to the velocity gradient. For this reason, it is used to model water and their dynamics" (Hervouet, 2007; Girault and Raviart, 1986; p. 317).

ITC (2010: p.14) stated that "the full Saint-Venant equations based on finite difference staggered grid solution can be described by three equations (2.1, 2.2 and 2.3): the continuity equation, and the momentum equation for the *x* and *y* directions.

Equation 2.1: continuity equation,

$$\frac{\partial(uh)}{\partial x} + \frac{\partial(vh)}{\partial y} + \frac{\partial h}{\partial t} = 0$$

Equation 2.2: momentum equation in *x direction,*

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + g\frac{\partial h}{\partial x} + \frac{n^2 u\sqrt{u^2+v^2}}{h^{\frac{4}{3}}} = 0$$

Equation 2.3: momentum equation in *y direction,*

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + g\frac{\partial h}{\partial y} + \frac{n^2 v\sqrt{u^2+v^2}}{h^{\frac{4}{3}}} = 0$$

Where *y* = depth of the channel from the reference level

x = longitudinal distance along the channel

t = time

h = water head elevation from reference level

u = flow velocities in x-direction

v = flow velocities in y-direction

n = Manning's coefficients (dimensionless)"

The Navier-Stokes Equation is given and interpreted as:

$$\rho[\frac{\partial V}{\partial t} + (V.\nabla)V] = -\nabla P + \rho g + \mu\nabla^2 V$$

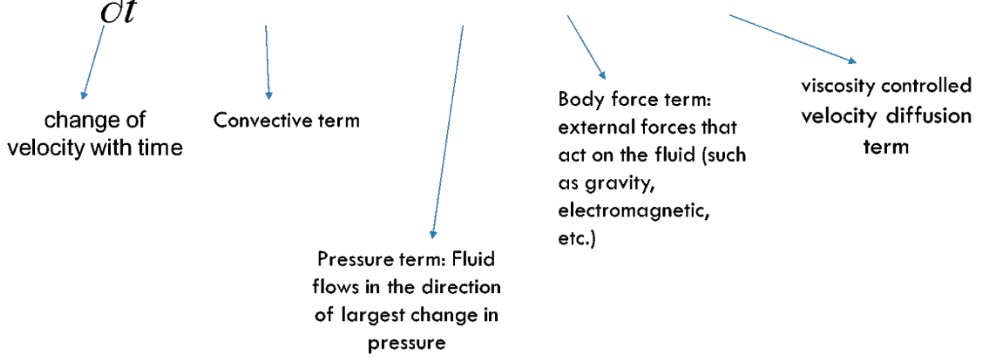

Figure 2.5: The Navier-Stokes equation (Hervouet, 2007; Girault and Raviart, 1986; p. 317)

Where; V is velocity, g is gravity and are vectors and P is pressure and is a scalar (Galdi, 2011, p.26). *Diagram and explanation courtesy of Dr Anand Mohan Verma.*

Table 2.3: Classification of inundation models (Pender, 2006)

Method	Description	Application	Typical computation times	Outputs	Example Models
1D	Solution of the one-dimensional St. Venant equations.	Design scale modelling which can be of the order of 10s to 100s of km depending on catchment size.	Minutes	Water depth, cross-section averaged velocity and discharge at each cross-section. Inundation extent if floodplains are part of 1D model, or through horizontal projection of water level.	Mike 11 HEC-RAS ISIS InfoWorks RS
1D+	1D plus a storage cell approach to the simulation of floodplain flow.	Design scale modelling which can be of the order of 10s to 100s of km depending on catchment size, also has the potential for broad scale application if used with sparse cross-section data.	Minutes	As for 1D models, plus water levels and inundation extent in floodplain storage cells.	Mike 11 HEC-RAS ISIS InfoWorks RS
2D-	2D minus the law of conservation of momentum for the floodplain flow.	Broad scale modelling and application where inertial effects are not important.	Hours	Inundation extent Water depths	LISFLOOD-FP JFLOW
2D	Solution of the two-dimensional shallow water equations.	Design scale modelling of the order of 10s of km. May have the potential for use in broad scale modelling if applied with very coarse grids.	Hours or days	Inundation extent Water depths Depth-averaged velocities	TUFLOW Mike 21 TELEMAC SOBEK InfoWorks-2D

2D+	2D plus a solution for vertical velocities using continuity only.	Predominantly coastal modelling applications where 3D velocity profiles are important. Has also been applied to reach scale river modelling problems in research projects.	Days	Inundation extent Water depths 3D velocities	TELEMAC 3D
3D	Solution of the three-dimensional Reynold's averaged Navier-Stokes equations.	Local predictions of three-dimensional velocity fields in main channels and floodplains.	Days	Inundation extent Water depths 3D velocities	CFX

The use of these models has been extended to model river flow in channels with floodplains (compound channels) (Chanson, 2004: p.309). In other words, flow in floodplains has become a component of one-dimensional channel flow and integrated with the St-Venant equations to simulate inundation (2D flows). Two advantages of this technique are: 1) it is assumed that flow in floodplain is following one direction parallel to the main channel, which is not true, and 2) the average velocity of cross-sections estimated by the St-Venant is meaningless when velocity varies across the floodplain. Recent advances in parameterisation and the conveyance estimation system have improved this method (e.g. Gupta, 2011; Chanson, 2004: p.313).

2.3.5 Choice and links between 1D and 2D models

1D and 2D models are applicable in rural floodplain modelling such as the Dagi catchment, however, they cannot be applied to flows in urban areas where flow is not uniform because of variations across built surfaces. 1D models are ideal for narrow floodplains with small widths not three times bigger than three times the river channel width. The Dagi floodplain has a narrow floodplain upstream in its tributaries and it broadens downstream with general variations in velocity and water levels and local changes in flow direction (Sullivan, 1993: pp.336; Loffler, 1977: p.94; Andrews, 1957: pp.15-26). Taking into consideration these characteristics, the combined 1D/2D modelling approach is appropriate for modelling flood characteristics and behaviour and its inundation extent in relation to hazards and risk assessments in the Dagi catchment.

Furthermore, 1D/2D- or 2D is relevant in river flood applications while 2D is the ideal choice in urban and coastal areas (Asselman et al., 2009). There are two types of 2D river floodplain modelling: 1. as a combined 1D/2D, modelled in 2D and 2. as a channel and floodplain flow combined and modelled together in a 2D grid. 1D/2D modelling is the available option for inundation modelling in the Dagi catchment because localised differences in velocity and water depths can be characterised, as well as changes in flow directions (Asselman et al., 2009; Syme, 2009). It allows floodplain conveyance to be better represented, however, momentum transfer and exchange processes between the river channel and floodplain are crudely modelled using 1D/2D (Syme, 2001; Evans, 2007; Syme et al., 2009; Fedak, 2012; Asselman et al., 2009). There is more computational cost and run time for 2D models (Asselman et al., 2009; Syme et al., 2009; Fedak, 2012).

There are many ways in which 1D and 2D modelling methods can be combined. Software programs such as SOBEK and TUFLOW can link 1D river model to 2D floodplain grids. The most commonly used approach is to connect a 1D river channel with a 2D floodplain through a lateral link. Thus, flows between them are represented by broad crested weir equations or depth discharge curves using differences in water level (Liang et al., 2007b; Evans et al., 2007; DHI, 2007a; WBM-BMT, 2008; Liang, 2010; Li et al., 2010; Balica et al., 2013; Jones, 2012; Asselman et al., 2009). This study will adopt this approach to create a 2D Dagi floodplain computational mesh and then link that to the 1D Dagi channel. However, this does not model the momentum exchange process between the river channel and the floodplain boundary because it depends on 3D river flow patterns which are not yet solved in the 1D river model. Improvements to this model characterisation are still progressing and this was reported in Liang et al. (2007b).

2.4 Agricultural changes and their impacts on flooding in developing countries

Studies conducted in the tropics on the hydrological consequences of deforestation or the replacement of forest by planted crops found that forest cover is desirable in areas of high rainfall and rugged topography (Nelson et al., 2006; Basiron, 2007; Germer, et al., 2008; Murom et al., 2008, RSPO, 2014). Forest cover protects the soil against raindrop impact and encourages infiltration so that soil erosion is reduced, while stream flow is regulated and dry period flows may be slightly increased (Ayoade, 1988; Rutherfurd et al., 2007; Gupta, 2011). Land use alteration of land cover influences the interception process to a greater extent, and aids in the development of distinctive flood characteristics and their behaviours in catchments (Rutherfurd et al., 2007; Fruchtman et al., 2012; Lopez-Vicente et al., 2012; Erskine et al., 2013; Montgomery, 2013) and the spatial extent of inundation (Li et al., 2012). Removal of tree cover also leads to the exclusion of interception loss, stem flow, and through fall components of the interception process and enables free fall of rainwater on exposed surfaces that becomes overland flow into waterways (Rutherfurd et al., 2007; Zhang et al., 2012; Deshmukh et al., 2013).

The hydrological characteristics of forested catchments and the consequences of replacing forest by oil palm are complex. This is because forests exist in a wide variety of environments (hydrological situations, slopes, soils and human pressures). Conversely, agricultural crops come in many sizes, foliage, leaf density and alignment. How much rain they intercept and transpire, and how much soil moisture is taken from the soil varies and it is complex to quantify water loss and availability (Rutherfurd et al., 2007). Different crops demand and transpire water at varying amounts depending on their maturity level. The benefits of forest cover include reduction in storm runoff and erosion, maintenance of soil fertility and equable climate (Rutherfurd et al., 2007; Nik, 1988; Sayer et al., 2012). The opposite happens when these processes are altered by the removal of natural vegetation and its replacement by non-native vegetation with less foliage. Along waterways in many agricultural landscapes (e.g. oil palm), riparian vegetation has been altered or cleared to make way for plantations, subsistence gardening and settlements (Rutherfurd et al., 2007; Basiron, 2007; Webb et al., 2010).

Forest cover in the Dagi catchment protects the soil against raindrop impact, encourages infiltration and regulates stream flow. However, native vegetation cover has been removed over the years (1968-present) by >80% and replaced by predominantly oil palm trees with less foliage. As of 2015, new tracts of native forests upstream of the Dagi including its tributaries are being cleared for oil palm cultivation. There are no data for the Dagi catchment to show the effects of vegetation removal with oil palm cultivation. Usually, oil palm is planted in stages of growth in the Dagi. This means younger trees have little foliage and canopy and the leaves are aligned at about 45^0 with small interception allowing for more stem flow and through fall in support of overland flow. In addition, bare ground in newly cleared forest areas upstream allows for raindrop impacts that seal off the soil pores hence lowering the infiltration rate. Consequently, more rainwater falls directly on the ground, or reaches field capacity quickly, and increases overland flow into the stream channels. In addition, growth stages of oil palm demand and transpire water at varying amounts depending on their maturity level. As can be expected, small transpiration losses come from areas under young palms, implying more water availability for infiltration and overland flow into stream channels. Generally, this contributes to the problem of floods in the catchment.

In addition, the Dagi catchment has an annual population growth rate of 3.92%, which is high by PNG standards (PNG National Statistical Office-NSO, 2013). This increase had been due to in-migration from other parts of PNG to develop oil palm and settler blocks and due to original settlers' children re-marrying and developing new livelihood strategies to seek out new livelihood in pristine forest environments. Since 1968 the catchment has been subjected to various types of land use dominated by oil palm cultivation. As a result, >80% of the native vegetation has been replaced with bare and levelled land surfaces associated with increased oil palm cultivation and subsistence gardening in riparian zones upstream and downstream of the catchment. Nik (1988) and Rutherfurd et al. (2007) postulated that an area of land with little vegetative cover can generate more runoff and flooding than an area with a good vegetation cover. In fact, the 2010 NDC report (from WNB NDC Office) for the Dagi catchment identified flooding as the major hazard affecting assets and livelihoods over the past 20 years (NDC, 2010). Also, the removal of riparian vegetation over the years for settlement, subsistence gardening, gravel extraction and extension of oil palm plots has completely removed its function as a flood protector.

Riparian vegetation plays important roles in flood protection as reported by Rutherfurd et al. (2007). Firstly, riparian plants influence water movement by physically contacting it. Likewise, plants thriving in dissimilar segments of the transection interplay with dissimilar flows. For example, immersed macrophytes and woody pieces in the channel bed interact with all flows. From stream banks, plants are adapted to little inundation. Here we can see a transition of plants from hydrophytes to grass to bushes and trees at the stream bank. Beyond stream banks, plants interrelate only with annual floods. In the 1980s and early 1990s I observed sufficient riparian vegetation beside the river and streams. The stream shape and size were in their natural form. I re-visited the catchment in 2007 and noticed significant morphological changes to the cross-sections of most reaches of the Dagi channels because of a large decline in primary vegetative cover. Rutherfurd et al. (2007) identified three ways a stream can be effected through the removal of riparian vegetation: (i) by disturbing the shape and size of the stream channel, (ii) by shifting the amount of water reaching the stream channel, and (iii) by varying the resistance to flow. When plants (including large woody pieces) have been ousted from stream channels, there are several instances of extensive vicissitudes in channel configuration (ibid.).

Consequently, in certain areas of the Dagi catchment where most riparian vegetation has been removed, there was little resistance and thus more water flowed directly into stream channels (ibid.). Even flows in channels flow freely with little or no resistance from riparian vegetation. The stream shape has broadened in most channels formerly seen as v-shaped and at the same time channel sizes have expanded. Similar changes have been reported in northern Australia by Montgomery and Piegay (2003) and Rutherfurd et al. (2007). Obviously, the clearance of riparian vegetation in the Dagi has re-defined the natural bankfull stage through many channel incisions. This has resulted in bed widening and extension of the drainage network by gullying in most parts of the catchment. Channel storage capacity has decreased as sediments accumulated and large discharge flow easily across most banks. There used to be large tree trunks in most stream channels of the Dagi but today they are absent.

Because of that, I observed several changes in the channel form of the Dagi catchment in 2007. Firstly, water flowed freely and fast downstream due to the absence of steps in the longitudinal profile and the shape seemed like those reported by Keller and Swanson (1979), Harmon et al., (1987), Marston (1982), Webb and Erskine (2003), and Rutherfurd et al. (2007). Secondly, sediment stockpile in watercourse and scour had dwindled and similar instances were reported in Harmon et al. (1987), Webb and Erskine (2003) and Rutherfurd et al. (2007). Thirdly, evolution of bars and benches has been underpinned as outlined in Malanson and Butler (1990), Webb and Erskine (2001) and Rutherfurd et al. (2007). Fourthly, bedload transport is not regulated similar to the findings of Beschta (1979), Fetherston et al. (1995) and Rutherfurd et al. (2007). Fifth, I noted the absence of localised scour similar to those reported in Abbe and Montgomery (1996) and Marsh et al. (2001) and Rutherfurd et al. (2007). Sixth, there was a decline in pools and riffles as outlined in Buffington et al. (2002), Marsh et al. (1999), Robison and Beschta (1990), Webb and Erskine (2003) and Rutherfurd et al. (2007). Finally, there were reduced overbank settlement of fine sediments (Gurnell and Gregory, 1981; Rutherfurd et al., 2007) along the Dagi floodplains.

Prior to oil palm development in Dagi catchment, flood velocity and depth were controlled by natural vegetation in this manner: 1. they occupied space directly in channel cross-sections and reduced capacity, 2. through vibration they used up energy in the flow, and 3. they reduced velocity by blocking the flow (Rutherfurd et al., 2007). Vegetation provides four scales of hydraulic effect: 1. from a single plant and a group of small plants (local backwater effect), then 2. from many plant communities at a given cross-section (combined backwater effects), then 3. from many plants in many cross-sections at a given reach (combined backwater effects), and finally result in 4. reducing the flood wave power as it continues to traverse the complete watershed (figure 2.6) (ibid.).

In addition, the removal of riparian vegetation upstream in the Dagi catchment has not allowed for enough blockage of flow and thus velocity has generally increased downstream. Unlike before, water is readily available for runoff and flows in the Dagi are unrestricted across most stream cross-sections.

An obvious feature of the landforms at the lower reaches of the Dagi catchment is the presence of peatlands. Unsuccessful attempts to drain peatlands were made in the lower Dagi by planting oil palm, so that water uptake by the palms would help drain it.

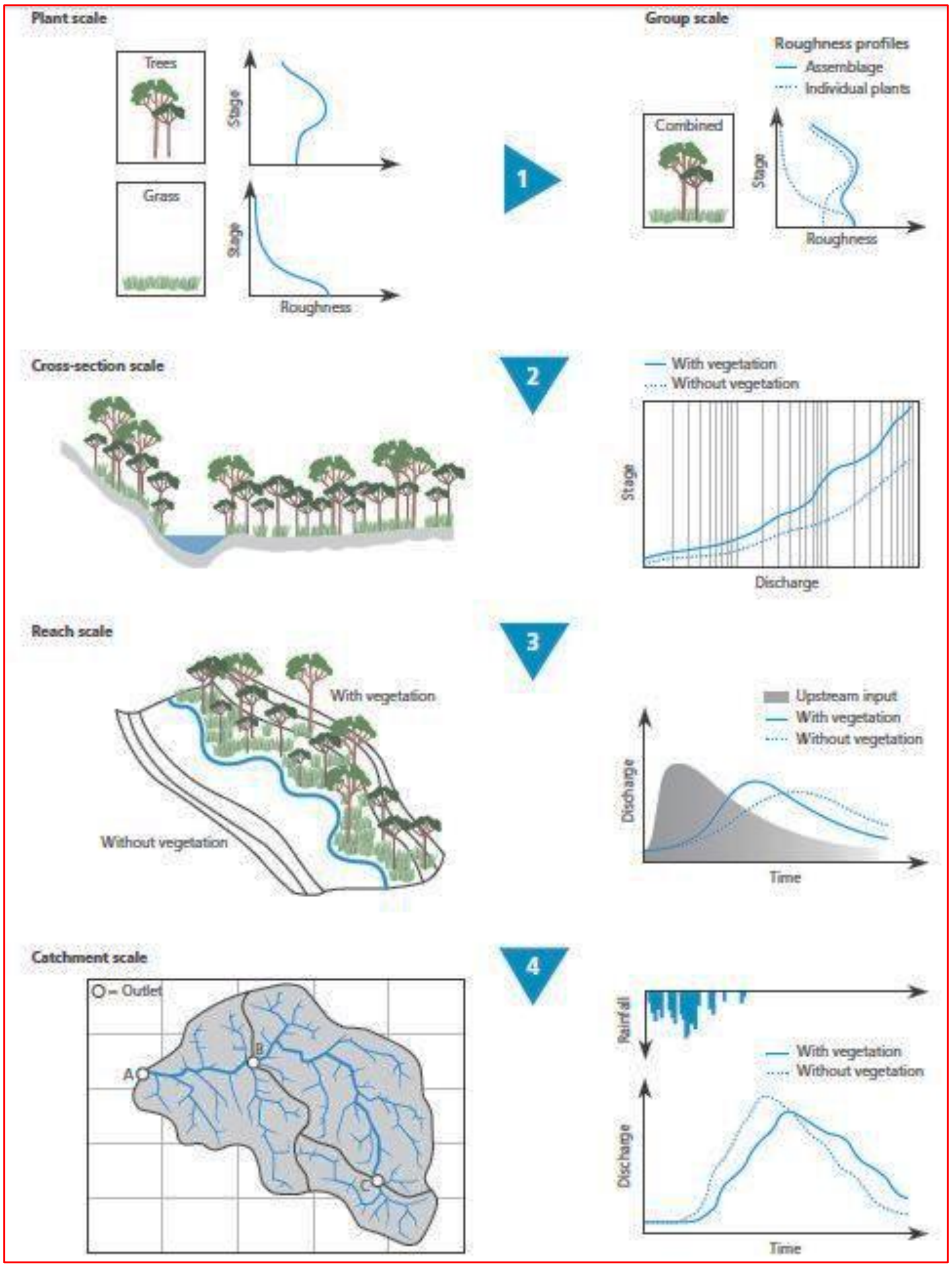

Figure 2.6: Theoretical illustration of the consequence of riparian vegetation on discharge at the plant, cross-section, reach and catchment scale in a tropical area, Australia (Rutherfurd et al., 2007, p.71).

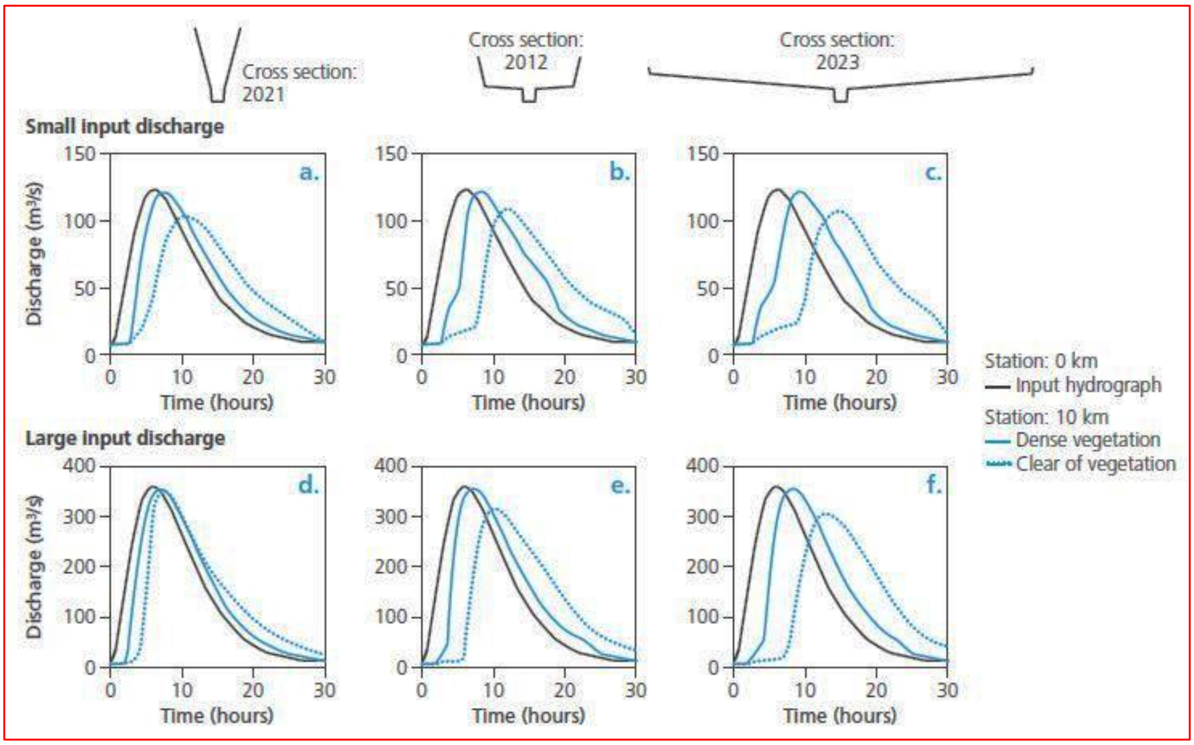

Figure 2.7: Replicated waves displaying the hydrographs for each cross-section with and without plants in a tropical area of Australia (Rutherfurd et al., 2007, p.78).

Altogether, the association among the determinants influencing water flowing downslope in the Dagi can be exemplified by Manning's equation (Manning, 1891). Manning (1891) stipulated that velocity in a channel is relative to the channel slope, channel bottom roughness, channel shape and flow depth. Rutherfurd et al. (2007, p.73) confirmed that the volume of water that can go past a certain cross-section hinges on reach slope, channel area and channel flow resistance. These variables are expressed in Manning's equation; $Q = AR^{2/3} S^{1/2}/n$ (Manning, 1891). The explanations of each variable used in this equation were detailed earlier. Naturally vegetated watercourses usually have greater roughness than similar channels (size and shape) with altered vegetation (ibid.). Despite using an unspecific roughness estimate of 0.05 for vegetated waterways, it was reported that its effectiveness differed with slope, depth and discharge (Gupta, 2011; Rutherfurd et al., 2007; Wilcox and Wohl, 2006; Abernethy and Rutherford, 1998; Simons and Richardson, 1962; Manning, 1891).

Abernethy and Rutherford (1998) and Rutherfurd et al. (2007) suggested the normal outcome was for the roughness to lessen as the stream bed became submerged, then the roughness reached a peak as grass and canopies traversed the flow. However, if stream slope is small (e.g. 0-5^{o}), the roughness effect of vegetation will be large. Consequently, when riparian vegetation is removed from streams, these processes are altered or removed. Water becomes readily available for runoff and flow becomes unrestricted across the stream cross-sections (e.g. figures 2.6 and 2.7). In times of heavy rainfall, this exacerbates the flood stage and may possibly inundate surrounding landscapes and increase the exposure of settlements to flood risks. This has been the case in the Philippines, where upland logging, followed by the cultivation of rice and other arable crops in riparian zones, increased overland flows and flooding resulted in the loss of livelihood assets for downstream communities (*Terra Daily*, 1st December 2004).

The main differences between the Dagi catchment in WNB (PNG), northern Australia and West African catchments lie in the amount of rainfall received annually that drives the hydrological cycle. Dagi receives >4000mm (PNG NWS, 2014), northern Australia around the Cairns region receives 2000mm (Australian Bureau of Meteorology, 2015) and Abia (Nigeria) receives 2193 mm rainfall (World Meteorological Organisation, 2016). The amount of rainfall received means the hydrological situations are different in each setting. When rainfall is combined with each local slope, soil type, land cover and land use influence on catchment, network and network characteristics will generate different flood characteristics and behaviour. For this reason, each catchment must be studied separately, not generalised.

2.5 Flood impacts, risks and vulnerability assessment in oil palm dominated landscapes.

2.5.1 Flood impact on livelihood assets and their vulnerability

Flood is the most common hazard and third most damaging globally after storms and earthquakes (Lal Narsey et al., 2009). Examples of statistics for flood damage, including examples from the Asia-Pacific region and in PNG, were discussed in Chapter 1 (see statistics compiled in tables 1.1, 1.2, 1.3 and 1.4 and figures 1.1 and 1.5). Flooding commonly devastates man, families, and regions during and after inundation has subsided (Water, 2013). The aftermaths of inundation and flood destruction are broadly categorised as tangible and intangible (Jongman et al., 2012). Flood damage is sub-partitioned into four kinds: "direct tangible (e.g. physical damage due to contact with water), indirect tangible (e.g. loss of production and income), direct intangible (e.g. loss of life) and indirect intangible (e.g. trauma)" (ibid.: p.3733-3735). Tangible damage concerns the monetary and actual ramifications of flooding (Water, 2013). It is straightforward to quantify in economic terms and alludes to belongings that have been impaired or ruined, along with property, services, utilities and infrastructure (ibid.). Intangible damage is the indirect impact of flooding to individuals and their lifestyles (ibid.). It is complex to quantify in economic terms but is humanly crushing and effects on people persist.

Instances of intangible damage constitute among others: loss of comfort at home, and psychological agony (Smith and Ward, 1998; Messner et al., 2007; Water, 2013).

The likelihood of a potentially damaging flood event is called a flood hazard (Chan et al., 2014; Schanze, 2006). Elements are "exposed" to floods and may be harmed. This is implied by the adverb "potentially damaging" (Chan et al., 2014: p.19). An "exposure is the nature and degree to which a system experiences physical, environmental, socioeconomic and political stress from flood hazards" (Adger, 2006: p.269). The attributes of these strains includes the magnitude, frequency, inundation area, depth, velocity and duration of the flood risk (Adger, 2006; Burton et al., 1993). ITC (2010: pp.12-14) defined "the elements at risk as the level of exposure" such as houses and buildings, crops, population, economic activities, transport, public services and utilities. Vulnerability is defined as the "degree of loss to a given element at risk at a given severity level" (ITC, 2010: pp.12-14; Wigati, 2008). Vulnerability has four components that can be influenced by floods and they are physical, social, economic, and environmental (Birkman, 2007; Vatsa, 2004; Cutter, et al., 2003).

The physical component refers to the location and characteristics of the built environment. The social component refers to people's wellbeing in communities and their demographic characteristics. The economic component is related to the economic status of the individual, community or society. The environmental component relates to the issues covering the physical, social and economic components that concern sustainable development. Vulnerability is caused by human interaction with the environment as well as with the cultural and political settings (UNISDR, 2004). Vulnerability assessment depends on how close communities are to the source of flood hazard, and their social and economic characteristics (Cutter et al., 2000). Furthermore, "vulnerability of the elements at risk" is related to the "degree of flood risk" (ITC, 2010: pp.12-14). "Flood risk is defined as the probability of harmful consequences, or expected losses (deaths, injuries, property, livelihoods, economic activity disrupted or environment damaged) resulting from interactions between natural or human-induced flood hazards and flood vulnerable conditions" (McCarthy, 2001: pp.35-38).

2.5.2 Flood risk studies on livelihood assets in oil-palm dominated landscapes

Studies conducted in oil palm landscapes differ according to researchers' backgrounds and objectives. Literature searches of studies conducted within the past 15 years are shown in table 2.4. Flood risks on livelihood assets has not been investigated in this landscape. Lal Narsey et al. (2009, p.25) called on developing countries whose economies are mostly agriculture based to *"urgently develop and strengthen specific geo-referenced baseline information related to key hazards, including* *socioeconomic information, livelihood assets and the costs, with specific reference to Pacific Island Countries and Territories (PICTs)"*.

According to a recent study by Hooijer et al. (2015), oil palm is said to have limited tolerance to flooding with conditions getting worse as climate change progresses. The study detailed the impact of peatland drainage for oil palm cultivation in Sarawak, Malaysia. This significant study made several recommendations. One of the key recommendations called for: *All tropical coastal inland areas, including lowland peatlands and its vicinity, and as a matter of urgency, require subsidence and flood analysis to be undertaken as part of land use and economic planning. While carbon emissions linked to climate change have been the focus of recent debates regarding peatland development, the flooding consequences of peatland drainage and oil palm cultivation is needed to receive much more attention as they affect direct economic interests and the lives of people living in these regions* (Hooijer et al., 2015, p.7).

Table 2.4: Research conducted in oil palm landscapes in the past 15 years.

General topic	Authors
General impacts of oil palm development on biodiversity loss, assessments and climate change.	Buchanan et al., 2008; Fitzherbert et al., 2008; Turner et al., 2008; Wilcove and Koh, 2010; Yule 2010; Azhar et al., 2011; Azhar et al., 2013; Edwards et al., 2013; Germer et al., 2008; Jennings et al., 2015; Immerzeel et al., 2014; Gray et al., 2014.
Impact of oil palm on carbon budget from riparian zones.	Adachi et al., 2011; Miettinen et al., 2011
Potential impacts to the environment from fresh fruit bunches.	Rist et al., 2010; Comte et al., 2012
Land use changes under oil palm and livelihoods.	Dennis and Colfer, 2006; Spiertz and Ewert, 2009; Wicke et al., 2011; Buschman et al., 2012; Cramb and Curry, 2012; Wich et al., 2012; Miyake et al., 2012; McMorrow et al., 2001; Koczberski and Curry, 2005; Chokkalingam et al., 2007; Huddleston et al., 2007; Ichikawa, 2007; Shariff and Khor, 2008; Doolittle, 2010; Webb et al., 2010; Sumarga and Hein, 2016; RSPO, 2014
Soil science and agronomy.	Banabas et al., 2008; Nelson et al., 2014; Rhebergen, 2012
Water balance.	Chan et al., 2007; Nelson et al., 2008
Unpublished PhD Thesis (oil palm agroforestry) and Nitrogen Loss Pathways.	Kwakye, 2015; Murom, 2007

2.5.3 Flood hazards, risk and the SPRC-Model

There are three steps in assessing flood hazards and risks that can be adapted and applied to oil palm landscapes and these are used in this case study (Bubeck et al., 2012; Schanze, 2006). Firstly, we should identify the hazard level, that is, the flood potential (including its main characteristics and behaviour), its recurrence and the levels of exposure (Schanze, 2006). Secondly, the vulnerability is assessed of the physical, social, economic and environmental components of the livelihood assets (ibid.). Finally, risk assessment is undertaken to demonstrate the physical and social consequences, as well as the financial calculations and losses (ibid.). These normally involve the use of maps and hydrological models using GIS databases to analyse, manipulate and display the results to increase the importance of these information to stakeholders (Schanze, 2006; Bubeck et al., 2012).

Flood risk emanates from the evolution of flood hazard and flood vulnerability (Schanze, 2006). The conceptual SPRC-Model) is used to relate to flood risk (figure 2.8) (Institute of Civil Engineers, 2001; Schanze, 2006). Schanze (2006: p.5) defines “a flood risk assessment as the identification, quantification and communication of flood risk”, which is achieved by using the SPRC-Model. It is a model that illustrates a straightforward causative continuity chain starting with the “meteorological and hydrological events either in inland or on coasts (sources) through the discharge and inundation (pathways) and the physical impacts on elements at risk (receptors) to the assessment of effects (consequences)” (ibid. pp. 6-8).

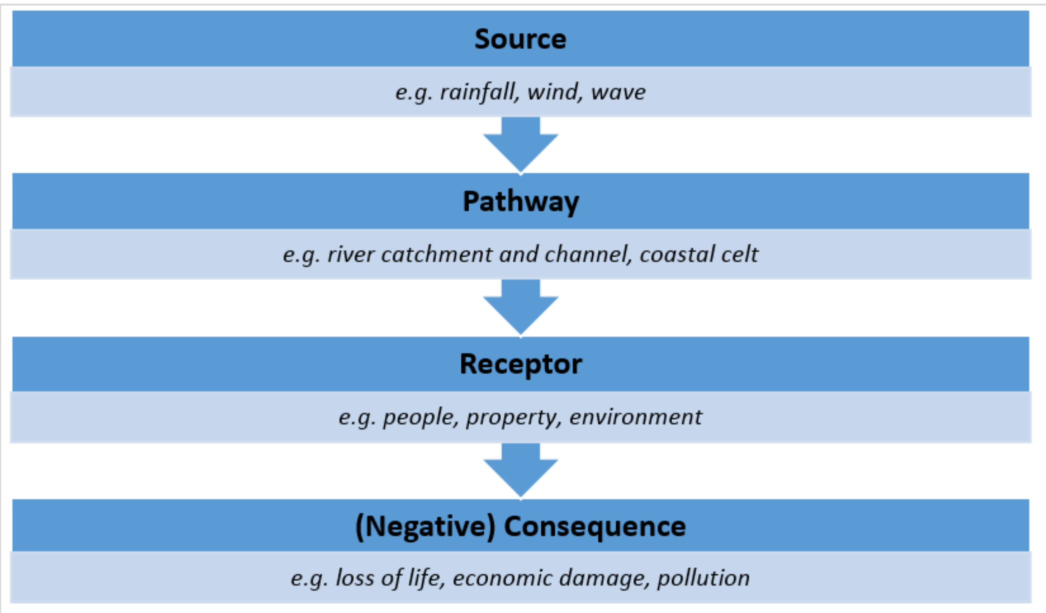

Figure 2.8: SPRC–Model (Institute of Civil Engineers, 2001).

According to Schanze (2006: p.11), the physical process is inferred from the chain connection "source", "pathway" and "receptor", while assessing the "(negative) consequence" is based on social beliefs. Flood hazards are represented by "source" and "pathway" and here reference is made to flood risk. The probability (p) of flood occurrence with a definite extent and any additional attribute (m) is ascertained by "Source" (ibid.). Two components contemplated in risk reduction are early warning (w) and the retention capacity of the source areas of inland floods (t) (ibid.). Inland discharge or coastal overflow and inundation (i) with various attributes (a) are described by the "pathway" (ibid.). Vulnerability is stated by interventions for flood control "Receptor" and "(negative) consequence" (ibid.). Susceptibility is defined by the "receptor" with involvement to reinforce, safeguard and be resilient to source (ibid.). Three examples of source are rainfall, wind and wave and two examples of pathway are river catchment and channel. Two examples of environment are people and property while three examples of (negative) consequence are life loss, livelihood, asset and economic damage, (r) (ibid.). The harm to values (v) denote "consequence" and interventions done to minimise, or to offset, damage (d) (ibid.). The expression of flood risk (f) is summarised in this operation (ibid., p.13):

$$\text{"Flood risk} = f\left((p, m, w, t)_{source}, (i, a, c)_{pathway}, (s, r)_{receptor}, (v, d)_{consequence}\right)\text{"}$$

The generative continuity of the SPRC-Model manifests for respective elements at risk and each flood hazard (ibid.). Interwoven connections prevail between channels, flood control interventions and the exposed vulnerable elements (Schanze, 2006, Bubeck et al., 2012). In many instances, multiple feedback instances are the result of those interrelationships. A "flood risk system" is a *modus operandi* that incorporates all related elements and processes functioning within it (Schanze, 2006: p.14). Floods in the Dagi River catchment are inland floods hydraulically connected to the coastal areas and cells typified by coastal floods (ibid.). The total risk analogous with a flood risk system is interpreted as the aggregate risk of all individual elements, and this concept is highly relevant to my study (Schanze, 2006, Bubeck et al., 2012).

2.6 Flood risk management

Flood risk management is defined "as decisions and actions undertaken to analyse, assess and (to try to) reduce flood risks" (Schanze, 2006: p.14). There are three tasks used for structuring flood risk management activities: risk analysis, risk assessment and risk reduction (figure 2.9) (Schanze, 2006; Gouldby et al., 2008; Bubeck et al., 2012).

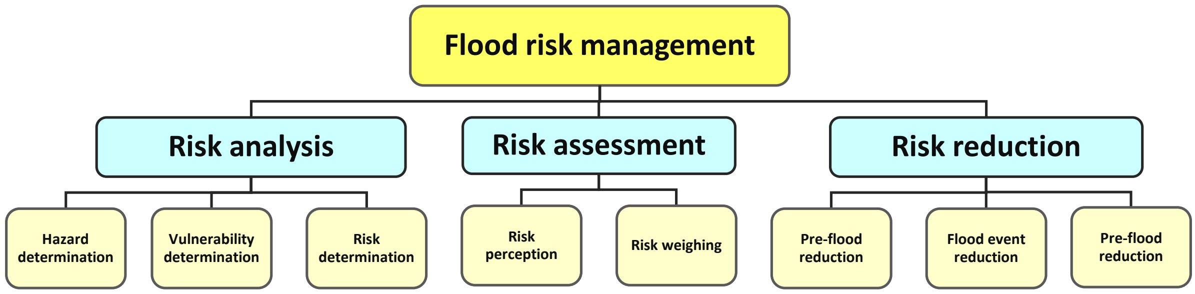

Figure 2.9: Flood risk management tasks and components (Schanze, 2006).

Provision of information about the past, present and future flood risks is accomplished by risk analysis. A risk assessment is a task performed to evaluate and compile people's perceptions about flood risks while interventions conducted to reduce potential flood risks are referred to as risk reduction (Schanze, 2006, Bubeck et al., 2012). Several pieces of information are required to accomplish each task and these include determining the hazard level after the flood event and implementing remedial actions (Schanze, 2006).

2.6.1 Risk analysis

This study will carry out a risk analysis to ascertain historical, present or future flood risks of the Dagi catchment (Schanze et al., 2006). It will determine flood hazard, vulnerability and risks in the catchment. There are many approaches to elucidate the flood risk system and in our case, rainfall frequency, flood characteristics and behaviour, hydraulic modelling of inundation, and estimation of economic costs (direct tangible economic losses) are analysis based on the SPRC-Model (ibid.). One of the challenges is to integrate ideas from diverse fields to address flood risk. Previous studies have been conducted using deterministic models together with statistical analysis on representing the rainfall-runoff processes with limited use of probabilistic methods (ibid.).

When the task of risk analysis is accomplished, results are given in analogue or digital formats and often used in early and real-time flood warning systems and evacuation, or as inputs to predict future flood risks (Aerts et al., 2014; Schanze, 2006). Information on water depth, velocity and flood frequency are represented as static 1D and 2D flood risk maps and this method is used widely (Schanze, 2006). However, the quality of information depends on the skill of the modeller as s/he attempts to overcome uncertainties in risk analysis. There are ongoing developments in software and methods to ensure risk maps are user-friendly, flexible and web-based. Many studies have used complete risk methods using specific data on potential flood damage (Schanze, 2006; Bubeck et al., 2012). To date, vulnerability is determined using peak discharges however there are few attempts at defining vulnerability as a function of expected damage (Schanze, 2006).

2.6.2 Risk assessment

Individuals in society assess flood risk results from scientific analyses at different angles. Others assess flood risks as part of project planning (e.g. figure 2.10). This also depends on collective perception and how certain risks are weighed and tolerated. Schanze (2006) stated that this distinction does not value risk analysis more than a risk assessment. In complementary ways, risk analysis provides information about theories and approaches on flood risks from a scientific perspective while risk assessment provides perceptions and risk weights because of societal behaviour (ibid.).

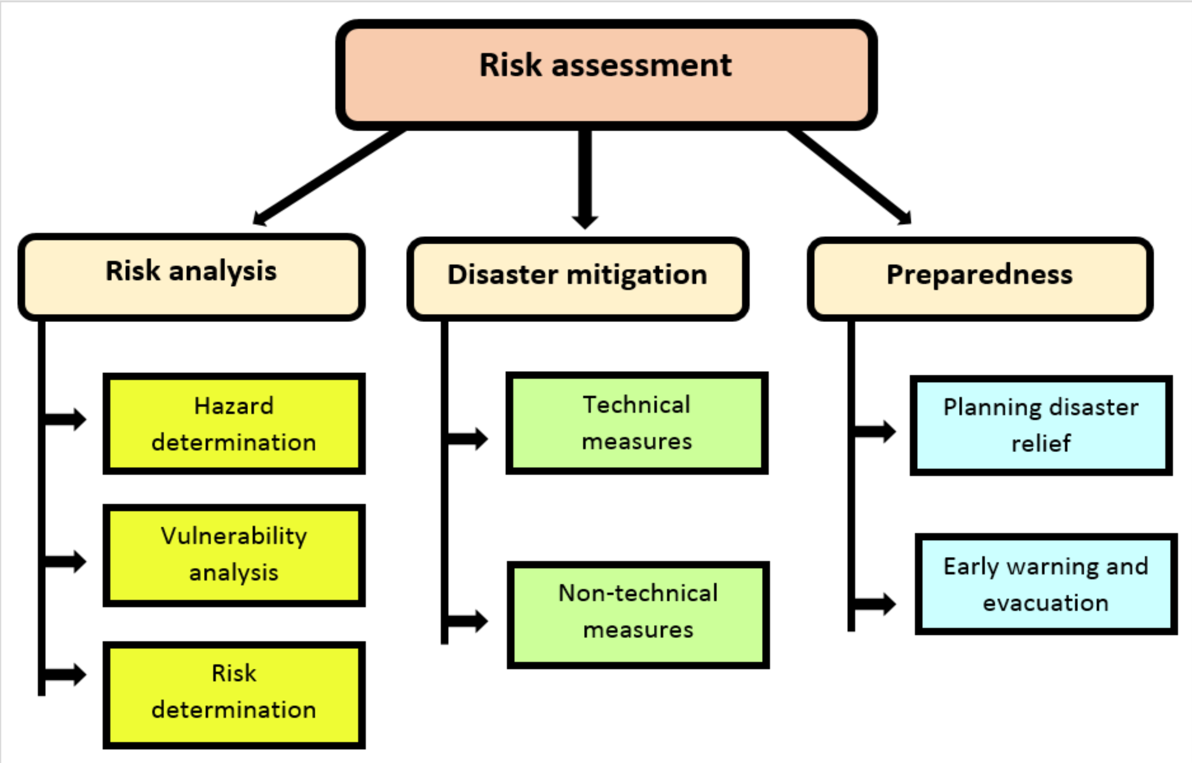

Figure 2.10: The risk assessment process seen from the perspective of project planning (Plate, 2002).

Risk assessment is a cost-benefit-analysis exercise. It covers the negative consequences (costs from risks and efforts of risk reduction) and the benefits (uses and opportunities) (Schanze, 2006). Multi-criteria methods to assess direct and indirect tangible and intangible "costs" have not been exploited because of the complexities of deriving costs and benefits. This emanates from sources with costs further linked with different sectors of society (ibid.).

2.6.3 Risk reduction

To reduce flood risks, direct physical actions and indirect intervention on human behaviour and their affairs are required (ibid.). There are permanent or temporary measures taken to reduce flood risks. Direct interventions by engineering works to modify stream channels, such as dam construction, is an example of a permanent measure (ibid.). Measures directly taken to reduce flood risks such as the placement of sand bags is an example of a temporary measure (ibid.). Flood risks are managed by structures based on regulatory, financial and communication mechanisms (ibid.). Regulatory instruments are interventions using legal mechanisms and come from water policies (e.g., flood protection acts). Funding incentives and provision of insurance cover according to land-use zones to protect communities from floods are common examples of financial instruments (ibid.). Transfer of know-how and exchange of information (preparation, warning and instructing) through the media, brochures and literature and through educational institutions such as JCU CMES - Centre for Disaster Studies and the PNG National Disaster Centre, are examples of communication mechanisms (ibid.). The SPRC-Model is related to these instruments and measures (ibid.).

Based on flood risk management, they can be systematised into pre-flood, flood event and post-flood interventions (ibid.). For example, zoning and building construction can be prevented from flood exposure by decreasing flood magnitude and their exposures in floodable areas by pre-flood interventions. Exposed elements can be protected by building structures such as dams and dykes, and helping communities to be flood resilient through preparedness (ibid.). According to Schanze et al. (2006), managing flood events is based on forecast and warning people as they progress. In many countries, different organisations are given this task and in PNG this function is performed by the National Weather Service. This is seen as a defence mechanism and at the same time a way to warn communities at risk to be prepared through information dissemination. Floods can be managed by structures purposely built to store water, and controlling its discharge so that the water height is reduced downstream. During a flood event, damages caused by floods can be mitigated by emergency response and evacuation. After a flood event, recovery involves provision of relief services such as food and medicine to those affected, and rebuilding of damaged livelihood assets. Flood risk management varies widely in many countries in terms of their effectiveness and efficiency, including the absence of flood insurance cover (ibid.). The outcome depends on the flood-risk system (ibid.).

Finally, it is important to note that linkages between risk analysis, assessment and reduction are prerequisites to a consistent flood-risk system (ibid.). It is a challenge to incorporate these into an operating system because of differences in approaches and devices used. A flood risk management framework is shown in figure 2.11 (ibid.). This framework does not require one to follow all the steps (ibid.). Again, it is based on the logic of the research question. Assessing flood risks to livelihood assets involves risk analysis, risk assessment and risk reduction using hydrological models.

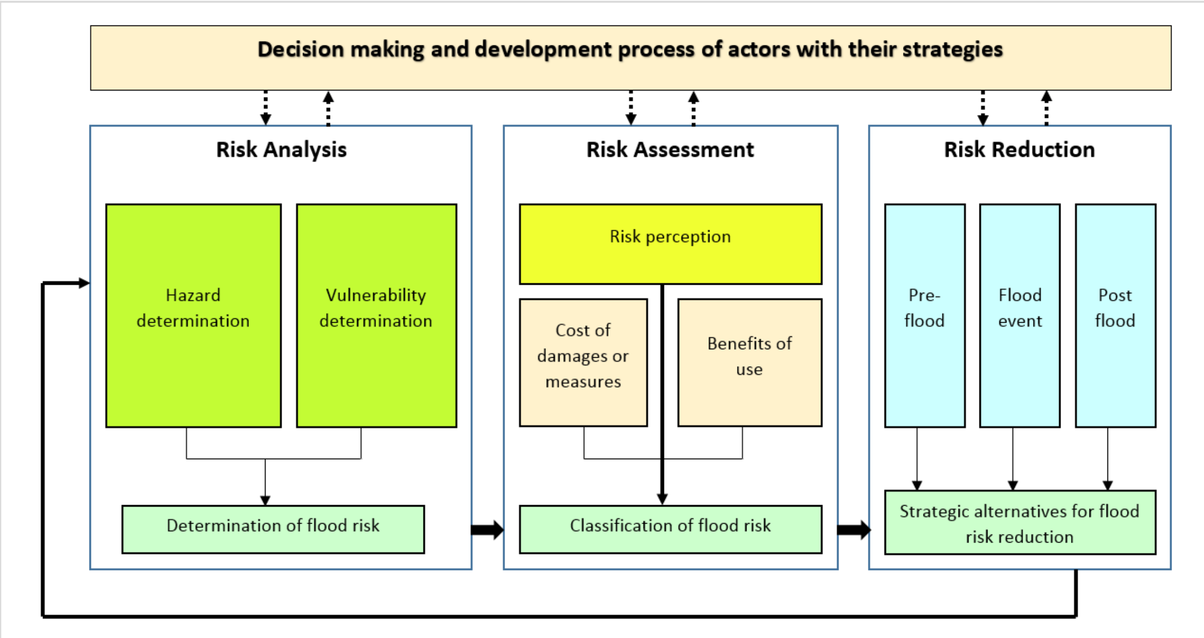

Figure 2.11: Framework for flood risk management (Schanze, 2006).

2.7 Challenges for flood risk research and prospects

There are many relevant aspects of flood risk management ranging from natural courses to public resolutions (ibid.). It is easy to understand a single entity but merging information from diverse sources such as integrating physical hydrological processes with social and economic data remains a challenge that needs to be tackled head on (ibid.). An important dimension is linking the socioeconomic realm to flood inundation, its extent and its risks (ibid.). Assessing flood risks is not a straightforward task. However, there are many approaches and techniques we can take to study and understand flood characteristics and behaviour, the extent of inundations and their impact on livelihood assets. Most of these approaches and techniques are viable if there are suitable geo-referenced datasets, they are of suitable resolution, employ relevant software and background knowledge and skills from researchers to achieve the research aim and objectives.

It appears that hydrological (and in some cases, socioeconomic) data can be a problem in ungauged or new sites in developing countries such as PNG. The methods reviewed require long-term discharge data and other variables from many gauging locations which are often not available in catchments in the tropics (McGregor, 1991). In many tropical developing countries (e.g. PNG), hydrological data are limited because of the nature of the topography (ibid.). In some countries, state hydrologic databases are not regularly updated due to economic constraints (ibid.). This emphasises the need for improved hydrological data collection in the long term for many tropical catchments. Because of these limitations, data collected from a small number of measuring stations or from short-term fieldwork might be evaluated to forecast maximum discharge in areas not measured (ibid.).

2.8 Conclusion

This chapter firstly reviewed flood dynamics in small tropical catchments with specific reference to the Dagi catchment. It went on to review the different flood modelling approaches and identified the most viable modelling approach for this study. Also the review critically analysed how agricultural changes in developing countries involved in oil palm development can influence flooding. Also it reviewed flood impacts, risks and the vulnerabilities of livelihood assets within an oil palm landscape. Finally, it reviewed the risk management process and investigated literature on flood risks management.

The generation of peak discharge is the consequence of the interplay between rainfall frequency, intensity and duration and catchment, stream network and channel characteristics. Many studies conducted in the tropics on the hydrological consequences of deforestation or the replacement of forests by planted crops found significant changes to stream morphology and dynamics. Oil palm development in many parts of the tropics has resulted in the removal of primary vegetation and was responsible for changing the stream morphology and its dynamics. However, no studies have been conducted to confirm the sources and causes of floods in oil-palm dominated landscapes and more specifically within the Dagi catchment. Flood generating conditions taken from studies elsewhere in tropical Australia, Africa, North and South America and Europe are not relevant to the Dagi catchment. I argue that the effect of vegetation clearance on stream morphology and hydrology and the build-up to flood generation are very different from those studied elsewhere. Flood generation due to vegetation removal combined with the amount of rainfall received in Dagi (>4000mm) will be different. And this can be compounded by the local topography and the replacement of natural vegetation by predominantly oil palm cultivation. Each flood will be different and will have its own characteristics and behaviour.

Morphological changes to the channel cross-sections, and extension of the drainage network by gullies, generally alter the hydraulics and hydrology. But peak discharges will be different due to variations in the amount of rainfall received, topographic effect and vegetative cover. This gives rise to floods in Dagi having their distinctive characteristics and behaviour. The above catchment changes together with those instigated by climate change are expected to exacerbate the flood stage, cause inundation with differing areal extents, and increase the future exposure of settlements to flood risks in oil-palm dominated landscapes. Quantifying this hazard and the risks it poses and documenting its impacts on livelihood assets within this oil-palm dominated landscape will go a long way towards mitigating future flood risks.

Hydrological modelling is an uncertain and probabilistic process riddled with challenges **(**Praskievicz and Chang, 2009). There is a need for more studies that can examine the combined effects of floods on livelihood assets in agricultural landscapes. The combined 1D/2D modelling approach is appropriate for modelling flood characteristics and behaviour and its inundation extent in relation to hazards and risk assessments in the Dagi catchment. The likely modelling option applicable in this study would be through a combination of SOBEK 1D2D, HEC-GeoRAS, HEC-HMS and HEC-RAS software. Each modelling program can perform certain tasks and create results that can be used as an input for another.

Based on the available data for the Dagi catchment, the Green and Ampt Loss, SCS unit hydrograph transform, recession base flow methods, and Muskingum Routing Method are the most relevant options for computing upstream and downstream discharges at catchment and sub-catchment scales. The HEC-GeoRAS and HEC-RAS modelling software can be used to create cross-sections and longitudinal profiles and velocity distributions for each discharge measuring points. They can also generate stream hydraulics data using a combination of Steady Flow (subcritical) and Unsteady Flows (supercritical). Recent advances in hydrological modelling software and platforms, together with GIS and remote sensing methods, provide the ideal pathway to understanding floods as they pose risks to livelihood assets.

It is obvious from the statistics that oil-palm dominated landscapes are vulnerable to flood risks. Flooding in oil palm growing provinces of PNG (WNB, East New Britain, New Ireland, Oro, Milne Bay, East and West Sepik) have been reported widely in the media. In Indonesia and Malaysia there are similar reports of flood risks in oil palm growing areas. Scientific assessment of flood risks and other hazards are important to help stakeholders to plan and better prepare for emergencies. However, progress in this area is often hindered by lack of flood risk data in most developing countries. For example, the Dagi catchment has virtually no data on flood risks besides those reported in the media. With lack of data, mitigation of flood risks to livelihood assets appears impossible in this landscape. More often, information on flood characteristics and behaviour, inundation and flood losses from overseas are used to generalise flood generating conditions in the tropics and this is scientifically unacceptable.

Anthropogenic climate change is expected to increase flood risks through more frequent heavy rainfall, increased catchment wetness, fluvial erosion, sea level rise and coastal erosion (Praskievicz and Chang, 2009). Flooding is already a problem in many oil palm landscapes and no study has been undertaken to show the relationships between floods and livelihood assets. Information is needed on the factors affecting peak discharge, flood characteristics and behaviour, the extent of inundation and the stream power affecting livelihood assets. This will help us to determine the risks to, and vulnerabilities of, livelihood assets. The roles played by population, land use and assets in affecting exposure and potential river flood risks is still unknown in oil-palm dominated landscapes. This information will help us to mitigate flood risks and develop policy plans to enable communities within oil palm landscapes to be resilient to flood risks. Based on the review, the most viable option to take in this study will be through a flood risk analysis that will ascertain past, present or future flood risks. It will determine flood hazards based on the area inundated by the flood. Based on this, it will analyse the vulnerability of livelihood assets and determine the flood risk of the Dagi catchment.

Finally, the interactive effects of floods are still not well understood at this stage in these landscapes (Praskievicz and Chang, 2009). Demand for dependable information on the effects of floods on livelihood assets will increase as population and rural agriculture advances into the new era (ibid.). This issue is becoming a concern with the onset of climate change (ibid.). Although uncertainty in hydrological modelling will not be eliminated, advances in the know-how of flood risks will enhance researchers' ingenuity to accomplish credible synopses relevant to agriculture as they respond to variability in the hydrological cycle (ibid.). These issues will provide an interesting pool of questions for researchers in the years ahead in the tropics.

Chapter 3.0: Site description

3.1 Choice

This study was conducted in the Dagi River catchment of WNB province, PNG. It is within the Hoskins oil palm project region situated on the northern coastline (figure 3.1). The choice to study the Dagi River catchment was driven by three factors. Firstly, riverine flooding is the only hazard posing risks to livelihood assets in the catchment and this makes it simpler to study than in areas with floods originating from both river and sea (Bouwer et al., 2010). Secondly, the area has been subjected to various types of land use dominated by oil palm cultivation, and has experienced a high annual population growth rate (3.92%) since 1968 (PNG NSO[9], 2013). The decision to develop oil palm and settler blocks led to in-migration and consequent population growth. High population growth often leads to changes in land use, livelihood strategies and asset ownership as wealth increases and these in turn are likely to be subject to loss from flood hazards. Lastly, the catchment is 492km^2, so that flood risks differ over the catchment. This makes it essential to document the spatial distribution of risks and damages (Bouwer et al., 2010).

3.2 Climate and vegetation

The climate is humid-tropical with distinctive wet (November-April) and dry (May-October) seasons each year (McKnight and Hess, 2000). The annual rainfall in the catchment can go up to 5000mm and as low as 1800mm (figure 3.2) (PNG NWS[10], 2014). Apart from these records, there are no spatial and temporal data available for the catchment. However, current data can be compared with the average annual rainfall of 3745 mm based on data between 1996 and 2013 recorded 32km away at Hoskins Airport (see figure 3.3 in appendix 3.1) (PNG NWS, 2014). The average daily maximum and minimum temperatures are 31^{O}C and 23.5^{O}C respectively, with little seasonal variation (figure 3.3) (PNG NWS, 2014). Before the Hoskins oil palm project was established in 1968, the catchment was covered with tropical lowland rainforests. At present, large tracts of natural rainforest exist only in the upper catchment, however, patches of secondary regrowth forests in isolated pockets of riparian zones remain near settlements at Hark, Togulo, Sarakolok, Kumbango, Mosa, Nahavio and Dagi.

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[9] The Papua New Guinea National Statistical Office is the state statistical agency set up by an Act of Parliament, the *Statistical Services Act (Chapter 386) 1980*, and is responsible for collecting, compiling and disseminating official statistical information to meet the needs of the government and public.

[10] The Papua New Guinea National Weather Service was established in 1975 and provides regional and national meteorological and climatological research, climatological information, and climate prediction and forecasting tools.

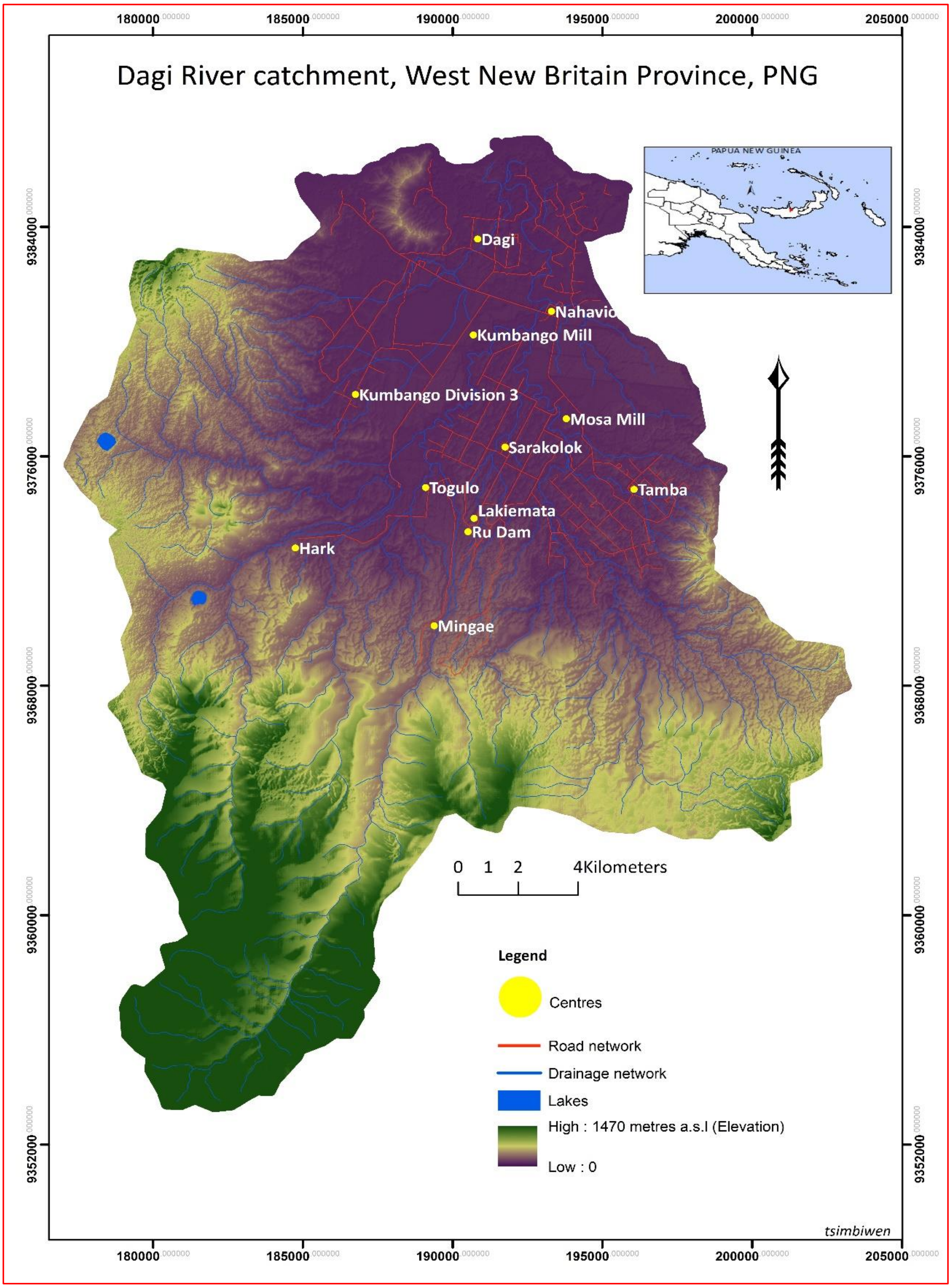
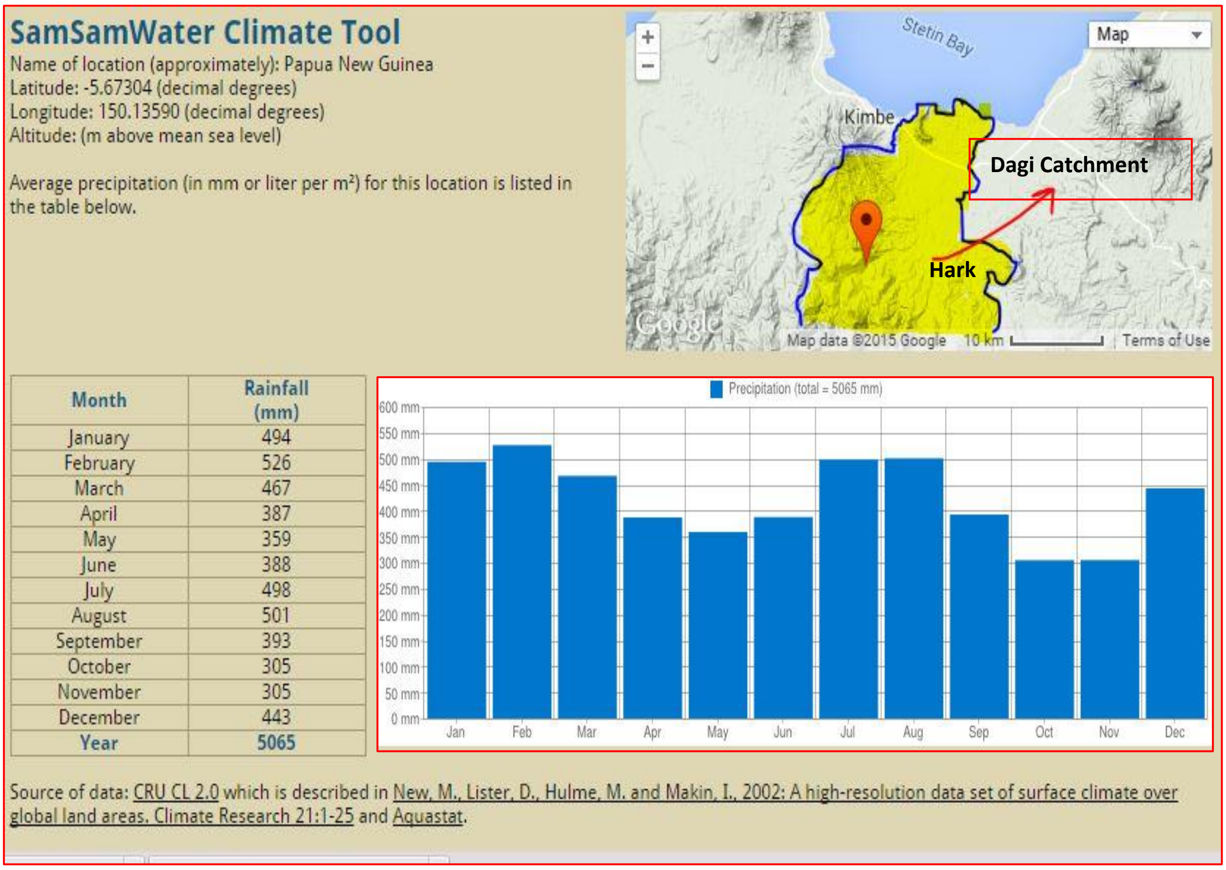
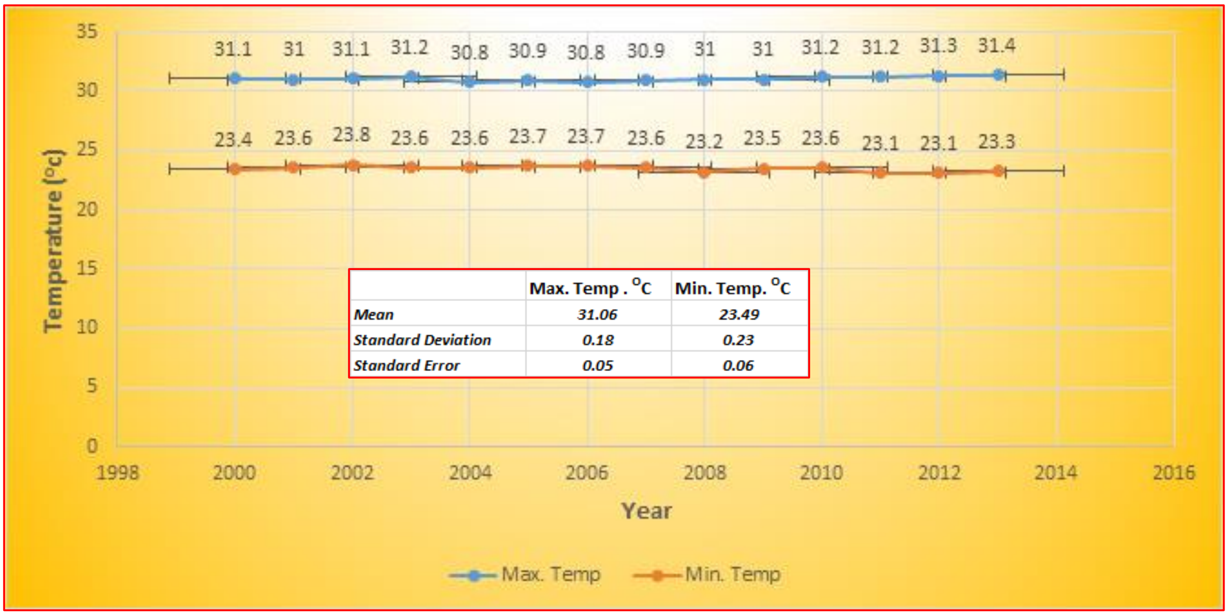


Figure 3.1: Dagi River Catchment, WNB province, PNG (Source: Advanced Land Observation Satellite ortho-rectified prism data from Remote Sensing Technology of Japan – RESTEC©XASA, 2014 and GIS data from PNG Resource Information System – PNGRIS, 2007).



Month	Rainfall (mm)
January	494
February	526
March	467
April	387
May	359
June	388
July	498
August	501
September	393
October	305
November	305
December	443
Year	5065

Figure 3.2: Average monthly and annual rainfall measured at Hark



	Max. Temp . °C	Min. Temp. °C
Mean	*31.06*	*23.49*
Standard Deviation	*0.18*	*0.23*
Standard Error	*0.05*	*0.06*

Figure 3.3: Annual maximum and minimum temperature measured at Hoskins Airport, between 2000 and 2013 (PNG NWS, 2014).

3.3 General geology, landforms, slopes and soils

The Dagi River catchment is overlain with mixed and undifferentiated igneous and sedimentary rocks, and volcanic-alluvial deposits and pyroclastics mostly from recent volcanic activity within the area (figure 3.4). The terrain is overlain with deposits of debris from the recent "Holocene explosive eruptions" from the nearby "Witori and Dakataua volcanoes" and has been modified by fluvial processes including overland flow (Webb et al., 2011: p.311). The topography consists of gently undulating terrain towards the coast and steep mountains in the interior of the catchment that form part of the Whiteman Ranges of New Britain (figure 3.1). On average, the elevation is about 800m in the mountain ranges and 15m above sea level in floodplains (figure 3.1). Landforms in the area are generally composite alluvial plains towards the estuary. To the west are deeply dissected older volcanic footslopes between 5-20^{O} and fans, with volcanic-alluvial plains, volcanic cones and domes (PNGRIS[11], 2007). To the south and east are mountains and hills with weak or no structural controls (figure 3.5). Dagi has a slope gradient between 0-2^{0} towards the flood plain, making the area susceptible to flooding during the wet season. Further towards the mountains the slopes vary from 3-20^{0} (figure 3.6).

Ninety-five per cent of the soils are volcanic in origin with alluvial soil deposits common along the floodplain and these are ideal for agriculture (PNGRIS, 2007). The northern coastal plain of WNB is characterised by sandy and alluvial volcanic ash soils that support a variety of crop cultivations (mainly oil palm) and subsistence gardening of food crops around riparian zones (Nelson et al., 2004). The soils are mostly "typic udivitrand", which are dominated by sandy textures with many pumice fragments (ibid.). They consist of "distinct layers of recent volcanic ash falls with little pedological development except for the presence of an A horizon with high organic matter content and have loamy sand to sandy loam texture." (Nelson et al., 2006: p.110). Along the Dagi flood plain, soils of the order "inceptisols" belong to the great group called eutrandepts (figure 3.7). These are moderately weathered brown ash soils that are fertile for agriculture. Other soil orders are "entisols" belonging to the troporthents great group. These are slope soils with thin layers that are easily eroded by overland runoff. Other orders of inceptisols are vitrandepts and eutropepts. Vitrandepts are unweathered sandy volcanic soils with black topsoil while eutropepts are brown alluvial soils found in forested areas (figure 3.7) (PNGRIS, 2007).

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[11] PNGRIS stands for Papua New Guinea Resource Information System. It subdivides the PNG map into Resource Mapping Units (RMUs). It contains information on natural resources (physical features, soils, climate, forests, vegetation), land use, and small-holder socio-economic activity. These data are linked to the RMUs.

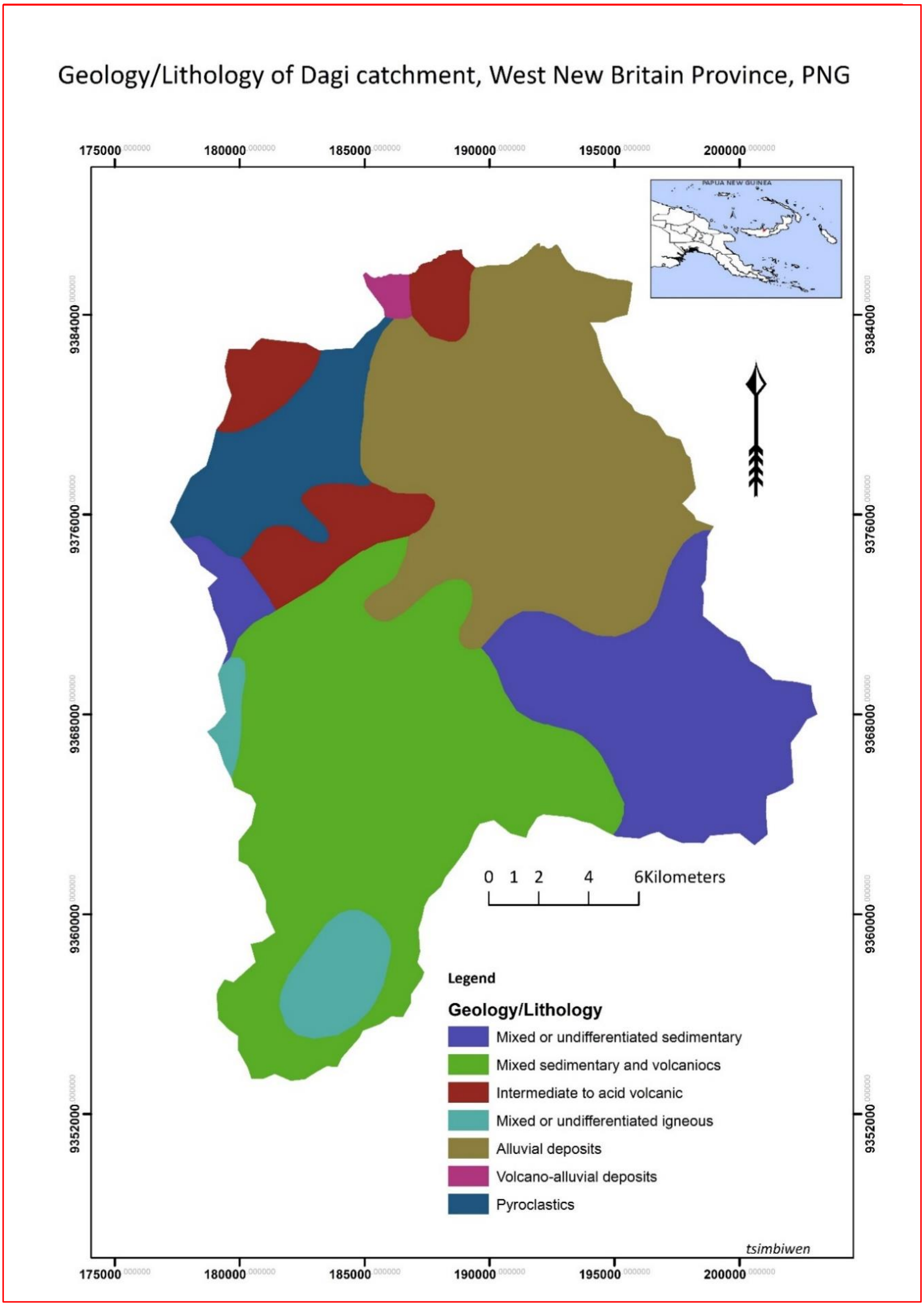

Figure 3.4: Geology and lithology of Dagi (PNGRIS, 2007).

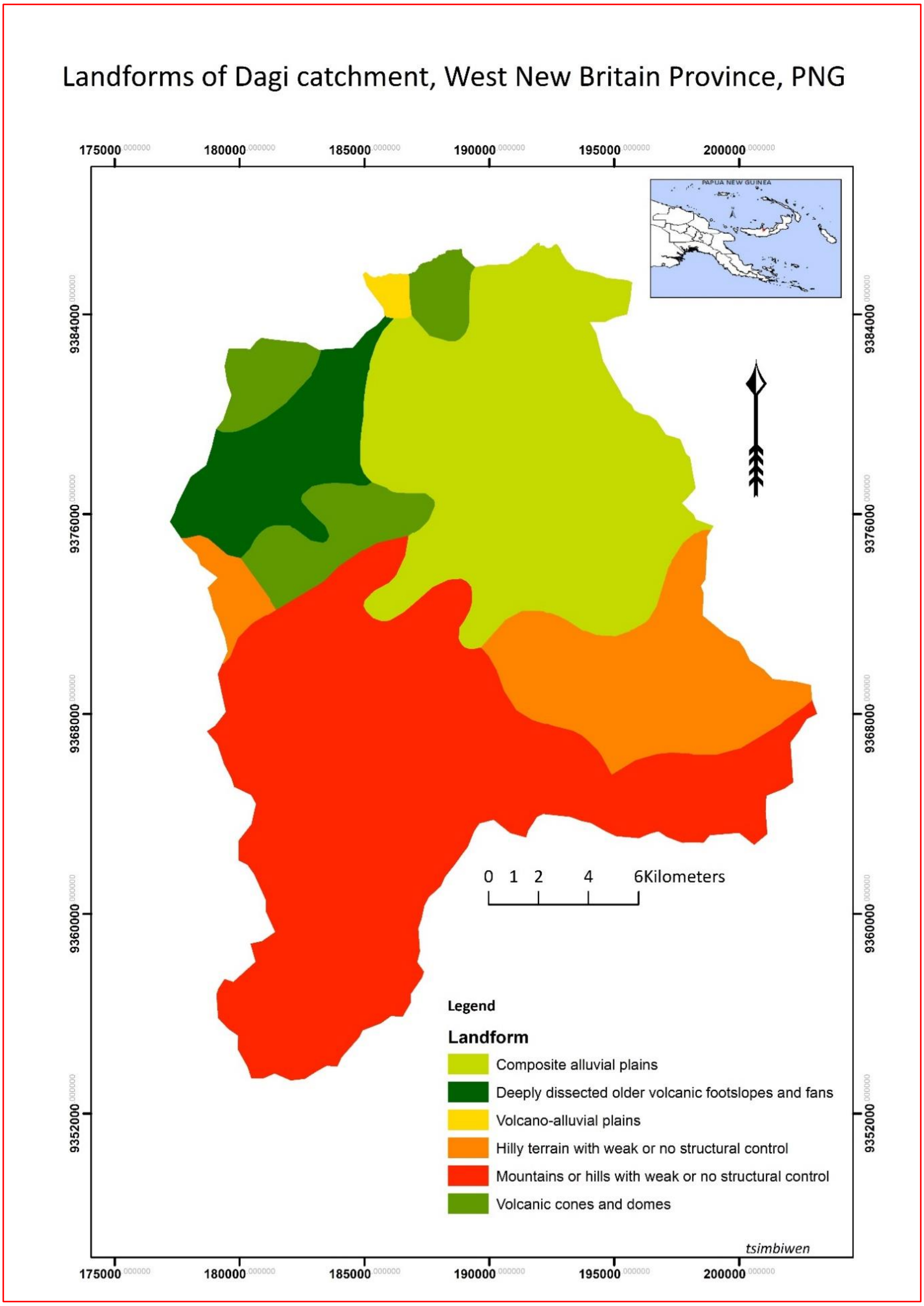

Figure 3.5: Landform of Dagi (PNGRIS, 2007).

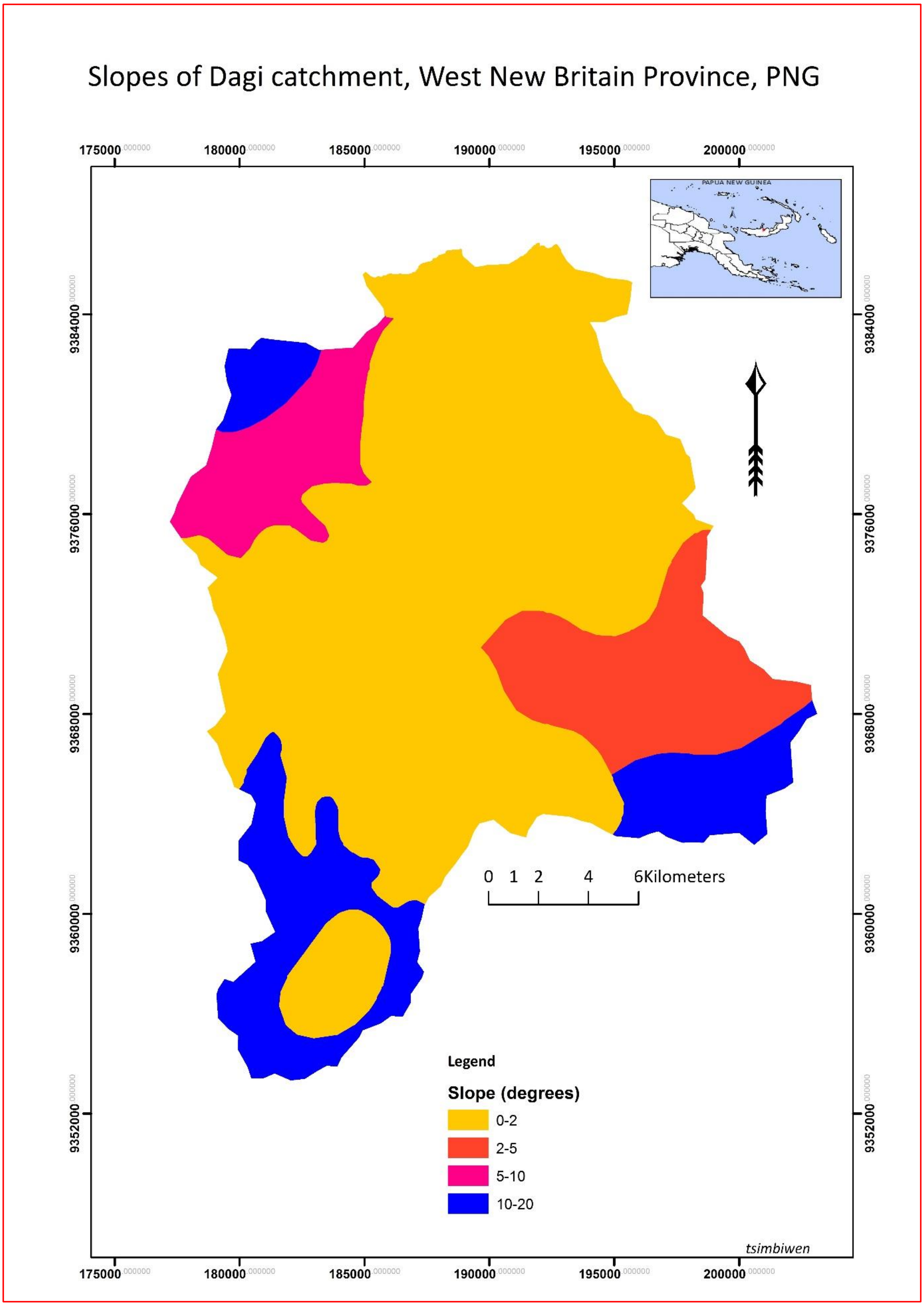

Figure 3.6: Slopes of Dagi (PNGRIS, 2007).

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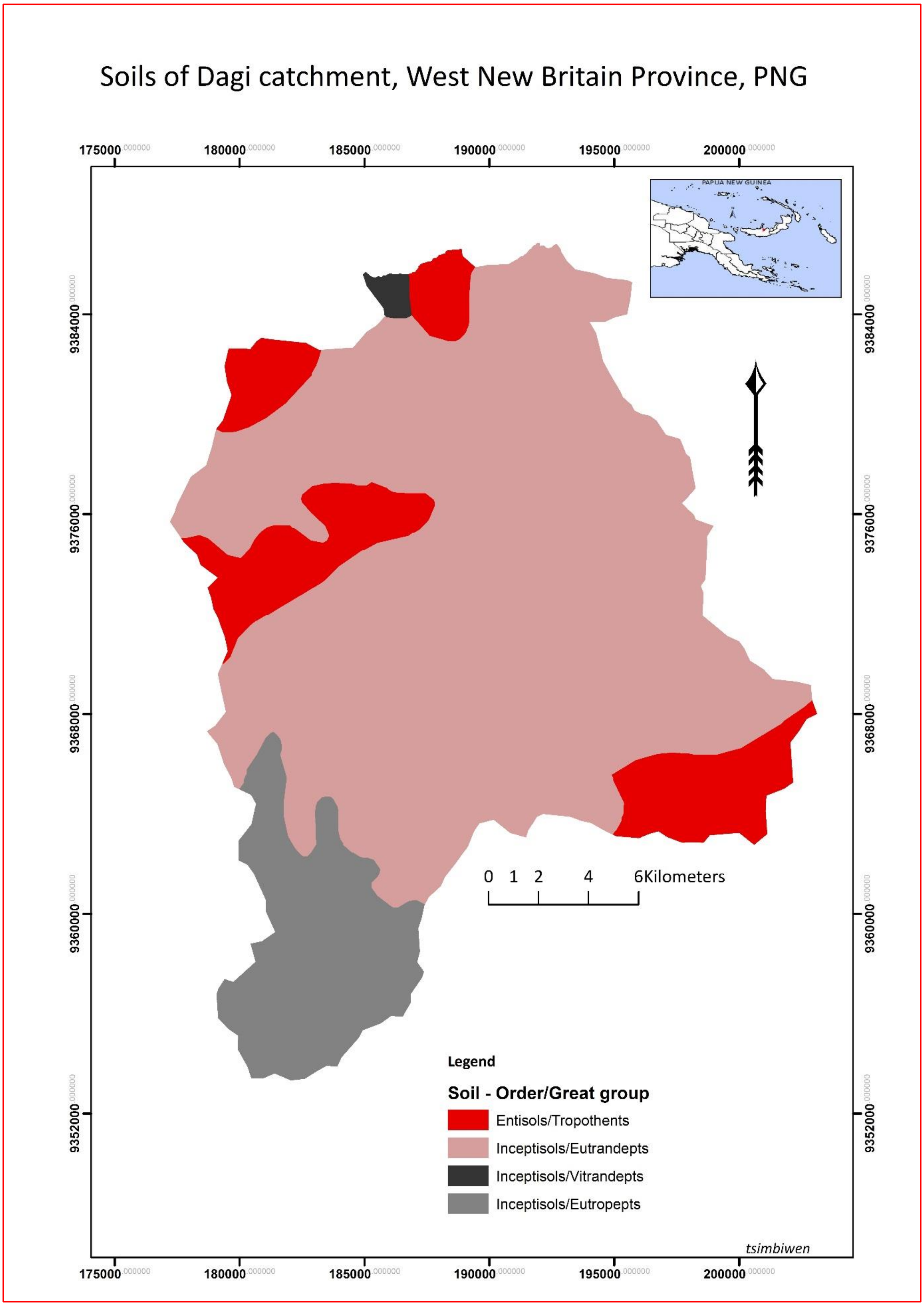

Figure 3.7: Soils of Dagi (PNGRIS, 2007).

3.4 Land use

The primary land use is oil palm cultivation on plantations and smallholder blocks (figure 3.8). Subsistence gardening, settlements, residential areas and logging are secondary land uses. Others include transport, buildings and a mini-hydro dam. Selective logging activity takes place in the upper catchment mostly during the dry season (May-October). The main infrastructure (roads, houses and factories) are mostly owned by a company called New Britain Palm Oil Limited. Government stations are found in the upper (Correctional Services Prison), middle (Department of Primary Industry, clinic and schools) and lower reaches of the catchment (DPI and school). Public facilities include clinics, gas stations, schools (mostly government run) and private houses. Most roads are sealed with bridges while roads in the oil palm plantations and settlements remain unsealed.

3.5 History and human interaction

Commercial oil palm cultivation commenced at Hoskins at the end of 1960 after a World Bank recommendation "that oil palm on a nucleus estate smallholder model[12] be introduced to WNB to diversify the agricultural economy and increase the export income of PNG" (Curry and Koczberski, 2012: p.6). This drove inauguration "of smallholder land settlement schemes (LSSs), initially at Hoskins in 1968 and then at Bialla in 1972" (ibid.). State agricultural leases lasting 99 years were given to settlers enlisted from densely populated regions of PNG and they were each re-settled in 6-6.5 ha blocks of land deemed sufficient to sustain a nuclear family (ibid.).

The LSSs were seen as a means to increase agricultural production, enable residents to have access to cash income and relieve pressure in densely populated areas of PNG (Koczberski and Curry, 2004; Hulme, 1984). It was believed that establishing the LSSs would replace communal land tenure in PNG with individual land tenure and transform it from a traditional subsistence economy to a market-based economy (Curry and Koczberski, 2012; Hulme, 1984). It was also believed that each settler on the LSSs would in time reap many social and economic benefits from the newly introduced individual land tenure and market economy and its success would spread to other parts of PNG (Curry and Koczberski, 2012).

[12] The nucleus estate-smallholder model was established for the oil palm industry in PNG based on the recommendation by World Bank. It is believed that establishing smallholder oil palm settlements near the central nucleus estate would have the benefit of seeking assistance from the central nucleus estate in terms of planting materials, fertilisers, technical advice, fruit pick up, transport, processing, and marketing oil palm (Christensen, 1986).

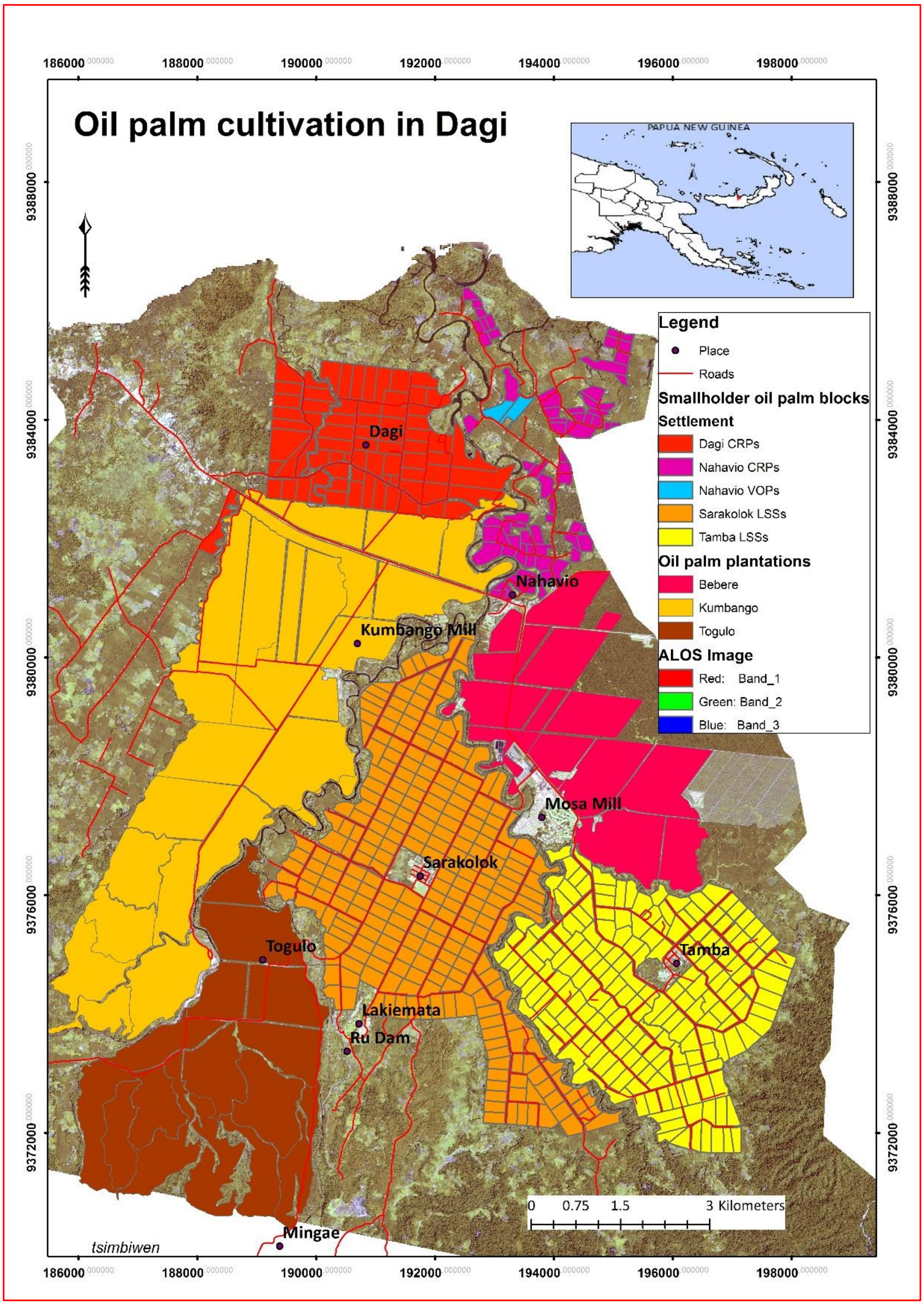

Figure 3.8: Oil palm cultivation in Dagi.

3.6 Modus operandi of oil palm production and local economy

Within the Asia-Pacific region, modes of oil palm production range from smallholder blocks to large plantations that are privately owned (Cramb and Curry, 2012). As highlighted in a red box in figure 3.9, the Dagi catchment falls under the "Nucleus Estate-Smallholder scheme (NES)" within the Hoskins project area (Cramb and Curry, 2012: pp.223-224). The NES scheme is subdivided into smallholder growers and plantations (ibid.). Smallholder growers are further sub-divided into those on state land under the LSS with a 99-year agricultural lease, as Village Oil Palms (VOPs), or as Customary Rights Purchase (CRPs). Plantations are established on land acquired from customary landowners. Plantations constitute 60% while smallholder oil palm blocks comprise 40% of the total planted area in the catchment (Orrell, 2012). The economic backbone is oil palm agriculture (95%) with only 5% from other sources such as subsistence cultivations and cocoa. Oil palm alone earns about 95% of the total earnings in Dagi and together with other oil palm growing areas contributes about 70% of the total revenue for WNB province (ibid.). Oil palm directly and indirectly generates 90% of the jobs for the population aged 15-60 years (Cramb and Curry, 2012).

Mode of production	Variants	Main countries
Estates	Private *and/or* state owned National *and/or* foreign company State land *or* customary land	Malaysia Indonesia PNG Solomon Islands
Managed smallholder schemes	Resettlement schemes for landless/land-poor *or in situ* schemes for existing landholders Landholders manage own lots *or* agency manages whole scheme on an estate basis Large-scale *or* small-scale schemes (mini-estates)	Malaysia
Nucleus estate–smallholder (NES) schemes	Private *or* state-owned plantation company as nucleus (providing mill and other infrastructure) Settlers on state land *and/or* local (customary) landholders as smallholder 'plasma'/'outgrowers' Smallholder cooperatives *or* individual settlers dealing directly with plantation company	Indonesia PNG Solomon Islands
Joint-venture schemes	Customary land is consolidated in a trust held by a government agency that forms joint venture company with private investor (Sarawak model) Customary landholders issued with communal title, conditional on development by a private or state-owned plantation company (Sabah model) Partnership schemes whereby company develops and manages land for farmers and pays 'rent' on basis of land area contributed (Indonesian model) Customary land leased to private company by Incorporated Land Group in return for land rentals, royalties on production and sometimes dividends (PNG model)	Malaysia (Sarawak and Sabah) Indonesia PNG
Assisted smallholders	Smallholders given planting grants (subsidised inputs) and technical advice Smallholder groups linked to input supplies, credit, technical advice, fruit bulking facility and processor	Malaysia Indonesia PNG Solomon Islands
Independent smallholders	Self-managed and self-funded (may receive some inputs on short-term credit) Smallholders in NES or other schemes who eventually become independent	Malaysia Indonesia PNG Solomon Islands

PNG = Papua New Guinea.

Figure 3.9: *Modus operandi* of oil palm production with Hoskins project highlighted in red box (Cramb and Curry, 2012).

3.7 Environmental concerns and Roundtable on Sustainable Palm Oil

There has been large-scale development of oil palm with the conversion of primary forests. Consequently, further clearance to plant oil palm on steep slopes (15-20^0) has altered the hydrologic cycle, heightened soil deterioration, and degradation of river channels (Cramb and Curry, 2012). Also, the clearance and draining of peatlands has culminated in subsidence, the exposure of livelihood assets to floods and the depletion of environmental functions (ibid.). In the past 10 years or so, there were significant policies that proceeded from these issues at the national and international levels. Most notable has been the establishment of the Roundtable on Sustainable Palm Oil (RSPO[13]) in 2004 (ibid.). Its purpose was to "promote improvements to the usage of sustainable oil palm products via sound international excellence and commitment of collaborators" (ibid.). Several players were brought together by RSPO. They include plantation companies and smallholder growers (producers), oil palm traders and processors, manufacturers of consumer goods, retailers, bankers and investors and NGOs (social and environmental) (ibid.).

However, controversies surround the RSPO's aim number 8, and this concerns the extensive conversion of tropical rain forests to oil palm monocultures (ibid.). This drives biodiversity loss, threatens valuable species of flora and fauna with extinction, and increases flood risks (ibid.). Some measures have been taken by New Britain Oil Palm Limited to preserve the environment through RSPO by gaining accreditation with the ISO 14001 standards for environmental best practice. However, it is difficult to achieve immediate results from stakeholders with diverse interests and is a challenge with pressing environmental issues such as flood risks in oil-palm dominated landscapes (ibid.).

3.8 Flood inundation and risks in Dagi

Inundation along the Dagi River occur during the wet season depending on rainfall, runoff and catchment characteristics. Inundation is an important component of natural stream processes (Adebayo and Jegede, 2010). However, it becomes a calamity where and when settlers develop and occupy space in areas exposed to floods (ibid.). It is well documented that as land use increases, it

[13] RSPO aims "to promote the production and use of sustainable palm oil for people, the planet and prosperity" (RSPO, 2014: pp.2-5). To do so cultivators are governed by 8 principles: "1. Commitment to transparency, 2. Compliance with applicable laws and regulations, 3. Commitment to long-term economic and financial viability, 4. Use of appropriate best practices by growers and millers, 5. Environmental responsibility and conservation of natural resources and biodiversity, 6. Responsible consideration of employees, and of individuals and communities affected by growers and mills, 7. Responsible development of new plantings, and 8. Commitment to continuous improvement in areas of activity" (ibid).

exacerbates floods through the alteration of both the catchment, network and channel characteristics (Valentin et al., 2008; Immerzeel et al., 2014). Presently there are no studies of the hydrodynamics of floods and how they may lead to inundation and cause hazards, and expose livelihood assets to flood risks.

Chapter 4.0: Flood characteristics and behaviour in an oil palm dominated landscape.

Summary

In the context of flood risks on assets and livelihoods, it is vital to accurately model the temporal and spatial patterns of discharge, volume, velocity, flood level, duration, flood frequencies and probabilities for a given rainfall scenario. An oil-palm dominated catchment in PNG was sub-divided into four sub-catchments. Missing data were collected from official sources and from field measurements including the 2014 rainfall data for 10 days and 12 hours. These data were organised in SAGA GIS (Conrad et al., 2015) and ArcGIS 10.2 (ESRI, 2010). To understand the rainfall and temperature pattern, data were analysed using a three-year moving average to fit and identify temporal variations effects, and reduce extreme values and abnormalities. All streams are perennial and this is linked to the temporal pattern of rainfall attributed to excess rainfall over infiltration. Flood events were simulated using HEC-HMS (USACE, 2013), HEC-RAS (USACE, 2010) and HEC-GeoRAS (USACE, 2009) methods. Rainfall-runoff simulation results showed unsteady rises in the hydrograph with distinct peaks in downstream sites. The distance between reaches, the amount, intensity, duration and frequency of rainfall, slope, stream channel and overbank roughness influenced velocity which in turn defined the shape, size and the time of rise of the hydrographs. The upstream reach generally showed a steep hydrograph with a peak discharge of 1326m^3/s (130.10MM) for 2010 at 13:00pm compared with that of 2014 which peaked at 12:30pm with 729m^3/s (86.96MM). Downstream reach generally showed a broader hydrograph with a peak discharge of 1158.4m^3/s (72.47MM) at 14:00pm in 2014 while in 2010 it was 2424.4m^3/s (109.67MM) that peaked by 14:30pm. Excluding 1st and 2nd order stream networks, the modelled catchment appears circular. As a result, rain falls at equidistant points and runoff reaches the stream at the same time to produce high peak discharge and a steep rising limb on the hydrograph. This explains the similarities between the two hydrographs despite the 2010 discharge being higher than that of 2014. All stream cross-sections and longitudinal profiles show evidence of overflow by total volumes with variations in velocity. The volume of water and slopes, channel and overbank roughness influenced velocity in both events. Velocity in all cross-sections decreased towards the banks and in the floodplains as they encountered roughness. The 2014 floods had an average velocity of 4.35m/s in the main channels upstream while downstream average velocity was 2.75m/s. The 2010 floods had an average velocity of 5.38m/s upstream while downstream average velocity was 3.76m/s. Floods in Dagi rise quickly upstream and flow fast downstream and this gives little time to warn and evacuate people. The stream power during floods increases downstream and this is risky. For example, the average stream power for 2014 in sub-

catchment 1 was 1915.12 N/m s, sub-catchment 2 was 1196.95 N/m s, sub-catchment 3 was 2393.89 N/m s, sub-catchment 4 was 1196.95 N/m s while downstream it was 9575.58 N/m s. Depending on rainfall input, slope and meteorological conditions, the flood durations varied. The flood duration from upstream in 2014 receded to normal level in three days (72 hours) but took seven days downstream. In 2010 the flood receded within four days upstream but took 11 days to reach normalcy downstream. Flood height varied for all sites in response to slopes. Flood height for 2014 in reach-1 was 2.65m, while in reach-5 it was 6.34m. In 2010, flood height was 3.88m at reach-1 while at reach-5 it was 7.5m. Flood frequency analyses were done using Log-Pearson Type III Distribution (Haan, 1977) and Gumbel's extreme value distribution techniques (Gumbel, 1960). The flood event of 2010 had a recurrence interval of 11 years (9.09%) while that of 2014 had a recurrence interval of 7.33 years (13.64%). This means floods in Dagi catchment are highly variable and this depends on many factors but primarily rainfall and slope characteristics.

4.1 Introduction

To address the issue of flood risks and vulnerabilities of livelihood assets requires information on flood characteristics and behaviour. There are currently large areas of oil palm landscapes where there is little or no information on current flood characteristics and behaviour and this is particularly true in the Dagi catchment. Climate change impacts on flood intensities is a reality and is threatening rural livelihoods across many agricultural landscapes (Sayers et al., 2011; IPCC, 2007; Kundzewicz et al., 2004; Scoones, 1998). Flood events have their own unique characteristics and are defined by their discharge, volume, velocity, depth and durations (Ayoade, 1988; Gladwell, 1993; Kundzewicz et al., 2004; Guo et al., 2014).

Flood behaviour is a term used to describe the movement of floodwaters across a stream cross-sectional area and its longitudinal profile (Croke et al., 2013; Ashworth et al., 2012). It defines flood dynamics when water moves from sub-catchments going downstream following a course along a river reach, junction and into storage areas in the flood plains or into an outlet. A flood wave refers to the surge and recede in water level as its peak moves gradually downstream (Gupta, 2011; Ayoade, 1988). The flood peak moves fast upstream while downstream larger volume of water slows down movement of flood peak and results in longer flood duration (Gupta, 2011). These flood characteristics and behaviours give reference to a flood magnitude, which is usually described in terms of the statistically derived frequency or return period (ibid.). The likelihood of floods being equivalent or surpassed in any year is referred to as its recurrence interval (ibid.). Flood levels, velocities, durations and the extent of flood inundation also depend on their probability of occurrence. These flood characteristics and behaviours in oil palm landscapes are not well understood and this study attempts to contribute to the knowledge gaps by using two modelling approaches.

This chapter begins by outlining the materials and methods used to investigate floods in Dagi. This is followed by a presentation of the results on the rate, volume and duration of flood discharge in hydrographs. Cross-sectional and longitudinal profiles, stage height, water depths and duration, peak and magnitude, roughness coefficients, velocity and stream power are presented and further discussed. Factors that affects floods are elaborated and conclusions are drawn based on the results.

4.2 Objective and research questions

The goal of this chapter is to:

Model the flood characteristics and behaviour at a sub-catchment and catchment level in an oil-palm dominated landscape.

To address the above intent, the following research enquiries were framed:

1. what are the discharges and volume of water contributed by floods in the reaches and junctions along the waterways?
2. how does the floodwater move and distribute along the stream cross-sections and longitudinal profiles?
3. what are the water depths and durations for floods?
4. what possible catchment factors may contribute to these flood characteristics and behaviour?
5. what are the probabilities of floods of different magnitudes in Dagi?

4.2 Materials and methods

4.3.1 Overall methodological process

To know the flood characteristics and behaviour requires historical rainfall data with information on the amount, duration, frequency and areal patterns of rainfall (Gupta, 2011; Ayoade, 1988). To avert a flood disaster, prediction and forecast of floods are done based on this rainfall information using empirical, statistical, analytical and modelling methods (Ayoade, 1988). These methods require data on water depth, volume of discharge, area of land inundated, seasonality of flooding and the frequency of floods of a given magnitude (Gupta, 2011; Ayoade, 1988). These data are generally not available in PNG, and especially not in WNB province (for example, the 2014 rainfall data[14]). Because of data limitations, catchment modelling provides the most recent method to predict and forecast floods (Gupta, 2011). Through modelling, an attempt is made to simulate the hydrological cycle in the catchment with the aid of computers. Parametric models use the relationships between physical parameters involved in hydrological events to generate non-recorded hydrological sequences (USACE, 2013).

Data on flood characteristics and their behaviour were generated by flood routing and hydraulic modelling (USACE, 2013; USACE, 2010; USACE 2009) (figure 4.1). Rainfall, discharge data and discharge measurements of short durations, together with topographical, river cross-section and frictional data collected during fieldwork were entered into the models. Flood discharge, volume, velocities and stream power were derived at the sub-catchment and catchment level using HEC-HMS (USACE, 2013). Information on stream hydraulics such as cross-section, water elevation, 1D inundation and rating curves were derived using HEC-RAS (USACE, 2010) and HEC-GeoRAS (USACE, 2009). This information, together with estimated flood discharges, were used to determine flood exceedance probabilities (Gumbel, 1960; Haans, 1977). The information generated will be the inputs for modelling inundation extent and flood risks on livelihood assets in the Dagi catchment (chapters 5 and 6).

[14] During the time of data collection, there were no 2014 rainfall data available at PNG National Weather Service. The 2014 data used to model the 2014 flood event were collected during fieldwork using a non-recording rain gauge for a duration of 10-days, 12 hours each in February, 2014 and January-February 2010.

4.3.1.1 HEC-HMS

HEC-HMS is a generalised modelling software that stands for Hydrologic Engineering Center of United States Army Corps of Engineers (USACE) – Hydrologic Modelling Software. It simulates precipitation-runoff processes of dendritic watershed systems and is applicable in many geographic areas to solve a range of problems such as in water supply and flood hydrology (USACE, 2013, p.1-3). It separates the hydrologic cycle into manageable components by separating their boundaries within a catchment. In each boundary, fluxes of energy and mass in the cycle are represented physically with a mathematical model (ibid.: p.4-5).

The physical watershed representation within a basin model is connected in a dendritic network to simulate runoff processes through elements (sub-basins, reach, junction, reservoir, diversion, source and sink) combined with meteorological data (short wave radiation, precipitation, evapotranspiration, and snowmelt) (ibid.: p.5). Not all meteorological components are required for simulations. Simple event simulations require only precipitation while continuous simulation requires additional meteorological data (ibid.: p.6). Meteorological components used in this study were rainfall data. The data for 2014 from the PNG NWS (2014) were not available during the time. A 10-day record from a non-reading rain gauge for the 2014 missing rainfall data were collected in the field. The inverse method was used in the meteorological model to determine the gauge weights (ibid.: p.4-6).

The parameters used in this research were the Simple Canopy, Simple Surface, the Green and Ampt Loss, SCS Unit Hydrograph Transform, Recession Base Flow Methods, Muskingum Routing Method, and Constant Loss/Gain (ibid.: p.4-9). A simulation is generated by combining a basin model, meteorological model, and control specifications using the selected parameters to compute upstream elements in a downstream direction (ibid.: p.4-6). Each mathematical model is ideal for different environments under different conditions and requires knowledge of the basin, the goals of the study, and personal judgement. The program produces hydrographs that are used directly or with other software for studies in flow forecasting, flood damage reduction and flood plain regulation (ibid.: p.3-5).

The program is limited by the following:

1. The mathematical models are deterministic. This means boundary conditions, initial conditions and parameters of the models are assumed to be known and to remain constant. However, they vary across space and time and the program does not guarantee that every simulation is going to yield the same result. Human and other processes will change parameters (ibid.: p.4-6).

2. Capability is limited in breaking long simulations into small segments and to manually change parameters between segments (ibid.).

3. The mathematical models in this program are uncoupled. The amount of evapotranspiration depends on soil moisture quantity in the real world. However, the program computes evapotranspiration, then followed by infiltration, which is the exact opposite of the hydrological process. The program needs to numerically link parameters and simulate simultaneously in much better fully coupled models (ibid.).

4. The basin model only allows for dendritic stream networks. This limits other stream networks such as radial or centripetal (ibid.).

5. The presence of any backwater within a stream network requires another hydraulic model because the design of HEC-HMS does not allow for the presence of backwater in stream networks (ibid.).

4.3.1.2 HEC-RAS

The Hydrologic Engineering Center of United States Army Corps of Engineers (USACE) – River Analysis System is a program that performs one-dimensional steady and unsteady river hydraulics calculations, sediment transport modelling and river temperature analysis (USACE, 2010; p.1). Computations are done for four one-dimensional hydraulic analyses: (1) steady flow surface profile; (2) unsteady flow simulation; (3) movable boundary sediment transport and (4) water quality analysis. The four components are represented by common geometric data, and hydraulic computations are routinely done (ibid.: p.2). In this study, both steady flow water surface profile and unsteady flow simulations were done.

According to USACE (2010; pp.5-8), steady flow modelling computes and solves the one-dimensional energy equation. It handles full network channels, a dendritic system or a river reach and models subcritical, supercritical and mixed flow regime water surface profiles. Energy losses by friction (Manning's equation) and contraction/expansion (change in velocity head multiplied by its coefficient) are computed. The unsteady flow component performs hydraulic calculations for cross-sections, dam breaks, analyses levee breaching and overtopping. This information is shown as graphs of x-y plots of river schematics, cross-section profiles, rating curves, hydrographs and inundation maps. It can perform three-dimensional multiple plots of river cross-sections and water surface profiles (USACE, 2010; p.5-22).

4.3.1.3 HEC-GeoRAS

According to USACE (2009: p.1-2), the Hydrologic Engineering Center of United States Army Corps of Engineers (USACE) – GeoRiver Analysis System is an extension program in ArcGIS that provides procedures, tools and utilities to prepare geometric data for import into HEC-RAS and generate GIS data from RAS output. Import files are created using a DEM of the river system in the ArcInfo TIN or a GRID format. In hydraulic modelling, high-resolution DEMs with a continuous surface are required to capture data of the bottom of a river channel and flood plain. Measurement units are relevant to the DEM coordinate system. According to USACE (2009: p.3) themes created are the stream centreline, flow path centrelines, main channel banks and cross-section cut lines, water surface profile and velocity data. They are exported from HEC-RAS and processed in HEC-GeoRAS within ArcGIS for analysis to visualise inundation depths and boundaries to assist floodplain mapping, flood damage computations, flood warning and responses. Additional layers include land use (for Manning's *n* values) and storage areas. GIS data created are transferred between HEC-RAS and ArcGIS with the HEC-GeoRAS extension using a formatted data exchange file (*.sdf) (USACE, 2009: p. 19). Although it is simple to use, users must have a thorough understanding of river hydraulics to create and interpret GIS datasets properly (ibid.).

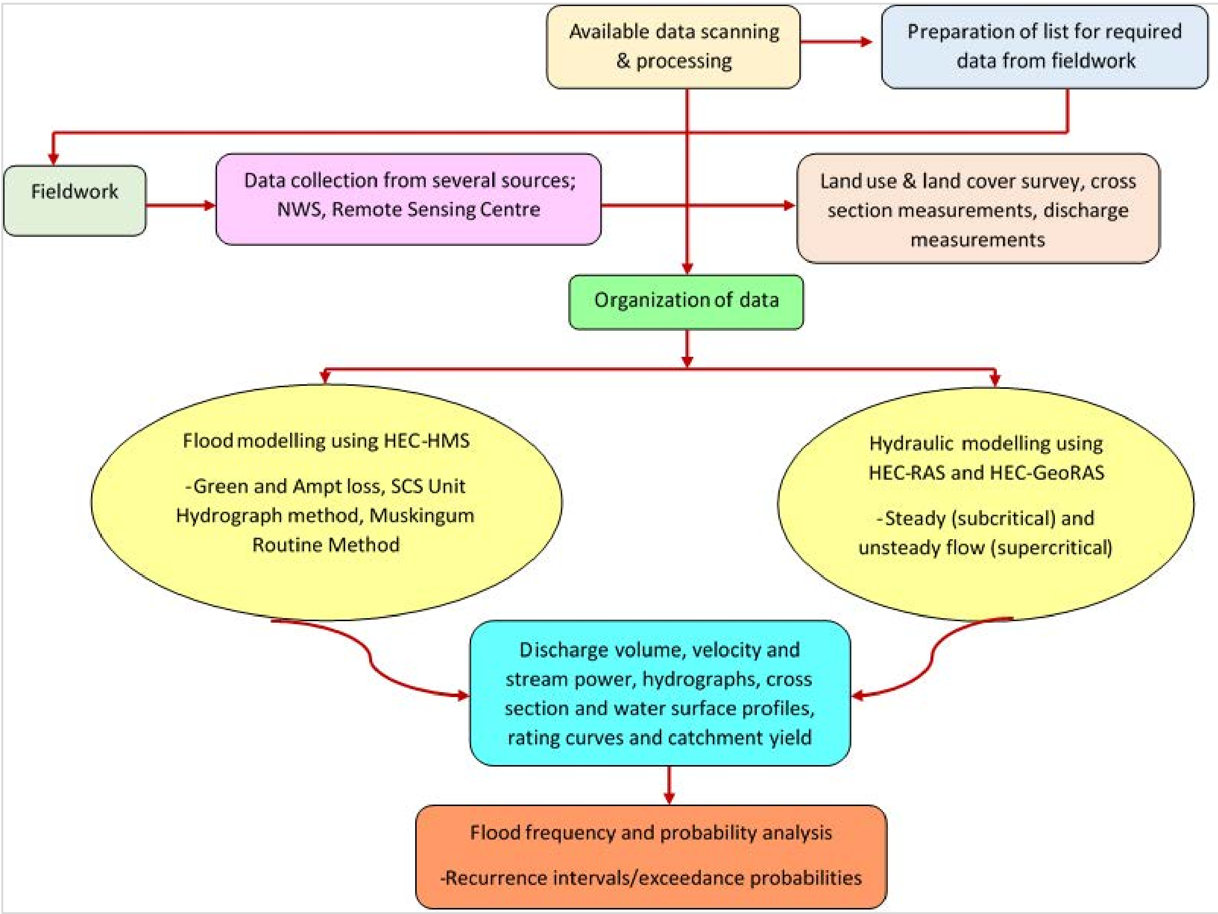

Figure 4.1: Work flow in chapter 4.

4.3.2 Input datasets

Meteorological data on temperature and rainfall were obtained from PNG NWS (2014) for Hoskins Airport at the daily level (1996-2013), and aggregated into monthly and annual means. The WNB Provincial Government Disaster Centre had estimates of average annual discharge data for the years 1980, 1990, 2000-2013 (NDC, 2013). However, they were not used as inputs into the models until they were validated with observed results and simulated model results. Slopes and landforms were derived from the PNGRIS database (PNGRIS, 2007). The drainage patterns[15] were demarcated into sub-catchments using the Dagi topographic map, geo-referenced in ArcGIS 10.2 and HEC-GeoRAS to *WGS 84/UTM Zone 56S.* These shape files were then exported into HEC-HMS and HEC-RAS modelling software. Stream types and their descriptions were based on Rosgen's (1994) classification, while the channel roughness coefficients were calculated using the Hicks and Mason (1991) scheme based on stream type for bankfull conditions (see table 2.1). Table 4.1 presents the datasets used.

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[15] 1st and 2nd order streams were excluded because of dense channel networks in the highest reaches of the Dagi catchment.

Table 4.1: Dataset, their sources and description.

Dataset	Source	Description	Resolution
Climate	PNG NWS	Temperature: 1996 - 2013 Rainfall: 1996 - 2013[16]	-
	PNGRIS	Rainfall: 1980, 1990 Temperature: 1980, 1990	1: 50,000 1: 50,000
Discharge	WNB Provincial Government	Average annual discharge estimates 1980, 1990, 2000-2013 for Dagi River Catchment	-
Physical Features	PNGRIS	Slopes, landforms	1: 50,000
Topographic Map	JCU, CMES Cartography Section	Sheet 8986 (Edition 1), Series 797 - drainage patterns	1: 50,000
DEM[17]	From topographic map contours	Digitised contours and spot heights	Resampled to 20m X 20m pixels
DSM[18]	RESTEC Japan ©XAXA	2014 Data	5m X 5m pixels

Elevation data is fundamental for generating the topography of the river channel and broader catchment. Before any DEM and DSM can be used for hydrological modelling, a hydrologically corrected surface needs to be created. Hence geometry was created from digitised contours and spot heights using the topographical map sheet of the area at a scale of 1:50,000 (figure 4.2a) (ITC, 2010). To create the surface, the "Topo to Raster" function was used in ArcGIS 10.2 (Earth Systems Research Institute – ESRI, 2010, pp.260). It interpolated the raster surface so that widespread restrictions for hydrological modelling (e.g. unconnected drainage, inaccurate delineation of ridges and streams)

[16] During the time of data collection, there were no 2014 rainfall data available at PNG National Weather Service. The 2014 data used to model the 2014 flood event were collected during fieldwork using a non-recording rain gauge for a duration of 10-days, 12 hours each in February, 2014 and January-February 2010.

[17] Digital Elevation Model is a digital model that represents continuous elevation values over a topographic surface by a regular array of Z-values, referenced to a vertical datum. They are used to represent the bare earth terrain without any manmade and vegetation features.

[18] Digital Surface Model is an elevation model that includes the tops of buildings, trees, power lines and any objects.

were minimised (Hutchinson, 1996; ITC, 2010) resulting in a realistic representation of the surface (figure 4.2b). The fill sinks method in the hydrology module of ArcGIS 10.2 was used to eliminate any defects in the height data to create a drainage network (figure 4.2c) (Earth Systems Research Institute – ESRI, 2010, pp.260). A surface was created with a 5m X 5m cell resolution compatible with the DSM resolution (figure 4.2d). Man-made terrain data including oil palm plantations were extracted from the DSM data, and rasterised using the "spatial analyst raster calculator tool" (figure 4.2d) (ibid.).

DEM extraction from the original DSM in SAGA[19] GIS was accomplished by three processes: 1. Subtraction of the elevated objects such as buildings and trees from DSM through: Modules/Grid filter/DTM filter slope based, and these gave two separated objects: bare earth and removed objects. 2. Filling the gaps of the raster cleared of objects through: Modules/Grid spline Interpolation/Multilevel B-Spline Interpolation from Grid, and 3. Polishing the DEM by: Modules/Grid-filter/Gaussian Filter. In ArcGIS 10.2 (ESRI, 2010, pp.260), the DEM derived from DSM was then clipped to the Dagi catchment polygon. The topo derived DEM, and the DEM derived from DSM, were each geo-referenced to *WGS 84/UTM Zone 56S.* Then they were converted to raster format using the "DEM to Raster" tool and mosaicked in the same units using the "Mosaic to New Raster" tool. Finally, the new DEM was resampled to 20m x 20m pixels to accommodate the topo derived DEM, and converted from raster to ASCII format to be compatible with other modelling software (chapter 5).

[19] System for Automated Geoscientific Analysis with immense capabilities for geodata processing and analysis programmed in the object oriented c^{tt} language (Conrad et al., 2015).

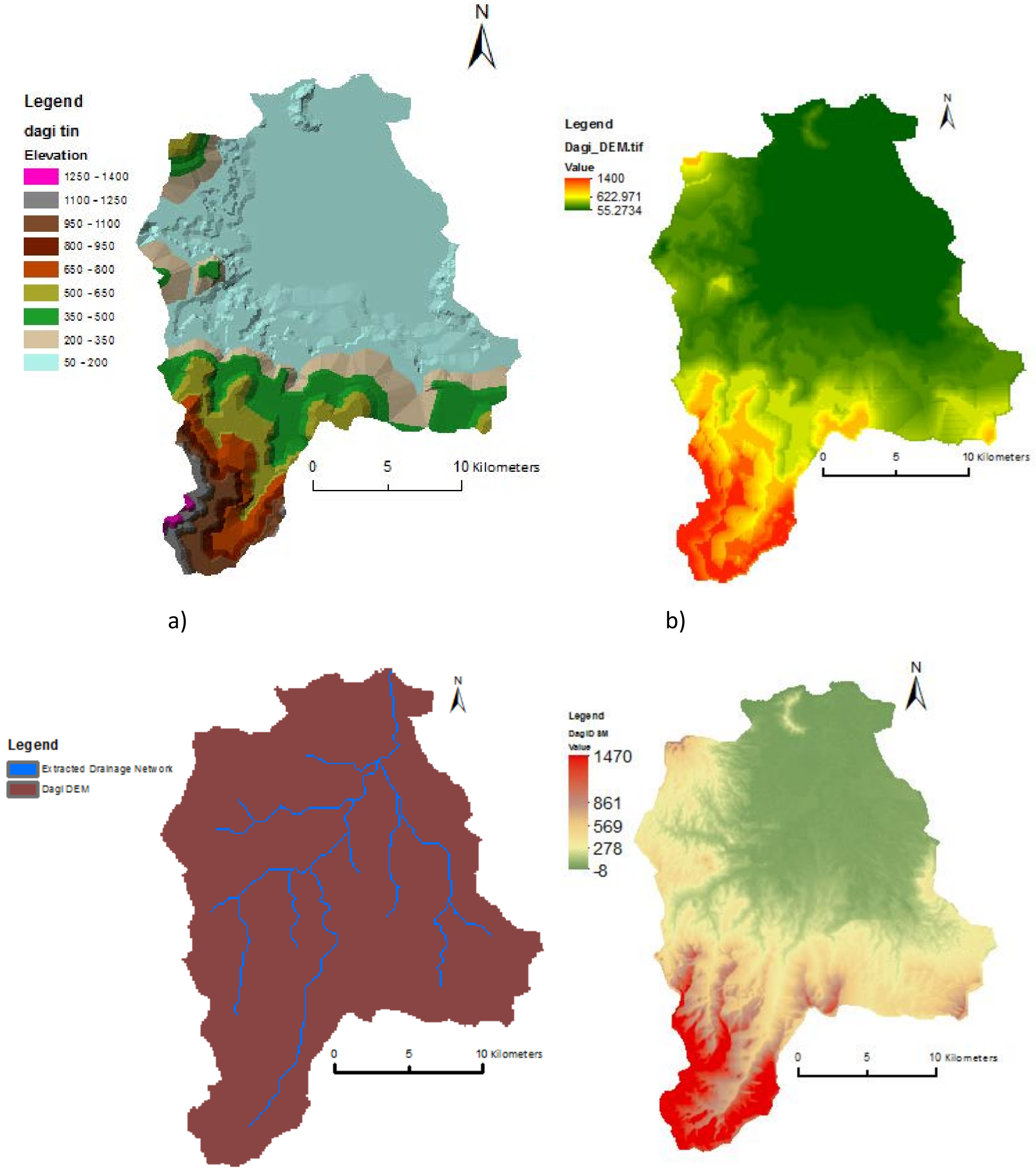


Figure 4.2: a) TIN[20] generated from digitised contours and spot heights, b) Generated DEM, c), extracted drainage network and d) DSM. *NB: Because of dense channel network in the highest reaches of the catchment, 1st and 2nd order streams are not shown on the map.*

[20] "Triangulated Irregular Network is usually represented by data stored in a data structure. It is used as a GIS to describe a three-dimensional surface as a set of irregularly shaped triangles. A set of points, called mass points, form the irregular triangles" (USACE, 2013: p.7).

4.3.3 Field data collection

Not all data for this study were available including historical records of river discharge and flood extents. That necessitated fieldwork in Dagi for three months. Of all the general climatic characteristics of Dagi, temperature and rainfall are important because their patterns influence the hydro-geomorphic behaviour of the unstable slopes, streams and river. Because Sarakolok (upstream) and Nahavio (downstream) DPI Stations are 12km apart and have a rain gauge each, rainfall data that spans 10 days and for a duration of 12 hours were also collected in February 2014 and January-February 2010. These were manually entered into the meteorological model component of HEC-HMS and used in the simulation.

The widths and depths of each cross-section per site were measured using a tape measure, staff gauge, compass, and poles during a dry season (low flows) in July 2010 (e.g. plate 4.1a). In each cross-section, bank stations were established to represent the river and stream banks during low flows, which were later plotted as reference points to define the flood depths and durations. Flood volume, depth and duration were required for simulation, modelling of its inundation extent, and to calibrate and validate model results. Discharge measurements were done using a Price AA Current Meter across shallow stream at equal intervals, while the floating method was used for the deep areas (e.g. plate 4.1b). Discharge was then averaged to a single value for each cross-section. Flood depths were determined from the reference bank stations and stream thalweg with the current extent identified by water marks on rocks and vegetation, plotted with GPS. Duration was measured by using reference poles placed along both banks and the time taken to recede to the poles (days) (figure 4.3, table 4.2 in appendix 4.1). People were also interviewed to gather information on past flood events.

a)

b)

Plates 4.1a and b: Cross-sectional and discharge measurements in 2010 dry season at Ru Creek (a) and Dagi upstream (b). *NB: Floats only used in deep channels.*

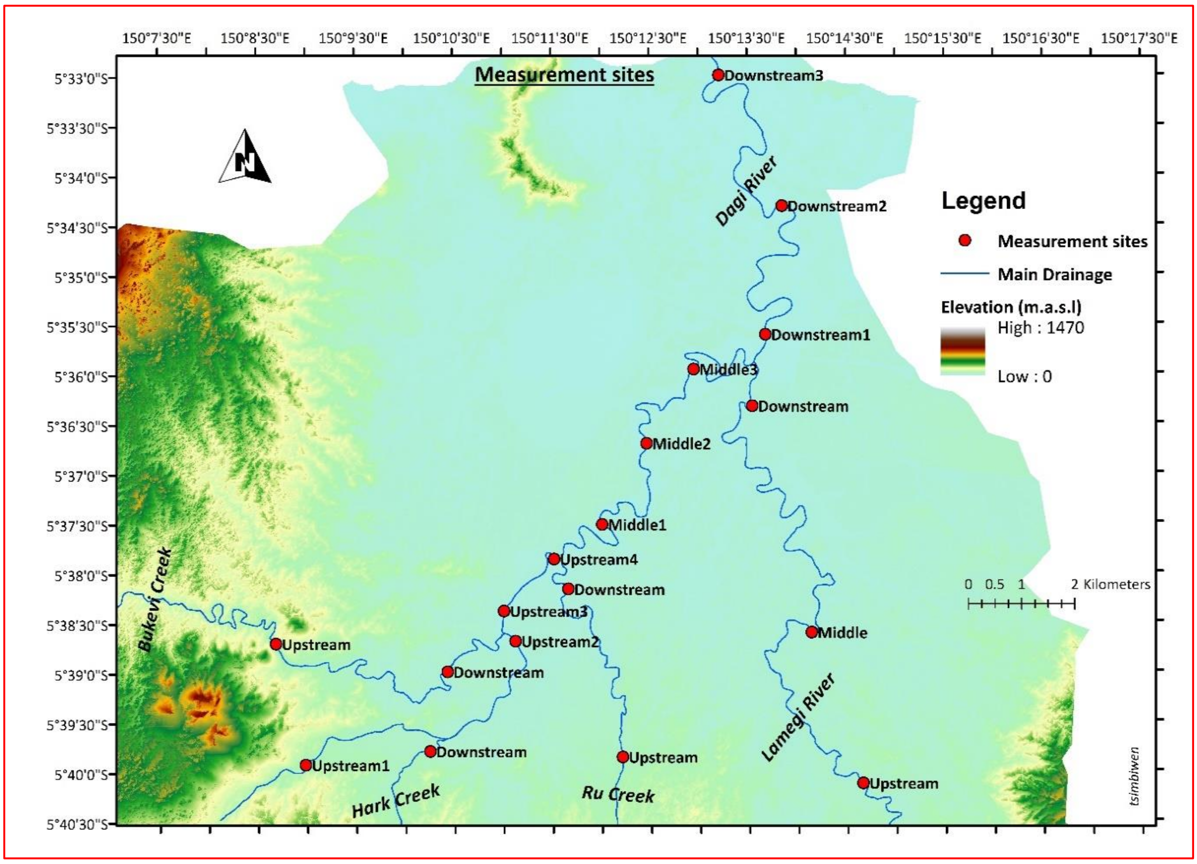


Figure 4.3: Measurement sites in Dagi catchment. *NB: 1st and 2nd order streams are not shown on the map because of dense channel networks in the highest reaches of the catchment.*

4.3.4 Analysis

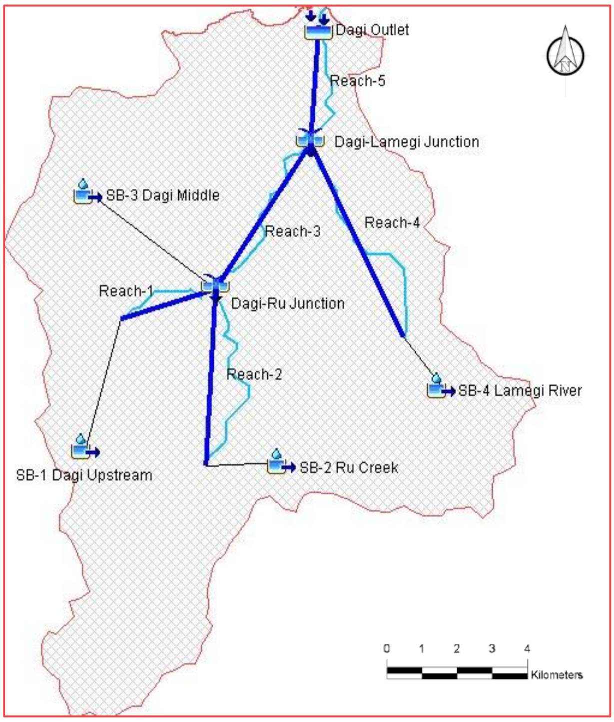
4.3.4.1 Analysis 1: Climate data

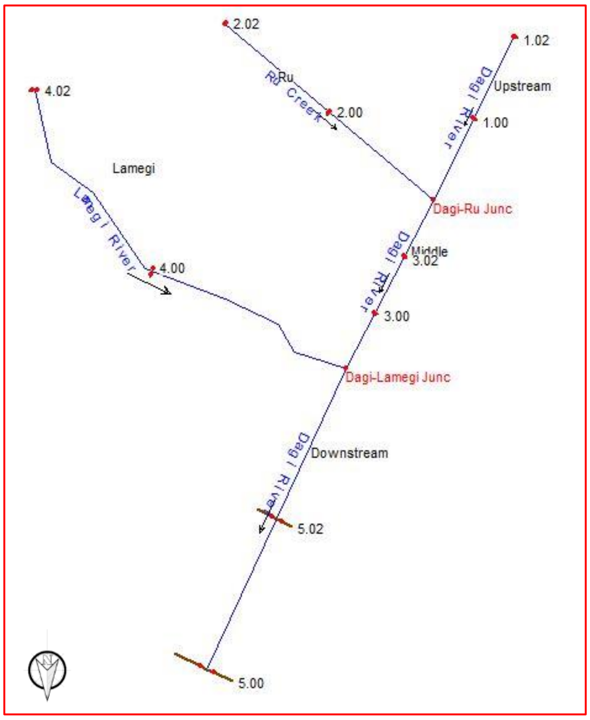
Before input into HEC-HMS, rainfall data were computed for their areal distribution patterns using the arithmetic mean method from two rain gauges. The temperature and rainfall data were differentiated by sample histograms, and observations were done on the outcome of discharge values (ITC, 2010). The average monthly temperature was derived by averaging each daily temperature value in the data series (ibid.) (figure 4.4 in appendix 4.2). These data were then graphically analysed based on their minimum and maximum trends as an intermediate step into model inputs (figure 4.5-4.6 in appendix 4.2). Similarly, daily rainfall data were averaged to a single value per month, analysed and plotted in a graph (figure 4.7 in appendix 4.2). Three-year moving averages were used to 1: reduce the effect of temporary variations in the temperature and rainfall data; 2: improve the fit of these data to show their trends more clearly using a smooth line; and 3: to highlight any value above or below the tendency so that any irregularity in values can be spotted and corrected (Bhattacharya, 2010). Data derived by this technique reveal the seasonal variation of climate in Dagi. After evaluating the data for fit using statistical models, the Log-Pearson Type III Distribution (Haans, 1977) and Gumbel's max statistical model (Gumbel, 1960) were chosen (ITC, 2010). They were used for additional examination because they gave reliable results in previous studies (e.g. Subyani, 2011; Boni et al., 2007). Finally, descriptive statistical analysis was done to observe spread of data.

4.3.4.2 Analysis 2: Modelling flood characteristics and behaviour

Two categories of flood models were used to determine the runoff resulting from a particular rainfall event and the flood characteristics and behaviour. The primary outputs from the hydrologic model per site were the discharge, velocity, stream power, distributions, water depths, and durations of flood that resulted from rainfall events (e.g. Gupta, 2011). The hydraulic model consisted of a linked 1D/2D model using a 3-metre grid. Model descriptions are given above and analysis done through them are described below.

Geometric data (junctions, connection nodes, and sinks) were created using HEC-GeoRAS extension in ArcGIS 10.2 following the procedures outlined in USACE (2009) and exported to HEC-HMS and HEC-RAS modelling software. By following HEC-HMS User's Manual Version 4.0 (USACE, 2009), the Dagi catchment model was created in HEC-HMS modelling software (figure 4.8a). The Green and Ampt Loss, SCS unit hydrograph transform and recession base flow methods, and Muskingum Routing Method were selected for this study (Gupta, 2011), and followed the procedures outlined in the HEC-RAS User's Manual Version 4.1 (USACE, 2010) to compute upstream and downstream discharges of Dagi River. Furthermore, the HEC-GeoRAS and HEC-RAS modelling software were used to create cross-sections and longitudinal profiles and velocity distributions for each discharge measuring point (figure 4.8b), based on the hydrological and cross-sectional data collected from fieldwork. Finally, stream hydraulics data (e.g. water surface elevation and wetted perimeter) were derived using a combined Steady Flow (subcritical) and Unsteady Flow (supercritical) under HEC-RAS menu options. Thus, both HEC-HMS, HEC-GeoRAS and HEC-RAS modelling software were used to model 2014 and 2010 floods. In addition, slopes and channel roughness values in Right Over bank (ROB), Channel and Left Over Bank (LOB) were calculated for each stream cross-sectional profile in *Excel* and were entered into the model parameters to compute stream hydraulic values (see table 2.1).





a) b)

Figure 4.8a and b: Dagi River catchment modelling network in HEC-HMS (a) and HEC-RAS cross-section schematics (b). *NB: Because of dense channel networks in the highest reaches of the catchment, 1st and 2nd order streams are not shown on the map.*

4.3.4.3 Analysis 3: Flood frequency and probability

Various flood frequency distributions can be used in statistical analyses such as the Normal Distribution (Bowers et al., 2012), Log-Normal distribution (Gottschalk et al., 2013), Gumbel Distribution (Zhang et al., 2012), and Log-Pearson Type III Distribution (Haans, 1977). They can estimate flood types but each possesses advantages and disadvantages. I used the Log-Pearson Type III Distribution (ibid.), which is the endorsed procedure for analysing flood occurrences (Gupta, 2011; US Water Advisor Committee, 1982). It is a numerical method used to fit flood occurrences and know their dispersals so that floods can be predicted (Gupta, 2011) (Appendix 4.3). This technique has the advantage of extrapolating current flood recurrence intervals to observe future events (Gottschalk et al., 2013).

The Frequency Factor Table determines the frequency factor (K) in a Log-Pearson Type III statistical distribution (Haan et al., 1994). The skewness coefficient was calculated and the desired return period was chosen where K is a function of these two variables and is listed in the table. Using the procedures outlined in Oregon State University (2005), the k-values for 2, 5, 10, 25, 50, 100 and 200 return periods were determined using the tables containing the frequency factor and skew coefficients (Cs). The Cs calculated was -0.87420534 and thus the value lies in between two given skew coefficients (appendix 4.4). The appropriate k-value was taken by linearly extrapolating between the two numbers. The general equation used was logQTr = avg (logQ) + [K (Tr, Cs)] x σlogQ; where logQTr is logarithmic of the peak discharge (Q) and its return period (Tr), logQ is the log of the maximum streamflow, K is the frequency factor, Cs is the skew coefficient used with return period in the frequency factor table to determine K, which subsequently determines the shape of the flood frequency diagram (asymmetry). σlogQ is the standard deviation (measure of spread of the mean dataset) of the peak discharges. Using this equation, the discharge associated with each recurrence interval was computed and displayed in semi-log graph paper. After the statistical data were calculated for Dagi, a flood frequency distribution was determined together with the likelihood of occurrence for different floods using the generated curves (Haans, 1977).

4.4 Results

4.4.1 Seasonal rainfall and runoff pattern in Dagi

The Dagi River system is "perennial" meaning it flows non-stop throughout the year at varying discharge volumes. It experiences high runoff in the wet season (November-April) and low runoff in the dry season (May-October). The different streams contributing water to the Dagi channel are perennial and this periodic pattern of the Dagi River are linked to its temporal rainfall sequence. It is attributed to excess rainfall over infiltration. A hydrograph in response to rainfall exemplifies the character and behaviour of the hydrological regime of the Dagi River (e.g. figure 4.9).

The differences between hydrographs at different locations indicate that variability in rainfall impacts the hydrological pattern of the Dagi River. The principal factor obviously influencing floods in Dagi is rainfall. The rainfall intensity and its duration means that more water is available for runoff over land and into stream channels. In-channel rainfall amounts contribute less to floods. As rain water moves over land, it is aided by slopes to flow fast downslope. Upstream contribution of water is greater than that of downstream because of the slopes as a major factor to aid overland flows into stream channels. The soil infiltration capacity is high. However, with increasing rainfall intensity and duration, soil infiltration decreases as they reach their field capacity and allow excess water available for runoff which are then aided by the slopes to be available in stream channels.

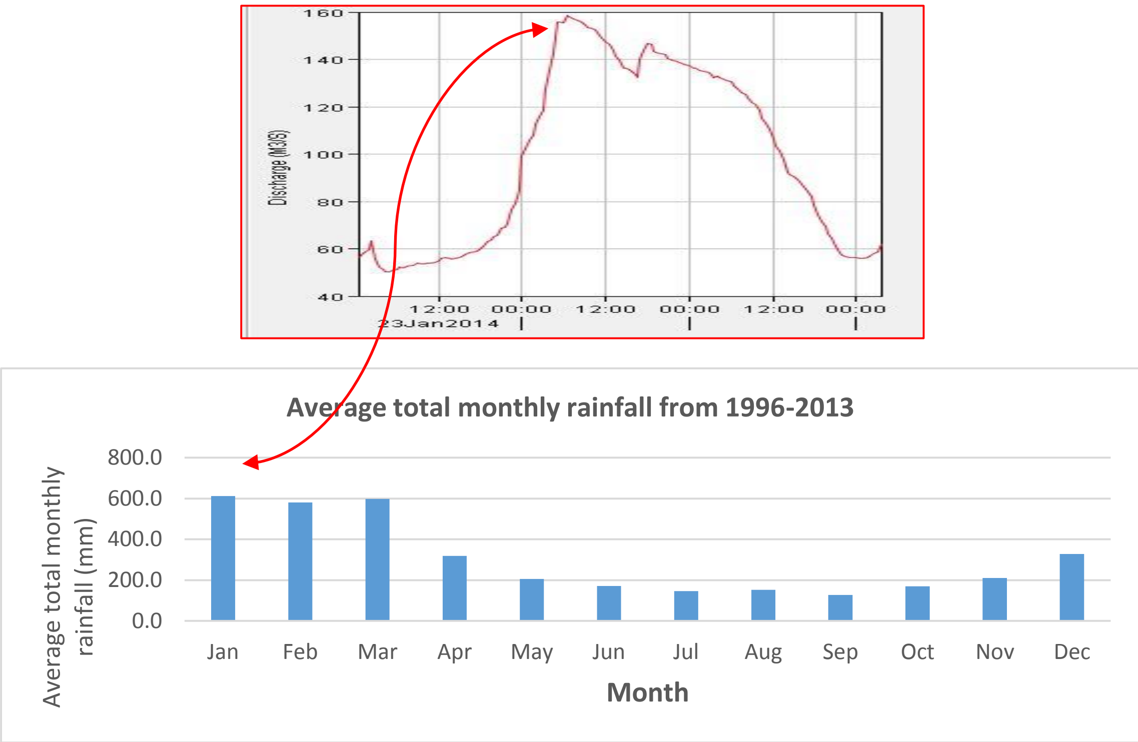


Figure 4.9: Distribution of average monthly rainfall from 1996-2013 in relation to a January hydrograph (PNG NWS, 2014).

4.4.2 Flood peak discharges and runoff volume from sub-catchments

According to USACE (2013:124), a discharge means outflow, and refers to the volume rate of water that is transported through a given cross-section per unit time expressed as cumecs, or cubic metres per second (m^3/s). In this study, discharge data on surface water represents the total fluid measured (including sediment, dissolved chemicals or biological material). It is reported in total volumes or time rates (m^3/s) (USACE, 2013; p.124). Volume is used here to refer to the thickness of the water layer in the field expressed in depths of millimetres (mm). In HEC-HMS program, the millimetre unit of depth is written as MM (ibid.). It is a method of comparing discharge (m^3/s) and rainfall (mm) with the basin area (A) of different years. Manually, it can be calculated as: Water Depth = *v/a*, where *v* is the volume of water and *a*, is the surface of the drainage area. HEC-HMS calculates volume (in MM) by several methods. The method used in this study was the SCS Unit Hydrograph Method[21] as described in HEC-HMS User's Manual Version 4.1 (USACE, 2013). Three practical applications following this method

[21] The SCS Unit Hydrograph Method was developed by the United States Department of Agriculture Soil Conservation Service (SCS). The method estimates rainfall excess from rainfall (Hjelmfelt, 1991). This method is described in detail by Lyon et al. (2004). It provides a good explanation of 2D overland flow (Hromadka et al., 1987; p.1422).

were outlined in Pistocchi and Mazzoli (2002, p.305-306), Yusop et al. (2007, p. 41-48) and Chandhari et al. (2014, p.253). The rate of rise of flood water greatly influences the flood runoff volumes dissipated in the Dagi catchment. Summarised in table 4.2 are the peak discharges, time and volumes contributed by each reach during the 2014 and 2010 floods.

The total peak discharge and volume in the reaches and junctions varies across space and time in the Dagi (table 4.3). In 2014, Reach-1 peaked at 12:30pm and discharge was 624.2m^3/s with a runoff volume of 86.96MM. Reach-2 peaked at 13:05pm and discharged 146.7m^3/s with a runoff volume of 59.48MM. Peak at the Dagi and Ru Junction was at 12:35pm with discharge and volume contributions of 743m^3/s with 80.51MM, respectively. Reach-3 discharged 1002.6m^3/s with 72.61MM in volume and peaked at 13:25pm. Reach-4 peaked at 13:00pm with discharge of 199.8m^3/s and volume of 71.6MM. At the Dagi and Lamegi River junction, peak discharge was at 13:15pm with 1187.6m^3/s and the volume was 72.47MM. In Reach-5, the peak discharge was at 14:15pm and contributed a total discharge of 1158m^3/s and a volume of 72.04MM.

In 2010, Reach-1 peaked at 12:30pm with discharge of 1179.8m^3/s and runoff volume of 130.10MM. Reach-2 contributed 333.9m^3/s and 101MM as it peaked at 13:05pm. Peak discharge at the Dagi and Ru junction was 1463.9m^3/s with a volume of 121.73MM when it peaked at 12:40pm. Reach-3 discharged 2082.7m^3/s with a volume of 112.30MM at the time of peak at 13:25pm. Reach-4 discharged 417.9m^3/s and contributed 113.60MM in volume when it peaked at 13:00pm. Reach-5 peaked at 14:20pm with a peak discharge of 2414.4m^3/s and volume of 109.67MM. In both years, the time of peak at most reaches was the same with only 5 seconds' difference for Dagi-Ru and Dagi-Lamegi junctions, and Reach-5. The time of peak at the Dagi outlet was between 14:15pm and 14:20pm from Reach 1 (12:30pm) for both flood events. Therefore, it takes almost two hours for floods to travel the 35-kilometre length to reach the Dagi outlet. The short travelling time difference was due to little roughness in the channel and overbank areas.

Table 4.2: Summary of simulated peak discharges and their volumes at sub-catchment, reach, junction and outlet during 2014 and 2010 floods.

Hydrologic Element	Drainage Area (km^2)	2014 Peak Discharge (m^3/s)	2014 Date/Time of Peak (24Feb)	2014 Volume (MM*)	2010 Peak Discharge (m^3/s)	2010 Date/Time of Peak (24Feb)	2010 Volume (MM)
SC* 1-Dagi upstream	204.31	729.0	11:30	87.02	1326.0	11:30	130.10
Reach-1	204.31	624.2	12:30	86.96	1179.8	12:30	127.95
SC2- Ru Creek	62.63	170.0	11:45	58.17	370.6	11:45	102.12
Reach-2	62.63	146.7	13:05	59.48	333.9	13:05	101.43
Dagi-Ru Junction	266.94	743.0	12:35	80.51	1463.9	12:40	121.73
SC3-Dagi middle	153.25	381.9	11:50	59.30	811.9	11:50	101.43
Reach-3	420.19	1002.6	13:25	72.61	2082.7	13:25	112.30
SC4-Lamegi River	71.75	231.6	11:40	71.97	466.5	11:40	115.91
Reach-4	71.75	199.8	13:00	71.60	417.9	13:00	113.60
Dagi-Lamegi Junction	491.94	1187.6	13:15	72.47	2471.9	13:20	112.49
Reach-5	491.94	1158.4	14:15	72.04	2414.4	14:20	109.67
Dagi Outlet	491.94	1158.4	14:15	72.04	2414.4	14:20	109.67

*SC = Sub-Catchment, often SB (Sub-Basin), refers to the same hydrological element. *MM* is HEC-HMS's way of expressing millimetre (mm) of depth.*

Two images are shown for peak discharges at the Dagi Bridge as they meet the remnants of the riparian vegetation (plates 4.1a and 4.1b).

a) b)

Plates 4.2a and Plate 4.2b: a) 2010 flood, picture taken from the Dagi Bridge looking upstream and b) 2014 flood looking downstream from the same bridge.

Hydrographs for each sub-catchment generally show a steady rise of the peak flow (cms[22]) from the initial simulation around 5:00am, however, as time progressed, the peak flows varied (figure 4.10 and 4.11). The variation in the time of peak is because of the distances from each sub-catchment upstream to the next and into the outlet. The travelling distance of flood waters between upstream and downstream reaches influenced how much time the discharge took before reaching the outlet and allowed their volumes to dissipate. For example, during the 2010 and 2014 floods, sub-catchment 1 showed a steady rise in the hydrographs from the initial storm at 5:00am and peaked around 11:30am, that of sub-catchment 3 (1 kilometre downstream) peaked at 11:45am while that of reach 5 which is 8km further downstream near the outlet peaked at 14:10pm. The amount of rainfall received influenced the shape and size of the hydrograph, meaning more or less floodwater moved through the system. For example, sub-catchment 1 shows a broader hydrograph with a peak discharge of 1326m^3/s for 2010 compared with the steep hydrograph for 2014 at 729m^3/s. It is obvious that a flood that escalates rapidly undoubtedly delivers shorter time to warn and evacuate people and their assets (Queensland Government, 2011).

[22] cms on the y-axis of the hydrograph refers to cumecs, which are read as cubic metres per second (m^3/s).

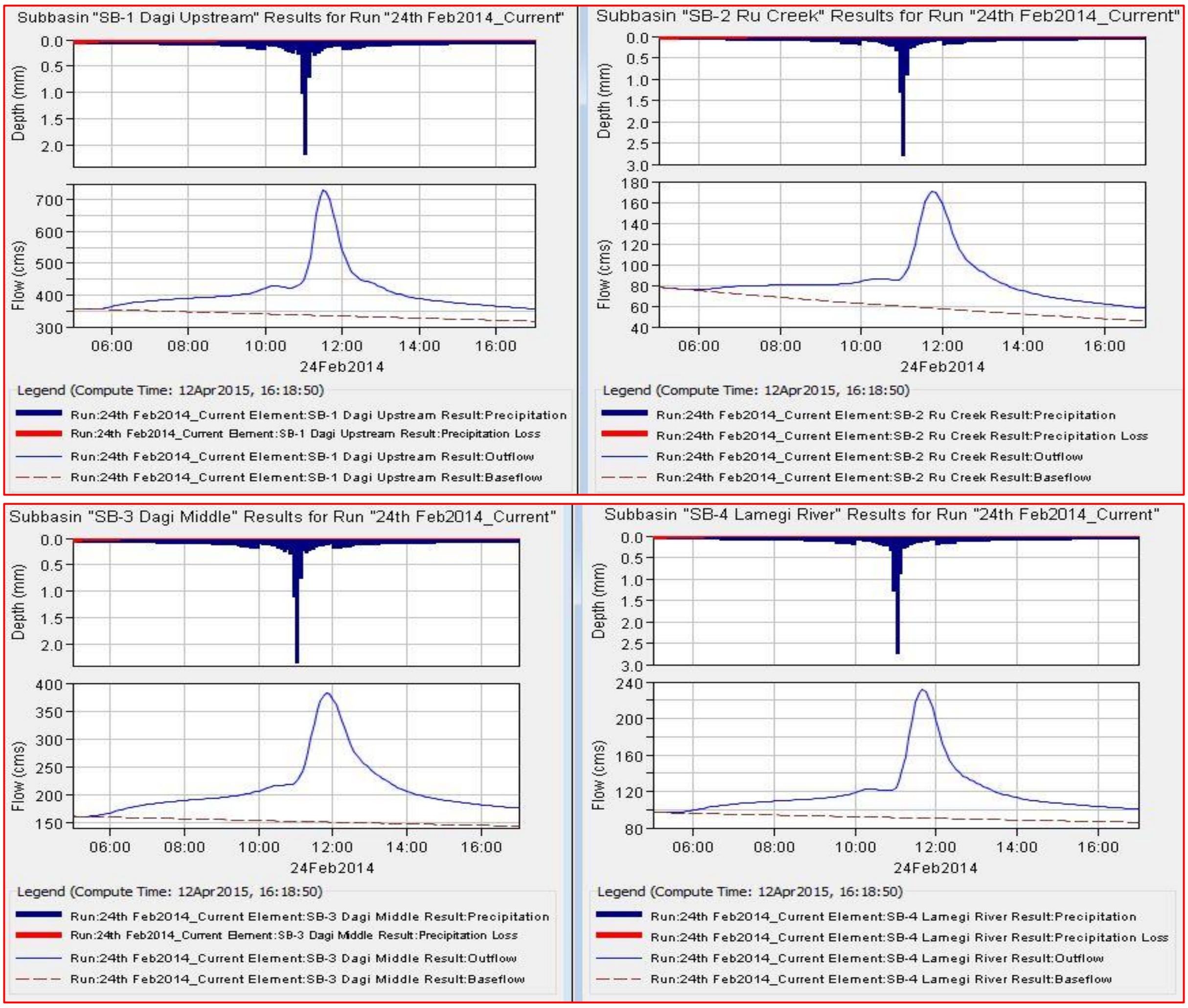


Figure 4.10: Flood hydrographs of sub-basins in Dagi on the 24th of February 2014 *NB: Modelling sites per sub-basin are shown in figure 4.8a. It is understood that the HEC-HMS program only presents units of rainfall depth as mm or inches in hydrographs. The depth on the y-axis shown in mm unit was supposed to be in metres.*

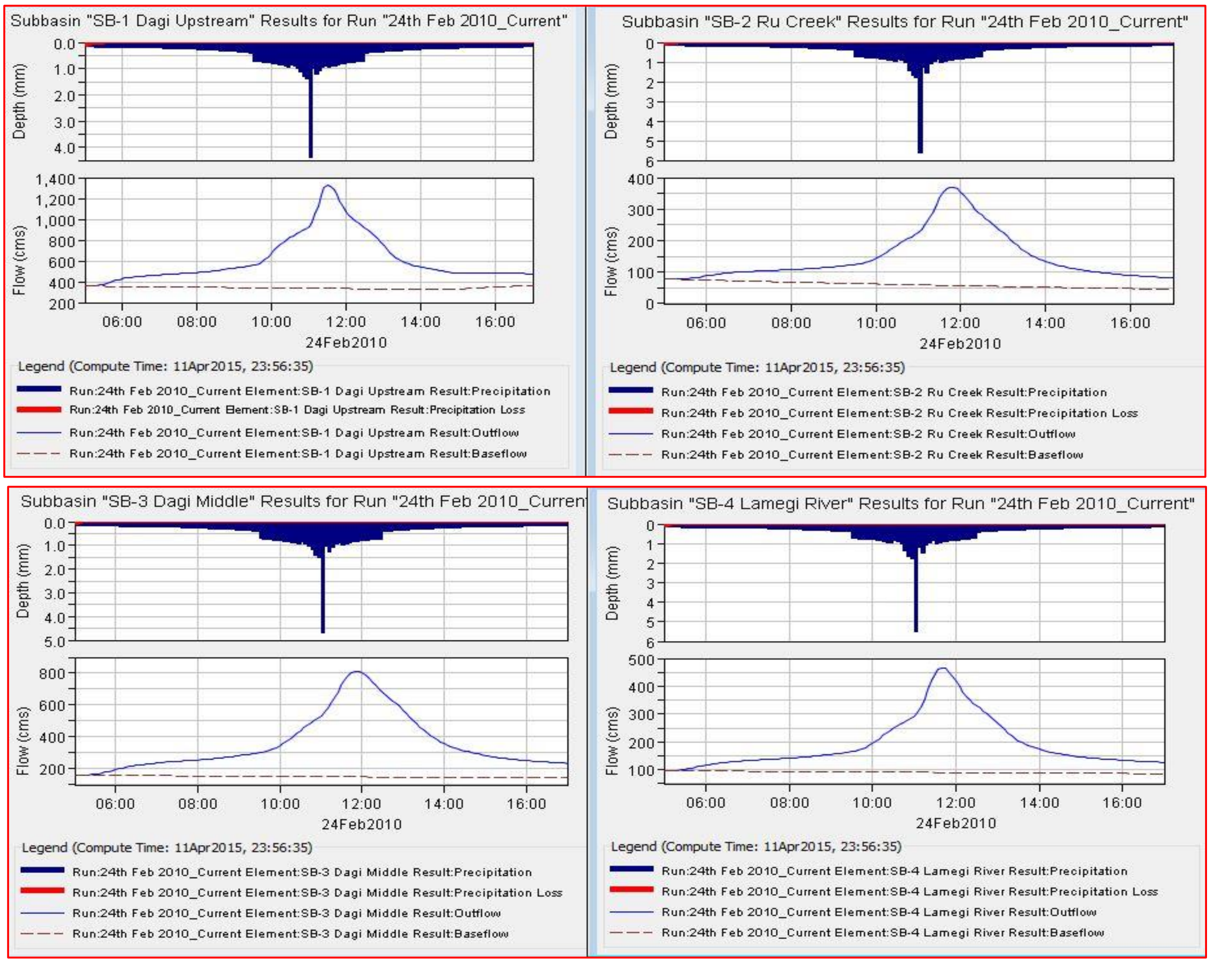


Figure 4.11: Flood hydrographs of sub-basins in Dagi on the 24th of February 2010. *NB: Modelling sites per sub-basin are shown in figure 4.8a. It is understood that the HEC-HMS program only presents units of rainfall depth as mm or inches in hydrographs. The depth on the y-axis shown in mm unit was supposed to be in metres.*

Sub-catchments contribute varying amounts of floodwater into waterways and this depends on drainage size, area and how much water overflows the river banks. For example, sub-catchment 1 drains an area of 203.31km^2 and contributes 729.0m^3/s in 2014 and 1326.0m^3/s in 2010 respectively (table 4.3). On the other hand, sub-catchment 3 drains an area of 53.25km^2 and contributes 381.9m^3/s in 2014 and 811.9m^3/s in 2010. In comparison, the outlet drains an area of 491.94km^2, and had a total of 1158.4m^3/s in 2014 and 2414.4m^3/s during the time of simulation.

The direct flood runoff and outflows from each reach in the sub-basins during the 2010 and 2014 floods are shown in figure 4.12, respectively. The peak flow was generally around 13:00pm for all the reaches with broad shaped hydrographs. Direct runoff is generally higher in 2010 than 2014 because

2010 received more rainfall. Direct runoff peaked between 11:30am and 12:00pm for all sub-catchments.

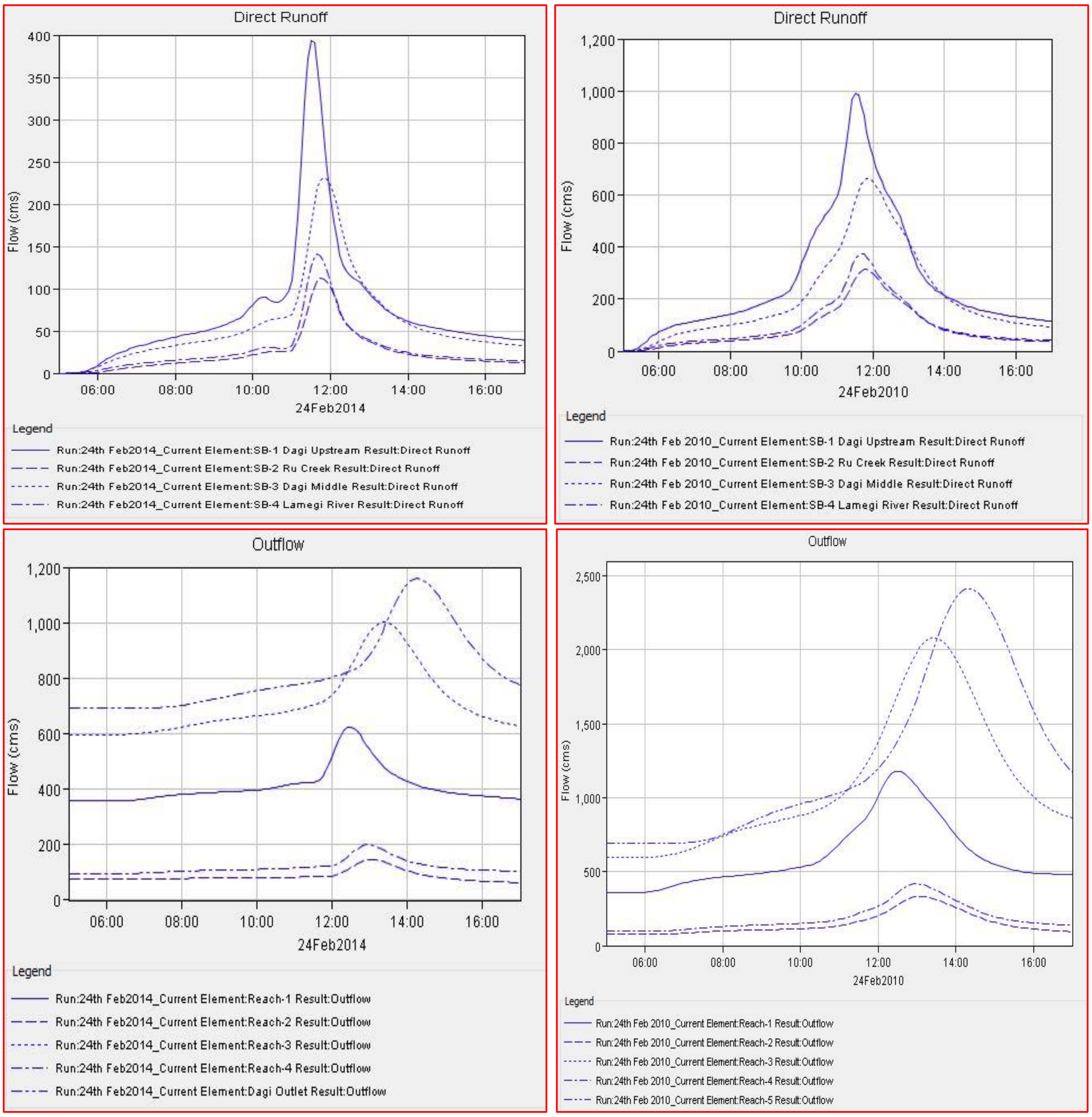


Figure 4.12: Direct flood runoff and outflows from all the reaches in the sub-basins in 2014 and 2010.

The peak outflow contributions for the Dagi-Ru junction for both 2010 and 2014 occurred between 12:00-13:00pm with steep hydrographs (figure 4.13). On the other hand, the peak flow for the Dagi-Lamegi junction was between 13:30pm and 14:00pm respectively. The variation in time is because of the travelling distance, slope and vegetation characteristics of the stream network and channels.

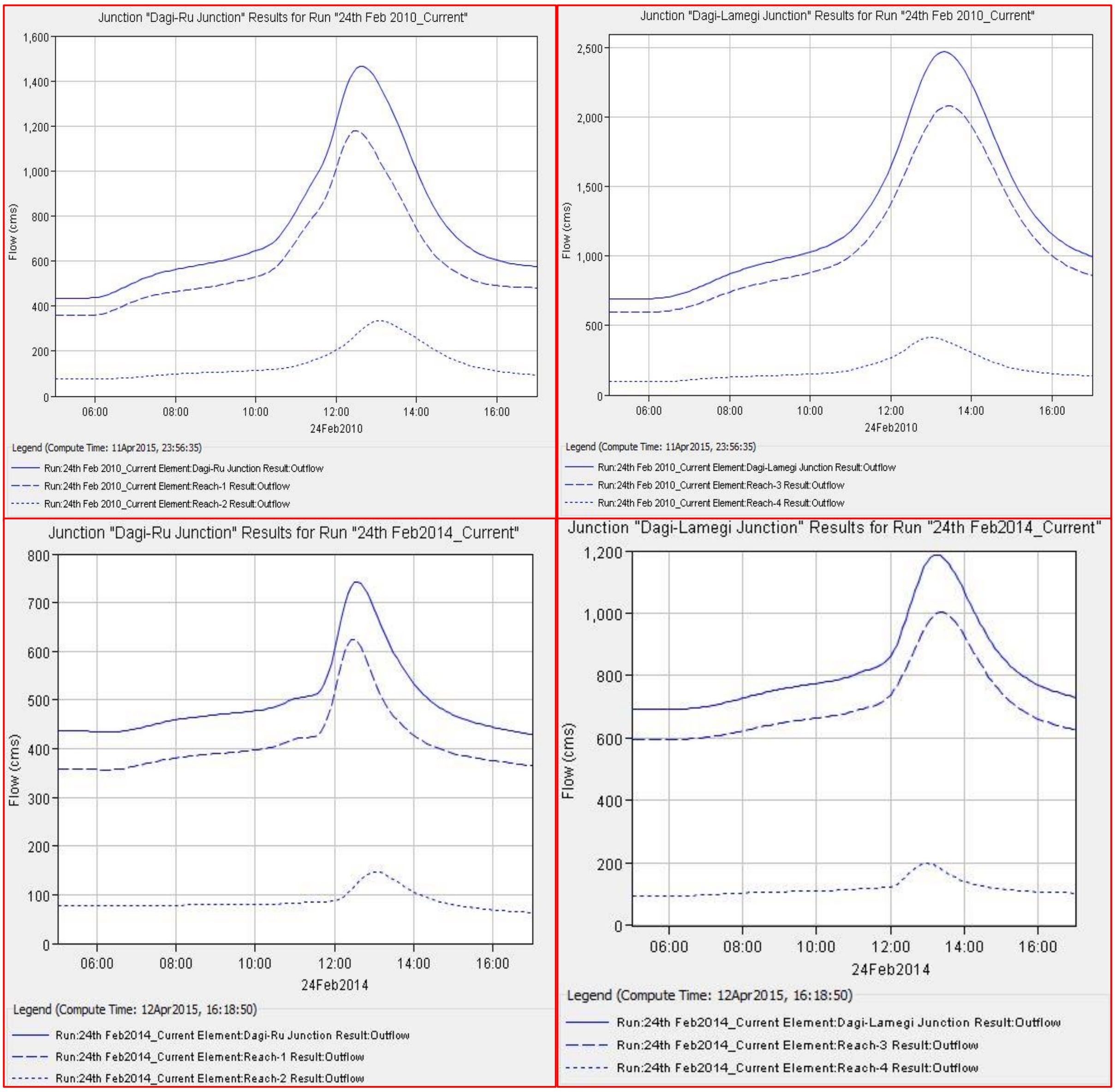


Figure 4.13: Flood outflows in Dagi-Ru junction and Dagi-Lamegi junction in 2010 and 2014.

Therefore, not all the flood water flows on to the next reaches and the junctions, due to water overflowing the river banks and causing a reduction in the total inflow and outflows into the next reach and junctions. The spatial extent of the channel flood is the topic for investigation in Chapter 5. Although detailed time series tables were created for all simulation runs showing the precipitation loss, excess and direct flow from each sub-catchment, only the 2014 results for Dagi upstream and downstream are presented in appendix 4.5 for comparative purposes.

The discharge and runoff volumes simulated for the 2010 and 2014 (figure 4.14) can be compared with the total estimated annual discharge from the WNB Provincial Government Disaster Office data (table 4.4 in appendix 4.6). Specific flood discharge volumes are not included here because they have been averaged to give an estimated annual figure. Thus, the simulation run was based on the rainfall, runoff measurements and catchment characteristic data gathered during the fieldwork for each sub-catchment. The flood discharge figures as presented above differs from the average annual values given in table 4.4 in appendix 4.6 for each year for the Dagi catchment. As shown in figure 4.14, the simulated peak discharges between upstream and downstream sites vary, with sub-catchment 1 (upstream) recording high discharges in both years as it had a large catchment area and steeper slopes, with consequently greater net rainfall and faster overland runoff in comparison to other sub-catchments.

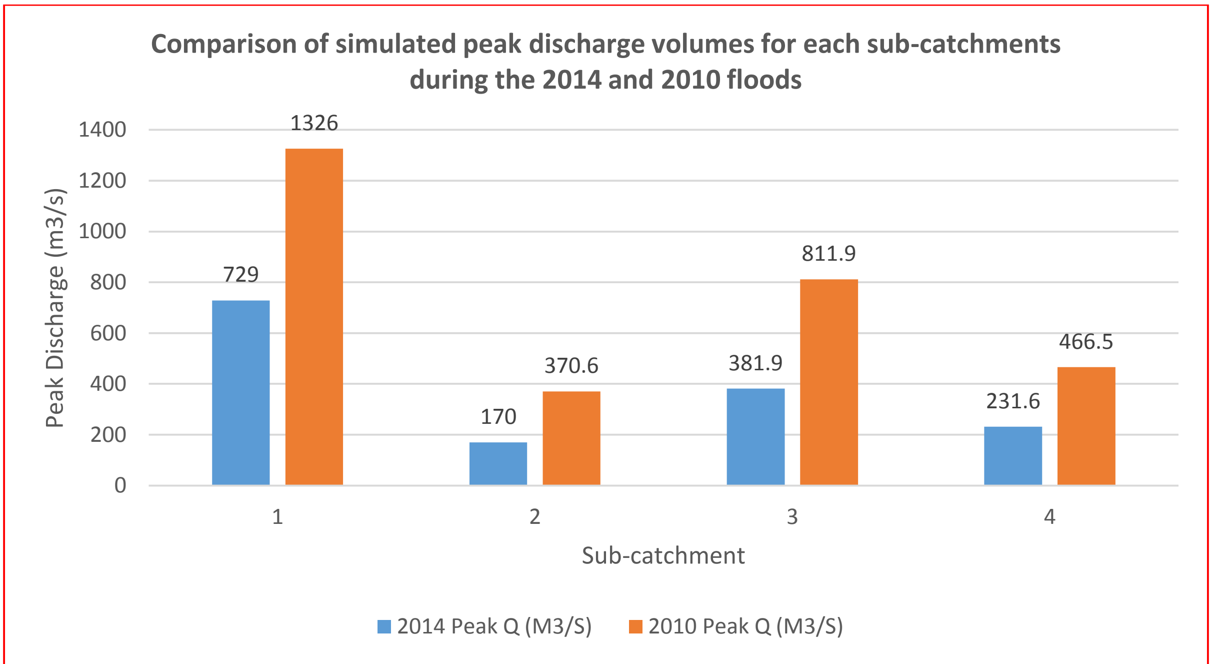


Figure 4.14: Comparison of simulated peak flow volumes for each sub-catchment during the 2014 and 2010 floods.

The specific yield for the main sub-catchments are presented in figure 4.15. Specific yield is defined as runoff per unit area of contributing catchment (Gupta, 2011). This is calculated separately for each sub-catchment. For example, the specific yield for sub-catchment 3 refers to the catchment areas between sub-catchment 1, 2 and 4 as shown by each drainage demarcation (figure 4.8a). Sub-catchment 1 contained the highest yield, reflecting rainfall intensity, frequency and duration in the mountains and the steeper slopes.

All sub-catchments show little variation in their yields, these being a function of rainfall characteristics and sub-catchment sizes. This means that a sub-catchment with a big size, will give high yield when there is high rainfall and vice versa. However, the volume of water contributed by different parts of the catchment can vary from season to season in a year. For example, from the initial yield in sub-catchment 1 in 2010 (130100MM), there is a decrease in yield at the outlet (115910MM). This is due to considerable floodplain storage along the main channel of the Dagi River, along sub-catchment 3, reach 3 and Dagi-Lamegi junction and reach 5 going to the outlet. The cross-sectional profiles along each reach is presented and discussed in the next section.

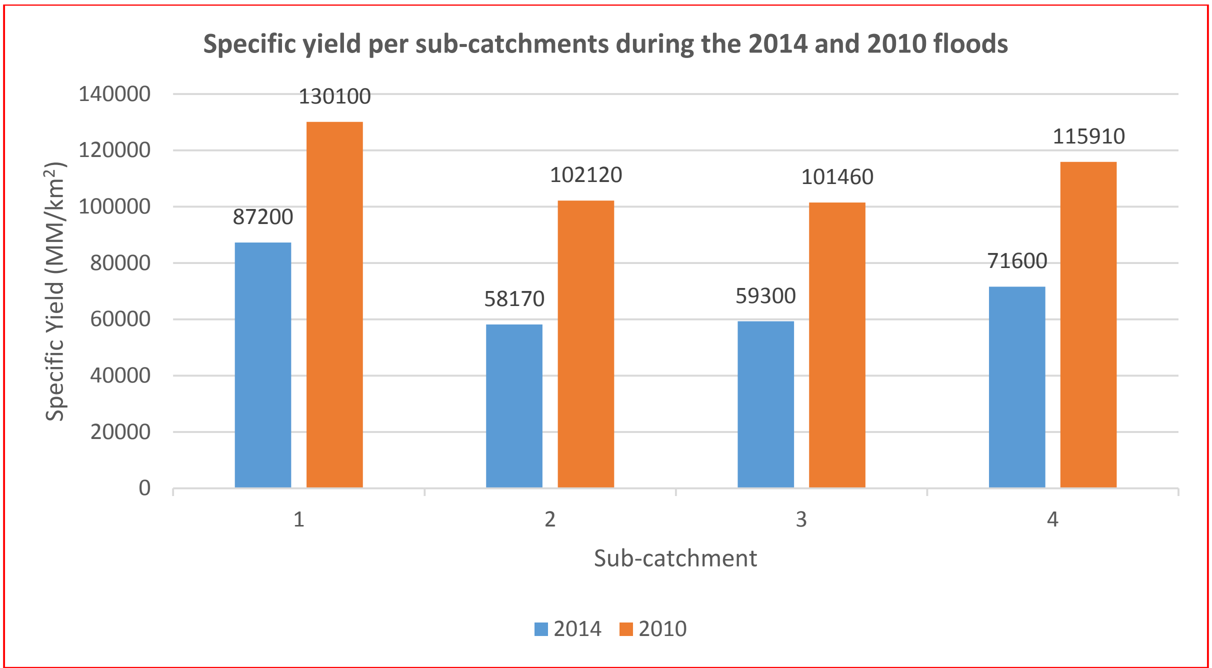
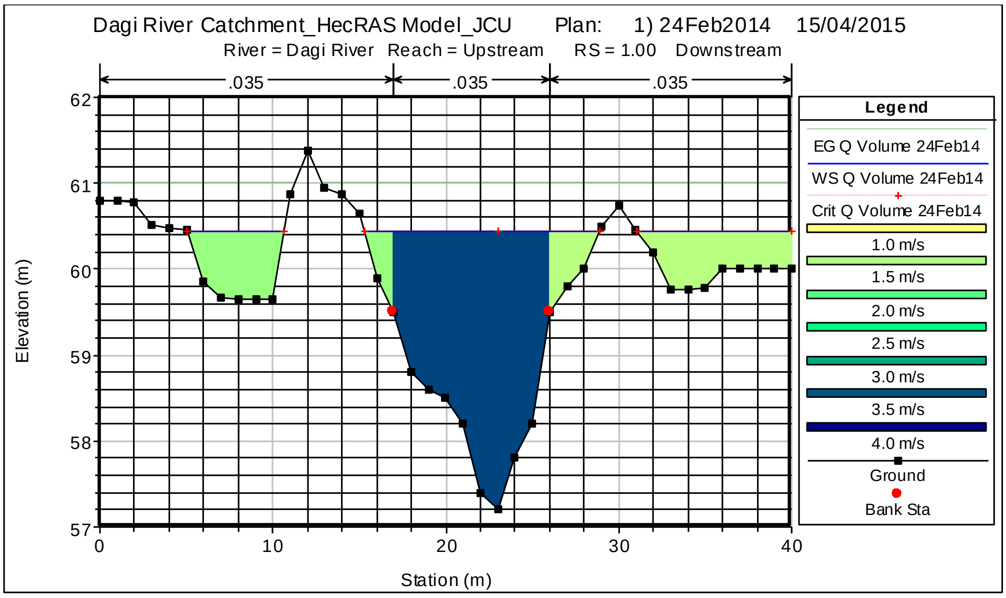


Figure 4.15: Specific yield per sub-catchments in 2014 and 2010 floods.

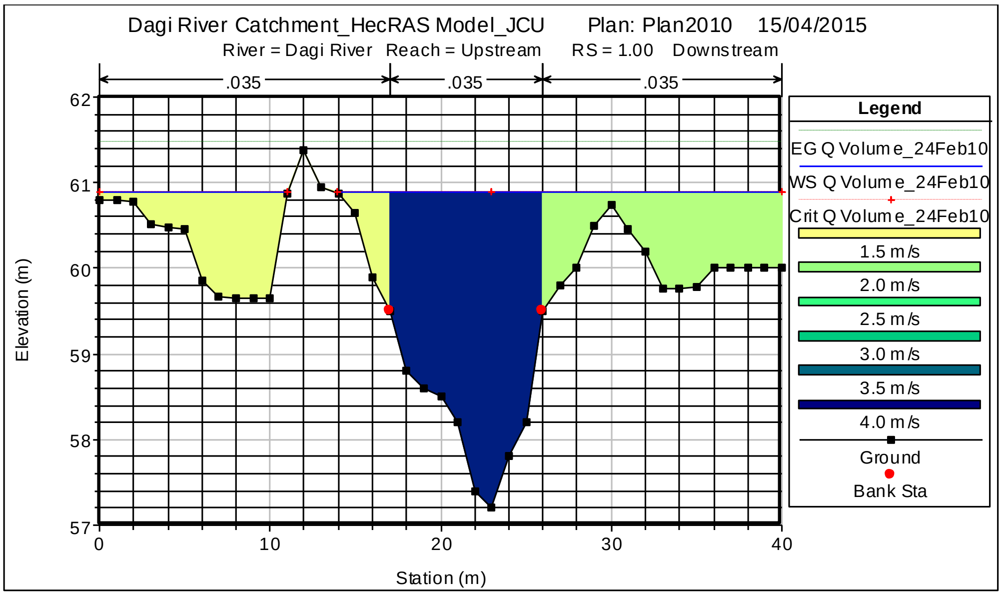
4.4.3 Volume, velocity and stream power distributions in cross-section and longitudinal profiles

The cross-section plots show the energy grade (EG), observed water surface (WS) and the critical depth elevations (crit.) in relation to the total volume of water. Velocity distributions across the cross-sections show the variation in patterns between the two flood events. All stream cross-sections show evidence of channel overflows by total volumes (plate 4.2, figures 4.16a-b, 4.18a-b, 4.19a-b, also see appendix 4.7 for other reaches). The longitudinal profiles for Dagi upstream and downstream are shown in figures 4.17a-b and 4.20a-b (see appendix 4.7 for other reaches).

Plate 4.3: Overflows of Dagi River into oil palm plantations in the middle reach during the 2010 flood.

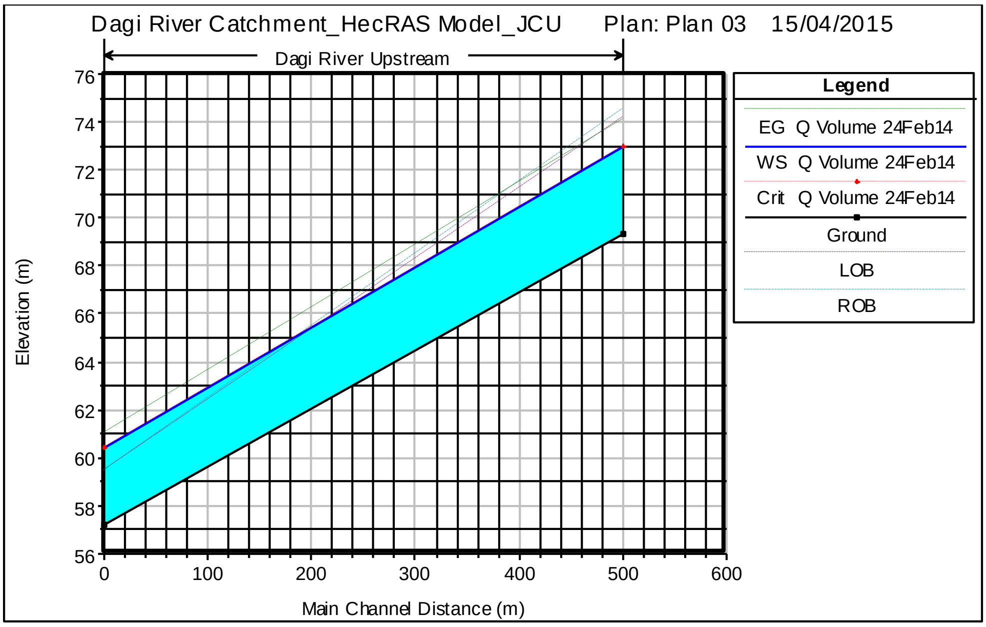


a)



b)

Figures 4.16a and 4.16b: Sub-catchment 1-Dagi River upstream cross-sectional profile plots.



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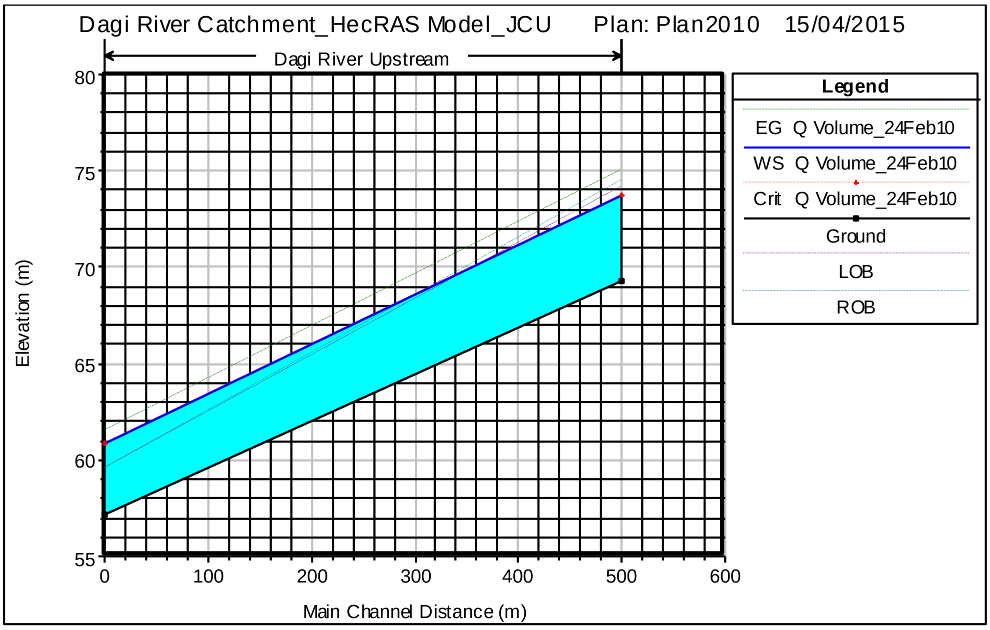
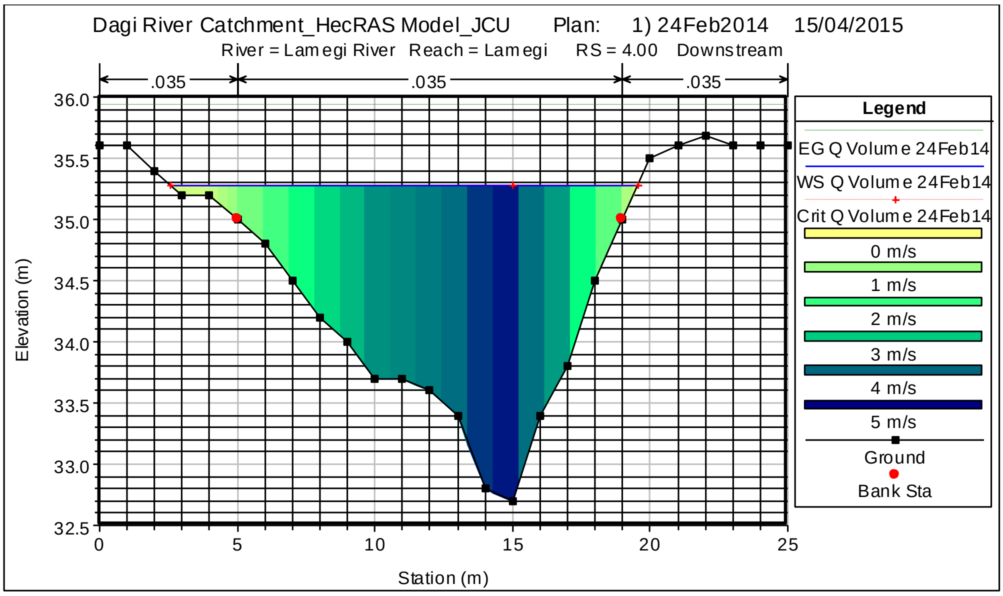
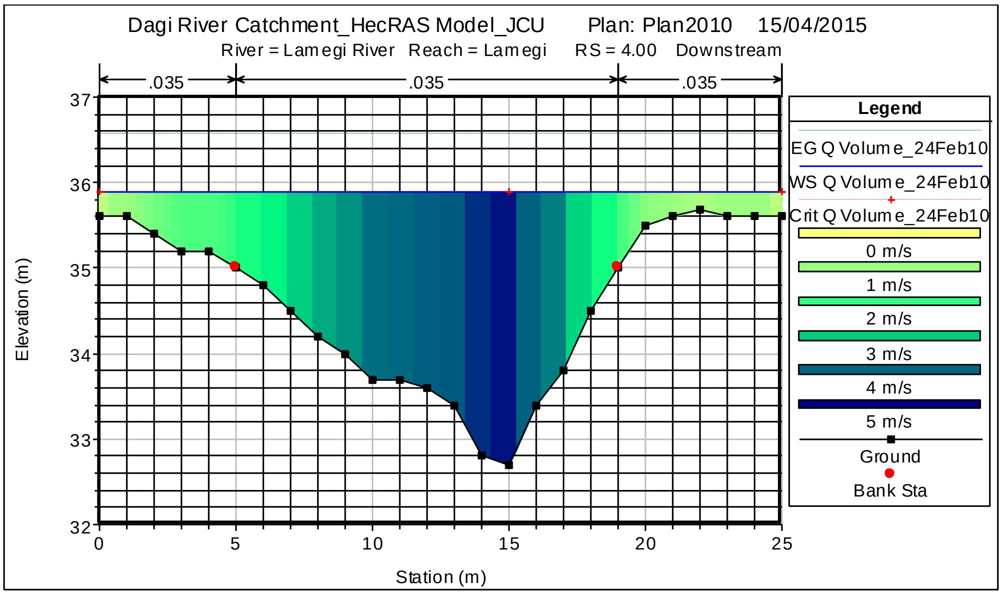


b)

Figures 4.17a and 4.17b: Sub-catchment 1-Dagi River upstream longitudinal profile plots.

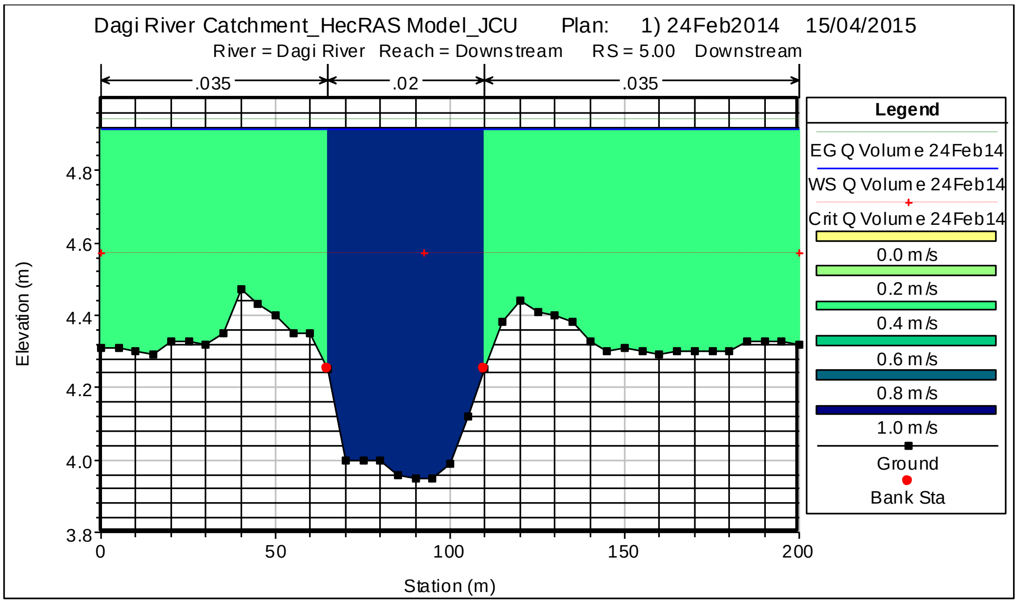


a)

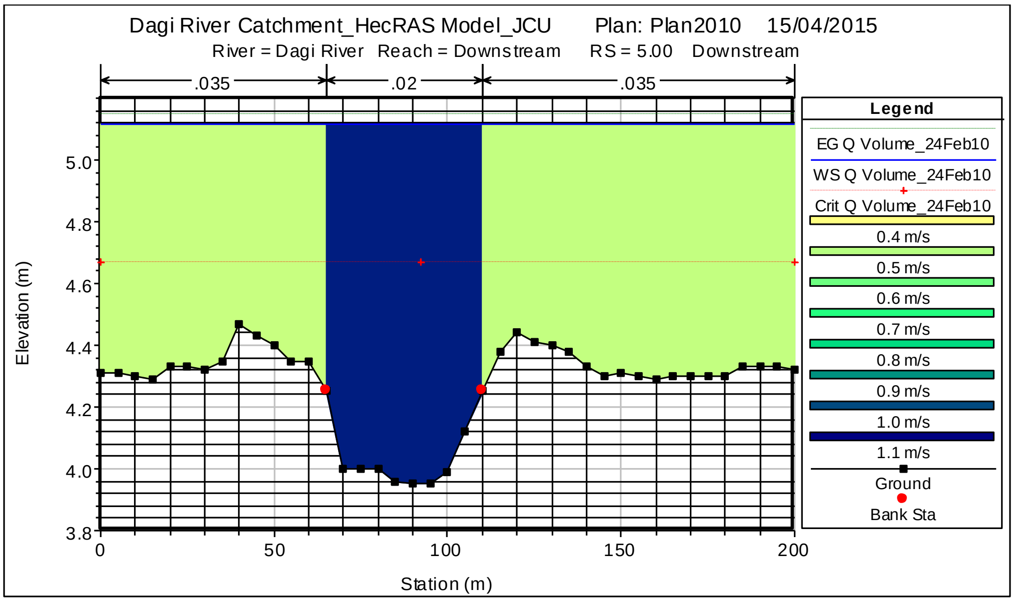


b)

Figures 4.18a and 4.18b: Sub-catchment 4-Lamegi River cross-sectional and velocity distribution plots.

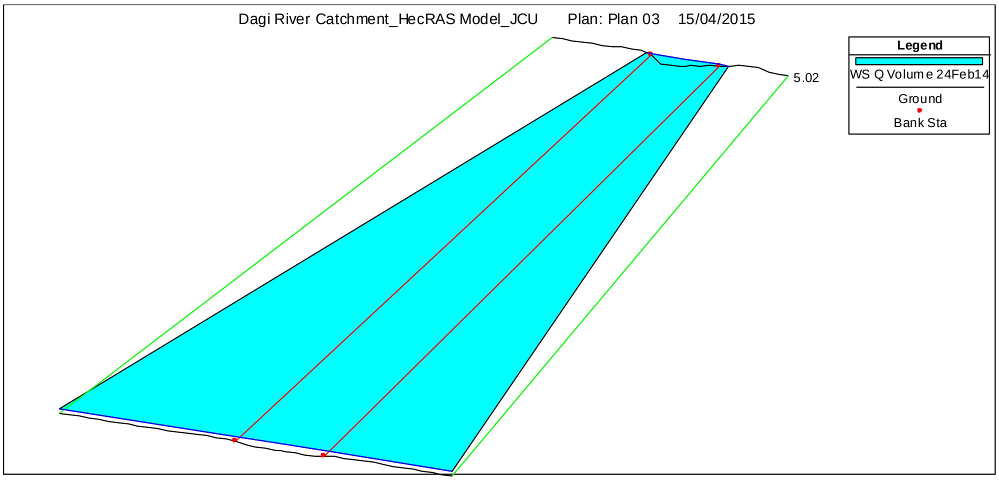


a)

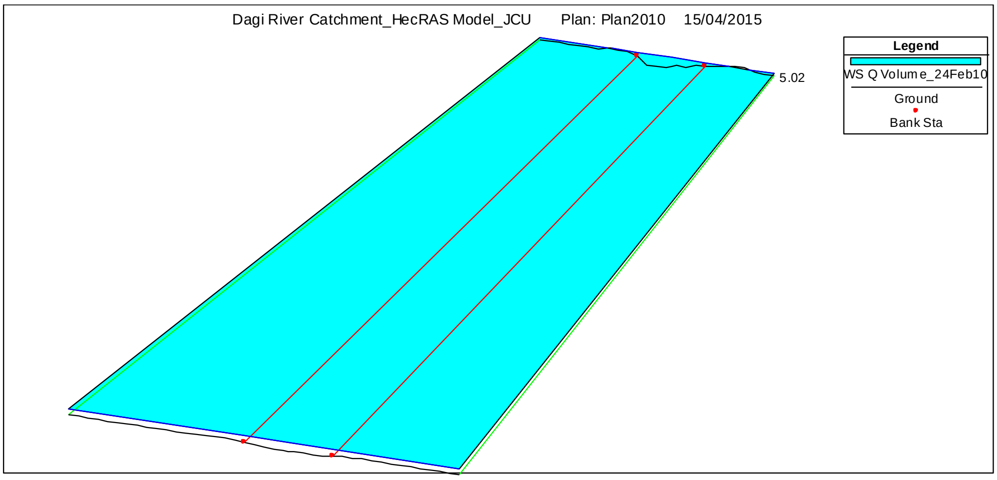


b)

Figures 4.19a and 4.19b: Sub-catchment 5-Dagi River downstream cross-sectional and velocity distribution plots.



a)



b)

Figures 4.20a and 4.20b: Sub-catchment 5-Dagi River downstream X, Y, Z longitudinal profile plots.

The simulation results for the flood duration on average is two hours during the time of peak discharge and recedes slowly in downstream sites. Velocity is highest in the middle of the channel for all cross-sections and decreases towards the banks as it overflows. The 2010 and 2014 floods have an average velocity of 4.0m/s in the main channels for Dagi upstream while Dagi downstream have an average velocity of 1.0m/s for 2014 and 1.1m/s for the 2010 flood. Slope and the channel roughness per sites (see table 4.2 in appendix 4.1) are the main factors that influence the velocity where in upper reach sub-catchments with steeper slopes water flows are faster than in downstream sub-catchments with lower gradients. In all cross-sections, the velocity decreases towards the banks and on to the floodplains as they encounter roughness (Ayoade, 1988; Gupta, 2011). As water overflows the banks, they encounter levees, slopes, vegetation, oil palm trees and man-made structures such as bridges or houses. It must be noted that although the cross-sections drawn in the graph appear to be steep to denote steep topography, this is not the case. A closer look at each sub-section shows little variation in the elevations used in each plot as we are dealing with a relatively flat area upstream and downstream compared with the rugged topography of the New Guinea mainland.

The 1D and 2D longitudinal profiles for each cross-section were calculated in HEC-RAS (e.g. figures 4.17a-b and 4.20a-b, others in appendix 4.5). Water travels faster upstream because the slopes are steeper than those downstream. Moreover, the EG is higher upstream (e.g. from 74-61 m.a.s.l at sub-catchment 1) while those downstream tend to be lower (e.g. 45.6-41.6 m.a.s.l at sub-catchment 2). The observed WS varies across each site in relation to the slopes and these were in response to the different amounts of rainfall received during the two wet seasons. The total volume of water discharged during the period of measurements confirms these responses from the input rainfalls and slopes. During the two floods, discharges were all above the critical depth elevation for all sites downstream with the 2010 floods much higher than that of 2014. Slopes, topography and the channel roughness plays a crucial role in initiating the velocity from one sub-catchment to another and thus influence the type of geomorphic work that the stream does in Dagi. The flow velocity can increase risks to livelihood assets. Destruction to infrastructure, soil erosion and risks to human life are instigated by faster flows due to the elevation gradient (Queensland government, 2011). The 2010 and 2014 flood velocities were not the same and these are the direct result of total rainfall, its intensity and duration during the two periods and the general slope of the area.

A plot of water surface elevation versus the flow rate for each computed cross-sectional profile is called a rating curve (Gupta, 2011). The plots were based on the simulated discharge values based on the rainfall amounts collected during the fieldwork and do not represent the final rating curve, as discharge values may be slightly higher than what is presented. Thus, using the simulation based on the 5-minute intensity duration rainfall values, a rating curve was plotted for each cross-section at the lower reach for each sub-catchment (e.g. figures 4.21 and 4.22, others in appendix 4.8). Generally, 2010 received more rainfall than 2014 and thus 2010 was a time of a major flood with much higher discharge as shown in the graphs. The water surface elevation was much higher for all sites in 2010 compared with that of 2014. The roughness coefficient decreases as we go downstream from each tributary and river (see table 4.2 in appendix 4.1). Sub-catchment 1 has a roughness coefficient of 0.065, sub-catchment 2 with 0.055, sub-catchment 3 with 0.029, sub-catchment 4 with 0.031 while downstream at the outlet the roughness coefficient is 0.029. This puts livelihood assets at risk because the stream power will be much higher as we go downstream and this will inflict more damage compared with upstream hydraulic conditions.

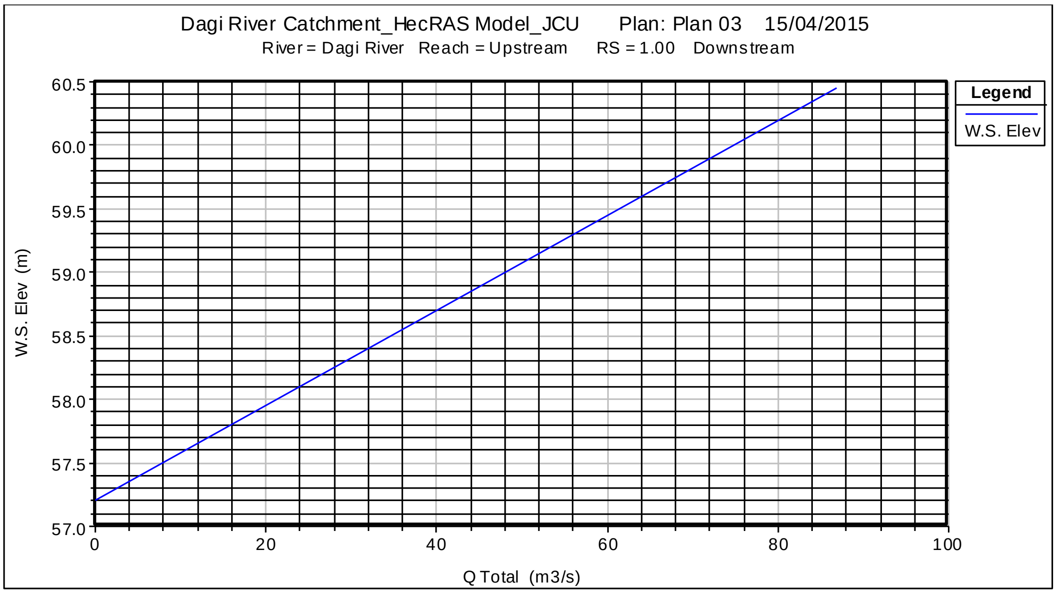


Figure 4.21: Rating curve based on computed water surface elevations for Dagi River upstream.

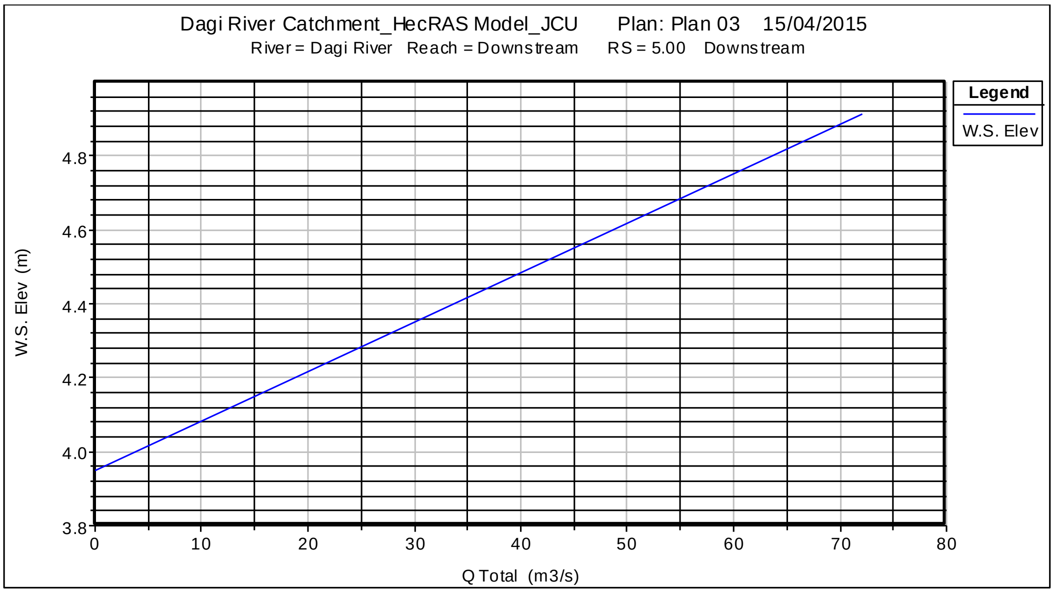


Figure 4.22: Rating curve based on computed water surface elevations for Dagi River downstream.

4.4.4 Stream velocity, water depth, duration and stream power in cross-sections

Summarised are the results for mean velocity, water depths, durations and stream power (table 4.3). The detailed output tables showing the stream hydraulic characteristics and properties at each cross-section for all sub-catchment sites are shown in appendix 4.9. It must be noted that in some stream reaches, these figures may be much higher depending on the catchment, network and channel characteristics of Dagi. For example, each flood event had variable water heights (m) and durations (days) for all sites, defined by their volumes. Of particular interest to this study is stream power.

According to Gordon et al. (2004), stream power is the amount of work done per unit time, where work and energy have the same units. It is an index used to describe the erosive capacity of streams, longitudinal profile shape, channel pattern, bed form development and sediment transport. Stream power per unit stream bed area (W_a) is defined by Bagnold (1966) as $W_a = T_oV$, where T_o is the shear stress at the bed (N/m^2) and V is the mean velocity (m/s) in the stream cross-section. Thus, W_a has units of N/m s (or $Watts/m^2$), where N is expressed as stream power per unit weight (a weight of 1 N) and work and energy are one unit written as m s.

Stream power is very important in the sense that it defines the amount of energy available to do the geomorphic work of erosion, transportation and deposition of sediments as it flows in response to the energy gradients created by the slopes along the waterway. During floods, the energy or power possessed by the stream causes damage to livelihood assets as it goes about doing its "geomorphic work". The average stream power for 2014 floods in sub-catchment 1 was 1915.12 N/m s, sub-catchment 2 was 1196.95 N/m s, sub-catchment 3 was 2393.89 N/m s, sub-catchment 4 was 1196.95 N/m s while downstream it was 9575.58 N/m s going towards the outlet. The 2010 stream power is slightly higher than that for 2014. The stream power increases as we go downstream and this may increase the potential for physical, social and economic impacts (chapter 5 and 6).

The results for the Dagi catchment reveal that as slopes become steeper, the velocity increases and more energy is used to rework channel materials. Frictional resistance upstream due to slope and vegetation caused dissipation of energy and thus we have lesser stream power for both years. The stream power increases as we go downstream as slope decreases and as discharge increased (Baker, 1987). Stream power also increased downstream to the middle reach because much of the flood remained within the channel at flows. In comparison, stream channels which flood their banks have low stream power (Brizga and Finlayson, 1990). The results in this study agree with the theory proposed by Langbein and Leopold (1964) that a stream's shape is a compromise between two opposing tendencies: (1) for energy to be expanded uniformly over the stream length, which reveal constant power, and (2) for the total expenditure of energy to be minimised over the length of a stream. In the Dagi catchment we have high stream power downstream for both years because of high discharge downstream, low slope and longitudinal profile is concave. These observations agree with the two theories proposed by Langbein and Leopold (1964).

Table 4.3: Summary of water depths, durations and stream power at each reach in Dagi.

Dagi Reach at each SC*	2014 Mean Velocity (m/s)	2014 Mean Water Depth (m)	2014 Duration (Days)**	Average*** Stream Power (N/m s)	2010 Mean Velocity (m/s)	2010 Mean Water Depth (m)	2010 Duration (Days)	Average Stream Power*** (N/m s)
Reach-1	2.28	2.65	3	1915.12	2.56	3.88	4	2322.63
Reach-2	1.94	2.62	2	1196.95	2.95	3.02	4	1476.31
Reach-3	3.43	4.65	6	2393.89	3.87	6.83	9	2687.12
Reach-4	3.28	4.22	3	1196.95	2.82	4.75	5	1487.36
Reach-5	2.82	6.34	7	9575.58	3.37	7.5	11	12765.24

*SC = Sub-Catchment, often SB (Sub-Basin), refers to the same hydrological element, ** the number of days taken to reach their normal stream level, ***averaged stream power. *NB: The stream velocity, water depths and durations for each reach are averages derived from both simulated and field observations.*

4.4.5 Flood frequencies and probabilities in the Dagi catchment

The flood frequency and probability analysis outcome are furnished in table 4.4 and figure 4.23. The results mean that a 2-year return period will have a discharge of 1219m^3/s, while a 5-year recurrence interval will have a discharge of 1241.65m^3/s. A 10-year return period would have a discharge of 1250.26m^3/s), 25-year (1256.03m^3/s), 50-year (1261.83m^3/s), 100-year (1264.74m^3/s) and 200-year (1270.57m^3/s) return periods, respectively (table 4.4). The discharge increases as the return period increases and this implies that a flood amid a big recurrence interval would discharge a bigger quantity than one with a small return period and agrees with the results found by Sop Lee and Nakai (2015).

Table 4.4: Flood frequency results using log-Pearson Analysis III method (Haan, 1977).

Tr*	K(-0.2)	K(-0.3)	Slope	K(-0.87420534)	Q (m^3/s)	Discharge (m^3/s) X10^x
2	0.132	0.148	-0.16	0.164	3.086	1219.00
5	0.856	0.854	0.02	0.852	3.094	1241.65
10	1.166	1.147	0.19	1.128	3.097	1250.26
25	1.448	1.407	0.41	1.366	3.099	1256.03
50	1.606	1.549	0.57	1.492	3.101	1261.83
100	1.733	1.66	0.73	1.587	3.102	1264.74
200	1.837	1.837	0.88	1.837	3.104	1270.57

Tr is the abbreviation for recurrence interval, which is defined as the average interval in years between annual events equalling or exceeding a given magnitude of a flood event likely to occur (Gupta, 2011).*

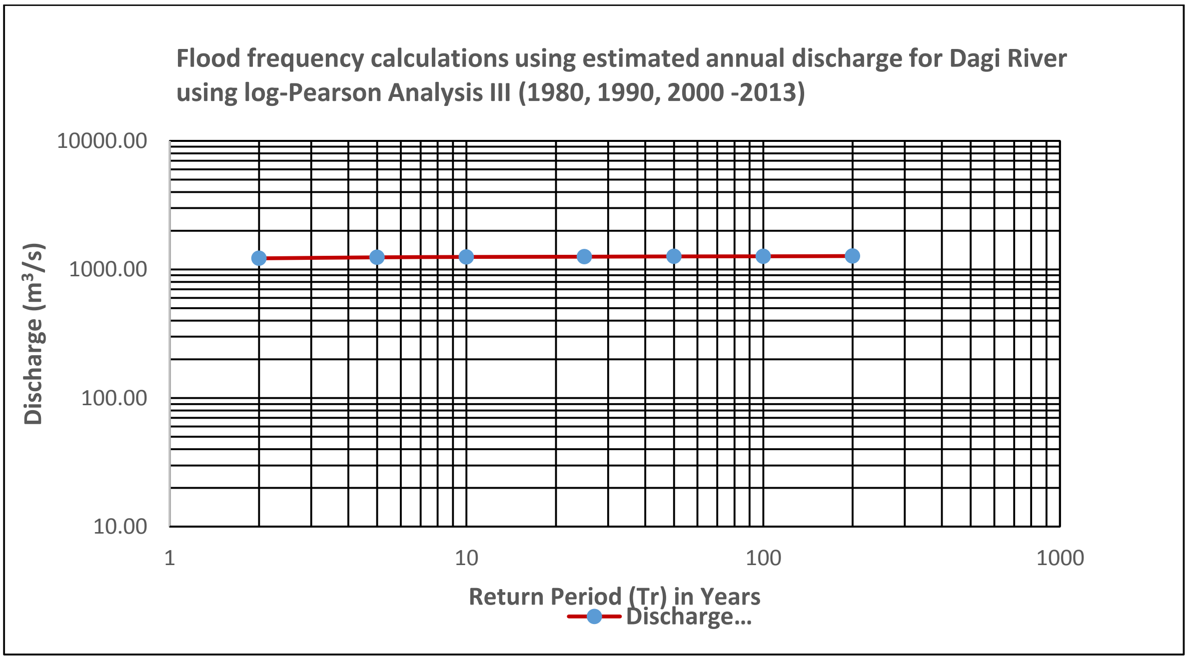


Figure 4.23: The Return Period (Tr) derived from the log-Pearson Analysis III method (Haan, 1977).

The frequency analysis using the Gumbel distribution method (Gumbel, 1960) and based on the same data showed similar results for the return periods (figure 4.24). Furthermore, the probability of exceedance versus discharge shows an increase as the discharge volumes increases for both methods (e.g. figure 4.25).

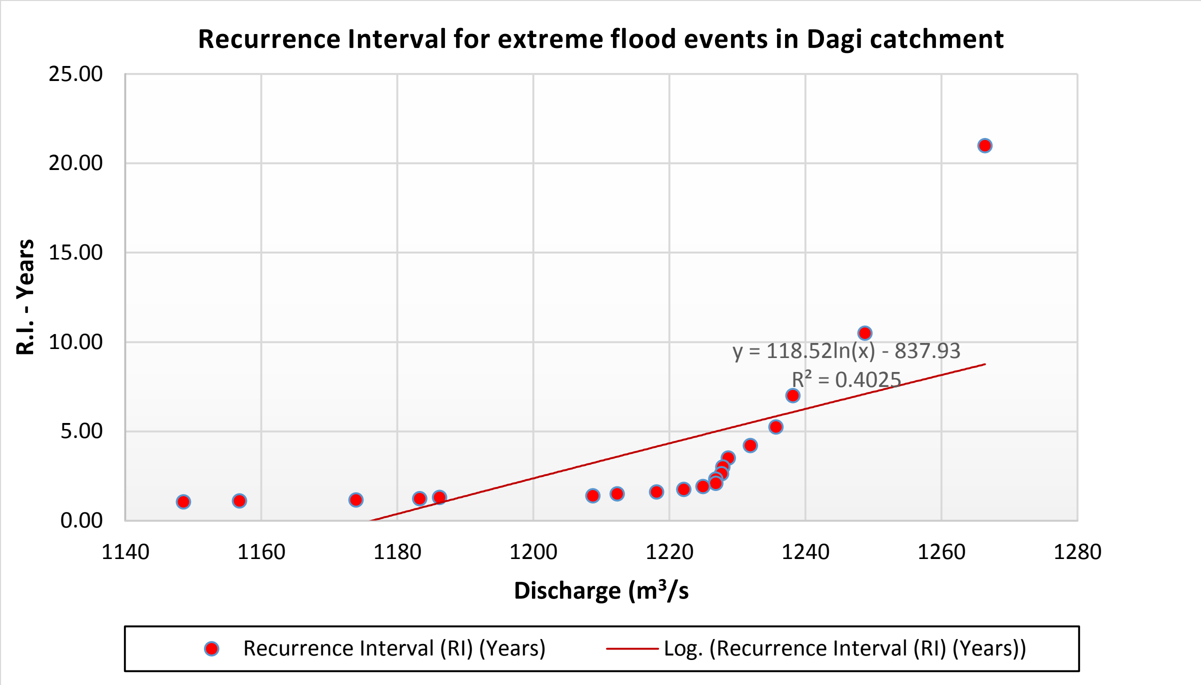


Figure 4.24: Recurrence interval computed using the Gumbel Distribution method (Gumbel, 1960).

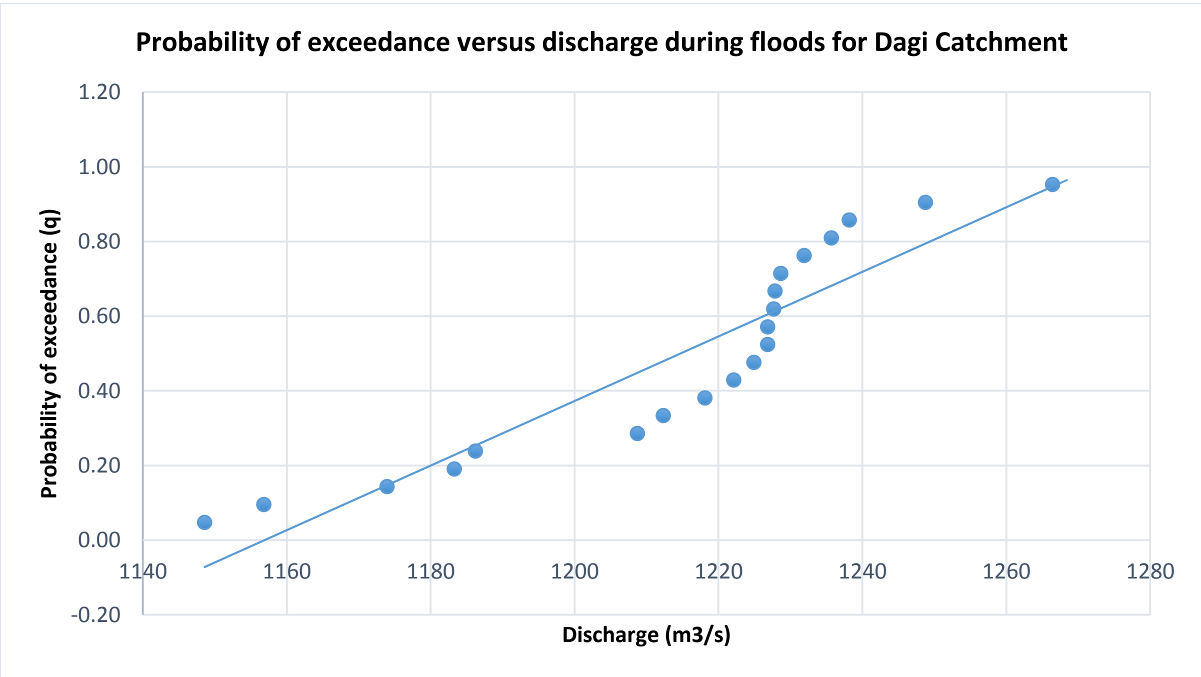


Figure 4.25: Probability of exceedance versus discharge trend line by Gumbel Distribution method (Gumbel, 1960).

Finally, the flood frequency analysis results obtained from both the Log-Pearson III and Gumbel distribution methods are summarised and presented in table 4.5. The recurrence interval is established on the chance that the particular flood occurrence will match or surpass in any year (Ries et al., 2004). For flood discharges of similar magnitudes as that of the 2010 event, they have 9.09 % probability with a return period of 11 years. This does not mean it will occur every 11 years; rather it simply means that the flood flow is expected to match to or surpass in any year if the flood generating conditions are right. In comparison, the 2014 event has a 13.64% probability with a recurrence interval of 7.33 years, meaning it may or may not occur but it is likely by a 13.64% chance of happening again.

Under the current climate change projections, discharge may vary from the results calculated here. The recurrence intervals estimated from the model floods for both 2010 and 2014 floods are quite realistic because overbank flows, inundation extents and amounts of damage were evident from field observations. Although the 2010 floods have 9.09% probability in any year, a small chance, the risk is always there. Even rare floods do not always reduce the chance of a similar event occurring again in a short time. This is confirmed in 2014 (13.64%), where a similar flood occurred. Two similar events occurred in only four years almost as predicted.

Many times, predictions based on computer simulations can be unrealistic because of variations in rainfall amount and extent, soil saturation before rainfall, catchment size and rainfall duration. Rain amount and extent vary across a catchment and the amount captured in the rain gauge and used to simulate peak discharge does not represent the actual amount. Soil moisture conditions existing before rainfall influence the amount of runoff. A small catchment requires short rainfall duration to generate runoff while large catchments require long durations. These factors can give unrealistic peak discharge values and wrong recurrence interval computation during modelling. In turn false information given to the public may subject them to more risks – it is man-made though, not natural flood risks as it should be.

Table 4.5: Flood probability and recurrence interval using both log-Pearson III (Haan, 1977) and Gumbel Methods (Gumbel, 1960)

Year	Annual Rainfall (mm)	Average Annual Discharge (Q) (m^3/s) (estimated)	Rank / Order (m)	Probability *(p)* (%)	Recurrent Interval (R.I.)
1998	4655.5	1266.42	1	4.55	22.00
2010	4439	1248.75	2	9.09	11.00
2014	4324.5	1240.77	3	13.64	7.33
2013	4239	1238.16	4	18.18	5.50
2005	4179	1235.68	5	22.73	4.40
2007	3908	1231.92	6	27.27	3.67
2012	3818.2	1228.65	7	31.82	3.14
1999	3805.2	1227.85	8	36.36	2.75
2003	3784	1227.68	9	40.91	2.44
2006	3519	1226.83	10	45.45	2.20
2008	3781.8	1226.82	11	50.00	2.00
2002	3653.4	1224.94	12	54.55	1.83
2000	3349.6	1222.13	13	59.09	1.69
2004	3280.8	1218.12	14	63.64	1.57
2009	3441.2	1212.35	15	68.18	1.47
2001	2909.6	1208.73	16	72.73	1.38
2011	2657.2	1186.22	17	77.27	1.29
1990	3745	1183.28	18	81.82	1.22
1997	2426.3	1173.92	19	86.36	1.16
1980	3543	1156.81	20	90.91	1.10
1996	2121.6	1148.56	21	95.45	1.05
			n=21		

NB: The 2014 annual rainfall data were recently updated and became available in 2016 after much of the analysis for this thesis was done based on fieldwork data. Fieldwork data for rainfall were collected from rain gauges for 10 days with a 12-hour duration in February 2014. Those data were used in rainfall simulation.

4.5 Discussion

4.5.1 Factors affecting flood characteristics and their behaviour in the Dagi catchment

4.5.1.1 Rainfall and duration

The rainfall-runoff simulation results for both 2014 and 2010 showed an unsteady rise in the hydrographs with distinctive peaks and steady recession in downstream sites. Variations in temperature and rainfall in Dagi greatly impacted on the hydrodynamic behaviour of the catchment. The amount, intensity, duration and frequency of rainfall defined the shape, size and the time of rise of the hydrographs. Pui et al. (2011) found significant differences in flood characteristics during and after antecedent conditions with corresponding rainfall intensities. Convective rainfalls of long duration and high intensity are similar in many tropical areas of the world (Beven, 2011; FAO, 2013). Analysis of short-term rainfall data suggested sound relationships controlling the magnitude aspect of convective rainfall common in the tropics (Battany et al., 2000; FAO, 2013).

In this study, peak discharges between the two simulated flooding events were related to high-intensity rainfall of 12-hours' duration which generated high runoff. Research in Malaysia showed 50% of gross rainfall occurred at magnitudes more than 20 mm/hour and 20-30% occurred at intensities more than 40 mm/hour (Zhu et al., 2015). However, this association appeared separate from the long-term mean rainfall at a specific setting because of variability in topography, moisture sources and prevailing wind systems (FAO, 2013). Similarly, Zhao et al. (2013) found that in catchments with large rainfall variability, disparities in water balance are more noticeable than those with little variations. Because the Dagi is a small catchment, spatial rainfall variability was very small.

4.5.1.2 Infiltration and storage capacity, permeability and transmissibility

The study area is dominated by mixed and undifferentiated igneous and sedimentary rocks together with sandy and alluvial volcanic ash soils (PNGRIS, 2007). The soil horizons had loamy sand to sandy loam texture (Nelson et al., 2004). Linsley et al. (1958) developed infiltration and storage capacity curves for different soil and bedrock types of the world. By relating the dominant bedrock and soil profile of the study area to these curves (chapter 3), it was clear that their storage capacities were low while their infiltration, permeability and transmissibility were high. These explained why discharge increased soon after high intensity rainfall events of a few hours during the 2014 and 2010 flood events. Hydrograph results for the simulations showed that after a few hours of intense rain, the rising limb appeared steeper with a shorter lag time and reached the peak quickly. It then receded slowly some hours after the initial rainfall stopped. Depending on the precedent soil moisture capacity and slope, studies have shown that the runoff initiation process persists if the rainfall intensity outpaces the actual soil infiltration capacity and ends once the pace of rainfall declines below the actual soil infiltration rate (e.g. Stone et al., 2008; FAO, 2013; Zhu et al., 2015).

Furthermore, the Dagi is perennial because it receives continuous rainfall throughout the year with the highest recorded during wet seasons. With continuous rainfall inputs, this also meant that the processes of infiltration, percolation and recharge of permeable aquifers were continuous (Ayoade, 1988). This study assumed that discharge from permeable underground water reservoirs through seepage and base flow enabled annual flows into channels, which in turn enabled tributary streams and rivers to flow all year. However, the assumptions made contrasted with a recent finding concerning water balance under oil palm (Chan et al., 2007). The study revealed that ground water in forested areas contributed about 90% during the dry season and about 40% of the total channel flows throughout the year. On the other hand, areas under oil palm contributed only 58% during the dry season and only 28% of the total channel flow throughout the year (ibid.).

The findings by Chan et al. (2007) when interpreted in the context of this study and based on theories outlined in Ayoade (1988), imply that more water was lost under oil palm. In fact, oil palm areas played a smaller role in the land stage of the water cycle. Here, oil palm trees absorbed and intercepted rainwater through their foliage and that became stem flow and was either evaporated or transpired back to the atmosphere. Those that have infiltrated were eventually taken up by the oil palm trees again, and consequently contributed less to groundwater recharge. From these, we can also deduce that the bulk of the water that contributed to floods came from non-oil palm growing areas mainly from forested areas, usually upstream. This becomes a water resource management issue if upstream areas that are usually forested, are cleared for oil palm cultivation.

Depending on the stages of maturity of the oil palm trees, younger trees have little foliage and canopy and the leaves are aligned at about 45^0 and thus interception is small with more stem flow and through fall. In addition, bare ground allows raindrop impacts that seal off the soil pores and lowers infiltration rates. Together, this means that more rainwater will fall directly on the ground, or reach field capacity quickly, and will be readily available for overland flow into channels and consequently cause floods over time.

4.5.1.3 Slope and elevation

The amount of runoff generated also depended on the slope and elevation. The average upstream slopes were 0.0296^{o} with mean height of 65m above sea level whereas near the outlet the average slopes were 0.0027^{o} with an average elevation of just 2m above sea level. In theory, slopes at higher elevation with sparse or no vegetation cover have little storage and infiltration capacity, permeability and transmissibility compared with high values for vegetated slopes (Ayoade, 1988; Gupta, 2011). In a recent study, Lane et al. (2013) modelled the response effects of a forested and a sparsely vegetated surface on hillslopes to downstream behaviour of flow magnitudes in a tropical watershed. Results showed that vegetated hillslopes with unchanged flow paths took about 75% of the time to reach peak discharge while that of sparsely vegetated hillslopes with changed flow paths took only 25% of the time to reach peak discharge.

Wakahara et al. (2014) observed the relationships between rainfall, topography and runoff and soil layer thickness in two adjacent basins in Sarawak, Malaysia. Observation showed that 19% of annual runoff occurred in an oil-palm cultivated catchment (21.97ha), while 46% was observed in a forested catchment (23.25ha). Hillslopes in the oil-palm cultivated catchment had excessive water loss, low base flow, and small runoff peak while hillslopes in a forested catchment were much higher with deep percolation and lateral flow with less water loss constituting 11% of the total rainfall. The two studies provided evidence that forested hillslopes upstream in Dagi have high infiltration capacity. Eventually it percolated and became groundwater storage, which then seeped into stream channels as base flow contribution to the overall channel runoff. In cleared and sparsely vegetated hillslopes of the catchment, rainfall did not have sufficient time to infiltrate, and eventually became overland flows travelling at high velocities into stream channels going downstream.

Past investigations on experimental runoff plots have confirmed that gentle slope plots yield less runoff than those with steep slopes (e.g. Sharma et al., 1986; FAO, 2013). Furthermore, observations suggest that runoff volumes increased with decreasing slope length (e.g. Sharma et al., 1986; FAO, 2013). Results from this study revealed that as we proceeded from upstream (increased slope length) going downstream (low slope length), the runoff volume increased. Arguably, these were owing to higher stream momentum and eventually lesser duration of accumulation upstream (FAO, 2013). In comparison to upstream, downstream reaches had lower flow velocities and greater time of concentration. We can also deduce from this study that water is exposed to infiltration and evapotranspiration for longer durations before its quantity and velocity reached the measuring points.

4.5.1.4 Water source areas

Based on Ayoade (1988), Wilson and Storm (1993), and PNGRIS (2007), the Dagi is characterised by high rainfalls, with no structural control and similar lithology and with a dendritic drainage pattern. The subsurface geology of the Dagi has homogeneous opposition to disintegration throughout so there are no obvious controls over the flow course of the tributaries. The tributaries connect to bigger channels at critically inclined angles that range between 0 and 20^0 before connecting with the Dagi at the junctions. There are three major tributaries with many smaller tributaries collecting and contributing water to the channel from rainfall and base flow. Depending on slope, the flow direction was not controlled and this caused rising water to flow laterally into depressions during intense rainfalls of long durations.

The results in this study showed that specific yield of runoff volume per unit area was determined by the drainage demarcation of each contributing sub-catchment. This meant that the sub-catchment with the greater unit area generated the highest specific yield. However, specific yields of water decreased in smaller sub-catchments. It is assumed that specific yields were in response to land conversion from forests to oil palm and subsistence cultivation. In turn, these were influenced by rainfall intensity, frequency and duration, soil and bedrock, base flow and slopes among others discussed above. These assumptions agreed with the results found by Nik (1988). He paired two small catchments in Malaysia from 1977 to 1986 to determine and quantify the effect of a typical forest land conversion to agricultural land use. Two catchments were treated after 3-5 years of calibration and subsequently planted with cocoa and oil palm. Results showed significant increases in water yield in both catchments. The highest increase occurred in the 2^{nd} and 4^{th} year after treatment, amounting to 706 mm (15%) for cocoa and 822 mm (470%) for oil palm in both catchments. Different magnitudes of annual yield were apparently reflected by the various activities of land conversion from timber harvesting, under-brushing, clear felling, road construction and planting of cover crops.

4.5.1.5 Channel: surface area, roughness and friction, slope and storage.

Results in this study also showed that the propagation characteristics of the flood hydrographs were narrowly linked to temporal vicissitudes in the average velocities which were a function of the channel distance and slope (Takemura and Fukuoka, 2013). The distance between reaches in channels defined the shape, size and the time of rise of the hydrographs. The upstream reaches generally showed steep hydrographs with a short lag time. As distance between reaches increased downstream the results showed much broader hydrographs in which a few hours were taken before they reached the peak discharge. Because the main channel distance was 35km in total length, the travelling times were much shorter. With physiographic influences as water moved downstream, there was an unsteady rise in the hydrographs with peaks some hours later. This meant that floods rose quickly upstream and flowed fast downstream and this obviously provided less time for warning and evacuation.

Takemura and Fukuoka (2014: p.156) showed that the "storage volume of a flood flow was produced by a decrease in the mean velocity as the retarding storage volume of that flood flow". Results in this study showed that slopes of the channels directly reflected stream velocity. In other words, the lower the channel gradients, the less the stream velocities, while the higher the channel slopes, the higher the stream velocities. Similarly, in upstream reaches, channels surrounded by steep slopes caused fast surface runoff. In terms of depth, the cross-sectional profiles revealed that upstream water sources were not very wide and because of the high gradient, they were very shallow. As the river moved downstream it collected water from overland flows and groundwater discharge and became wider and deeper due to different erosion methods (hydraulic action, abrasion, attrition and solution). This increased the wetted perimeter and changed the cross profile of the river.

It was also recorded that in the upper course of the river, velocities were at their lowest due to large angular boulders creating a rough channel shape and therefore friction. Vegetation cover upstream created more resistance than downstream. Together they created more water resistance. From this analysis, we can conclude that the roughness of a river channel had an impact on its wetted perimeter, efficiency and cross profile. River roughness decreased as the river progressed downstream because there was little resistance and friction due to the smoother beds, banks and removal of most natural riparian vegetation. Consequently, this increased river efficiency and was also linked to the fact that sediments downstream were normally silts and clays. Also, rocks were small and rounded compared with the large angular boulders upstream. Therefore, it can be concluded that high discharges along sparsely vegetated riparian zones reduce roughness and increased velocity downstream.

Furthermore, stream velocities were inversely related to channel roughness but increased at a pace proportionate to the square root of the channel gradient (ibid.). Hartly et al. (2013) and Dueck (2013) showed that smooth channels encouraged fast runoff whereas a rough channel encouraged slow runoff. This study revealed that discharge varied directly with cross-sectional areas of the channel and the average stream velocities at bank full flows. Discharge also showed direct relationships with the shapes and sizes of the cross-sectional areas along the channels. On average, upstream tributaries which were v-shaped and narrow showed small discharge. Discharge increased downstream where the channel appeared to be u-shaped and wider. This study also showed that both velocity and discharge increased downstream because more water was flowing into the river channel from many tributaries and groundwater sources across the catchment.

Finally, the drainage network influences how much surface water is stored in the river channel (Irish et al., 2014; Wooton, 2012). The whole drainage network in the Dagi has many meandering channels with short downstream distances before the next bend. Meandering channels in the Dagi are characterised by pools and riffles and grow wider downstream as the slopes decrease. Stein et al. (2013) observed that water stored in pools along the concave bends were much higher than the convex banks as compared with upstream channels. This study observed that as continuous inputs from the upstream source areas increased, the water level also increased and inundation in most cases occurred along the concave bends of the meandering channels than the convex bends. Therefore, the interplay of these catchment, network and channel factors in the Dagi exacerbated and influenced stream velocity and stream power, and water depths (Mouche et al., 2012; Rhoads et al., 2012), rates and volumes of discharge (Mouche et al., 2012), areas inundated and flood durations (Di Crescenzo et al., 2015).

4.5.2 Probabilities of floods of different magnitudes in ungauged catchments

Despite lack of historical flood records, more than half the annual floods in Dagi have exceedance probabilities of more than 50% (table 4.6) and this can be attributed to the rainfall distribution and catchment characteristics. A similar pattern has been observed by Bernadera et al. (2007) in an empirical investigation of the behaviour of flood probability, distribution and occurrence of rainfall distributions. Results showed that as rainfall distributions increased, the frequency of floods increased by 35%, corresponding to various climate and hydrological conditions, and drainage areas. Similarly, Subyani (2011) quantified the hydrological characteristics and flood probabilities in a wadi in Saudi Arabia using Gumbel’s extreme value distribution (Gumbel, 1960) and log-Pearson type III distribution (Haans, 1977) on daily maximum rainfall data spanning 40 years. The study identified probable maximum rainfall estimates, and then estimated the probable maximum floods of wadis for different return periods. Utilising a selection of annual maximum of 24-hour rainfall from eight stations, frequency of rainfall was analysed. Results showed that flood responses varied by 62% due to rainfall distribution. Using a simple distributed hydrological model, Boni et al. (2007) analysed flood probabilities for ungauged catchments. The distribution of flood frequency was provided for both gauged and ungauged stream segment in a homogenous area utilising data taken out from rainfall inspections. A genuine dispensation of flood occurrences was forecasted in ungauged catchments, where no discharge time series was available.

4.6 Conclusions and recommendations

The main input that generates floods in Dagi is rainfall. Runoff contributed from sub-catchments enters the waterways and increases runoff that leads to the total volume of flood water. It moves along a river reach as it is further discharged downstream to the junctions and outlet. As flood waters are being discharged, they pass through the channels while being altered by many factors associated with the catchment, network and channel characteristics (Ward, 1978). The most important factors that influenced flood characteristics and behaviour were the total amount of rainfall, their intensity, duration and frequencies. Slope of the area played a crucial role in conveying overland runoff into the river system via tributaries. These relationships are illustrated by the shape of the hydrographs in each of the reaches, junctions and outlet. Travelling time of the flood wave is dependent on the distance from upstream and downstream lengths of the stream, thus a steady rise in the hydrograph with a peak some hours later.

Channel roughness also affects the stream velocity while infiltration decreases as rainfall duration increases. All stream cross-sectional profiles show evidences of flood overflows with high velocities in stream channels and decreases towards the river banks. The duration of flood waters was shorter upstream while those downstream showed longer durations. These flood durations are a function of slope, topography and meteorological conditions especially wind and sunshine. Data on interception and evapotranspiration defining water surplus for runoff were not available and there is a need for further research.

The probabilities and the recurrence interval of any extreme flood event in Dagi were based on using estimated figures provided by the WNB Disaster office and needs further verification in future. The most important need is to have a daily series of rainfall data for upstream and downstream stations that spans a long period. With daily rainfall data for a long period, simulations results can be compared and the flood probabilities can be verified. The simulation run in this study was based on the rainfall, runoff measurements and catchment characteristic data gathered during the fieldwork for each sub-catchment. In all water level stations calculated in this study, minor differences between the observed and simulated water depth fell below the critical level of 5 indicating a clear agreement with the water depths (Alkema, 2007: p.50-53). This means that the model is close to accurate with a few errors introduced. This is addressed in detail in chapter 5 (table 5.4).

Chapter 5.0: Flood inundation and hazards modelling in an oil palm dominated landscape.

Summary

Catchments in oil-palm dominated landscapes experience floods resulting in the loss of livelihood assets (de Moel et al., 2011). A need exists to model flood inundation extents at a sub-catchment and catchment level to define hazard zones that will assist in flood-risk planning and mitigation. SOBEK is a model based on 1D/2D hydrodynamic numerical modelling approach that uses the full form of the Saint-Venant equations (1871) to predict flood flow and 2D inundation extents (Delft Hydraulics, 2001; Delft Hydraulics, 1990). A supervised classification following the maximum likelihood algorithm used a high-resolution ALOS multispectral imagery ©XASA (RESTEC, 2014) and identified four main land cover classes. The roughness values determined for each land cover based on Manning's roughness coefficient (Arcement and Schneider, 1989) were: 1. tree cover (oil palm and native spp.) = 0.045; 2. water bodies = 0.033; 3. grass and shrub cover = 0.035; and 4. bare ground and built-up areas = 0.150. The surface roughness (friction) values obtained from land cover classification were used to analyse data for the grid and provided the appropriate values for calibration. Maximum extent of water outside of the channel varied in both years with the 2010 flood recording the highest areal inundation extent (36.5 ha) compared with 2014 (33.4 ha) at the downstream reach. The combined 1D/2D inundation depth for 2014 varied across the channels from as low as 0.05m to as much as 6.5m compared with that of 2010 (0.05-7.5m). Variations in inundation depths between upstream and downstream reaches were attributed to slopes, dendritic river patterns and channel characteristics of the area, including man's influence in deepening the channels through gravel extractions. The 2010 inundation flow areas were much larger than those of 2014 due to high rainfall and the influence of channel and geological characteristics of the Dagi. Because of the relatively flat topography with no flood protection in all reaches, high peak discharge breaches the bankfull stage and inundates an average radius of 500m. The 2010 flood event inundated a large area (79.9 ha) compared with that of 2014 (55.2 ha), with most inundation occurring in the middle and lower reaches. Decreasing roughness downstream increased stream power. Frictional losses were high upstream because of the steep slopes, large boulders and gravels and more vegetation cover. Frictional losses decreased downstream towards the outlet as slopes decreased, and as flow encountered cobbles, pebbles and less vegetation. The average observed and simulated water depth values differed with different frictional values from -0.08m0.98m (2014), and 0.01m and 0.31m (2010) respectively. The model slightly overestimated as well as underestimated the values in the boundary regions but at the peak discharge areas the ranges of difference for the simulation were 0.32m, 0.39m to 0.54, 0.38 and 0.10m respectively. The

validation result based on depths and velocities combined with different frictional values revealed mean deviation of inspected and modelled figures between 0.40m and the deviation at the crest between 0.24m and 0.55m for the 2014 flood event. The 2010 flood manifest mean deviation of 0.45m between inspected and modelled data with the variation differing at the zenith between 0.32m and 0.54m. Thus, the modelled peaks agreed with the observed results. Using depth and velocity characteristics, inundated areas were classified into hazard levels as medium, high and very high.

5.1 Introduction

Inundation caused by riverine floods are defined as the rising of a body of water which overflow on to normally dry land (Sayers et al., 2011). In areas where there are settlements, inundation caused by riverine floods can be hazardous to people and their properties. Disasters caused by flood inundation occur often in many places when water level suddenly rises or flow rapidly over land (Tsubaki and Fujita, 2010). This calamity afflicts and causes distress anywhere on earth such as in urban areas, rural villages or oil-palm dominated landscapes, and this hazard does not respect any population density (ibid.). In areas of high population density, inundation inflicts devastation to the overall wellbeing including laceration and death. Consequently, suitable administration strategies for this must be developed (ibid.). In the prognosis and management of this disaster, apprehension of the profound mechanisms of flooding is indispensable since appraisal of risks hinges on reliable flood data (ibid.). Consequences of flood hazard are its risks, and the vulnerability and exposure of livelihood assets that can be collectively approximated with high accuracy (Arrighi et al., 2013). Hazard mapping is done in many countries but assessing flood risks involves more than just hydraulic inundation modelling (ibid.). Conversely, mathematical analysis of flood damages and its quantification visualised by risk maps are still at a preliminary level in many landscapes such as those under oil palm cultivation (ibid.).

Flood inundation and hazards are complex phenomena to study in the real world. To understand the complexities involved, hydrological models are commonly used to simplify and study real-world complexities and visualised at a catchment and sub-catchment level. 1D and 2D-hydraulic flood propagation hydrodynamic representations were established using shallow water equations and are frequently utilised for flood risk assessment (Mason et al., 2014). The representations give an approximate area of flood, its depths, velocities and hazards over time (ibid.). Calibration, sensitivity, optimisation and validation of any model are important steps to test its accuracy. The outputs relate to vulnerability levels to evaluate the impairment related to inundation phenomenon, thereupon granting valuable data to update agencies involved with risks and emergencies (ibid.).

The assessment of inundation hazards and risks often lacks holistic approaches. Therefore, it is important to assess the hazard involved to reflect real-world scenarios. This will improve knowledge of risks involved and lessen setbacks by progressing comprehension through simulation of distinct flood events (ITC, 2010). Predicting floods and modelling realistic world situations is gruesome and calls for mastery to thoroughly investigate and analyse the available data in terms of accuracy and quality (ibid.). Transforming hazards into risks entails initiation of suitable relationships between hazard strength and the level of devastation of the dissimilar exposed elements (Smith, 2001; ITC, 2010). Creation of a new record of exposed elements and their risks in the Dagi catchment will help local authorities make development and management plans.

As calculated in chapter 4, a flood is predicted to recur across the Dagi floodplain approximately every 11 (2010) and 7.33 (2014) years. Establishment of settlements, subsistence gardening and oil palm cultivation in the flood zone is not “risky” but simply foolish. The WNB Provincial Disaster Centre continues to help people who make bad choices in flood zones. Maps of flood hazards and risks generated in this study are planning tools and will be used to define areas unsuitable for settlement and economic uses. Ignorance of advice would deny any form of assistance from the National Disaster Centre.

This chapter begins by outlining the materials and methods for determining the extent of inundation and hazards in the Dagi catchment. Inundation components modelled are the maximum velocity, and maximum depth during the 2014 and 2010 floods. These will then be used to generate and define flood hazards maps that will be used for assessing flood risks. This is followed by results, discussion and study assumptions, limitations, and conclusions. Recommendations will end this chapter.

5.2 Objective and research questions

Using the Dagi catchment as a landscape dominated by oil palm, chapter 5 aims to:

Model flood inundation extents at a sub-catchment and catchment level to define hazard zones that will assist in assessing flood risks to livelihood assets.

To address the above aim, research questions were:

1. what are the spatial inundation extents for the 2014 and 2010 floods using SOBEK 1D/2D hydrodynamic model?

2. what is the sensitiveness of the SOBEK 1D/2D hydrodynamic representation to frictional estimates?

3. how well does the SOBEK 1D/2D hydrodynamic model fit the observed 2014 and 2010 flood hazard scenarios?

5.3 Materials and methods

5.3.1 Overall methodological process

To model flood inundation extents and define the hazard zones required data on water depth, volume of discharge, area of land inundated, seasonality of flooding and the frequency of floods of a given magnitude (Gupta, 2011; Ayoade, 1988). These data were calculated in chapter 4, except the need for data on the area of land inundated and the level of hazards to livelihood assets. Efforts were made to model the inundation extent in the Dagi catchment to define the level of hazards in the area. Data on the inundation extent and hazards in this chapter will be generated by flood routing and hydraulic modelling using HEC-RAS Beta 5.0, HEC-GeoRAS, and SOBEK 1D/2D (figure 5.1). The use of these models provided reliable results in recent studies (see Poretti et al., 2011; Balica et al., 2013; Quiroga et al., 2013). The data (both from fieldwork and simulated) generated in chapter 4 were used to determine flood inundation extents and hazard levels. In addition, land use and cover frictional data needed in this chapter were missing. Identifying the roughness values for land use and cover is important in flood inundation modelling because they create resistance or friction to flood flows, alter their direction and reduce stream power. Calibration and validation of the model utilised data from the 2014 and 2010 flood occurrences. These data included maximum depth and maximum velocity of the events. Not all data required to complete the study were available so fieldwork was undertaken for three months to collect additional data (see chapter 4). The results on inundation extent and the distribution of velocity, depth and stream power will be the inputs for assessing flood risks on livelihood assets in chapter 6.

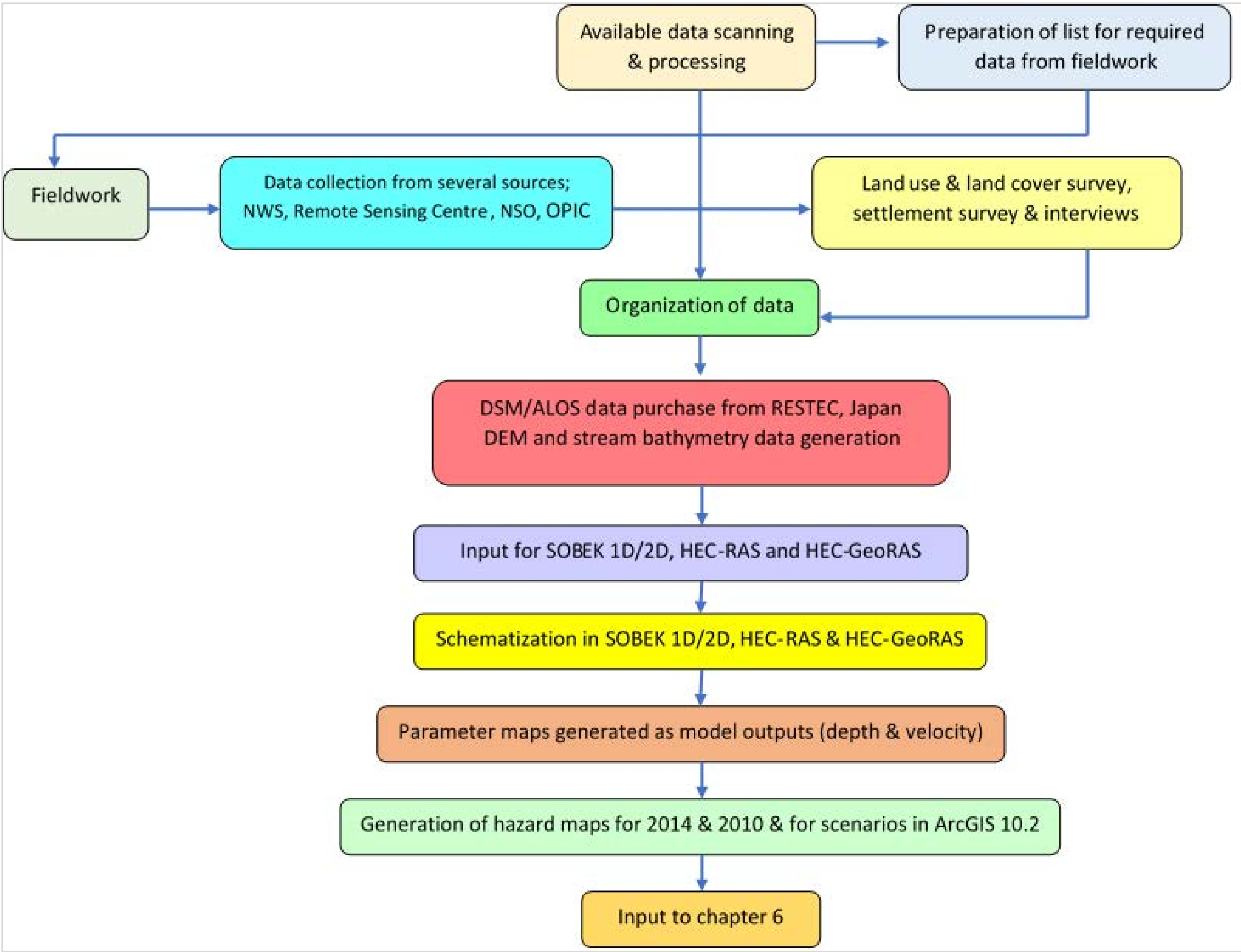


Figure 5.1: Work flow in chapter 5.

5.3.2 Input datasets

Table 5.1 presents the datasets used.

Table 5.1: Dataset, their sources and description

Dataset	Source	Description	Resolution
Land cover	PNGRIS database	PNG Database	1: 50, 000
Topographic Map	JCU, CMES Cartography Section	Sheet 8986 (Edition 1), Series 797	1: 50,000
DEM	From topographic map	Digitised contours and spot heights	Resampled to 20m X 20m pixel sizes
DSM	RESTEC Japan ©XAXA	2014 Data	5m X 5m pixels
ALOS Imagery	RESTEC Japan ©XAXA	2014 Data, 4 band multispectral	5m X 5m pixels

Because the flood plain is relatively flat with few contour lines, spot heights on the Dagi topographic map were identified and digitised together with the contours. These data were then integrated with the GPS elevation and river bathymetry data collected during fieldwork and interpolated into a DEM. A high-resolution Digital Surface Model (DSM) and ALOS multispectral image covering Dagi were purchased from RESTEC Japan, ©XASA, to be used for land cover classification to derive roughness values, and as a background image of the area. These data were sent via ftp after a 3-month delay. The topo derived DEM was then integrated with the DSM extracted DEM data (see chapter 4). The satellite imagery and all the spatial datasets were geo-referenced and rectified where necessary to *WGS 84/UTM Zone 56S*.

5.3.2.1 Land cover map and Manning's roughness coefficient (*n*)

Land cover data were available within the PNGRIS database but required validation and updating. This was to see whether there had been major land cover changes since the PNGRIS database was last updated in 2007. A supervised classification was undertaken based on a 4-band (4, 3, 2, and 1) composite RGB ALOS multispectral imagery using the maximum likelihood classification algorithm. Classification was based on training the signatures of each pixels by digitising the polygon shape files on an area that belongs to a known land cover class in the imagery. An example of the training signatures based on each band is summarised for water bodies in appendix 5.1. The land cover classification identified 10 classes. However, only those that were observed to influence flood velocity and stream power were important in this study. Therefore, the 10 land cover classes were further re-classified into four classes of land cover for the case study area (appendix 5.1). Minor land cover changes from forests to oil palm were 3km away from the floodplain. Because the land cover in PNGRIS was from 2006 classification and outdated, I decided to use the current classification to derive the roughness values based on Manning's roughness coefficient (table 5.2, figure 5.2). The derived roughness values were entered into SOBEK 1D/2D, HEC-RAS and HEC-GeoRAS models for simulation.

Table 5.2: Manning's roughness coefficient used for catchment surface roughness (Acrement, 2008)

Land cover type	Manning's n coefficient
Tree cover (oil palm and tree species)	0.045
Water bodies	0.033
New clearing and grass cover	0.035
Bare ground/built-up areas	0.150

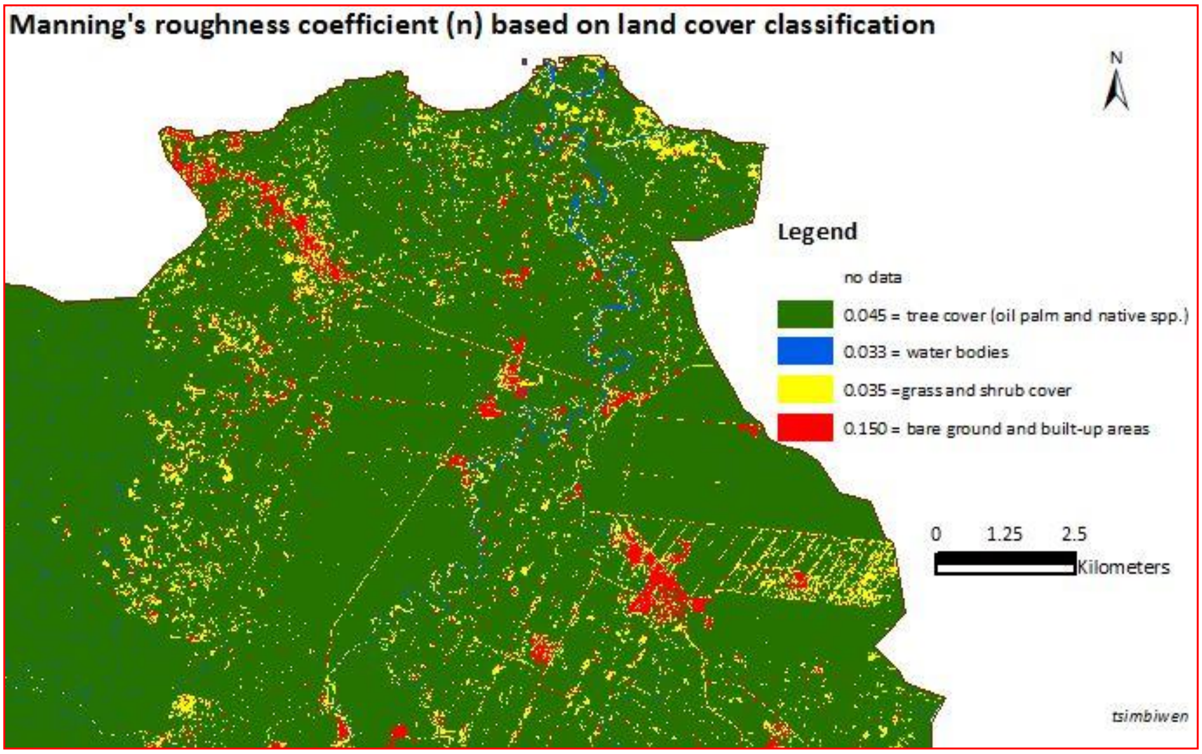
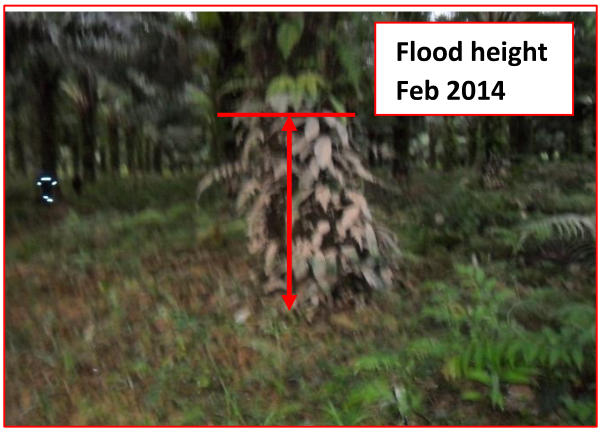
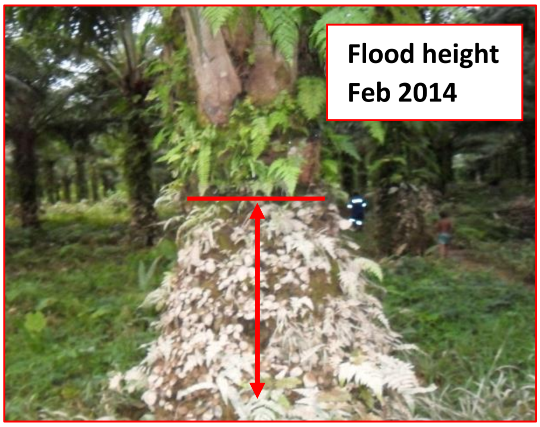


Figure 5.2: Manning's roughness coefficient *(n)* based on land cover classification.

5.3.3 Field data collection

The fieldwork to address this chapter involved data collection related to the current and past flood inundations. Knowledge from locals living within the smallholder oil palm blocks, settlements and company officials and workers provided valuable perspectives for this research. Data for past inundation occurrences focused on eye-witness accounts and perspectives of local experts. Because this is a relatively new study area in relation to flood risks, there were few “facts” available. Those available with the PNG National Disaster Centre were all descriptive in nature. Water depths for past events were based on local views and observations, however the 2014 flood event was measured at various breach locations upstream and downstream. This involved observing high-water marks left on oil palm trees or on vegetation as the flood receded (plates 5.1a and 5.1b) and taking the height of the water marks from the reference stream bank stations. This was then used for the calibration of the model.





a) b)

Plates 5.1a and b: Observed high water marks left on oil palm trees after flood receded.

Flood volume (m^3), velocity distribution (m/s), flood depth (m) and duration (hours/days) data were required to model flood inundation extents and hazards of the area, and for calibration and validation of model results. The fieldwork (July 2010 during the dry season, February 2010 and February-April 2014 during floods) focused on collecting these hydrological data in the area and most procedures were explained in chapter 4. GPS coordinates of the outer limit of inundation extents from the stream banks were collected at respective sites. Fieldwork also involved gathering information on past flood events by interviewing people living upstream and downstream.

5.3.4 Analysis: Flood inundation extents and hazard modelling

5.3.4.1 Analysis 1: Data preparation

The drainage network was sub-divided on the DEM into 5m x 5m grid cells for pin-pointing breaches along river banks and for 2D overland flow simulation in SOBEK 1D/2D software (Delft Hydraulics, 2001) (figure 5.3). Further boundary conditions were then demarcated (figure 5.4). The SOBEK 1D/2D model was initially selected because it allowed for the fast computation of both 1D and 2D channel and overland flow (Delft Hydraulics, 2001) (figure 5.5). Finally, the longitudinal profile of the catchment was demarcated using the elevation data.

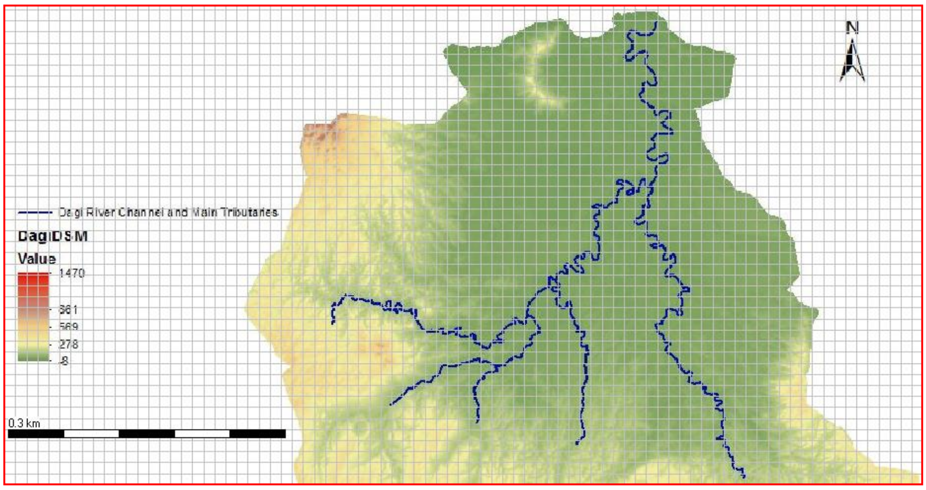


Figure 5.3: Sub-division of the drainage network on the DSM into 5m x 5m grid cells for pin-pointing breaches along river banks and for 2D overland flow simulation in SOBEK 1D2D software (Delft Hydraulics, 2001).

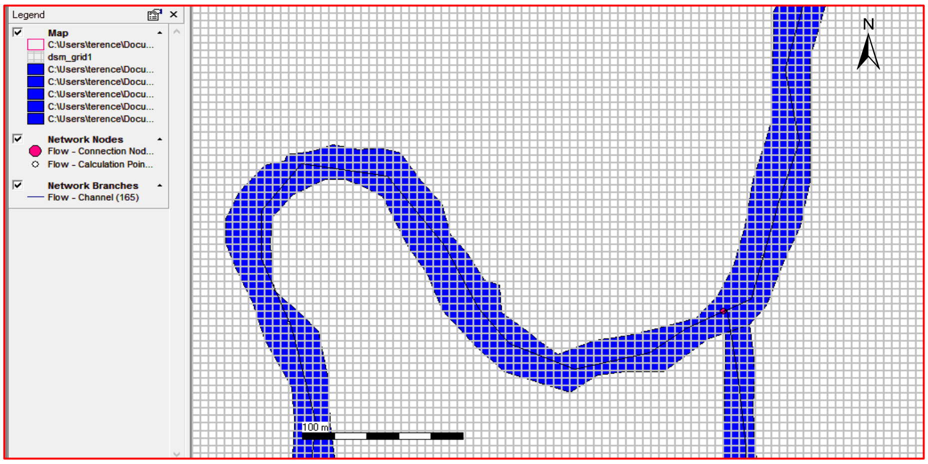


Figure 5.4: Preparation of the drainage network for the demarcation of boundary conditions and schematisation in SOBEK 1D/2D software (Delft Hydraulics, 2001).

According to Delft Hydraulics (2001: p.110), the 1D/2D theory combination using SOBEK-Rural are executed in this manner:

- 1D and 2D passages are simulated concurrently
- 1D waterway is interpreted via interpolating cross-section statistics
- pairing of 1D and 2D dominions are accomplished via 1D at computation points (figure 5.6a)
- anytime and anywhere when discharge surpasses a stream reach's retention capacity as delimited by the 1D domain, only then, 2D computation is initiated (figure 5.6b) to imitate overland movement, being dependent on topography, as depicted in the 2D grid

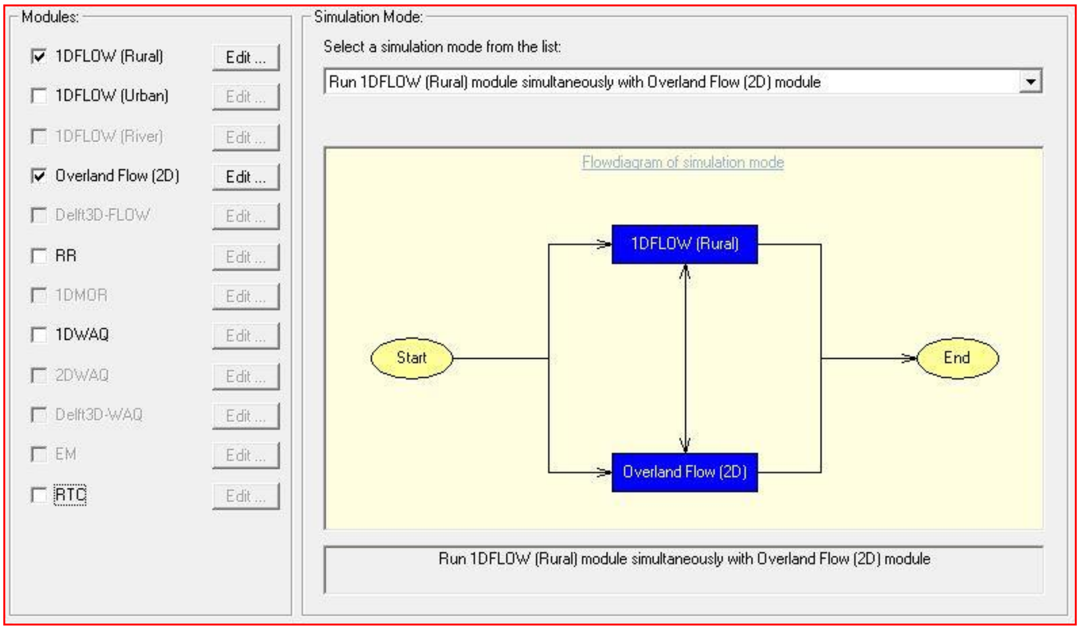
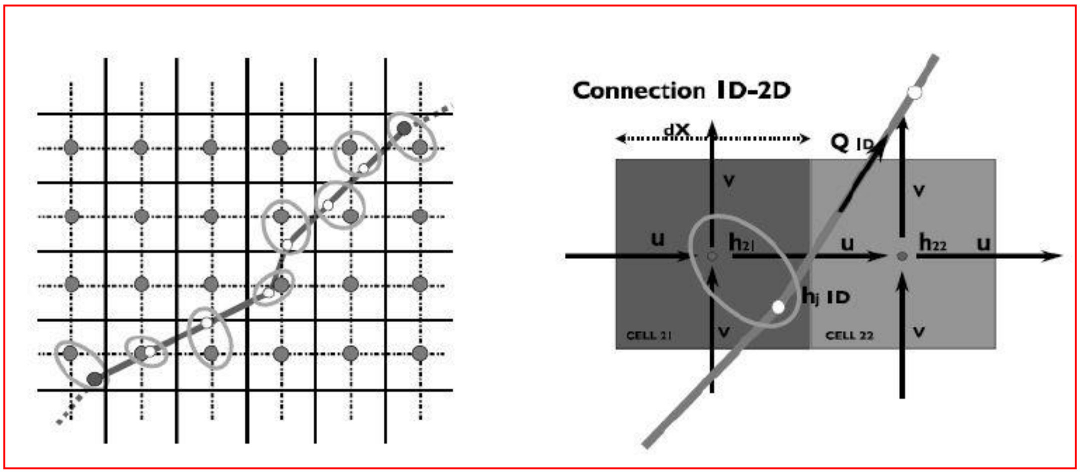


Figure 5.5: Combined SOBEK 1D/2D Simulation Modules for the Dagi flood inundation modelling (Delft Hydraulics, 2001).



a) b)

Figure 5.6a and 5.6b: Integrating 1D and 2D Mesh where h is water level, u and v are velocities in x and y direction, dX is the mesh size, Q is discharge in 1D branch) (ITC, 2010; Delft Hydraulics, 2001).

In this study, the model approach solves the full Saint-Venant equations based on finite difference staggered grid solution (Alkema, 2007: p.50-53; Saint-Venant, 1871). The floodplain was modelled using the 2D modelling approach described by three equations (5.1, 5.2 and 5.3): the continuity equation, and the momentum equation for the *x* and *y* directions (Lomulder, 2004: p.21; Alkema, 2007: p.50-53; Saint-Venant, 1871).

Equation 5.1: continuity equation,

$$\frac{\partial(uh)}{\partial x} + \frac{\partial(vh)}{\partial y} + \frac{\partial h}{\partial t} = 0$$

Equation 5.2: momentum equation in *x direction,*

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + g\frac{\partial h}{\partial x} + \frac{n^2 u\sqrt{u^2 + v^2}}{h^{\frac{4}{3}}} = 0$$

Equation 5.3: momentum equation in *y direction,*

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + g\frac{\partial h}{\partial y} + \frac{n^2 v\sqrt{u^2 + v^2}}{h^{\frac{4}{3}}} = 0$$

Where *y* = depth of the channel from the reference level[23]

x = longitudinal distance along the channel

t = time

h = water head elevation from reference level

u = flow velocities in x-direction

v = flow velocities in y-direction

n = manning coefficients (dimensionless)

In this research, the reference level indicator was the bankfull stage. Indicators used to identify the bankfull stage were the tops of point bars (these define the lowest possible bankfull stage), a change in perennial vegetation, slope or topographic breaks along the bank, bank undercuts just below the bankfull stage, stain lines on boulders evidenced by lichens, and changes in the particle size of bank material (Harrelson et al., 1994, p.61). The field determination of the bankfull stage involved detective work. I travelled along reaches and marked indicators using a Garmin GPS on both river banks, taking note of channel features like bars, boulders and roots of trees that would affect surface elevation, or direct current. The elevations of the bankfull indicators were recorded using a Garmin GPS on both

[23] The benchmark or reference level established in this study was the bankfull stage. It is defined as the level at which water start to flow over the floodplain. A bankfull stage is indicated by the flat depositional surface adjacent to many stream channels. It is easy to identify along low gradient and meandering reaches, however, in steep hilly areas upstream, it was hard to identify them so good judgement came into play.

stream banks to plot a longitudinal profile of bankfull elevation of the entire reach. GPS points were plotted on to the DEM. The points were connected to generate two lines all throughout the drainage for both banks. The two lines became the reference levels for both stream banks used in this study. In 2010, during fieldwork, I carried out a survey using a level and rod in a reach and plotted a longitudinal profile establishing elevation of existing water surface, channel bottom, bankfull stage, floodplains, terraces and slope. In a few instances, where such information was not available, I used my personal judgement of the local hydrology and experience to determine the reference level. The modelling results based on GPS points generally fell almost in line with those done using the level and rod.

5.3.4.2 Analysis 2: Boundary conditions

Boundary conditions are described as the "exchange of water mass between the study area and outside of it during the model run" (Alkema, 2007: p.24). Proper techniques are required to measure water flowing in and out of the Dagi (ITC, 2010). Representation for the boundary conditions in the Dagi were established on precise recurrence intervals calculated for the flood years from 2000 to 2014 with an upstream and downstream boundary (ibid.). Discharge data input into the model's upstream boundary came from both fieldwork and the PNGRIS database (Deltares, 2015: p.74). Hourly discharge data were derived from the existing rating curve for the 2010 and 2014 floods (see chapter 4) to achieve consistency in the observed hourly depth information which will be used later to validate each flood (ibid.). The upstream boundary consists of the measured discharge data while that downstream was a fictional lake condition that was stationed to confine 8m of water in elevation (Deltares, 2015: p.85). Based on Alkema (2007: pp.50-53), a steady height of water was defined to maintain lake conditions so that water could flow freely during the model run. An important task done using values of surface roughness (wall and bed) during flood modelling was sensitivity analysis (Deltares, 2015: p.85; Alkema, 2007: p.54). Chow (1959) provided the Manning's coefficient that was used to select a roughness value for each land cover type (table 5.2 and figure 5.2).

5.3.4.3 Analysis 3: Schematisation of model

To obtain suitable results in this flood inundation assessment, SOBEK 1D/2D through an interface tool such as a GIS called NETTER was used to schematise Dagi hydrodynamics. The Dagi river network (including tributaries) was schematised and its attributes (e.g. cross-section data and boundary conditions) were defined in 1D network with their respective 2D surfaces (Deltares, 2015: p.74, Alkema, 2007: p.54). The initial conditions of the Dagi model were adjusted to its hydrodynamic behaviour and simulation tests were run until it reached the normal river conditions, which persisted after simulation (Deltares, 2015: p.76). Those conditions were saved in RESTART files for future simulations. Cross-sections had flow and bottom width values tied to respective trapezium shapes and were added into the Dagi model (Deltares, 2015: p.76; Alkema, 2007: p.54) (Appendix 5.2). In the schematics, a node is connected to each of the Dagi reaches which in turn defines its course (ITC, 2010). The river bed and water flow were interpolated in the model using cross-section data entered earlier (ITC, 2010). Such important information must be defined correctly because large errors will overestimate or underestimate the inundation extent as reported by Sanders (2007).

Limited data for the 2010 and 2014 Dagi floods were utilised for setting up the model. These include the date, time, original water height and the time intervals for generating input maps (ITC, 2010). A few unsteady computations were utilised together with combined 1D channel flow and overland 2D flow within SOBEK (Deltares, 2015: p.79; ITC, 2010). NETTER used vector layers as references to schematise the Dagi network (ITC, 2010). There are different requirements of the 1D and 2D modules to be used as inputs for processing (Deltares, 2015: p.83; Alkema, 2007: p.50-53; ITC, 2010). The Dagi DEM was the input for the 2D overland flow together with the generated frictional values. The Dagi 1D channel flow required cross-sections, connection nodes, boundary nodes and calculation points and these were schematised in NETTER (ITC, 2010) (appendix 5.2). Finally, when the combined 1D/2D simulation was run in SOBEK, the pre-processor of the program failed during geometric data execution. Everything did not work out as expected even after some past positions were combined to accommodate the 2D ramifications at a fixed pixel level (ITC, 2010) (appendix 5.2).

After three months of attempts to rectify the failure, two problems were found: the first was caused by the input DEM data and the second was the computation time and processing power of the computer with high-resolution data. The first problem is commonly encountered in inundation modelling when using a DEM extracted from LiDAR DSM (Priestnall et al., 2000; Sanders, 2007; Fewtrell et al., 2008; Coveney et al., 2010). During the time of DSM non-landform feature extraction to convert to the DEM, some portions of the topography were also removed, resulting in uneven elevation in the DEM, thus the error in the geometric pre-processor (appendix 5.2). To refine and correct this problem using the same procedure is time consuming, especially after three months. The second problem was the computation time: processing power on my laptop and desktop was limited when I attempted to resolve flows on the resampled DEM derived from the high resolution 5m x 5m grid cells. To accurately solve this problem is physically intensive and time consuming, and it is done using the grid resampling technique in ArcGIS following the bilinear gridding approach.

Thus, being limited by time and to quickly overcome the two problems and generate results, I attempted HEC-RAS 4.1, HEC-RAS Beta 5.0 (2015 version) and HEC-GeoRAS. Several cross-sections along the river were derived from X-cut lines, streamline centre lines, and flow paths to combine with the existing bathymetry of the river based on fieldwork using HEC-RAS and HEC-GeoRAS modelling software (figure 5.7). A Dagi River TIN and DEM was generated (figure 5.8a and b). It was then combined with the DSM extracted DEM to generate a combined DEM (figure 5.9) with river bathymetry data with a stream centreline, and bank lines as flow path centrelines added (figure 5.10). The other information is in appendix 5.2 showing segments of a reach with XS-Cut lines drawn near a depression where inundation was mostly likely to occur.

Each cross-section was then assigned a river and bank station number. GPS coordinates of the flood extent and inundation were digitised into a polygon and generated into a 2D computational mesh with each face point (fp) assigned a unique number (figure 5.11). Figure 5.12 is an example of a 2D flow area along the catchment which was linked to the 1D river channel through which high water breaches the levees and inundate the Dagi floodplain. These data were exported within a schema from HEC-RAS Beta 5.0 to HEC-GeoRAS within ArcGIS 10.2 and SOBEK 1D/2D environments for simulations (figure 5.13). The measurement sites (upstream and downstream) were included in the schema together with fieldwork data and interpolated. The surface roughness (friction) values obtained from land cover classification provided suitable data and were analysed in grids. Ideal outcomes were obtained from model calibration (ITC, 2010). Final output for the model sensitivity analysis and its preferences are discussed below.

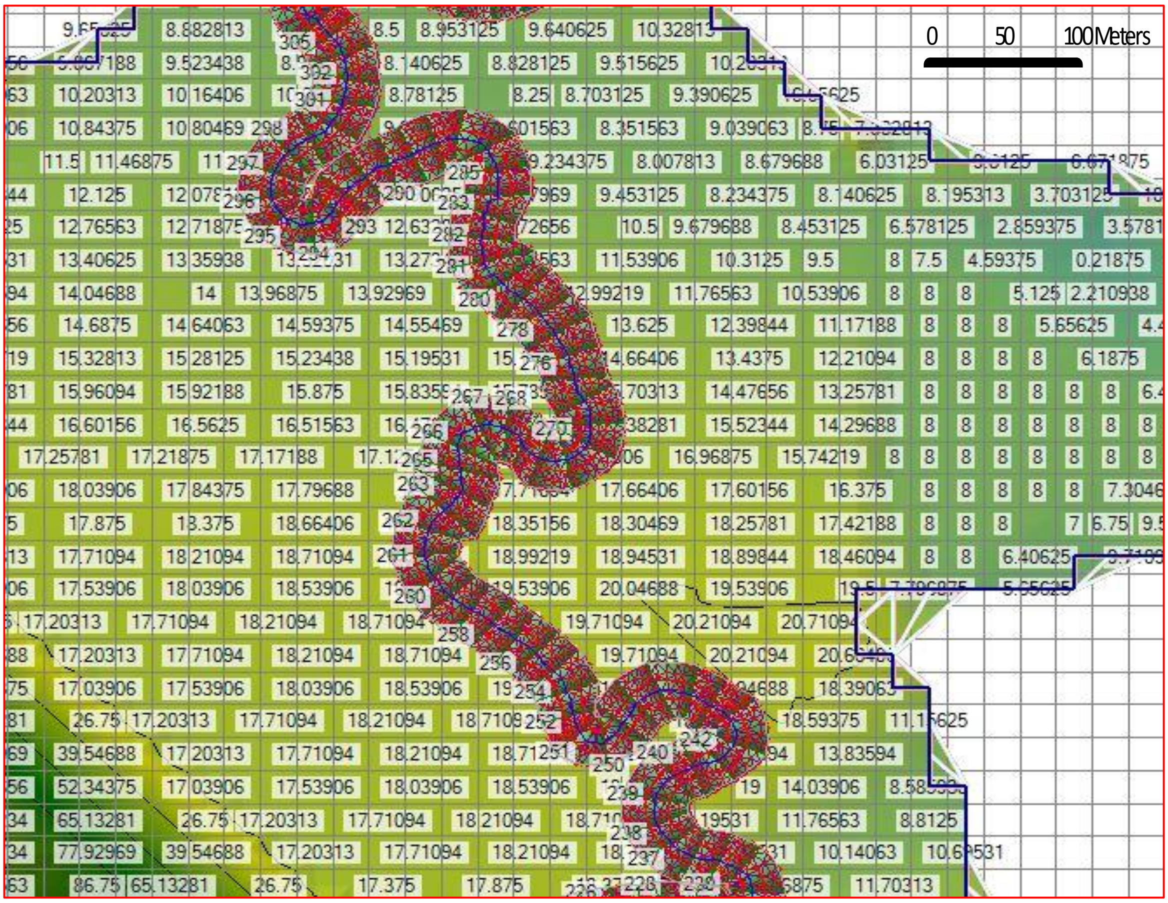
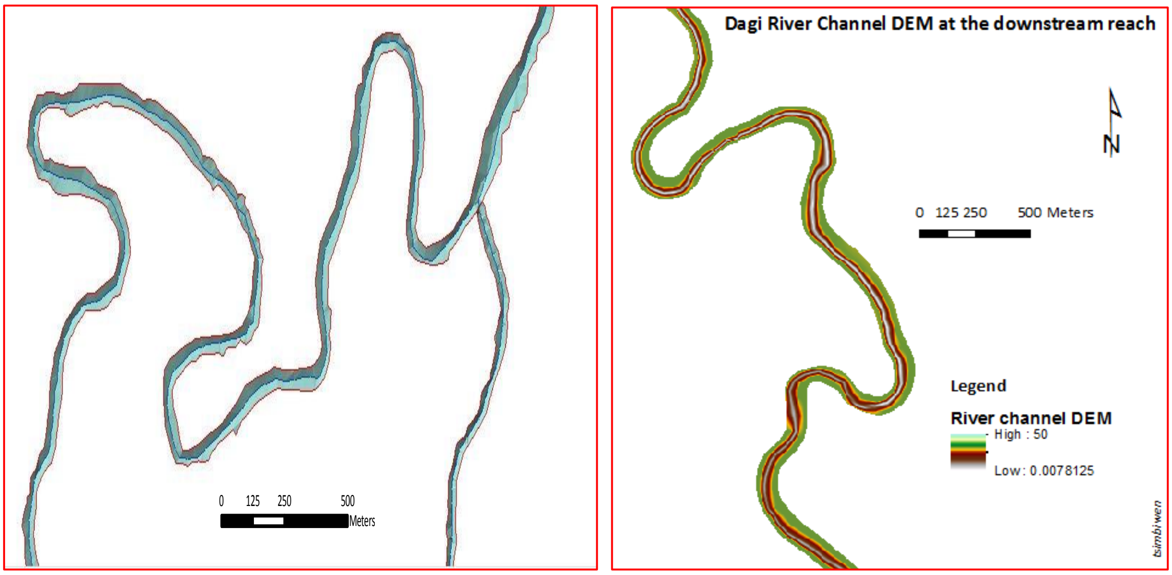


Figure 5.7: Interpolation of the DEM and river bathymetry data.



a) b)

Figure 5.8a and 5.8b: Derived TIN (a) and DEM (b) of the river channel.

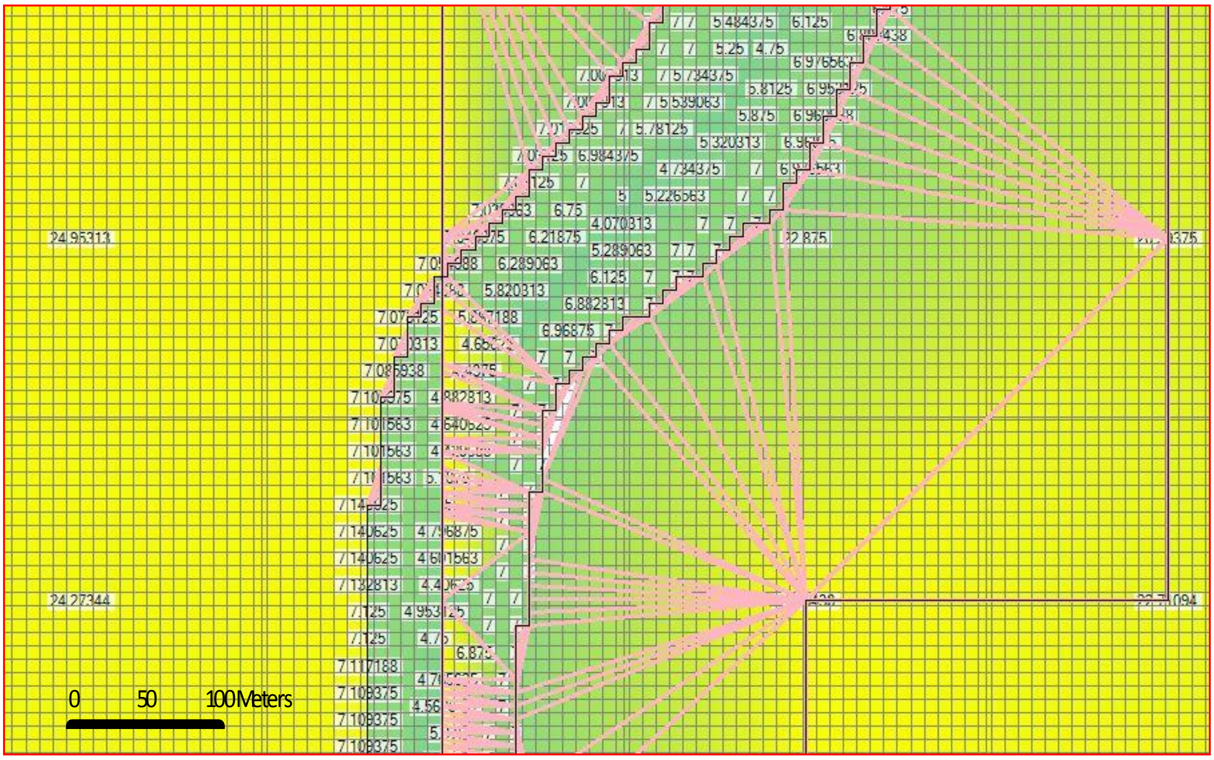


Figure 5.9: Interpolation of River TIN and DEM to derive a combined DEM

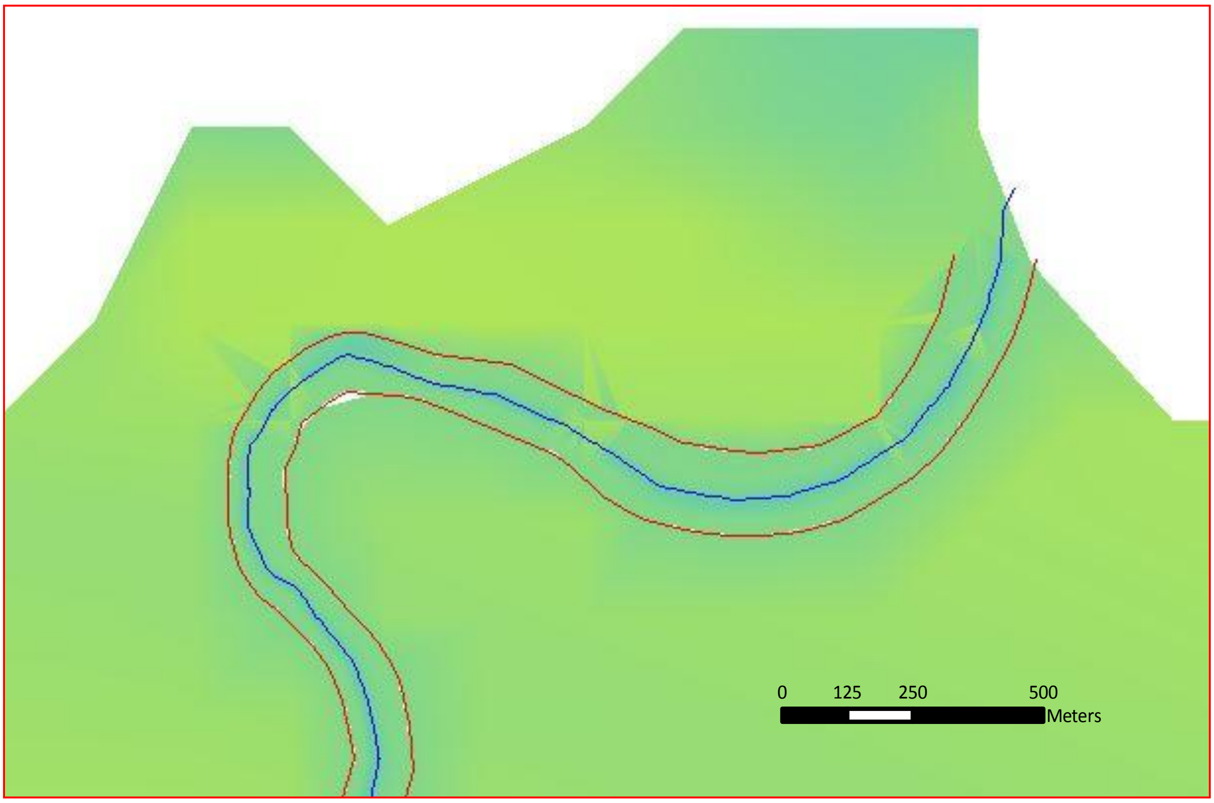


Figure 5.10: DEM with river bathymetry data with stream centreline, and bank lines as flow path centrelines added.

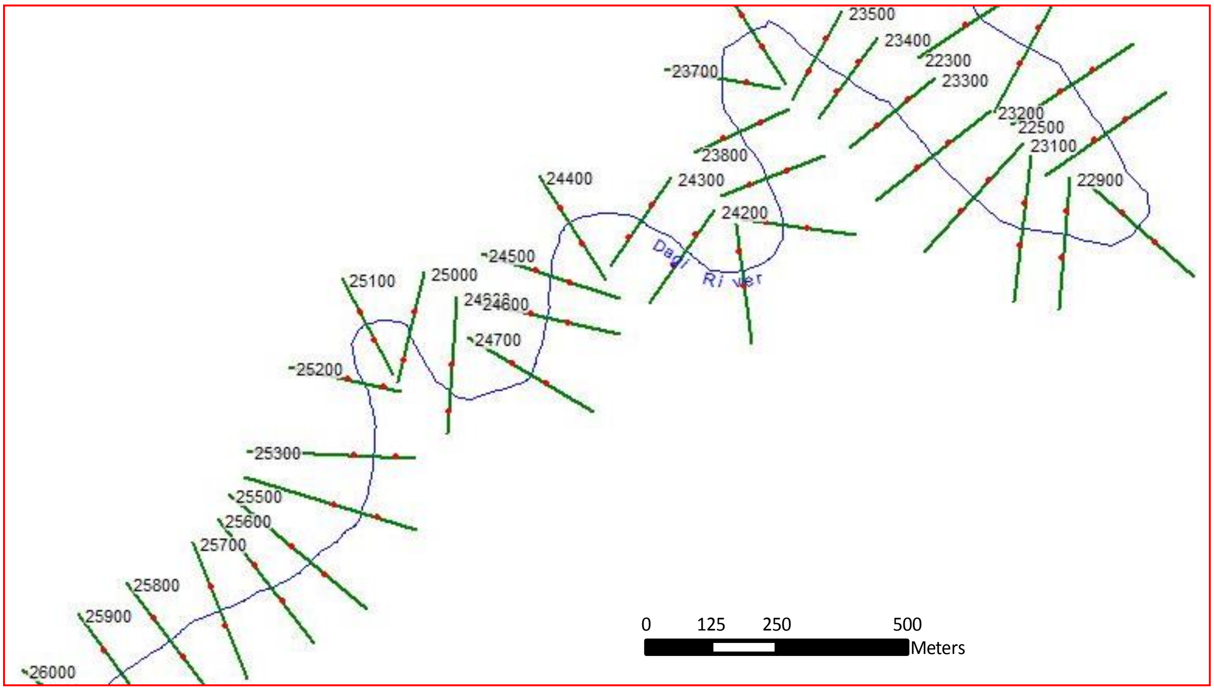


Figure 5.11: XS-Cut lines showing the bank station for each cross-section derived from the combined DEM.

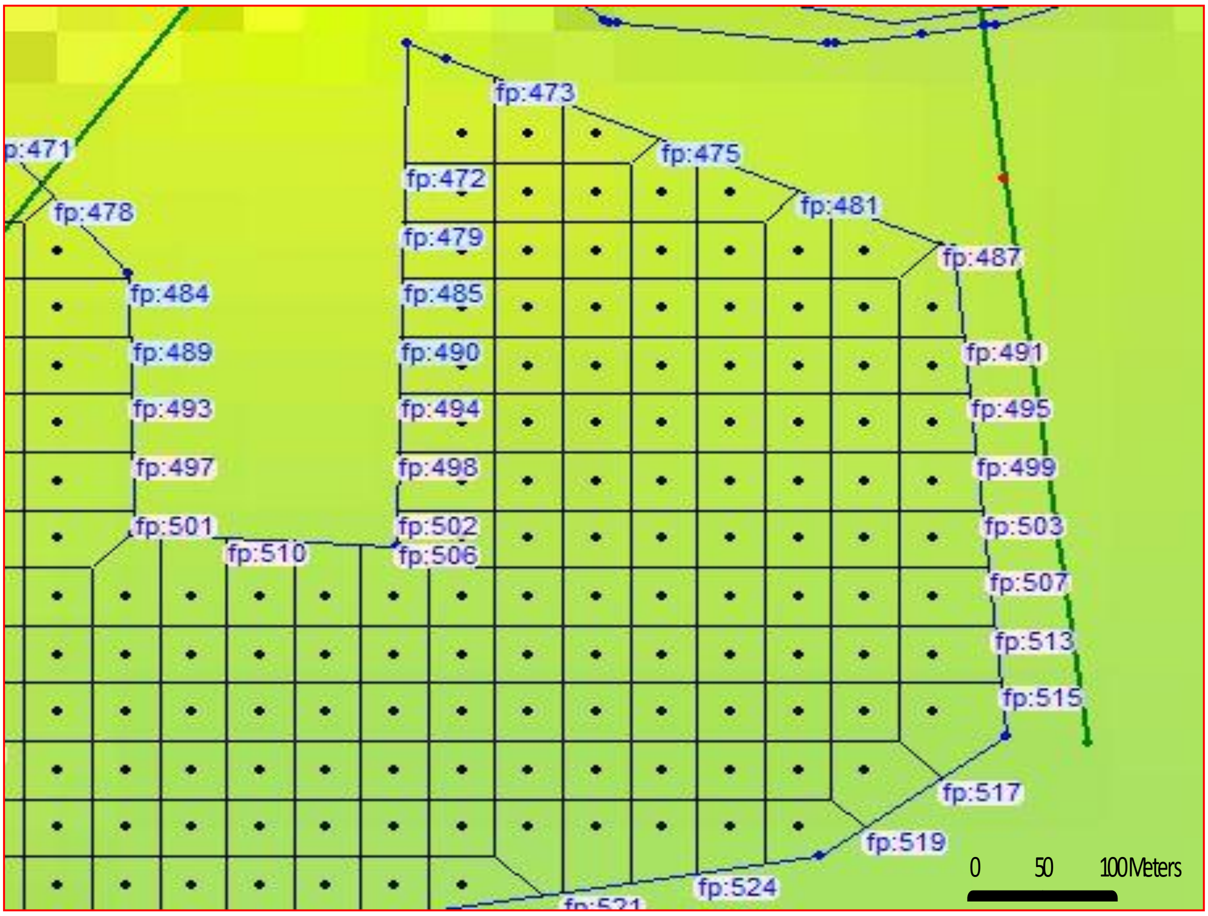


Figure 5.12: GPS coordinates of the flood extent were digitised into a 2D area and converted into a 2D computational mesh with each face point (fp) assigned a unique number.

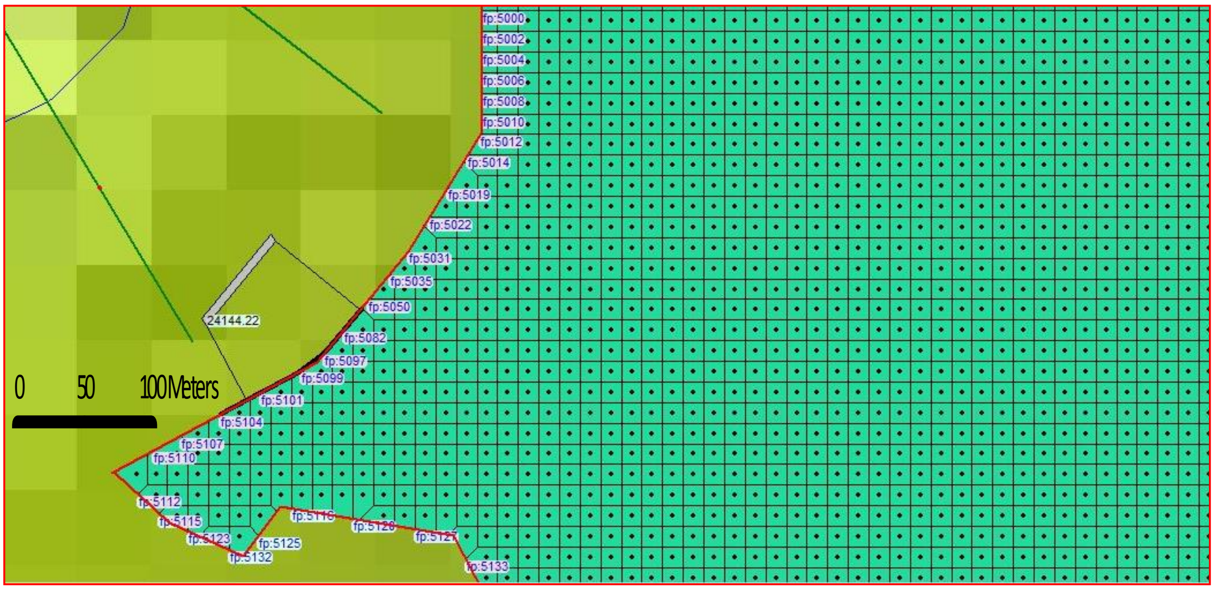


Figure 5.13: A 2D area along the catchment now linked to the 1D River channel through which high water breaches the levees and inundates the Dagi floodplains.

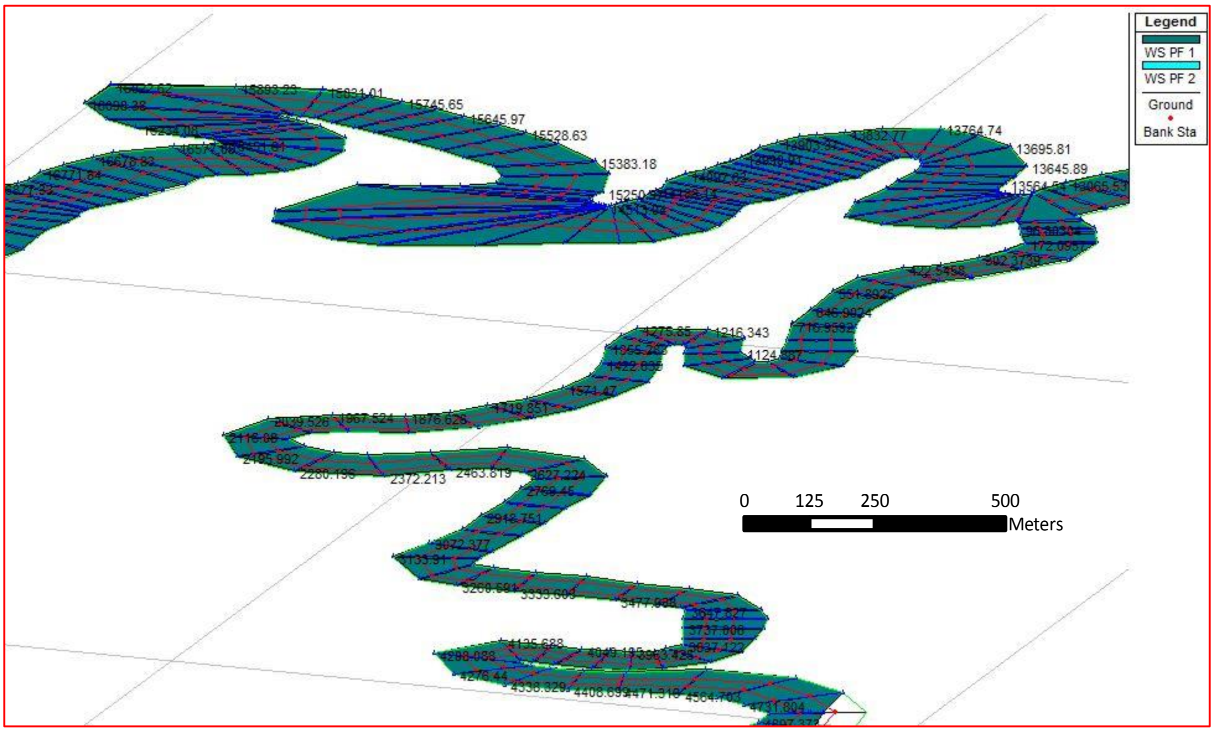


Figure 5.14: A zoomed segment of the exported schema from HEC-RAS Beta 5.0 to HEC-GeoRAS within an ArcGIS 10.2 environment and SOBEK 1D/2D.

5.3.4.4 Analysis 4: Generation of parameter maps

The combined 1D/2D simulation was run in HEC-RAS, HEC-RAS Beta 5.0 (2015 version), and SOBEK 1D2D and then exported to HEC- GeoRAS through which flood depths, velocity, stream power, shear stress and many other flood parameters were generated along each cross-section (e.g. figure 5.14). The model outputs were maps showing the characteristics of floods in 2010 and 2014 including statistics on flood behaviour. The most relevant to this chapter were the maximum depths and maximum velocities needed for inundation and hazard mapping:

A. **Maps of maximum flood height/depth (m):**

   They present the 2010 and 2014 Dagi flood characteristics along reaches in sub-catchments shown by the maximum water height/depth in metres revealing hazard zones. They indicate areas that were inundated and exposed livelihood assets in Dagi catchment. Such visualisations indicate the amount of likely flood damage in Dagi for a given recurrence interval (ITC, 2010; Alkema, 2007).

B. **Maps of maximum flood speed/velocity (m/s):**

   They reveal the maximum speed/velocity (in metres per second) during the 2010 and 2014 Dagi flood along reaches in sub-catchments. They show areas where speed is highest or lowest to determine the level of damage that can be caused and is used to identify the hazard level (ibid.).

The results from the Dagi model were translated into ArcGIS compatible formats that were later used to define hazards, vulnerability and risks.

5.4 Results for inundation and hazard

5.4.1 Flood inundations in 1D channels

The total flood volume (m^3) in the main river channel varied between distances from upstream (35km) to the outlet (0km) during the 2014 and 2010 floods (figure 5.15). In 2010, the total volume was 6,400m^3 at 32km, 16,000m^3 at 24.5km, and 23,000m^3 at the outlet. At the same distances in 2014, the total recorded volume was 5,900m^3, 15,000m^3, and 22,000m^3 at the outlet. The graphs showed that the flood volume was higher during the 2010 flood than that of 2014. Both flood events showed increases in the flood volume from upstream reaches going downstream where concentration is highest in the lower reaches.

As volume concentration increased downstream for both flood events, inundation occurred along the reaches. The same colour has been used in the figures for the 2014 and 2010 1D inundation extent for comparison purposes and the depths show little variations in the channels. This was the reason a close-up map is inserted below the broader scale catchment inundation to see some of the differences in the depths. The 2014 maps show that inundation depths generally increased downstream in the 1D channels except for the Ru and Dagi upstream reaches (figure 5.16 and appendix 5.4). The depth in upstream reaches was between 5m to 6.5m in the Ru and Dagi. The channels at the Ru and Dagi were artificially deepened by extraction of gravels to fix oil palm plantation roads, and indirectly made way for more flood storage. The 2010 map shows little variations from the 2014 1D inundation of the channels (figure 5.17 and appendix 5.4). The main difference can be observed in the deepened channels at the Ru and Dagi with a maximum depth of 7.5m, in response to high rainfall inputs in 2010. Another minor difference can be seen at Mosa Oil Mill (figure 5.18 and appendix 5.4) and this was due to excavations along the Lamegi River to allow vehicles to access the sand banks. Generally, 1D inundation in both 2014 and 2010 floods are quite similar because they were at their bankfull stage (maximum 1D extent). The big difference in the inundation extent for both years can be seen in the 2D over flows on to the floodplains.

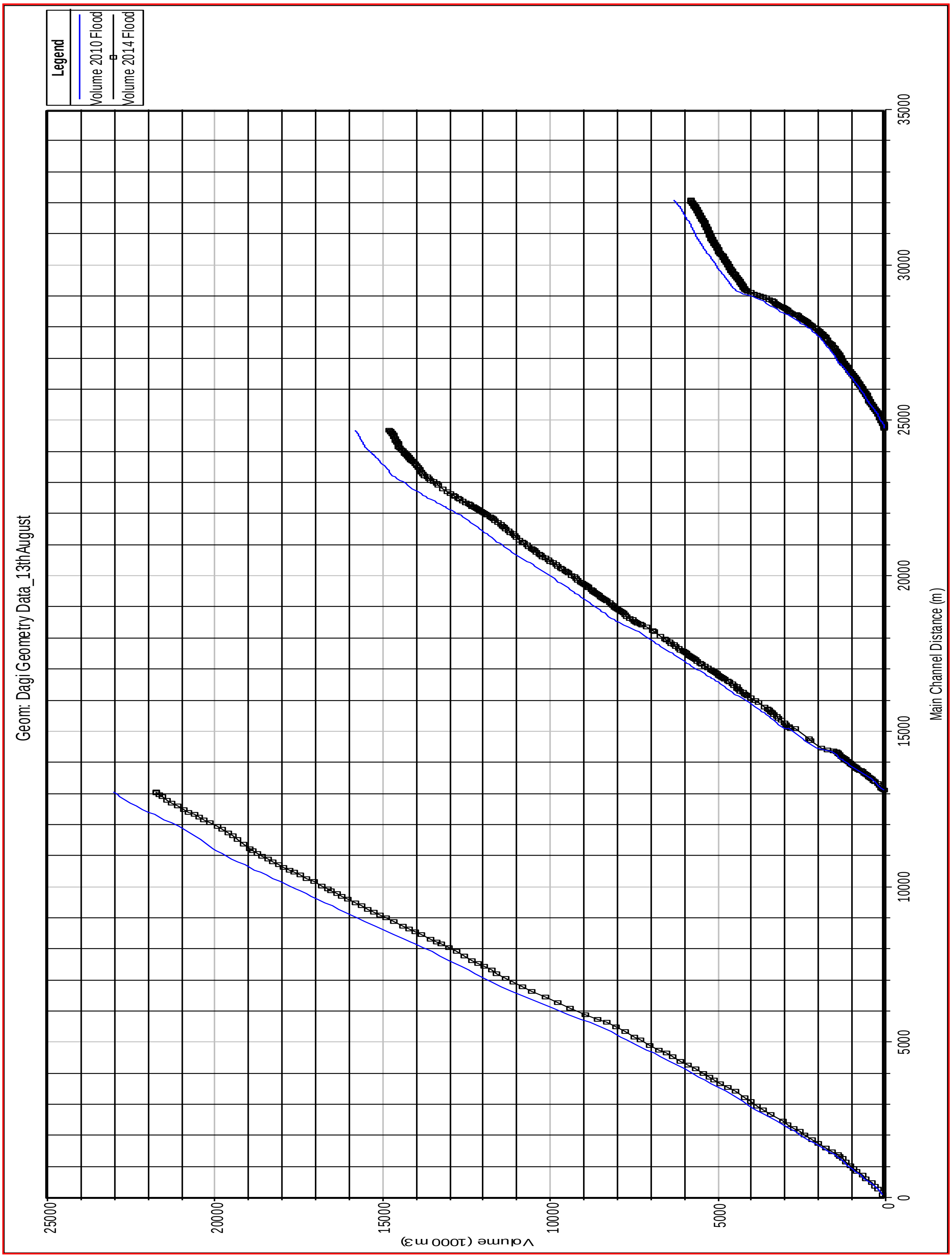


Figure 5.15: Summarised flood volume shown by the black line (2014) and blue line (2010) going downstream, (from right side). *NB: Channel length from the mouth is 0km and going upstream to 35km (headwaters). NB: There are two ways of expressing volumes when using HEC-HMS modelling software. They are expressed either in 1. MM or 2. M^3. The volume above are expressed in M^3, which is the equivalent of the MM unit derived in chapter 4 and are consistent. NB: The value of volume is 1000 m^3 per interval (in bracket) and not to be interpreted as X1000 m^3.*

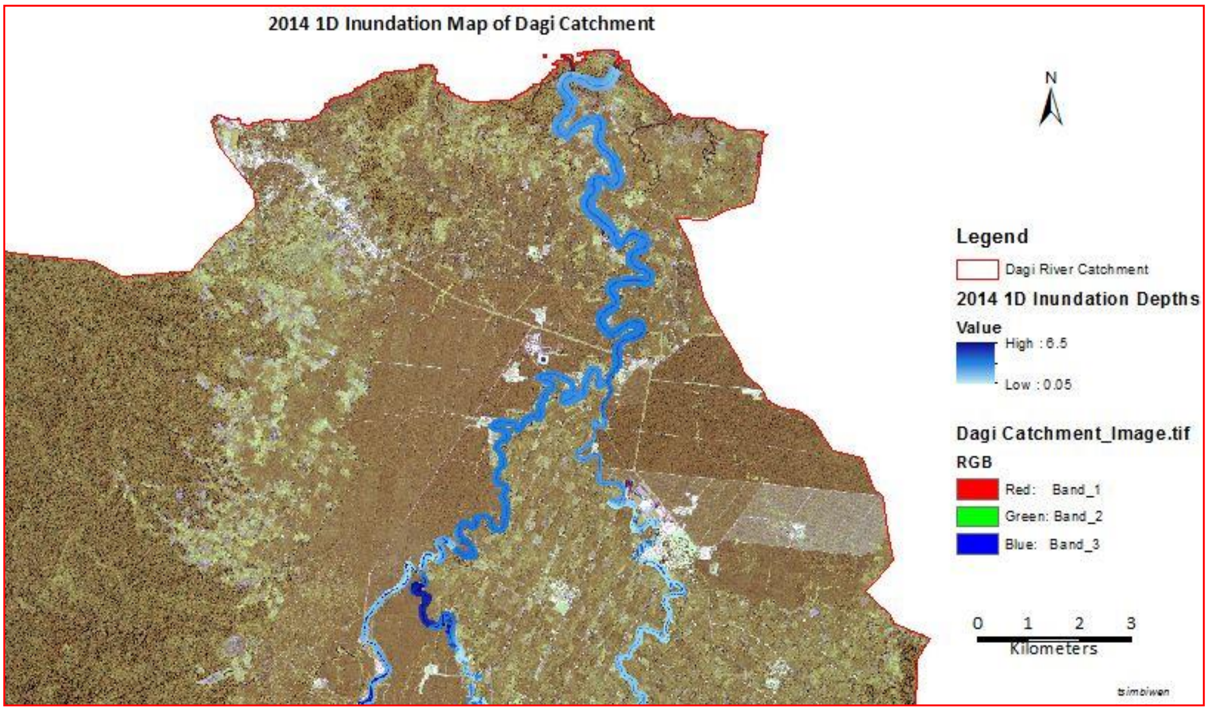


Figure 5.16: 2014 1D inundation depth distribution for 2014.

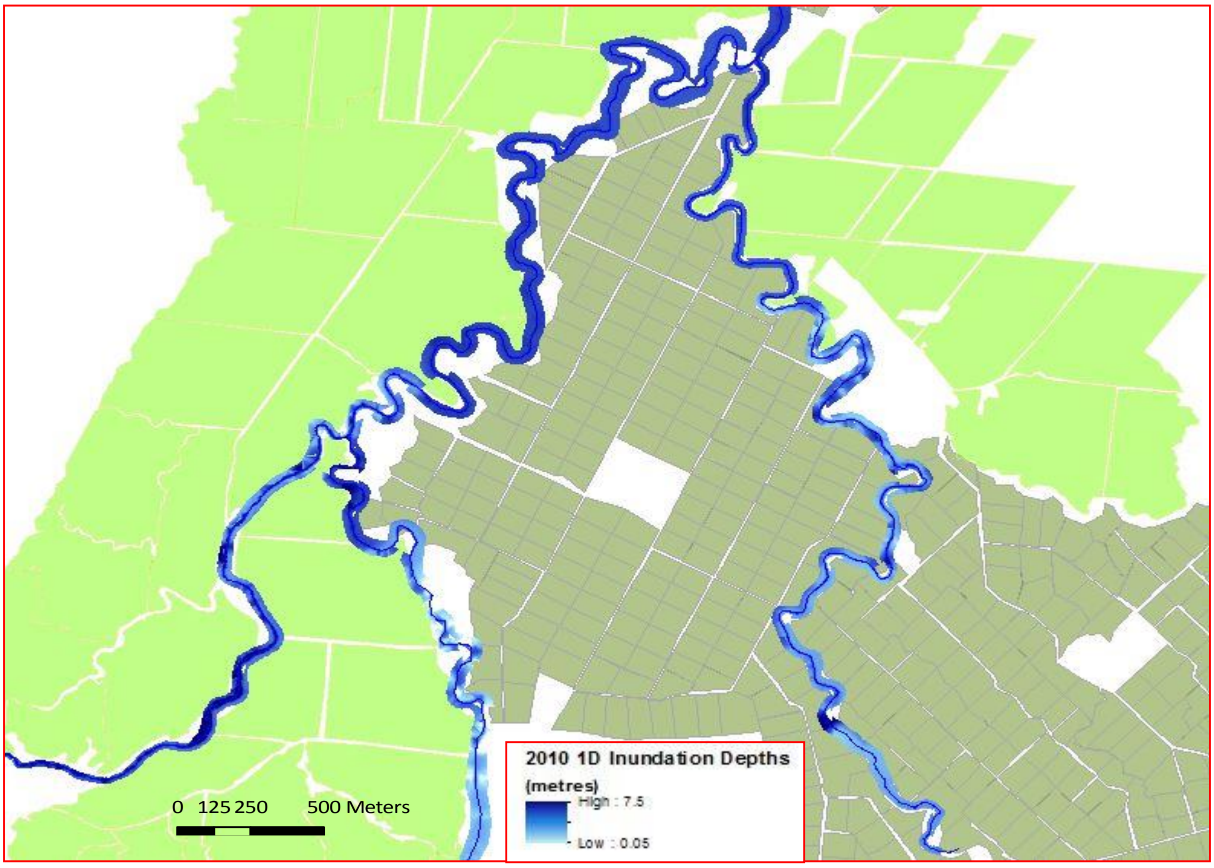
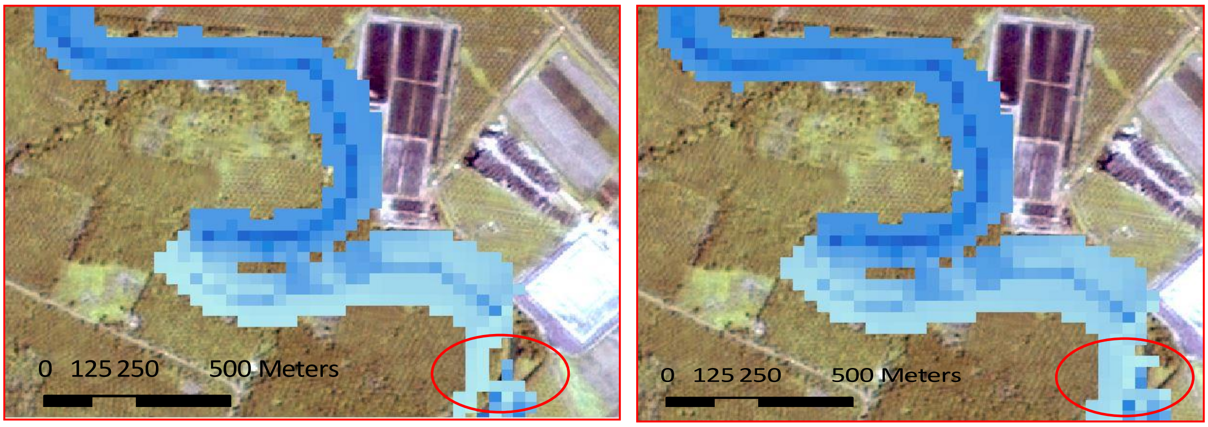


Figure 5.17: A close-up view of the 2010 1D inundation depth distribution.



2014 2010

Figure 5.18: A close-up view of 1D inundation depth and extent with minor differences at Mosa.

5.4.2 Inundations in combined 1D channels and 2D flow areas

Presented in table 5.3 are the computed results for the maximum extent of water outside the main river channel. There are no data for the Ru and Lamegi reaches for the 2014 flood event for computations. Based on the existing data, the 2010 flood has a higher inundation extent compared with that of 2014. The exceedance probabilities are 0.0085238 and 0.0076190 respectively and both years had more inundation in the lower reaches but decreased upstream. The out-of-channel extents of maximum water along the Dagi varied for both years. The 2010 flood recorded the highest areal extent of inundation for all reaches with 36.5 hectares at the downstream reaches.

Table 5.3: Inundation extent for 2014 and 2010 floods.

Year	Exceedance Probability	River/Reach	Out-of-stream-bank	Maximum water extent out-of-channel (m^2/km^2)	Maximum water extent out-of-channel (ha)
2014	0.0085238	Dagi - Upstream	Yes	63, 003 / 0.063	6.3
		Dagi - Middle	Yes	154, 568 / 0.155	15.5
		Dagi -Downstream	Yes	333,369 / 0.334	33.4
		Ru	No	-	-
		Lamegi	No	-	-
2010	0.0076190	Dagi - Upstream	Yes	65, 113 / 0.065	6.5
		Dagi - Middle	Yes	170, 915 / 0.171	17.1
		Dagi -Downstream	Yes	364,248 / 0.365	36.5
		Ru	Yes	95,630 / 0.096	9.6
		Lamegi	Yes	102,525 / 0.102	10.2

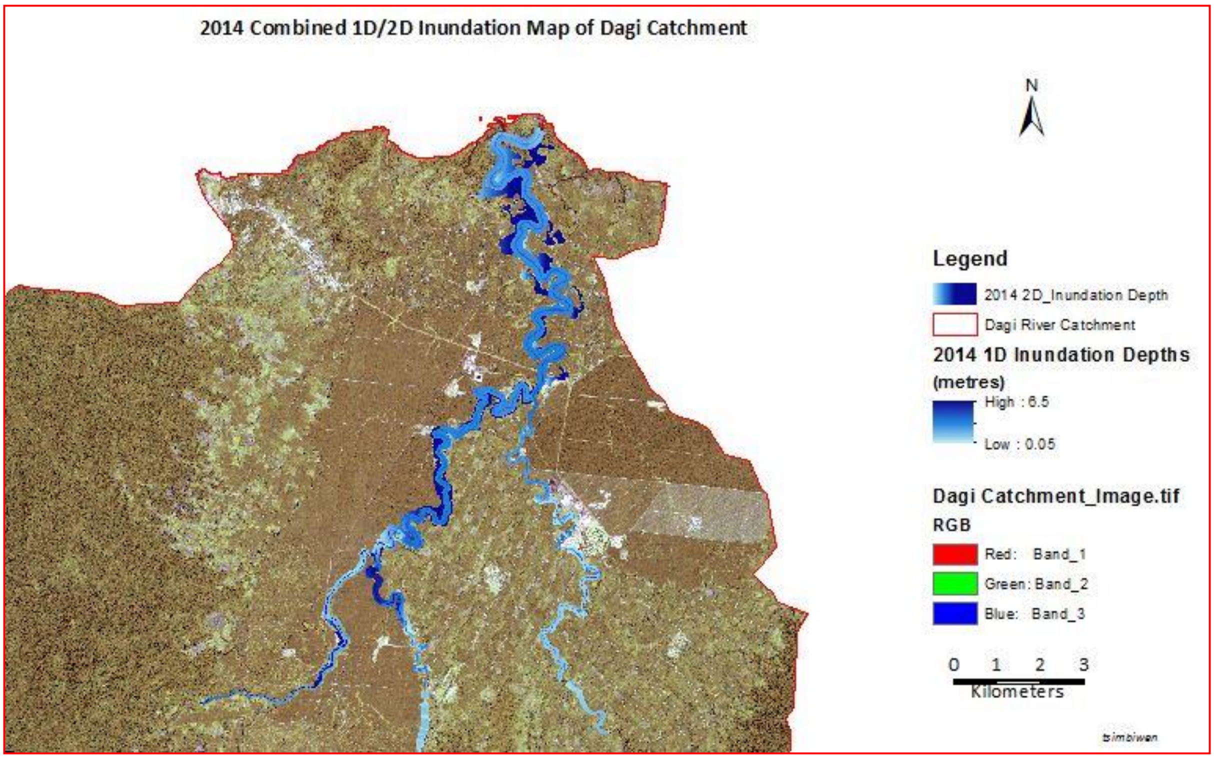


Figure 5.19: Combined 1D/2D inundation depth for 2014.

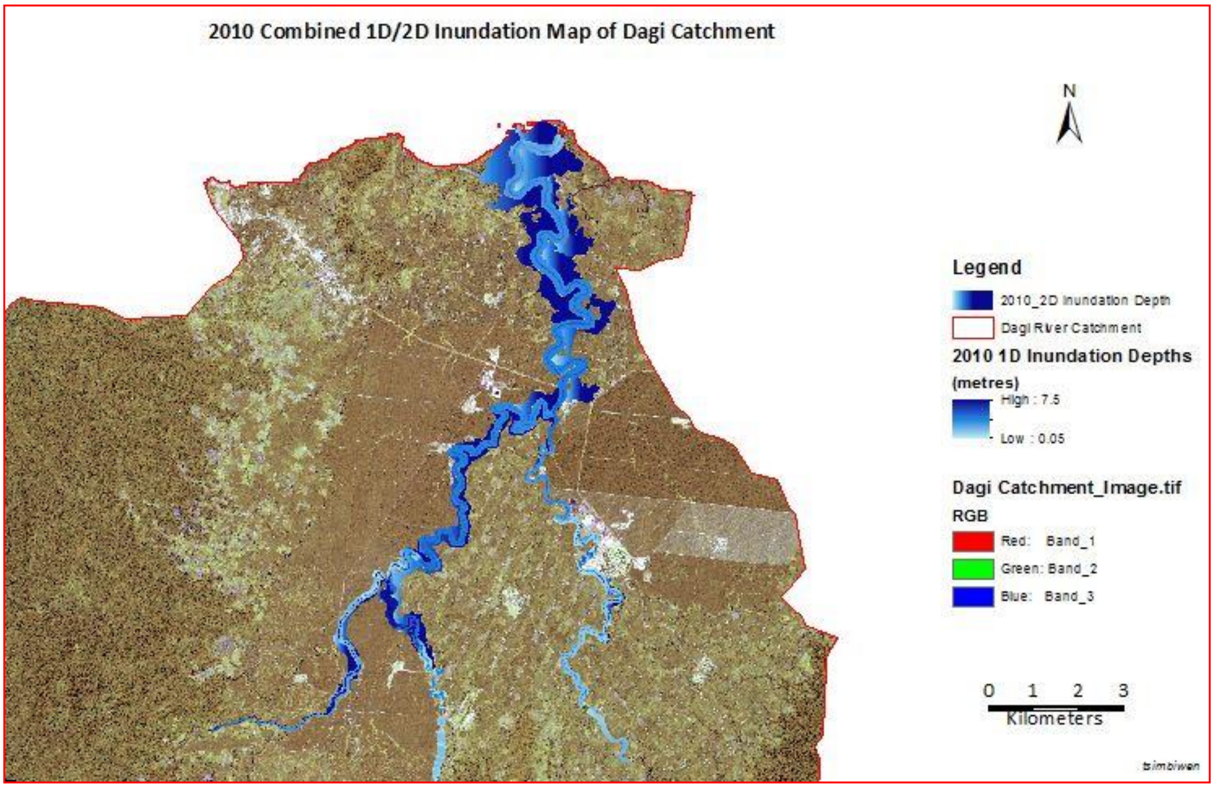


Figure 5.20: Combined 1D/2D inundation depth for 2010.

The combined 1D/2D inundation depth for 2014 (figure 5.19) varies across the channels with those of 2010 (figure 5.20). Inundation depth varies from as low as 0.05m to as much as 6.5m in most reaches for 2014 and the same pattern can be seen on the map for 2010. In 2014, downstream reaches had the highest inundation extents compared with those upstream, and the pattern was the same for 2010. These patterns can be attributed to an increase in the volumes of water from upstream reaches that caused increased inundation downstream. Between 2010 and 2014 floods, 2010 recorded the highest areal inundation extent with downstream reaches showing the largest. In some stream reaches, inundation depths varied from upstream and downstream and this has been attributed to the slopes, dendritic river pattern and channel characteristics of the area, including man's influence in deepening the channels through gravel extractions. Upstream reaches had slightly narrowed flow areas due to higher slopes and flows tended to follow a defined pathway downstream. On the other hand, flow areas increased in extent downstream as the gradient decreased. The 2010 flow area was much larger than that of 2014 due to high rainfall inputs and the influence of channel and geological characteristics of Dagi.

5.4.3 Velocities and flow travel time in channels

The velocity results in 1D channels for both 2014 and 2010 flood events generally showed increases downstream because of increased volumes of water with little differences (e.g. figure 5.21, also see appendix 5.5). On average, velocity in channels can go much higher from 2.0m/s to 8.0m/s to as much as 20m/s depending on the magnitude for both flood events and as low as 0.01m/s. Velocity is highest in reaches with steep gradients. As can be seen on the maps, velocity is also highest in straight channels and along meander bends, and lowest in the concave sections of the channels where more storages are allowed.

Velocity is also influenced by roughness in the channel and overbank areas, where areas with more debris and vegetation tends to lower the velocity due to frictional resistance. In the stream channels, velocity is highest in the middle and decreases towards the banks. Turbulences in the channels due to obstructions (e.g. a tree) reduces the stream velocity, while in channels with less obstructions increases the velocities across the channels. Velocity is generally high upstream, in the middle and at the lower reaches of the Dagi. This can be attributed to water contributed from the tributaries, which in turn increased the velocity as the slope gradient decreased. In the tributary reaches, velocity is lower because of the frictional resistance of the vegetation and because of their small sub-catchment sizes, where little is contributed from the ground water sources and from the overland flows (chapter 4).

On the other hand, velocity varies in 2D flow areas because they encounter more frictional resistance than the channels. High velocities in 2D areas can be attributed to the slope gradients that give them energy to flow fast. Flow times also varied for both years and this has been attributed to the channel distances between reaches to the outlet (figure 5.22). Flow travel time from 25km upstream to the middle reach (13km) was 55 minutes for the 2014 flood event while that of 2010 was 1 hour. At 22km upstream, the travel time to the outlet was 1 hour 55 minutes for 2014 while that for 2010 was 2 hours. An interesting observation is that flow durations for the two sampled floods were similar in the two reaches. The 2010 flood travelled just slightly more slowly despite having almost twice the discharge (after almost twice the rainfall). The travel time varies slightly between reaches due to the influence of slope, channel types and frictional resistances.

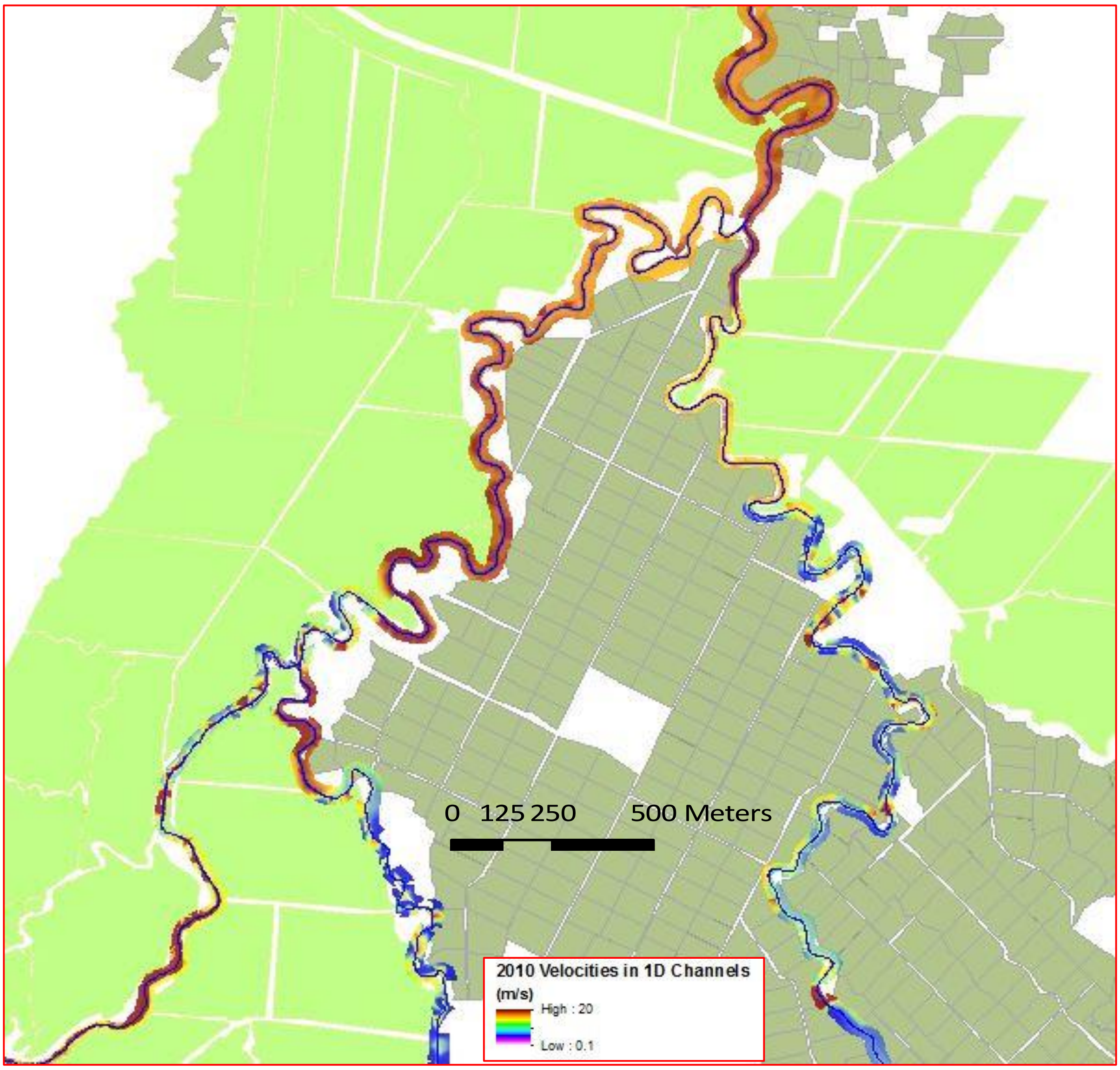


Figure 5.21: 2010 velocity distribution at a close view.

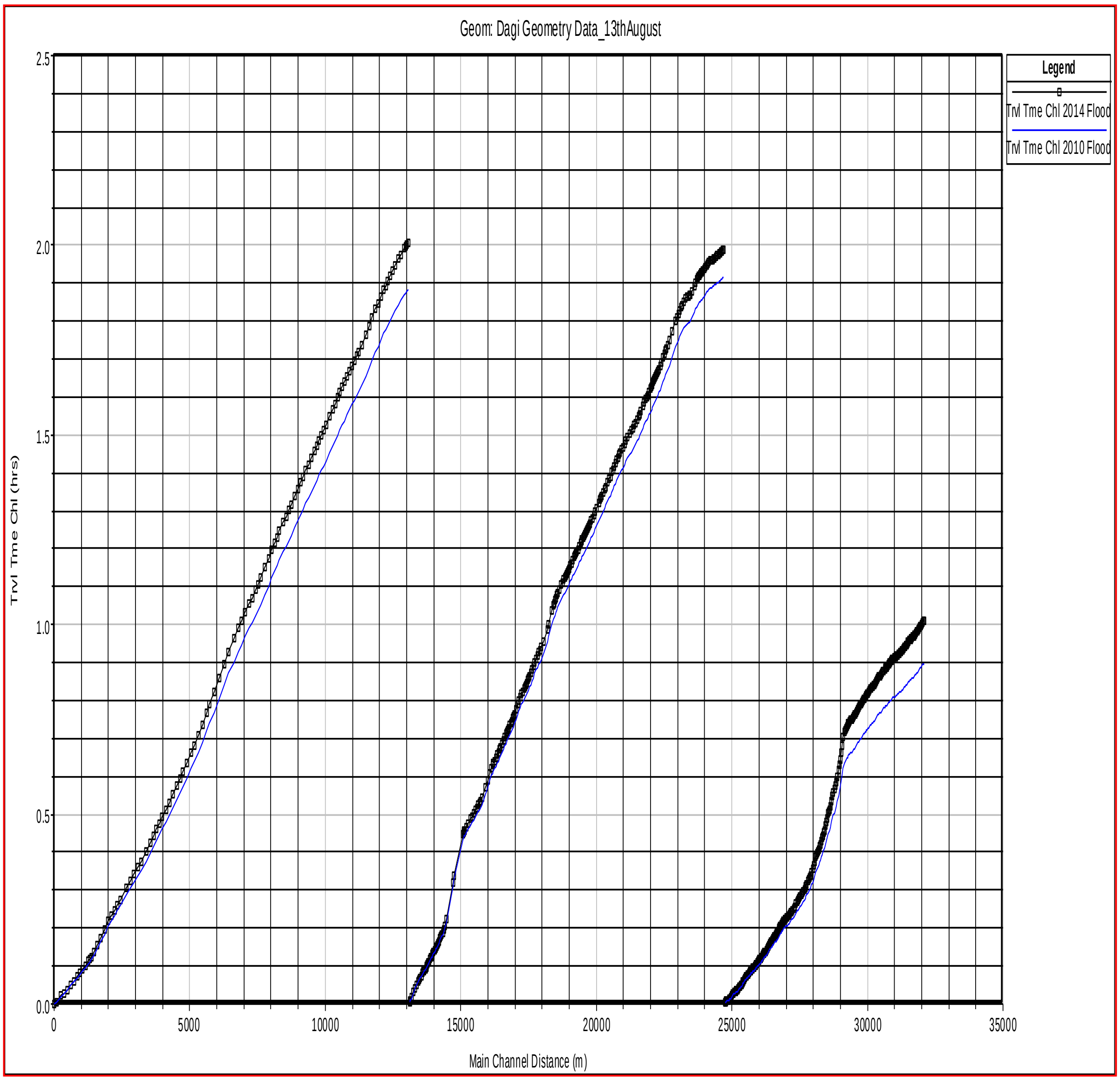


Figure 5.22: Flow travel time along the main river reaches.

5.5 Calibration, model sensitivity and validation: water heights and frictional values.

This section presents and explains the results of the calibration, optimisation, model sensitivity analysis and their validation (Muthukrishnan et al., 2006). These being completed were established upon the susceptible factor of resistance data for 2014 and 2010 for 12 hours and were compared with the water heights from fieldwork. During model optimisation, an explicit consensus or discrepancy must be reached between the measured and the simulated data (Alkema, 2007; ITC, 2010). Adjustment checks were made to compare between the measured and simulated data (Muthukrishnan et al., 2006).

Table 5.4: Observed and simulated water depths at selected sites.

Year	Water Level Station	Observed water depth	Simulated water depth	Difference
2014	Dagi – Upstream (Hark)	3.96	3.97	0.01
	Dagi – Middle (Palei's Block)	5.88	5.65	-0.23
	Dagi –Downstream (Segurum's Block)	5.94	5.27	-0.67
	Ru (Delis's Block)	4.35	3.79	-0.56
	Lamegi (Bebere Plantation)	4.47	4.32	-0.15
2010	Dagi – Upstream (Hark)	4.82	4.48	-0.34
	Dagi – Middle (Palei's Block)	5.85	5.93	-0.08
	Dagi –Downstream (Segurum's Block)	7.13	6.65	-0.48
	Ru (Delis's Block)	5.55	4.57	-0.98
	Lamegi (Bebere Plantation)	4.55	4.86	0.31

There are minor differences between the observed and simulated water depths for all water level stations (table 5.4). If the differences go beyond the critical level of 5, this means that there were mistakes in data originating from fieldwork or from simulations, and the model outputs would not be accurate enough to suit the purpose (Alkema, 2007). The above results indicate almost a clear agreement between the observed and simulated water depths. This means that the model is close to accurate with a few errors introduced.

The most reliable water depths will be from field observations, then the computer-based simulation because computer-based simulations introduce errors (e.g. channel geometry) and alter the actual results. Through the calibration exercises for both 2014 and 2010, results agreed.

Table 5.5: Comparing fieldwork and calibration data for model sensitivity analysis to roughness data using 2014 and 2010 data.

Time	Observed water depth (m): Dagi upstream-2014	Modelled water depth (m): Dagi upstream-2014	Difference at Dagi upstream-2014	Observed water depth (m): Dagi upstream-2010	Modelled water depth (m): Dagi upstream-2010	Difference at Dagi upstream-2010
5:00am	3.85	4.52	0.67	3.83	4.57	0.74
6:00am	4.02	4.23	0.21	4.06	4.24	0.18
7:00am	4.13	4.57	0.44	4.15	4.58	0.43
8:00am	4.24	4.66	0.42	4.26	4.68	0.42
9:00am	4.28	5.00	0.72	4.3	5.04	0.74
10:00am	4.47	4.64	0.17	4.49	4.86	0.37
11:00am	4.88	4.98	0.10	4.9	5.22	0.32
12:00pm	5.10	5.34	0.24	5.13	5.45	0.32
1:00pm	4.77	5.15	0.38	4.78	5.17	0.39
2:00pm	4.32	4.87	0.55	4.34	4.88	0.54
3:00pm	4.19	4.57	0.38	4.20	4.58	0.38
4:00pm	3.96	4.05	0.09	3.98	4.08	0.10

Similarly, the comparative values between the vertical and horizontal frictional values for the channels along Dagi upstream, middle, and lower reaches show little differences (table 5.5). The parametric approach analyses model sensitivity to different parameters and this was accomplished by altering Manning's roughness coefficient within the channel cross-sections (ITC, 2010). The roughness data for vegetation were shown in table 5.2 and figure 5.2. The riparian vegetation in the Dagi catchment is moderate to low as we go downstream while upstream has high vegetation cover. Cobbles, pebbles and sand are common downstream while large boulders and gravels are dominant upstream. The influence of low roughness going downstream increases stream power (e.g. figure 5.23). Frictional losses tend to be high upstream because of the slopes, and low downstream as the river loses its continuity and momentum due to energy loss from friction towards the outlet.

Based on these factors, frictional data were extracted and a sensitivity analysis test was executed. Noticeably, Manning's *'n'* vertical and horizontal frictional data produced precise results in comparison with those of 2014 and 2010 (tables 5.4 and 5.5). Mean observation and simulation data for water depths differed per various frictional figures: -0.08m to -0.98m, and 0.01m and 0.31m. There were slight over-estimations and under-estimations in modelled data along the fringes, however, in peak discharge zones, the best simulated difference ranges from 0.32m, 0.39m to 0.54, 0.38 and 0.10m. This was because comparison was undertaken for one point. Many points of inspection in reaches would route floods better and improve model calibration. Based on past research results (e.g. Alkema, 2007 and ITC, 2010), SOBEK 1D/2D modelling with a combination with HEC-RAS and HEC-GeoRAS predicted satisfactory results taking into consideration data availability and quality.

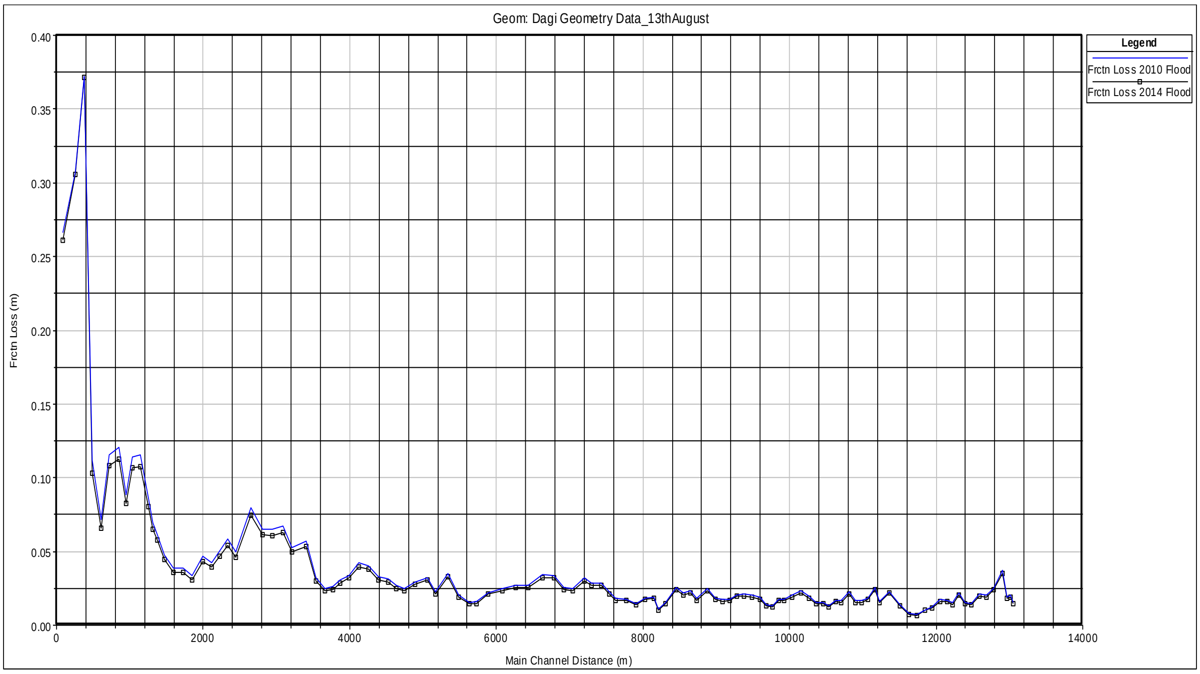


Figure 5.23: Frictional losses of stream power in the lower reach of the Dagi River.

Validation of the model simulation can be assessed by comparisons with flood events (Alkema, 2007). The respective flood events in 2014 and 2010 were selected because water height data collected during fieldwork on intervals of one hour were on hand. These data per site were used to validate model results by plotting them together to examine the differences (figures 5.24 and 5.25). Mean average difference from the validated results revealed 0.40m and peak differences were between 0.24m and 0.55m for the 2014 flood event. The validation results for 2010 revealed only a difference of 0.45m while peak differences were between 0.32m and 0.54m. The peaks of the modelled results agreed well with the observed results. Over-estimation of modelled outcome has been attributed to many mistakes in the relationship between Q-h, hydrograph shape and its nature, extracted DEM that was resampled, stream geometry as connected in the DEM and model grid, volume of objects such as tree crops and friction values.

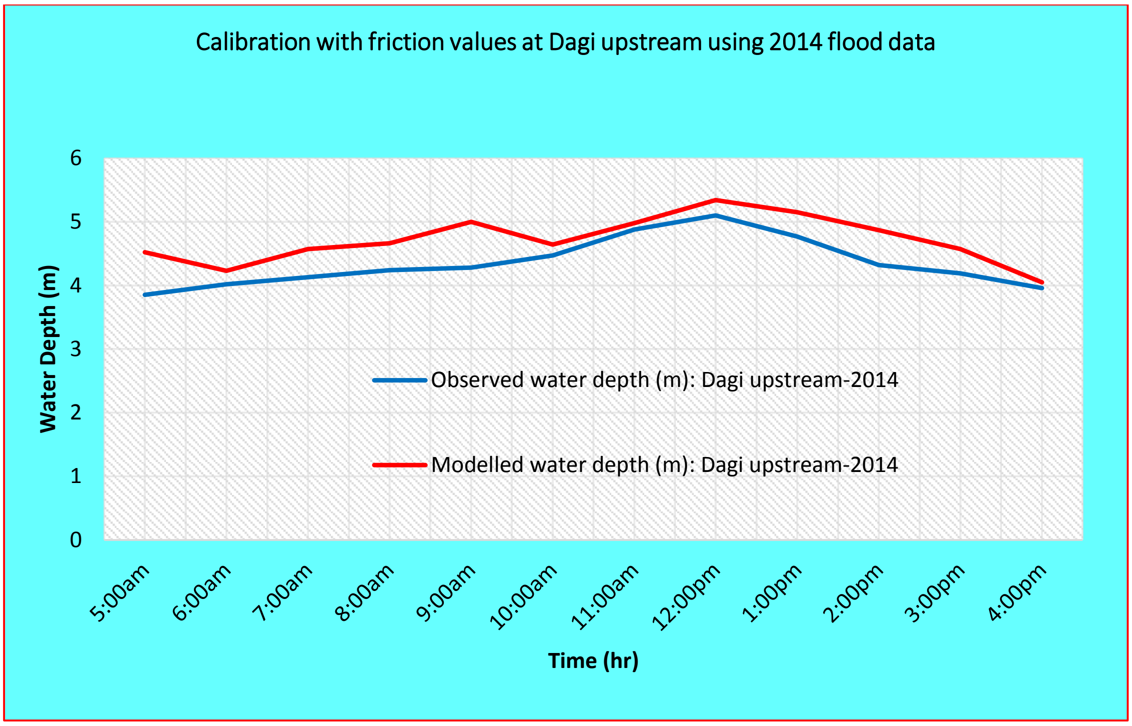


Figure 5.24: Calibration with frictional values for 2014 flood.

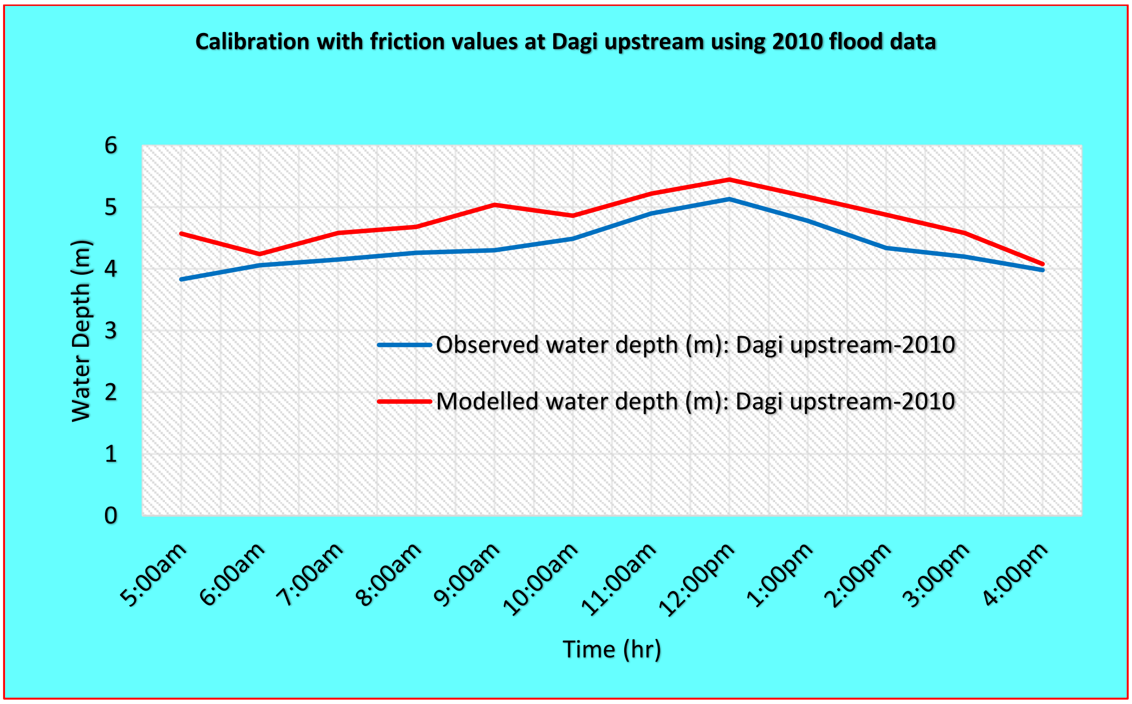


Figure 5.25: Calibration with frictional values for 2010 flood.

The statistical performance indicator results in table 5.6 were based on equation 5.1 to 5.3.

Table 5.6: Statistical performance indicator results.

Average simulated	2014	4.6
	2010	5.3
Average observed	2014	4.9
	2010	5.6
% bias	2014	12.22
	2010	15.34
RMSE	2014	0.81
	2010	0.79
Nash Sutcliffe	2014	0.75
	2010	0.71

5.6 Hazard Maps for the 2014 and 2010 floods

Numerous amalgamation of flood characteristics can be used to express a flood hazard and in this research, flood depth and velocity were used (Ramsbottom et al., 2003). Selected vehicles, including adults and children, basically relates flood hazards associated with wading (ibid.). In this study, worst case hazard levels per pixel were integrated with the flood hazard simulated maps (ibid.). Flood hazard estimation is based on the factors that triggered and caused it (ITC, 2010). These include inundation expanse, time and its onset, number of time it occurred and size, and any events instigating the flood (ibid.). To estimate hazards, flood depth and velocity maps are generated via model simulations (Alkema, 2007; ITC, 2010). The flood recurrence interval was calculated and then combined with flood depth and velocity to assess its hazard (ibid.). Flood affected areas were identified in a depth range between 0m-6.5m for 2014 and 0m-6.5m for 2010. Flood affected areas were also identified in the velocity range between 0-20m/s damage scale for both years. The recurrence interval for both depth and velocity were included.

Using the computed flood inundation extent data based on velocity and depth for 2014 and 2010 flood events in all reaches (table 5.3 and appendix 5.6), flood hazard maps of the area were drawn using the inundation parameter maps as the base maps. The lighter and darker red zones show areas of hazards outside the river channel (overtopping of the bank). The highest depth of water in the 2014 event was 6.5m (figure 5.26) while that in 2010 was 7.5m (figure 5.27). The lowest depth for both years was 0.05m. The differences in the peak discharge and modelled water height were around 0.0m to 0.6m. The maximum velocity of water in the main stream channel during peak discharge for 2014 and 2010 was 20m/s and the lowest was 0.1m/s. Velocity is highest in the channel and decreases towards the banks and in the floodplain as the effect of friction increases. Areas of inundation were classified into hazard levels using these depth and velocity characteristics as the classification criteria (see chapter 6). Downstream reaches of the Dagi River comprise areas with very high inundation and velocity, where water has gone over the banks into areas of land use, posing hazards to assets and livelihoods.

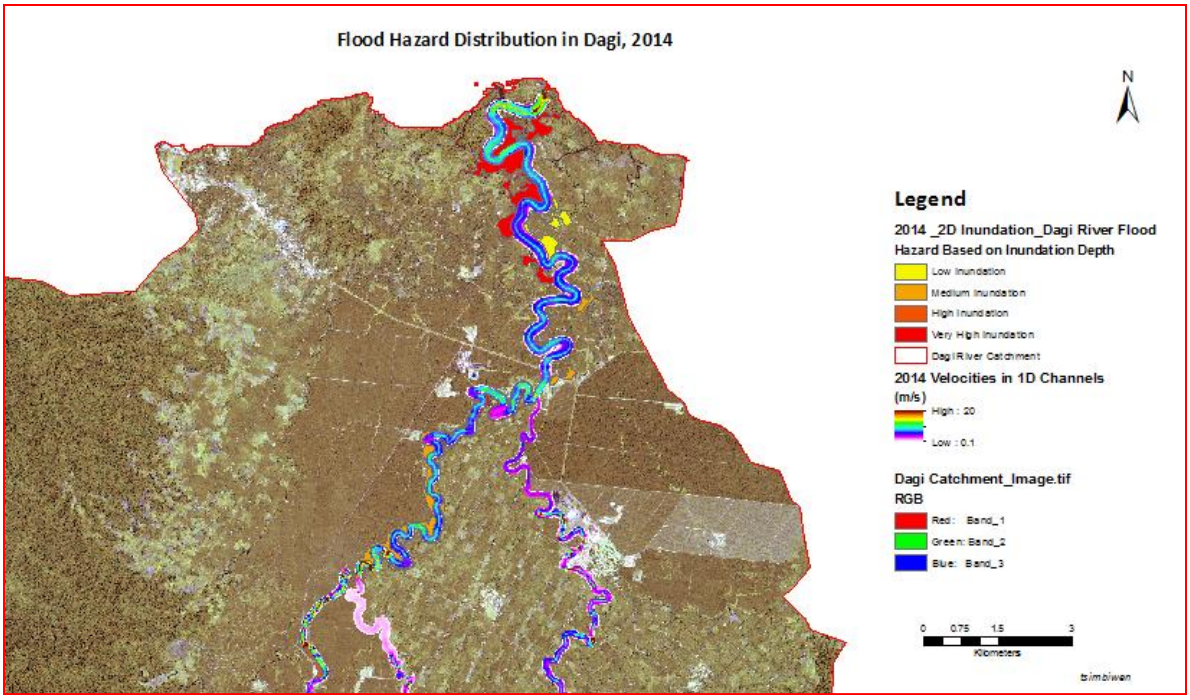


Figure 5.26: Flood hazard distribution in Dagi, 2014.

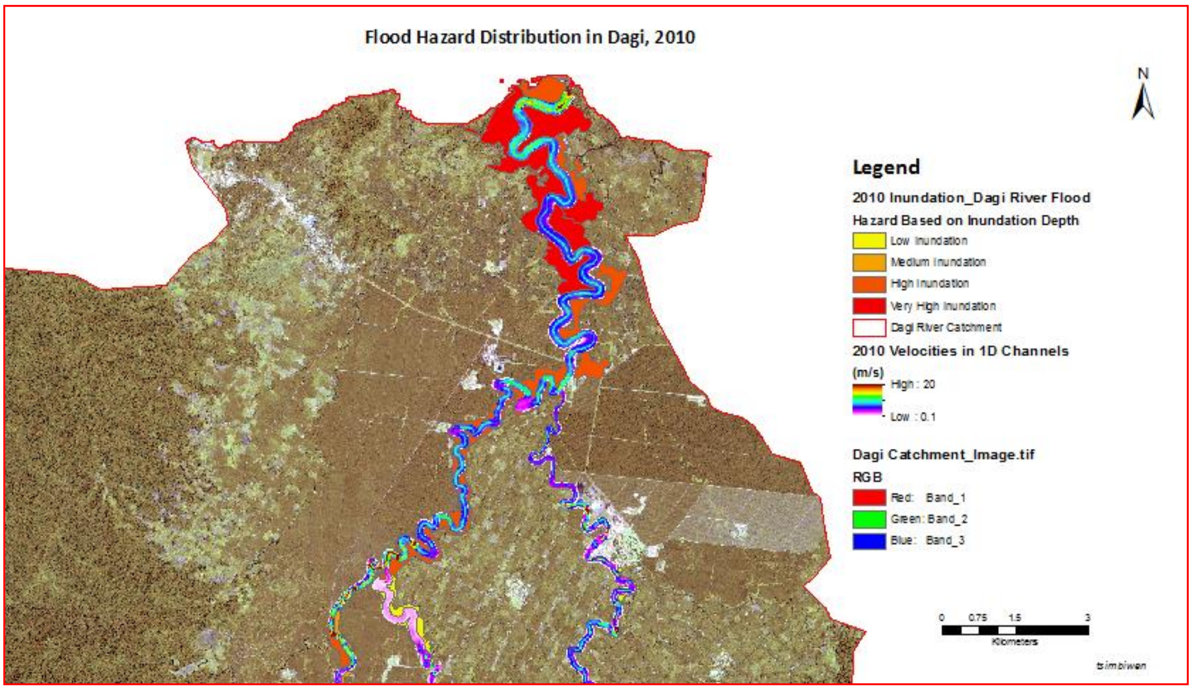


Figure 5.27: Flood hazard distribution in Dagi, 2010.

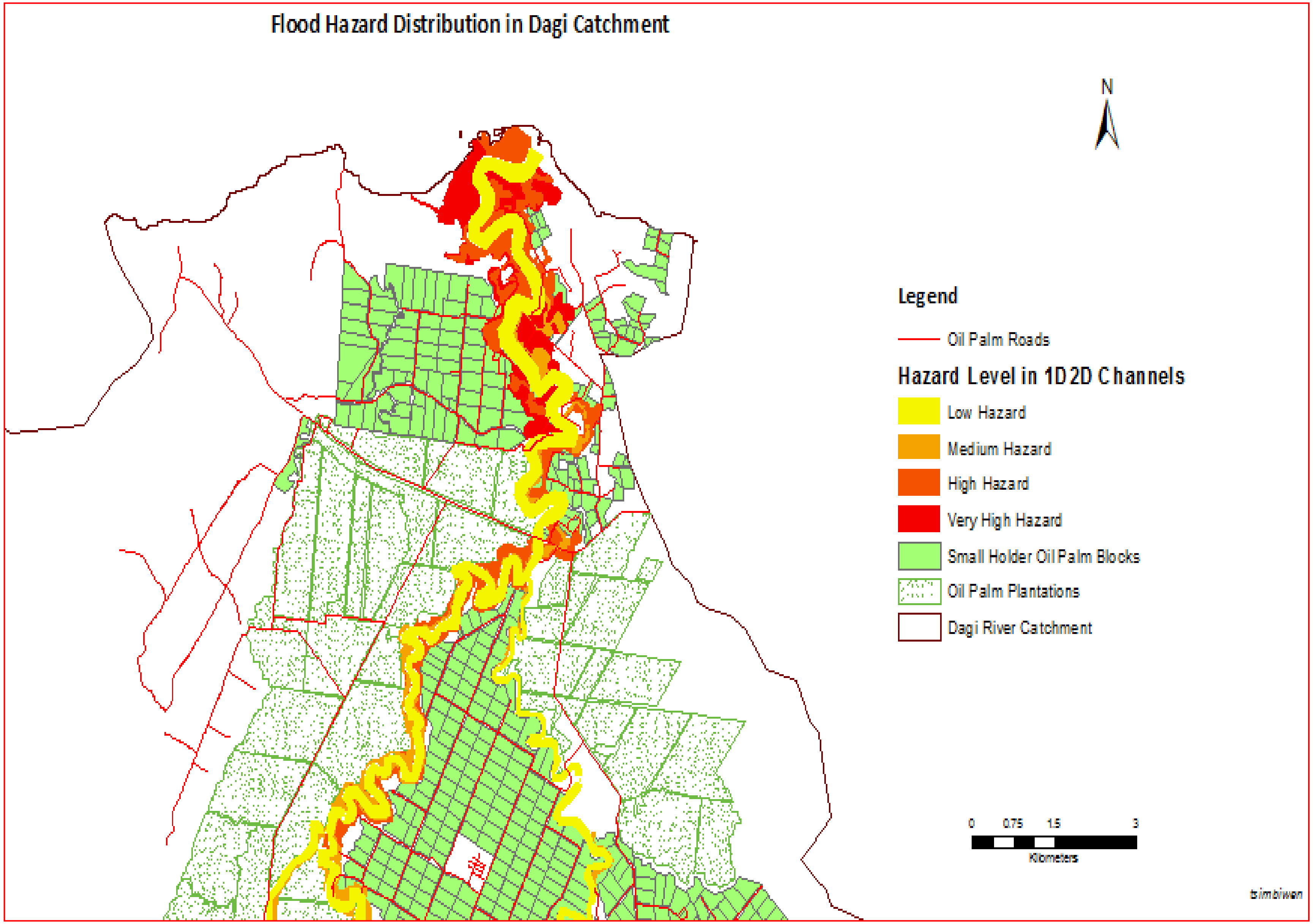


Figure 5.28: Overall flood hazard distribution in Dagi catchment.

The 2014 and 2010 flood hazard maps were combined to give an overall flood hazard map for the Dagi Catchment (figure 5.28). All areas of inundation were categorised based on inundation depth and velocity. Despite high velocity and depth, river channels have been categorised as low hazard areas (shown in yellow) because man does not live in channels. Medium, high and very high hazard levels showed on the map were defined by water depth, velocity and topographic characteristics such as slopes. This does not mean that any area close to the river is always a hazardous area (chapter 6).

5.7 Discussion

This chapter was designed to model the spatial extent of inundation and identify hazard areas in an oil-palm dominated landscape. Since most of this landscape is dominated by oil palm, focus was on model sensitivity to frictional data. Model output were correlated with flood hazard scenarios during the 2014 and 2010 floods.

An inundation depth of 0.1m was arbitrarily set as the lower limit for hazards and up to as much as 6.5m for 2014 flood and 7.5m for the 2010 floods. These heights were measured from the reference stream bed to the extent of the flood waters over the levees. Model results suggest that the spatial inundation extent is higher downstream compared with other areas in the catchment. The 2010 inundation extent was 79.9 hectares, which is greater than that of the 2014 flood event (55.2 hectares). The 2010 flood event inundated a larger area due to higher rainfall in 2010 as the main input into the catchment. The 2014 event figures were lower than those of 2010 event because of the differences in amounts of rainfall received. Based on my observations, these results are expected. Tennakoon (2004) investigated comprehensive vicissitudes in flood hazard zones of Naga City in The Philippines, for 17.5 and 10 years' recurrence interval flooding. Results showed that 92% of inundated areas for the 10 years' recurrence interval, inundation were in commercial areas. Results for the 17.5 years return period flood accounted for 96% of the commercial zone inundated. 34% of agricultural, 21% of the residential and 13.88% of the commercial zones were affected through inundation.

Flood velocities play a critical role in compounding hazards in the areas. The results show that velocities are highest upstream and decrease downstream as a function of frictional resistance during non-flood conditions. During the two flood events, however, results show the opposite. Floods increased in velocity downstream. Because downstream areas have higher inundation, hazards become obvious as velocity increases downstream into those inundated areas. Regardless, the results show that the model simulated flood inundation extent agreed well with the observed inundation extent. The simulated results with appropriate input data, initial condition, boundary conditions, assumption applied to the model, roughness coefficient values and coarse representation of the grid resolution could generate a very good simulated flood inundation extent as confirmed by the calibration and validation results.

In similar studies, Lomulder (2004) – from his evaluation of a model calibrated using two scenarios – found consistent and satisfactory results. The sensitivity of the Dagi model was influenced by the topography of the flood plain and channel friction as inundation propagated and these results are similar to those reported by Hesselink et al., (2003) and ITC (2010). Channel roughness played a more important role than overland roughness values during the calibration process of the Dagi inundation model and the results are quite similar to those outlined by Werner et al. (2005) and ITC (2010). Furthermore, there are apprehensions about the simulated results and uncertainties in roughness coefficient (Manning's *"n")* to reconstruct historical flood events (Wohl, 1998; ITC, 2010). A total of 20% of the results were influenced when the "n" values were changed by 25% (Wohl, 1998). Channel parameters also affect roughness coefficients and these include density and height of vegetation, meandering channels, debris and sediment amounts together affect model output (Acrement, 2008; ITC, 2010). The inundation performance indicator analysis was based on the water level per reach. Overall, the model could generate a very good simulated inundation extent to assess flood risks. Some factors influenced inundation results in this study and they have interrelated importance in the input data, process representation and model validation (Horritt and Bates, 2001).

5.7.1 Factors affecting inundation extent and flood hazards

5.7.1.1 Flood volume, lag time and depth

Damaging flooding is attributed to the fact that the Dagi catchment had since the late 1960s undergone land use and cover changes. However, historical data is non-existent for this catchment so it was not possible to enumerate the consequences of these changes on the volume of flood, and its depths. Li, et al. (2013) quantified flood volume and depths due to land use and land cover changes. Four multi-linear regression equations were used on land use and land cover data from 1956, 1970, 1980, 1995, 2000 and 2005. Then they computed the impacts of land use and land cover changes on the lag time, flood peak and volume and depths. The results showed an increase in volume, lag time, peak and flood depths as land use and land cover changes between 1956 and 2005. Large variations in volume, lag time, peak, and flood water depths corresponded with each stage of land use change and land cover conversions (ibid.).

Short lag time in any flood event provides little time for warning and evacuation, and this is the case in the Dagi. Flood levels rose quickly and may be hazardous during the night when people were asleep.

During the 2010 flood, flood waters increased rapidly around 4:30am and when people realised, they were not able to evacuate most of their belongings, but only were able to save themselves. Fujita et al. (2014) observed lag times of two flood events during two different return periods and related it to the loss of lives in Japan. Their results showed that the flood with shorter lag time inundated large areas and killed 20 people as they were in the process of evacuation. In comparison with the previous, a second flood had longer lag time, with only eight casualties. Their detailed investigation between the two floods revealed that people have a knowledge of the first flood and were better prepared for the second flood event which resulted in only eight casualties. Results in this study also agree that in areas with well-educated population, flood casualties were lower. Since runoff behaves in response to dynamic hydraulic influence from interlacing landforms, land cover and many water origin, modelling the routes of floods over sizeable floodplains is demanding and this was reported by Rudorff et al. (2014). Their study analysed topography and hydrology as factors that controlled the dynamics of inundation along the lower Amazon River (2440km^2). Results showed that floodplain-to-river discharge represented only 54% while 93% was represented by diffuse overbank flows. In the current research, inundation was influenced by slope gradients where water tend to occupy depressions by diffuse overbank flows.

5.7.1.2 Flood velocity, stream power and damage

During the 2014 and 2010 floods, observed and modelled results showed that in areas with high stream velocity and power, there were high risks of drowning and erosion, including damage to livelihood assets. Channel and bank roughness, and slope affected the stream velocity and power. All stream cross-sectional profiles showed evidence of flood overflows with varying velocities and stream power within the main stream channels and overbank areas. Because upstream channels had boulders and vegetation along the banks, this limited the stream velocity and power, despite high slopes. Stream velocity and power were highest downstream since vegetation was mostly weeds that provided little frictional resistance. For all sites, stream velocity and power decreased further from the banks as it encountered shrubs. Stream power during the two flood events increased downstream and that was risky.

These results are consistent with those of Gallegos et al. (2012) which showed that in inundated areas characterised by high velocity and stream power, damage to infrastructure was 50-78% higher compared with only 10% in areas with low stream velocity and power. Ferencevic et al. (2012) overlaid a gridded stream power distribution map for an entire catchment with GPS points showing areas of flood damage. The GPS points showing where major damage occurred were highly correlated with areas of high velocity and stream power. Stream power is recognised as a force of formation and development of river morphology and interacts between channels and floodplains. Song et al. (2014) studied 10 river sections and analysed stream power both in-channel and on the floodplain. Results derived from a 10-year-averaged discharge showed that unit stream power was around .33 of bankfull discharge and unit power, while a 10-year-peak discharge and unit stream power was nearly 1.6 times the bank full conditions. Their study showed that unit stream power was proportional to the increase of stream discharge, while the increase rate of unit in-channel stream power was three times that of unit stream power on the floodplain. Results also showed that the distribution of the hydraulic parameters under 10-year-peak discharge conditions indicated that only 1-10% of stream flow were generated by floodplain flow, but 40-75% volume of water were located on the floodplain. The variation in the increasing rate of the stream power was dominated by the local roughness height, while the stream power distributed on the floodplain mainly depended on the local slope of the sub-catchment. The results in this oil palm dominated landscape agrees with these patterns.

5.7.2 Modelling inundation and hazards

This research had several uncertainties and limitations associated with inundation and hazard modelling. Firstly, available data only observed the extent of flood plotted using GPS including the maximum height of water left as water marks on oil palm, boulders and vegetation after the flood receded. An in-depth assessment of the performance of the model performances was limited so comparisons of maximum extent of inundation were disadvantaged. Secondly, fieldwork data including velocity measurements were limited to point locations in selected sites. Similar cases have been reported (Hunter et al., 2007; Miguez et al., 2012; EA, 2010). Thirdly, the magnitude of errors in observed data was significant because of the differences between HEC-HMS, SOBEK 1D2D, HEC-RAS 4.1, HEC-RAS Beta 5.0, and HEC-GeoRAS models and was rectified. These differences were documented in Vanderkimpen et al. (2009). Fourthly, there were doubts in fieldwork flood data to validate boundary conditions in upstream and downstream reaches. Contributions (% volume) made by water inflows coming from very small tributaries, groundwater and surface floodwater in the Dagi are not known at this stage. Zhao et al. (2011) and Miguez et al. (2012) stated that minor contributions, when added up, increased the total volume and the results would have been different. Furthermore, a challenge experienced was limited data on important topographic details (e.g. drainage pathways) that were not captured in the floodplain DEM. However, these were rectified by TIN interpolation of the bathymetry data and integrated with the DEM extracted from the DSM data. If these are not corrected, they will affect the flow routes and inundation patterns during simulations, and may affect the computation of the exact inundation extents that defined the overall hazard areas. These effects on model results have been documented in Hunter et al. (2007), Booij et al. (2011) and Fedak (2012).

Simple models sometimes do not give desirable results while large ones are ineffective in giving good results leading to improper modelling of inundations and hazards. Some model results in this study were very difficult to verify and relied on my experience and judgement of the area which provided the solutions. Finding an appropriate model for inundation and hazard modelling was initially a challenge. It must be verified through trial and error (time consuming and back-breaking exercise) until a suitable one is found that gives best results to properly assess flood risks. The aim is to find a balance among all available simple and computer-intensive models to produce good results. Vanderkimpen et al. (2009) quantified the impact of hydraulics, flood damage and flood risk from MIKE 11 and SOBEK 1D/2D/3D modelling software. Results agreed but with little dissimilarity due to minor unavoidable differences in concepts and implementation.

5.7.2.1 Flood areal extent, duration and hazards

The areal extents, duration and hazards varied between the two flood events. Results showed that overtopping inundation occurred within 500m of all banks of the Dagi River. There are no protection measures for all reaches in this rural floodplain. The 2010 flood event inundated a large area (79.9 hectares) and had greater impacts compared with the 2014 inundation (55.2 hectares) with slightly less impacts. Most inundation was reported in the middle and lower reaches while duration of inundation was longer downstream and exposed many land-use elements. Floods lasted longer and provided greater impacts owing to the increased exposure of roads and bridges, oil palm, subsistence gardens and houses and buildings over time. Many other livelihood assets were exposed to longer flood durations and are not documented here. The duration of flood waters was shorter upstream while those downstream had longer durations. These flood durations were a function of slope, topography and meteorological conditions especially wind and sunshine.

Huang et al. (2012) estimated the frequency patterns of inundation over space and time and how local hydrology and floodplain ecosystems could be affected. Results showed that 12.5% of all study areas were represented by the maximum inundated areas which were inundated once and had a duration of 7 hours with high vulnerability (45%) of flood plain ecosystems. However, 27.8% of the total inundated area which were inundated twice in 11 years represented 9 hours and had low vulnerabilities (15%). Masoero et al. (2013) reconstructed a 1951 catastrophic flood that inundated a large area (1080km^2). Results showed that flooded areas increased by 40% due to barriers along the floodplains and took 5-15 days to reach the sea. At the same time, there was an over-estimation of peak flood discharge by 20% thus increasing uncertainty. Kobayashi et al. (2013) estimated direct house/crop economic loss experienced during a flood disaster in Japan. At least JPY23.0 billion was estimated for houses in economic loss while JPY0.67 billion was for crop loss when inundation was at 7.0m with a duration of 12 hours. Andre et al. (2013) reported that in 75% of reconstruction costs in residential buildings that were flooded related to internal goods, with localised impairment to building structure but unimportant. High dispersal in costs and water depth were noticed suggesting high risk in combining damage functions with insurance data.

Furthermore, before an inundation it was observed that peak discharge passed over its channels on to floodplain through its channels and by diffusive overbank flow (Trigg et al., 2013). These waters were distributed in the floodplain based on its internal connections, barriers and storages (ibid.). Accumulation of discharged water increased the water level, and inundation occurred. Most houses in Dagi have short posts and many went under water. Young oil palm trees and gardens were inundated. Duration downstream on average was more than 10 hours to three days while upstream ranged from 3-6 hours to three days depending on the flood magnitude. They returned to the stream via drainage linkage or were infiltrated or evaporated (ibid.). This surface water connectivity was not studied here. However, I am assuming that they do provide clues on how a floodplain functions, including its ecology, sediment transfer and risks to flood (ibid.). Hudson et al. (2013) found large variations in discharge time linked with floodplain inundation compared with inundation of channel banks. Results showed 10% of discharge times were linked with 87% floodplain inundation surface while 53% overtopped channel bank profile. The study also showed that a 25% duration overtopped very little channel bank but floodplain inundation was 50%. Tingsanchali and Karim (2010) estimated hazard using an impact-based technique and assessed the level of hazards in the Phrae floodplain in Thailand and 78% of the floodplain lay in the hazard zone of 100-year recurrence interval flood whereas only 22% was not affected by flood risk. Risk areas defined as low constituted 33%, medium 11%, high 28%, and severe 6%. These results were similar to the total damage reported earlier (ibid.).

5.7.3 Assumptions in this study

Hydrological processes are not spatially homogenous. Thus, assumptions and transformations must be introduced to incorporate all these heterogeneities of a catchment in a model. Assumptions reveal some degree of uncertainty, and are associated with model results due to choice and effect of generalisations of input data and the effect on outcomes. Assumptions can contribute to the overall uncertainty of results. In any modelling, error-free results are least practical and in reality, impossible.

Therefore, the most practical approach for modellers is to make the model, data and error assumptions explicit to decision makers (Dottori et al., 2013). The results generated from methods used in this study simulated inundation extents well and hazards maps were produced. The main reason for the successful execution was my familiarity with the study area, and prior fieldwork data that was used to validate the results.

This study used a physically-based numerical approach to solve numerically the real-world process based on the full Saint-Venant equation using finite difference solution grid. However, the real world is continuous in space and time. Modelling the spatial representation of the real world is based on discrete sampling and discretised on a grid for the representation of the land surface processes. Seyfried et al. (2011) mentioned among the many problems encountered with physical-based models is the difficulty in parameterisation, validation and representation of land surface processes on a grid. The raster DEM serves as a basis for flood modelling and flood inundation prediction. Any DEM processing is subject to some degree of error and uncertainty, and results in a raster DEM do not perfectly match the real-world elevations. Small differences in DEM used in the input to flood modelling can lead to large effects on overall predictions. Concern arises for the quality of the generated DEM and the choice of the grid spatial resolution. The DEM in this study was fit for this study after correcting problems outlined above. The effects of my choice for determining accurate flood inundation extent and flood water depth requires further research.

5.7.3.1 Land surface roughness parameterisation

Surface roughness coefficients were specified in the model used in this study. Other surface roughness does exist and is not specified and represented in the grid resolution of the DEM. These may have considerable effect on the flow direction and timing. Further studies could conduct sensitivity analysis for surface roughness that incorporates scale and heterogeneity. Yu (2006a) found that roughness coefficient is sensitive in direct relation to grid resolution.

5.7.4 Study limitations

Like many modelling studies, this study has found several critical issues and they are briefly discussed below:

As an input to NETTER, raster DEM needs to be converted to ASCII file format with a specific file header. The raster DEM is in ESRI binary raster floating file format and has *.au* files that store statistics, coordinates and projection information about the raster file. During conversion of this *.au* file to ASCII file in NETTER, error was noticed. The solution was to fix it by realigning all the columns and rows in the same fashion. Spatial data comes in different formats and resolutions. In putting these into a common scale, assumptions and transformations were made. Alemseged and Rientjes (2007) study showed that the effects of selected boundary do not propagate into the model domain. These limit the modelling process. There is difficulty in specifying complex variation and roughness characteristics in the model. It is not possible to match a numerical model set-up to real-world properties. This limits the full functioning of the model.

5.7.4.1 Effects of river geometry

Inaccuracies can arise due to river cross-section data obtained at a different time compared with when the time study was conducted. The river cross-sections may have changed geometry (e.g. sedimentation) and need updating to match the study period. This limits model applications.

5.8 Conclusions and recommendations

By comparing the simulated results with the surveyed flood extent, it can be concluded that simulated results are close to the actual situation. 1D/2D SOBEK, HEC-RAS Beta 5.0 and HEC-GeoRAS are found capable of simulating flood events under normal or extreme flood conditions. They provide maximum inundation levels and determine damages in affected areas.

Many factors can affect the accuracy of the flood simulations: input data, initial conditions, boundary conditions, model assumptions, geometric data, parameter values and DEM spatial resolution. Model error results in the inability of the flood model to predict inundation accurately, even given the correct estimates and input. Model error will always be a factor since no model can represent the real-world system correctly and this study noted some factors that were corrected.

Future studies should:

1. Conduct sensitivity analysis for surface roughness that incorporates scale and heterogeneity.

Chapter 6 will assess flood risks using maps of hazards obtained from inundation modelling in this study to identify exposed features at risk. It is a continuation of this chapter and will go towards assessing the overall flood risk of the Dagi catchment.

Chapter 6.0: Flood risks and vulnerabilities of livelihood assets in an oil palm dominated landscape.

Summary

The Dagi catchment has been vulnerable to floods because of its situation in the path of monsoon rains, its location on coastal lowlands and increased oil palm cultivation. This study used risk methods established on exhaustive exploration of risks (Gain and Hoque, 2013). It estimated flood hazards using geo-processing tools and hydrodynamic models that represented flood intensities in 2014 and 2010. It estimated vulnerability based on the percentage of livelihood assets damaged as the consequence of flood velocity and depth. This study used a combination of qualitative and quantitative risk assessment methods. A qualitative assessment of risk was performed using maps of inundation depth and vulnerable land uses. The level of vulnerability and risk zones were identified based on the assigned land use weights, hazard and vulnerability assessment criteria. Vulnerability curves for the Dagi catchment were generated using flood velocity and depth and functions. Using the weights and criteria, and land use curves, raster-based vulnerability and risk maps were drawn in relation to three exceedance probabilities. Quantitative risk assessment involved estimating the total costs of exposed elements (direct tangible) based on the damage functions and classified according to their type. Results show that houses and buildings incurred the greatest costs (34.3%), then leaching of fertilisers (27.2%), followed by deaths from drowning incidents (23.7%), subsistence gardens (11.4%), roads (2.6%), damaged oil palm trees (0.8%), non-pick-up of fresh fruit bunches (0.02%) and formal job income loss (0.01%). These differences are well below the threshold value of 20%. The total economic costs based on the elements at risk is PGK77,869,451 equivalent to US$26,545,696 (23rd Sept 2015 exchange). The results reveal that floods with high occurrence probability inflict lesser destruction compared to greater damage delivered by rare flood events. Future research should: 1. Aim to reduce uncertainty in damage measurements, 2. investigate costs distributions, and risks transfers, and look at ways to assess costs to support decisions, and 3. use multivariate approaches to integrate insurance data with land use elements.

6.1 Introduction

A variety of damage can be caused by floods to people, infrastructure, cultural heritage, agricultural and ecological systems, and industrial production (Messner et al., 2006). Koivumäki et al. (2010) categorised damage as being direct or indirect and are either tangible or intangible. Regardless of its connection with flood water and category, damage inflicted is reflected in incurred monetary costs. Water depth, discharge, velocity, area of inundation and seasonality are factors in damage type and amount (ibid.). Damage done directly to livelihood assets is approximated by damage functions relating to flood characteristics such as velocity and water depth (Koivumäki et al., 2010; Jonkman et al., 2008). When damage is expressed in monetary terms, then damage functions are regarded as absolute (Koivumäki et al., 2010; Apel et al., 2009). But when damage is stated as a percentage of the total monetary cost of an element, the functions are regarded as relative (Koivumäki et al. 2010; Oliveri, et al., 2000). Flood risk management is an approach used to control flood damage by combining all tasks targeted at maintaining and improving catchment preparedness in handling peak discharges and severe rainfall events (Koivumäki et al. 2010; de Bruijn et al., 2007).

Furthermore, assessing and managing flood risks goes deeper than just inundation analysis using hydraulic models and visualising them in hazard maps. Currently flood hazard maps are used but progress is slow in quantifying damages and visualising them by creation of risk maps (Arrighi et al., 2013). Consequently, a UNEP directive was made for the creation of local, regional and national flood hazard and risk maps in preparedness for climate change projections on extreme events (ibid.). Koivumäki et al., (2010: p.167) stated that "Flood risk is the product of flood hazard, vulnerability and exposure". The most effective tool that can be used to manage flood risk is information dissemination and flood risk mapping is one medium of providing such information (ibid.). There are many flood maps generated based on their purpose but they all fall into two categories: 1. flood hazard maps showing inundation with different exceedance probabilities complemented by flood depth and velocity, and 2. flood risk maps showing elements at risk and the risk zones. Flood hazard maps indicate flood intensity and flood risk maps show the likely unfavourable consequences analogous to floods (van Alpen et al., 2007; Merz et al., 2007; de Moel et al., 2009; Koivumäki et al., 2010).

To assist decision making, an economic evaluation is often carried out for projects designed to manage floods (Arrighi et al., 2013). Projects that follow this concept target agricultural areas in floodplains because the likely damages inflicted by floods there are often lower than in big cities with their industries (ibid.). Additionally, damages in rural agricultural areas are not often quantified and this influences decisions regarding such projects, so an economic evaluation is an important issue that needs to be tackled (ibid.). Similarly, there is currently little or no information on flood risks and the vulnerabilities of livelihood assets within large areas of oil palm landscapes. Thus, there is a need for a risk-based understanding of floodplains; specifically, about the need to live with floods rather than trying to control them (King et al., 2013).

This research follows a risk-based approach (de Moel et al., 2011; Kreibich et al., 2015) to manage flood risks and vulnerabilities of livelihood assets within oil palm landscapes. It will be focused on direct tangible economic costs while risk assessment will be both qualitative and quantitative (Badilla, 2002; Kazama et al., 2010). A flood risk model combines information from 1. flood hazard (inundation depth and velocity), 2. exposure (land use elements), 3. "value of elements at risk, and 4. susceptibility of the elements at risk to the hydrological condition (depth-damage curves)" (de MOEL and Aerts, 2011: pp.412-414). The total monetary loss at different exceedance probabilities are obtained through the generation of risk curves from which the average annual risk is derived (ITC, 2010). This chapter begins by outlining the materials and methods used in this study. It will be followed by an assessment of flood hazards and vulnerabilities of physical, social and economic elements. Using this information, land use elements that are exposed will be used to assess flood risks. This involves an analysis of a sample of exposed physical, social and economic elements. The degree of risk is determined based on water depth and velocity damage functions. Study assumptions, limitations, conclusions and recommendations will conclude this chapter.

6.2 Objective and research questions

Using a case study area to assist disaster planning, hazard and risk mitigation, this chapter aims to:

Assess flood hazards, the level of vulnerability and determine the degree of risk as a function of inundation depth and velocity within an oil-palm dominated landscape.

To address the objective, the following research questions are formulated:

1. what is the level of flood hazards?
2. what is the degree of physical, social and economic vulnerability?
3. what is the magnitude of risk as a function of water depth and velocity?

6.3 Materials and methods

This study has assessed flood hazards and vulnerable physical, social and economic land use elements within the study area. It focused on direct tangible economic costs following both qualitative and quantitative risk assessment approaches. Because of time constraints, only some vulnerability indicator elements under each category were selected (physical, social and economic), then analysed and were used to assess flood risk. During fieldwork, economic values of exposed elements were obtained and evaluated. Maximum flood depth and velocity results were extracted from the flood models to deliver the flood hazard categorisation. This chapter will follow a simple workflow (figure 6.1).

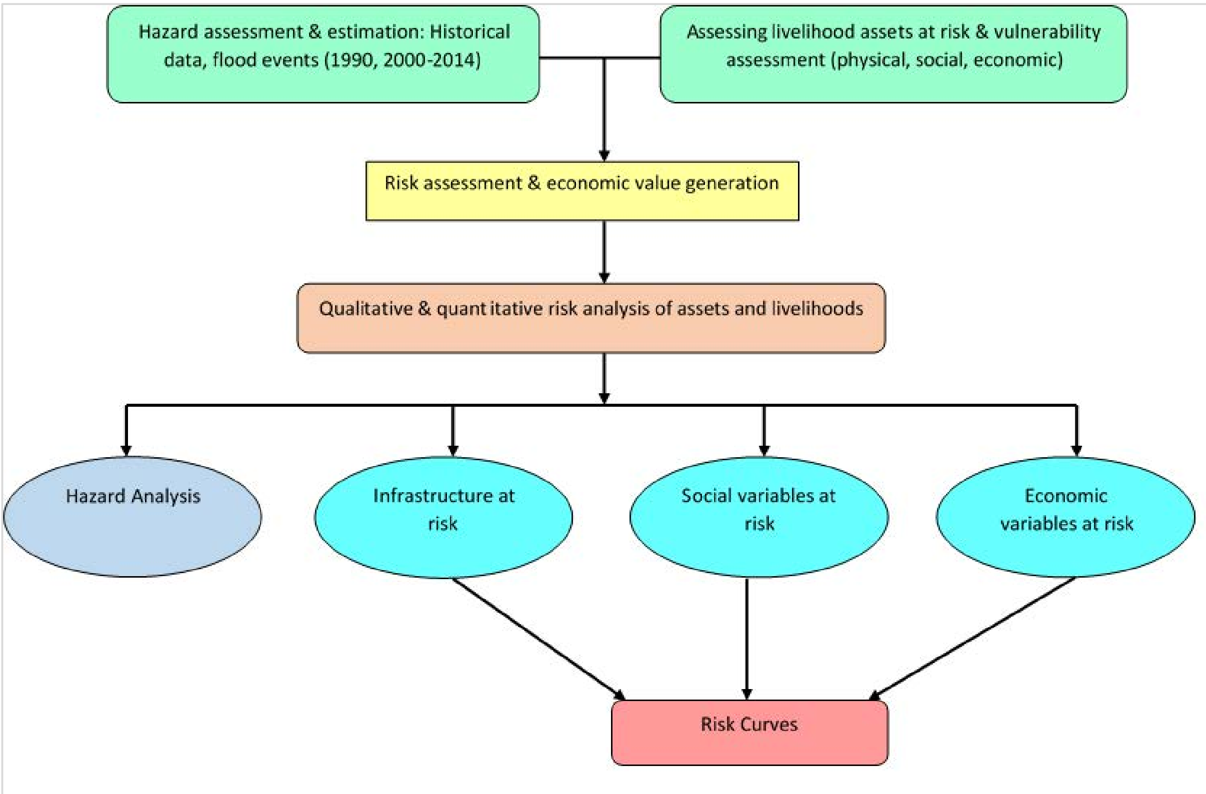


Figure 6.1: Work flow in chapter 6.

6.3.1 Materials: datasets, software and hardware

An ALOS satellite imagery of the area was purchased from RESTEC Japan, ©XASA. This was used as a background image to visualise elements at risk, vulnerability level and risk zones. Table 6.1 shows the datasets, their sources, their descriptions and spatial resolutions used in this study.

Table 6.1: Dataset, their sources and description

Dataset	Source	Description	Resolution
Population (age and sex)	PNG NSO	2011 Census updated by RMU and LLG	1:50, 000
Population (age and sex)	PNGRIS database	2000 Census by RMU and LLG	1:50, 000
Land use (e.g. oil palm cultivation)	PNGRIS database	2007 updated by RMU and LLG	1:50, 000
Livelihood/economic activities (e.g. gardening in riparian zones)	PNGRIS database	2007 updated by RMU and LLG	1:50, 000
Infrastructure (e.g. roads, houses, buildings)	PNGRIS database	2007 updated by RMU and LLG	1:50, 000
Topography, slope, elevations (relief)	PNGRIS database	2007 updated by RMU and LLG	1:50, 000
ALOS Imagery	RESTEC Japan©XAXA	2014 Data	5m X 5m pixels

The main software used in this study was ArcGIS 10.2. It was used to map flood hazard zones, vulnerability levels and flood risk areas. The hardware that was used to collect data out in the field was an Etrex Garmin GPS.

6.3.2 Methods

6.3.2.1 Hazard assessment and estimation

Based on the parameter maps, hazard was assessed by computing the annual exceedance probability using estimated discharge data and flood events recorded between 1980 and 2013. Land use inundated by the 2014 and 2010 floods shown by each hazard map based on velocity and depth were identified and visualised. The 2014 hazard map used a 0.05-6.5m damage scale with each annual exceedance probability while that of 2010 used a scale of 0.05-7.5m. Flood hazard impact impinges on many facets of man, his space and economy (Smith, 2001). Invaluable knowledge was received from the locals (smallholders, company and government employees). Data for flood hazards were mainly based on eyewitness accounts, and statements based on what happened during past events aided with a few photographs (plates 6.1-6.23 and figure 6.3 in appendix 6.1). These were then related to the sites shown by the GPS coordinate points showing the inundation extents and were plotted. Hazard maps can be created by reconstructing the linkages between flood characteristics and its impacts (consequence) on man and his space (Rahman, 2006). Hazard maps were created using the flood depth criteria given in chapter 2 by the Australian Bureau of Meteorology (2012) and that given by CSIRO (2000) shown in table 6.2 in appendix 6.2. Assessment of hazard is interlinked with vulnerable elements (exposure) and is used to assess risk magnitude. Tennakoon (2004) combined flood parameters to assess hazards in Naga City in The Philippines (figure 6.2 in appendix 6.3).

6.3.2.2 Elements at risk and vulnerability assessment

Because this is a relatively new study area in relation to flood hazards and risks, there are few facts available. Even the facts available with the PNG National Disaster Centre were all descriptive in nature. These missing data were collected during fieldwork in July 2010 during the dry season, February 2010 during a period of flood and in February-April 2014 during the wet season during a flood event. Information on elements at risk were gathered by interviews and field observations (e.g. figure 6.3 in appendix 6.1). The perceptions on the issue of flooding was gathered from local people and employees during formal and informal discussions. Critically, these methods are not ideal for past flood events because information given from lack of memory or hearsay can be misleading and exaggerated (Lecarpentier, 1963). A Stage-Damage Method using the relationship between flood velocity, depth and duration with exposed elements is the most relevant approach (ITC, 2010). PNG does not have a national stage-damage function. Because many developed countries overseas have well established stage-damage functions on land use elements (e.g. Australia, Netherlands & UK), they were derived and adapted into this study because this has been used in past studies to assess vulnerability (e.g. Alkema, 2007; ITC, 2010).

6.3.2.3 Risk assessment of physical elements

The total physical and actual elements at risk were obtained by overlaying the 2014 and 2010 flood hazards maps and identified using overseas vulnerability curves (ITC, 2010). This was then overlaid on the overall hazards maps based on the combined 2014 and 2010 floods in 1D channels and 2D bank overflow areas and inundation. The total number of elements that fall within each of the inundation hazard zones (figure 5.36) were then identified as at risk. Any affected elements that fall within each zone were investigated (ibid.). The information collated from the interviews are presented in *Excel* tables and attached in appendices 6.4, 6.5, 6.6 and 6.7. These investigations combined the information from the hazard map and those collected from fieldwork which were then divided into upstream and downstream segments.

6.3.2.4 Vulnerability assessment

This study assessed vulnerability by using vulnerability curves (or damage function) on vulnerable elements identified in section 6.3.2.2 based on inundation depths and velocity and their relative damage functions (ibid.). Specific vulnerability curves in this research were plotted using these functions. Identification and visualisation of each damaged land use was based on these damage functions (ibid.).

6.4. Risk assessment and economic value generation

Risk was assessed using results simulated from the model and risk elements already identified based on their magnitude and probability of occurrence of risk (ibid.). In this study, two types of risk assessments were conducted: qualitative and quantitative.

6.4.1 Qualitative risk assessment

Risk was assessed qualitatively using maps of flood depths and vulnerability for each class of land use (ibid.). Weightings were allocated to different classes of land use based on their economic level of significance in the area from 10 (minimal) to 100 (maximum) (ibid.) (table 6.3). Oil palm is the main source of cash income and employment, and is given a relative weight of 100. Subsistence gardening is the second most important income source throughout the catchment. Subsistence gardens are common in riparian zones so this is given a relative weight of 60 while houses and buildings were given a minimal weight of 10. Roads (sealed and unsealed) contribute to the transport of goods and services and keep the local economy functioning so this factor is given a relative weight of 30. The flood risk zonation was also derived from the hazard and vulnerability criteria (table 6.4). The rationale is that low inundation depths will pose less flood risk and vulnerability whereas increasing depths will increase vulnerability of exposed elements. The level of vulnerability and risk zones to be mapped were identified based on the assigned weights and criteria assessment. The results are presented in section 6.6.5.

Table 6.3: Showing the weight assigned for different land uses classes.

S. No.	Land use types	Assigned relative weight*
1	Oil palm (Grown in plantations and small holder blocks combined).	100
2	Subsistence garden (along riparian zones)	60
3	Houses and buildings (e.g. of infrastructure) -	10
4	Roads (sealed and unsealed roads combined)	30

*Assigned relative weight contribution to the local economy from the catchment: 10 = minimal, 100 = maximum.

Table 6.4: Risk zonation based on hazard and vulnerability criteria.

Type of Assessment	Criteria of Assessment	Classification (metres)	Risk zones*
Hazard	Water depth	0.05-0.5	Low
		0.5 - 1.5	Medium
		1.5 - 3.0	High
		Above 3m	Very High
Vulnerability	Level of vulnerability	0.0-0.35	Low
		0.36-0.55	Medium
		0.56-0.75	High
		0.76 -1.0	Very High

*Risk zones: lowest depth of inundation and vulnerability level = 0.05 (low risk), Inundation depth greater than 3m and vulnerability level between 0.76-1.0 will have very high flood risk.

6.4.2 Quantitative risk assessment

Exposed elements identified using maps of vulnerability were each allocated a mean cost in PNG Kina (PGK) and converted to US Dollars to approximate the real cost of each livelihood asset that was ruined or harmed. These figures were derived from face-to-face interviews and simulations. The results are shown in tables 6.8 to 6.13 in section 6.6.6.

6.5 Generation of risk curves

A curve was drawn to represent the flood risk. Risk curves provide data on the likelihood of maximum loss at a particular exceedance probability. An area in the curve delineates the estimated monetary cost for each damaged element at each exceedance probability. Respective curves are shown in figures 6.24, 6.25, 6.25, 6.26 and 6.27 in section 6.6.7.

6.6 Results

6.6.1 Hazard assessment and estimation

Available historical records and the calculated exceedance probabilities of flood events in the catchment are only available for the years 1980, 1990 and between 2000- 2014. There was a total of 21 flood events in that period (table 6.5). It is assumed that any inundations in land use areas are referred to in this study as “hazard areas”. Flood hazards are common in areas where there are inundations of long duration and high depth. Based on the 2014 and 2010 calculations, depths can go as high as 7.5m at the stream thalweg and vary across zones of inundations in the flood plains. These are evidenced by water marks on vegetation and structures.

Table 6.5: Flood exceedance probability from 1980, 1990 and 2000-2014 for Dagi River derived using the log-Pearson Analysis III method.

Year	Exceedance Probability (1/Tr) *
1990	0.005
1996	0.009
1997	0.0014
1998	0.0018
1999	0.0023
2000	0.0027
2001	0.0032
2002	0.0036
2003	0.0041
2004	0.0045
2005	0.0050
2006	0.0055
2007	0.0059
2008	0.0064
2009	0.0068
2010	0.0073
2011	0.0077
2012	0.0082
2014	0.0086
1980	0.0091
2013	0.0095

*1/Tr refers to the exceedance probability, Tr is the return period (see chapter 4 appendix 4.3 for the calculations).

Four flood hazard categories were identified in figure 5.36 and re-classified as low, medium, high and very high (figure 6.4). During the 2010 and 2014 flood events, most inundations along the Dagi River were along the lower reaches. There was a total of 55.2 hectares inundated in the 2014 floods, however, the figure for the 2014 flood may have been higher if data was available for Ru Creek and the Lamegi River (table 6.6). The 2010 flood event inundated a total of 79.9 hectares. For both years, inundation was highest along the lower reaches with the 2014 event comprising 60.5% of the total. The lower reaches of the Dagi showed 45.7% of the 2010 flood total. Contrasting between the total inundated area between the two years (135.1 hectares), the 2010 flood inundated 59.2% while the 2014 flood inundated only 40.8% of the total. This means that the 2010 flood inundated 18.4% more than the 2014 flood.

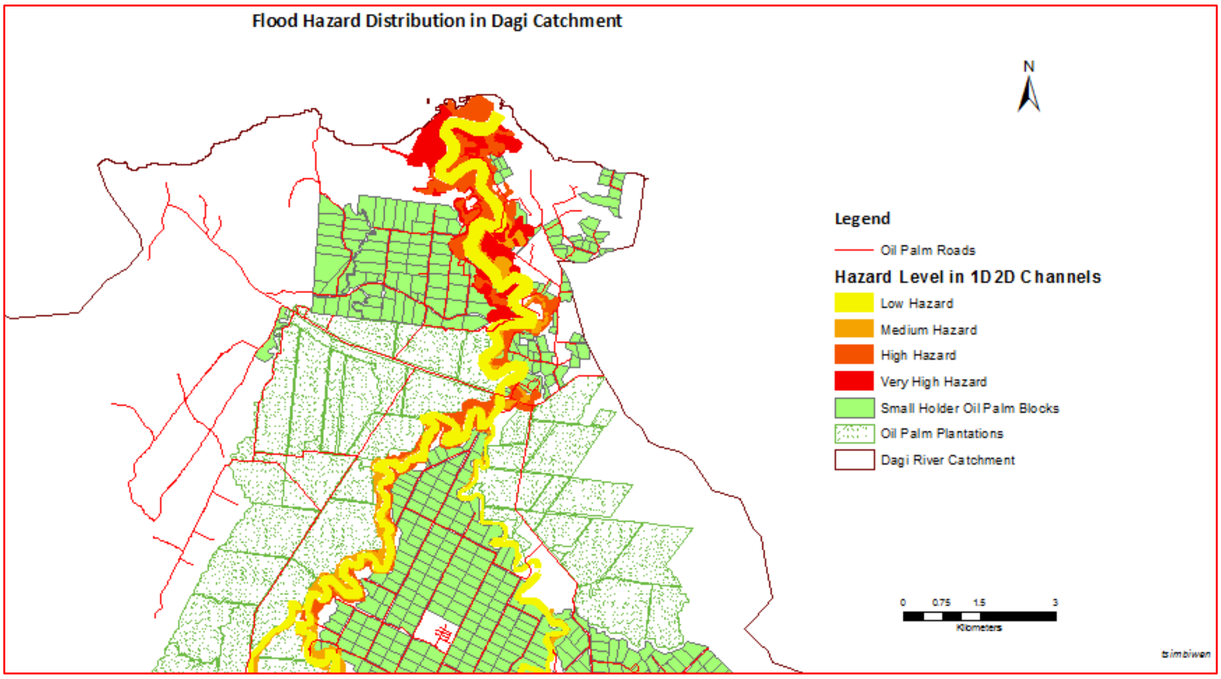


Figure 6.4: Overall flood hazard distributions in the Dagi catchment.

Table 6.6: Average water depths and total land area inundated in the 2014 and 2010 floods.

Year	River/Reach	Average Water Depth* (m)	Total Inundated Area (ha)
2014	Dagi - Upstream	3.96	6.3
	Dagi - Middle	5.76	15.5
	Dagi - Lower	5.61	33.4
	Ru	4.07	-
	Lamegi	4.70	-
2010	Dagi - Upstream	4.65	6.5
	Dagi - Middle	5.89	17.1
	Dagi - Lower	6.97	36.5
	Ru	5.06	9.6
	Lamegi	4.71	10.2

**Average values derived from observed and simulated water depths.*

6.6.2 Elements at risk

Major physical elements identified were roads, subsistence gardens, houses and buildings and oil palm trees. There were two types of roads: sealed and unsealed. Sealed roads are mostly the main roads while plantation and smallholder block roads remain unsealed. Subsistence gardens are sub-divided into market and self-consumption. Based on the type of building materials, houses are subdivided into permanent, semi-permanent and bush material. Buildings are sub-divided based on ownership: an oil palm company, government and private. Company buildings comprise office complexes, factories and others owned by the company. Government buildings comprise DPI stations, clinics and aid posts, schools, CIS and an electricity dam. Private buildings are categorised into those owned by churches, NGOs and individuals. Oil palm trees are categorised based on ownership: those grown on smallholder blocks owned by people from all over PNG, and others in plantations owned by Kulim Berhad Limited and the PNG government. These elements at risk are all shown together for 2014 and 2010, at a combined scale and at varying resolutions (figures 6.5, 6.6, 6.7, 6.8, 6.9 and 6.10).

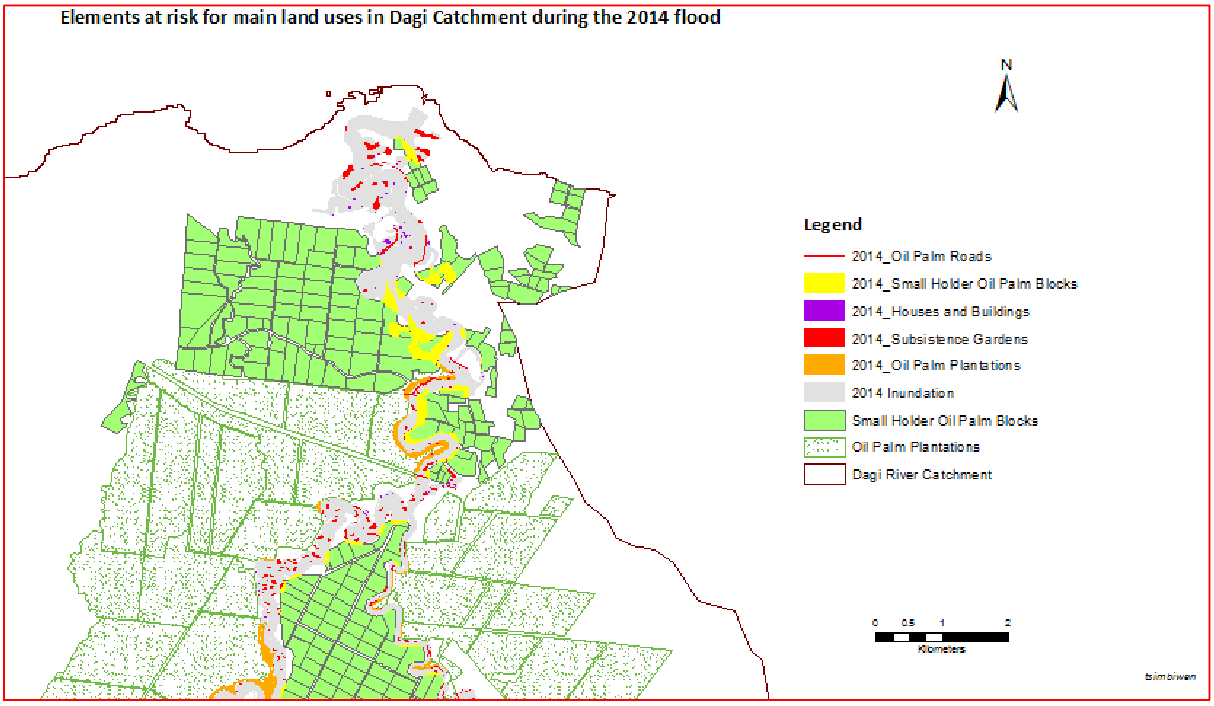


Figure 6.5: Elements at risk along the Dagi River during the 2014 flood.

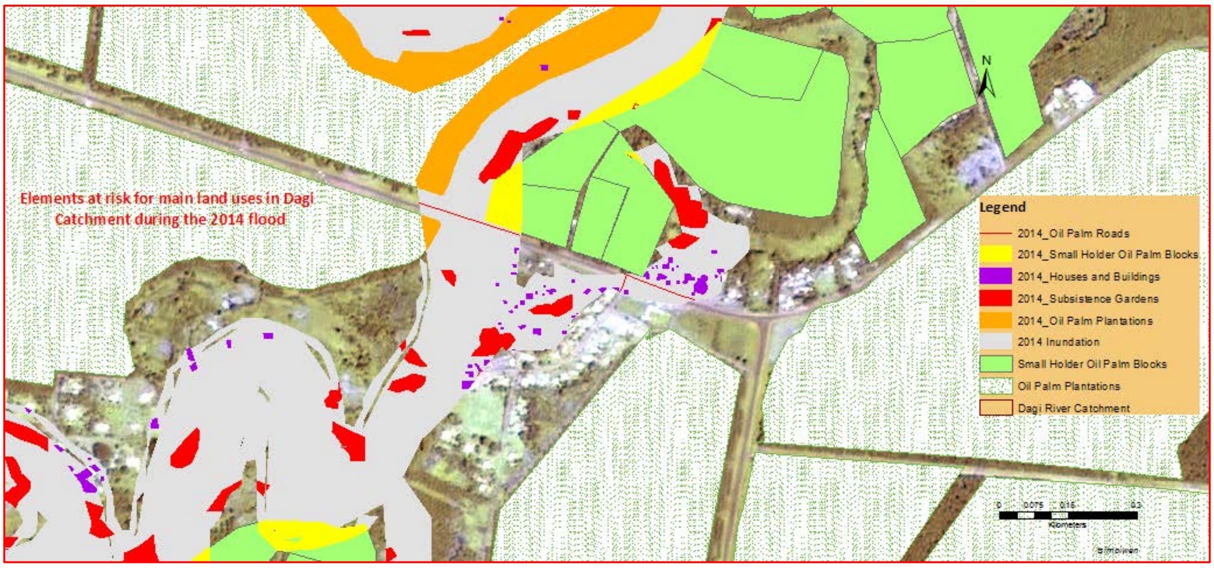


Figure 6.6: Elements at risk around Kumbango plantation and Nahavio station during the 2014 flood.

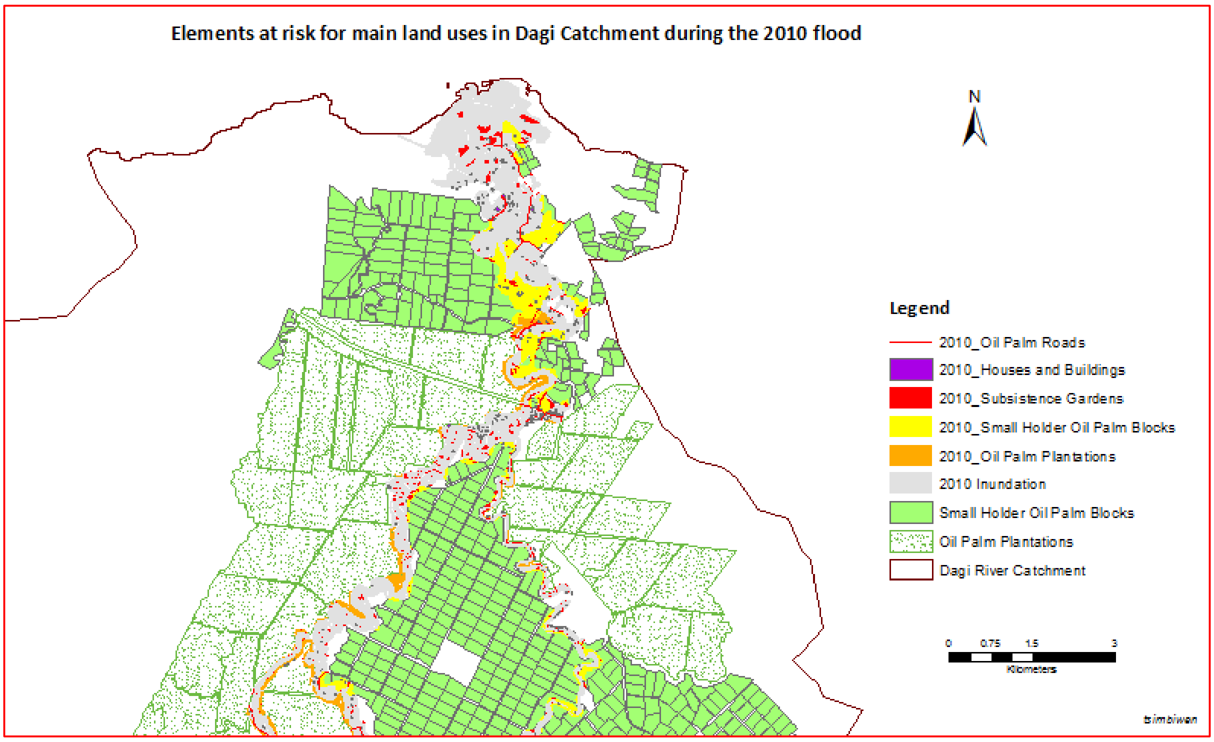


Figure 6.7: Elements at risk along the Dagi River during the 2010 flood.

Figure 6.8: Elements at risk around Kumbango plantation and Nahavio station during the 2010 flood.

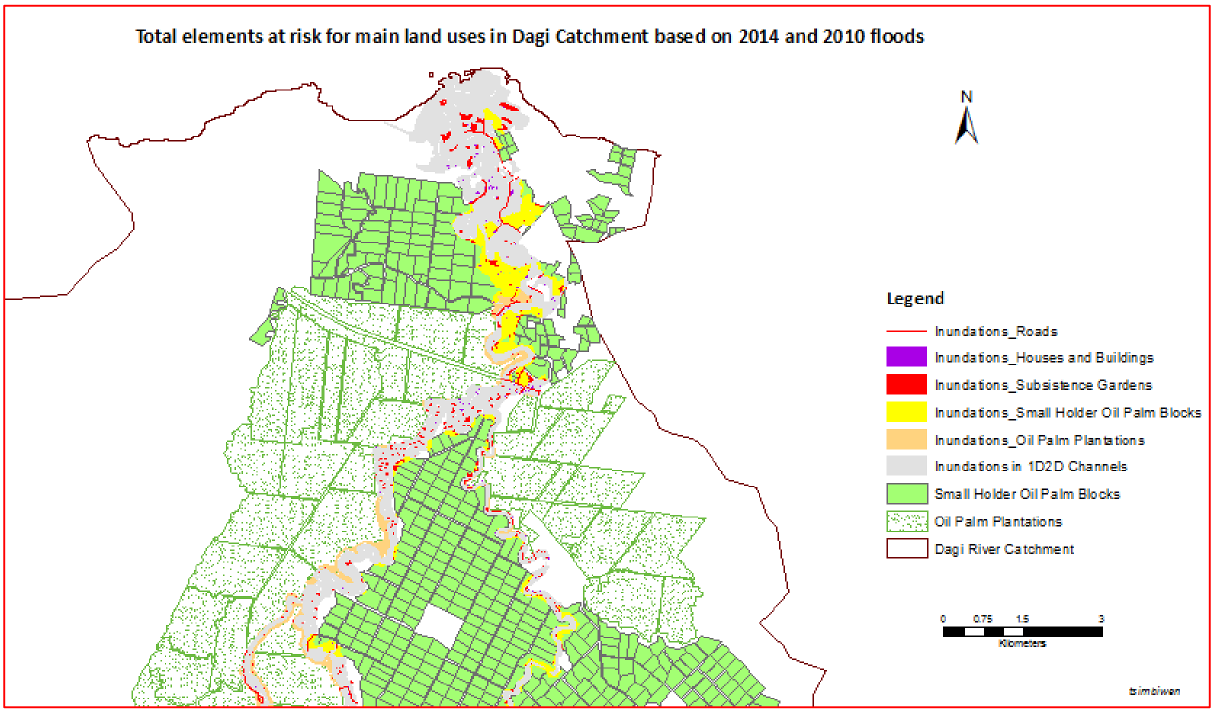


Figure 6.9: Total elements at risk along the Dagi River based on the 2014 and 2010 floods.

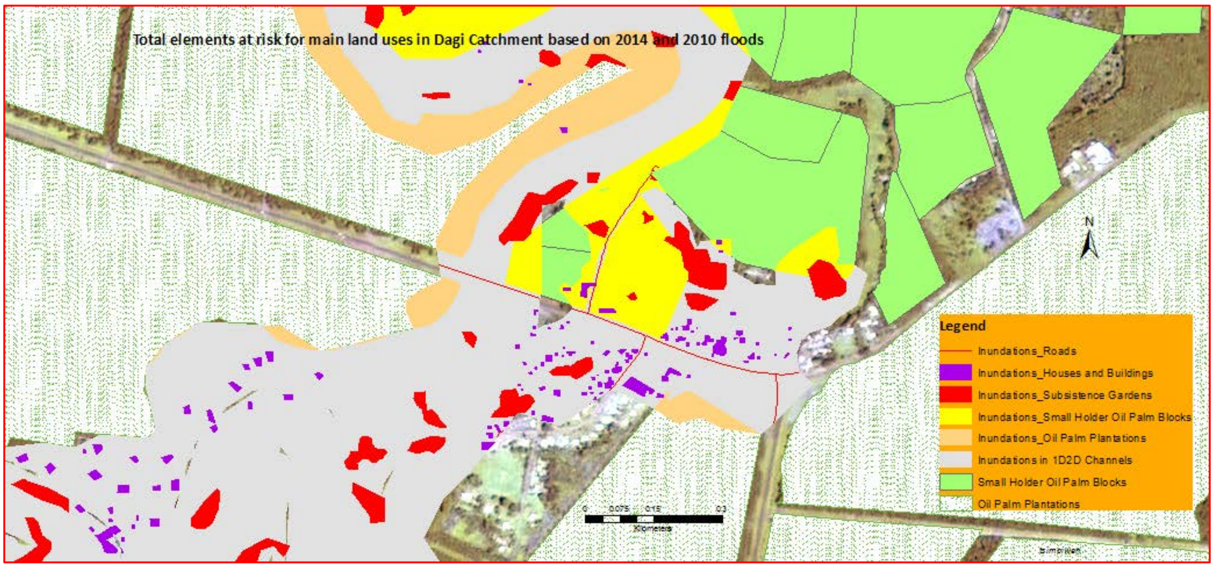


Figure 6.10: Total elements at risk around Kumbango plantation and Nahavio station based on the 2014 and 2010 floods.

6.6.3 Assessing physical elements at risk

Assessments of total physical elements at risk are collated in table 6.7. There were 29 portions of roads affected with a total distance of 5.6km in 2014. 2010 figures show 42 road segments affected with a total length of 11.13km. During the 2014 and 2010 floods, combined figures show a total of 71 road segments totalling 16.77km affected. Flooded roads limit the level of accessibility in terms of evacuation and pick-up of oil palm fresh fruit bunches (FFB) and has an economic cost involved. There were a total of 324 houses and buildings affected in 2014, covering an area of 0.07km^2. The 2010 figures are slightly higher than this. Similarly, the total elements at risk in 2010 are much higher than 2014 because it was a bigger flood event.

In summary, in the 2014 and 2010 flood events, there were 71 road segments totalling 16.77km and a combined total of 718 houses and buildings covering an area of 0.17km^2 affected. Furthermore, there were 577 subsistence gardens mostly in riparian zones along waterways totalling an area of 0.98km^2 impacted. There were 32 smallholder oil palm blocks affected that covered an area of 12.78km^2 whereas in oil palm plantations, it was 10.55km^2 with 33 in total.

Table 6.7: The assessment of total elements at risk between 2014 and 2010 floods.

Year	Land use	Area (km^2)	Total Count
2014	Roads (km)	5.64	29
	Houses and Buildings	0.07	324
	Subsistence Gardens	0.48	271
	Smallholder Oil Palm Blocks	1.11	15
	Oil Palm Plantations	0.90	15
2010	Roads	11.13	42
	Houses and Buildings	0.10	394
	Subsistence Gardens	0.51	306
	Smallholder Oil Palm Blocks	11.67	17
	Oil Palm Plantations	9.65	18
Overall	Roads	16.77	71
	Houses and Buildings	0.17	718
	Subsistence Gardens	0.98	577
	Smallholder Oil Palm Blocks	12.78	32
	Oil Palm Plantations	10.55	33

The total number of roads inundated during the 2014 flood represents 40.8% of the total while that of 2010 flood represented 59.2%. This reveals a difference of 18.3% between the two years. The total number of houses and buildings inundated in 2010 was slightly higher (9.8%) than that of 2014. The total tally for subsistence gardens reveals that the 2010 flood inundated 35 more subsistence gardens than that of 2014, which is 6.1% and slightly higher than expected. The total number of smallholder oil palm blocks inundated during the 2014 flood represented 46.9% while that of the 2010 flood represented 53.1%. Thus, the amount of smallholder oil palm blocks inundated during the 2010 flood event was slightly higher by 6.3%. Finally, oil palm plantations inundated during the 2010 flood event represented 54.6% of the total compared to 45.5% for 2014, revealing a difference of 9.1%.

Figure 6.11 shows the total exposed population by census units. The census units have their boundaries along the Dagi River channel and its tributaries. The highest total population exposed was at Sarakolok settlement with 3142 people. Because of its situation between the Lamegi and the Dagi Rivers, the population is vulnerable to flood hazards. This is followed by Tamba Settlement, Kumbango plantation, Mosa Oil Mill, Dagi settlement, Nahavio OPIC, Togulo plantation, Mingae village, and Bebere plantation at division 3 (figure 6.11). By gender, males are more exposed than the females for all settlements because of their higher numbers and mobility. Males are more mobile due to involvement in more economic activities than females.

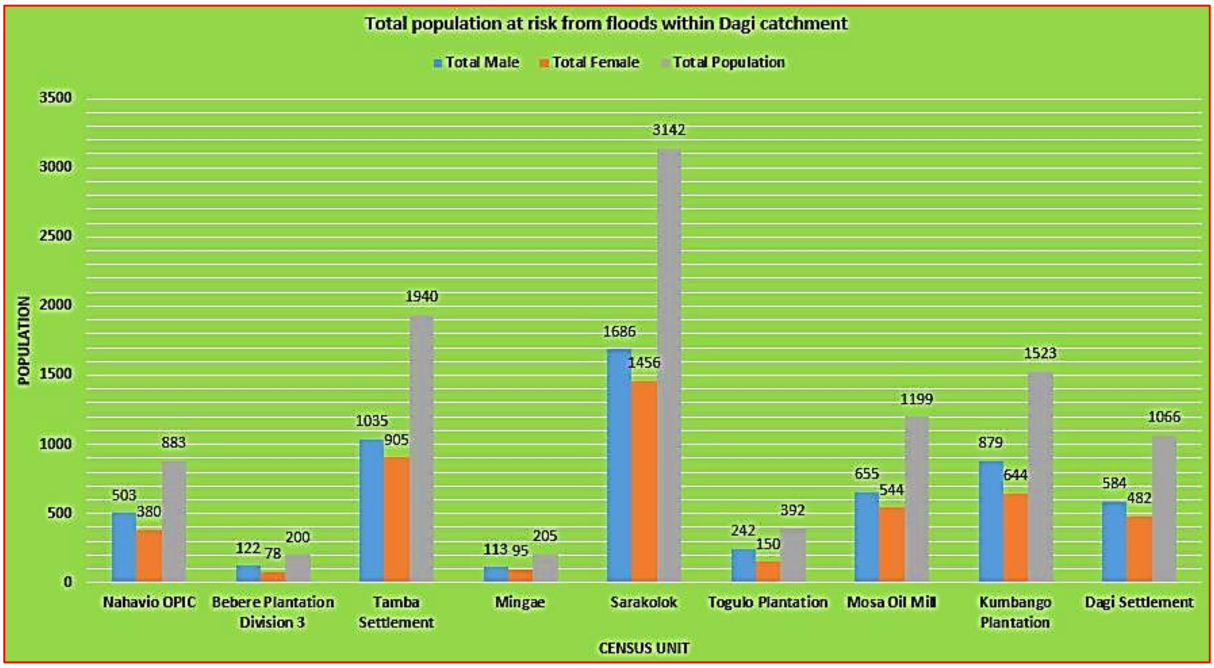


Figure 6.11: Total exposed population from floods in the catchment (Based on PNG NSO data, 2013).

The investigations conducted on the number of affected elements and those collated from the interviews are presented in *Excel* tables and attached in appendices 6.4, 6.5, 6.6 and 6.7. They reveal different elements that were affected from flood events in the past 13-15 years at a sub-catchment and catchment level. However, only the selected exposed elements are presented below. Tables 6.8-6.13 show the losses from selected exposed elements for the 2014 and 2010 flood events. It must be noted that floods are an annual event in the catchment with different characteristics and behaviour, extent of inundations and the levels of exposure. However, qualitative and quantitative data over the years for these parameters are lacking. Presented below are for 2014 and 2010 events where data is available.

6.6.4 Vulnerability assessment and maps

PNG does not have a national stage-damage function or vulnerability curve to assess vulnerability. Due to the absence of any alternative and even though tropical floods are qualitatively different from those in temperate areas, these curves are used here in the analysis. Flood velocity and depth and their correlative roles were used to generate the vulnerability curves. The land use classes used in this study were roads, subsistence gardening, oil palm grown on plantations and smallholder blocks, houses and buildings and population loss. The stage-damage function for road traffic was derived from figure 6.12 (see appendix 6.9) as indicated by a black arrow. Agriculture and houses were based on figures 6.13 and 6.14 (see appendix 6.9). Values for buildings were extracted from figure 6.15 while those for low rise dwelling houses prevalent in the study area were taken from figure 6.16 (see appendix 6.9). The stage-damage function values for population mortality were extracted from figure 6.17 (see appendix 6.9). Using these functions, the specific vulnerability curve for this study was plotted (figure 6.18).

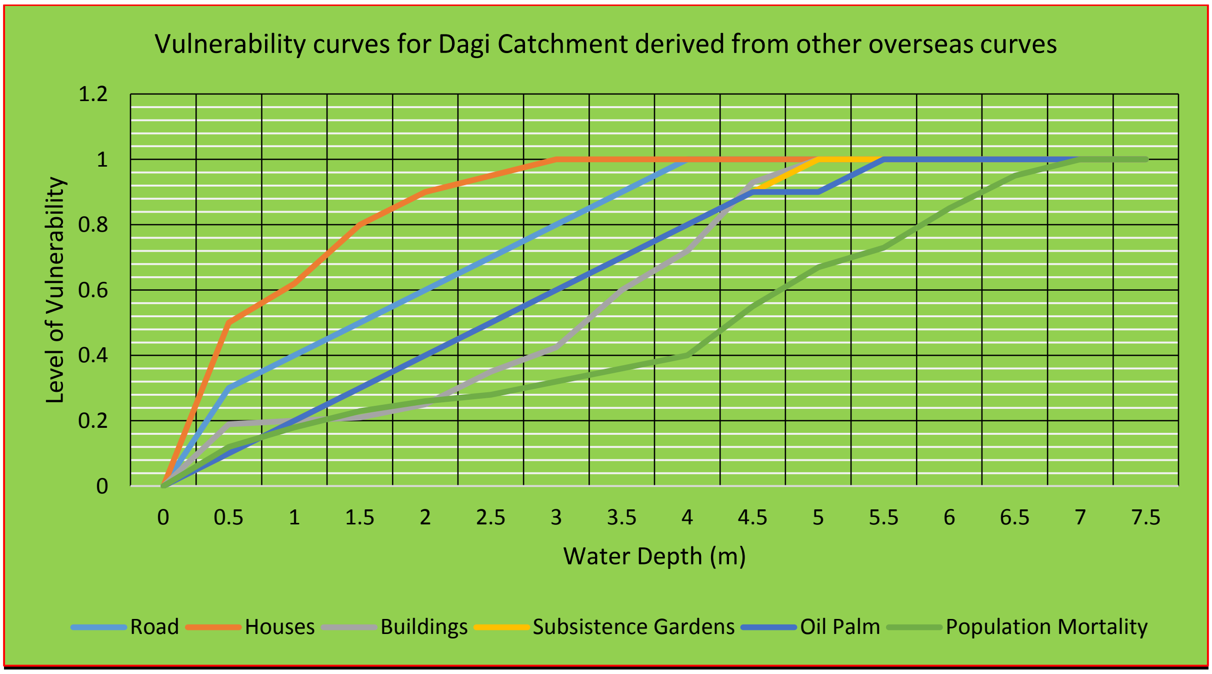


Figure 6.18: The specific vulnerability curve for this study derived from figures 6.12-6.17 (see appendix 6.9). *NB: Vulnerability level 0 = no vulnerability, and 1 = maximum vulnerability.*

The functions were used to identify damage maps for each type of land use and weighted into classes from highest to lowest using the 2014 and 2010 floods and then combined into an overall damage map. All selected exposed elements are a function of the level of vulnerability and water depth (figure 6.18). For any flood event, the water depth defines the level of vulnerability of any exposed element. For example, if a water depth of 1m inundated roads, this will identify the level of vulnerability at 0.4 for smaller vehicles. An increase of water depth to 3.5m increases the level of vulnerability to 0.85 for large vehicles that pick up oil palm fruit bunches.

Using these damage function curves, land use types were identified. The vulnerability was identified using the highest to lowest weights for each land use class. These were then used to draw vulnerability maps to assess flood risk for the different elements. Figure 6.19 shows the vulnerability map for oil palm trees and road networks based on the vulnerability curve. Figure 6.20 shows the vulnerability map of subsistence gardens along riparian zones while figure 6.21 shows the vulnerability map for houses and buildings. Land use vulnerability is shown by the different colour shading on all maps. These maps were used for assessing risk for all the exposed elements.

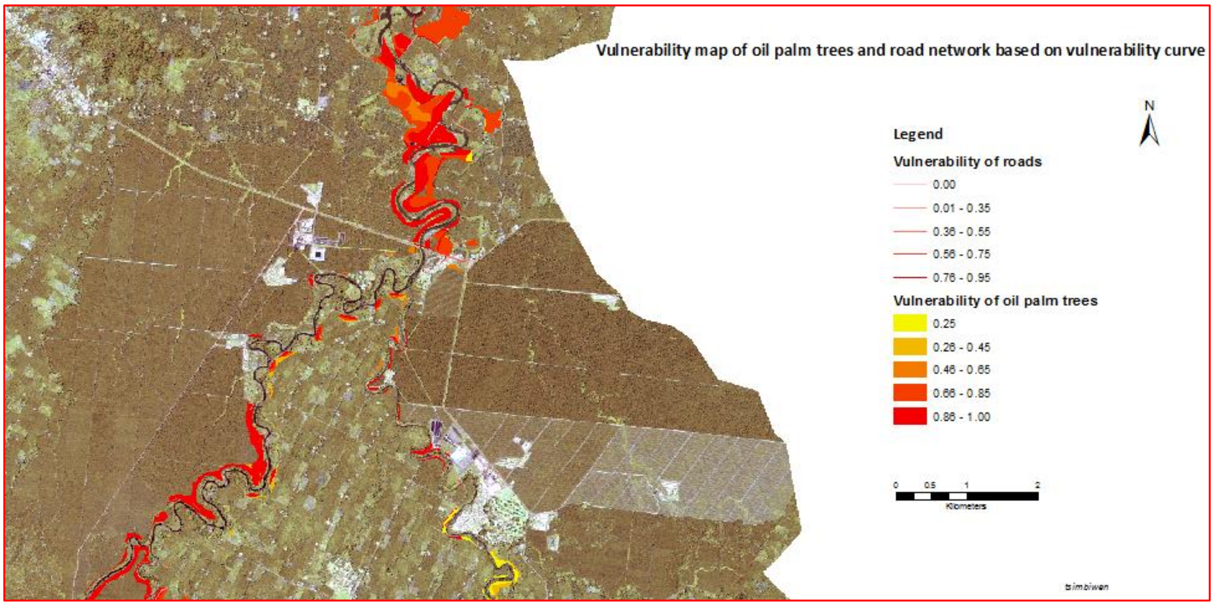


Figure 6.19: Vulnerability map for oil palm trees and road networks based on the vulnerability curve along the Dagi River.

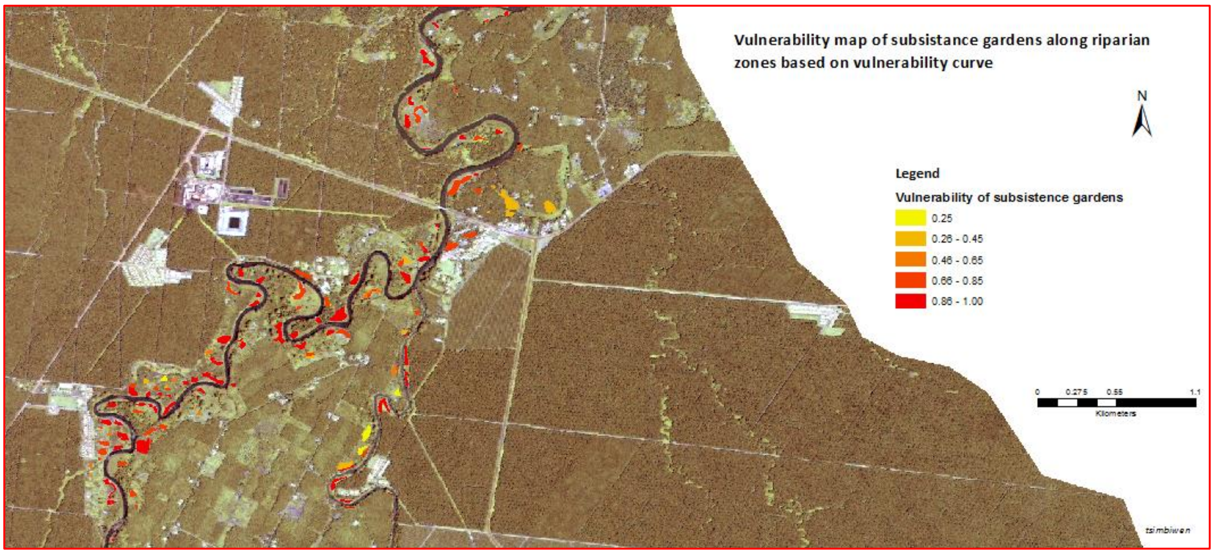


Figure 6.20: Vulnerability map of subsistence gardens in riparian zones based on vulnerability curve along the middle reaches of the Dagi River.

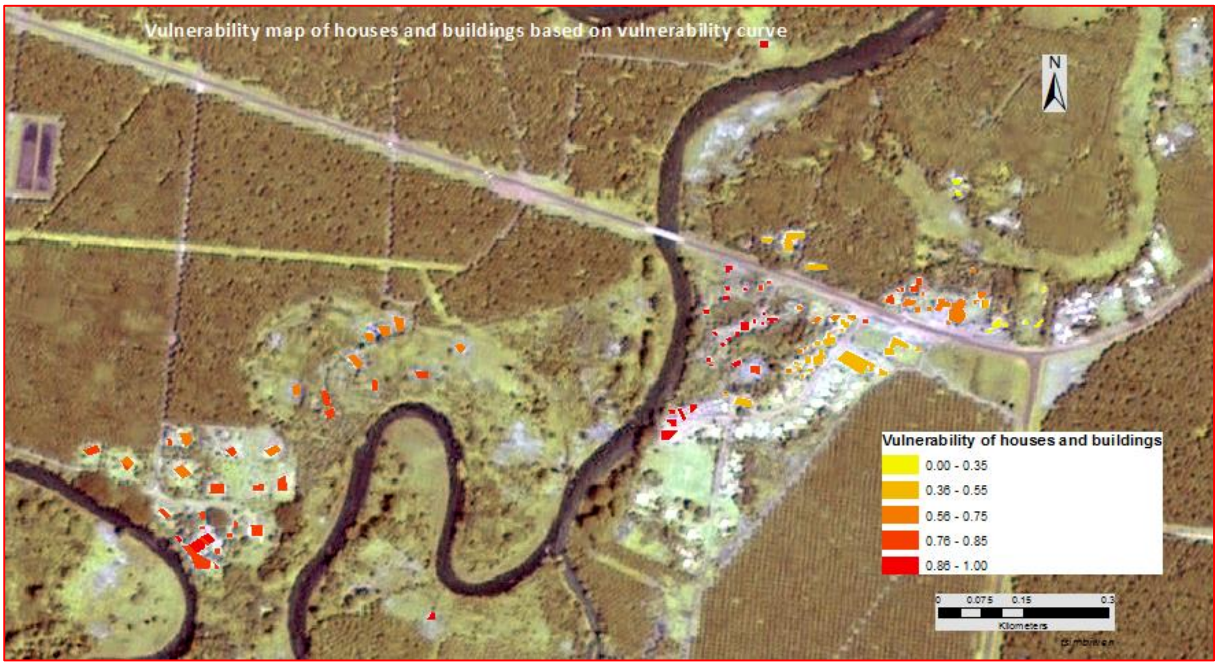


Figure 6.21: Vulnerability map for houses and buildings based on the vulnerability curve around Kumbango plantation and Nahavio station.

In summary, vulnerability decreases away from the river banks for all exposed elements as a function of depth and velocity. Highly vulnerable elements are those found towards the stream edges falling in the class range of 0.86-1.0. The vulnerability range decreases to a lower class (0.00-0.35) further away from the stream banks. Elements closer to the stream edges also increase their level of vulnerability and decrease further away from the river or stream banks. In some cases, especially along the upstream reaches, slope influences velocity and flow directions. For example, in the middle reach of the Lamegi River, subsistence gardens are towards the edges of the river but have lower vulnerability scores (0.00-0.25) because the over flows were in the opposite bank.

6.6.5 Qualitative risk assessment

For each type of land use and high vulnerability level, weights were used to identify risk zones. Maps were drawn based on these with the premise that the higher the vulnerability and the greater the hazards, the higher the risk and vice versa based on tables 6.3 and 6.4 (see appendix 6.8). Using these criteria, risk maps were drawn for all land use classes based on their combined exposures to the 2014 and 2010 flood hazards with respect to the role of vulnerability. The risk maps are shown in figure 6.22 for roads, houses and buildings. Figure 6.23 shows the risk zones for subsistence gardening while figure 6.24 shows that for oil palm. Subsistence gardens and houses and buildings are presented in high resolution. This is because their small sizes limits visualisation if presented on the whole map.

Figure 6.22: Risk map for roads and houses and buildings around Kumbango plantation and Nahavio station.

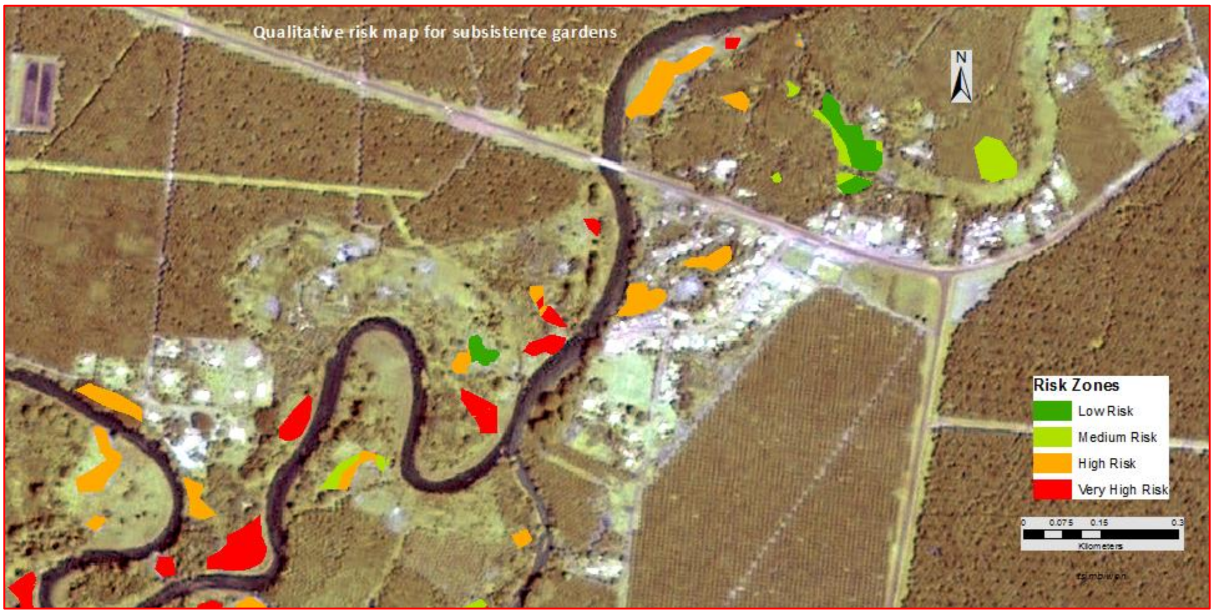


Figure 6.23: Risk map for subsistence gardens around Kumbango plantation and Nahavio station.

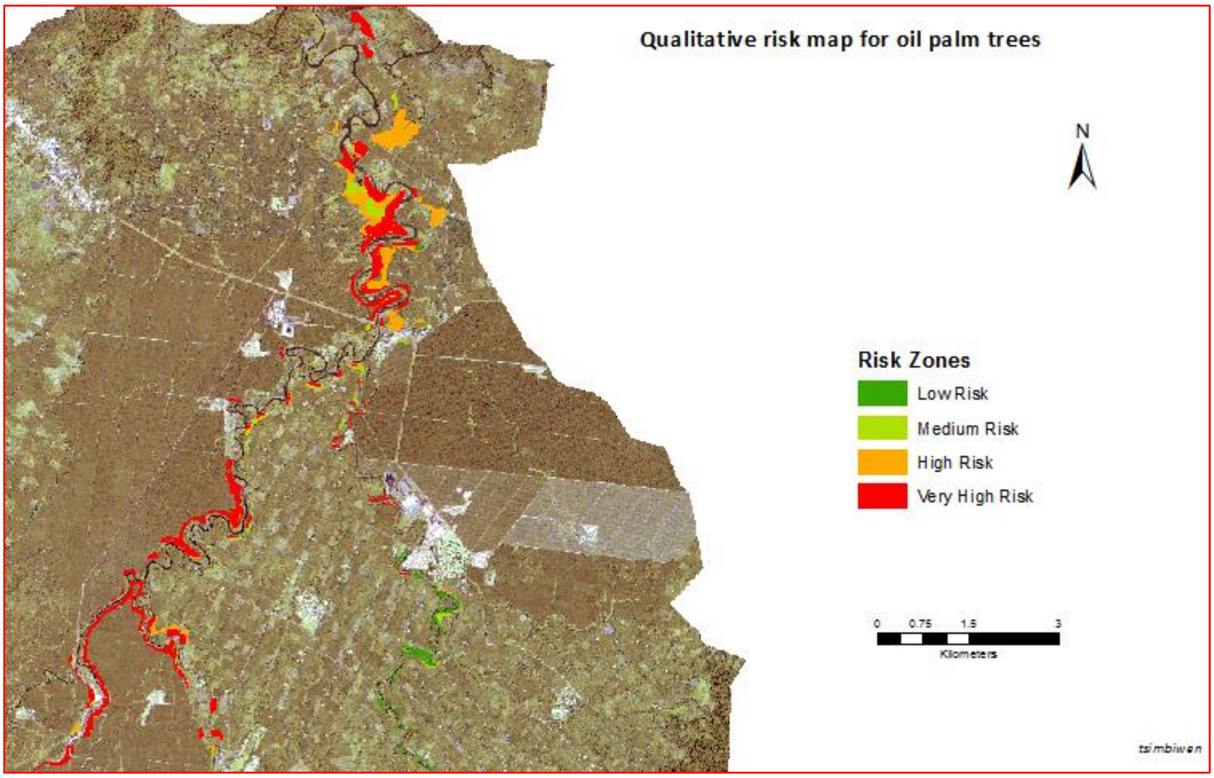


Figure 6.24: Risk map for oil palm trees along the reaches of the Dagi River.

The risk zones for each of the land use classes do not follow any pattern. This is because the weights for each land use types and the higher level of vulnerability were combined to give prominence to each land use. Maps were drawn based on the premise that the higher the vulnerability and the greater the hazards, the higher the risk. However, the risk zones show a pattern different from this premise. For example, upstream reaches are mostly characterised by low water depths. However, the map shows areas of high risk for oil palm along the Dagi river banks. This means that despite low water depths, high velocity does the damage by uprooting oil palm trees and increases the risk (plates 6.19 and 6.20 in appendix 6.1).

6.6.6 Quantitative risk assessment

Tables 6.8-6.15 show the flood damage of the exposed elements between 2014 and 2010. All values were gathered from inundation simulations and face-to-face interviews. The assessment of economic damage for exposed elements was based on the damage functions and classified according to their types. Table 6.16 summarises the total economic costs incurred for the exposed elements from flood hazards in the study area. The value of economic damage is in Papua New Guinea Kina (PGK) and converted to the USD.

Table 6.8: Assessment of economic damage for roads.

Road type	Area affected in 2014 (m^2)	Area affected in 2010 (m^2)	Value per m^2 in PGK (est.)*	Total damage for 2014 (PGK)	Total damage for 2010 (PGK)	Total Damage (PGK)
Sealed	1,735.47	3,475.36	200	347,094	695,072	1,042,166
Unsealed	3,906.27	7,656.74	100	390,627	765,674	1,156,301
TOTAL	5,641.71	11,132.10	300	737,724	1,460,746	2,198,467

**These are my estimated figures for the Dagi and costs could be higher or lower in future.*

A damaged sealed road will cost more to repair so I put down an estimated economic cost of K200 per m^2 of damage while unsealed roads will cost less so an estimated value of K100 was given (table 6.8). Each value was then multiplied with the total area per year to give the total cost for that year. The total cost of sealed and unsealed roads was then added to give their respective totals. The total costs for each road type per year were then added to give the overall cost of damage for all road types in the two years. The costs for damaged sealed road in 2014 was K347,094 representing only 33.3% while the 2010 total was K695,072 representing 66.7% of the total costs. Damaged unsealed roads incurred 33.8% (K390,627) for 2014 while that of 2010 was K765,674, representing 66.2% of the total costs for unsealed roads. The total damage for all road types represented 33.6% for 2014 (K737,724) while 66.4% (K1,460,746) was incurred in 2010. The 2010 total road cost is slightly higher than 2014 by 32.8%. This means that road damage in 2010 incurred more economic costs than in 2014 because it was a bigger flood event that inundated and exposed many roads. The 2014 and 2010 flood events inflicted a total estimated economic cost of K2,198,467.

Table 6.9: Assessment of economic damage for houses and buildings.

House or building type	Area affected in 2014 (m^2)	Area affected in 2010 (m^2)	Value per m^2 in PGK (est'd)*	Total damage for 2014 (PGK)	Total damage for 2010 (PGK)	Total Damage (PGK)
Permanent houses	6,455.36	10,685.32	250	1,613,840	2,671,330	4,285,170
Semi-permanent houses	22,861.79	36,894.58	125	2,857,724	4,611,822	7,469,546
Bush material houses	27,593.56	33,412.67	5	137,968	167,063	305,032
Government buildings	9,634.82	12,986.18	500	4,817,410	6,493,090	11,310,500
Oil palm company buildings	3,242.33	4,752.51	750	2,431, 747	3,564, 382	5,996, 129
TOTAL	69,787.86	98,731.26	1,630	11,858, 689	17,507, 688	29,366,377

**These are my estimated figures for the Dagi and costs could be higher or lower in future.*

Permanent houses are expensive to repair or rebuild and I put down K250 per m^2 (table 6.9). This value decreases to K5 per m^2 for bush material houses. Bush material houses are not expensive because they can be replaced using cheap materials from the environment. Government buildings are expensive because, beside their construction materials, they hold valuables such as faxes or printer machines and documents. I put down an estimated economic value of K500 per m^2 of damage. Company buildings are economic assets, because they make money for the company, so I gave an estimated economic value of K750 per m^2. Each of the values were then multiplied with the total area affected each year to give the damage's total cost. Total cost for each house and building type were then added to give their respective total costs. The total costs for each house and building type per year were added to give the overall cost of damage in the two years. The total damage costs for all houses in 2014 and 2010 was K12,059,747. Between the years, 2014 represents 38.2% (K4,609,532) of the overall costs while 2010 represents 61.8% (K7,450,215). The total damage costs for all houses in 2010 was 23.6% higher than that for 2014. For government buildings, 42.6% of the overall costs occurred in 2014 while 57.4% for 2010, with a difference of 14.8%. The results are quite high because during the 2010 flood events most offices were covered with flood waters for some days. From company records, 2010 represents a time of damage to its infrastructure. Buildings alone represented 59.5% of the costs which is 18.9% higher than 40.6% for 2014.

Table 6.10: Assessment of economic damage for subsistence gardens.

Subsistence garden type	Area affected in 2014 (m^2)	Area affected in 2010 (m^2)	Value per m^2 in PGK (est'd)*	Total damage for 2014 (PGK)	Total damage for 2010 (PGK)	Total damage for both years (PGK)
Market	385,792.83	403,359.45	10	3,857,928.3	4,033,594.5	7,891,522.8
Self - consumption	88,743.46	99,116.67	10	887,434.6	991,166.7	1,878,601.3
TOTAL	474,536.29	502,476.12	20	4,745,362.9	5,024,761.2	9,770,124

**These are my estimated figures for the Dagi and costs could be higher or lower in future.*

Subsistence gardens are subdivided into either market gardens where crops are only grown to be sold at the local market, or for self-consumption, which are only grown to meet household needs (table 6.10). However, many times subsistence gardens serve both purposes, where the surplus is sold at the local market for cash to buy store goods. From my experience, a damaged market and self-consumption garden will each have an estimated economic cost of K10 per m^2. This depends on the type of food crops grown. In an average garden along the Dagi River, sweet potato is a common staple grown. Within a square metre, a sweet potato mound can yield many tubers, and when sold can earn as much as K10. Similarly, a taro is cultivated within a square metre and can yield as much as K10. Using the value of K10 as the unit price per m^2, it was multiplied with the total area affected each year to give the total cost of damage. The total cost per year was then added to give total cost. This was further added to give their overall cost of damage in the two years. The 2010 flood incurred 51.1% of the total costs to market gardens while that of 2014 was 48.9%. There was little difference in the costs (2.2%) between 2014 and 2010 flood events. The self-consumption category represented 52.8% for 2010 while 47.2% was for 2014 in terms of overall economic costs. Similarly, there was a small difference, 5.6%. Both categories of subsistence garden are common in riparian zones because much of the land has already been planted with oil palm. The total damage value in both 2014 and 2010 was K9,770,124.

Table 6.11: Assessment of economic damage for leaching of fertilisers in areas of oil palm inundated.

Oil palm ownership type	Area affected in 2014 (m^2)	Area affected in 2010 (m^2)	Value per m^2 in PGK (est'd)*	Total damage for 2014 (PGK)	Total damage for 2010 (PGK)	Total damage for both years (PGK)
Smallholder oil palm blocks	1,112,108	11,666,522	1	1,112,108	11,666,522	12,778, 630
Company plantations	898,333	9,649,720	1	898,333	9,649,720	10,548, 053
TOTAL	2,010,441	21,316,242	-	2,010,441	21,316,242	23,326,683

**These are my estimated figures for the Dagi and costs could be higher or lower in future.*

Oil palm are subdivided into two groups of ownership, as being owned on a block or by a company (table 6.11). From my experience as a smallholder settler, oil palm trees are planted 10m apart to allow for its foliage to get sufficient sunlight while its roots get sufficient nutrients to produce its fruits. Over the years of cultivation, nutrient levels have declined under oil palm so investments are made to apply fertilisers to boost production. However, beneath the oil palm canopy are open spaces where during an inundation these fertilisers are dissolved and leached into the streams thus lowering productivity (e.g. Murom et al., 2008; Nelson et al., 2006). Therefore, I am giving an estimated value of K1 per m^2 for the loss of fertilisers when oil palm areas are inundated. This unit value is multiplied with the area affected for each year and their totals were added. The two totals were further added to give the total damage. The total damage for 2014 (8.6%) is much lower than that of the 2010 flood (91.4%). The 2010 figure is larger because a large area was inundated that led to the loss of more fertilisers. Fertiliser losses from company plantations represented 45.2% of total damage while losses from smallholder blocks represented 54.8% of the total economic damage for both years. Company plantations are better planned and managed than smallholders and this may be the reason for this figure.

Table 6.12: Economic damage for non-pick-up of FFB between 2000 and 2014.

Year	Number of times FFB not picked up	Unit value per non- pickup per harvest in PGK (estimated)*	Total Revenue Loss (PGK)
2000	5	K600	K3, 000
2001	1	K600	K600
2002	-	-	-
2003	3	K600	K1, 800
2004	-	-	-
2005	6	K600	K3, 600
2006	-	-	-
2007	5	K600	K3, 000
2008	1	K600	K600
2009	-	-	-
2010	12	K600	K7, 200
2011	-	-	-
2012	-	-	-
2013	6	K600	K3, 600
2014	3	K600	K1, 800
TOTAL	42	---	K25, 200

**These are my estimated figures for the Dagi and costs could be higher or lower in future (fieldwork interviews, see appendix 6.4-6.7).*

Harvested oil palm bunches and fruits are usually lined up in nets awaiting fruit trucks to pick up within four days, and transported to the mill for processing. A net will weigh almost a tonne. In an average block comprising 4 hectares of oil palm, the average total number of nets would be four if all hectares are harvested. This means that a block would sell 4 tonnes of oil palm to the company, which processes and exports them. The world market price for a tonne of oil palm as of 15th September, 2015 was US$480 (www.indexmundi.com), equivalent to K1,408. The company takes off their share for transport and milling and a block holder gets about K600 per tonne. On average, a block holder gets K2,400 a fortnight (K600 X 4 tonnes). During times of flood when road access is cut off, fruit in the nets is not picked up so they decompose and become a loss. Therefore, the unit value of loss during a non-pickup time is K600, though it may be more for company plantations. This is then multiplied with the number of times fruit is not picked up and this gives the final figure for the year.

2010 was a bigger flood, most roads were inundated and fruit trucks were not able to access locations to pick up fruit quickly so most fruit decayed and that gave a higher figure (see plate 6.21 in appendix 6.1). The total cost between 2000 and 2014 was K25,200. This estimated figure is inclusive of oil palm plantations, though it may be higher. Through inundation of plantation roads, accessibility to harvest fruits by workers were denied for some days (see plates 6.4, 6.6, 6.19, 6.21 and 6.22 in appendix 6.1). Fruit on the palms remained unharvested and decayed. Fruit placed in the nets at pick-up points near the roads also decomposed when fruit trucks were denied access by high water depths.

Table 6.13: Economic damage for oil palm trees between 2000 and 2014.

Year	Number of oil palm tree destroyed by flood	Unit value per palm destroyed by flood in PGK (estimated)*	Total Damage (PGK)
2000	6	10,00	60,000
2001	3	10,000	30,000
2002	2	10,000	20,000
2003	2	10,000	20,000
2004	1	10,000	10,000
2005	10	10,000	100,000
2006	2	10,000	20,000
2007	4	10,000	20,000
2008	4	10,000	40,000
2009	1	10,000	10,000
2010	14	10,000	140,000
2011	2	10,000	20,000
2012	3	10,000	30,000
2013	9	10,000	90,000
2014	6	10,000	60,000
TOTAL	69	---	690,000

**These are my estimated figures for the Dagi and costs could be higher or lower in future (fieldwork interviews, see appendix 6.4-6.7).*

The number of oil palm trees destroyed between 2000 and 2014 was collated from fieldwork data (table 6.13, appendix 6.4-6.7). Data show the total number oil palm trees destroyed based on interview of smallholders who have blocks near the Dagi River, and company officials. Oil palm still survived during and after inundation, however, it is the velocity with high stream power that does the damage by uprooting the oil palm trees, with younger palms more vulnerable. On average an oil palm tree has a commercial life span of 25 years (Murom et al., 2008). During this life span, and depending on world market prices, an average oil palm can return approximately K10,000 to a grower (OPIC, 2012). Using this detail, for each oil palm tree destroyed by flood, I am giving a unit value of K10,000 per palm, because there were no data on the ages of each palm destroyed. The total number of palm(s) destroyed was multiplied with the unit value of cost per palm to give the total for that year. The value for each year was then added to give the overall total economic loss. Between 2000 and 2014, there were a total of 69 trees destroyed by floods worth K690,000, with the 2010 flood representing 20.3% of the total losses.

Value of human life can be calculated based on information on income earned annually, working years left before retirement, and rate of tax, life insurance, savings, and other assets (Manifold, 2014; www.lifehappens.org). This kind of confidential information is difficult to obtain in rural PNG. Many people in PNG do not die of old age, but due to many other causes (e.g. health). The average life expectancy in PNG is 65 years and children start informal work from 15 years of age onward (NSO, 2013). This means a human life in PNG will work for 40 years (i.e. 65-15). Since most growers in Dagi earn an average income of K2,400 a fortnight from the sale of their oil palm (see explanations for table 6.12), they will earn around K62,400 per annum (i.e. K2,400 X 26 fortnights). During the 40 years of their working life, they would have earned K2,496,000 (i.e. K62,400 X 40 years). Deaths from floods does not discriminate by age so this figure would be less for a 40-year-old life and greater for a 15-year-old boy. In my calculation, I am excluding life insurance that are common in developed countries, because it is non-existent in Dagi for a simple oil palm grower. The calculated fortnightly value is inclusive of taxes and exclusive of savings depending on people's choice. This exclusion is based on my experience as a smallholder block owner in Dagi. Therefore, I am only using the annual earnings from oil palm and multiplying that by the 40 years of working life to give the final figure.

On the other hand, the value of human life claimed by compensation payments are culturally derived in PNG based on the level of education, pride of the tribe and the number of children, and defined by the cause of the death, e.g. wilful murder of an innocent life would incur more compensation from the killer's tribe. Relatives can put varying demands from K100,000 to as much as K1,000,000, but negotiated to an agreeable figure. In our case, a flood causing death in PNG is different because a flood is not a man from whom compensation can be claimed. This is quite different from developed countries where so many things (e.g. life insurance and assets owned) add up to give figures in millions of dollars. An example is EPA having a standard life value of $9.1 million per year, while $7.9 million for US Food and Drug Administration. There was a total of five flood related deaths between 2000 and 2014 as gathered from face-to-face interviews. Therefore, the loss of five lives would be valued at PGK12,480,000 (table 6.14). This figure may be overestimated or underestimated because the exact ages of deaths were not given so the figures were calculated based on an average Papua New Guinean 40-year working life.

Table 6.14: Assessment of economic cost for deaths from drowning between 2000 and 2014.

Year	Total deaths from drowning incidents (upstream and downstream)*	Value per death in PGK (estimated)	Total economic cost of deaths in PGK (estimated)	Total economic costs incurred (PGK)
2000	1	2,496,000	2,496,000	2,496,000
2001	-	-	-	-
2002	-	-	-	-
2003	-	-	-	-
2004	-	-	-	-
2005	1	2,496,000	2,496,000	2,496,000
2006	-	-	-	-
2007	1	2,496,000	2,496,000	2,496,000
2008	-	-	-	-
2009	-	-	-	-
2010	1	2,496,000	2,496,000	2,496,000
2011	-	-	-	-
2012	1	2,496,000	2,496,000	2,496,000
2013	-	-	-	-
2014	-	-	-	-
TOTAL	5	12,480,000	12,480,000	12,480,000

**These are estimated figures for the Dagi based on life values in the US (https://en.m.wikipedia.org).*

People in formal jobs do not earn the same pay due to several criteria such as qualifications, experience and trade and so their salaries vary from K500, K1,000 and as much as K1,500 a fortnight. Based on this range, I am using an average of K1,000 per fortnight (table 6.15). Workers reside in oil palm blocks or in company plantations and commute to work. When road access is denied during an inundation, they do not go to work. The number of days absent from work results in a loss of income. So, I am calculating the loss of income as follows: in general, for public servants, there are 10 working days while private sectors have 12 working days, so let us assume that all work 12 days to earn K1,000 a fortnight, then K1,000 divided by 12 working days gives us around K84 earned per day. A day of absenteeism results in a deduction of K84 in the salary. The total number of days absent from work is multiplied by K84 to give the total income loss. Between 2000 and 2014, there were 150 days' work absenteeism due to floods which resulted in the loss of K12,600 from formal job incomes. The 2010 flood incurred the highest job income losses of K3,948 while in 2008 there was only one day of absenteeism that lost K84.

Table 6.15: Formal job income loss between 2000 and 2014 due to floods.

Year	Number of times absent from work	Unit value per cut in a day's salary in PGK (estimated)*	Total Income Loss (PGK)
2000	8	84	672
2001	2	84	168
2002	4	84	336
2003	7	84	588
2004	3	84	252
2005	25	84	2, 100
2006	2	84	168
2007	9	84	756
2008	1	84	84
2009	2	84	168
2010	47	84	3, 948
2011	2	84	168
2012	5	84	420
2013	26	84	2, 184
2014	7	84	588
TOTAL	150	---	12,600

**These are my estimated figures for the Dagi and costs could be higher or lower in future (source: fieldwork interviews, see appendix 6.4-6.7).*

Table 6.16: Total economic costs of damage incurred for exposed elements from flood hazards.

Exposed elements	Total economic costs incurred in 2014 (PGK)*	Per cent (%) of total costs	Total economic costs incurred in 2010 (PGK)*	Per cent (%) of total costs	TOTAL ECONOMIC COSTS*	PER CENT (%) OF TOTAL COSTS
Roads	737,724	3.8	1,460,746	3.2	2,198,467	2.6
Houses and buildings	11,858,689	61.3	17,507,688	38.6	29,366,377	34.3
Subsistence gardens	4,745,363	24.5	5,024,761	11.1	9,770,124	11.4
Fertilisers leaching	2,010,441	10.4	21,316,242	47.1	23,326,683	27.2
Non-pickup of oil palm FFB (2000-2014	-	-	-	-	25,200	0.02
Damaged oil palm trees (2000-2014)	-	-	-	-	690,000	0.8
Deaths from drowning incidents (2000-2014)	-	-	-	-	12,480,000	23. 7
Formal job income loss (2000-2014)	-	-	-	-	12,600	0.01
TOTAL ECONOMIC COSTS	PGK19,352,217 equivalent to US$6,597,171**	100	PGK45,309,437 equivalent to US$15,445,987	100	PGK77,869,451 equivalent to US$26,545,696	100

*These are my estimated figures for the Dagi and costs could be higher or lower in future. **The currency conversion was done on the 23rd of September 2015 at the rate of 1 PGK equal to US$0.34090 using the OANDER currency converter.*

The total costs for roads, houses and buildings, subsistence gardens and fertilisers were based on simulations for the 2014 and 2010 floods respectively derived from tables 6.8-6.11. The total costs for the non-pick-up of FFB, damaged oil palm trees, deaths from drowning incidents and loss of formal job income were respectively derived from tables 6.12-6.15. These figures were then added up to give the final total economic cost of damage incurred for exposed elements from flood hazards (table 6.16). By observing the overall total economic costs, it is obvious that houses and buildings alone incurred the greatest costs (34.3%). This is followed by leaching of fertilisers (27.2%), deaths from drowning incidents (23.7%), subsistence gardens (11.4%), roads (2.6%), damaged oil palm trees (0.8%), non-pick-up of FFB (0.02%) and formal job income loss (0.01%). These differences are well below the threshold value of 20% (Vanneuville et al., 2006). The total economic costs based on the elements at risk is PGK77,869,451. This is equivalent to US$26,545,696 (23rd Sept 2015 exchange). Further explanations are given by the risk curves based only on the values for the exposed elements during 2014 and 2010 floods.

6.6.7 Risk curves

A risk curve provides data on the likelihood of extreme loss for any recurrence interval for an exposed element (ITC, 2010) (figures 6.25-6.28). Using roads as an example, the annual risk curve can be derived by firstly calculating the recurrence interval of a flood occurrence. This data is then identified on the curve by starting with the y-axis and then related horizontally to the curve intercept. Suppose we have an exceedance probability of 0.008 as in the case of the 2014 flood event, then obviously, it would be R_1 or risk one and T_2 or exceedance probability two. If return period is used, then it will be return period two. The space between the current exceedance probability and the next boundary of the exceedance probability defines the total area of the element at risk. Once the area is determined, it is multiplied with the estimated unit cost to give the average annual risk for that element in the catchment. For each exceedance probability, monetary costs are estimated from the mean annual risk covered by the area delineated inside the risk curve (ibid.). These are delineated as T_1, T_2, T_3 and R_1, R_2 and R_3 for each exceedance probability (figures 6.25-6.28). Using this information, the annual risk for an exposed element in the catchment can be calculated in the long term.

All risk curves for the exposed elements in the Dagi Catchment show that the higher the likelihood of the flood event happening, damage level is lower than those rare flood events that cause more damage. The estimation of annual flood risk was from the damage related to the 2014 (exceedance probability = 0.008) and 2010 (exceedance probability = 0.007) to a maximum exceedance probability of 0.001. Flood risk has a close relationship with damage and data suggest similar tendencies showing agreement in the annual flood risk with <20% difference.

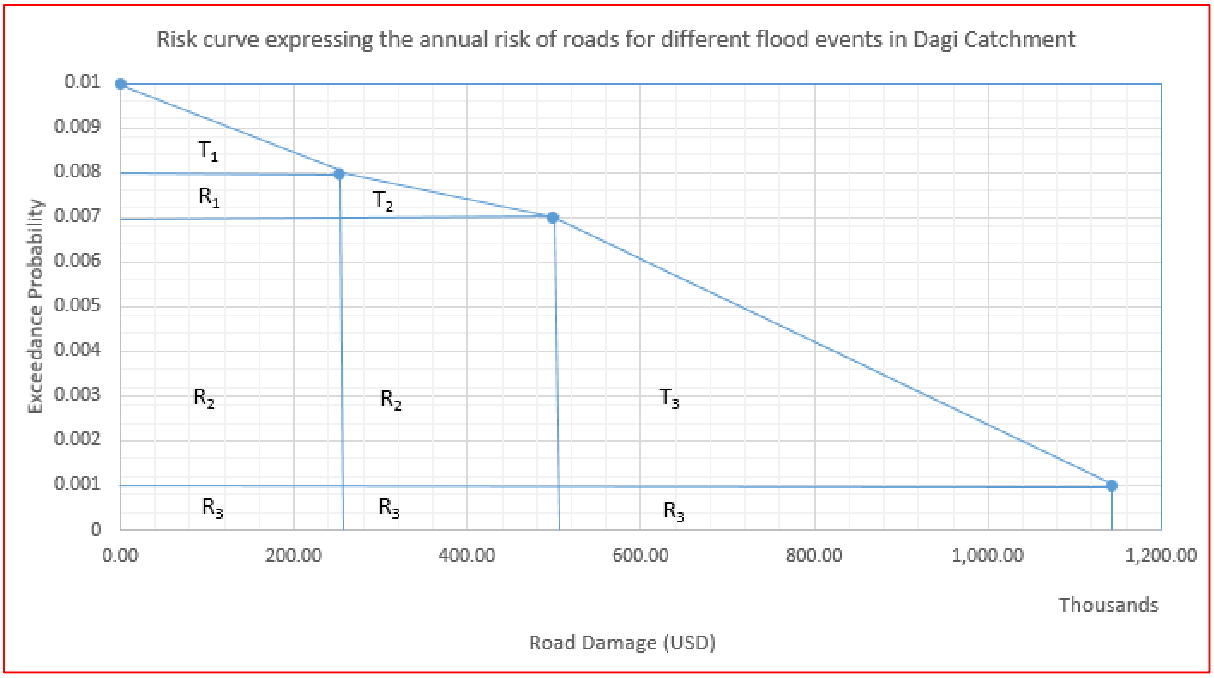


Figure 6.25: Annual risk curve for road economic losses per exceedance probability.

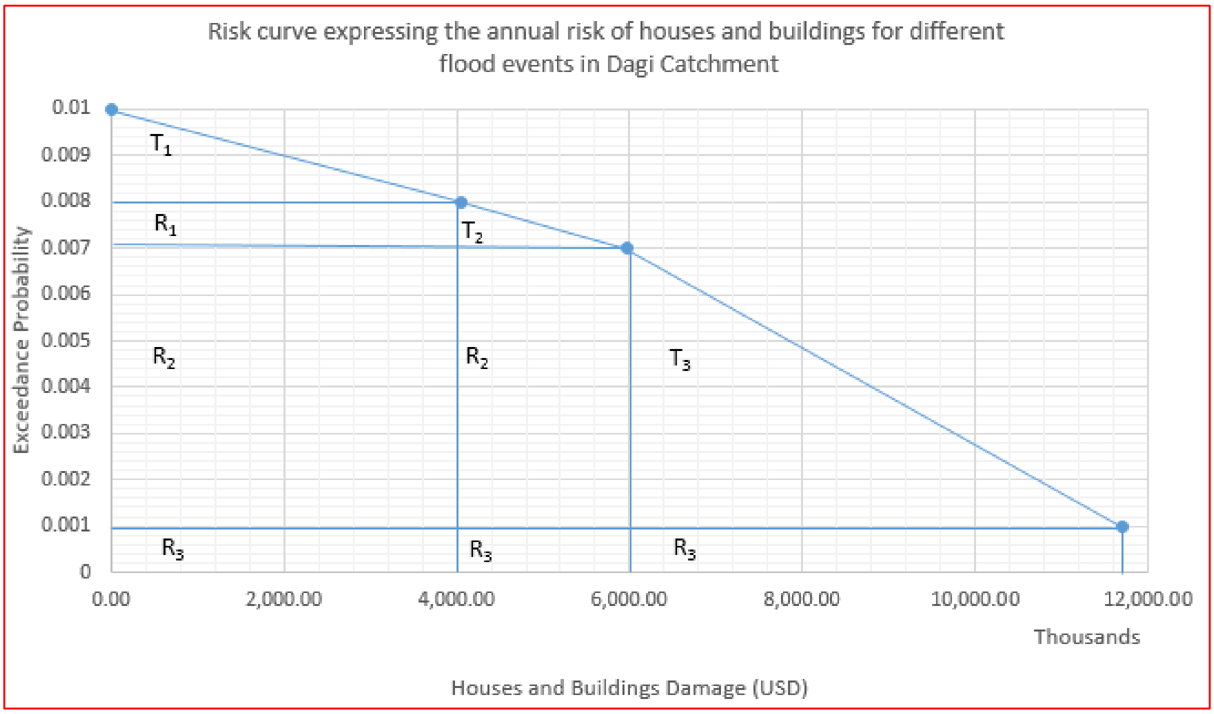


Figure 6.26: Annual risk curve for house and building losses per exceedance probability.

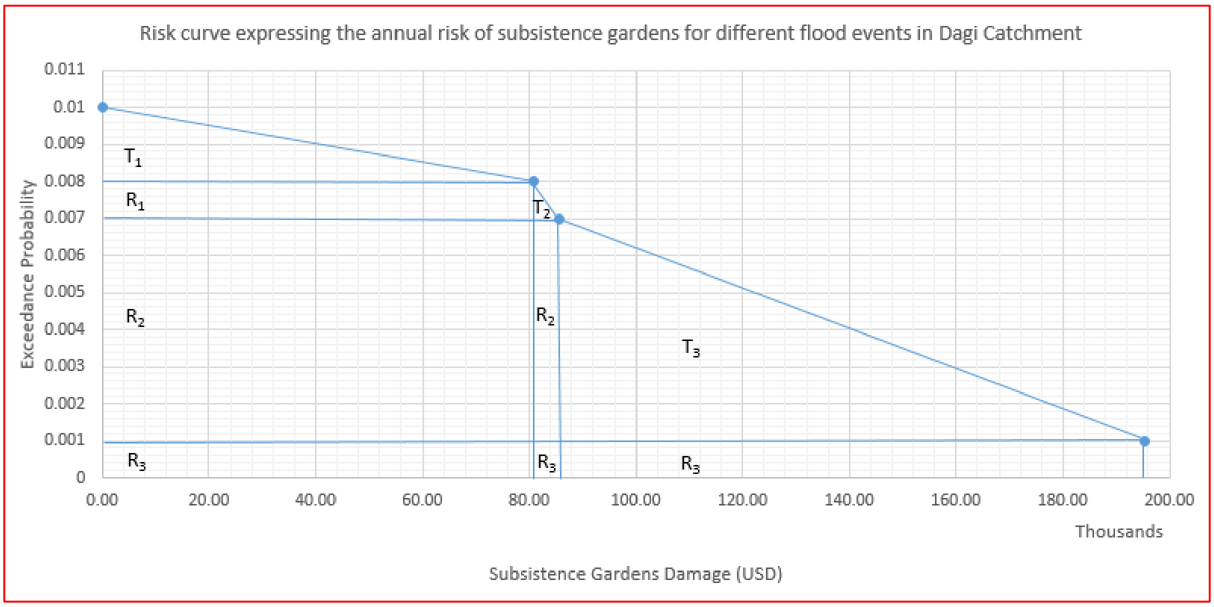


Figure 6.27: Annual risk curve for subsistence gardening losses per exceedance probability.

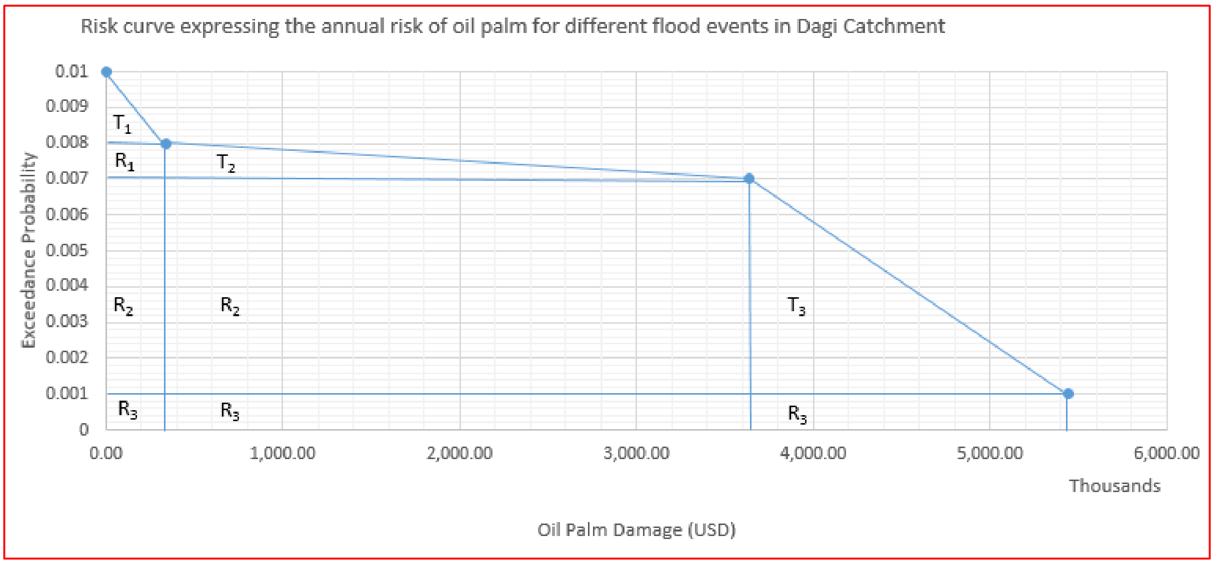


Figure 6.28: Annual risk curve for oil palm losses oil palm per exceedance probability.

6.7 Discussion

Traditional flood study designs "are increasingly supplemented by risk-oriented methods for comprehensive analysis" (Gain and Hoque, 2013: p.219). This study used flood hazard maps prepared from geo-processing tools based on SOBEK 1D/2D and HEC-RAS Beta 5.0 models and ArcGIS 10.2. Raster-based vulnerability maps and expected damage maps of several exceedance probabilities were then produced. The analysis in this chapter was designed to assess flood risks and vulnerabilities of exposed elements in oil palm landscapes. The study qualitatively and quantitatively assessed the level of hazards and the vulnerabilities based on a sample of physical, social and economic elements exposed during the 2014 and 2010 flood events. Costs associated with the selected exposed elements during the two flood events were compared based on their current estimated economic values. These results were used to determine the degree of risk as a function of inundation depth and velocity.

6.7.1 Hazard level

Floods are an annual event during the wet seasons in tropical catchments. The level of hazard varies according to flood characteristics and their behaviour, level of inundation and the level of exposure of land use elements. In most cases, however, historical qualitative and quantitative data are lacking. The results generated in this study were based on the available data for 2014 and 2010 flood events. Plates 6.1-6.23 in appendix 6.1 show images of various livelihood assets damaged by flood during the 2014 and 2010 flood events. The assessment of total elements at risk between the 2014 and 2010 floods showed a combined total of 71 roads with a total distance of 16.77km. Houses and buildings had a combined total of 718 covering 0.17km^2, while there was a total of 577 subsistence gardens covering 0.98km^2 exposed to flooding in these two years. There were 32 smallholder oil palm blocks covering 12.78km^2 which had a total count of 32, while oil palm plantations had a total count of 33 covering 10.55km^2. Between the two years, 2010 had the highest figures for all the exposed elements compared with 2014.

There is a direct relationship between flood hazard level and the inundation depth. It can be seen that hazard level increases as water depth increases. High hazard areas are associated with high water depths common in the middle and lower reaches of the Dagi catchment. High water depths were the result of increased volumes of water contributed from upstream tributaries and the river channel. The 2010 flood event had high hazards because it inundated a larger area for all sites. This increased the exposure of elements than compared with the 2014 flood event. A recent simulation study on roads showed that increases in mean inundation depth and total flood volume extend the length of roads damaged from 481km (37%) to 1,398km (74%) (Dawod et al., 2014).

Furthermore, risk patterns are highly dependent on exposure at different temporal and spatial dimensions. Belmonte et al. (2011) studied exposures at different temporal frequencies and spatial locations and found large exposures were during nights, weekends and holidays in land use zones dominated by agriculture and residence. During nights, weekends and on holidays, most people are at home and thus allow for more exposure. Czajkowski, et al., (2014) reported considerable variations in exposure and mean losses upstream and downstream of a drainage network that were in similar and different risk zones.

Information gathered during the fieldwork relating to drowning accidents and deaths can be unreliable in instances where the respondent has to recall some years back. At times, those living upstream were reporting the same losses that were already reported downstream. This increases the tally of total losses and consequently increases the economic costs based on these uncertainties. Harvatt et al., (2011) studied flood events and sea level rises in risk areas to document the experiences and their relationship among households. The study showed that 30% of the respondents gave information based on eyewitness observation while 70% gave information from third-party sources.

In this study, it was demonstrated that during the 2014 flood, 40.8% of the flood plain went under water while 59.2% was recorded for the 2010 event. Thus the 2010 flood inundated 18.4% more than that of 2014. This was based on the combined inundation extent for both years. Topography, relief and geology played a crucial role in influencing the extents of inundations. These figures could be lower if flood protection measures are in place. The results are consistent with those of Masood et al. (2012), who investigated inundation extents in Dhaka, Bangladesh. More than 60% of eastern Dhaka are inundated for up to 7.55m of water and affected annually due to the absence of flood protection barriers and limited flood disaster preparedness.

6.7.2 Level of physical, social and economic vulnerability

Flood damage is dependent on factors such as flow speed, time, safeguard and relationship between floods and these damages are averaged and described using stage-damage function (Boettle et al., 2011). This function assesses highest water level being the primary damage determining factor and are commonly used in Australia and Europe. Unfortunately, PNG does not have a stage-damage function or vulnerability curve to assess vulnerability. However, curves relevant to the exposed element from overseas can be used to create new vulnerability curves to suit local settings, but these will need much modification in the future to make them relevant to Papua New Guinean conditions. Results from this study show that vulnerability decreases further away from the river banks for all exposed elements. This was a function of depth and velocity. Furthermore, depth and velocity are a function of slope, topography and volume of discharge. High slopes will have low inundation depths, but maintain high velocity so exposed elements will tend to be impacted by velocity rather than depth. High depths and longer durations of inundation in depressions increases losses over time and these are more common along the lower reaches of the catchment.

An increase in flood risks is expected globally due to climate change and population growth (Cammerer et al., 2013). General observations in this study reveal that in future, flood losses will rise as settlements expand and oil palm cultivation increases in and around floodplains. Growth in wealth also increases livelihood assets and consequently increases the vulnerability of exposed elements in future. Cammerer et al. (2013) analysed the spatial and temporal advance of flood exposure as land use changed. In flood-exposed residential areas, the "overall risk" increased by 119% while in areas where building restrictions were excluded flood risk increased by 159%.

6.7.3 Risk zones

Risk zones for each land use class do not follow any pattern because the combination of weights and levels of vulnerability gives a unique risk level of identity (see table 6.3 and 6.4 in appendix 6.8.). Risk zones do not follow the premise that the higher the vulnerability and hazard level, the higher the risk. Results in this study follow a different pattern than this premise. For example, in areas of low water depths, there are areas of high risk. This means that despite the low depths, high velocity becomes an important factor for damage. For example, in areas under oil palm cultivation with low water depth, high velocity does the damage by uprooting oil palm trees and increases the risks (see plates 6.19 and 6.20 in appendix 6.1). Carrasco et al. (2013) in his prediction of inundation height using different recurrence interval obtained the following results: 1-year (2.02m), 10-year (2.39m), and 100-year (2.84m). These were classified into high, moderate, and low-risk zones based on 34m^2, 1,073m^2 and 31,821m^2 of occupied area, respectively. However, the results showed that besides houses, flood risks on other infrastructure (e.g. walkways and recreational structures) were from high velocity.

The hazard maps and risk maps generated in this study are not precisely related because high hazard does always produce high risk. This observation can also be confirmed by Christian et al. (2013). Results revealed that flood risk is spatially distributed and highly probable. The study found that flood risks were influenced by rainfall time and boundary condition level, while less variation in flood risks were due to rainfall distribution patterns, movement of rainfall and frictional coefficients.

6.7.4 Qualitative and quantitative risk assessment

Assessing flood damage does have uncertainties in stage-damage functions and there are differences in the approaches that were used to estimate the value of exposed assets (Bubeck et al., 2011). Damage in terms of economic costs are higher in 2010 for all the exposed elements than the 2014 flood event. These figures are based on estimates and they could be much higher or lower. For example, data for deaths from drowning may also be estimated or underestimated because economic costs associated with it also depended on many social and economic characteristics of the Dagi catchment. Bubeck et al. (2011) studied relative changes in the genesis of flood as it develops into inflicting damage from land use changes between 1990 and 2030, purposely to confirm the reliability of simulation. Development of flood damage differed by 1.4 factor with relative estimates due to applying various model applications. Differences in estimated absolute damage from 3.5 to 3.8 factor were small because of differences in the damage functions. Flood risks was assessed based on selected elements at risk covered by inundation in the study area. If we were to include the indirect tangible and intangible economic costs of damage (limited by time to collect them), figures will be slightly higher than those presented above. Appendixes 6.4-6.7 are data on parameters collected during the fieldwork in the study area. Furthermore, a few costs such as soil erosion and land loss were not included in the calculations because they need to be verified through further analysis and it was not possible with current time limitations.

By observing the total costs between the 2014 and 2010 flood events, it is obvious that houses and buildings alone incurred the greatest costs (34.3%) from the overall total. This is because there are so many resources in houses and buildings. Once a house or building is inundated by a flood event, these resources are also affected and the cost increases. The exposed element that incurred a lot of economic costs were oil palm in both smallholder blocks and plantations. Since this is an oil palm landscape, the economy in the catchment and the province is driven by this cash crop. Floods bring economic activities associated with oil palm to a stand-still depending on characteristics and behaviour, the extent of inundation related to velocity and depth, and consequent hazards and risks posed. It has a multiplier effect on the costs and can get out of proportion depending on the flood event at any one time.

Costs associated with deaths from drowning incidents can vary depending on circumstances by not taking heed of precautions or warning signs. It is individual oriented and can be controlled unlike other exposed elements. Shabanikiya et al. (2014) showed that crossing the flood on foot is one of the two major causes of flood-related deaths. Their study determined risk factors associated with risky behaviour of crossing the flood on foot and modelling behaviour of people when exposed to flood. Results reveal that among people between the ages of 18-35 years, those who do not take flood warnings seriously, individuals who do not have experience of exposure to flood, and those who believe they have moderate to advanced level of swimming skills, were identified as high-risk groups.

6.7.5 Risk curve and degree of risk

Management of flood risks is about embracing an approach that is based on risk where the likelihood and flood consequences produces flood risk. This study used a common approach to assess flood risk in the estimation of damage caused by floods with different recurrence intervals (exceedance probabilities). It uses this information to graph recurrence interval (exceedance probability) versus the economic loss for each element as a risk curve and was finally used in the estimation of risk using the area below the risk curve (Ward et al., 2011). Calculations using the risk curves are useful for doing a cost-benefit analysis if any mitigation measures are proposed. As an example, annual risk derived from the road curve is US$251,490.11 based on the exceedance probability of 0.008 for the 2014 flood event (figure 6.25). This implies that US$251,490.11 must be set aside annually for the catchment as an insurance for this loss. On the other hand, if mitigation measures are undertaken, this will increase the safety level and thus the area under the curve will be reduced. Thus, the reduced area has the benefit of further reducing the total annual cost from US$251,490.11 to a lesser figure for roads.

As illustrated in previous studies (e.g. ITC, 2010), to effectively take measures to prevent or reduce flood risks, mean annual risks must be correctly calculated. Should suitable protective measures be taken in the short and long term to counter floods in the Dagi catchment, and in many other oil palm landscapes, the average annual risk investment must improve. This is an important consideration for government authorities and stakeholders involved with the oil palm industry. Annual flood risk is a significant tool for guiding better decisions into the future.

6.7.6 Critical issues and study limitations

In this study, the construction of return period-loss curves was based on various presumptions on flood damage severity that contributed to uncertainties and they were: flood depth interpolation, usage of various flood damage curves, and effects of different characteristics of simulated flood events. Thorough understanding of costs will efficiently reduce flood risks. In this study, direct tangible costs received relatively large recognition with little consideration for intangible and indirect effects. These other data are valuable additions, but there is no information in the study area. Cost distributions and risk transfers, and cost assessments in decision support is the way forward in future research.

6.8 Conclusions and recommendations

This chapter has practically demonstrated the definition of flood in oil palm landscapes “as the product of flood probability” (flood hazard), “exposure” (livelihood assets including man), and “vulnerability” (flooding in Dagi) (Feyen et al., 2012: pp.47-52). To address this definition, discharges with exceedance probabilities of 0.01, 0.008, 0.007 and 0.001 were used to define the inundation extents, depth and velocity. The extent of inundation, velocity and depths that exposed livelihood assets and caused damages were converted into monetary values. This used the new PNG flood-depth functions and land use data. The assessment of flood risks demands approximates of regular impairment or harm created by floods of definite characteristics and behaviour (Boettle et al., 2011).

One important point to notice is that the monetary values were based on estimates. These values may be much higher or may be much lower “as a function of flood depth” and velocity, as well as other catchment characteristics that are not studied here (Feyen et al., 2012: p.49). Figures are prone to doubt; however, they give signals of possible subsequent progress in flood risk in a shifting environment based on population and climate (ibid.). More precise estimates require more observations (Baart et al., 2011) and this has not been the case in this study because of time constraints and lack of qualitative and quantitative data. The numbers are also a quantification of impact that can enable comparisons between places and times. They are indicators rather than exact numbers.

There are procedural issues involved when assessing flood risks. First is the lack of data because extreme flood events are rarely documented and therefore historical data is scarce. This reduces the ability to develop suitable flood risk management models for oil palm landscapes. Secondly, establishing standard procedures to archive current damage data greatly assists fabrication of experimental damage functions (Blaikie et al., 2014). Regardless, sources of interdependent information on flood hazards and asset vulnerability factors are compulsory for modelling damages (ibid.). Finally, the use of many methods, integration of insurance information with land use elements is a subject for future research (ibid.).

From this study, it is obvious that future studies must investigate the following:

1. Include all costs involved. This will involve investigating cost distributions, risk transfers and how costs can be effectively used as a decision support.
2. The use of multivariate approaches, integration of insurance data with land use elements is a subject for future research.

The degree of risks generated in this chapter will be used as a guide in the last chapter to propose options for flood disaster planning, hazard and risk mitigation in oil palm landscapes. These data are useful because they will help the economies that are dependent on oil palm agriculture for their sustenance. Therefore, the last chapter is a discussion of the findings from the overall research. It draws conclusions from this research compared with other similar work. Based on these research findings, options are investigated.

Chapter 7.0: General discussions, conclusions and recommendations

7.1 Introduction

This chapter integrates all findings from the study. An oil-palm dominated landscape in PNG was used as a case study of flood risks on livelihood assets at a catchment and sub-catchment scale. The discussion, conclusions and recommendations in this chapter are based on data chapters 4, 5 and 6 which followed the procedures shown in figure 7.1. Chapter 4 used fieldwork data and hydrological models to determine flood characteristics and behaviour. Water depths, velocity and duration were observed during two wet seasons in 2014 and 2010. Flood discharges in terms of peak and magnitude were analysed using rainfall data that were simulated using HEC-HMS. The results were shown in hydrographs and presented in graphs and tables at the sub-catchment level.

Chapter 5 used SOBEK 1D/2D, HEC-RAS Beta 5.0, HEC-RAS 4.1 and HEC-GeoRAS modelling software within an ArcGIS 10.2 environment to model and visualise inundation and hazards. Modelling and visualisation of inundation and hazards were based on flood depth and velocity. It determined the spatial extent of inundation and the stream power available for further damage. The results were reported in maps, tables and graphs showing the spatial distribution of the inundation extents based on depth and velocity in 1D and 2D channels. Maps were produced showing flood hazard distributions.

Chapter 6 identified the livelihood assets at risk and their vulnerabilities. It investigated the elements at risk from the 2014 and 2010 floods. Based on flood hazard and vulnerability assessments, exposed elements based on land use and population were identified. Risk assessment was undertaken following a risk-oriented approach. Firstly, it determined the flood hazard based on inundation depth and velocity; secondly the exposure of land use; thirdly the economic value of livelihood assets at risk and; lastly the vulnerability of livelihood assets at risk to water depth and velocity using depth-damage curves. It assessed flood hazards, vulnerability and risks following both qualitative and quantitative approaches. Risk curves for this oil-palm dominated landscape were generated. Results were presented as maps, tables and graphs.

In relation to chapters 4, 5 and 6, this chapter evaluates the relative roles population, land use and livelihood assets play in affecting exposure and potential river flood risk. It also investigates how damage caused by floods contributes to increasing losses on livelihood assets. Finally, by using this information, this chapter goes on to investigate management options for flood disaster planning, hazard and risk mitigation in oil-palm dominated landscapes and across different sectors.

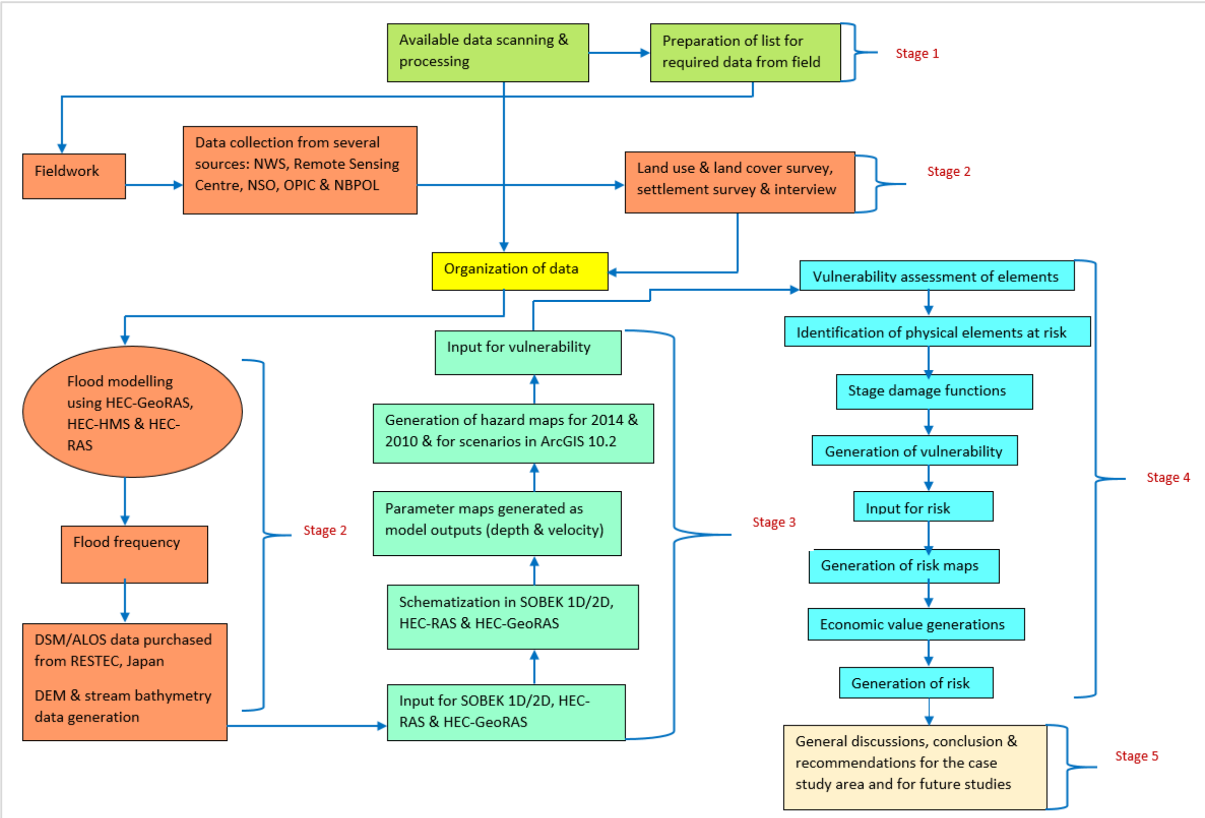


Figure 7.1: Overall procedures followed in this research.

7.2 Role of population, land use and livelihood assets on flood exposure and potential risks

Riverine flood risk is a product of both physical and human geographical activities. Close observations are required of the roles played by population, land use and livelihood assets in affecting exposure and potential flood risks. The livelihood assets at risk in this study are interpreted as the degree of subjection of people, agriculture, economic pursuit, infrastructures, public services and utilities to the impacts of a hazard, such as riverine flood (Nott, 2006). Vulnerability is determined by the extent of deprivation of a certain livelihood asset at risk at a particular degree of intensity (Wigati, 2008). In turn, it is moulded by actions which increase the sensitivity of people to physical, social, economic or environmental losses in future (UNISDR, 2006; ITC, 2010). These constituents of vulnerability were merged to ascertain comprehensive vulnerability to riverine flood (Karmakar et al., 2010). The exposure of population, land use and cover, and livelihood assets were also appraised to encompass their consequence on the extremity of floods (ibid.). To understand flood risks over space and time, data on flood probability, vulnerability, and exposure of livelihood assets were used (ibid.).

7.2.1 Oil palm dominated land use and rural livelihoods

The rural economy is dominated by oil palm in more than 55,000 hectares planted with 7,700 people in formal employment, and an annual turnover of K640 million (AUD$300m) as per the 2007 world market price (Integrated Traceability Solution - ITS GLOBAL: 2011; Curry and Koczberski, 2012). It is an important cash crop being identified as an appropriate vehicle for an investment project to improve rural livelihoods (Koczberski et al., 2009). New Britain Palm Oil Limited (NBPOL), the majority owned (58%) subsidiary of Kulim Berhad Limited of Malaysia Oil Palm, cultivates and manages palms on plantations (ibid.). On small blocks of land, oil palm is cultivated by people from all over PNG referred to as "smallholder oil palm blocks". NBPOL owns 60% of the total oil palm grown in the Dagi catchment while 40% are owned on blocks by smallholder growers.

Smallholder oil palm growers fall into three groups (figure 7.1): (1) on small blocks of land established in the late 60s and early 70s under the land settlement schemes (LSS), (2) on blocks of land bought by settlers from traditional landowners known as the customary rights purchase (CRP), and (3) on land owned by traditional owners known as village oil palm (VOP) (Webb et al., 2011). When the oil palm industry grew, the company purchased customary lands to develop new plantations. Also, families living near the nucleus estate started planting oil palm and this has increased in the past 20 years when cocoa and copra declined in their world market prices (Curry and Koczberski, 2012). VOP growers have their traditional livelihood intact still engaged in the subsistence economy.

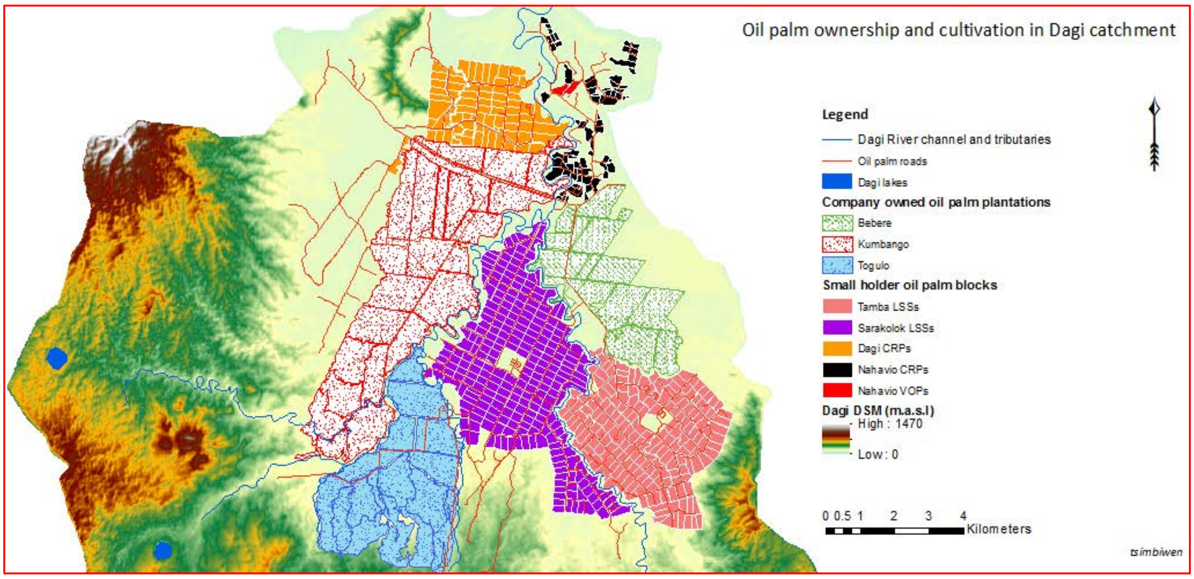


Figure 7.2: Categories of oil palm growers.

7.2.2 Changes in population and oil palm productivity in LSS

The total population in 2011 for Dagi was 36,380 persons with 6,139 households (PNG NSO, 2013). This population constitutes 13.8% of the provincial total (see figure 7.2 in appendix 7.1). In the Dagi catchment, population has grown over the years and is continuing at an annual rate of 3.92% (ibid.). With favourable prices for palm oil due to global demand for food security, more uncultivated land is cleared and planted with new crops. New settlements are built, and people have been settling along the flood plains. In many studies that were conducted in urban areas of the world, these have been the major cause of increasing losses from floods (Droogers and Aerts, 2004; Botzen et al., 2010, Klijn et al., 2012). Floods instigated by climate change will cause increasing losses as population and livelihood assets increase (Messerli, 2006; Gersonius et al., 2008; Hartmann, 2011; George, 2012). Furthermore, accurate risk evaluation requires knowledge of the specific location of livelihood assets. Bouwer et al. (2010) showed that flood casualties decreased despite population growth when the location of the exposed population was known. Cammerer et al. (2013) projected increases in global flood risk and damages in the next 30-50 years. The projected losses were due to increases in population, settlements, industrial complexes and assets accumulation in floodplains (ibid.).

Population density has increased from 5.9 persons in the 1970s to 13.3 persons and in 2000 it was 18 people per smallholder oil palm block since the establishment of the LSS (Curry and Koczberski, 2012). Rapid population growth based on PNG NSO (2013) data showed an average growth from 2000 to 2011 of 3.92%. This has led to considerable social (e.g. customary obligations) and economic pressures (e.g. meeting all the costs of an increased number of people living on the same block), particularly when oil palm prices were low. Population growth is now becoming a critical factor since economic and population pressures are emerging because of these LSS (Koczberski et al., 2001). The average number of persons per smallholder oil palm block has more than doubled between 1968 and 2015 when the sons and daughters of the original settler marry and have children and continue to live in the oil palm block (ibid.). Increase in the total number of people in a block and households (table 7.1) shows that returning to their home province is difficult because through time the ties with their relatives in the original village had weakened (ibid.). There are several families with many households sharing all the resources on a block and this creates economic pressure when income from oil palm is divided among them (ibid.).

Table 7.1: Mean populations and numbers of households per LSS block, Hoskins, 2000 (Koczberski et al., 2012: p.330).

LSS Sub-division	Year Established	Mean Population Per Oil Palm Block*	Mean Number of Households Per Block
Kapore	1968	11.5	2.5
Tamba	1968	17.4	3.9
Sarakolok	1969	9.8	1.8
Kavui	1972	17.2	4
Siki	1982	11.4	2.6
Total		13.3	2.9

**A block in LSS subdivisions has on average between 6-8 people per block (Koczberski et al., 2001).*

This problem is made worse by declining soil fertility due to continuous use over the years that leads to reduced income. Webb et al., (2011) found instances of widespread reduction in soil nutrients in many smallholder oil palm blocks in PNG. Thus, yields and smallholder incomes are often low (ibid.). Each family in blocks needs money for health, education, food and other needs and this creates conflict and instability (Koczberski et al., 2001).

7.2.3 Livelihood strategies

In response to socioeconomic pressure from the existing oil palm blocks, smallholders pursue new strategies to sustain their livelihood such as going into subsistence gardening, poultry, piggery and trade store businesses (ibid.) (figure 7.3). Koczberski et al., (2012: p.290) defined "livelihood strategies are defined as those activities undertaken by smallholder households to provide a means of living".

People who have access to employment outside their blocks have a better material standard of living than those blocks without a wage earner. Their houses are permanent, have tanks for water and white goods financed from their savings from the off-block employment (Koczberski et al., 2001). In highly populated blocks, income from off-block employment supports family members who are unemployed and living on the same block. Smallholders work in oil palm plantation estates as casuals or permanent employees and provides financial relief to meet demands such as paying school fees, bride prices and other family obligations. Only a minority with professional skills such as accountants or teachers work in non-agricultural wage labour. Some with trade skills work in workshops or in managerial positions with New Britain Oil Palm Limited.

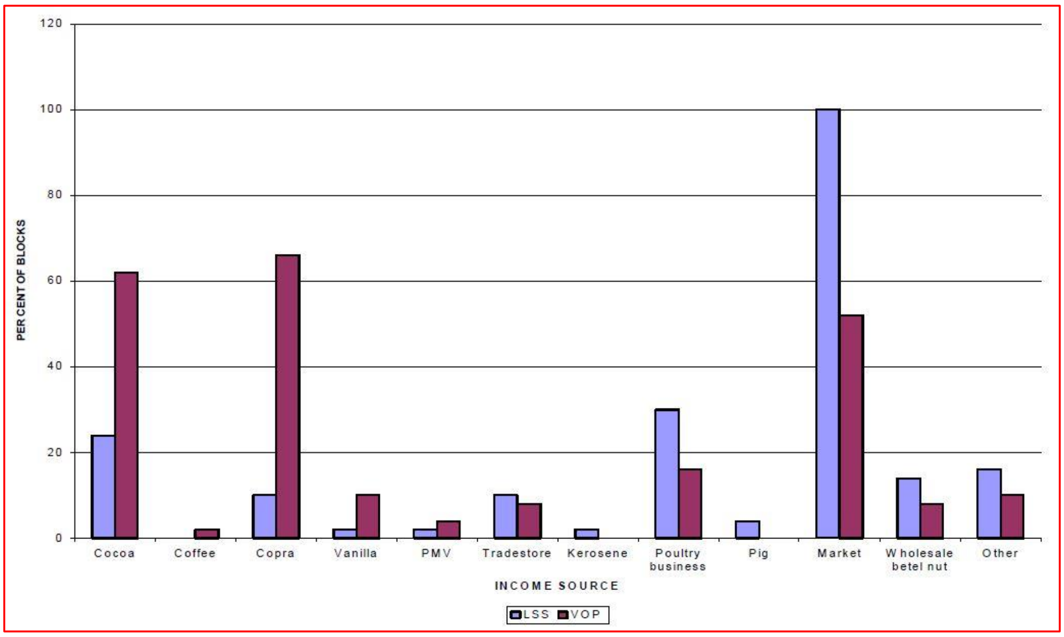


Figure 7.3: Hoskins smallholder non-oil palm income sources (*Koczberski et al., 2001).*

Some smallholders who have saved sufficient money buy new customary land to cultivate oil palm (CRP blocks) while others buy other oil palm blocks (LSS or CRPs) that are up for sale and resettle with their families to start a new life (Koczberski and Curry, 2005). The prices of blocks in LSS centres are shown in table 7.2 in appendix 7.2 and they ranged between K15, 000 and K35,000, however, the price has increased since 2000 to as much as K185,000. Many smallholders in the LSS supplement their income from the sale of oil palm by doing a range of activities to generate income (figures 7.3 and 7.4). Subsistence gardening is the most common type with a range of crops grown and sold in local markets (figure 7.5). Most of these crops are grown in riparian zones that would otherwise act as flood buffers. In blocks with many family members, houses are often built in the riparian buffer zones, to have more "space" away from other, more crowded locations (see figures 6.20 and 6.21). Such livelihood strategies are for economic security and social stability and may not be sustainable within the Dagi River catchment (ibid.). This practice is environmentally unsustainable because it leads to the removal of riparian vegetation and reduces its function as a buffer against flood impact such as soil erosion.

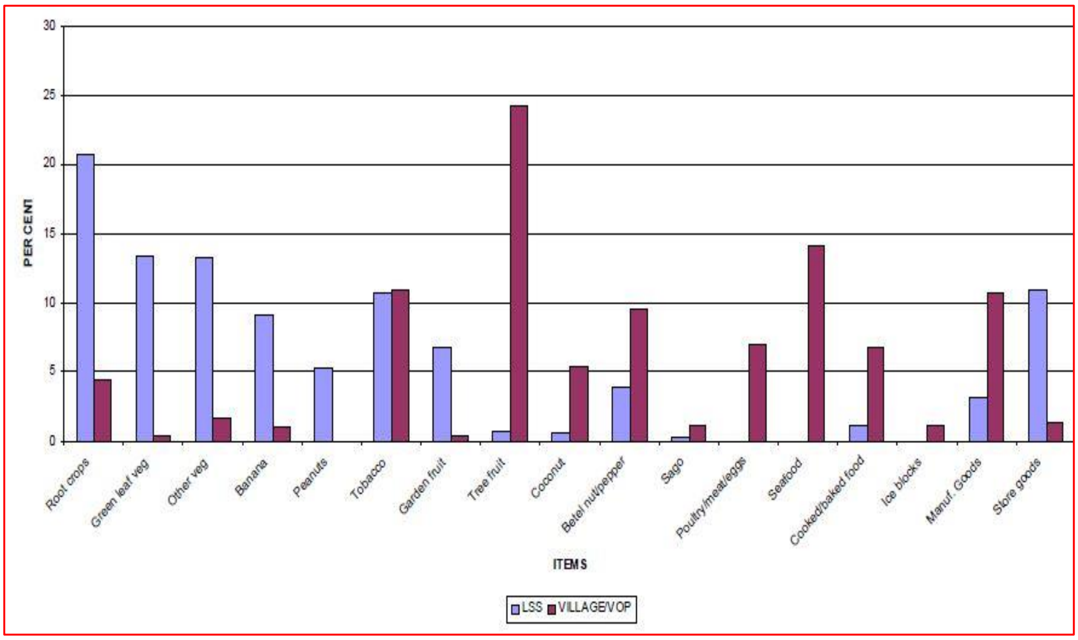


Figure 7.4: Different group of items sold at the market by women from LSS and VOPs (*Koczberski et al., 2001).*

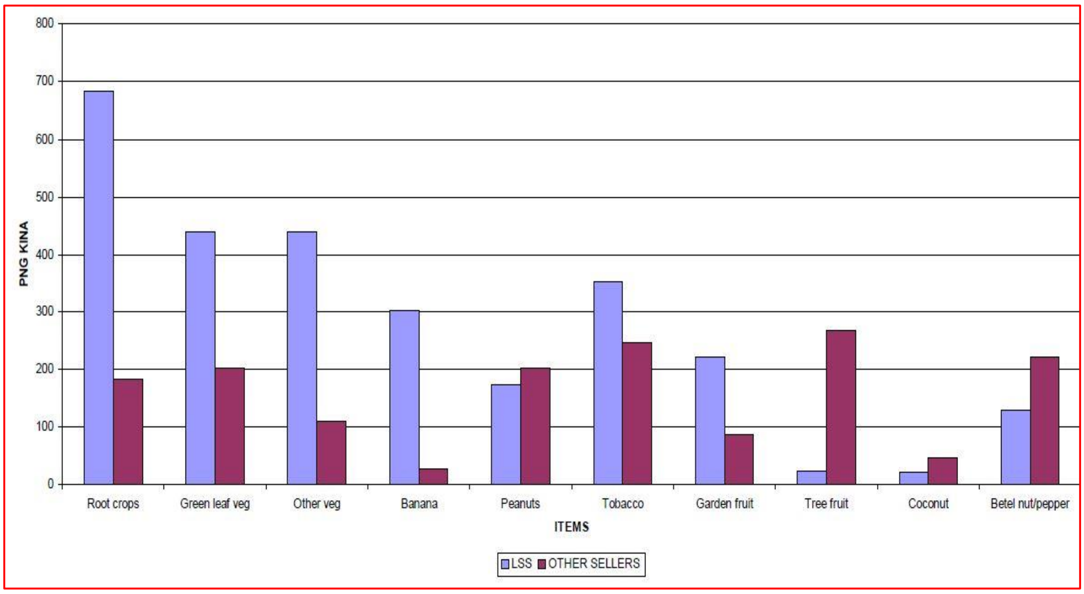


Figure 7.5: Values of different garden produce sold at the local markets (*Oil Palm Industry Corporation (OPIC) files).*

7.2.4 Floods and livelihood assets in the Dagi catchment

High peak discharge that constitutes its natural flow conditions is not a natural disaster in the Dagi River catchment (Adebayo and Jegede, 2010). However, flood disasters are to a degree man-made as they occur where and when settlers put themselves at risk by developing and occupying flood-exposed areas in the catchment. Faced with social and economic pressures from within their smallholder blocks and left with limited alternative options for seeking a livelihood, settlers and their children develop, occupy and cultivate the remaining 2 hectares of land along its floodplains. Settlers make one of four choices: 1. plant more oil palm trees to boost production, and eventually increase their incomes (figure 7.6 and table 7.3, figure 7.7); 2. cultivate food and cash crops to be sold at the local markets (figure 7.5); 3. build new houses to settle along the floodplains, or 4. a combination of the first three options. Because there are limited alternatives for many settlers to make a living, flood risks are often ignored. These livelihood strategies also increase the exposure of their livelihood assets to annual floods, and thus they are more vulnerable to floods in the catchment.

Crop	Annual Growth rate (%)*	
	Smallholder	Plantation/estate
Palm Oil (fresh fruit bunch)	4.3	8.3
Cocoa	2.7	-4.1
Coffee	2.0	-2.9
Rubber	3.2	-3.3

Source: Bourke and Harwood (2009)
*Calculations are based on the growth rate from 1986 to 2005 The 1986 figure is a mean for the three-year period 1985–1987; likewise, the 2005 figure is a mean for the period 2004–2006 For rubber, the period is 1986–2000 (1999–2001)

Figure 7.6: Oil palm volume growth rates compared with cocoa, coffee and rubber in PNG, 1986–2005.

Table 7.3: Total hectares of oil palm in smallholder blocks for 1998 and 2000 *(PNG OPRA, 2001).*

Project	1998 Smallholder Oil Palm (hectares)	2000 Smallholder Oil Palm (hectares)
Hoskins	11,180	16,148
Bialla	9,279	11,250
Popondetta	9,931	13,000
Milne Bay	1,060	1,338
New Ireland	975	1,285
TOTAL	32,425	43,021

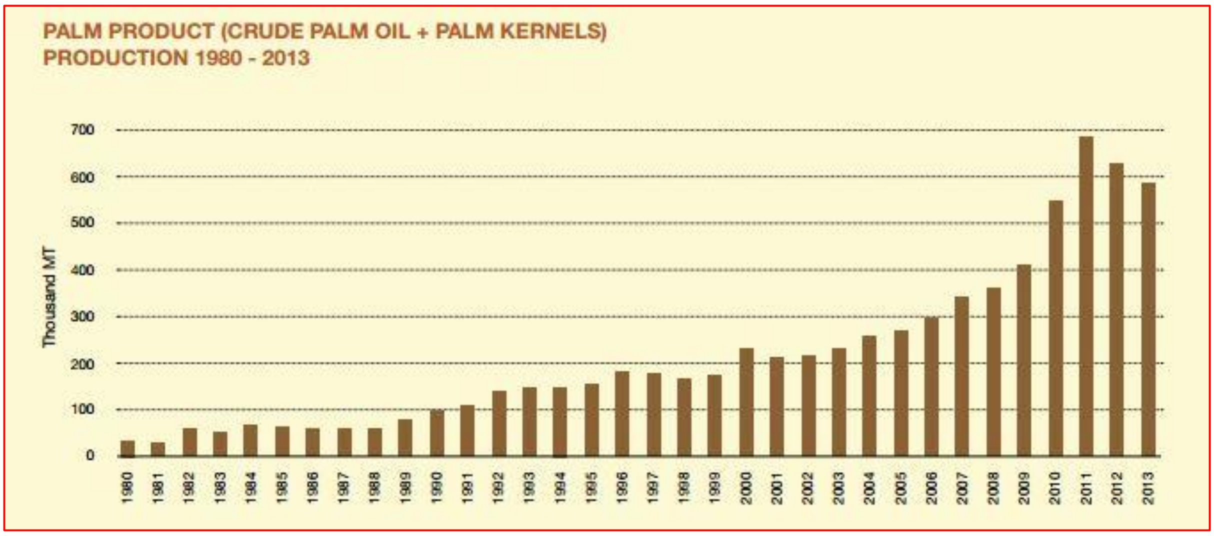


Figure 7.7: Palm oil production in thousand metric tonnes from 1980 – 2013 for Hoskins Project (NBPOL Annual Report, 2014).

7.2.5 Oil palm dominated agriculture and their effects on hydrology and stream hydraulics

People have exercised some influence on the hydrological cycle through the way they have used the land through oil palm agriculture, subsistence gardening and settlements. It is well documented in the literature that as land use increases, it further exacerbates floods through the alteration of both the catchment, network and channel characteristics (Valentin et al., 2008; Bubeck et al., 2010; Hartmann, 2011). Large change in rural vegetation and land use have taken place in the tropics since the last century (Efiong, 2011). These changes have been due to an increase in population and a cash economy introduced through oil palm exports (Webb et al., 2011; Sayer et al., 2012). Besides, people need land to cultivate food and commercial crops and the increase in human population in many parts of the tropics means increased pressure on land, and the conversion of forest to plantation and subsistence agriculture. Agricultural developments contribute to flooding mainly through the removal of the native vegetative cover and replacing it with non-native cash crops. Studies have found that this disturbs the natural hydrological processes of interception, evapotranspiration and infiltration among others (Nelson et al., 2006; Basiron, 2007; Gemma et al., 2008; Murom et al., 2008, Webb et al., 2010).

Forest cover protects the soil against raindrop impact and encourages infiltration so that soil erosion is reduced and the stream flow is regulated, as flood peaks are reduced while dry period flows may be slightly increased (Nelson et al., 2006; Murom et al., 2008). The opposite happens when vegetative cover is removed and replaced by oil palm, with less foliage. An area of land with little vegetative cover would generate more runoff than an area with a good vegetation cover (e.g. Nik, 1988). Many studies have shown that land use alteration of land cover influences the interception process to a greater extent, and aids in the development of distinctive flood characteristics and their behaviours (Fruchtman et al., 2012; Vicente et al., 2012; Erskine et al., 2013; Montgomery, 2013) and the spatial inundation extent (Li et al., 2012). Removal of tree cover also leads to the exclusion of interception loss, stem flow, and through fall components of the interception process and enables free fall of rainfall on exposed surfaces that becomes overland flow into waterways (Zhang et al., 2012; Deshmukh, 2013).

Runoff characteristics are also influenced by the evapotranspiration processes through water loss enhanced by the onset of agricultural land use and climate change (Deshmukh, 2013) and by the availability of surplus soil moisture for runoff (Chaplot, 2013). Also, a forest transpires a lot of water and because of their deep root systems trees can tap water at considerable depths, especially during the dry season (Nik, 1988). Because of this the water yield from a forested catchment is often less than that under oil palm (Hamilton and King, 1983; Nik, 1988; Foley et al., 2005; Brown et al., 2005). When forest is cleared for oil palm there is a reduction in evapotranspiration which may cause the water table to rise. During heavy rainfall, this has led to overland flows and increased stream discharge and may cause floods (Nik, 1988; Brown et al., 2005). However, this may not always be the case. For example, oil palm requires a lot of water to grow. Little is known at this stage how much water oil palm absorbs and transpires according to its maturity, although attempts have been made on these questions (Nelson et al., 2006; Murom et al., 2008).

Riparian vegetation plays important roles in flood protection as reported by Rutherfurd et al. (2007). Firstly, they exist in cross-section (e.g. submerged reeds and wood) and interact by coming into contact with water and affecting all flows (ibid.). From stream banks, plants are adapted to little inundation. Here we can see a transition of plants from hydrophytes to grass to bushes and trees at the stream bank. Beyond stream banks, plants interrelate only with annual floods. In the 1980s and early 1990s I observed sufficient riparian vegetation beside the river and streams. The stream shape and size were in its natural form. I re-visited the catchment in 2007 and noticed significant morphological changes to the cross-sections of most reaches of the Dagi channels because of a large decline in primary vegetative cover. Rutherfurd et al., 2007) identified three effects of the removal of riparian vegetation: (i) disturbing the shape and size of the stream channel, (ii) shifting the amount of water reaching the stream channel, and (iii) varying the resistance to flow. When plants (including large woody pieces) have been ousted from stream channels, there are several instances of extensive vicissitudes in channel configuration (ibid.).

Consequently, in certain areas of the Dagi catchment where most riparian vegetation has been removed, there was little resistance and thus more water flow directly into stream channels (ibid.). Even flows in channels flow freely with little or no resistance from riparian vegetation. The stream shape has broadened in most channels formerly seen as v-shaped and at the same time channel sizes have expanded. Obviously, the clearance of riparian vegetation in the Dagi has re-defined the natural bankfull stage through many channel incisions. This has resulted in bed widening and extension of the drainage network by gullying in most parts of the catchment. Channel storage capacity has decreased as sediments accumulated and large discharge flows easily across most banks. There used to be large tree trunks in most stream channels of the Dagi but today they are absent. Similar changes have been reported in north Australia by Montgomery and Piegay (2003) and Rutherfurd et al. (2007).

I observed several changes in the channel form of the Dagi catchment in 2007. Firstly, water flows freely and fast downstream due to the absence of steps in the longitudinal profile and the shapes seem similar to those reported by Keller and Swanson (1979), Harmon et al., (1987), Marston (1982), Webb and Erskine (2003), and Rutherfurd et al. (2007). Secondly, sediment stockpile in watercourse and scour has dwindled and similar instances were reported in Harmon et al. (1987), Webb and Erskine (2003) and Rutherfurd et al. (2007). Thirdly, evolution of bars and benches have been underpinned as outlined in Malanson and Butler (1990), Webb and Erskine (2001) and Rutherfurd et al. (2007). Fourthly, bedload transport is not regulated similar to the findings of Beschta (1979), Fetherston et al. (1995) and Rutherfurd et al. (2007). Fifth, the absence of localised scour similar to that reported in Abbe and Montgomery (1996) and Marsh et al. (2001) and Rutherfurd et al. (2007). Sixth, decline in pools and riffles as outlined in Buffington et al. (2002), Marsh et al. (1999), Robison and Beschta (1990), Webb and Erskine (2003) and Rutherfurd et al. (2007). Finally, there was reduced overbank settlement of fine sediments (Gurnell and Gregory, 1981; Rutherfurd et al., 2007) along the Dagi floodplains.

Prior to oil palm development in Dagi catchment, flood velocity and depth were controlled by natural vegetation in these ways: 1. they occupied space directly in channel cross-sections and reduced capacity, 2. through vibration they used up energy in the flow, and 3. they reduced velocity by blocking the flow (Rutherfurd et al., 2007). Vegetation provides four scales of hydraulic effect: 1. from a single plant and a group of small plants (local backwater effect), then 2. from many plant communities at a given cross-section (combined backwater effects), then 3. from many plants in many cross-sections at a given reach (combined backwater effects), and finally result in 4. reducing the flood wave power as it continues to traverse the complete watershed (figure 2.6) (ibid.).

In addition, the removal of riparian vegetation upstream in the Dagi catchment has not allowed for enough blockage of flow and as a result velocity has generally increased downstream. Unlike before, water is readily available for runoff and flows in the Dagi are unrestricted across most stream cross-sections. Furthermore, Abernethy and Rutherford (1998) and Rutherfurd et al. (2007) described the normal outcome was for the roughness to lessen as the stream bed is submerged, then the roughness attains a peak as the grass and canopies traverse the flow. However, if stream slope is small (e.g. 0-5^{o}), the roughness effect of vegetation will be large. Consequently, when riparian vegetation is removed from streams, these processes are altered or removed. Water becomes readily available for runoff and flow becomes unrestricted across the stream cross-sections. In times of heavy rainfall, this exacerbates flood stages and may possibly inundate surrounding landscapes and increase the exposure of settlements to flood risks. This has been the case in the Philippines, when upland logging, followed by the cultivation of rice and other arable crops in riparian zones, increased overland flows and flooding resulted in the loss of livelihood assets for downstream communities (*Terra Daily*, 1st December 2004).

The main difference between the Dagi catchment in WNB (PNG), northern Australia and West African catchments is in the amount of rainfall received annually that drives the hydrological cycle. Dagi receives >4000mm (PNG NWS, 2014), northern Australia around Cairns receives 2000mm (Bureau of Meteorology, 2015) and Abia, Nigeria, receives 2193 mm rainfall (World Meteorological Organisation, 2016). The amount of rainfall received means the hydrological situations are different in each setting. When rainfall is combined with each local slope, soil type, land cover and land use influence on catchment, network and network characteristics will generate different flood characteristics and behaviour.

7.2.6 Past, present and outlook of flood risks in an oil palm dominated landscape

Increases in rainfall, together with variations to the catchment, network and channel characteristics, and the development and occupation of floodplains, increases flood risks to livelihood assets (Booij, 2005; Botzen and Van Den Bergh, 2009; Box, 2009; Steyaert et al., 2011). Such conditions and activities make livelihood assets within the catchment more vulnerable to floods. This has happened in the 2014 and 2010 flood events when high seasonal river discharges and bank overflows inundated the flood plain where many people are settled. Time series data on discharge characteristics and behaviour and the extent of inundation, and the levels of exposure to floods are very limited. However, some data on these events collected during the fieldwork are collated in table 7.4 and figure 7.8. During the fieldwork, I interviewed 28 people at Sarakolok LSS and 30 people at Nahavio DPI Station to get their perceptions on flood experiences in Dagi. 68% out of the 28 respondents from Sarakolok LSS, and 87% out of the 30 respondents from Nahavio DPI Station said there had been increased incidences of flooding affecting their livelihoods unlike before (table 7.4). I also interviewed people upstream and downstream along the Dagi River during the fieldwork to seek people's views on the exposure of livelihood assets, human and environmental health to flood risks. Their responses were quantified by estimating the economic costs associated with smallholder oil palm blocks and company owned oil palm plantations (figure 7.8). Upstream, there were 70 people interviewed in smallholder blocks while 60 people were interviewed in company plantations. Downstream, 180 people were interviewed in smallholder blocks while in company plantations, 65 people were interviewed. The results showed great contrasts upstream and downstream. More than 60% living downstream on smallholder blocks and company plantations believe that they are more exposed to flood risks whereas upstream the figures were less. For both sites, more than 50% agree that there is increased incidence of floods, waterborne diseases and disruption of transport access and communication. Overall estimated costs were much higher downstream than upstream.

Table 7.4: Perceptions of people's experiences in relation to flooding in Dagi catchment.

Flood Risks	Sarakolok LSS *(n*= 28) %***	Nahavio DPI Station *(n = 30) %*
Loss of access to cropland during wet season	0	53
Water pollution and loss of access to safe drinking water	43	70
Loss of primary cropland	29	10
Displacement/resettlement	11	0
Increased incidence of floods	64	87
Disruption to transport -access to urban areas	46	7

n refers to the number of people interviewed, while% refers to the number of people out of the total interviewed (X 100) who confirm the occurrence of each of the flood hazards over the years from personal experience (fieldwork interviews, 2014).*

There are few mitigation procedures put in place in a rural catchment like the Dagi to reduce flood hazards in terms of casualties, loss of livelihood assets and the associated economic costs. It was for that reason that this assessment of flood risks and vulnerability of livelihood assets was carried out to quantify their levels of exposure, and impacts in this oil-palm dominated landscape. These results were presented in chapters 4, 5 and 6 and further discussed in this chapter.

Flood Risks	SHBU[1] (n*=70) %**	COPU[2] (n=60) %	SHBD[3] (n=180) %	COPD[4] (n=65) %	OVERALL ESTIMATED MONETARY COSTS*** (PGK 000s)	OVERALL ESTIMATED USD 000'S (1PGK = 0.34090 USD)
Loss of access to cropland	34	36	89	75	150	51.135
Water pollution/loss of access to safe drinking water	77	45	86	68	100	34.09
Loss of primary subsistence gardens	53	55	85	75	500	170.45
Increased property damage	65	75	87	74	1000	340.9
Displacement/resettlement	48	22	90	17	1000	340.9
Increased floodplain sediment	33	24	85	81	300	102.27
Increased water-borne diseases	56	57	74	68	300	102.27
Increased incidence of floods	85	87	95	92	500	170.45
Disruption to transport/access to town/communication	83	85	91	88	2000	681.8
				TOTAL	**5, 850**	**1, 994.26**

n* refers to the total number of people (elderly/middle aged and both males and females) interviewed.
%** refers to the percentage (number of respondents divided by the total number of respondents interviewed) sample population who agrees with the risks posed by annual flooding events.
[1] refers to the abbreviation for small holder oil palm blocks upstream.
[2] refers to the abbreviation for company owned plantations upstream.
[3] refers to the abbreviation for small holder oil palm blocks downstream.
[4] refers to the abbreviation for company owned plantations downstream.
***refers to the overall total estimated costs of risks and losses from 2000-2014 for all upstream and downstream sites.
PGK refers to the abbreviation for Papua New Guinea Kina, which is the national currency. USD refers to the United States Dollar at 23/09/15 exchange rate.

Figure 7.8: Other exposed elements, their risks and the monetary costs (*fieldwork interviews, 2014).*

Flood related issues faced by rural communities engaged in agriculture will become worse in future if climate change happens according to current projections. Feyen et al. (2012) evaluated the ramifications of climate change for SRES A2 (high emission) and B2 (low emission) scenarios for future flood risk in Europe. They used discharges recurrence intervals of 2, 5, 10, 20, 50, 100, 250 and 500 years to predict damages. The projected results indicated that flood damage will rise in many parts of Western Europe and incur between EU14-21.5 billion. The estimated number of people likely to be affected by floods will be 250,000-400,000. Flood damage in all landscapes will increase and threaten rural livelihoods and the likely damage has not been quantified in much detail yet. However, damage will vary depending on how far people live from a river, the type of building structures and their heights, and the land use type of properties situated in floodplains (Ghanbarpour et al., 2014).

7.3 Implications for flood disaster planning, hazard and risk mitigation across sectors

Based on results and experiences, flood disaster planning must be done by relevant government and private sector authorities to mitigate hazards and risks in areas like the Dagi that do not have this in place. Flood impacts on oil palm agriculture will also impact other sectors and collaboration is important for the economy. As a way forward, some suggestions for flood disaster planning, hazard and risk mitigation are outlined.

7.3.1 Management options for flood disaster, hazard and risk planning across sectors

As can be seen in this study, flood risks on livelihood assets are full of uncertainties and these limit effective planning for flood risk and disaster reduction. More improvements to the methodologies are needed before reliable estimates of flood risks and impacts are obtained. It involves involving various interested parties in a scheme that develops research to investigate long-term effects of flood hazards and build local stakeholder capacity to make decisions despite uncertainties (Prabhakar et al., 2009). This requires starting a dialogue to understand the big picture of reducing long-term risks at a local scale (Schelfault et al., 2011). There were restrictions of strategic thinking at the national level and regional planning to date needs to be inculcated in local level disaster risk reduction and policies (Meyer, 2013). The greatest need is to leap from seeing locals as just mere implementers to being innovators so that self-learning would evolve into tangible results (Ciavola et al., 2012).

Prevention of floods is impossible; however, we can reduce its impacts and vulnerability in risk prone areas (ibid.). Instead of structural defence, deploying a risk-based management approach using diverse measures can minimise the economic and social drivers and improve the governance of flood risks (ibid.). There is a need for greater preparedness than ever in the Dagi catchment, and the results and experiences shared here may also be true for other oil-palm dominated landscapes. More emphasis must be placed on pre-disaster planning motivated by social learning processes (ibid.). Similarly, planning on flood risk calculations is important. Setting up maximum safety standards based on the calculated flood risks is a way forward, and this was investigated by Mertens et al. (2011). Developing effective approaches to estimate the costs linked to flood hazards is also a way forward (ibid.). Three components of resilience concerning any disaster usually interplay and they are institutional interplay, flood management tools, and risk communications (Ciavola et al., 2012). Addressing these effectively will be a positive step taken before flood resilience and management can be effective.

During a planning exercise, it is better to identify roads with low flood immunity and reconstruct them by increasing their heights. This must be done in reference to the annual exceedance probability that inundates the roads. This will provide alternative evacuation and emergency response routes during floods. Proposals based on best management practices, principles and guidelines must be the case for the medium, high and very high risk areas that enhance local ecological and hydrological values, and at the same time strengthening economic activities to sustain rural livelihoods (Carrasco et al., 2013). In Dagi and other rural communities in PNG and elsewhere, people do not have the luxury of a car, and prefer taking shortcuts to their destinations by crossing flooded rivers and tributaries on foot with the confidence that they are expert swimmers. These have been one of the major causes of drowning incidents and fatalities from high velocity currents. Therefore, appropriate group training programs must be set up for communities to reduce risky behaviour of crossing a flood on foot. Furthermore, flood zoning and land use regulation, flood insurance programs, and structural measures of levee construction or tree buffers are ideal options for an effective management of flood risks in the Dagi River catchment. These must also be the agenda priorities for effective collaboration for all stakeholders in government, donor agencies, private sector and local communities.

Measures to implement mitigation of risks must be feasible both socially and economically (table 7.5) (Ciavola et al., 2012). At the same time preparedness must be very effective in terms of costs after the overall costs of a flood disaster are added (ibid.). Sustainable adaptation measures usually require minimisation of the costs of floodplain protection measures while maintaining floodplain resilience (ibid.). To fulfil these requirements, the application of costs and benefits are appropriate (ibid.). Thus, estimations of total damages caused by floods using an appropriate method is essential for decision-making processes and management in flood plain communities (ibid.). Outlined below are various mitigation measures with consideration for costs and best practices for cost assessments.

7.3.2 Risk mitigation measures

Like many parts of PNG, no building codes are enforced in the Dagi. People build houses according to their traditional, semi-permanent or permanent housing designs. The current study has attempted to assist risk reduction planning by mapping flood risk and vulnerable areas. These data will greatly assist in planning for future land use planning against floods. An example is when the risk and vulnerable areas may be used to restrict further floodplain occupation and development by increasing the widths away from the floodplain. The distance between the banks and the extended width can allow protection measures like replanting native tree species back in riparian buffer zones. Awareness to prevent people from making gardens, planting oil palm or building houses will ensure that it performs its function as a flood buffer. However, in theory, it sounds good but a real challenge remains in Dagi under the current socioeconomic situation. This was a derived function of population density, livelihood strategies and risk probabilities. In some instances, people may prefer hard structures like flood walls, intrusion barriers, or levee construction but it is costly and permission must be sought from block owners for them to give away fertile land for such purposes. Soft structures such as riparian buffers are possible but it is not easy to convince individual block owners along waterways. With these challenges, the way forward is for the establishment of a risk governance system to responsibly enforce communal adaptation means, while further motivations are desired to fortify adjustment of people (ibid.). The other option is for quasi-real time warning measures for capable jurisdictions that allow for the enforcement of appropriate emergency measures in case of floods (ibid.). Trained manpower is lacking and the costs of setting up and running warning systems are some of the challenges to be addressed collectively (ibid.).

There are many measures to protect livelihood assets against floods and the risk of floods. Physical infrastructure and options to mitigate risks are grouped into hard and soft options (ibid.). Table 7.5 shows these options for managers to take and the challenges which may or may not be possible to achieve in Dagi.

Table 7.5: Hard and soft flood risk mitigation options (Ciavola et al., 2012: p.22).

Option	Protect (effort to use of vulnerable areas)	Accommodate (effort to continue living in vulnerable areas by adjusting living and working habits)	Retreat (effort to abandon vulnerable areas)	Likelihood of implementation in Dagi Catchment
Hard	Flood walls, floodwater intrusion barriers, levee construction.	1. Adapting to drainage/flow routes.	1. Relocate threatened buildings.	1. Difficult/not possible, permission need to be sought from block holders - many will not agree.
Soft	Flood plain restoration, e.g. creation of riparian buffers.	1. New building codes to ensure people build houses with long and strong posts to withstand maximum water depth and velocity. 2. Growing flood resistant crops like edible ferns. 3. Early warning and evacuation systems.4, Risk-based-hazard insurance.	1. Land use restriction. 2. Set-back zones (people must agree to move to safer areas).	1.Possible, but needs greater awareness to convince people to move despite current socioeconomic conditions, otherwise people are prepared to take risks*

**Risk communication was given in advance by the NDC and WNB provincial government, but was not taken heed of. Warnings were also issued to some Highlands people in lower Dagi not to build houses, however, these were ignored because of no alternative options to move to. During the 2010 floods, they were affected, however, disaster officials hesitated to provide relief in response to these neglects. Financial incentives were later given after reminding them to vacate risk prone areas. When I visited in 2014, they were still living there!*

7.3.3 Cost considerations and best practices for cost assessments

This study used the stage-damage function approach and the reliability of the costs depended on this method. Table 7.6 summarises the main characteristics of all cost assessment methods. To address specific hazards, at least one of these methods must be selected for assessing direct, indirect and intangible costs of flood hazards (Ciavola et al., 2012). Based on the type of costs to be assessed from flood damage, choosing the appropriate method would go a long way to ensure that better decisions are made for now and into the future in oil palm dominated landscapes.

Table 7.6: Main characteristics of costs assessment methods (Ciavola et al., 2012: pp.45-46).

Method	Type of assessed costs	Expected precision	Ability to deal with the dynamics of risk	Main types of data needed	Main data Sources	Effort and resources
Multivariate model	(in)direct	Reasonable	Yes, through probabilistic risk analysis	Historical disaster data, public expenditures, meteorological data, physical and socioeconomic variables	Statistics (land planning agencies, weather services, previous research)	Low
Damage Function Approach	Direct*	Good	Yes	Meteorological and hydrodynamic data (e.g. wind speed, water depth), built capital data	Census offices, weather services, land-use offices, insurance companies	High
Zone-based Damage estimation	Direct	Medium	Yes, through predictive methods	Aerial photographs, structural damage property values, erosion data, floodplain development over time	Remote sensing centres, census offices, meteorological institutes, previous reports	Low

Probable Maximum Loss	Direct	Medium	Yes	Flow depth, asset exposure, buildings characteristics and location, flood zone, replacement cost, water depth	Flood map, hazard loss estimation database, county tax assessor's office, building stock surveys	Medium
Input-output models	Indirect*	Good	Yes	Input-output tables; production capacity; adaptation and demand parameters, disaster data	Economic analysis, statistical and census offices	Medium
Contingent valuation** method	Intangible	Reasonable	Yes	Flood characteristics, stated willingness to pay, environmental conditions, socioeconomic data	Surveys, environment agencies, flood hazard research centre	High
Hedonic*** pricing method	Intangible	Good	Yes, through the determination of flood risks	Flood characteristics, revealed willingness to pay from environmental conditions, insurance and housing market data	Housing market data services, national flood insurances programs, previous research	High

**including the costs due to disruption of production processes. **Contingent valuation is a method used to estimate the value that a person places on a good not exchanged in regular markets. It is implemented jointly with other valuation techniques such as hedonic pricing for non-market goods ***Hedonic pricing refers to people's pleasure, likes or dislikes about something. For example, people do not want to buy houses in hazard prone areas so the housing market price drops because they do not want to take the risks, or may want the property because of the beautiful scenery despite the risks.*

Availability of and access to data to assess flood risk is a challenge in many rural landscapes. It determines the type of approach to be used. For this reason, this study used the damage function approach instead of other methods (table 7.6). This approach can measure direct costs with precision and can deal with the dynamics of flood risks. It only requires meteorological data, hydrodynamic data and built capital data. Meteorological data were acquired from the PNG National Weather Service and fieldwork, land use and built capital data were obtained from PNGRIS and satellite images, while fieldwork data were combined with GIS and satellite data to do simulations and assess flood risks. Despite the high efforts and resources required, it provided the results using facilities available at James Cook University.

Other methods were not viable because I did not have the data they require for the Dagi catchment. Although the multivariate model method is a reasonable approach to take, it requires data on historical flood disasters and public expenditures, where there is none for Dagi. The zone-based damage estimation method is also a good approach but again it is limited by data on property damage, property values and erosion data. The probable maximum loss method is also limited by lack of data on building characteristics, flood zone and replacement costs, flood map, hazard loss estimation database and building stock surveys. The input-output modelling approach relies on historical disaster data in which there was none. Contingent valuation and hedonic pricing methods assess intangible costs, and these are outside the scope of this research. An attempt was made to gauge opinions by interviewing NBPOL, OPIC employees and to gain settlers' experience on flood risks. However, both methods are complex economic models and require extensive interviews of a variety of stakeholders in which the available time limited this research. Therefore, the damage function approach was the most viable option taken in this study and it produced the results needed for flood risk assessment. Information made available through this method, can be used as inputs for other methods.

7.4 Summary

Because oil palm dominated landscapes are vulnerable to flood hazards, a flood risk assessment was conducted as a case study in the Dagi River catchment (492km^2) of WNB province, PNG. This research was conducted between January and April in 2014 in 18 carefully selected sites sub-divided into four sub-catchments to assess flood risks on assets and livelihoods. This study aimed to generate key information to assist flood disaster planning, hazard and risk mitigation measures to be undertaken in future by those involved in the oil palm industry and by government authorities in PNG.

7.4.1 Data preparation

- the extraction of DEM from DSM was problematic with Global Mapper, QGIS and Geomatica, however, SAGA GIS provided the solution. The grid cell of the extracted DEM was 5m x 5m and it was verified and resampled with a DEM generated from spot heights and contours to a 20m X 20m spatial resolution.
- rainfall-runoff simulation with HEC-HMS produced quality results while running SOBEK 1D/2D modelling software to simulate inundation was problematic for flood flows in 1D channels and 2D areas.
- results imported and exported between SOBEK 1D/2D and ArcGIS 10.2, HEC-RAS 4.1, HEC-RAS Beta 5.0 and HEC-GeoRAS software produced good results in the end.

Conclusion:

- despite lack of time series rainfall data records for the catchment, short-term rainfall measurements can be used to simulate discharge in a non-traditional way.
- simulation errors in the SOBEK 1D/2D model due to DEM resolution can be overcome by combining HEC-RAS 4.1, HEC-RAS Beta 5.0 and HEC-GeoRAS modelling software interactively with SOBEK 1D/2D and ArcGIS 10.2. This served the purpose of representing the surface for inundation and hazards modelling.

7.4.2 Objective 1 – Model flood characteristics and behaviour at sub-catchment and catchment level

In this context, it was vital to accurately model the temporal and spatial patterns of discharge, volume, velocity, flood level, duration, flood frequencies and probabilities for a given rainfall scenario. Missing data were collected from official sources and from field interviews and measurements including the

2014 rainfall data for 10-days and 12 hours. These data were organised in SAGA GIS and ArcGIS 10.2. To understand the rainfall and temperature pattern, data were analysed using a 3-year moving average to fit and identify temporal variations effects, and reduce extreme values and abnormalities. Flood events were simulated using HEC-HMS, HEC-RAS and HEC-GeoRAS methods. This information became inputs into flood simulations using HEC-HMS, HEC-RAS models and HEC-GeoRAS. HEC-HMS simulated flood characteristics and behaviour during the 2010 and 2014 flood events by following the Green and Ampt loss, Unit Hydrograph, and Muskingum Routine methods while HEC-RAS and HEC-GeoRAS modelled steady (sub-critical) and unsteady (supercritical) flows. Across the catchment, the approach generated results on the discharge and volume, velocity and stream power, hydrographs, cross-sections and water surface profiles, rating curves and catchment yield. Further analysis was done to determine flood probabilities (recurrence intervals/exceedance probabilities) from the discharge records and specifically for the 2010 and 2014 flood events using Gumbel distribution and Log-Pearson III Methods.

Research Question 1: What are the discharges and volume of water contributed by floods in the reaches and junctions along the waterways?

Of all the five reaches and two junctions modelled along the Dagi waterway, the following total discharges (Q) and volume (MM) contributed during the 2010 and 2014 floods are summarised in this order: The 2010 flood contributed 11.4% Q and 127.95MM (16%) while during the 2014 flood 12.3% Q and 16.9% MM were respectively contributed from reach 1 (Dagi upstream) draining an area of 204.31km^2. Along reach 2 (Ru Creek), Q was 3.3% with 12.7% MM (101.43MM) while in 2014 they were 2.9% Q and 11.5% MM from an area of 62.63km^2. 14.0% Q and 15.3% MM were in 2010 while 2014 had 14.7% Q and 15.6% MM that came from the Dagi-Ru junction with a drainage area of 266.94km^2. In 2010 it was 20.1% Q and 14.1% MM of total volume while 2014 was 19.8% Q and 14.1% MM that came from a drainage area of 420.19km^2 at reach 3 (Dagi middle). In reach 4 (Lamegi River) that drains an area of 71.75km^2, the 2010 flood contributed 4.1% Q and 14.2% MM while 3.9% Q and 13.9% MM during the 2014 flood. During the 2010 flood, 23.8% Q and 14.1% MM were at the Dagi-Lamegi junction with a total drainage area of 491.94km^2 while that of 2014 were 23.5% Q and 14.1% MM respectively. Finally, the 2010 flood contributed 23.3% Q and 13.7% MM at reach 5 (Lower Dagi) draining an area of 492km^2 while that of 2014 were 22.9% Q and 14.0% MM respectively.

Of the total Q in 2010 and 2014 floods, 67.2% Q was contributed in 2010 while 32.8% Q was contributed in 2014. The difference between 2010 and 2014 flood Q was by 34.4%. The total volume contribution in 2010 was 60.8% MM while 39.2% MM was for the 2014 flood with a difference of

21.6% MM. The differences in peak Q between 2010 and 2014 floods in each sub-catchment (SC) were as follows: SC 1 = 29.1%, SC 2 = 38%, SC 3 = 36% and SC 4 = 34%. The difference in specific yield (MM/km^2) in each SC are as follows: SC 1 = 2.7%, SC 2 = 1.7%, SC 3 = 1.1%, and SC 4 = 0.1%.

Conclusion:

- all streams in the Dagi catchment are perennial due to the temporal and spatial rainfall patterns attributed to excess rainfall over infiltration.
- specific yields are defined by each SC size and the total amount of rainfall received at each SC that contributed varying amounts of discharge and volume to the total channel flows.
- peak discharge and volume from each reach increased at junctions as they moved downstream and are predictable in Dagi catchment.

Research Question 2: How does the flood water move and distribute along the stream cross-sections and longitudinal profiles?

The upstream reaches generally have a steep hydrograph with a peak discharge of 1326m^3/s (130.10MM) for 2010 at 13:00pm compared with that of 2014 which peaked at 12:30pm with 729m^3/s (86.96MM). Downstream reaches generally showed a broader hydrograph with a peak discharge of 1158.4m^3/s (72.47MM) at 14:00pm in 2014 while in 2010 it was 2424.4m^3/s (109.67MM) that peaked by 14:30pm. The 2010 floods had an average velocity of 5.38m/s upstream while downstream average velocity was 3.76m/s. The 2014 floods had an average velocity of 4.35m/s in the main channels upstream while downstream average velocity was 2.75 m/s. The average stream power for 2010 in SC 1 was 2322.63 N/m s, SC 2 was 1476.31 N/m s, SC 3 was 2687.12 N/m s, SC 4 was 1487.36 N/m s while downstream it was 12765.24 N/m s. The average stream power for 2014 in SC 1 was 1915.12 N/m s, SC 2 was 1196.95 N/m s, SC 3 was 2393.89 N/m s, SC 4 was 1196.95 N/m s while downstream it was 9575.58 N/m s. All stream cross-sections and longitudinal profiles graphically shown in the Dagi hydraulic models for all reaches showed bankfull overflow by total volumes with slight variations in velocity.

Conclusion:

- the distance between reaches, the amount, intensity, duration and frequency of rainfall, slope, stream channel and overbank roughness influenced velocity which in turn defined the shape, size and the time of rise of the hydrographs.

- hydrographs generally showed short lag time upstream with natural vegetation while downstream had shorter lag time due to little resistance.
- velocity increased downstream as roughness decreased while velocity in all cross-sections decrease towards the banks and in the floodplains as they encounter roughness.
- travelling time of the flood wave depended upon the distance between reaches, however, floods in Dagi rise quickly upstream and flow fast downstream and this provides less time for warning and evacuation.
- the stream power during floods increases downstream and this is risky.

Research Question 3: What are the water depths and durations for the 2010 and 2014 floods?

During the 2010 flood, the mean water depth for reach 1 was 3.88m with a duration of 4 days, reach 2 was 3.02m with 4 days' duration, reach 3 was 6.83 metres with 9 days' duration, reach 4 was 4.75m with 5 days' duration and reach 5 was 7.5m for up to a duration of 11 days. During the 2014 flood, the mean water depth was 2.65m for reach 1 with a duration of 3 days, 2.62m for reach 2 with 2 days' duration, 4.65m for reach 3 with 6 days' duration, 4.22m for reach 4 with 3 days' duration and 6.34m for reach 5 with a duration of 7 days.

Conclusion:

- all stream cross-sections and longitudinal profiles graphically shown in the Dagi hydraulic models for all reaches show bankfull overflow by total volumes with slight variations in velocity.
- flood height varies for all sites in response to slopes.

Research Question 4: What possible catchment factors may contribute to these flood characteristics and behaviour?

Excluding 1st and 2nd order streams, the modelled catchment shape appears circular and rain falls at equidistant points from one another and runoff reaches the stream at the same time. The current land cover is reflected in the roughness coefficient. SC 1 has a roughness coefficient of 0.065, SC 2 with 0.055, SC 3 with 0.029, SC 4 with 0.031 while downstream at the outlet the roughness coefficient is 0.029. Dagi is a small catchment with high-intensity rainfall of 12-hours duration with most floods having exceedance probabilities of over 50%. Dagi is dominated by mixed and undifferentiated igneous and sedimentary rocks together with alluvial volcanic ash soils. The average upstream slopes were 0.0296^{o} with an average elevation of 65m above sea level whereas near the outlet the average slopes were 0.0027^{o} with an average elevation of just 2m above sea level.

Conclusion:

- despite the 2010 discharge being higher than that of 2014, the similarities in the two hydrographs was a result of the circular catchment shape which allowed rainfall of varying intensity and duration to be received, and together with alluvial volcanic ash soils and slope they generated overland runoff to reach the stream at the same time to produce high peak discharge.
- for both flood events, the increase in stream power going downstream were due to the drop in catchment and channel slope gradients, increase in discharge, few meanders, concave longitudinal profiles and decline in the frictional resistance from vegetation.

Research Question 5: What are the probabilities of floods of different magnitudes in Dagi?

The flood event of 2010 had a recurrence interval of 11 years (9.09%). The 2014 flood had a recurrence interval of 7.33 years (13.64%). The 1998 Dagi flood had a recurrence interval of 22 years (4.55%) chances of re-occurrence while the 2005 flood had 4.40 years (22.73%). From the flood records in Dagi catchment, 25% of the total had a recurrence interval greater than 4 years (<22% probability), while 75% had a recurrence interval of less than 4 years (>22% probability).

Conclusion:

- small spatial variability in the rainfall was due to the small size of the Dagi catchment.
- annual floods in Dagi have exceedance probabilities of over 50%.

7.4.3 Objective 2 – Model flood inundation extents at a SC and catchment level to define hazard zones.

In this context, inundation extent and hazards were generated by flood routing and hydraulic modelling procedures using HEC-RAS Beta 5.0, HEC-GeoRAS, and SOBEK 1D/2D. A supervised classification following the maximum likelihood algorithm used a high resolution ALOS multispectral imagery in ArcGIS 10.2 and identified four main land cover classes. Information was also obtained from interviews about past inundation events and field measurements in 18 selected sites for model calibration. Analysis involved demarcating the drainage network in the DEM into 5m x 5m grid cells to pin-point breaches along river banks and for 2D overland flow simulation in SOBEK 1D/2D. The boundary conditions for the model were also set based on specific return periods calculated for the flood years from 2000 to 2014. The network was schematised and attributes were defined for the 1D network and 2D surface in SOBEK 1D2D model.

Research Question 1: What were the spatial inundation extents for the 2010 and 2014 floods using SOBEK 1D/2D hydrodynamic model?

The maximum extent of water outside of the bankfull channel varied in both years with the 2010 flood recording the highest areal inundation extent (36.5 hectares) compared with 2014 (33.4 hectares) at the downstream reach. The combined 1D/2D inundation depth for 2014 varied across the channels from as low as 0.05m to as much as 6.5m compared with that of 2010 (0.05-7.5m). The 2010 flood event inundated 79.9 hectares, or 59% of the total area of inundation between the two years. The 2014 inundated 55.2 hectares which is 41% of the total area inundated between the two years. This represents a difference of 18%, with 2010 having a larger flood than 2014. For both floods, most inundation occurred in the middle and lower reaches of the catchment.

Conclusion:

- good quality spatial inundation and hazard extent maps were derived and showed that most inundations were in the lower reaches of the Dagi River for both flood events.
- during inundations for both flood events between upstream and downstream reaches, variations in the volume, lag time, depth, velocity and stream power were caused by the catchment and channel slope gradients, dendritic river pattern, and concave and convex longitudinal profiles across most reaches, and stream cross-sections including man's influence in deepening the channels through gravel extractions and amount of vegetation cover.
- the 2010 inundation flow areas were much larger than that of 2014 due to high rainfall received during that year.
- overtopping inundation occurred within 500m of the banks of the Dagi River, a result of no protection levels from relatively rural floodplain for all reaches.
- inundation depths and duration were due to slope, soil characteristics and the channel storage capacity.

Research Question 2 - What is the sensitivity of the SOBEK 1D/2D hydrodynamic model to frictional values?

The roughness values determined for each land cover based on Manning's roughness coefficient were: 1. tree cover (oil palm and native spp.) = 0.045, 2. water bodies = 0.033, 3. grass and shrub cover = 0.035, and 4. bare ground and built-up areas = 0.150. The average observed and simulated water depth values differed with different frictional values from -0.08m to -0.98m (2014), and 0.01m and

0.31m (2010) respectively. The peak discharge's range of difference for the simulation were 0.32m, 0.39m to 0.54, 0.38 and 0.10m respectively.

Conclusion:

- calibration of the inundation and hazard model was validated based on observed and simulated events and the results agreed well.
- through sensitivity analysis, model sensitivity and simulation accuracies were directly influenced by friction values within and outside stream channels for all reaches.
- the surface roughness (friction) values obtained from land cover classification were used to analyse data for grid and provided the appropriate values for calibration.
- frictional losses were high upstream because of the steep slopes, large boulders and gravels and more vegetation cover.
- frictional losses decreased downstream towards the outlet as slopes decreased, and as flow encountered cobbles, pebbles and less vegetation.
- decreasing roughness downstream increased stream power.

Research Question 3 - How well does the SOBEK 1D/2D hydrodynamic model fit the observed 2014 and 2010 flood hazard scenarios?

The validation results based on depths and velocities combined with different frictional values showed average difference of observed and modelled data between 0.40m and the difference at the peaks between 0.24m and 0.55m for the 2014 flood event. The 2010 flood showed an average difference of 0.45m between observed and modelled data with the range of difference at the peaks between 0.32m and 0.54m.

Conclusion:

- assumptions made in trying to represent the real world into the model also yields some degree of uncertainty in model results. Model set-up, boundary conditions, surface roughness and river geometry, can limit the accuracy of flood inundation and hazard simulations despite inputs of correct estimates. Model error will always be a factor since models cannot represent the real world correctly.
- when many models are used in inundation and hazards modelling, they can increase uncertainties and affect flood areal extent, duration and hazard results.
- there was agreement between the actual results and the model peaks.

7.4.4 Objective 3 – Assess flood hazards, the level of vulnerability and determine the degree of risk as a function of inundation depth and velocity.

In this context, the study followed a risk-based approach focused on direct tangible economic costs and used a combination of qualitative and quantitative risk assessment methods. Qualitative risk assessment was performed based on flood inundation depth maps and land use vulnerability maps. The level of vulnerability and risk zones was identified based on the assigned land use weights, hazard and vulnerability assessment criteria. Vulnerability curves for the Dagi catchment were generated based on flood depth and velocity and its relative functions. Using the weights and criteria, and land use curves, raster-based vulnerability and risk maps were drawn in relation to three exceedance probabilities. Quantitative risk assessment involved estimating the total costs of exposed elements (direct tangible) based on the damage functions and classified according to their type. The total numbers of physical elements at risk were identified based on the vulnerability curves from overseas. The actual elements at risk were obtained by overlaying the hazards maps for the 2014 and 2010 floods. This was then overlaid on the overall hazards maps based on the combined 2014 and 2010 floods in 1D channels and 2D bank overflow areas and inundation.

Research Question 1: What is the level of flood hazards?

Four flood hazard categories in Dagi were identified: low, medium, high and very high. There was a total of 55.2 hectares inundated in the 2014 floods. The 2010 flood event inundated a total of 79.9 hectares. For both years, inundation was highest in the lower reaches of the Dagi River with the 2014 flood comprising 60.5% of the total. The lower reaches of the Dagi showed 45.7% of the 2010 flood total. Contrasting between the total inundated area between the two years (135.1 ha), the 2010 flood inundated 59.2% while the 2014 flood inundated only 40.8% of the total. This means that the 2010 flood inundated 18.4% more than the 2014 flood.

The assessment of total elements at risk between the 2014 and 2010 floods showed a combined total of 71 roads with a total distance of 16.77km. Houses and buildings had a combined total of 718 covering 0.17km^2, while there was a total of 577 subsistence gardens covering 0.98km^2 exposed to flooding in these two years. There were 32 smallholder oil palm blocks covering 12.78km^2 which had a total count of 32, while oil palm plantations had a total count of 33 covering 10.55km^2.

Conclusion:

- flood hazard maps and stage-damage curves are useful aids in the identification of the physical elements at risk and their level of vulnerability.
- by using maps of inundation extents and flood hazards, a qualitative approach can be used in data-poor areas to determine the degree of risk especially when economic values of elements at risk are non-existent for different land uses.

Research Question 2: What is the degree of physical, social and economic vulnerability?

Major physical elements identified at risk were roads, subsistence gardens, houses and buildings and oil palm trees. The total number of roads inundated during the 2014 flood represented 40.8% of the total while that of 2010 flood represented 59.2%. This reveals a difference of 18.3% between the two years. The total number of houses and buildings inundated in 2010 was slightly higher (9.8%) than that of 2014. The total tally for subsistence gardens reveals that the 2010 flood inundated 35 more subsistence gardens than that of 2014, which is slightly 6.1% higher than expected. Furthermore, total number of smallholder oil palm blocks inundated during the 2014 flood represented 46.9% while that of 2010 flood represented 53.1%. Thus, the amount of smallholder oil palm blocks inundated during the 2010 flood event was slightly higher by 6.3%. Finally, oil palm plantations inundated during the 2010 flood event represented 54.6% of the total compared to 45.5% for 2014, revealing a difference of 9.1%.

Highly vulnerable elements are those found towards the stream edges falling in the class range of 0.86-1.0 for all identified physical elements. 80% of the subsistence garden fall in the range of 0.86-1.0 for all reaches within 500m of channels indicated as on the vulnerability map and referred to as very high risk indicated on the risk map. 35% of the roads are classed as medium risk falling in between 100m which have vulnerability level falling between 0.56-0.75. Oil palm trees have 95% falling in the range of 0.86-1.00 within 500m of channels were classed at very high risk as indicated on the map. 80% of houses and buildings vulnerability level between 0.76-0.85 classed as high risk.

Conclusion:

- areas identified as vulnerable were defined by their level of risks which were assessed qualitatively and quantitatively.

- livelihood assets and population are more vulnerable to floods in locations that have low slope and broad channel cross-sections and longitudinal profiles. Such locations are influenced by velocity and changes in flow directions.

Research Question 3: What is the magnitude of risk as a function of water depth and velocity?

Overall results showed that houses and buildings incurred the greatest costs (34.3%), leaching of fertilisers (27.2%), followed by deaths from drowning incidents (23.7%), subsistence gardens (11.4%), roads (2.6%), damaged oil palm trees (0.8%), non-pick-up of fresh fruit bunches (0.02%) and formal job income loss (0.01%). Differences were well below the threshold value of 20%. The total economic costs based on the elements at risk was PGK77,869,451 equivalent to US$26,545,696 (23rd September 2015 exchange). Of the total economic costs for both years, 30% were incurred during the 2014 flood while the 2010 flood incurred 70%.

Conclusion:

- risks and associated costs are dependent on the area of inundation, depth and velocity because their attributes interact and incur varying economic costs.
- quantitative risk assessment of elements at risks can be made in monetary values based on estimates using expected current market values based on inundation extents, however, there are uncertainties involved with any estimates.
- the economic costs associated with flood risks can be estimated using risk curves in data-poor regions and at the same time future predictions of average risks can be made from risk curves that can provide useful information for flood disaster planning, hazard and risk mitigation.

7.4.5 Objective 4 – Determine the relative roles population, land use and livelihood assets play in affecting exposure and potential river flood risks.

In this context, results from chapters 4, 5 and 6 were evaluated to determine the relative roles population, land use and livelihood assets played in affecting exposure and potential river flood risk. It investigated how damages caused by floods contributed to increasing losses on livelihood assets.

Research Question 1: What roles do population, land use and livelihood assets play in affecting exposure on flood exposure and potential risks?

There is an average growth from 2000 to 2011 of 3.92%. Numbers increased from 5.9 persons per smallholder oil palm block in the 1970s to 13.3 persons in 2000 to an estimated 18 persons in 2010.

There was declining soil fertility and reduced income from oil palm with increasing financial obligations in pursuit of livelihood strategies to secure a living. Of all livelihood activities, except oil palm cultivation, subsistence gardening comprised >70% of the total. Annual growth rate of oil palm cultivation between 1986 and 2005 was 4.3% for smallholder and 8.3% for plantation and estates. Smallholders in the Hoskins Oil Palm Project area showed an 18% increase in oil palm plantings between 1998 and 2000.

Conclusion:

- increases in population in small holder oil palm blocks over the years has led to increases in land use and livelihood assets as people seek out livelihood strategies.
- vegetation clearance to make way mostly for oil palm and subsistence cultivation, and settlements in riparian zones were the key drivers.
- vulnerability to floods were due to modification of the hydrological cycle with consequent alteration of stream channel morphology and hydraulics over the years.
- depending on the flood characteristics and their behaviour, and inundation extents, there are associated risks in all unprotected reaches when and where people settle in the floodplain next to the channels.
- this study has shown that Dagi is highly prone to flood hazards and risks.
- using risk information, flood disaster planning, hazard and risk mitigation measures can now be taken within an oil palm dominated landscape.

7.4.6 Objective 5 – Investigate management options for flood disaster planning, hazard and risk mitigation across sectors.

In this context, an interview of people upstream and downstream along the Dagi River was conducted during the fieldwork to seek people's views on the exposure of livelihood assets, human and environmental health to flood risks. 28 people at Sarakolok LSS and 30 people at Nahavio DPI Station were interviewed to get their perceptions on flood experiences in Dagi. The results were further investigated with the existing literature (in this study and elsewhere) to develop options for managing flood and planning for disaster, hazard and risk mitigation.

Research Question 1: What are the most viable management options?

Results showed that 68% out of the 28 respondents from Sarakolok LSS, and 87% out of the 30 respondents from Nahavio DPI Station said there have been increased incidences of flooding affecting their livelihoods unlike before. More than 50% agreed that there is increased incidence of floods, water borne diseases and disruption of transport access and communication in the Dagi catchment. Analysis of the documents showed that challenges remain in the setting of Dagi catchment between hard and soft measures in terms of costs and between land ownership and user rights. The way forward was for the establishment of a risk governance system to better implement public adaptation measures, while more incentives for strengthening adaptation of individuals.

Conclusion:

- flood risk management options must involve engaging all stakeholders in the oil palm industry across economic, social, environmental and political sectors at all levels. Joint collaborations and priorities should be focused on empowerment through institutions, educational awareness, social networks, structural engineering, financial support, scientific research and information sharing. For these to work, it must have the political will and the support it deserves.
- the local players must not be seen as implementers to address flood risk issues. Instead, they must be empowered to be innovators of flood disaster planning, hazard and risk mitigation measures to safeguard their future livelihoods.
- this study has led to the generation of key information available for flood disaster planning, hazard and risk mitigation measures to be undertaken in future.
- due to the costs involved, land ownership and user right settings for both soft and hard control measures to be undertaken, unconventional adaptation measures are the most viable option available for the Dagi catchment.

7.5 Study limitations and recommendations

7.5.1 Study limitations

Chapter 4 modelled flood characteristics and behaviour along Dagi at a sub-catchment (SC) and catchment level. Computations were based on a short period of rainfall data collection.

- an urgent task is to re-establish a representative rain gauge network to collect daily series of climate data at stations in the catchment. With long-term data, simulations can bring better results where flood probabilities can be verified with results obtained in this study.

Chapter 5 modelled flood inundation extents at a SC and catchment level to define hazard zones.

- other surface roughness does exist and was not specified and represented in the grid resolution of the DEM, which had some effects on the flow direction and timing, however, these had little effect on the results in this study.
- in future studies, it is important to conduct sensitivity analysis for surface roughness of any study site so that models can be able to incorporate scale and heterogeneity.

Chapter 6 assessed flood hazards, the level of vulnerability and determined the degree of risk as a function of inundation depth and velocity.

- the current study only estimated costs based on selected elements at risk. Future studies in the catchment must include all costs involved. This will involve investigating cost distributions, and risks transfers and in what ways cost assessment can function as part of decision support.
- this study followed the damage function approach based on direct costs and was restricted by lack of data on past flood events and the non-existence of insurance data. Using multivariate approaches, integration of insurance data with land use elements is a flexible and simple approach to adopt in future research.

7.5.2 Recommendations for authorities in PNG government and New Britain Palm Oil Limited.

Flood problems concern both the smallholder oil palm growers represented by the government through the Oil Palm Industry Corporation (OPIC) and oil palm plantations owned and operated by New Britain Palm Oil Limited. Joint collaborations between these two sectors are needed to fund the costs involved in planning and implementing flood mitigation measures in the Dagi catchment. The following are the recommended options to take among others:

To mitigate flood risks, the recommended measures for implementation are by conventional and unconventional means.

- *Conventional:*

  i. New Britain Palm Oil Limited be prepared to meet the cost of planting trees as flood buffers to protect its plantations near waterways. This would involve establishing suitable width extents in riparian zones and police flood buffer zones against harvest of timber.

- *Unconventional:*

  i. the WNB provincial disaster office carry out community education campaigns and workshops among the local people (settlers and company workers) and make them more conscious about the true flood risk of the area.
  ii. strengthen transparency in risk communication between the locals and the authorities.
  iii. Jointly the WNB provincial disaster should empower locals through provision of financial assistance to those are proactive (innovative) and take ownership of flood mitigation to fall as acceptable flood risks[24] rather than that defined by the results in this study. They should not be seen as implementers of government policies but innovators.

To end this thesis, the study has assessed flood risks on livelihood assets in the case study area. It followed a logical sequence by understanding flood characteristics and their behaviour that in turn inundated and caused hazards. That in turn exposed land use elements, thus causing them to be vulnerable to the effects of flooding. Areas identified as vulnerable were defined by their level of risks which were assessed qualitatively and quantitatively. The costs associated with the risks was then measured with an economic cost. Using risk curves, economic costs could be estimated in data poor regions. Using risk information, flood disaster planning, hazard and risk mitigation measures can now be taken within an oil palm dominated landscape. Therefore, this research served as a baseline study

[24]Defined as those falling below the probabilities and or consequences of the two modelled flood events.

that can be used for comparative studies in other oil palm dominated landscapes as well as in other agricultural landscapes. Future research must address the research gaps outlined above.

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Chapter 3.0: Appendix

Appendix 3.1: Rainfall records at Hoskins Airport from 1996-2013

Monthly rainfall data for Hoskins area from 1996 to 2013

Site Name: **Hoskins Weather Office** Site Number: **35043**
Latitude: **-5.4600** Longitude: **150.4000** Elevation: **8.000**

Rainfall (mm)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1996	314	183.2	310.4	83.2	83.2	100.8	89.8	177	168	255.2	59.8	297	2121.6
1997	411	578.4	401	116	208	74.6	74.4		88	29.8	174.6	270.9	2426.3
1998	608	578.4	676.3	452	321.8	295	215	155	112	162.2	389.4	392.4	4357.3
1999	531	1044	398.6	168	96.8	338.6	182	119	115	268.2	216.4	328.4	3805.2
2000	480	135.8	555.4	274	560.8	74.2	77.2	290	88.6	175	223.6	414.6	3349.6
2001	146		438.2	263	192.6	283	242.4	140	156	85.8	247	716.2	2909.6
2002	584	908.4	593.8	303	105.6	263.4	178.2		44.4	251.4	153.2	267.6	3653.4
2003	582	677.8	723.8	388	201.6	66.8	123.4	160	114	189.8	72.6	484	3784
2004	641	543.2	837.8	174	308	163.8	129.2	43.8	137	175.8	81.8	44.8	3280.8
2005	616	615.2	729.2	839	154	49	125.4	117	140	120.2	260.4	413.2	4179
2006	464	740.4	498.6	452	92	203.6	189.8	175	290	17	158.4	238.8	3519
2007	773	639.8	587	158	130.8	121.2	82.4	162	119	156.8	574.4	404.4	3908
2008	1258	384.4	275.2	508	168.8	303	200.2	107	126	97.8	165.8	187.2	3781.8
2009	480	447.2	747.4	231	236.8	336.8	102.6	191	112	144.8	123.2	288	3441.2
2010	1093	762.2	689.8	476	230	50.4	79.6	181	161	253	306.8	156.2	4439
2011	328	328.2	433.4	176	276.4	88.8	298.8	22.4		191.8	203.4	310.8	2657.2
2012	646	628	759.4	342		91.6	99.6	204	164	270	293.4	321	3818.2
2013	1058	686.8	1099	346	134			200	34.8	203.8	96.2	380	4239

Figure 3.3: Rainfall records at Hoskins Airport, 32km away from Dagi catchment from 1996-2013.

Chapter 4.0: Appendix

Appendix 4.1 – Climate Data: Monthly maximum and minimum temperature and rainfall data

Monthly maximum temperature data for Hoskins from 1996 to 2013													
Site Name: Hoskins Weather Office Site Number: 35043													
Latitude: -5. 4600 Longitude: 150.4000 Elevation: 8.000													
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1996	31.2	30.6	30.5	31.3	31.5	31.5	31.1	31.5	31.1	31.8	31.6	31.2	31.2
1997	30.3	29.9	30.5	32.1	31.7	31.6	30.8	31.7	31.8	32.9	31.7	31.1	31.3
1998	29.8	30.3	29.9	31.1	31.4	31.3	31.1	31.4	32	31.6	31	30.9	31
1999	31.1	29.8	31.2	31.2	31.5	31.1	31	31	31.5	31.3	31.1	31	31.1
2000	30.6	31.7	30.6	31.2	30.4	31.3	30.5	31	32.1	31.5	31.5	30.7	31.1
2001	30.3		31	31.1	31.6	30.7	30.6	31.1	31.5	32	31.4	30.1	31
2002	30.4	29.9	30.4	31	31.9	31.2	31.2	31.5	32.3				31.1
2003						31.6	30.8	30.7	30.8	31.7	31.7	31.4	31.2
2004	30.4	30.1	30.5	31.4	30.9	30.4	30.3	30.8	31	31.4	31.6	31.1	30.8
2005	30.1	29.9	30.6	30.9	31.2	31.1	30.7	30.9	31.1	31.8	31.3	31.1	30.9
2006	30.7	29.6	30.5	30.8	31.2	31.1	30.8	29.7	30.6	32.1	31	31.6	30.8
2007	30.3	29.9	30.3	31.3	31.2	31.7	31	30.8	31	31.4	30.6	31.1	30.9
2008	29.1	30.8	31.2	30.5	31.1	31	31	31.3	31.3	31.8	31.6	31.1	31
2009	30.7	29.8	29.8	31	31.4	30.9	30.7	30.8	31.5	32	31.7	31.3	31
2010	29.1	29.9	30.3	31.2	31.8	31.3	31.8	32.3	31.9	31.6	31.3	31.5	31.2
2011	31	30.8	30.8	31.2	31.1	30.7	30.5			31.6	32	32.1	31.2
2012	30.8	30.6	30.5	30.8		31.4	31.6	31.3	31.3	31.5	32.1	31.9	31.3
2013	30.1	30.7	30.3	31.7	32.1			30.9	32.6	31.7	31.6	32.1	31.4
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Average	30.4	30.3	30.5	31.2	31.4	31.2	30.9	31.1	31.5	31.7	31.5	31.3	31.1
Lowest	29.8	29.8	29.9	31	30.4	30.4	30.3	30.7	30.8	31.3	31	30.1	30.5
Highest	31.2	31.7	31.2	32.1	31.9	31.6	31.2	31.7	32.3	32.9	31.7	31.4	31.7

Monthly minimum temperature data for Hoskins from 1996 to 2013

Site Name: Hoskins Weather Office Site
Number: 35043

Latitude: -5.
4600 Longitude: 150.4000 Elevation: 8.000

Minimum
Temp (°C)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1996	23.3	23.3	22.9	23.4	23.5	23.5	23.7	23.1	23.2	23	23.2	23.4	23.3
1997	23.1	23.4	24.8	24	23.4	24.1	24	23.9	23.1	24.1	23.1	23.7	23.7
1998	24.1	24	24	23.9	24.1	24	23.8	23.5	23.5	22.9	22.9	23.6	23.7
1999	23.4	23.4	23.3	23.4	23.5	22.8	23.3	23.2	23.3	23.1	23.1	23.7	23.3
2000	23.4	23.3	23.1	23.3	23	23.1	23.1	23.6	23.5	23.4	23.6	23.8	23.4
2001	23.4		23.1	23.5	24.2	23.6	24.1	24	23.4	23.5	23.5	23.5	23.6
2002	23.8	23.6	23.7	23.2	24.4	23.9	24.2	24.3	23.5	23.3	23.6	23.5	23.8
2003	23.6	23.5	23.3	23.7	24.1	23.4	23.7	23.9	23.5	23.7	23.7	23	23.6
2004	23.8	23.8	23.9	23.4	23.9	24	23.5	23.5	24.1	23.2	23	23	23.6
2005	23.8	23.8	23.6	23.8	23.9	23.7	24	24	23.7	23.3	23.5	23.5	23.7
2006	23.6	23.6	23.3	23.3	23.4	23.6	23.6	23.2	23.9	24.9	23.7	23.7	23.7
2007	23.8	23.8	23.4	23.6	23.7	23.7	24.3	23.2	23.5	23.1	23.5	23.4	23.6
2008	23.3	23.5	23	23.2	23.3	22.9	23.1	23.2	22.8	23	23.4	23.4	23.2
2009	23.2	23.5	23.4	23.5	23.6	23.2	23.4	23.3	23.7	23.8	23.8	23.5	23.5
2010	23.7	23.7	23.9	24	24.2	23.5	22.7	24.3	23.2	23	23.2	23.4	23.6
2011	23.3	23.1	23.3	23.2	23.3	23	22.4			23.1	23.3	23.4	23.1
2012	22.9	22.7	23	23.2		22.9	23.2	23.3	23.4	23.3	23.3	22.9	23.1
2013	23.4	23.2	23.7	23.4	23.3			23.2	24	22.8	22.8	22.9	23.3

Stat	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	23.5	22.2	23.5	23.5	22.4	22.2	22.2	22.3	22.2	23.4	23.3	23.4	23.5
Lowest	23.1	22.7	22.9	23.2	23	22.8	23.1	23.1	23.1	22.9	22.9	23	23
Highest	24.1	24	24.8	24	24.4	24.1	24.2	24.3	24.1	24.1	23.7	23.8	24.1

Monthly rainfall data for Hoskins area from 1996 to 2013													
Site Name: Hoskins Weather Office Site Number: 35043													
Latitude: -5. 4600 Longitude: 150.4000 Elevation: 8.000													
Rainfall (mm)													
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1996	313.6	183.2	310.4	83.2	83.2	100.8	89.8	177	168.4	255.2	59.8	297	2121.6
1997	411	578.4	401	115.6	208	74.6	74.4		88	29.8	174.6	270.9	2426.3
1998	608	578.4	676.3	452	321.8	295	215	155	111.8	162.2	389.4	392.4	4357.3
1999	530.8	1044.2	398.6	167.6	96.8	338.6	182	119	115	268.2	216.4	328.4	3805.2
2000	480.4	135.8	555.4	274.2	560.8	74.2	77.2	290	88.6	175	223.6	414.6	3349.6
2001	146		438.2	262.8	192.6	283	242.4	140	155.8	85.8	247	716.2	2909.6
2002	584.2	908.4	593.8	303.2	105.6	263.4	178.2		44.4	251.4	153.2	267.6	3653.4
2003	581.8	677.8	723.8	388.2	201.6	66.8	123.4	160	114.4	189.8	72.6	484	3784
2004	640.8	543.2	837.8	174.4	308	163.8	129.2	43.8	137.4	175.8	81.8	44.8	3280.8
2005	616.4	615.2	729.2	839.4	154	49	125.4	117	140	120.2	260.4	413.2	4179
2006	464.4	740.4	498.6	451.8	92	203.6	189.8	175	289.6	17	158.4	238.8	3519
2007	772.6	639.8	587	157.8	130.8	121.2	82.4	162	118.8	156.8	574.4	404.4	3908
2008	1258.4	384.4	275.2	507.8	168.8	303	200.2	107	125.8	97.8	165.8	187.2	3781.8
2009	480	447.2	747.4	231	236.8	336.8	102.6	191	112	144.8	123.2	288	3441.2
2010	1093.4	762.2	689.8	475.8	230	50.4	79.6	181	161.2	253	306.8	156.2	4439
2011	327.6	328.2	433.4	175.6	276.4	88.8	298.8	22.4		191.8	203.4	310.8	2657.2
2012	645.8	628	759.4	341.6		91.6	99.6	204	163.6	270	293.4	321	3818.2
2013	1057.6	686.8	1099.2	346.2	134			200	34.8	203.8	96.2	380	4239
Stat	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Average	611.8	581.3	597.5	319.3	206.0	170.9	146.5	152.7	127.6	169.4	211.1	328.6	3,415.60
Lowest	146	135.8	275.2	83.2	83.2	66.8	74.4	22.4	34.8	17	59.8	44.8	1,043.40
Highest	1258.4	1044.2	1099.2	839.4	560.8	338.6	242.4	290	289.6	268.2	574.4	716.2	7,521.20

NB: During the time of data collection, there were no 2014 rainfall data available at PNG National Weather Service. The 2014 data used to model the 2014 flood event were collected during fieldwork using a non-recording rain gauge for a duration of 10-days, 12 hours each in February, 2014 and January-February 2010.

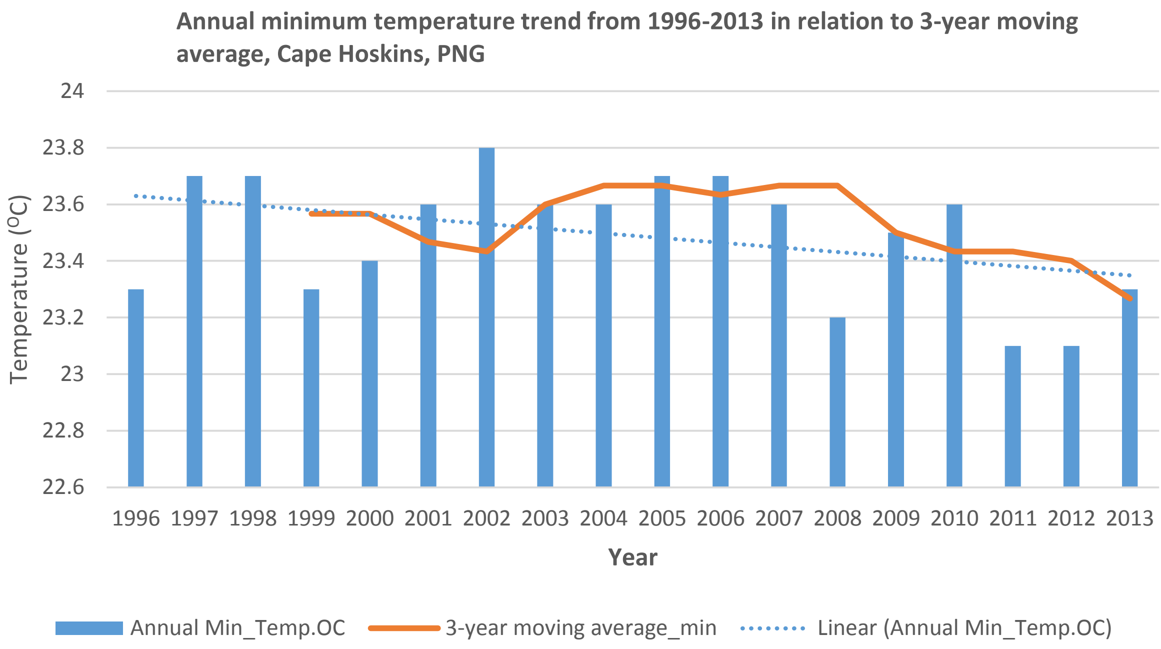


Figure 4.4: Annual minimum temperature trend from 1996-2013 in relation to a 3-years moving average (Source: PNG NWS, 2014).

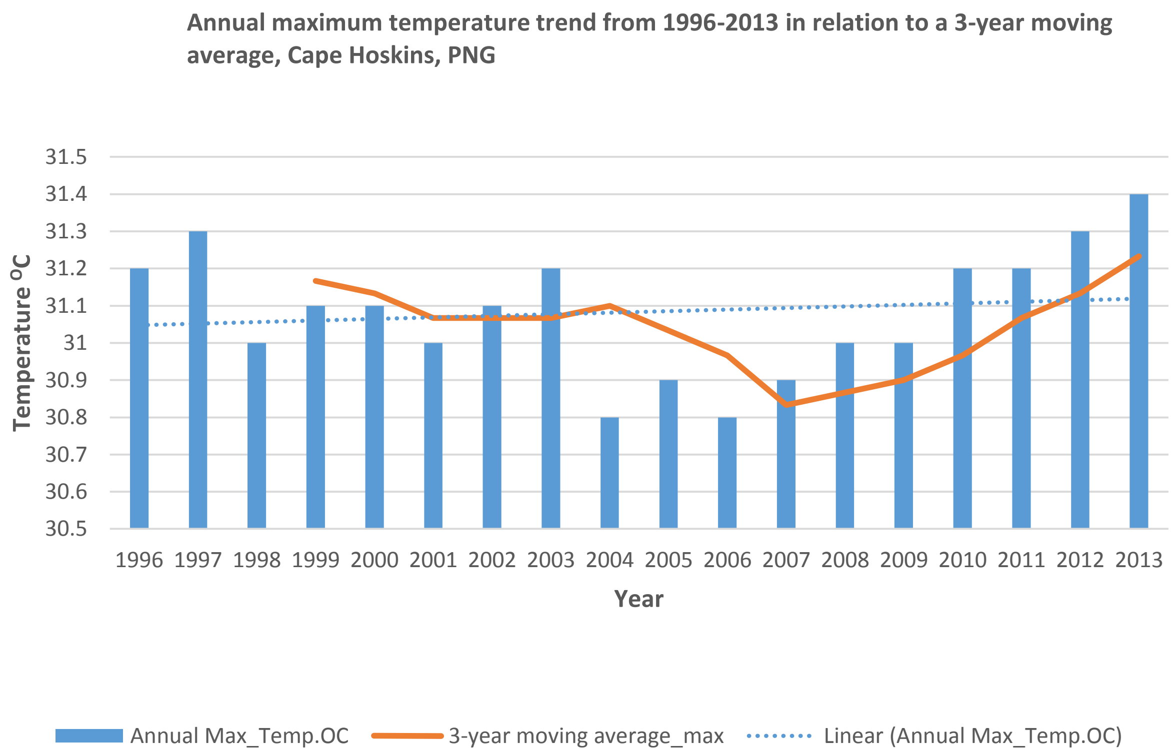


Figure 4.5: Annual maximum temperature trend from 1996-2013 in relation to a 3-years moving average (Source: PNG NWS).

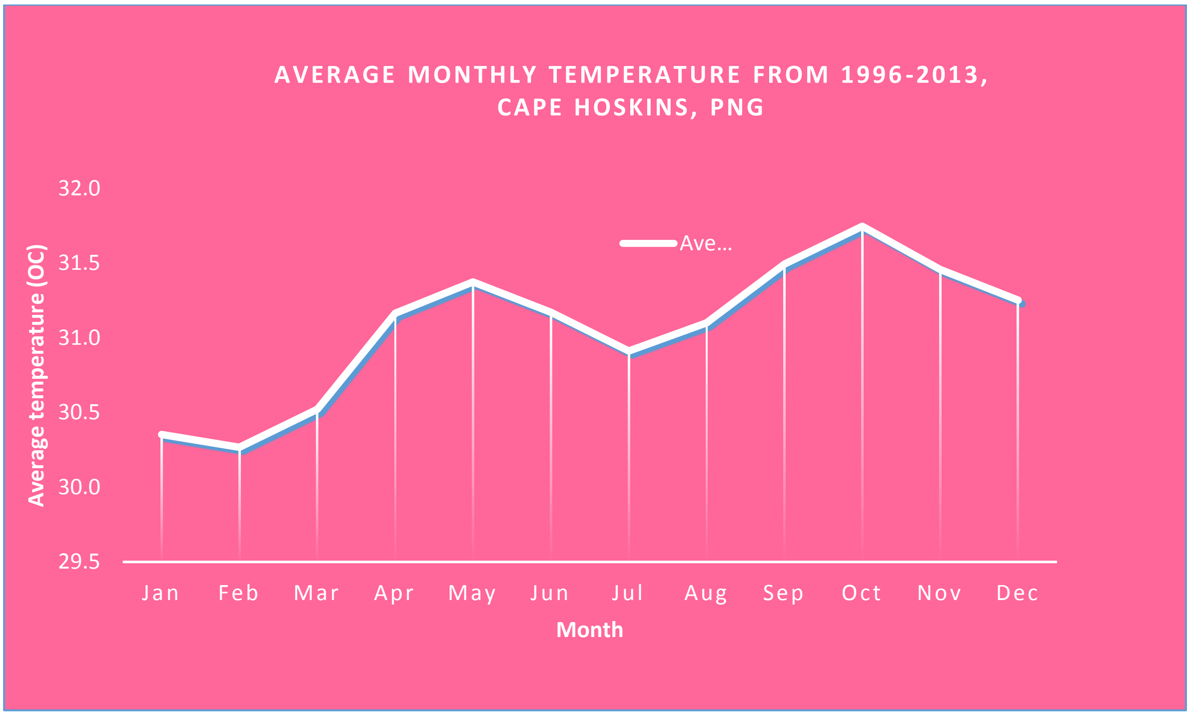


Figure 4.6: Average monthly temperature on an annual basis from 1996-2013, Cape Hoskins, PNG (Source: PNG NWS)

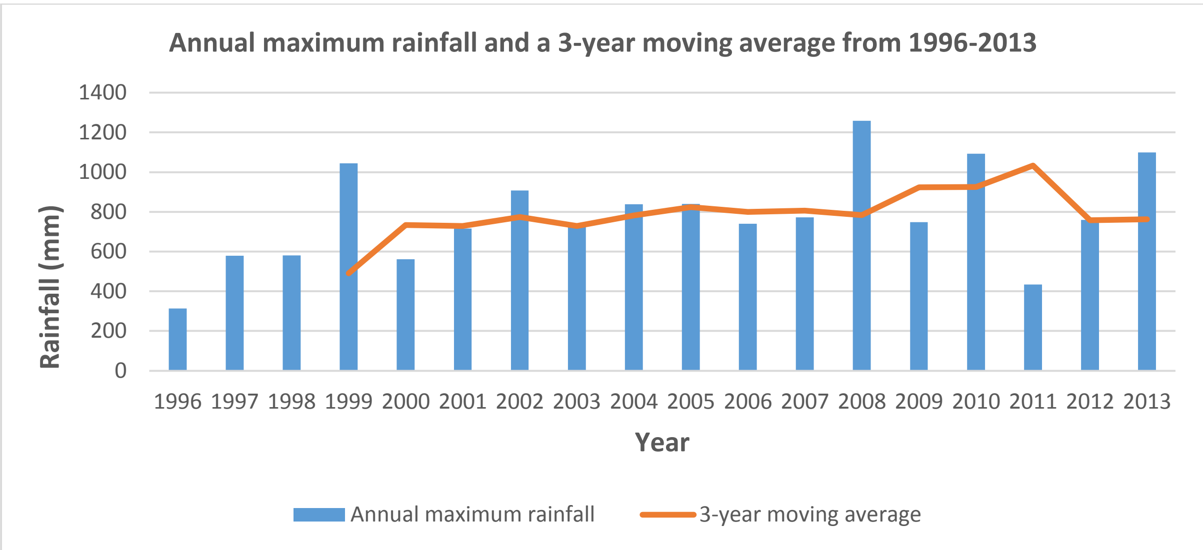


Figure 4.7: Graph showing the rainfall trend and its relation with a 3-years moving average (Data source: PNG NWS)

Appendix 4.2: Frequency Factors K for Gamma and log-Pearson Type III Distributions (Haan, 1977)

	Recurrence Interval in Years							
	1.0101	2	5	10	25	50	100	200
SKEW COEFFICIENT	Per cent Chance (>=) = 1-F							
Cs	99	50	20	10	4	2	1	0.5
3	-0.667	-0.396	0.420	1.180	2.278	3.152	4.051	4.970
2.9	-0.690	-0.390	0.440	1.195	2.277	3.134	4.013	4.904
2.8	-0.714	-0.384	0.460	1.210	2.275	3.114	3.973	4.847
2.7	-0.740	-0.376	0.479	1.224	2.272	3.093	3.932	4.783
2.6	-0.769	-0.368	0.499	1.238	2.267	3.071	3.889	4.718
2.5	-0.799	-0.360	0.518	1.250	2.262	3.048	3.845	4.652
2.4	-0.832	-0.351	0.537	1.262	2.256	3.023	3.800	4.584
2.3	-0.867	-0.341	0.555	1.274	2.248	2.997	3.753	4.515
2.2	-0.905	-0.330	0.574	1.284	2.240	2.970	3.705	4.444
2.1	-0.946	-0.319	0.592	1.294	2.230	2.942	3.656	4.372
2	-0.990	-0.307	0.609	1.302	2.219	2.912	3.605	4.298
1.9	-1.037	-0.294	0.627	1.310	2.207	2.881	3.553	4.223
1.8	-1.087	-0.282	0.643	1.318	2.193	2.848	3.499	4.147
1.7	-1.140	-0.268	0.660	1.324	2.179	2.815	3.444	4.069
1.6	-1.197	-0.254	0.675	1.329	2.163	2.780	3.388	3.990
1.5	-1.256	-0.240	0.690	1.333	2.146	2.743	3.330	3.910
1.4	-1.318	-0.225	0.705	1.337	2.128	2.706	3.271	3.828
1.3	-1.383	-0.210	0.719	1.339	2.108	2.666	3.211	3.745
1.2	-1.449	-0.195	0.732	1.340	2.087	2.626	3.149	3.661
1.1	-1.518	-0.180	0.745	1.341	2.066	2.585	3.087	3.575
1	-1.588	-0.164	0.758	1.340	2.043	2.542	3.022	3.489
0.9	-1.660	-0.148	0.769	1.339	2.018	2.498	2.957	3.401
0.8	-1.733	-0.132	0.780	1.336	1.993	2.453	2.891	3.312
0.7	-1.806	-0.116	0.790	1.333	1.967	2.407	2.824	3.223
0.6	-1.880	-0.099	0.800	1.328	1.939	2.359	2.755	3.132
0.5	-1.955	-0.083	0.808	1.323	1.910	2.311	2.686	3.041
0.4	-2.029	-0.066	0.816	1.317	1.880	2.261	2.615	2.949
0.3	-2.104	-0.050	0.824	1.309	1.849	2.211	2.544	2.856
0.2	-2.178	-0.033	0.830	1.301	1.818	2.159	2.472	2.763
0.1	-2.252	-0.017	0.836	1.292	1.785	2.107	2.400	2.67
0	-2.326	0.000	0.842	1.282	1.751	2.054	2.326	2.576
-0.1	-2.4	0.017	0.846	1.27	1.716	2.000	2.252	2.482
-0.2	-2.472	0.033	0.850	1.258	1.680	1.945	2.178	2.388
-0.3	-2.544	0.050	0.853	1.245	1.643	1.890	2.104	2.294
-0.4	-2.615	0.066	0.855	1.231	1.606	1.834	2.029	2.201
-0.5	-2.686	0.083	0.856	1.216	1.567	1.777	1.955	2.108
-0.6	-2.755	0.099	0.857	1.200	1.528	1.720	1.880	2.016
-0.7	-2.824	0.116	0.857	1.183	1.488	1.663	1.806	1.926
-0.8	-2.891	0.132	0.856	1.166	1.448	1.606	1.733	1.837
-0.9	-2.957	0.148	0.854	1.147	1.407	1.549	1.660	1.749
-1	-3.022	0.164	0.852	1.128	1.366	1.492	1.588	1.664
-1.1	-3.087	0.180	0.848	1.107	1.324	1.435	1.518	1.581
-1.2	-3.149	0.195	0.844	1.086	1.282	1.379	1.449	1.501
-1.3	-3.211	0.210	0.838	1.064	1.240	1.324	1.383	1.424
-1.4	-3.271	0.225	0.832	1.041	1.198	1.270	1.318	1.351
-1.5	-3.33	0.240	0.825	1.018	1.157	1.217	1.256	1.282
-1.6	-3.880	0.254	0.817	0.994	1.116	1.166	1.197	1.216
-1.7	-3.444	0.268	0.808	0.970	1.075	1.116	1.140	1.155
-1.8	-3.499	0.282	0.799	0.945	1.035	1.069	1.087	1.097
-1.9	-3.553	0.294	0.788	0.920	0.996	1.023	1.037	1.044

-2	-3.605	0.307	0.777	0.895	0.959	0.980	0.990	0.995
-2.1	-3.656	0.319	0.765	0.869	0.923	0.939	0.946	0.949
-2.2	-3.705	0.330	0.752	0.844	0.888	0.900	0.905	0.907
-2.3	-3.753	0.341	0.739	0.819	0.855	0.864	0.867	0.869
-2.4	-3.800	0.351	0.725	0.795	0.823	0.830	0.832	0.833
-2.5	-3.845	0.360	0.711	0.711	0.793	0.798	0.799	0.800
-2.6	-3.899	0.368	0.696	0.747	0.764	0.768	0.769	0.769
-2.7	-3.932	0.376	0.681	0.724	0.738	0.740	0.740	0.741
-2.8	-3.973	0.384	0.666	0.702	0.712	0.714	0.714	0.714
-2.9	-4.013	0.390	0.651	0.681	0.683	0.689	0.690	0.690
-3	-4.051	0.396	0.636	0.660	0.666	0.666	0.667	0.667

Appendix 4.3: Flood Frequency Calculations using estimated Peak Discharge for Dagi River using log-Pearson Analysis III.

Flood Frequency Calculations using estimated Peak Discharge for Dagi River using log-Pearson Analysis III							
	Rank	Peak Q (m^3/s)	(m^3/s)	avg(logQ))^2	avg(logQ))^3	(Tr)= [(n+1)/m]	= [1/Return Period or 1/Tr]
1990	1	1266.42	3.103	0.000333	0.00000607	21.00	0.04762
1996	2	1248.75	3.096	0.000147	0.00000179	10.50	0.09524
1997	3	1238.16	3.093	0.000071	0.00000060	7.00	0.14286
1998	4	1235.68	3.092	0.000057	0.00000043	5.25	0.19048
1999	5	1231.92	3.091	0.000039	0.00000024	4.20	0.23810
2000	6	1228.65	3.089	0.000026	0.00000013	3.50	0.28571
2001	7	1227.85	3.089	0.000023	0.00000011	3.00	0.33333
2002	8	1227.68	3.089	0.000023	0.00000011	2.63	0.38095
2003	9	1226.83	3.089	0.000020	0.00000009	2.33	0.42857
2004	10	1226.82	3.089	0.000020	0.00000009	2.10	0.47619
2005	11	1224.94	3.088	0.000014	0.00000005	1.91	0.52381
2006	12	1222.13	3.087	0.000008	0.00000002	1.75	0.57143
2007	13	1218.12	3.086	0.000002	0.00000000	1.62	0.61905
2008	14	1212.35	3.084	0.000001	0.00000000	1.50	0.66667
2009	15	1208.73	3.082	0.000004	-0.00000001	1.40	0.71429
2010	16	1186.22	3.074	0.000103	-0.00000105	1.31	0.76190
2011	17	1183.28	3.073	0.000127	-0.00000142	1.24	0.80952
2012	18	1173.92	3.070	0.000216	-0.00000318	1.17	0.85714
1980	19	1156.81	3.063	0.000444	-0.00000936	1.11	0.90476
2013	20	1148.56	3.060	0.000585	-0.00001414	1.05	0.95238
		AVERAGE	AVERAGE	SUM	SUM		
		1214.691	3.084	0.002262	-0.00001942		
			EXCEL FUNCTIONS				
			VAR	Variance:	0.000119059		
			STDEV	Standard Deviation:	0.010911418		
			SKEW	Skew Coefficient (Cs):	-0.87420534		

Appendix 4.4: An example of time series results for HEC-HMS simulation runs showing upstream and downstream Dagi River for the 2014 flood.

Project: Dagi River Catchment Model   Simulation Run: 24th Feb2014_Current
Subbasin: SB-1 Dagi Upstream

Start of Run: 24Feb2014, 05:00   Basin Model: Dagi River Catchment_Current
End of Run: 24Feb2014, 17:00   Meteorologic Model: GaugeWeightsFeb2014
Compute Time: 21Apr2015, 14:32:53   Control Specifications: Dagi Control Specifications

Date	Time	Precip (MM)	Loss (MM)	Excess (MM)	Direct Flow (M3/S)	Baseflow (M3/S)	Total Flow (M3/S)
24Feb2014	05:00				0.0	357.5	357.5
24Feb2014	05:05	0.07	0.07	0.00	0.0	357.2	357.2
24Feb2014	05:10	0.07	0.07	0.00	0.0	357.0	357.0
24Feb2014	05:15	0.07	0.07	0.00	0.0	356.7	356.7
24Feb2014	05:20	0.07	0.07	0.00	0.0	356.4	356.4
24Feb2014	05:25	0.07	0.06	0.01	0.0	356.1	356.1
24Feb2014	05:30	0.07	0.06	0.02	0.2	355.8	356.0
24Feb2014	05:35	0.07	0.05	0.02	0.7	355.5	356.2
24Feb2014	05:40	0.07	0.05	0.03	1.6	355.2	356.8
24Feb2014	05:45	0.07	0.04	0.03	2.9	354.9	357.9
24Feb2014	05:50	0.07	0.04	0.03	4.8	354.6	359.4
24Feb2014	05:55	0.07	0.04	0.04	7.0	354.3	361.4
24Feb2014	06:00	0.08	0.04	0.04	9.5	354.0	363.5
24Feb2014	06:05	0.08	0.04	0.04	12.0	353.8	365.7
24Feb2014	06:10	0.08	0.03	0.04	14.4	353.5	367.9
24Feb2014	06:15	0.08	0.03	0.04	16.7	353.2	369.9
24Feb2014	06:20	0.08	0.03	0.05	18.9	352.9	371.8
24Feb2014	06:25	0.08	0.03	0.05	20.9	352.6	373.5
24Feb2014	06:30	0.08	0.03	0.05	22.7	352.3	375.0
24Feb2014	06:35	0.08	0.03	0.05	24.3	352.0	376.4
24Feb2014	06:40	0.08	0.03	0.05	25.9	351.7	377.6
24Feb2014	06:45	0.08	0.03	0.05	27.3	351.4	378.8
24Feb2014	06:50	0.08	0.03	0.05	28.6	351.2	379.8
24Feb2014	06:55	0.08	0.03	0.06	29.9	350.9	380.8
24Feb2014	07:00	0.08	0.03	0.06	31.1	350.6	381.6
24Feb2014	07:05	0.08	0.03	0.06	32.2	350.3	382.5
24Feb2014	07:10	0.09	0.03	0.06	33.2	350.0	383.3

Project: Dagi River Catchment Model   Simulation Run: 24th Feb2014_Current
Sink: Dagi Outlet

Start of Run: 24Feb2014, 05:00   Basin Model: Dagi River Catchment_Current
End of Run: 24Feb2014, 17:00   Meteorologic Model: GaugeWeightsFeb2014
Compute Time: 21Apr2015, 14:32:53   Control Specifications: Dagi Control Specifications

Date	Time	Outflow (M3/S)
24Feb2014	07:10	693.8
24Feb2014	07:15	694.0
24Feb2014	07:20	694.4
24Feb2014	07:25	694.8
24Feb2014	07:30	695.4
24Feb2014	07:35	696.1
24Feb2014	07:40	697.0
24Feb2014	07:45	698.0
24Feb2014	07:50	699.1
24Feb2014	07:55	700.5
24Feb2014	08:00	701.9
24Feb2014	08:05	703.6
24Feb2014	08:10	705.3
24Feb2014	08:15	707.2
24Feb2014	08:20	709.2
24Feb2014	08:25	711.3
24Feb2014	08:30	713.5
24Feb2014	08:35	715.8
24Feb2014	08:40	718.2
24Feb2014	08:45	720.7
24Feb2014	08:50	723.1
24Feb2014	08:55	725.6
24Feb2014	09:00	728.2
24Feb2014	09:05	730.7
24Feb2014	09:10	733.2

NB: Because of the length of the rows, data has been shortened to see only some results as an example.

Appendix 4.5: Estimated annual rainfall, temperatures and discharge within the Dagi Catchment

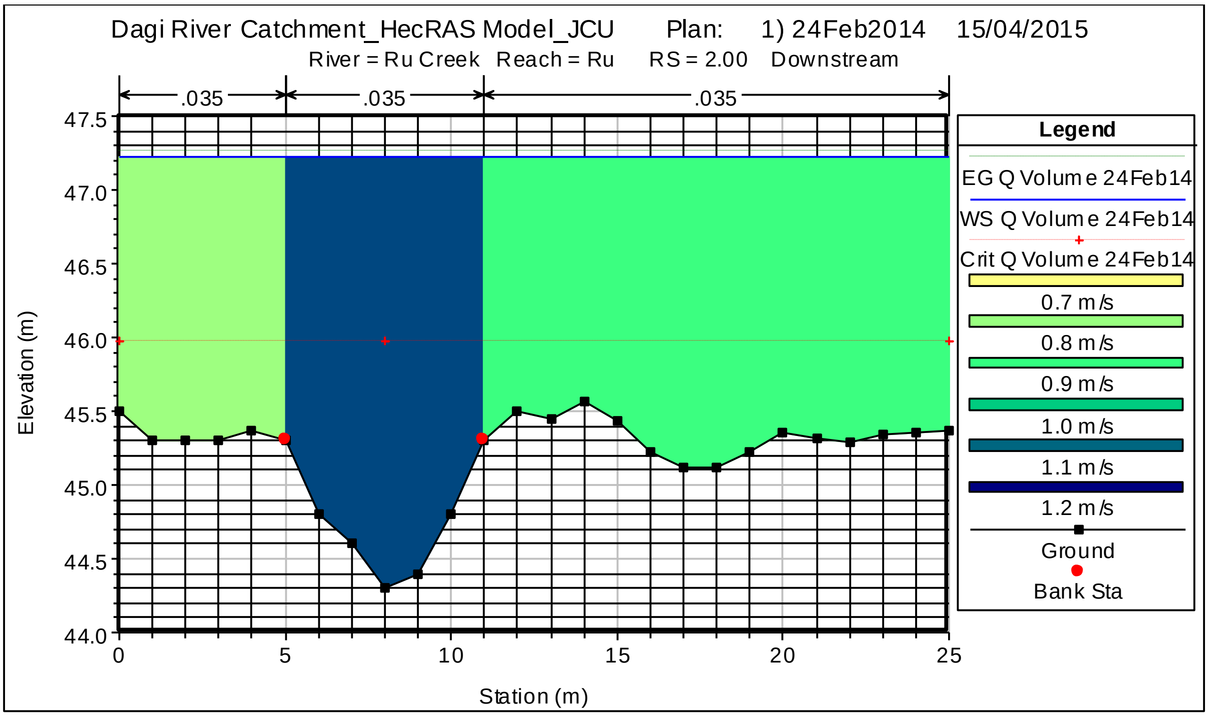
Table 4.4: Estimated annual rainfall, temperatures and discharge within the Dagi Catchment.

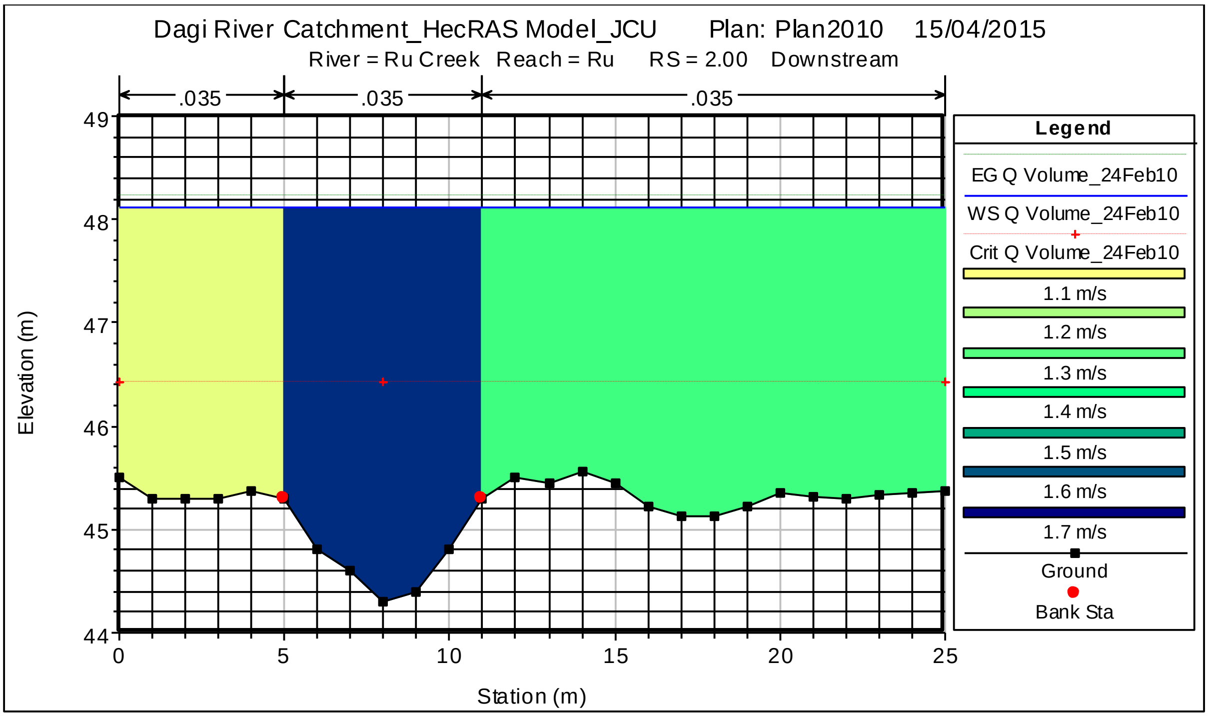
(Source: WNBPG Disaster Office, 2013)

Year	Annual Rainfall (mm)	Annual Min. Temp. (^{O}C)	Annual Max. Temp. (^{O}C)	Average Annual Discharge (Q) (m^3/s) (estimated)
1980	3543	23.9	31.1	1156.81
1990	3745	23.6	31.2	1183.28
1996	2121.6	23.3	31.2	1148.56
1997	2426.3	23.7	31.3	1173.92
1998	4655.5	23.7	31	1266.42
1999	3805.2	23.3	31.1	1227.85
2000	3349.6	23.4	31.1	1222.13
2001	2909.6	23.6	31	1208.73
2002	3653.4	23.8	31.1	1224.94
2003	3784	23.6	31.2	1227.68
2004	3280.8	23.6	30.8	1218.12
2005	4179	23.7	30.9	1235.68
2006	3519	23.7	30.8	1226.83
2007	3908	23.6	30.9	1231.92
2008	3781.8	23.2	31	1226.82
2009	3441.2	23.5	31	1212.35
2010	4439	23.6	31.2	1248.75
2011	2657.2	23.1	31.2	1186.22
2012	3818.2	23.1	31.3	1228.65
2013	4239	23.3	31.4	1238.16
2014	4324.5	23.2	31.1	1240.77
NB: The 2014 annual rainfall data were recently updated and became available in 2016 after much of the analysis to the thesis were done using fieldwork data. Fieldwork data for rainfall were collected from rain gauge for 10 days with a 12-hour duration in February 2014 which were used in rainfall simulation.				

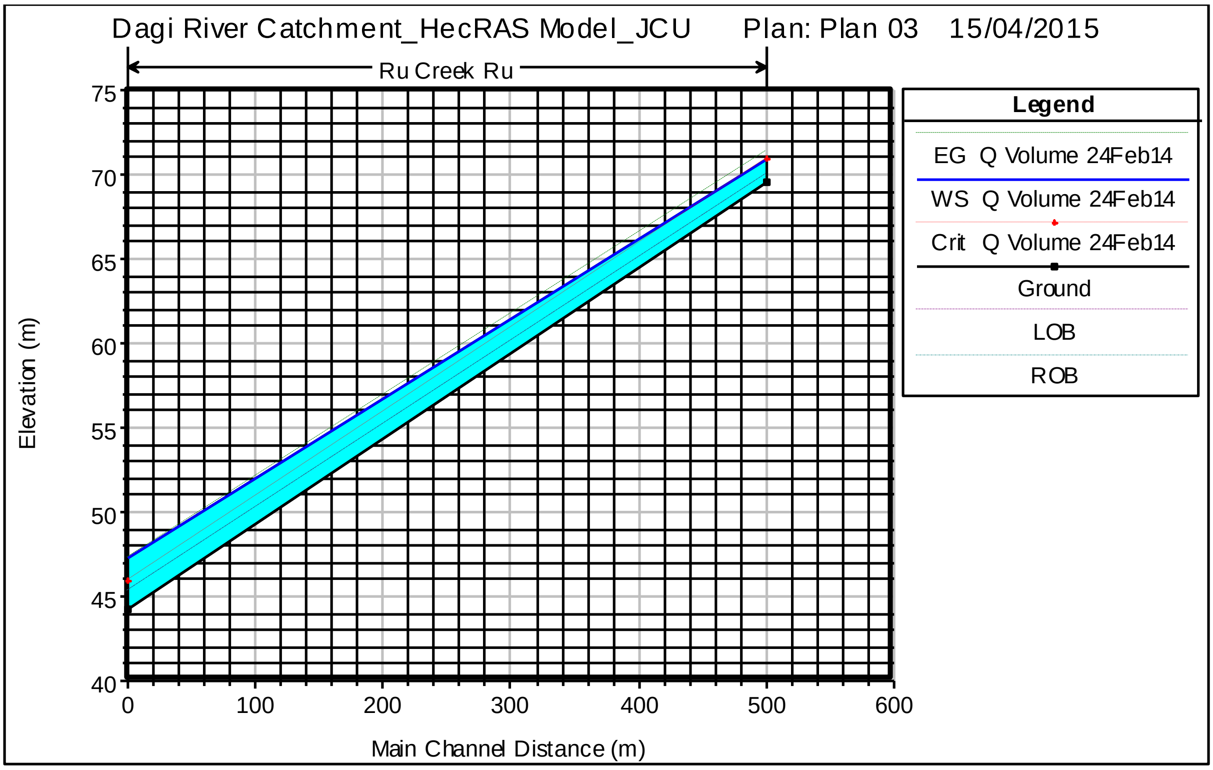
Appendix 4.6: Distribution of floodwater, velocity and stream power in cross-sections

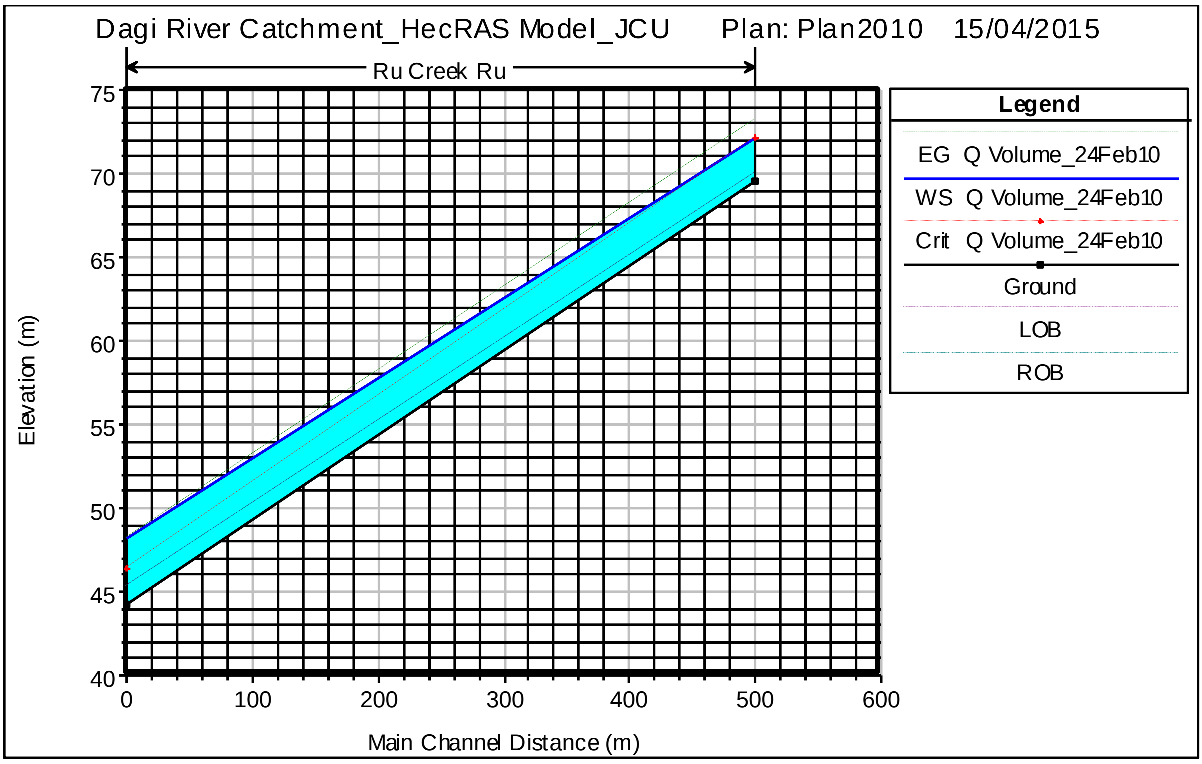
SC 2: Ru Creek- Cross-sectional plots for Ru Creek during 2014 and 2010 floods



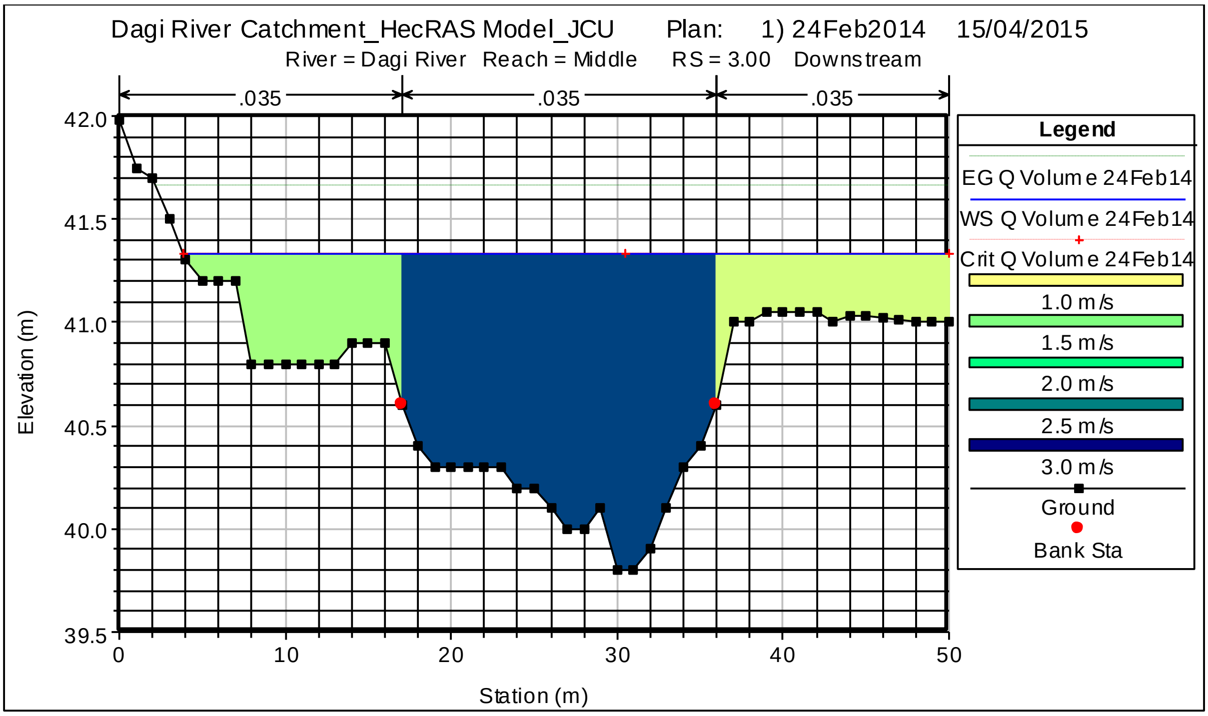


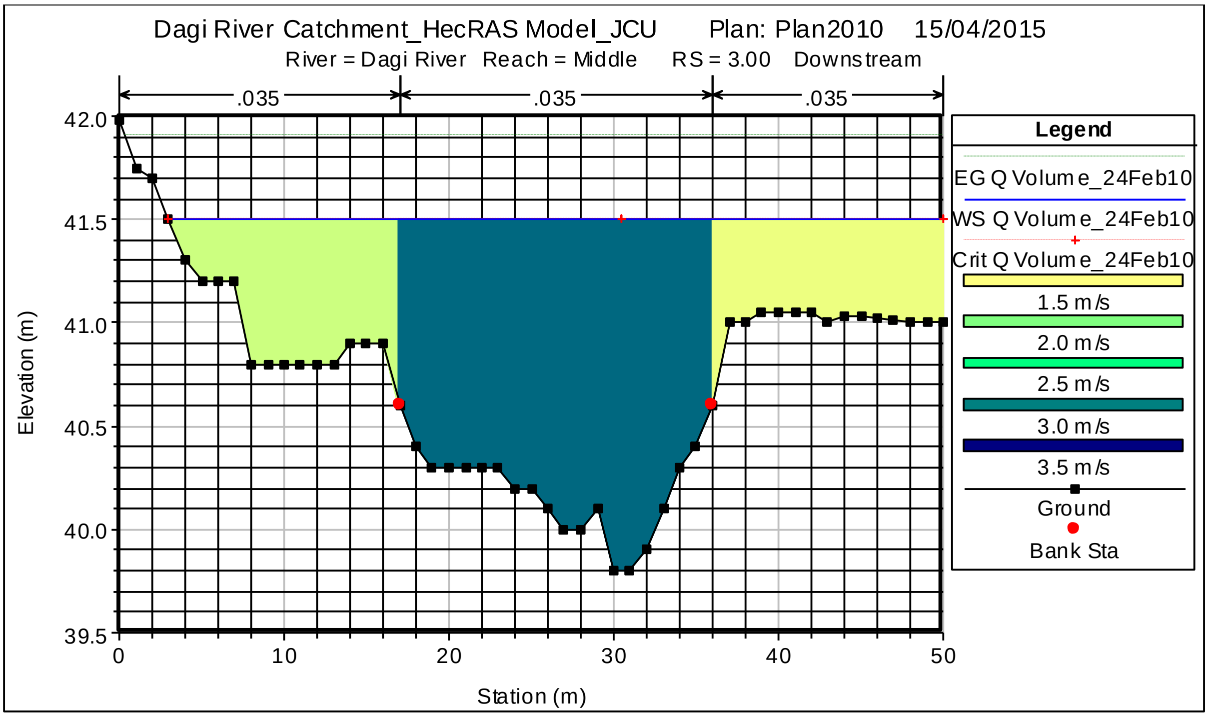
Longitudinal profile plots for Ru Creek during 2014 and 2010 floods



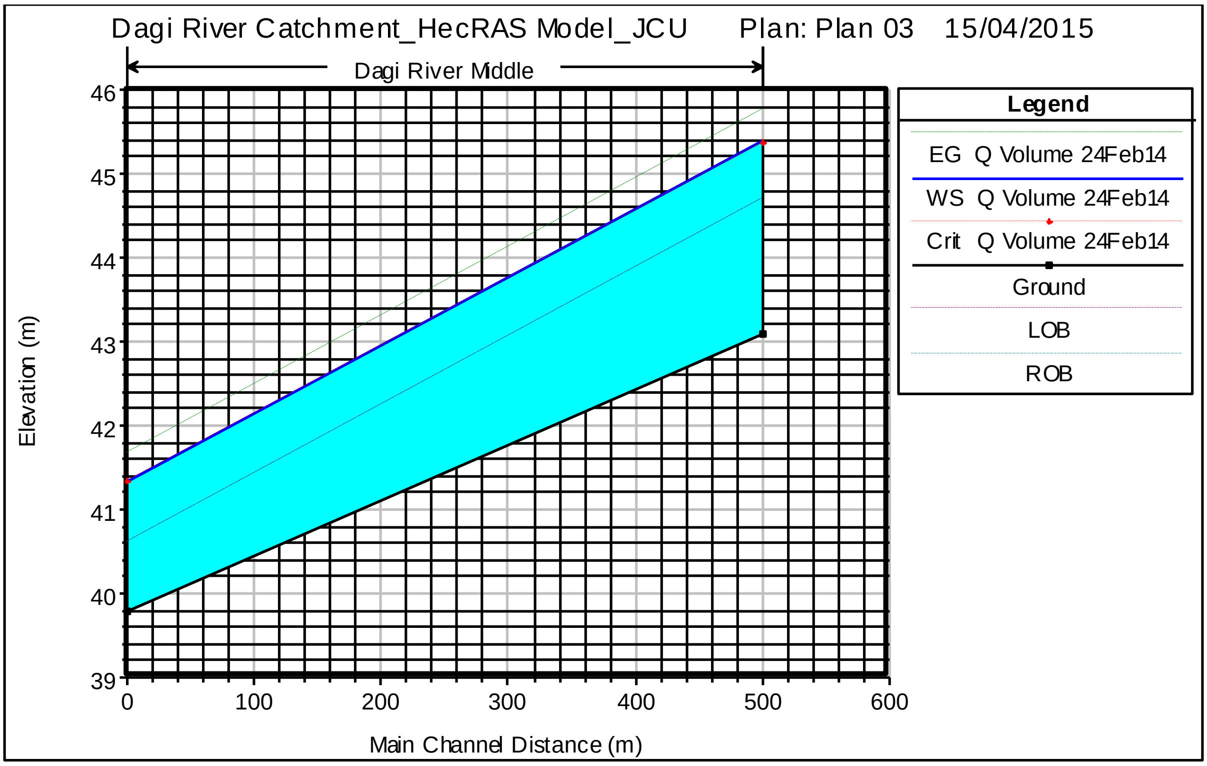


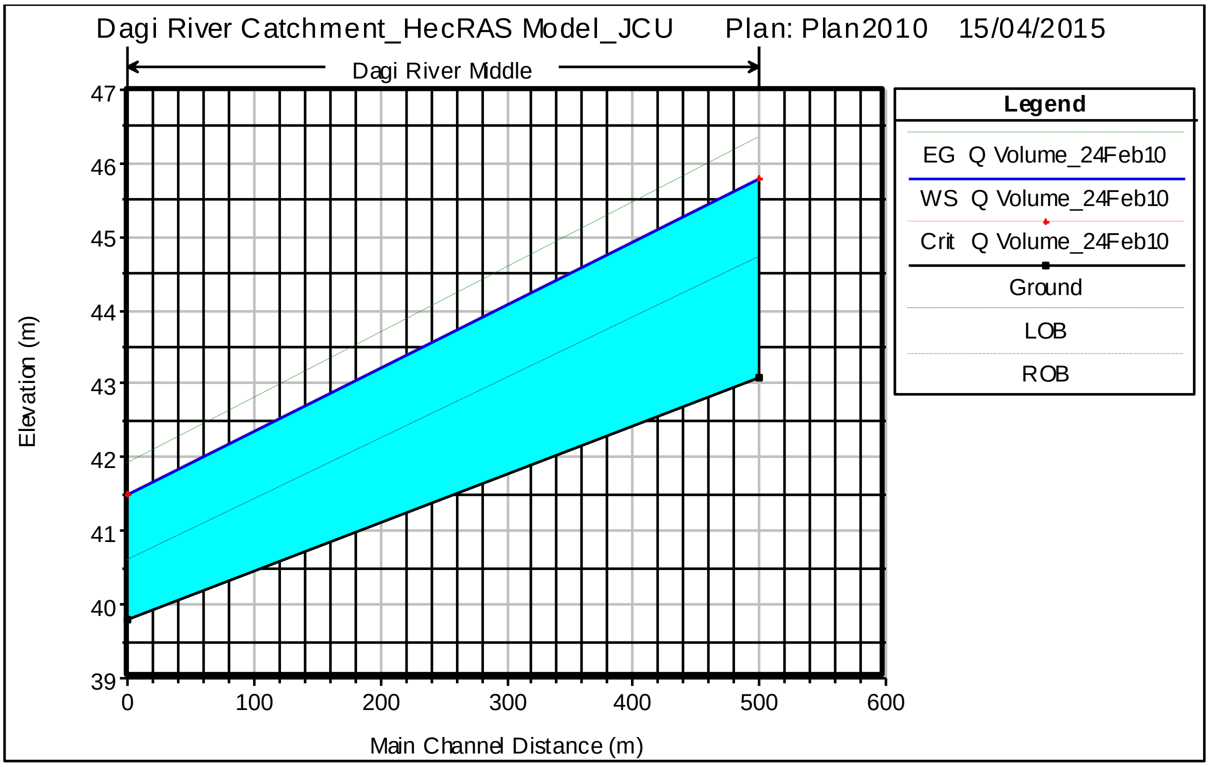
SC 3: Dagi River - Middle Reach Cross-sectional plots during 2014 and 2010 floods

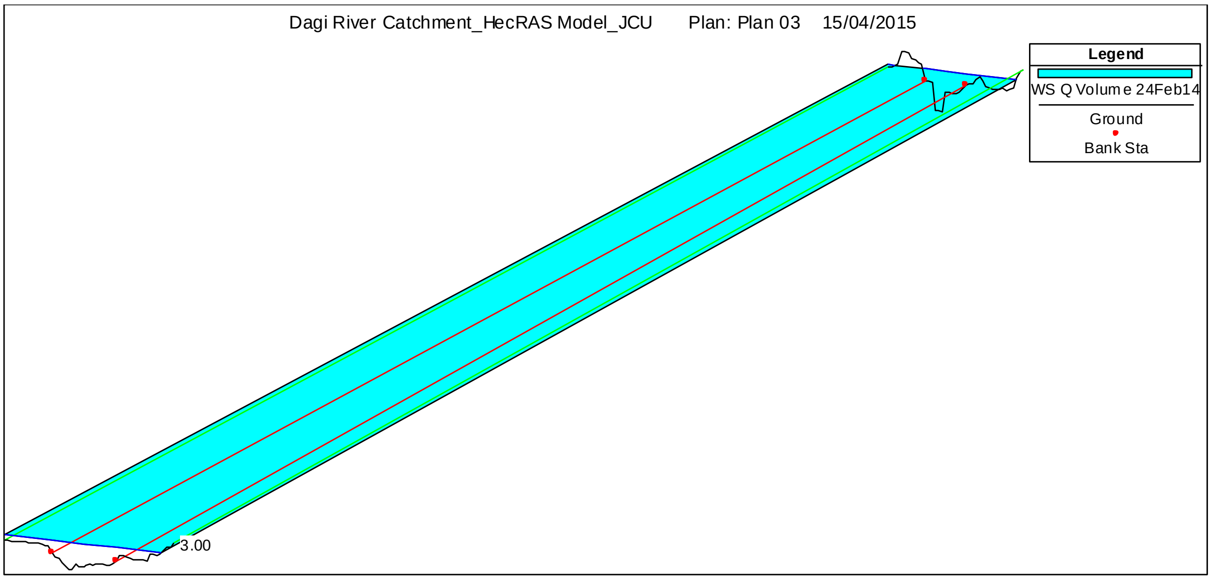


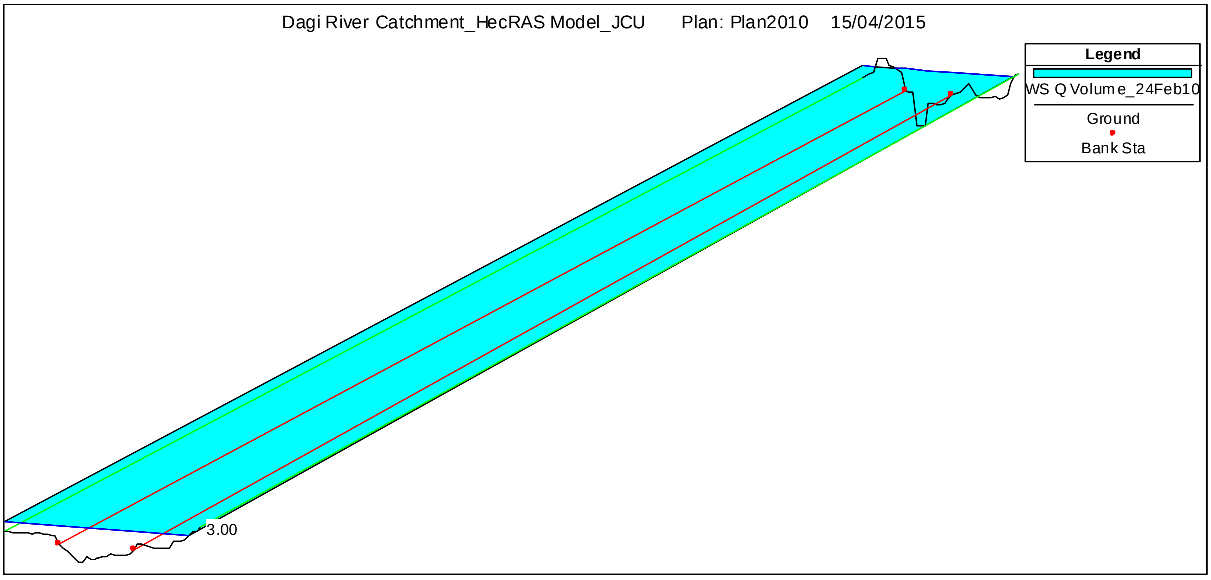


Longitudinal profile plots for Dagi River - Middle Reach during 2014 and 2010 floods

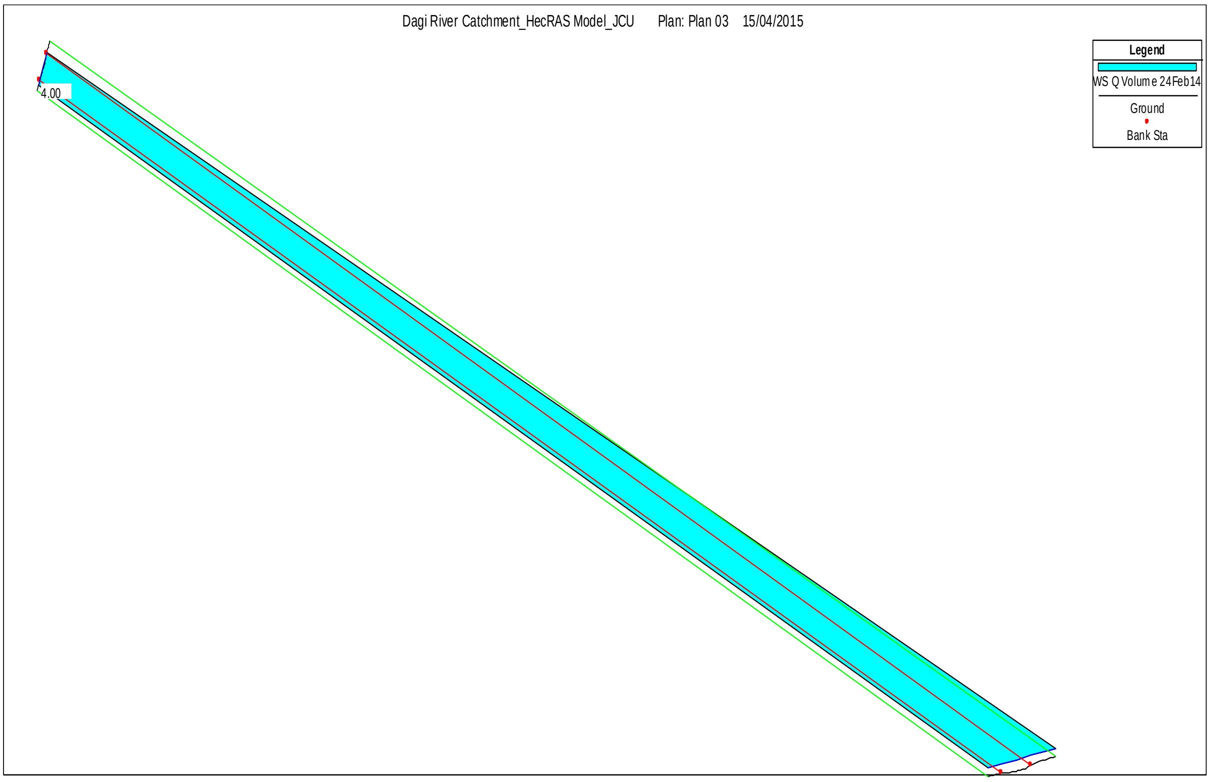





Dagi River Catchment_HecRAS Model_JCU Plan: Plan 03 15/04/2015
Legend
WS Q Volume 24Feb14
Ground
Bank Sta
3.00

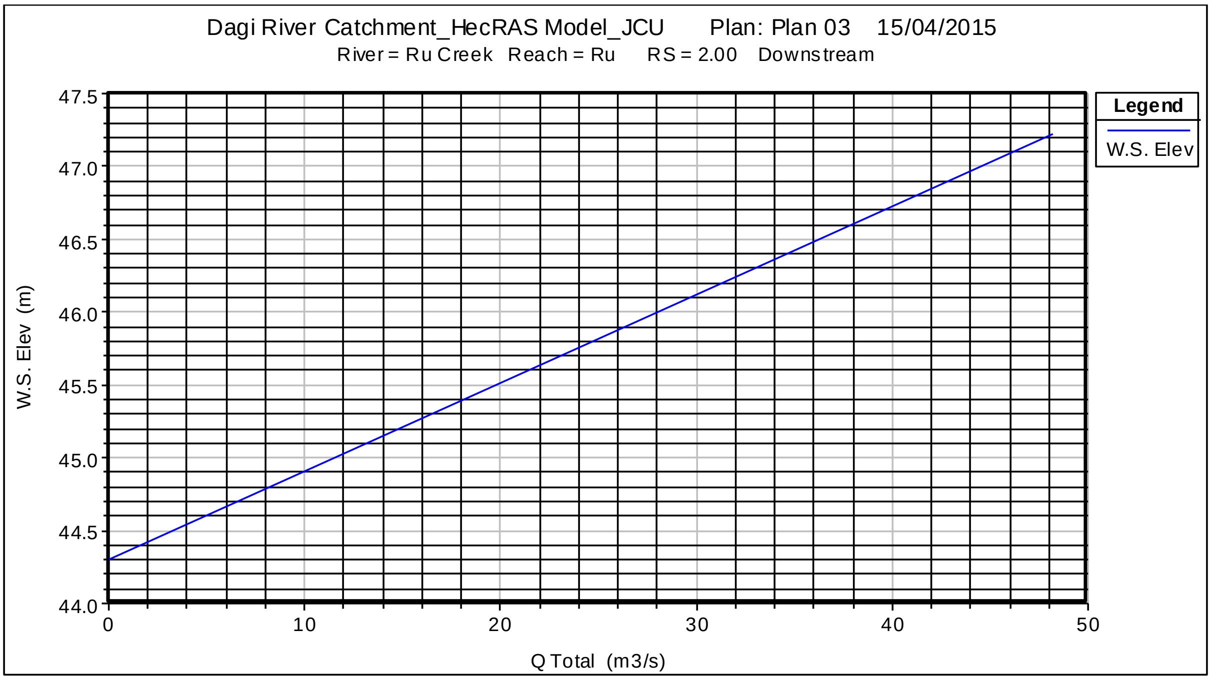

Dagi River Catchment_HecRAS Model_JCU Plan: Plan2010 15/04/2015
Legend
WS Q Volume_24Feb10
Ground
Bank Sta
3.00

Z, Y, Z longitudinal profile plots for Lamegi River during 2014 and 2010 floods.

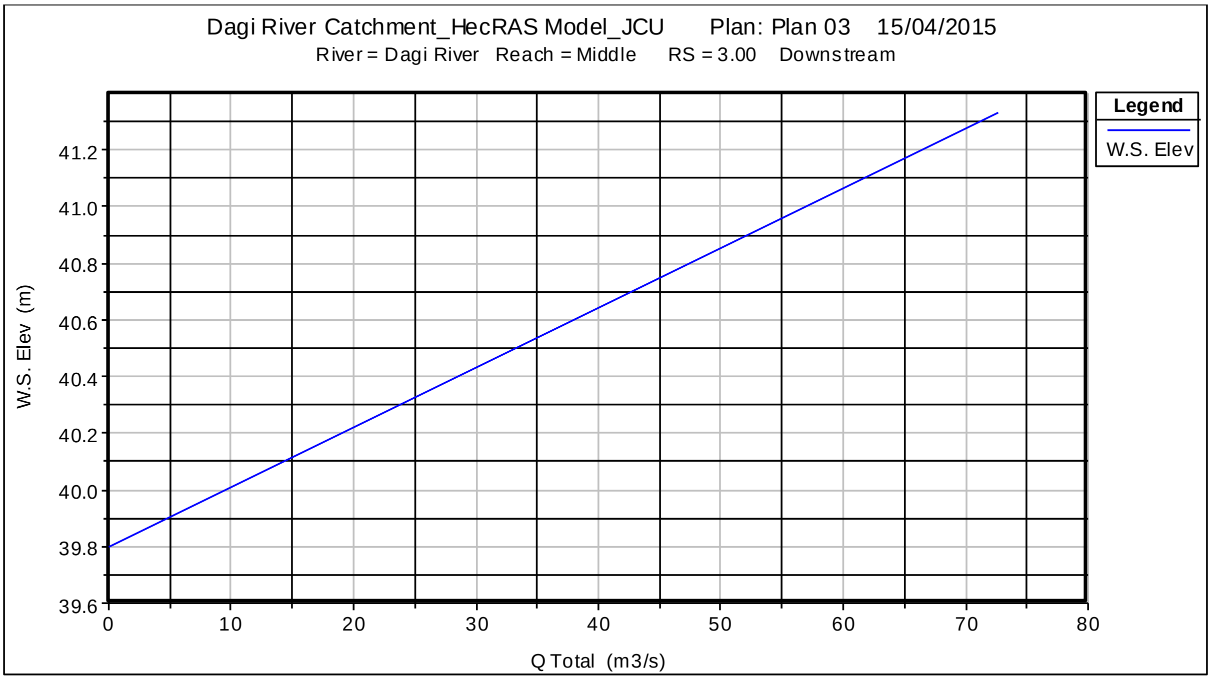


Appendix 4.7: Water surface profiles and rating curves

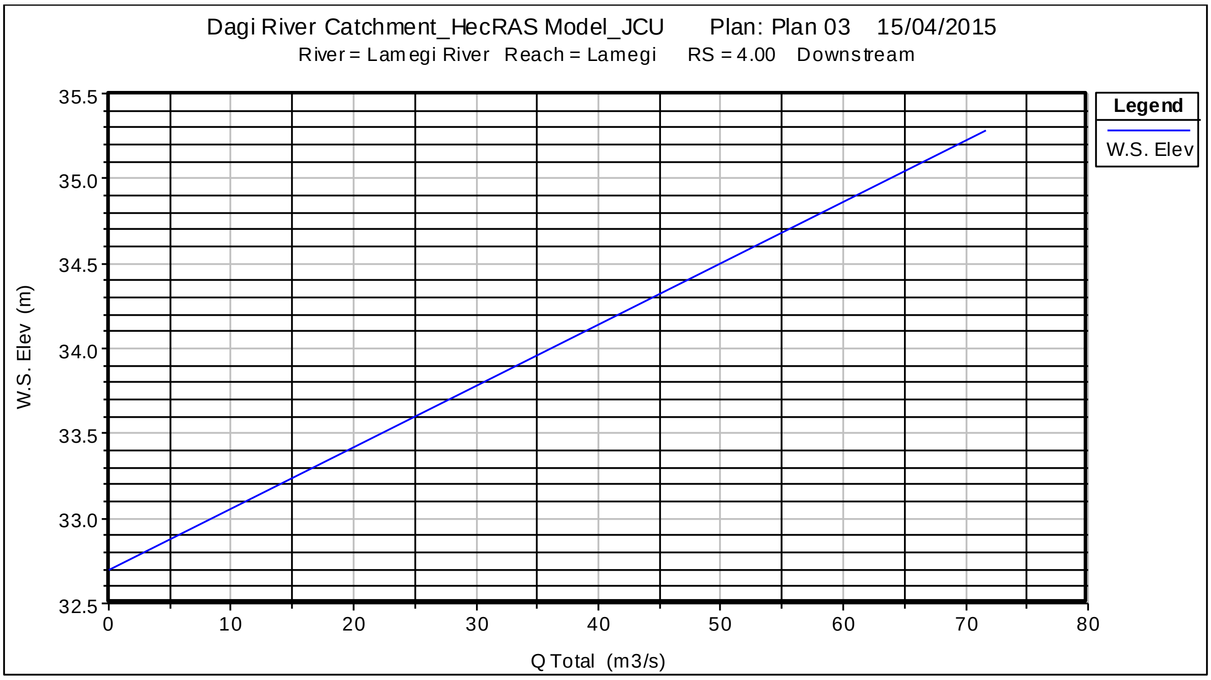
Rating curve based on computed water surface elevations for Ru Creek.



Rating curve based on computed water surface elevations for Dagi River-Middle Reach.



Rating curve based on computed water surface elevations for Lamegi River



Appendix 4.8: Stream hydraulics data

Detailed output tables for Dagi River-Upstream during the 2014 and 2010 floods

River: Dagi River | Profile: Q Volume 24Feb14
Reach: Upstream | RS: 1.00 | Plan: 24Feb2014

Plan: 24Feb2014 Dagi River Upstream RS: 1.00 Profile: Q Volume 24Feb14

		Element	Left OB	Channel	Right OB
E.G. Elev (m)	61.01	Wt. n-Val.	0.035	0.035	0.035
Vel Head (m)	0.56	Reach Len. (m)	1000.00	1000.00	1000.00
W.S. Elev (m)	60.45	Flow Area (m2)	4.57	19.84	5.83
Crit W.S. (m)	60.45	Area (m2)	4.57	19.84	5.83
E.G. Slope (m/m)	0.006782	Flow (m3/s)	7.31	71.45	8.20
Q Total (m3/s)	86.96	Top Width (m)	7.38	9.00	11.89
Top Width (m)	28.27	Avg. Vel. (m/s)	1.60	3.60	1.41
Vel Total (m/s)	2.88	Hydr. Depth (m)	0.62	2.20	0.49
Max Chl Dpth (m)	3.25	Conv. (m3/s)	88.8	867.6	99.5
Conv. Total (m3/s)	1055.9	Wetted Per. (m)	8.20	10.47	12.65
Length Wtd. (m)	1000.00	Shear (N/m2)	37.09	125.97	30.65
Min Ch El (m)	57.20	Stream Power (N/m s)	1915.12	0.00	0.00
Alpha	1.34	Cum Volume (1000 m3)	6.09	17.69	3.12
Frctn Loss (m)	7.51	Cum SA (1000 m2)			
C & E Loss (m)	0.06				

River: Dagi River | Profile: Q Volume_24Feb10
Reach: Upstream | RS: 1.00 | Plan: 24Feb2010

Plan: 24Feb2010 Dagi River Upstream RS: 1.00 Profile: Q Volume_24Feb10

		Element	Left OB	Channel	Right OB
E.G. Elev (m)	61.47	Wt. n-Val.	0.035	0.035	0.035
Vel Head (m)	0.59	Reach Len. (m)	1000.00	1000.00	1000.00
W.S. Elev (m)	60.88	Flow Area (m2)	9.30	23.75	11.59
Crit W.S. (m)	60.88	Area (m2)	9.30	23.75	11.59
E.G. Slope (m/m)	0.006107	Flow (m3/s)	14.91	91.53	21.51
Q Total (m3/s)	127.95	Top Width (m)	14.06	9.00	14.00
Top Width (m)	37.06	Avg. Vel. (m/s)	1.60	3.85	1.86
Vel Total (m/s)	2.87	Hydr. Depth (m)	0.66	2.64	0.83
Max Chl Dpth (m)	3.68	Conv. (m3/s)	190.8	1171.2	275.2
Conv. Total (m3/s)	1637.2	Wetted Per. (m)	15.30	10.47	15.28
Length Wtd. (m)	1000.00	Shear (N/m2)	36.40	135.81	45.41
Min Ch El (m)	57.20	Stream Power (N/m s)	1915.12	0.00	0.00
Alpha	1.40	Cum Volume (1000 m3)	11.57	22.11	6.89
Frctn Loss (m)	7.38	Cum SA (1000 m2)			
C & E Loss (m)	0.01				

Detailed output tables for Ru creek during the 2014 and 2010 floods.

River: Ru Creek Profile: Q Volume 24Feb14

Reach: Ru RS: 2.00 Plan: 24Feb2014

Plan: 24Feb2014 Ru Creek Ru RS: 2.00 Profile: Q Volume 24Feb14

		Element	Left OB	Channel	Right OB
E.G. Elev (m)	47.27	Wt. n-Val.	0.035	0.035	0.035
Vel Head (m)	0.05	Reach Len. (m)	1000.00	1000.00	1000.00
W.S. Elev (m)	47.22	Flow Area (m2)	9.43	15.12	26.44
Crit W.S. (m)	45.97	Area (m2)	9.43	15.12	26.44
E.G. Slope (m/m)	0.000496	Flow (m3/s)	7.50	17.09	23.58
Q Total (m3/s)	48.17	Top Width (m)	5.00	6.00	14.00
Top Width (m)	25.00	Avg. Vel. (m/s)	0.80	1.13	0.89
Vel Total (m/s)	0.94	Hydr. Depth (m)	1.89	2.52	1.89
Max Chl Dpth (m)	2.92	Conv. (m3/s)	336.8	767.6	1059.3
Conv. Total (m3/s)	2163.7	Wetted Per. (m)	6.74	6.38	15.93
Length Wtd. (m)	1000.00	Shear (N/m2)	6.79	11.51	8.07
Min Ch El (m)	44.30	Stream Power (N/m s)	1196.95	0.00	0.00
Alpha	1.05	Cum Volume (1000 m3)	8.52	15.34	13.43
Frctn Loss (m)	1.48	Cum SA (1000 m2)			
C & E Loss (m)	0.03				

River: Ru Creek Profile: Q Volume_24Feb10

Reach: Ru RS: 2.00 Plan: 24Feb2010

Plan: 24Feb2010 Ru Creek Ru RS: 2.00 Profile: Q Volume_24Feb10

		Element	Left OB	Channel	Right OB
E.G. Elev (m)	48.22	Wt. n-Val.	0.035	0.035	0.035
Vel Head (m)	0.10	Reach Len. (m)	1000.00	1000.00	1000.00
W.S. Elev (m)	48.12	Flow Area (m2)	13.94	20.53	39.08
Crit W.S. (m)	46.42	Area (m2)	13.94	20.53	39.08
E.G. Slope (m/m)	0.000701	Flow (m3/s)	15.74	33.85	51.84
Q Total (m3/s)	101.43	Top Width (m)	5.00	6.00	14.00
Top Width (m)	25.00	Avg. Vel. (m/s)	1.13	1.65	1.33
Vel Total (m/s)	1.38	Hydr. Depth (m)	2.79	3.42	2.79
Max Chl Dpth (m)	3.82	Conv. (m3/s)	594.4	1278.6	1957.7
Conv. Total (m3/s)	3830.8	Wetted Per. (m)	7.65	6.38	16.83
Length Wtd. (m)	1000.00	Shear (N/m2)	12.53	22.12	15.96
Min Ch El (m)	44.30	Stream Power (N/m s)	1196.95	0.00	0.00
Alpha	1.05	Cum Volume (1000 m3)	13.89	20.50	20.63
Frctn Loss (m)	1.83	Cum SA (1000 m2)			
C & E Loss (m)	0.05				

Detailed output tables for Dagi River-Middle Reach during the 2014 and 2010 floods.

River: Dagi River Profile: Q Volume 24Feb14

Reach Middle RS: 3.00 Plan: 24Feb2014

Plan: 24Feb2014 Dagi River Middle RS: 3.00 Profile: Q Volume 24Feb14

E.G. Elev (m)	41.66
Vel Head (m)	0.33
W.S. Elev (m)	41.33
Crit W.S. (m)	41.33
E.G. Slope (m/m)	0.007678
Q Total (m3/s)	72.61
Top Width (m)	46.17
Vel Total (m/s)	2.28
Max Chl Dpth (m)	1.53
Conv. Total (m3/s)	828.6
Length Wtd. (m)	1000.00
Min Ch El (m)	39.80
Alpha	1.25
Frctn Loss (m)	5.60
C & E Loss (m)	0.00

Element	Left OB	Channel	Right OB
Wt. n-Val.	0.035	0.035	0.035
Reach Len. (m)	1000.00	1000.00	1000.00
Flow Area (m2)	5.29	21.94	4.58
Area (m2)	5.29	21.94	4.58
Flow (m3/s)	7.16	60.11	5.34
Top Width (m)	13.17	19.00	14.00
Avg. Vel. (m/s)	1.35	2.74	1.17
Hydr. Depth (m)	0.40	1.15	0.33
Conv. (m3/s)	81.7	686.0	61.0
Wetted Per. (m)	13.30	19.16	14.41
Shear (N/m2)	29.94	86.22	23.93
Stream Power (N/m s)	2393.89	0.00	0.00
Cum Volume (1000 m3)	2.85	24.28	2.39
Cum SA (1000 m2)			

River: Dagi River Profile: Q Volume_24Feb10

Reach Middle RS: 3.00 Plan: 24Feb2010

Plan: 24Feb2010 Dagi River Middle RS: 3.00 Profile: Q Volume_24Feb10

E.G. Elev (m)	41.91
Vel Head (m)	0.41
W.S. Elev (m)	41.50
Crit W.S. (m)	41.50
E.G. Slope (m/m)	0.008159
Q Total (m3/s)	101.46
Top Width (m)	47.01
Vel Total (m/s)	2.56
Max Chl Dpth (m)	1.70
Conv. Total (m3/s)	1123.2
Length Wtd. (m)	1000.00
Min Ch El (m)	39.80
Alpha	1.21
Frctn Loss (m)	4.15
C & E Loss (m)	0.02

Element	Left OB	Channel	Right OB
Wt. n-Val.	0.035	0.035	0.035
Reach Len. (m)	1000.00	1000.00	1000.00
Flow Area (m2)	7.57	25.13	6.93
Area (m2)	7.57	25.13	6.93
Flow (m3/s)	12.87	77.69	10.89
Top Width (m)	14.01	19.00	14.00
Avg. Vel. (m/s)	1.70	3.09	1.57
Hydr. Depth (m)	0.54	1.32	0.50
Conv. (m3/s)	142.5	860.1	120.6
Wetted Per. (m)	14.16	19.16	14.58
Shear (N/m2)	42.78	104.94	38.03
Stream Power (N/m s)	2393.89	0.00	0.00
Cum Volume (1000 m3)	7.11	31.55	9.01
Cum SA (1000 m2)			

Detailed output tables for Lamegi River during the 2014 and 2010 floods.

River: Lamegi River | Profile: Q Volume 24Feb14

Reach: Lamegi | RS: 4.00 | Plan: 24Feb2014

Plan: 24Feb2014 Lamegi River Lamegi RS: 4.00 Profile: Q Volume 24Feb14

E.G. Elev (m)	35.94	Element	Left OB	Channel	Right OB
Vel Head (m)	0.66	Wt. n-Val.	0.035	0.035	0.035
W.S. Elev (m)	35.28	Reach Len. (m)	1000.00	1000.00	1000.00
Crit W.S. (m)	35.28	Flow Area (m2)	0.28	19.82	0.08
E.G. Slope (m/m)	0.010945	Area (m2)	0.28	19.82	0.08
Q Total (m3/s)	71.60	Flow (m3/s)	0.19	71.35	0.06
Top Width (m)	16.96	Top Width (m)	2.40	14.00	0.56
Vel Total (m/s)	3.55	Avg. Vel. (m/s)	0.70	3.60	0.75
Max Chl Dpth (m)	2.58	Hydr. Depth (m)	0.12	1.42	0.14
Conv. Total (m3/s)	684.4	Conv. (m3/s)	1.9	682.0	0.6
Length Wtd. (m)	1000.00	Wetted Per. (m)	2.43	15.00	0.63
Min Ch El (m)	32.70	Shear (N/m2)	12.22	141.81	13.46
Alpha	1.03	Stream Power (N/m s)	1196.95	0.00	0.00
Frctn Loss (m)	6.45	Cum Volume (1000 m3)	0.35	23.22	0.14
C & E Loss (m)	0.09	Cum SA (1000 m2)			

River: Lamegi River | Profile: Q Volume_24Feb10

Reach: Lamegi | RS: 4.00 | Plan: 24Feb2010

Plan: 24Feb2010 Lamegi River Lamegi RS: 4.00 Profile: Q Volume_24Feb10

E.G. Elev (m)	36.58	Element	Left OB	Channel	Right OB
Vel Head (m)	0.69	Wt. n-Val.	0.035	0.035	0.035
W.S. Elev (m)	35.88	Reach Len. (m)	1000.00	1000.00	1000.00
Crit W.S. (m)	35.88	Flow Area (m2)	2.71	28.26	2.02
E.G. Slope (m/m)	0.007552	Area (m2)	2.71	28.26	2.02
Q Total (m3/s)	113.60	Flow (m3/s)	4.29	107.00	2.31
Top Width (m)	25.00	Top Width (m)	5.00	14.00	6.00
Vel Total (m/s)	3.44	Avg. Vel. (m/s)	1.58	3.79	1.15
Max Chl Dpth (m)	3.18	Hydr. Depth (m)	0.54	2.02	0.34
Conv. Total (m3/s)	1307.2	Conv. (m3/s)	49.3	1231.2	26.6
Length Wtd. (m)	1000.00	Wetted Per. (m)	5.34	15.00	6.41
Min Ch El (m)	32.70	Shear (N/m2)	37.61	139.48	23.28
Alpha	1.15	Stream Power (N/m s)	1196.95	0.00	0.00
Frctn Loss (m)	4.16	Cum Volume (1000 m3)	4.68	33.11	6.55
C & E Loss (m)	0.11	Cum SA (1000 m2)			

Detailed output tables for Dagi River-Downstream Reach during the 2014 floods.

River: Dagi River | Profile: Q Volume 24Feb14
Reach: Downstream | RS: 5.00 | Plan: 24Feb2014

Plan: 24Feb2014 Dagi River Downstream RS: 5.00 Profile: Q Volume 24Feb14

E.G. Elev (m)	4.94
Vel Head (m)	0.03
W.S. Elev (m)	4.91
Crit W.S. (m)	4.57
E.G. Slope (m/m)	0.000400
Q Total (m3/s)	72.04
Top Width (m)	200.00
Vel Total (m/s)	0.56
Max Chl Dpth (m)	0.96
Conv. Total (m3/s)	3601.6
Length Wtd. (m)	
Min Ch El (m)	3.95
Alpha	1.65
Frctn Loss (m)	
C & E Loss (m)	

Element	Left OB	Channel	Right OB
Wt. n-Val.	0.035	0.020	0.035
Reach Len. (m)			
Flow Area (m2)	36.87	40.04	52.20
Area (m2)	36.87	40.04	52.20
Flow (m3/s)	14.35	37.04	20.65
Top Width (m)	65.00	45.00	90.00
Avg. Vel. (m/s)	0.39	0.93	0.40
Hydr. Depth (m)	0.57	0.89	0.58
Conv. (m3/s)	717.4	1851.7	1032.5
Wetted Per. (m)	65.61	45.01	90.60
Shear (N/m2)	2.20	3.49	2.26
Stream Power (N/m s)	9575.58	0.00	0.00
Cum Volume (1000 m3)			
Cum SA (1000 m2)			

River: Dagi River | Profile: Q Volume_24Feb10
Reach: Downstream | RS: 5.00 | Plan: 24Feb2010

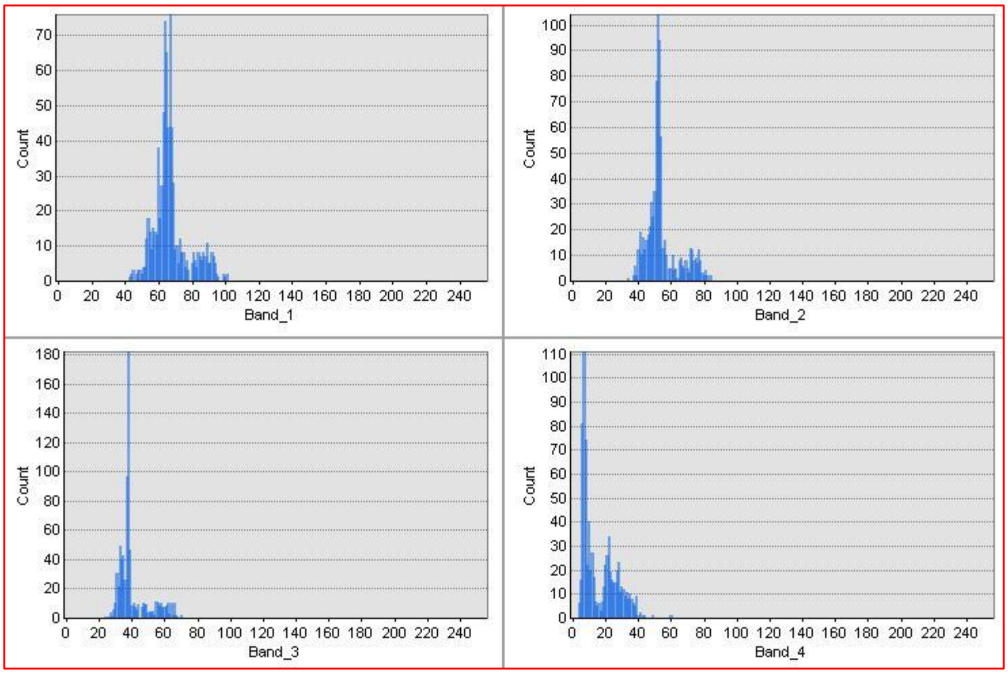
Plan: 24Feb2010 Dagi River Downstream RS: 5.00 Profile: Q Volume_24Feb10

E.G. Elev (m)	5.15
Vel Head (m)	0.03
W.S. Elev (m)	5.12
Crit W.S. (m)	4.67
E.G. Slope (m/m)	0.000400
Q Total (m3/s)	109.67
Top Width (m)	200.00
Vel Total (m/s)	0.65
Max Chl Dpth (m)	1.17
Conv. Total (m3/s)	5483.3
Length Wtd. (m)	
Min Ch El (m)	3.95
Alpha	1.56
Frctn Loss (m)	
C & E Loss (m)	

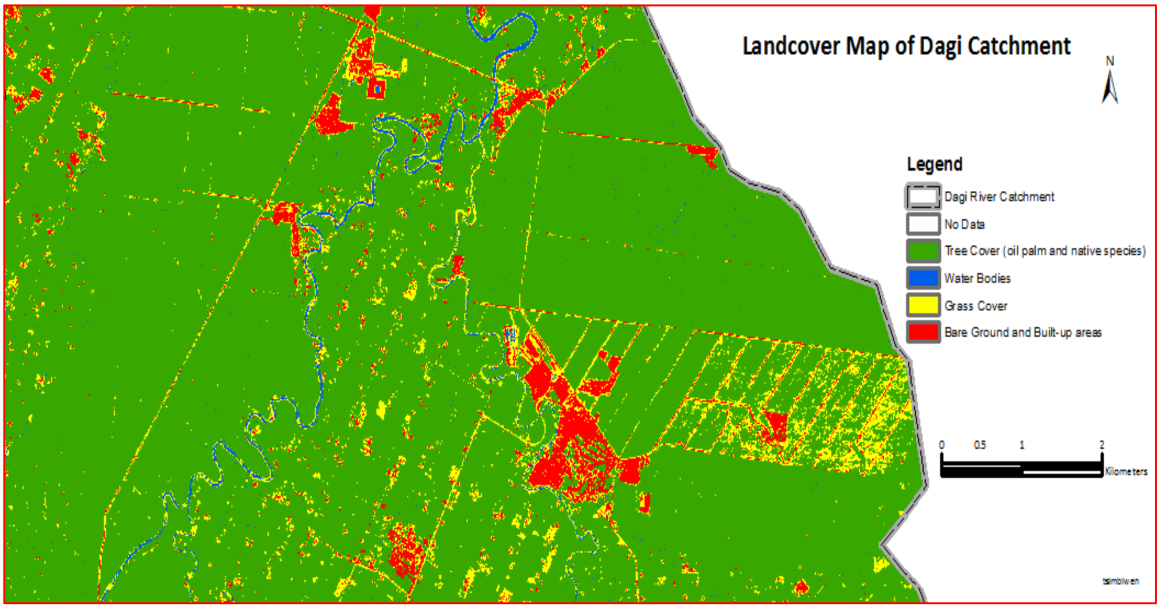
Element	Left OB	Channel	Right OB
Wt. n-Val.	0.035	0.020	0.035
Reach Len. (m)			
Flow Area (m2)	49.96	49.10	70.31
Area (m2)	49.96	49.10	70.31
Flow (m3/s)	23.76	52.03	33.88
Top Width (m)	65.00	45.00	90.00
Avg. Vel. (m/s)	0.48	1.06	0.48
Hydr. Depth (m)	0.77	1.09	0.78
Conv. (m3/s)	1187.7	2601.4	1694.2
Wetted Per. (m)	65.81	45.01	90.80
Shear (N/m2)	2.98	4.28	3.04
Stream Power (N/m s)	9575.58	0.00	0.00
Cum Volume (1000 m3)			
Cum SA (1000 m2)			

Chapter 5.0: Appendix

Appendix 5.1: Maximum likelihood classification to derive roughness values for Dagi.

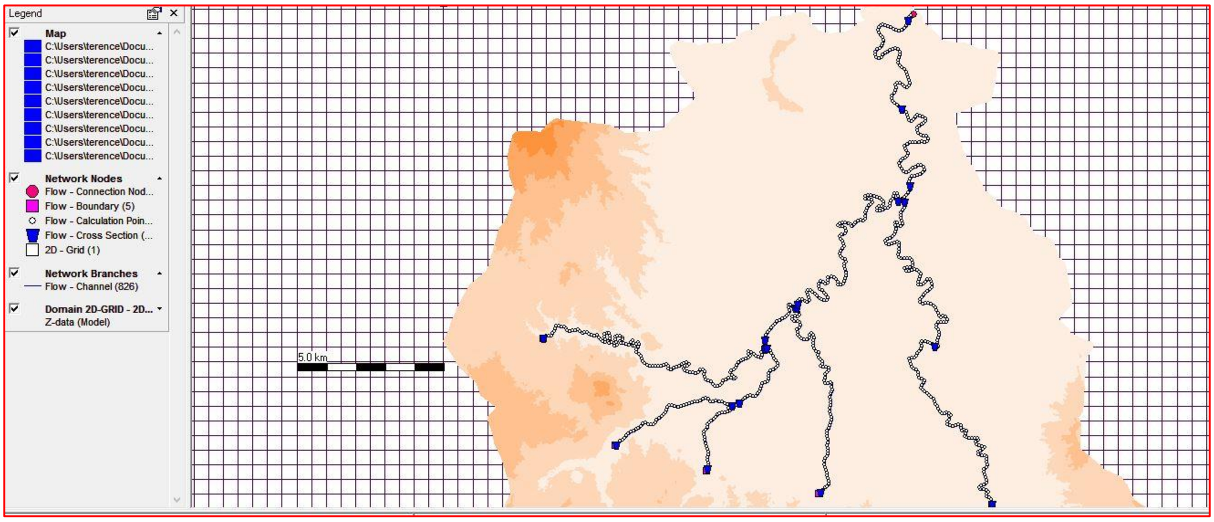


An example of histogram of training samples for water bodies as per spectral bands.

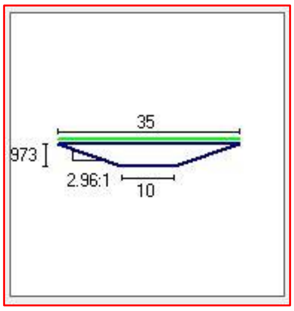


A subset of the overall land cover map of Dagi catchment

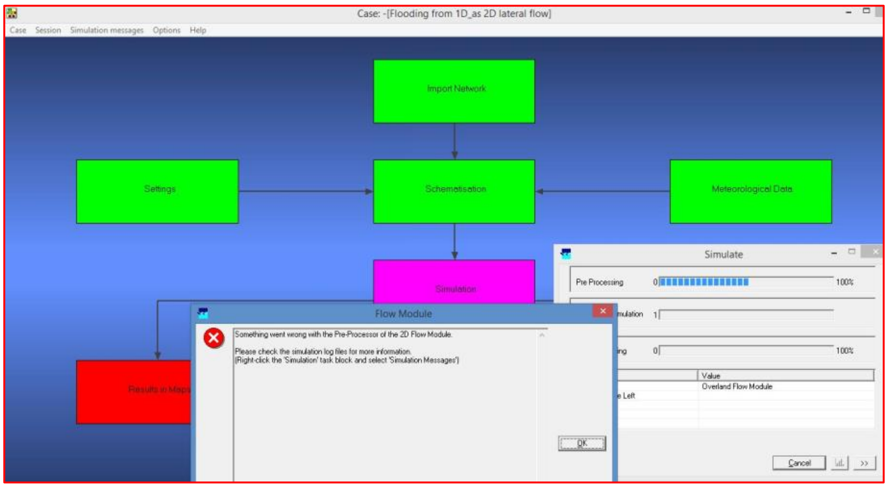
Appendix 5.2: Modelling errors and successful execution



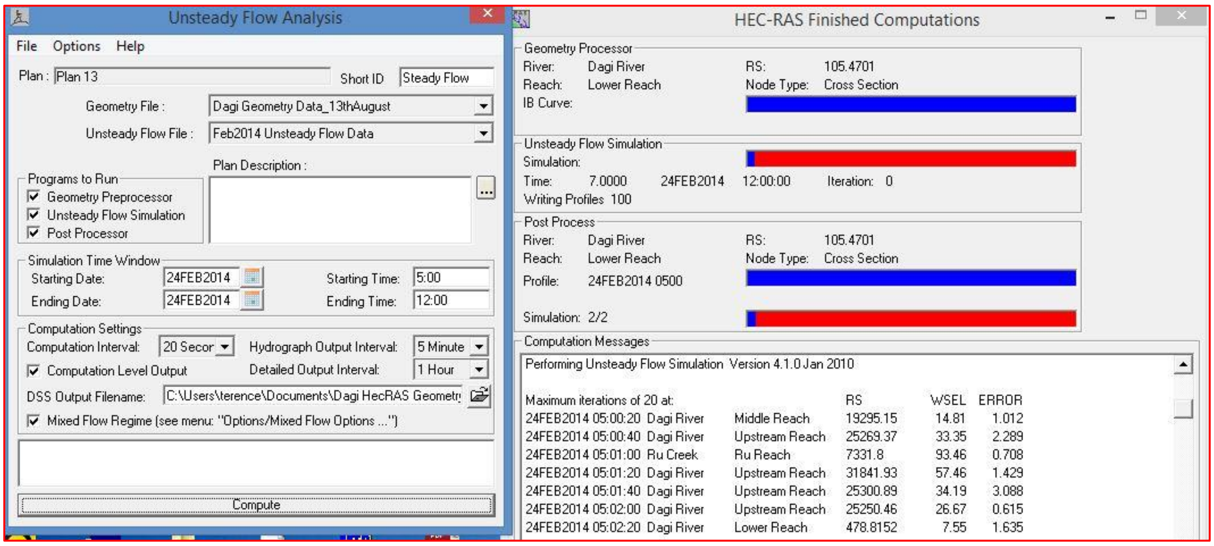
Schematisation in SOBEK 1D2D



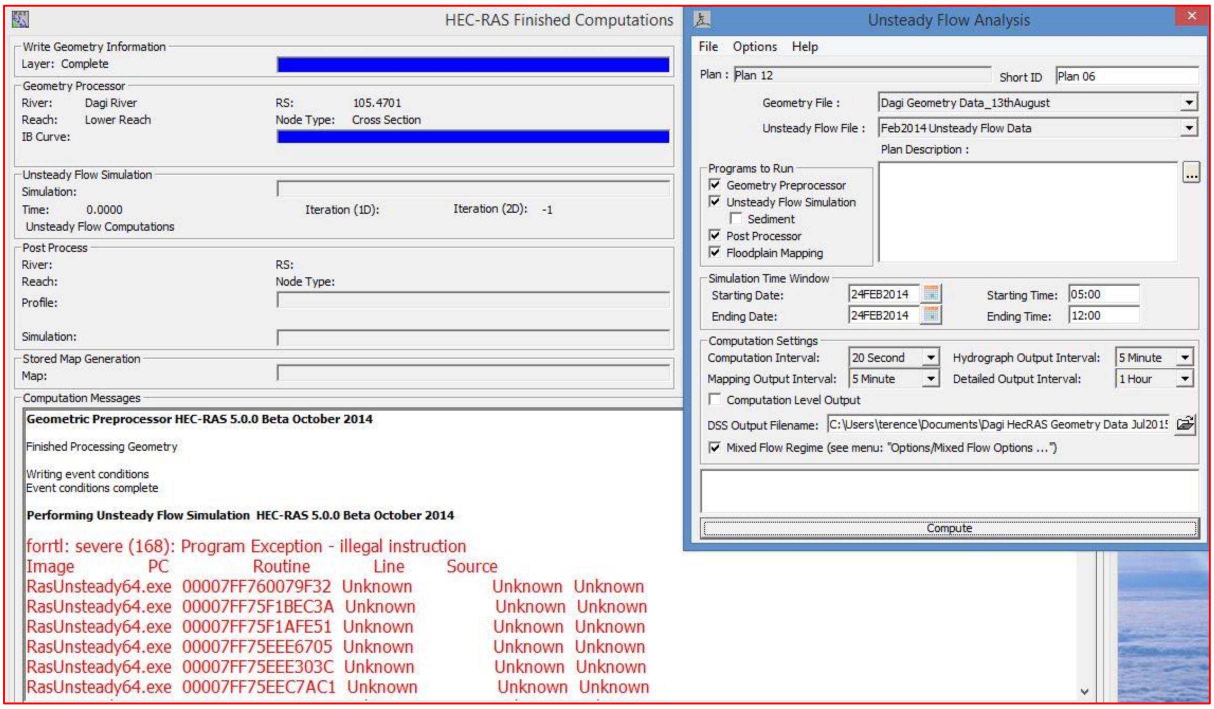
Model schematisation for a cross-section in SOBEK 1D2D.



Simulation Error in SOBEK 1D2D Model.



Simulation error in HEC-RAS 4.1.



Simulation error in HEC-RAS Beta 5.0

Floodplain Delineation Using Grids

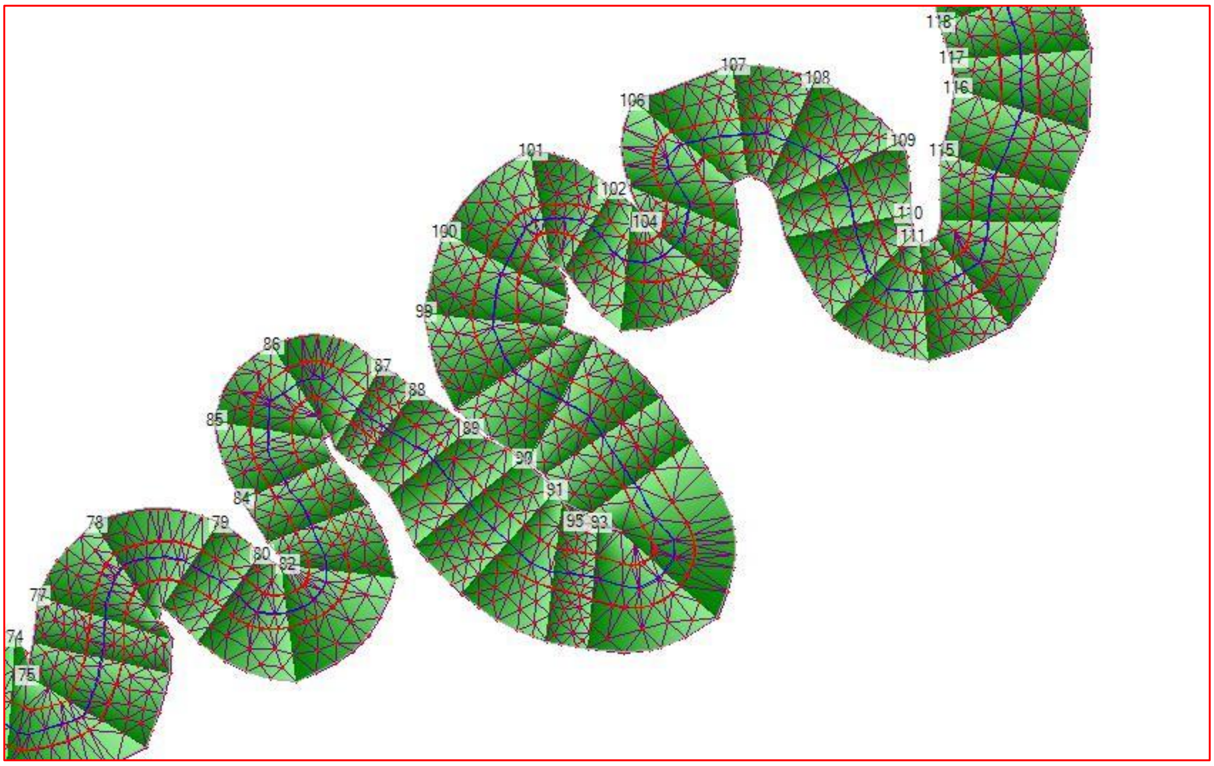
Start Time	Type	Message
27/08/2015 10:53:00 PM	Information	Configuration XML obtained.
27/08/2015 10:53:00 PM	Information	Spatial Analyst and 3D Analyst licenses validated.
27/08/2015 10:53:00 PM	Information	Starting floodplain delineation ...
27/08/2015 10:53:00 PM	Information	Verify if the RAS export file has already been read
27/08/2015 10:53:00 PM	Information	XS cutline and bounding polygon feature classes obtained.
27/08/2015 10:53:09 PM	Information	Floodplain delineation started for profile PF 1
27/08/2015 10:53:09 PM	Information	Checking if the water surface TIN for the current profile PF 1 exists.
27/08/2015 10:53:09 PM	Information	Water surface TIN for the current profile PF 1 exists.
27/08/2015 10:53:09 PM	Information	Constant GRID constructed.
27/08/2015 10:53:09 PM	Information	Starting to create water surface GRID.
27/08/2015 10:53:12 PM	Information	Water Surface GRID created.
27/08/2015 10:53:12 PM	Information	Obtaining the bounding polygon.
27/08/2015 10:53:12 PM	Information	Bounding polygon feature obtained.
27/08/2015 10:53:12 PM	Information	Water surface GRID obtained.
27/08/2015 10:53:13 PM	Information	Starting to use water surface grid for delineation.
27/08/2015 10:53:13 PM	Information	Subtracting the terrain GRID from water surface GRID for profile PF 1.
27/08/2015 10:53:19 PM	Information	Subtraction of grids successful for profile PF 1.
27/08/2015 10:53:19 PM	Information	Adding water depth GRID to map for profile PF 1...
27/08/2015 10:53:21 PM	Information	Depth grid added to map.
27/08/2015 10:53:21 PM	Information	Converting floodplain GRID to polygon for profile PF 1.
27/08/2015 10:53:23 PM	Information	Successfully converted floodplain GRID to polygon for profile PF 1.
27/08/2015 10:53:23 PM	Information	Creating floodplain feature class for profile PF 1.
27/08/2015 10:53:26 PM	Information	Floodplain feature class created for profile PF 1.
27/08/2015 10:53:26 PM	Information	Deleted transient dissolve shapefile for profile PF 1.
27/08/2015 10:53:27 PM	Information	Adding floodplain feature class to map for profile PF 1...
27/08/2015 10:53:29 PM	Information	Floodplain feature layer created for profile PF 1.
27/08/2015 10:53:29 PM	Information	Trying to remove temp rasters...
27/08/2015 10:53:29 PM	Information	Floodplain delineation completed for profile PF 1.
27/08/2015 10:53:29 PM	Information	Execution time: 0 hr 0 min 20 s
27/08/2015 10:54:59 PM	Information	Total execution time for all profiles: 0 hr 1 min 58 s

Successful execution of simulation (2014 flood).

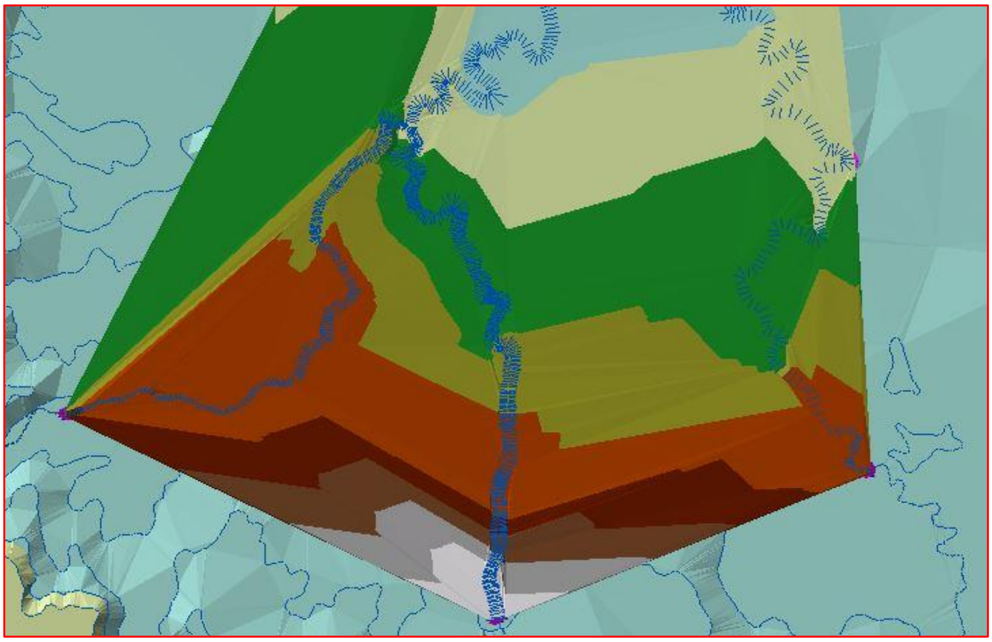
Floodplain Delineation Using Grids

Start Time	Type	Message
28/08/2015 12:07:45 AM	Information	Configuration XML obtained.
28/08/2015 12:07:45 AM	Information	Spatial Analyst and 3D Analyst licenses validated.
28/08/2015 12:07:45 AM	Information	Starting floodplain delineation ...
28/08/2015 12:07:45 AM	Information	Verify if the RAS export file has already been read
28/08/2015 12:07:45 AM	Information	XS cutline and bounding polygon feature classes obtained.
28/08/2015 12:07:48 AM	Information	Floodplain delineation started for profile PF 2
28/08/2015 12:07:48 AM	Information	Checking if the water surface TIN for the current profile PF 2 exists.
28/08/2015 12:07:48 AM	Information	Water surface TIN for the current profile PF 2 exists.
28/08/2015 12:07:48 AM	Information	Constant GRID constructed.
28/08/2015 12:07:48 AM	Information	Starting to create water surface GRID.
28/08/2015 12:07:51 AM	Information	Water Surface GRID created.
28/08/2015 12:07:51 AM	Information	Obtaining the bounding polygon.
28/08/2015 12:07:52 AM	Information	Bounding polygon feature obtained.
28/08/2015 12:07:52 AM	Information	Water surface GRID obtained.
28/08/2015 12:07:52 AM	Information	Starting to use water surface grid for delineation.
28/08/2015 12:07:52 AM	Information	Subtracting the terrain GRID from water surface GRID for profile PF 2.
28/08/2015 12:07:57 AM	Information	Subtraction of grids successful for profile PF 2.
28/08/2015 12:07:57 AM	Information	Adding water depth GRID to map for profile PF 2...
28/08/2015 12:08:00 AM	Information	Depth grid added to map.
28/08/2015 12:08:00 AM	Information	Converting floodplain GRID to polygon for profile PF 2.
28/08/2015 12:08:01 AM	Information	Successfully converted floodplain GRID to polygon for profile PF 2.
28/08/2015 12:08:01 AM	Information	Creating floodplain feature class for profile PF 2.
28/08/2015 12:08:03 AM	Information	Floodplain feature class created for profile PF 2.
28/08/2015 12:08:03 AM	Information	Deleted transient dissolve shapefile for profile PF 2.
28/08/2015 12:08:03 AM	Information	Adding floodplain feature class to map for profile PF 2...
28/08/2015 12:08:05 AM	Information	Floodplain feature layer created for profile PF 2.
28/08/2015 12:08:06 AM	Information	Trying to remove temp rasters...
28/08/2015 12:08:06 AM	Information	Floodplain delineation completed for profile PF 2.
28/08/2015 12:08:06 AM	Information	Execution time: 0 hr 0 min 17 s
28/08/2015 12:08:12 AM	Information	Total execution time for all profiles: 0 hr 0 min 27 s

Successful execution of simulation (2010 flood).

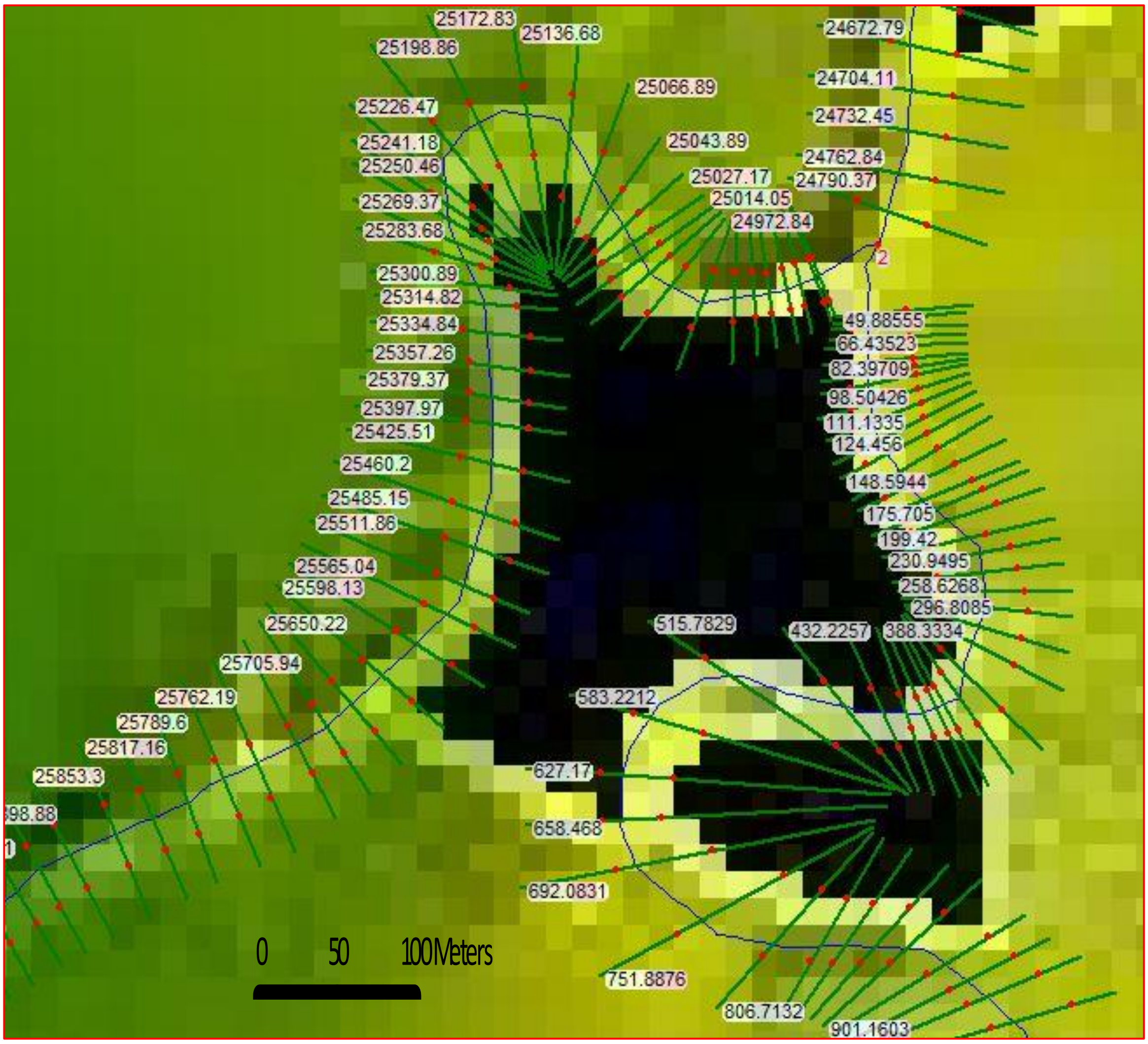


Interpolated river bathymetry data



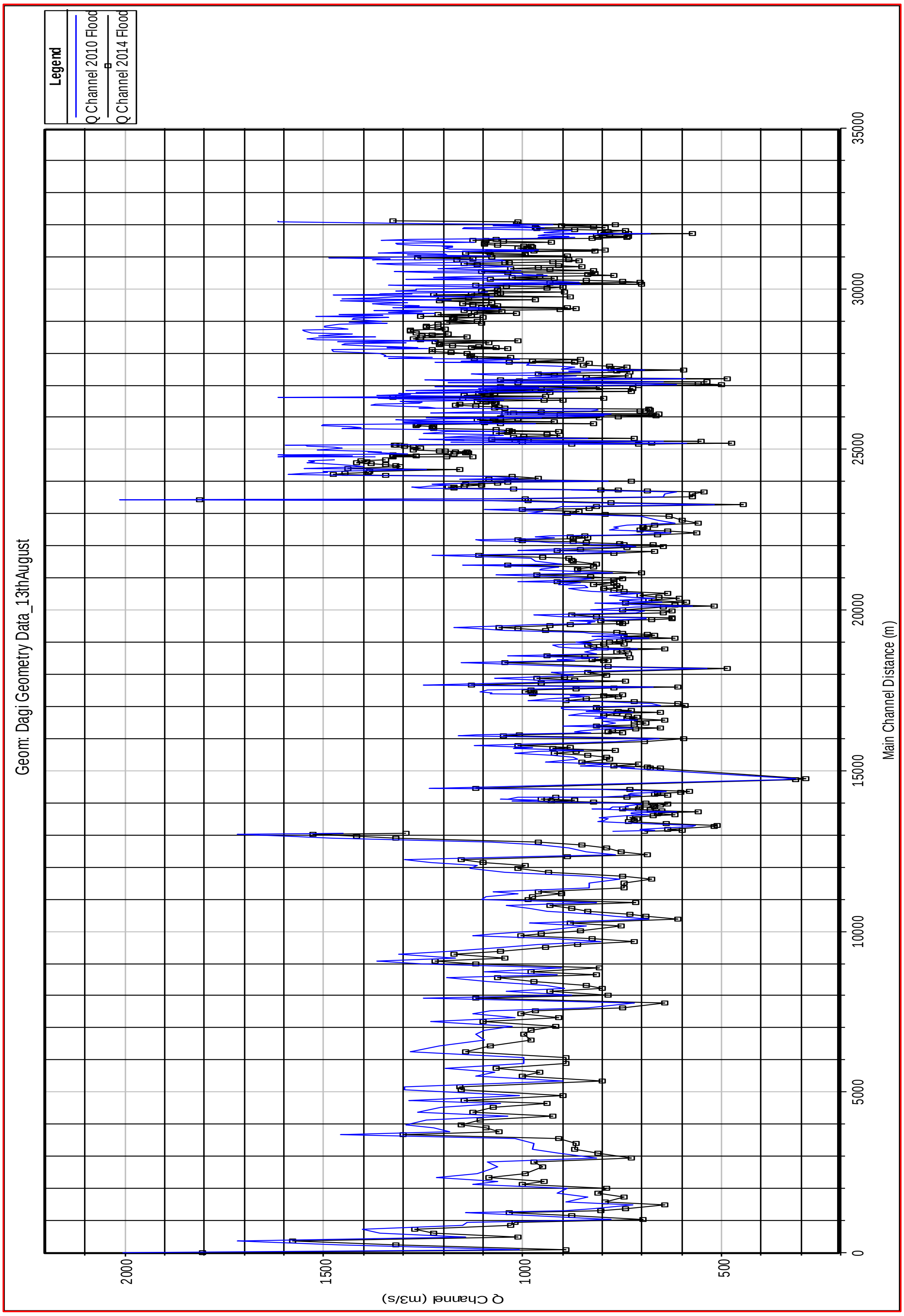
Water surface elevation TIN

Appendix 5.3: X-Cut lines, river and bank stations along each reach.

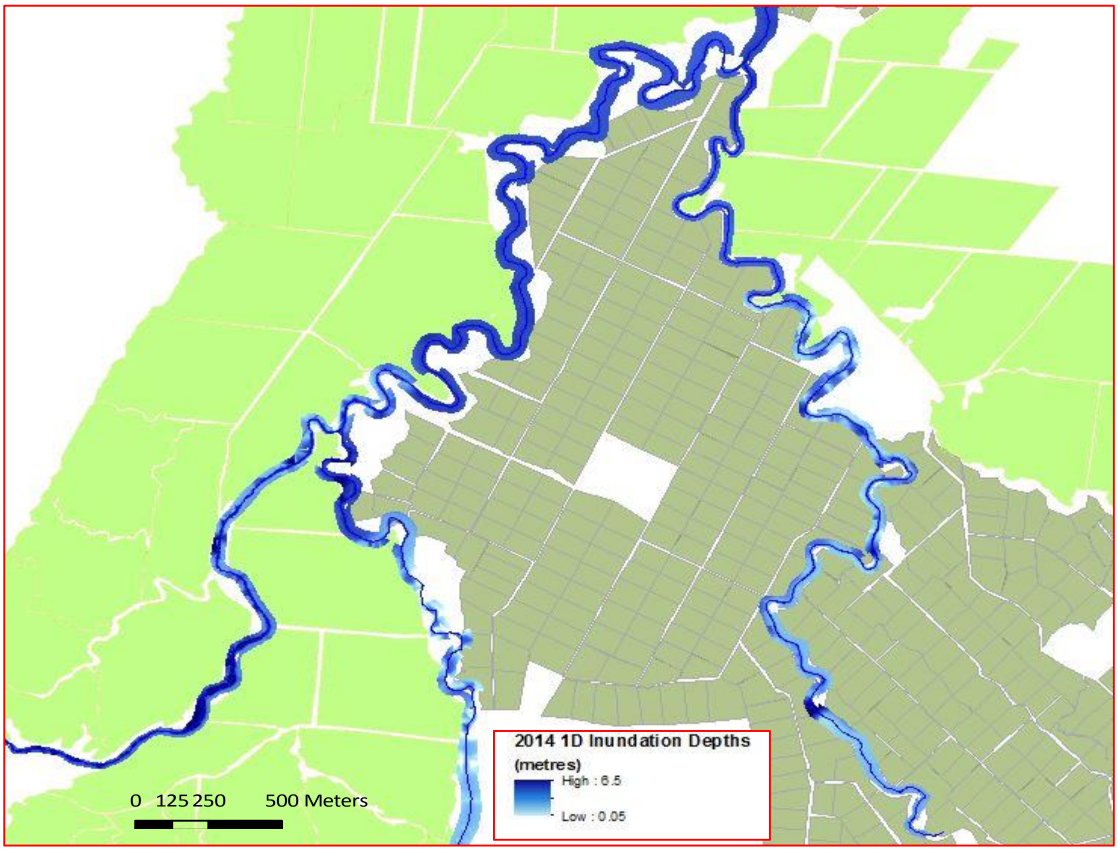


XS-Cutlines, river and bank stations, per reach and river junctions as nodes with elevation depressions shown in black where inundation would most likely occur.

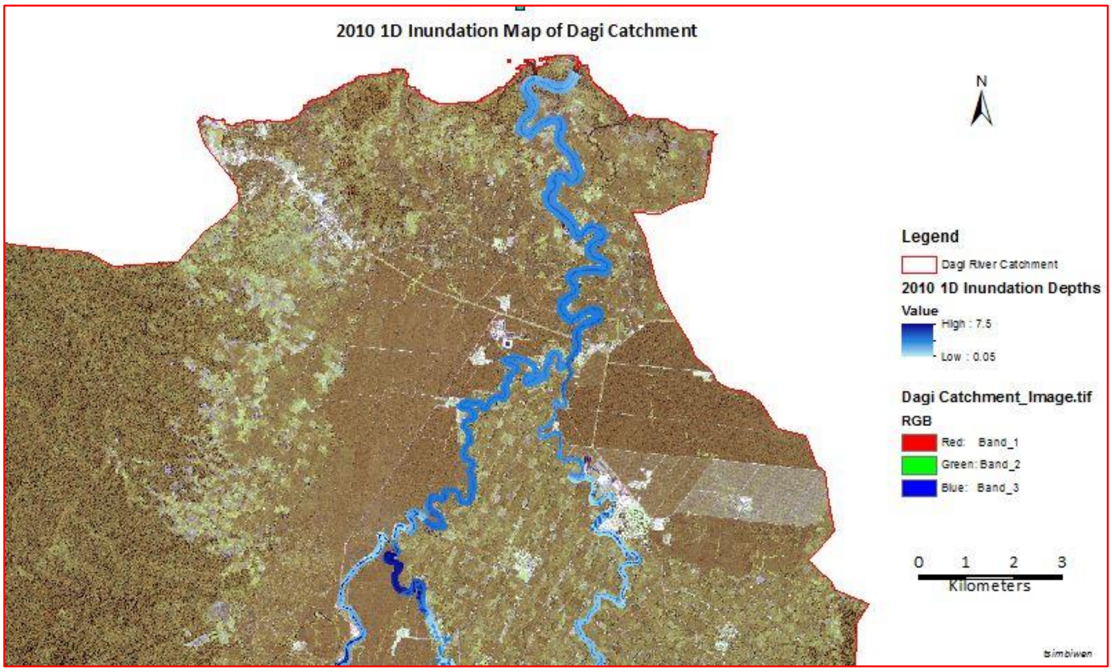
Appendix 5.4: Discharge and 1D and 2D Inundation results



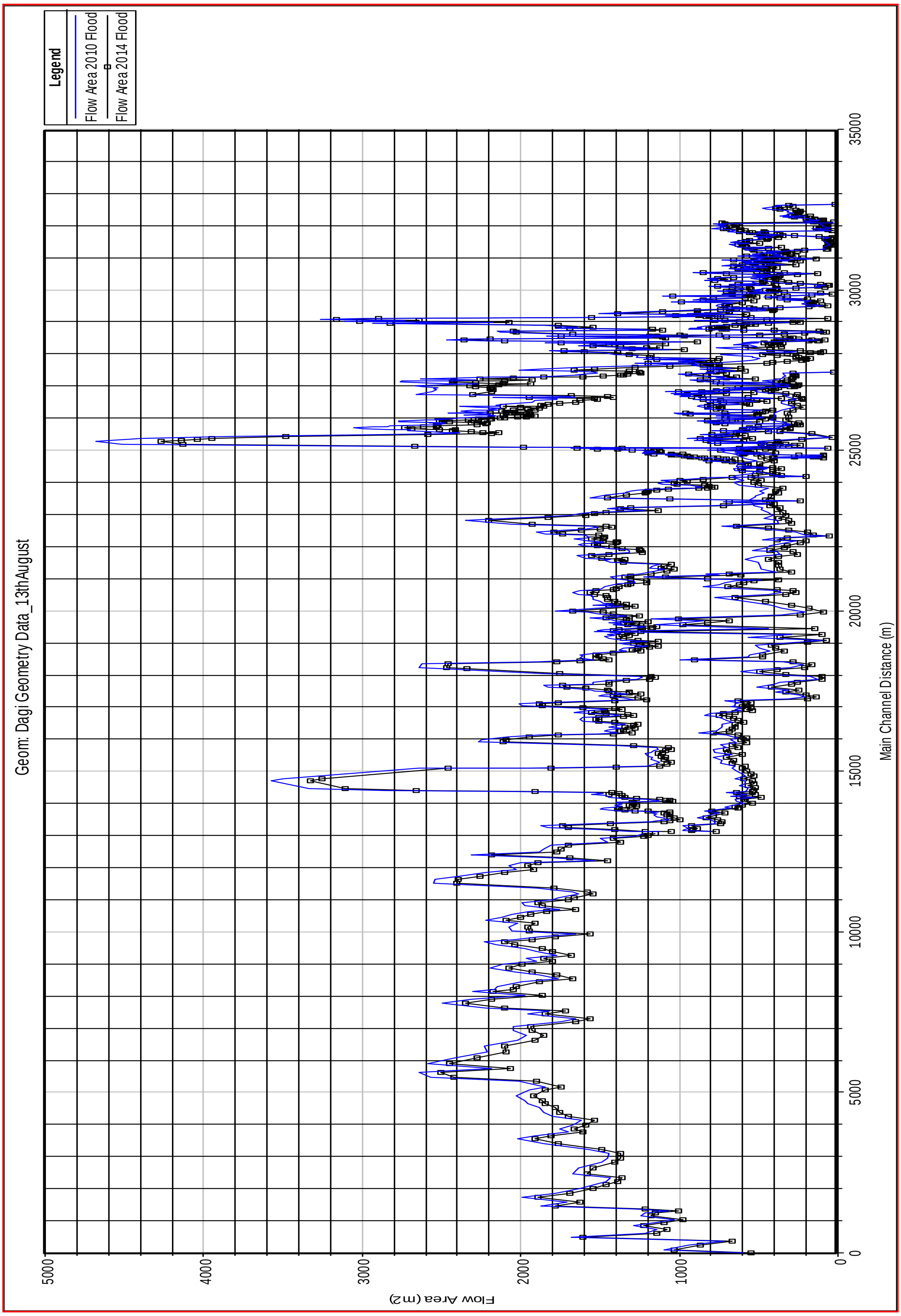
Discharge in Dagi from upstream going downstream for both 2014 and 2010 floods



A close-up view of the 2014 1D inundation depth distribution.

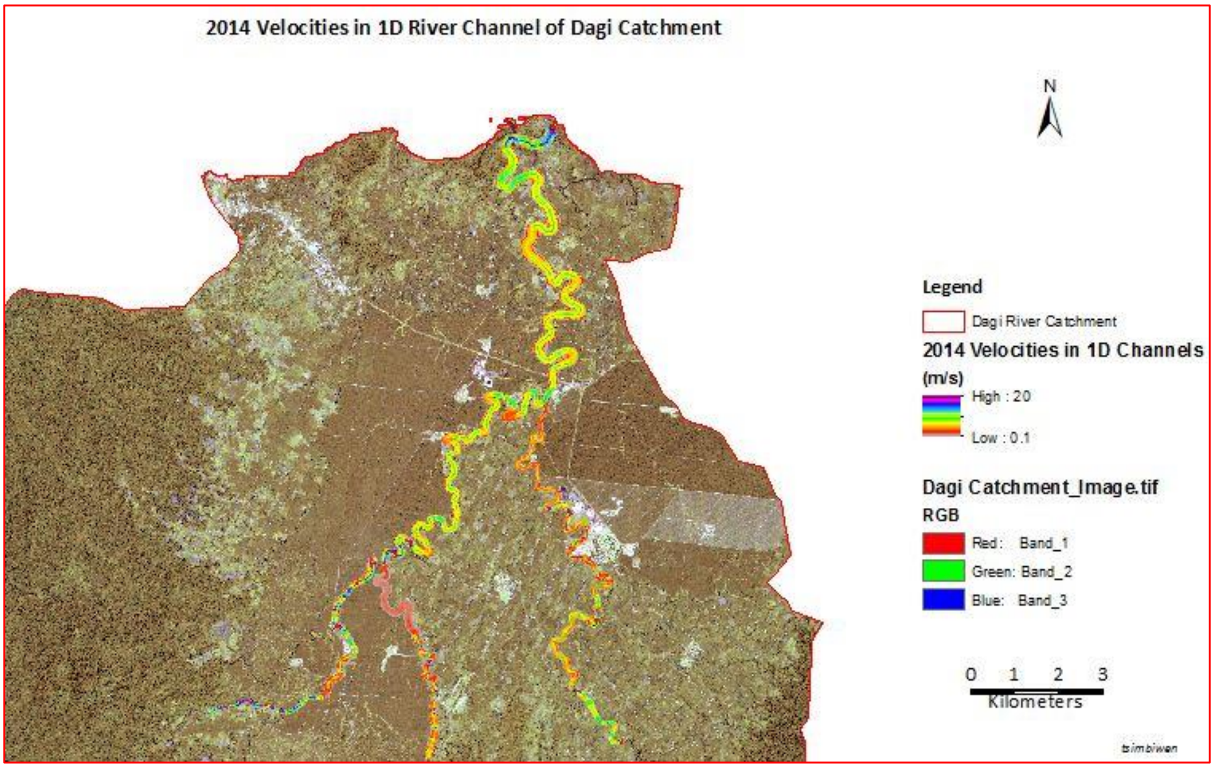


2010 1D inundation depth distribution.

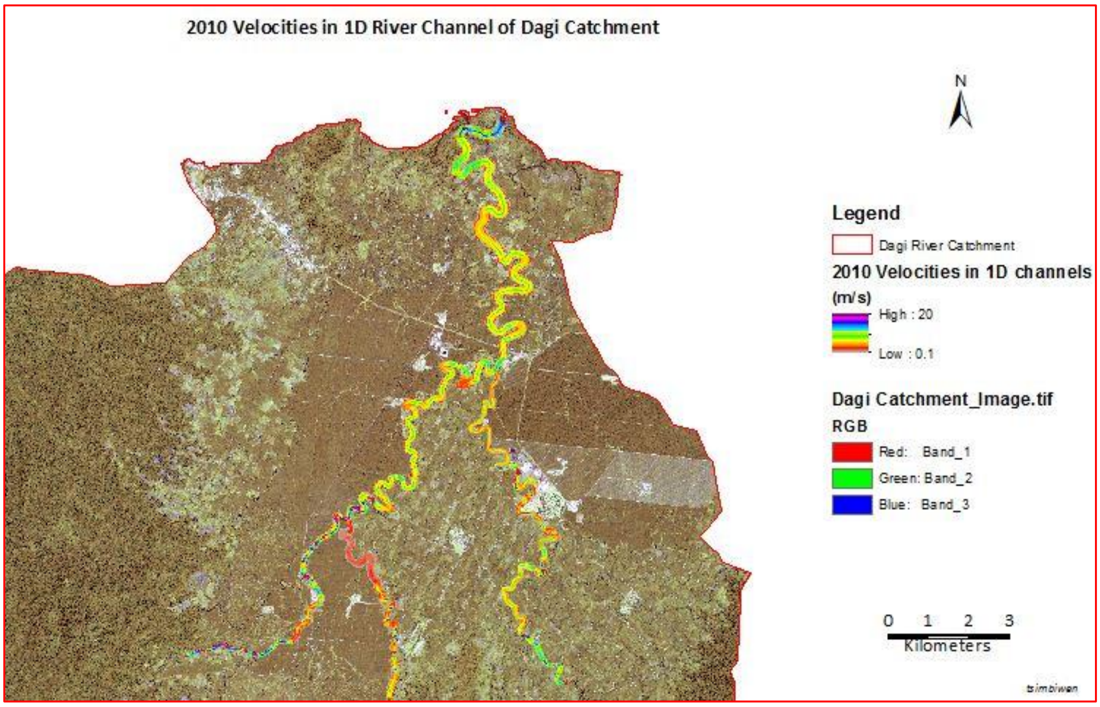


Total flow area (m^2) for both flood events.

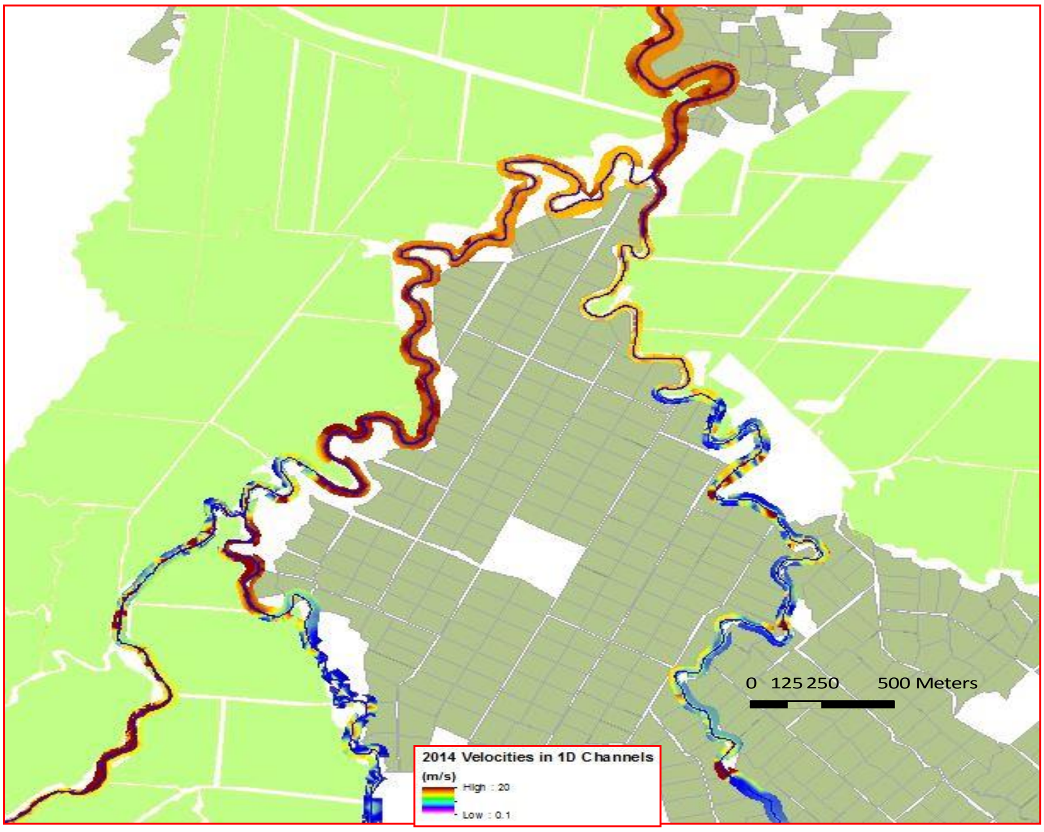
Appendix 5.5: Velocity distribution



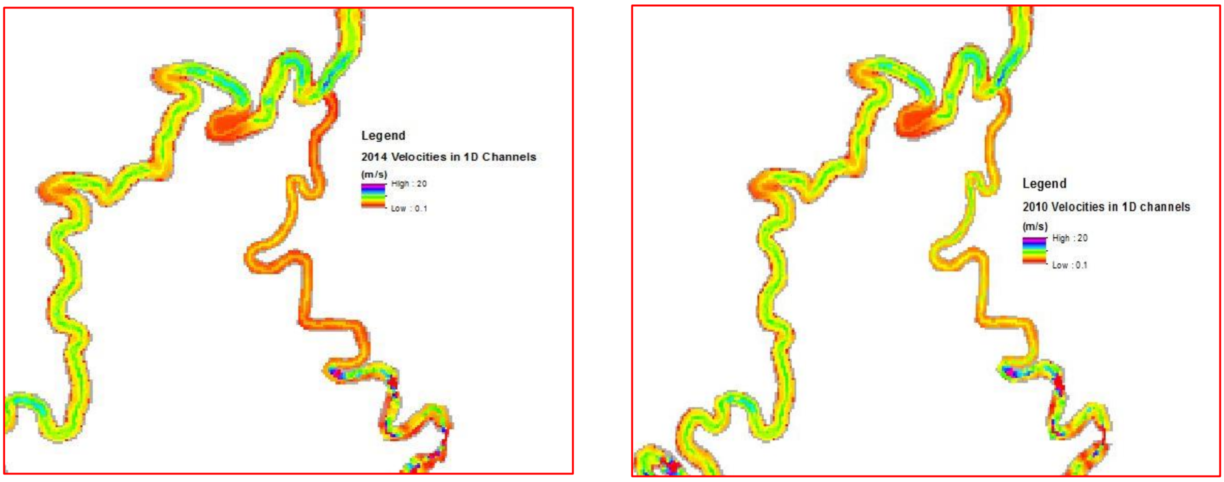
2014 velocity distribution



2010 velocity distribution.

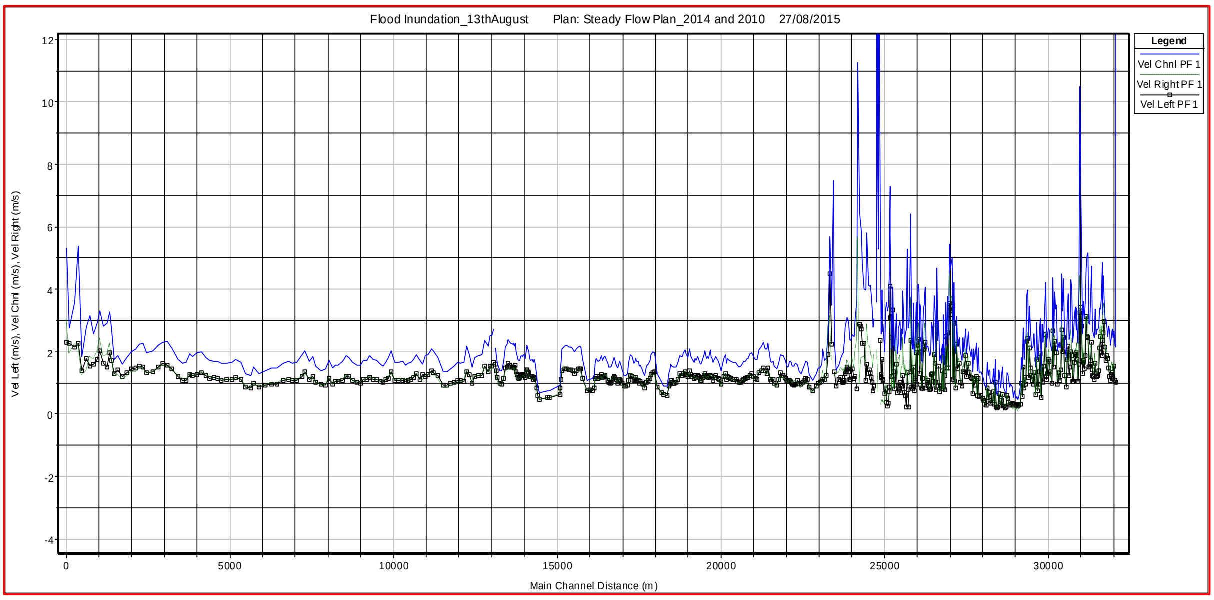


2014 velocity distribution at a close-up view.



a) b)

Spatial distribution of velocity in 2014 and 2010.



Graphical representation of velocity distribution across the channel for 2014 (Profile 1).

Appendix 5.6: Inundated, water depth and land use

Inundated area compared with water depth using two case examples of land use.

Year	River/Reach	Average Water Depth* (m)	Total Inundated Area (ha)	Inundated Area (ha) (Oil Palm Plantations)	Inundated Area (ha) (Oil Palm Blocks)
2014	Dagi - Upstream	3.96	6.3	2.27	-
	Dagi - Middle	5.76	15.5	4.62	2.84
	Dagi - Lower	5.61	33.4	3.68	9.73
	Ru	4.07	-	-	-
	Lamegi	4.70	-	-	-
2010	Dagi - Upstream	4.65	6.5	2.64	-
	Dagi - Middle	5.89	17.1	6.17	3.95
	Dagi - Lower	6.97	36.5	4.63	13.75
	Ru	5.06	9.6	3.44	3.89
	Lamegi	4.71	10.2	2.31	4.47

**Average values taken from observed and simulated water depths.*

Chapter 6.0: Appendices

Appendix 6.1: Damages caused by floods to livelihood assets.

Plate 6.1: Sealed road eroded by flood

Plate 6.2: Oil palm plantation road inundated, accessibility denied.

Plate 6.3: Oil palm road eroded by flood

Plate 6.4: Main road inundated by flood and disrupted transport.

Plate 6.5: Vehicle trapped in a ditch.

Plate 6.6: Road along an oil palm block.

Plate 6.7: Food gardens.

Plate 6.8: A garden recently inundated.

Plate 6.9: Damaged cucumber.

Plate 6.10: A damaged taro.

Plate 6.11: Bush material housing area.

Plate 6.12: Semi-permanent house.

Plate 6.13: A small holder block.

Plate 6.14: Inside a hall

Plate 6.15: Accessibility by canoe.

Plate 6.16: Properties inundated.

Plate 6.17: Oil palm uprooted.

Plate 6.18: Bamboo uprooted by high velocity.

Plate 6.19: Young oil palm inundated.

Plate 6.20: Oil palm access denied.

Plate 6.21: Decomposed oil palm fruits.

Plate 6.22: Disaster assessment.

WEST NEW BRITAIN PROVINCIAL ADMINISTRATION

DISASTER & EMERGENCY DIVISION

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P O Box 430, KIMBE
West New Britain Province
Papua New Guinea

Villages and Oil Palm Settlement Areas affected by Flood Waters

2

1. Communities living along the Dagi River and its tributaries, Morokea VOP and the Buvusi Oil Palm Settlement areas within the Mosa LLG and Kimbe town areas reported to the Disaster Office of the homes being flooding by the rising Dagi river and its tributaries including the unexpectedly high water run-offs resulting from the heavy rainfall experienced in the last 72 hours.
2. Communities living along Daliavu river in the Ismin Oil Palm Settlement areas has also reported to Disaster Office of their food gardens and Oil Palm Plantations being destroyed by the flood waters. There were also reports of houses downstream along Dagi River and its tributaries being inundated with water and threatening people's livelihood.
3. Reports was also received of Residential houses belonging to NBPOL employees residing at Kumbago Plantation executive residence being flooded by Dagi river.

Figure 6.3: Extract from a Disaster and Emergency Division report of the WNB Provincial government.

Plate 6.23: Disaster relief supplies to affected areas by Provincial Authorities – PNG style.

Appendix 6.2: Hazard categories and characteristics

Table 6.2: Flood hazard categories and their characteristics based on CSIRO (2000) criteria.

Hazard Category	Flood Base Event	Characteristics
Low	100 yr.	Areas that are inundated in a 100-yr. flood, but the floodwaters are relatively shallow (typically less than 1m deep) and are not flowing with velocity, adult can wade.
High-Wading Unsafe	100 yr.	The depth and / or velocity is sufficiently high that wading is not possible, risk of drowning.
High-Depth	100 yr.	Areas where the floodwaters are deep (>1m), but are not flowing with high velocity. Damage only to building contents, large trucks able to evacuate.
High Floodway	100 yr.	Typically, areas where there is deep water flowing with high velocity. Truck evacuation not possible, structural damage to light framed houses, high risk to life.
Extreme	100 yr.	Typically, areas where the velocity is >2m/s. All buildings likely to be destroyed, high probability of death.

Appendix 6.3: Hazard Level

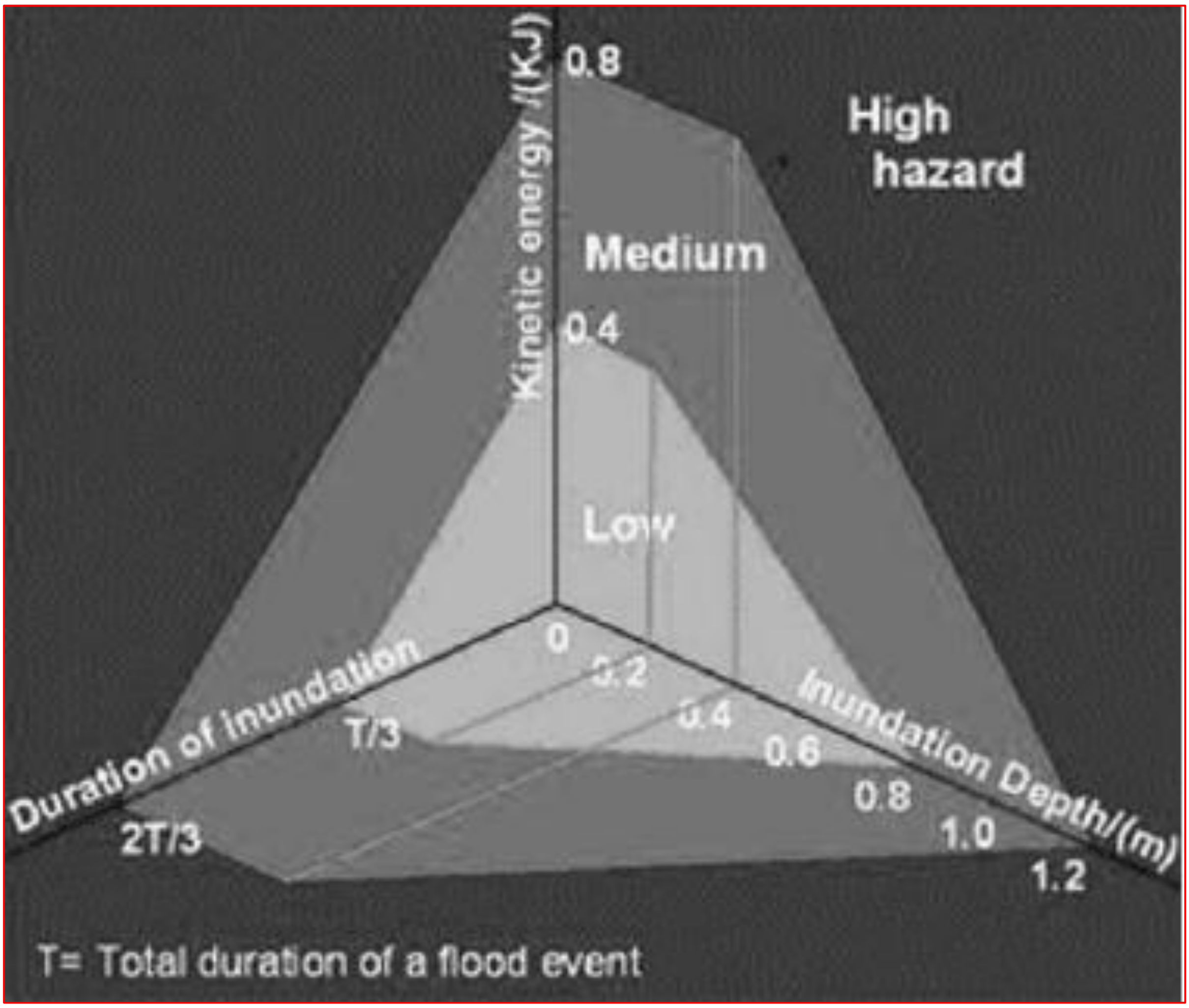

Figure 6.2: Flood hazard classification based on multiple flood characteristics (Tennakoon, 2004).

REPORTED CASES OF LOSSES THROUGH FLOODING IN THE DAGI RIVER BASIN FROM 2000 - 2014

Terence Simbiwen - COLLATED QUESTIONNAIRE DATA

Dagi upstream_small holder oil palm blocks (n* = 70) — **SITE 1 - Small holder blocks upstream**

Year	Tot.Pop	TotalHouses	HouseType	Avg.IncomeSource	Annual Rainfall (mm)	CASES OF LOSSES OR DAMAGES DUE TO FLOODING: ROADS[1] Gullying	ROADS[1] Destroyed	B[2]	NP FFB[3]	SE/LLS[4] SE	SE/LLS[4] LL	OPT[5]	OCC[6]	SG[7] U	SG[7] D	D[8] ND	D[8] D	H[9]	HHG[10]	SS[11]	EC[12]	V[13]	FJI[14]	EE COSTS (PGK 000's)[15]
2000	417	41	perm/semi	Oil palm/gardens	3349.6	1	0	0	2	3	0	3	5	3	1	1	0	1	5	1	1	1	2	163.1
2001	418	41	perm/semi	Oil palm/gardens	2909.6	1	1	0	1	1	0	1	3	1	1	1	0	0	0	0	1	0	1	97.05
2002	418	41	perm/semi	Oil palm/gardens	3653.4	1	0	0	0	1	0	0	1	1	0	0	0	0	0	0	1	0	0	18.4
2003	419	43	perm/semi	Oil palm/gardens	3784.0	1	0	0	0	1	0	0	1	1	0	0	0	0	0	0	2	0	0	13.6
2004	423	43	perm/semi	Oil palm/gardens	3280.8	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	1.5
2005	423	43	perm/semi	Oil palm/gardens	4179.0	1	1	0	1	1	0	4	5	5	2	0	0	1	7	1	3	1	7	353.05
2006	423	44	perm/semi	Oil palm/gardens	3519.0	1	0	0	0	1	0	0	1	1	0	0	0	0	0	0	1	0	0	14.5
2007	425	44	perm/semi	Oil palm/gardens	3908.0	1	0	0	1	2	0	2	2	2	2	0	0	1	4	1	2	0	3	113.65
2008	425	44	perm/semi	Oil palm/gardens	3781.8	2	0	0	0	1	0	1	3	1	0	0	0	0	0	0	2	0	0	30
2009	428	46	perm/semi	Oil palm/gardens	3441.2	1	0	0	0	1	0	0	1	1	0	0	0	0	0	0	1	0	0	13.3
2010	428	46	perm/semi	Oil palm/gardens	4439.0	3	2	3	4	7	1	8	12	8	4	1	0	3	26	2	4	2	12	1179.9
2011	428	46	perm/semi	Oil palm/gardens	2657.2	1	0	0	0	2	0	0	3	0	0	2	0	0	0	0	1	0	1	18.55
2012	429	46	perm/semi	Oil palm/gardens	3818.2	0	0	0	0	1	0	1	2	2	0	0	0	0	0	0	1	0	1	10.05
2013	429	47	perm/semi	Oil palm/gardens	4239.0	4	1	1	2	4	1	5	7	7	3	2	0	2	14	1	3	1	4	531.1
2014	430	47	perm/semi	Oil palm/gardens	3657.1	2	0	0	1	2	0	2	1	1	0	1	0	0	0	0	1	0	2	36.2
					TOTAL	**20**	**5**	**4**	**12**	**28**	**2**	**27**	**47**	**35**	**13**	**8**	**0**	**8**	**56**	**6**	**25**	**5**	**33**	**2593.95**

TOTAL = 2593.95

*n= the total number of people (elderly/middle aged and both males and females) interviewed

1 Refers to the total number of roads categorised as sealed or unsealed that has led to gullying or were completely washed away and destroyed by flooding events.

2 Bridges: Refers to the total number of both bridges and culverts that have been eroded, damaged or washed away during flooding events thus cutting off the road links

3 Non Pickup of Fresh Fruit Bunches: Refers to the total number of times per 10 smallholder blocks when oil palm Fresh Fruit Bunches (FFB) in small holder oil palm blocks were not picked up by company vehicle to the mill as roads were cut-off by flooding events.

4 Soil Erosion and Land Loss: Refers to the observed total number of 1) soil erosion, and 2) land being lost to new owner on the opposite river bank as river changes its meander to create new land boundary after flooding events.

5 Oil Palm Trees: Refers to the total number of all oil palm trees (regardless of young or mature ages) damaged, uprooted or carried away by flooding events

6 Other Cash Crop: Refers to the total number of cultivated crops damaged or destroyed by flood. Together with subsistence gardening, they are used as a form of income security in times of low world market prices for palm oil.
Examples of such cash crops includes cocoa, coconut, betelnut, taun, mangos, tulip, sago and robusta coffee. These are usually planted along waterways because most of the land are occupied by oil palm trees.

7 Subsistence Gardens; U = uprooted, D= Destroyed: Refers to the total number of gardens that had a good number of food crops completely destroyed, uprooted or washed away by flooding events.

8 Drown; ND= Nearly Died, D = died: Refers to the total number of people who nearly died from drowning or have died from drowning during flooding events.

9 Houses: Refers to the total number of houses that were destroyed or carried away by flood events

10 Household Goods: Refers to the total number of household goods (e.g. kerosine stove) that were destroyed or carried away by flood events

11 Service Structures: Refers to the total number of service structures (aidposts/schools/church buildings: tally of each added together to come up with one number) that are either damaged or washed away.

12 Economic Centers: Refers to the total number of local markets, tradestores and shops impacted directly or indirectly by flood events.

13 Vehicles: Refers to the total number of vehicles/cars/motorbikes that are either damaged or washed away.

14 Formal Job Income: Refers to the total number of people earning formal job income who were affected by flood events because they cannot be able to go to work resulting in loss of income from their fortnightly salary.

15 Estimated Economic Cost: These refers to the total estimated monetary costs in Papua New Guinea Kina (PGK) resulting from the losses or damages of each of the parameters from 1-12 per annum.
For e.g., if someone died from drowning, the costs are both direct (funeral expenses etc) and in-direct (number of money to be earned in the years remaining in that person's life).
NB: These are estimated figures of costs:- data on these are not available, however, the figures were estimated based on all the likely monetary values/costs of losses or damages in the adjacent columns.

Appendix 6.4: Small holder oil palm blocks upstream.

REPORTED CASES OF LOSSES THROUGH FLOODING IN THE DAGI RIVER BASIN FROM 2000 - 2014

Terence Simbiwen - COLLATED QUESTIONNAIRE DATA

Dagi upstream_company owned oil palm plantations ***(n* = 60)*** — **SITE 2 - Company owned oil palm plantations upstream**

Year	Tot.Pop	TotalHouses	HouseType	Avg.IncomeSource	Annual Rainfall (mm)	CASES OF LOSSES OR DAMAGES DUE TO FLOODING: ROADS[1]		B[2]	NP FFB[3]	SE/LLS[4]		OPT[5]	OCC[6]	SG[7]		D[8]		H[9]	HHG[10]	SS[11]	EC[12]	V[13]	FJI[14]	EE COSTS (PGK 000's)[15]
						Gullying	Destroyed			SE	LL			U	D	ND	D							
2000	452	40	Permanent	Salary/subsist.garden	3349.6	1	0	0	0	1	0	1	0	1	0	1	0	0	0	0	2	0	3	16.7
2001	454	40	Permanent	Salary/subsist.garden	2909.6	1	0	0	0	1	0	1	0	1	0	0	0	0	0	0	0	0	0	13.8
2002	453	40	Permanent	Salary/subsist.garden	3653.4	0	0	0	0	0	0	1	0	1	0	1	0	0	0	0	1	0	0	15.4
2003	456	40	Permanent	Salary/subsist.garden	3784.0	0	0	1	1	1	0	0	0	1	0	0	0	0	0	0	3	0	0	157.3
2004	454	40	Permanent	Salary/subsist.garden	3280.8	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	2	0	0	13.6
2005	462	40	Permanent	Salary/subsist.garden	4179.0	1	0	2	1	1	0	1	0	1	1	0	0	0	0	0	4	1	5	375.9
2006	465	40	Permanent	Salary/subsist.garden	3519.0	1	0	0	0	0	0	0	0	0	2	0	0	0	0	0	1	0	0	12.5
2007	468	45	Permanent	Salary/subsist.garden	3908.0	1	0	0	1	1	0	0	0	1	1	1	1	0	0	0	2	0	3	201.0
2008	468	45	Permanent	Salary/subsist.garden	3781.8	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0	1	0	0	13.1
2009	469	45	Permanent	Salary/subsist.garden	3441.2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	10.6
2010	472	45	Permanent	Salary/subsist.garden	4439.0	3	1	1	1	1	0	3	0	2	4	2	1	0	0	0	4	1	12	511.2
2011	473	52	Permanent	Salary/subsist.garden	2657.2	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	3.5
2012	475	52	Permanent	Salary/subsist.garden	3818.2	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	2	12.1
2013	475	52	Permanent	Salary/subsist.garden	4239.0	1	1	0	1	1	0	1	0	0	1	0	0	0	0	0	2	0	7	269.6
2014	478	52	Permanent	Salary/subsist.garden	3657.1	1	0	0	0	1	0	2	0	1	0	0	0	0	0	0	1	0	0	17.8
					TOTAL	**13**	**2**	**4**	**5**	**9**	**0**	**12**	**0**	**10**	**11**	**5**	**2**	**0**	**0**	**0**	**25**	**2**	**32**	**1644.0**
																								TOTAL = 1644.0

**n= the total number of people (elderly/middle aged and both males and females) interviewed*

1 Refers to the total number of roads categorised as sealed or unsealed that has led to gullying or were completely washed away and destroyed by flooding events.

2 Bridges: Refers to the total number of both bridges and culverts that have been eroded, damaged or washed away during flooding events thus cutting off the road links

3Non Pickup of Fresh Fruit Bunches: Refers to the total number of times per 10 smallholder blocks when oil palm Fresh Fruit Bunches (FFB) in small holder oil palm blocks were not picked up by company vehicle to the mill as roads were cut-off by flooding events.

4 Soil Erosion and Land Loss: Refers to the observed total number of 1/ soil erosion, and 2/ land being lost to new owner on the opposite river bank as river changes its meander to create new land boundary after flooding events .

5 Oil Palm Trees: Refers to the total number of all oil palm trees (regardless of young or mature ages) damaged, uprooted or carried away by flooding events

6 Other Cash Crop:Refers to the total number of cultivated crops damaged or destroyed by flood. Together with subsistence gardening, they are used as a form of income security in times of low world market prices for palm oil.

Examples of such cash crops includes cocoa, coconut, betelnut, taun, mangos, tulip, sago and robusta coffee. These are usually planted along waterways because most of the land are occupied by oil palm trees.

7 Subsistence Gardens; U = uprooted, D= Destroyed: Refers to the total number of gardens that had a good number of food crops completely destroyed,uprooted or washed away by flooding events.

8 Drown; ND= Nearly Died, D = died: Refers to the total number of people who nearly died from drowning or have died from drowning during flooding events.

9 Houses:Refers to the total number of houses that were destroyed or carried away by flood events

10 Household Goods: Refers to the total number of household goods (e.g. kerosine stove) that were destroyed or carried away by flood events

11Service Structures: Refers to the total number of service structures (aidposts/schools/church buildings: tally of each added together to come up with one number) that are either damaged or washed away.

12 Economic Centers: Refers to the total number of local markets, tradestores and shops impacted directly or indirectly by flood events.

13 Vehicles: Refers to the total number of vehicles/cars/motorbikes that are either damaged or washed away.

14Formal Job Income: Refers to the total number of people earning formal job income who were affected by flood events because they cannot be able to go to work resulting in loss of income from their fortnightly salary.

15 Estimated Economic Cost: These refers to the total estimated monetary costs in Papua New Guinea Kina (PGK) resulting from the losses or damages of each of the parameters from 1-13 per annum.

For e.g., if someone died from drowning, the costs are both direct (funeral expenses etc) and in-direct (number of money to be earned in the years remaining in that person's life).

NB: These are estimated figures of costs:- data on these are not available, however, the figures were estimated based on all the likely monetary values/costs of losses or damages in the adjacent columns.

Appendix 6.5: Company owned oil palm plantations upstream.

Appendix 6.6: Small holder oil palm blocks downstream.

REPORTED CASES OF LOSSES THROUGH FLOODING IN THE DAGI RIVER BASIN FROM 2000 - 2014

Terence Simbiwen - COLLATED QUESTIONNAIRE DATA

Dagi downstream_smallholder oil palm blocks (n* - ###) — SITE 3 - Smallholder oil palm blocks downstream

Year	Tot.Pop	TotalHouses	HouseType	Avg.IncomeSource	Annual Rainfall (mm)	CASES OF LOSSES OR DAMAGES DUE TO FLOODING: ROADS[1] Gullying	ROADS[1] Destroyed	B[2]	NP FFB[3]	SE/LLS[4] SE	SE/LLS[4] LL	OPT[5]	OCC[6]	SG[7] U	SG[7] D	D[8] ND	D[8] D	H[9]	HHG[10]	SS[11]	EC[12]	V[13]	FJI[14]	EE COSTS (PGK 000's)[15]
2000	4048	350	perm/semi	Oil palm/gardens	3349.6	3	0	0	2	1	0	1	1	1	0	0	0	0	0	0	4	0	2	68.55
2001	4050	350	perm/semi	Oil palm/gardens	2909.6	0	0	0	0	1	0	1	1	0	0	1	0	0	0	0	1	0	1	56.35
2002	4051	350	perm/semi	Oil palm/gardens	3653.4	1	0	0	0	1	0	1	2	0	0	0	0	0	1	0	2	0	3	91.20
2003	4051	350	perm/semi	Oil palm/gardens	3784.0	1	0	0	1	1	1	1	1	0	0	0	0	1	2	0	1	1	4	117.10
2004	4054	350	perm/semi	Oil palm/gardens	3280.8	0	0	0	0	1	0	1	1	0	0	0	0	0	1	0	2	0	2	61.25
2005	4059	352	perm/semi	Oil palm/gardens	4179.0	2	0	0	3	1	0	3	3	2	1	0	0	1	2	1	5	1	6	314.20
2006	4063	352	perm/semi	Oil palm/gardens	3519.0	1	0	0	0	1	0	1	1	0	0	0	0	0	1	0	2	0	2	88.25
2007	4064	354	perm/semi	Oil palm/gardens	3908.0	1	0	0	2	1	0	2	2	1	1	0	0	1	5	0	2	1	2	697.90
2008	4064	354	perm/semi	Oil palm/gardens	3781.8	1	0	0	0	1	0	1	1	1	0	1	0	0	0	0	1	0	1	132.40
2009	4065	354	perm/semi	Oil palm/gardens	3441.2	0	0	0	0	1	0	1	1	0	0	0	0	0	2	0	1	0	2	83.30
2010	4066	354	perm/semi	Oil palm/gardens	4439.0	2	1	1	5	3	2	2	5	1	2	0	0	1	10	1	8	2	6	1695.00
2011	4068	355	perm/semi	Oil palm/gardens	2657.2	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	1	0	1	45.25
2012	4070	355	perm/semi	Oil palm/gardens	3818.2	1	0	0	0	1	0	1	1	1	0	0	0	1	8	0	1	1	1	456.30
2013	4072	360	perm/semi	Oil palm/gardens	4239.0	2	1	1	2	2	1	2	2	2	1	1	0	1	8	1	12	2	4	1465.30
2014	4074	360	perm/semi	Oil palm/gardens	3657.1	1	1	0	1	1	0	1	1	1	1	0	0	0	0	0	3	1	2	117.09
					TOTAL	**16**	**3**	**2**	**16**	**18**	**4**	**20**	**23**	**10**	**6**	**3**	**0**	**6**	**40**	**3**	**46**	**9**	**39**	**5489.44**

TOTAL - 5489.44

*n= the total number of people (elderly/middle aged and both males and females) interviewed

1 Refers to the total number of roads categorised as sealed or unsealed that has led to gullying or were completely washed away and destroyed by flooding events.

2 Bridges: Refers to the total number of both bridges and culverts that have been eroded, damaged or washed away during flooding events thus cutting off the road links

3 Non Pickup of Fresh Fruit Bunches: Refers to the total number of times per 10 smallholder blocks when oil palm Fresh Fruit Bunches (FFB) in small holder oil palm blocks were not picked up by company vehicle to the mill as roads were cut-off by flooding events.

4 Soil Erosion and Land Loss: Refers to the observed total number of 1) soil erosion, and 2) land being lost to new owner on the opposite river bank as river changes its meander to create new land boundary after flooding events.

5 Oil Palm Tress: Refers to the total number of all oil palm trees (regardless of young or mature ages) damaged, uprooted or carried away by flooding events

6 Other Cash Crop:Refers to the total number of cultivated crops damaged or destroyed by flood. Together with subsistence gardening, they are used as a form of income security in times of low world market prices for palm oil.

Examples of such cash crops includes cocoa, coconut, betelnut, taun, mangos, tulip, sago and robusta coffee. These are usually planted along waterways because most of the land are occupied by oil palm trees.

7 Subsistence Gardens; U = uprooted, D= Destroyed: Refers to the total number of gardens that had a good number of food crops completely destroyed,uprooted or washed away by flooding events.

8 Drown; ND= Nearly Died, D = died: Refers to the total number of people who nearly died from drowning or have died from drowning during flooding events.

9 Houses:Refers to the total number of houses that were destroyed or carried away by flood events

10 Household Goods: Refers to the total number of household goods (e.g. kerosine stove) that were destroyed or carried away by flood events

11Service Structures: Refers to the total number of service structures (aidposts/schools/church buildings: tally of each added together to come up with one number) that are either damaged or washed away.

12 Economic Centers: Refers to the total number of local markets, tradestores and shops impacted directly or indirectly by flood events.

13 Vehicles: Refers to the total number of vehicles/cars/motorbikes that are either damaged or washed away.

14Formal Job Income: Refers to the total number of people earning formal job income who were affected by flood events because they cannot be able to go to work resulting in loss of income from their fortnightly salary.

15 Estimated Economic Cost: These refers to the total estimated monetary costs in Papua New Guinea Kina (PGK) resulting from the losses or damages of each of the parameters from 1-12 per annum.

For e.g., if someone died from drowning, the costs are both direct (funeral expenses etc) and in-direct (number of money to be earned in the years remaining in that person's life).

NB: These are estimated figures of costs:- data on these are not available, however, the figures were estimated based on all the likely monetary values/costs of losses or damages in the adjacent columns.

Appendix 6.7: Company owned oil palm plantations downstream.

REPORTED CASES OF LOSSES THROUGH FLOODING IN THE DAGI RIVER BASIN FROM 2000 - 2014

Terence Simbiwen - COLLATED QUESTIONNAIRE DATA

Dagi downstream_company owned oil palm plantations *(n* = 65)*

SITE 4 - Company owned oil palm plantations downstream

Year	Tot.Pop	TotalHouses	HouseType	Avg.IncomeSource	Annual Rainfall (mm)	CASES OF LOSSES OR DAMAGES DUE TO FLOODING: ROADS[1]		B[2]	NP FFB[3]	SE/LLS[4]		OPT[5]	OCC[6]	SG[7]		D[8]		H[9]	HHG[10]	SS[11]	EC[12]	V[13]	FJI[14]	EE COSTS (PGK 000's)[15]
						Gullying	Destroyed			SE	LL			U	D	ND	D							
2000	1215	200	Permanent	Salary/subsist.garden	3349.6	2	0	0	1	0	0	1	0	1	2	1	1	0	0	0	1	0	1	87.35
2001	1218	200	Permanent	Salary/subsist.garden	2909.6	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10.00
2002	1223	200	Permanent	Salary/subsist.garden	3653.4	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	2	0	1	13.10
2003	1223	200	Permanent	Salary/subsist.garden	3784.0	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0	3	1	3	113.00
2004	1225	200	Permanent	Salary/subsist.garden	3280.8	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	1	161.55
2005	1226	200	Permanent	Salary/subsist.garden	4179.0	3	1	1	1	1	0	2	0	0	1	0	1	0	0	0	6	0	7	515.60
2006	1228	200	Permanent	Salary/subsist.garden	3519.0	0	0	1	0	1	0	1	0	0	0	0	0	0	0	0	2	0	0	105.50
2007	1229	200	Permanent	Salary/subsist.garden	3908.0	1	0	1	1	0	0	0	0	0	1	1	0	0	0	0	3	0	1	15.30
2008	1332	210	Permanent	Salary/subsist.garden	3781.8	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0	2	0	0	15.50
2009	1332	210	Permanent	Salary/subsist.garden	3441.2	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	11.50
2010	1332	210	Permanent	Salary/subsist.garden	4439.0	4	1	0	2	2	0	1	0	1	2	2	0	0	0	0	7	1	17	421.00
2011	1337	210	Permanent	Salary/subsist.garden	2657.2	0	0	0	0	2	0	0	0	2	0	0	0	0	0	0	1	0	0	11.60
2012	1338	210	Permanent	Salary/subsist.garden	3818.2	1	0	0	0	1	0	1	0	1	0	0	1	0	0	0	2	0	1	104.80
2013	1338	210	Permanent	Salary/subsist.garden	4239.0	0	1	1	1	2	0	1	0	2	1	0	0	0	0	0	4	1	11	535.70
2014	1343	210	Permanent	Salary/subsist.garden	3657.1	1	0	0	1	1	0	1	0	1	0	0	0	0	0	0	2	0	3	20.60
					TOTAL	**18**	**3**	**4**	**9**	**11**	**0**	**10**	**0**	**8**	**7**	**5**	**3**	**0**	**0**	**0**	**38**	**3**	**46**	**2142.10**

TOTAL = 2142.1

**n= the total number of people (elderly/middle aged and both males and females) interviewed*

1 Refers to the total number of roads categorised as sealed or unsealed that has led to gullying or were completely washed away and destroyed by flooding events.

2 Bridges: Refers to the total number of both bridges and culverts that have been eroded, damaged or washed away during flooding events thus cutting off the road links

3Non Pickup of Fresh Fruit Bunches: Refers to the total number of times per 10 smallholder blocks when oil palm Fresh Fruit Bunches (FFB) in small holder oil palm blocks were not picked up by company vehicle to the mill as roads were cut-off by flooding events.

4 Soil Erosion and Land Loss: Refers to the observed total number of 1) soil erosion, and 2) land being lost to new owner on the opposite river bank as river changes its meander to create new land boundary after flooding events .

5 Oil Palm Trees: Refers to the total number of all oil palm trees (regardless of young or mature ages) damaged, uprooted or carried away by flooding events

6 Other Cash Crop:Refers to the total number of cultivated crops damaged or destroyed by flood. Together with subsistence gardening, they are used as a form of income security in times of low world market prices for palm oil.

Examples of such cash crops includes cocoa, coconut, betelnut, taun, mangos, tulip, sago and robusta coffee. These are usually planted along waterways because most of the land are occupied by oil palm trees.

7 Subsistence Gardens; U = uprooted, D= Destroyed: Refers to the total number of gardens that had a good number of food crops completely destroyed,uprooted or washed away by flooding events.

8 Drown; ND= Nearly Died, D = died: Refers to the total number of people who nearly died from drowning or have died from drowning during flooding events.

9 Houses:Refers to the total number of houses that were destroyed or carried away by flood events

10 Household Goods: Refers to the total number of household goods (e.g. kerosine stove) that were destroyed or carried away by flood events

11Service Structures: Refers to the total number of service structures (aidposts/schools/church buildings: tally of each added together to come up with one number) that are either damaged or washed away.

12 Economic Centers: Refers to the total number of local markets, tradestores and shops impacted directly or indirectly by flood events.

13 Vehicles: Refers to the total number of vehicles/cars/motorbikes that are either damaged or washed away.

14Formal Job Income: Refers to the total number of people earning formal job income who were affected by flood events because they cannot be able to go to work resulting in loss of income from their fortnightly salary.

15 Estimated Economic Cost: These refers to the total estimated monetary costs in Papua New Guinea Kina (PGK) resulting from the losses or damages of each of the parameters from 1-13 per annum.

For e.g., if someone died from drowning, the costs are both direct (funeral expenses etc) and in-direct (number of money to be earned in the years remaining in that person's life).

NB: These are estimated figures of costs:- data on these are not available, however, the figures were estimated based on all the likely monetary values/costs of losses or damages in the adjacent columns.

Appendix 6.8: Weights and criteria

Table 6.3: Showing the weight assigned for different land uses classes

S. No.	**Land use types**	**Assigned relative weight**
1	Oil palm (Grown in plantations and small holder blocks combined).	100
2	Subsistence garden (along riparian zones)	60
3	Houses and buildings (e.g. of infrastructure) -	10
4	Roads (sealed and unsealed roads combined)	30

Table 6.4: Risk zonation based on hazard and vulnerability criteria

Type of Assessment	Criteria of Assessment	Classification (metres)	Risk zones
Hazard	Water depth	0.05-0.5	Low
		0.5 - 1.5	Medium
		1.5 - 3.0	High
		Above 3m	Very High
Vulnerability	Level of vulnerability	0.0-0.35	Low
		0.36-0.55	Medium
		0.56-0.75	High
		0.76 -1.0	Very High

Appendix 6.9: Vulnerability curves from overseas

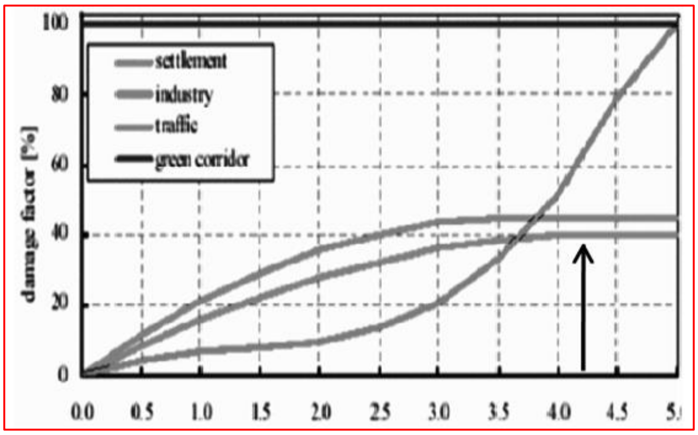

Figure 6.12: Stage-damage function for road traffic (Scorzini et al., 2015).

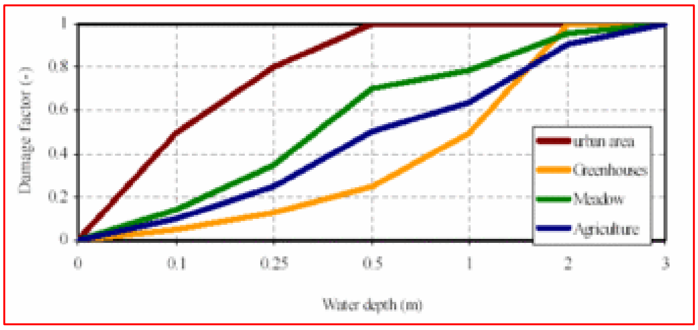

Figure 6.13: Stage-damage function for agriculture (Scorzini et al., 2015).

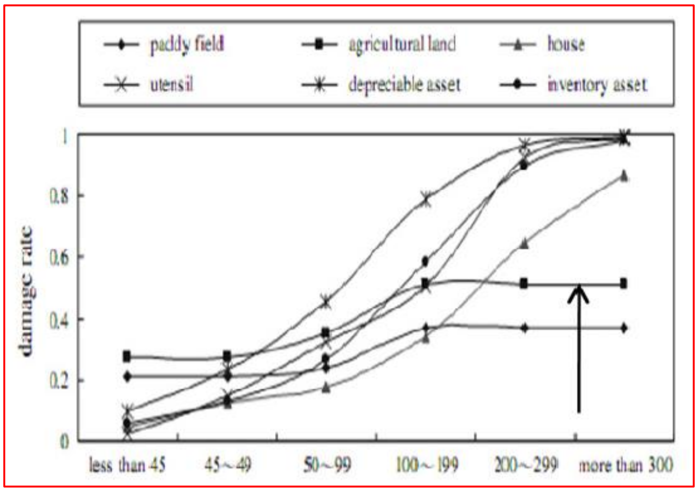

Figure 6.14: Stage-damage function for agricultural land, house and paddy field (Scorzini et al., 2015).

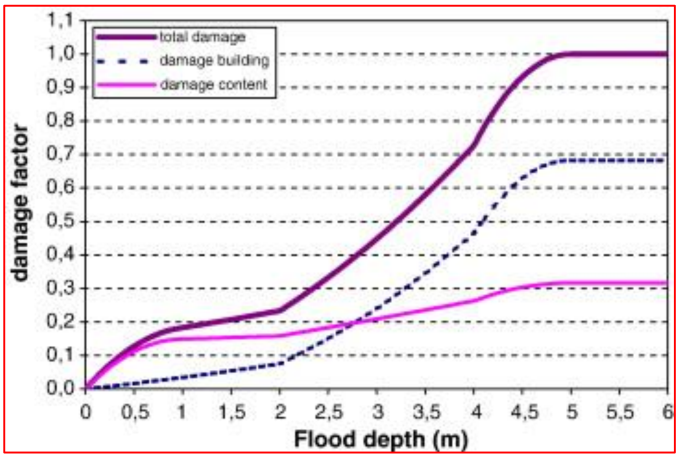

Figure 6.15: Stage-damage function for buildings (Scorzini et al., 2015).

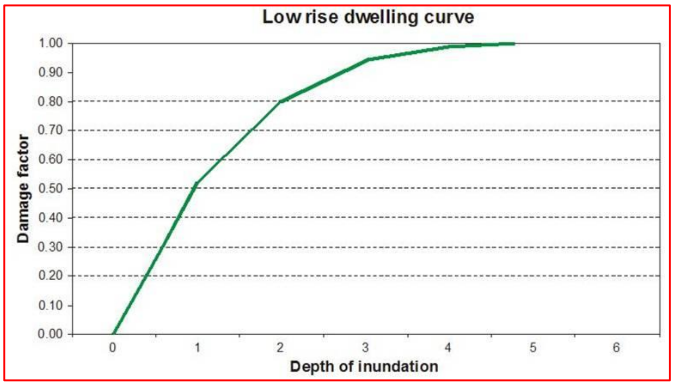

Figure 6.16: Stage-damage function for low rise dwelling houses (Scorzini et al., 2015).

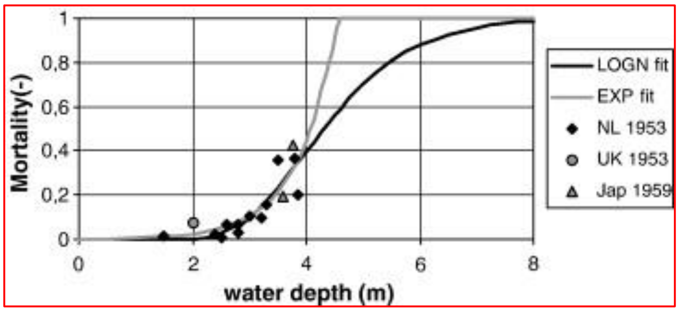

Figure 6.17: Stage-damage function for population mortality from floods (Scorzini et al., 2015)

Chapter 7.0: Appendix

Appendix 7.1: Population Census Data for Dagi

POPULATION IN BRIEF

WEST NEW BRITAIN PROVINCE	
Total population	264,264
Proportion of PNG's total population	3.6%
Annual growth rate since 2000 census	3.3%
Sex Ratio	111 males per 100 females
Average household size	5.2 persons
District with highest population count	Talasea; 189,999

WEST NEW BRITAIN PROVINCE

POPULATION BY DISTRICTS AND LLGs - 2000 and 2011 CENSUS

19		2000 CENSUS				2011 CENSUS				% of Province Total	Average House Hold Size
		House holds	Persons	Male	Female	House holds	Persons	Male	Female		
19	WEST NEW BRITAIN	33,574	184,508	99,015	85,493	50,744	264,264	138,942	125,322	100.0	5.2
01	KANDRIAN/GLOUCESTER	10,628	55,716	28,907	26,809	16,278	74,265	38,412	35,853	28.1	4.6
01	Gasmata Rural	1,674	9,012	4,858	4,154	2,158	11,439	5,948	5,491	4.3	5.3
02	Gloucester Rural	1,690	9,303	4,792	4,511	2,148	11,940	6,209	5,731	4.5	5.6
03	Kandrian Coastal Rural	2,458	12,596	6,611	5,985	5,739	17,073	8,878	8,195	6.5	3.0
04	Kandrian Inland Rural	2,162	10,014	5,109	4,905	2,615	13,248	6,889	6,359	5.0	5.1
05	Kove Kaliai Rural	2,644	14,791	7,537	7,254	3,618	20,565	10,488	10,077	7.8	5.7
02	TALASEA	22,946	128,792	70,108	58,684	34,466	189,999	100,530	89,469	71.9	5.5
06	Bialla Rural	6,627	36,188	20,099	16,089	10,283	58,373	30,938	27,435	22.1	5.7
07	Bali Witu Rural	2,360	13,734	7,183	6,551	2,815	16,665	9,166	7,499	6.3	5.9
08	Hoskins Rural	3,172	19,327	10,135	9,192	4,498	27,665	14,109	13,556	10.5	6.2
09	Kimbe Urban	2,428	14,184	7,738	6,446	5,078	22,923	11,920	11,003	8.7	4.5
10	Mosa Rural	4,190	24,837	13,610	11,227	6,139	36,380	19,281	17,099	13.8	5.9
11	Talasea Rural	4,169	20,522	11,343	9,179	5,653	27,993	15,116	12,877	10.6	5.0

Figure 7.2: 2000 and 2011 total population and households in Dagi Catchment, Mosa Rural LLG (*Source: NSO, 2013).*

Appendix 7.2: LSS block sale prices

Table 7.2: LSS block sale prices for 1999-2000, Hoskins

Year of Sale	Sub-division	Block Details	Sale Price
1999	Kapore	6 ha block. 4 ha planted to oil palm	K15, 000
2000	Sarakolok	6 ha planted to oil palm, good house and trade store on block.	K35, 000
2000	Sarakolok	6 ha block. 4 ha planted to oil palm	K19, 000
2000	Sarakolok	6 ha block. 4 ha planted to oil palm	K30, 000
2000	Kavui	6 ha block. 4 ha planted to oil palm	K20, 000
2000	Kavui	6 ha block. 4 ha planted to oil palm	K25, 000
2000 ***(not yet sold)***	Kavui	6 ha block. 4 ha planted to oil palm. Back portion of block hilly and unsuitable for oil palm.	K27, 000
2000	Kapore	6 ha block. 4 ha planted to oil palm	K20, 000

Source: Oil Palm Industry Corporation (OPIC) files, 2001