University of Southern Queensland

Faculty of Health, Engineering and Sciences

LiDAR Data for DEM Generation and Flood Plain Mapping

A dissertation submitted by

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In fulfilment of the requirements of

Courses ENG4111 and ENG4112 Research Project

Towards the degree of

Bachelor of Spatial Science (Surveying)

Submitted:

30th October 2014

Abstract

On Monday 10 January 2011, a 1 in 100 year storm cell quickly developed over the Toowoomba city dumping intensive rain in a short period of time in the Gowrie Creek catchment (ICA, 2011). This caused extensive flash flooding over the entire catchment including West Creek before destroying the central business district and causing loss of life. To ensure that damage is reduced and lives are saved in the future, areas requiring mitigation need to be identified. To identify these areas characteristic analysis, slope analysis, flood plain mapping and hydrological modelling can be utilised. To complete this highly accurate Digital Elevation Models (DEM) generated from Airborne Light Detection and Ranging (LiDAR) data can be utilised. LiDAR is a surveying technology that can collect large amounts of accurate data compared to traditional survey methods. Stream networks and catchment boundaries were generated utilising Arc Hydro at multiple different thresholds. Slope analysis was also completed highlighting the flood plain and the possible effects of urbanisation. Hydrological modelling using the Storm Water Management Model (SWMM) also showed extensive velocities and volumes with assumptions. These results showed that West Creek had extensive problems with urbanisation throughout the catchment. It also highlighted the issues with West Creek and East Creek meeting and the inability of the system to handle both creeks flood waters once they merge. To proactively mitigate floods analysis should be completed before floods occur and using the worst case flood data.

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30/10/14

Acknowledgements

I would first like to acknowledge my supervisor for this project, Dr Xiaoye Liu. Her expertise in this field is unquestionable and without which, I would not have been able to complete this research project.

I would also like to acknowledge and thank the Toowoomba Regional Council. The Toowoomba council provided the LiDAR data that was utilised in the analysis without which, there would be no results.

I would also like to acknowledge Mr Alex Darton for all of his computer expertise. Without Alex I would not have been able to successfully install the Arc Hydro extension onto my computer and for this is I am forever grateful

Finally I would like to acknowledge and thank my friends, family and girlfriend for supporting and helping me get through this tough final period of my university degree.

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Chapter 1 Introduction

1.1 Introduction

Living in Queensland presents many risks and dangers when it comes to weather. One of these risks that can affect nearly everyone in some way is flash flooding. Flash flooding is the result of a sudden and unexpected amount of intense rainfall falling over a small area, generally with steep terrain in a short period of time (ICA, 2011). However living approximately 700 metres above sea level in the city of Toowoomba would allow complacency when it comes to flooding. Yet on Monday, 10 January 2011 a 1 in 100 year storm cell quickly developed over the city dumping intensive rain in a short period of time over the Gowrie Creek catchment area (ICA, 2011). This in combination with long term drenching rain that had been previously falling in the weeks leading up to the event, lead to one of the most devastating floods in recent time (ICA, 2011).

The Gowrie Creek catchment is a combination of Gowrie, East, West and Black Gully Creeks. East and West Creeks contain much of the cities rainwater catchment and converge just before the central business district (CBD). The catchment is heavily urbanised with multiple manmade features located within and along the waters flow path.

The intense rainfall that occurred over only a few short hours created flash flooding that caused damage throughout the creeks and destroyed the CBD from where East and West Creeks converged. Lives were lost and millions of dollars worth of damage occurred to the infrastructure within the central business district. The floodwaters then went down the Toowoomba Range and hit the un-expecting town of Grantham, where the entire town sustained heavy damage and more lives were lost. The floodwaters then continued down the system to join with other floodwaters in the Brisbane River before leaving to sea (SKM, 2011). An efficient and accurate flooding mitigation system would have reduced the severity of what was lost within this event, and any other flooding event. Figure 1 highlights the type of water that was flowing through the central business district of Toowoomba causing loss of life and infrastructure damage.

Figure 1: The floodwaters running through the Toowoomba central business district on the afternoon of the flash flooding event (Cook, Frew & Wen, 2011).

In this case the flooding occurred so rapidly that the warning systems were barely able to recognise the event before it had already happened. In a case like this flood mitigation requires implementation before an extreme event such as this is to occur. This would reduce the severity of the flood giving people more time to prepare, saving money and lives (ICA, 2011). To perform such a task highly accurate spatial data on the catchment area is vital for the mitigation of such events (SKM, 2011). Spatial data of such accuracy and size cannot be collected by traditional survey methods, instead requiring a different modern type of surveying.

Airborne Light Detection and Ranging (LiDAR) is a rapidly developing piece of technology that can collect large amounts of spatial data in a short period of time (Sangster, 2002). This data can be collected faster than traditional surveying methods whilst still providing accurate results (Kraus and Pfeifer, 1998). The collection of such dense spatial data in a short period of time allows the generation of high-resolution Digital Elevation Models (DEM). The DEM is a useful spatial data output that can be utilised in several types of analysis. Some of these analysis methods include flood plain mapping, characteristic analysis and hydrological modelling. The DEM can be utilised within software packages such as ArcGIS and other modelling software packages for characteristic analysis and modelling (Coleman et al., 2002; Sithole and Vosselman, 2003). These software tools allow for analysis that can be used in future flood forecasting and mitigation, which may save lives and millions of dollars’ worth of damages. This project looks to utilise the airborne LiDAR data to generate a high quality DEM for a characteristic analysis of the catchment area. This data can then be used to perform hydrological modelling making judgements on the catchments capabilities to deal with rainfall events.

1.2 Research Aim and Objectives

The aim of this project is to utilise LiDAR data to generate a high quality DEM for characteristic analysis of the West Creek catchment and hydrological modelling to assist in future flash flood mitigation. Within this research topic there are multiple objectives based on this aim.

1.2.1 Objective 1

Identify information and methods related to Airborne LiDAR data, hydrological analysis, modelling and flood plain mapping.

There is a broad range of information on LiDAR data including its history, data types, collection methods and possible uses. Each of these needs to be analysed to ensure there is a broad understanding of the topic, with an emphasis on the hydrological applications of the data. A broad understanding will allow correct and in-depth analysis in the later stages of the project. Therefore it is an objective of this project to gain as much information and knowledge as possible on LiDAR data and its application to waterways.

1.2.2 Objective 2:

Create a Digital Elevation Model.

In order to perform characteristic and hydrological analysis on the LiDAR data a DEM will require generation. Appropriate software capable of producing such a map will be required. Once the map is generated a characteristic analysis can be performed highlighting any areas of interest.

1.2.3 Objective 3:

Utilise the Digital Elevation Model in Hydrological Analysis.

Once the DEM is created hydrological analysis can be performed and a flood plain map generated. The use of appropriate software such as Arc GIS will allow a hydrological analysis of the mapped plain. This objective will lead towards the final goal of identifying areas that require flood mitigation.

1.2.4 Objective 4:

Perform Hydrological Modelling

To further strengthen the analysis and provide more useful information hydrological modelling is to be completed. Through the use of appropriate software information such as expected flow rates, velocities and volumes may be generated when incorporating appropriate meteorological data. This will help highlight any areas of interest that may not be highlighted in other analysis.

1.2.5 Objective 5:

Analyse results to determine areas requiring flood mitigation.

Once all of the mapping and modelling is completed all of the collected data requires analysis. This analysis will aim to determine characteristics or physical problems within the waterway, which may lead to flooding.

1.3 Justification

This project has many benefits that may arise from its completion. The first and foremost benefit of utilising airborne LiDAR data for flood plain mapping, analysis and hydrological modelling is flood mitigation. Flooding in Australia affects nearly everyone in some form and its mitigation to reduce damage and save lives is of utmost importance. Having the information and techniques available to take a proactive approach to mitigation is extremely important in future work. This project will also help highlight the capabilities of airborne LiDAR data and its appropriate software. Highlighting its application to such an important task will help promote airborne LiDAR data as a high quality and useful survey technology and technique.

1.4 Dissertation Overview

This dissertation contains multiple chapters relevant to the work completed. There are five main chapters in total and each is given a brief overview below.

Chapter 1 Introduction - This chapter gives an introduction to the topic. There is background information relevant to the project being undertaken with the need for the project highlighted. This chapter also states the aim and objectives of the project to be met throughout.

Chapter 2 Literature Review – This chapter goes over relevant literature to the project. It covers airborne LiDAR, DEMs, and hydrological modelling.

Chapter 3 Methodology – This chapter highlights the methods utilised to achieve the objectives of the project. It includes information about the study area, the data collection, the generation of the DEMs, the characteristic analysis and the hydrological modelling.

Chapter 4 Results and Discussion – This chapter highlights the results of the methodology. It also goes into detail about each of the results and their relevance to the objectives of the project.

Chapter 5 Conclusions – This chapter concludes the project summing up all of the information found and makes recommendations for the future.

There is also an extra chapter at the end which contains multiple appendices relevant to the information within the dissertation.

1.5 Conclusion

This chapter has provided an extensive background into the project. It has highlighted flooding as a common occurrence within Australia and that it needs to be dealt with proactively. Through the use of LiDAR data, analysis can be completed on the catchment to obtain any important information regarding its hydrological behaviour. Mitigation may then be implemented to ensure that such an event does not happen again in the future. The justification of completing this project has been described with mitigation highlighted as the key outcome. The objectives of the project have also been detailed and the dissertation outline has been provided. The following chapter will detail the literature relevant to meeting the objectives of this project.

Chapter 2 Literature Review

2.1 Introduction

To gain a full understanding on all of the information related to this topic and the objectives stated in the previous chapter, a literature review was completed. Several areas were identified as key to the topic and were thoroughly researched. These areas are airborne LiDAR, DEMs, and hydrological modelling. This review looks to give an extensive insight into each of these key areas reviewing previous research and studies.

2.2 Airborne LiDAR

Airborne Light Detecting and Ranging (LiDAR) also referred to as LiDAR, Laser Altimetry or Airborne Laser Scanning (ALS) is an active remote sensing technique originally designed to measure the topography of the earth's surface (Hollaus, Kraus & Wagner, 2005).

2.2.1 Airborne LiDAR History

The history of LiDAR is extensive with the technologies involved being studied for an extended period of time. Flood (2001) states that LiDAR data and the technologies involved around it have been studied since the 1960s. For multiple years to come there were multiple experiments involving the advancement of the laser and its usage. Multiple results were returned, both positive and negative. The first major advancement occurred in the 1980s when research and design of Airborne LiDAR for topographic data collection started. This history is further highlighted by Butler et al. (1984) and Bufton et al. (1991) who both reviewed the advancements in the technology at their time of arrival. This research and design then came into fruition in the 1990s when commercial LiDAR systems became operational and available for any surveyor wishing to utilise them, at a high price. Since then LiDAR has come to the forefront of surveying technology becoming a recognised and well used method of geographical data collection. This type of technology and its many uses is an area that will continue to be active in research and development in the future (Pfeifer and Briese, 2007; Flood, 2001).

Many of the improvements with LiDAR in the modern age involve the sensors, data processing aspects, increased accuracy, a wider spectrum range and extraction of object properties (Pfeifer and Briese, 2007). One of the major modern advances in the technology revolves around the continued improvement of the laser pulse repetition rate. Flood (2001) states that the maximum pulse repetition rate previously available for commercial systems was 50 kHz. However Lemmens (2007) who compared multiple Airborne LiDAR systems only six years later states that the maximum repetition rate for commercial systems was around or even higher than 250 kHz. Now seven years later again there are commercial systems available with repetition rates above 500 kHz for commercial use (Leica, 2014). This dramatic improvement in a short period of time shows that LiDAR has and will continue to improve as more modern technology continues to be developed, providing access to fast, cheap and dense spatial data. These advances in technology have presented many modern applications for LiDAR data including hydrological modelling and flood plain mapping (Berglund et al., 2007).

2.2.2 Airborne LiDAR System

An airborne LiDAR system is typically composed of three main components that work together to collect the spatial data. These three components are the laser scanner, the Global Positioning System (GPS) receiver and the Inertial Measurement Unit (IMU) (Hollaus, Kraus & Wagner, 2005; Pfeifer & Briese, 2007). Figure 2 shows how the systems work together along with the aircraft to collect spatial data. The laser scanner consists of a pulse generator and a receiver to gather the information of the reflected pulses from the terrain. The laser works by emitting short infrared pulses towards the earth's surface. These pulses can be sent at rates of up to 500 kHz in modern systems with a faster pulse generation rate resulting in more data in a shorter period of time (Leica, 2014). A photodiode within the scanner then measures the backscatter echoes from the pulse generator. The echoes received by the photodiode are dependent on the objects within the travel path of the laser pulse. The distance between sensor and the object that it meets can then be determined by multiplying the time it took for the light to transmit and return by the speed of light (Watkins, 2005). Therefore laser scanners measure the round trip of multiple echoes from one laser pulse generated from the scanner (Hollaus, Kraus & Wagner, 2005; Pfeifer & Briese, 2007). An airborne LiDAR survey requires the knowledge of where the plane is, so the GPS receiver is used to record the aircrafts trajectory. The receiver in conjunction with a base receiver on a known position gives a real time position of the plane as it flies. In general flight, aircrafts do not stay straight and level, so the IMU unit within measures the movements of the aircraft. The aircraft can move in three possible directions depending on conditions including roll, pitch and yaw. The IMU measures the roll, pitch and yaw of the plane to allow adjustments to the collected data if necessary (Dias & Webster, 2006). Each of these types of plane movement is highlighted in figure 2.

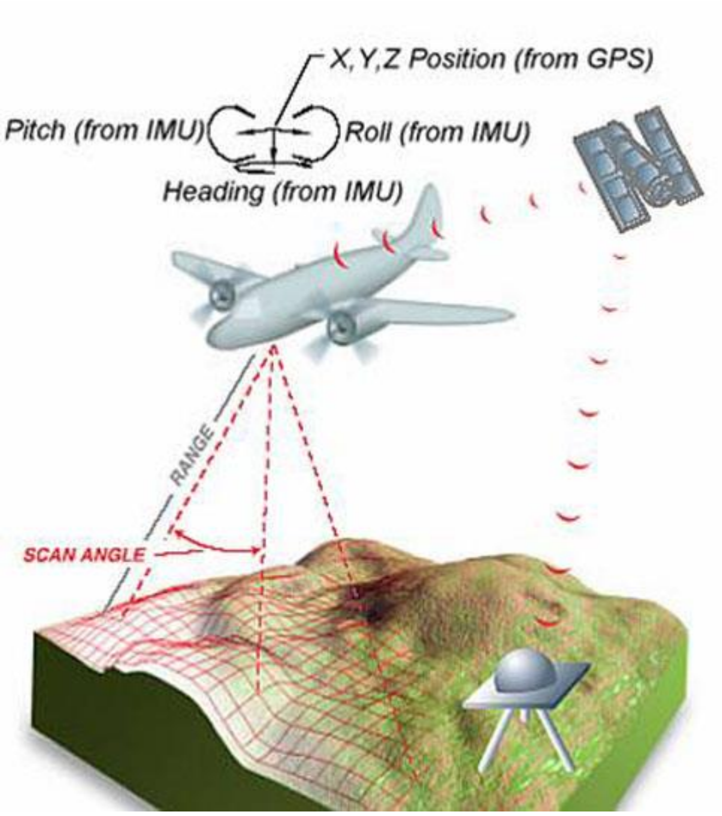

Figure 2: An Airborne LiDAR system highlighting the scanner, GPS and IMU unit (Ohio Department of Transportation, 2014).

2.2.3 Airborne LiDAR Accuracy

The accuracy of the LiDAR data collected is reliant on the accuracy capabilities of the GPS and IMU units. According to BC-CARNS (2006) airborne GPS units are capable of accuracies of approximately 5 cm horizontally and 10 cm vertically. It also states that the IMU units are capable of accuracies of a couple of centimetres. This means that LiDAR data should be able to achieve accuracies of approximately 15 cm root mean square (RMSE) in vertical and 20 cm RMSE in horizontal. This accuracy over a mass scale in dense data is more than enough for the purpose of flood plain mapping and analysis. These accuracies are beneficial for many surveying applications and can be best represented in a DEM.

2.2 Digital Elevation Models

Airborne LiDAR data has multiple possible uses throughout the surveying world. However the main use for the technology in modern surveying is spatial analysis. There has been a significant increase in the use of LiDAR data for DEM generation as more reliable and accurate LiDAR systems are developed (Sithole and Vosselman, 2003).

2.2.1 Data Source for Digital Elevation Models

Within the surveying profession there are several different ways to collect spatial data depending on the requirement of the client. Traditional survey methods of terrain data collection such as field surveying using total station, GPS and photogrammetry are capable of yielding high accuracy terrain data. These methods can however be extremely labour and time intensive when it comes to collecting highly accurate spatial data over a large-scale area. This extra labour and time makes them inefficient and costly to surveying businesses, making large-scale spatial data collection difficult. Traditional methods also provide many data collection issues in areas such as forests where data cannot be easily collected due to vision problems (Liu, 2008). The problems presented by traditional survey methods are where airborne LiDAR can fill in the gap of efficient terrain data collection. Airborne LiDAR can collect dense data quickly and accurately penetrating through forest areas, overcoming traditional methods of terrain data collection (Liu, 2008). Kraus and Pfeifer (1998) demonstrated that this was the case by confirming that DEMs generated by LiDAR in forests achieved the same accuracy as photogrammetry in open areas.

Modern LiDAR data capture methods and technology allow for mass collection of high-density data resulting in an accurate representation of the earth's terrain. This however presents other issues with data such as storage capacity, processing power and manipulation capabilities. Sangster (2002) highlights that there are several factors, which contribute to the density of the airborne LiDAR data. These were the pulse rate of the laser, the altitude of the platform (flying height), the width of the swath, the speed of the aircraft and the amount of overlap. Each of these needs to be considered when collecting spatial data and the effects they may have on the processing stage after collection.

The study completed by Liu (2008) looks to overcome the issues of storage, capacity and manipulation of airborne LIDAR data by focusing on LiDAR data filters, interpolation methods and LiDAR data reduction. The section important to this study is the LiDAR data reduction and the problems that can occur with it. The main point deduced from Liu (2008) is that it is crucial to filter or extract the bare earth points from the LiDAR data. However many of the systems available still had floors and some manual editing was required.

A major advantage of airborne LiDAR data is that it has the capability of presenting objects in a three-dimensional object space immediately after collection (Al-Ruzoug et al., 2005). After collection the LiDAR points are initially represented with latitude, longitude and ellipsoidal height based on the World Geodetic System 1984 (WGS84) reference ellipsoid. These coordinates on the ellipsoid can be transformed to a national or regional coordinate system depending on the required use, accuracy and size of the survey. If the survey is small and only for limited use, the data can be converted using a regional datum. However if the data collection area is large and has beneficial use for the state or country, a national system should be used. Elevations can also be converted from ellipsoidal heights to orthometric heights based on a national or regional height datum by using a geoid model. These heights can then be used within the DEM as terrain heights (Dias & Webster, 2006; Chandra et al., 2007).

The scanner in an airborne LiDAR survey can measure the backscatter signal from any surface that the beam makes contact with. These non-ground surfaces can include man-made objects, vegetation or wildlife that are under the laser at time of collection (Barber & Shortrudge, 2004; Gesch et al., 2006). Multiple returns of the one pulse occur when the laser pulse meets a target that does not completely block the path of the pulse, allowing the remained of the pulse to continue on to a lower target (Anderson, McGaughey & Reutebuch, 2005). These non-ground points have multiple applications but as Liu (2008) highlights the separation of these from the ground points is a vital step in the creation of a highly accurate DEM for characteristic analysis.

Another type of data that is collected in an airborne LiDAR survey, which contributes to the improvement of DEM quality, is the intensity of the backscatter laser pulse. The backscatter signal is a function of multiple variables including the laser power, beamwidth, range, atmospheric transmission and target cross section (Briese et al., 2004). The intensity is created by the optical signal received at the sensor being converted to an electrical signal by a photo detector. This electrical signal is then quantised to a digital number by the system, which is the intensity value. This can then be interpolated to a geo-referenced intensity image, which can assist in surface classification of DEM's (Briese et al., 2004; Han et al., 2002)

2.2.2 Digital Elevation Model Generation and Output

To complete the generation of a flood plain map there are several types of outputs that may be generated. These outputs include, but are not limited to topographic surface models, thematic land cover maps and two-dimensional hydraulic surface flow models (Hollaus, Kraus & Wagner, 2005). The DEM plays a major role in their production due to the DEMs slope, aspect and drainage networks all being key parameters. The accuracy of these parameters within the DEM plays a major role in further modelling (Hollaus, Kraus & Wagner, 2005).

The study completed by Liu (2008) highlights that the Inverse Distance Weighted (IDW) interpolation method is a suitable interpreter of high density LiDAR data. The IDW interpolation method assumes that each collected point has an influence locally, which diminishes with distance. It works well with dense evenly distributed data but does not work as effectively if the points are sparse or uneven (Childs, 2004). In Liu, McDougall and Zhang (2011) they generate a high quality DEM from LiDAR data for characteristic analysis utilising the IDW interpolation method within ArcGIS 10 software. Liu (2008) also highlights that to improve efficiency and maintain accuracy the extraction and inclusion of terrain elements such as break lines with the DEM is an important step. Finally Liu (2008) also states that the DEM resolution must match the LiDAR density, be able to reflect the changes over the terrain surface and represent the terrain features. Each of these is vital in generating a DEM that is capable of flood modelling.

A study completed by Liu and Zhang (2010) looked into the automated delineation of drainage networks from high resolution DEMs. The study was completed as the drainage networks are highlighted as one of the main factors in flood analysis and prediction. The area used for the study covered the entire Toowoomba City. The extraction of the drainage networks was completed utilising the Arc Hydro extension of ArcGIS software. The study highlights that the use of a threshold within the software is important in providing a detailed drainage network from the DEM. The choice of threshold was shown to have a direct influence on the detail of the stream network generation. The study found that a high resolution DEM can provide a detailed delineation of the drainage network and the catchment if the correct threshold is chosen.

The aforementioned study was furthered by Liu, McDougall and Zhang (2011) who completed a characteristic analysis of a flood plain utilising airborne LiDAR data. To complete this analysis the Arc Hydro extension within ArcGIS 10 software was utilised. They further extended on the software's use highlighting that it can be utilised to perform several forms of analysis after performing multiple steps. The major steps involve sink filling, identification of the direction of flow, determination of the flow accumulation and definition of the stream. It concluded that many different outputs are available for flood modelling from LiDAR generated DEMs including longitudinal profiles, shape indices, and hypsometric curves. Each of these outputs is beneficial in flood plain analysis and will be of use in this study.

2.2.3 DEM Accuracy

Apan et al. (2008) completed a study on the accuracy requirements of a DEM for use with catchment management. To perform this study a catchment area over the Condamine River was utilised to generate a DEM from airborne LiDAR data. The broad requirements and key needs for a catchment DEM from both an operational and strategic perspective were determined through the use of a workshop. There were eighteen participants in the workshop who represented multiple different stakeholders within Queensland. The result of this workshop can be seen in table 1.

Table 1: The applications defined by the participants of the workshop and the accuracies required (Apan et al., 2008).

Application Area	Coverage and Accuracy
Planning scheme/development assessment*	± 1m
Hydrological modelling*	<0.5m
Farm layout redesign – cultivation and intensive feedlot*	0.05m-0.5m
Transport corridor planning*	± 1m
Salinity prediction and control*	± 5m
Riparian management*	±1-2m
Soil erosion control and modelling*	± 1m
Risk management*	±1-2m
Bio-security – disease spread, spray drift*	± 1m
Visibility analysis – tourism	5-10m
Insurance risk and assessment*	<0.5m
Water management plans and sub-catchment delineation*	0.5-1m
Environmental impact assessment and management	± 5-10m
Disaster planning and management (flood and fire)*	± 1m
Natural resource management	5-10m
Noise studies/assessment – corridor planning*	± 1-2m
Telecommunications planning, visibility analysis*	1-5m
Cross slope/batter analysis*	<1m
Land and water management plans*	<0.5m
Tourism	20m
Infrastructure planning and risk assessment*	0.5-1m

* Applications that cannot be supported by existing DEM

It can be seen in table 1 that the areas relevant to this study are the hydrological modelling, Disaster planning and management (flood and fire) and insurance and risk assessment. These areas have a required accuracy of ±1 m, <0.5 m and <0.5 m respectively. This study concluded that to produce such results extreme care has to be taken when collecting the LiDAR data to generate the DEM. The methods utilised to reduce it are also critical ensuring that the ground points are accurately represented in the model.

2.3 Hydrological Modelling

As modern technology continues to improve there are always improvements in software that make once difficult tasks, far easier. Much can be said about this in the area of hydrological modelling with the development of many software packages capable of modelling floodwaters. To perform hydrological modelling one of the key data sets is the spatial data inputted

(Elliot and Trowsdale, 2006). The accuracy of the inputted data is vital for the overall accuracy of the model. Hollaus et al. (2005) performed an analysis of airborne LiDAR and its usefulness for hydrological modelling. The study utilised an object based land cover classification to perform the analysis. It was found that the accuracy of the DEM is crucial in minimising the uncertainties that can result in flood modelling.

2.3.1 Hydrological Modelling Software

Elliot and Trowsdale (2006) performed a comparison of multiple urban stormwater management software's. They completed this study by comparing multiple software's against identified attributes including intended use, temporal use and scale, catchment and drainage network representation, runoff generation, contaminants in the models, devices and technologies included, user interface and cost. The three most important attributes to this study are the catchment and drainage network representation, runoff generation and cost. The study found that the Model for Urban Stormwater Improvement Conceptualisation (MUSIC), MOUSE, Storm Water Management Model (SWMM) and P8-UCM were best when representing a catchment and drainage network. Each software utilising a spatially distributed link-node drainage network causes this. This works by representing each element within the catchment as a node and connecting them together. Each node can then have flow control devices or treatments placed on them to give a true representation of how they are in the field. This study also found that MOUSE, SWMM and MUSIC were greater at generating runoff due to their capability to use daily calculations (MUSIC), initial and continuing loss (MOUSE) and a Green-Ampt infiltration (SWMM). It is highlighted that there is no one method that is better than any of the others when generating runoff which each being beneficial to the modelling. Finally the study showed that of the three mentioned software models SWMM is the only one that is available free for download and use. From this study it can be seen that MOUSE, SWMM and MUSIC are three software models that are quite capable of being used for the hydrological modelling of a stormwater management system. However due to availability MUSIC and SWMM will be the two software models researched and compared.

2.3.2 MUSIC and SWMM

Coleman et al. (2002) identify MUSIC as a powerful modelling tool. The software was created as many designers were designing stormwater management strategies ineffectively trying to achieve cost effective outcomes. Coleman et al. (2002) highlights multiple capabilities of MUSIC including:

- Determining the water quality from specific catchments.
- Predicting the performance of specific stormwater treatment measures.
- Designing integrated stormwater management plans for each catchment.
- Evaluating the success of specific treatment measures.

It is noted that MUSIC is a tool to be used as decision support and not as design software. The software's main use lies in testing stormwater management techniques, not designing them (Coleman et al., 2002). Coleman et al. (2002) highlights that MUSIC utilises the algorithm developed by Chiew et al. (1997). This algorithm works off the concept that stormwater runoff is generated from impervious surfaces. The model is based on the definition of the impervious area and the two moisture storages (deep and shallow) highlighted in figure 3.

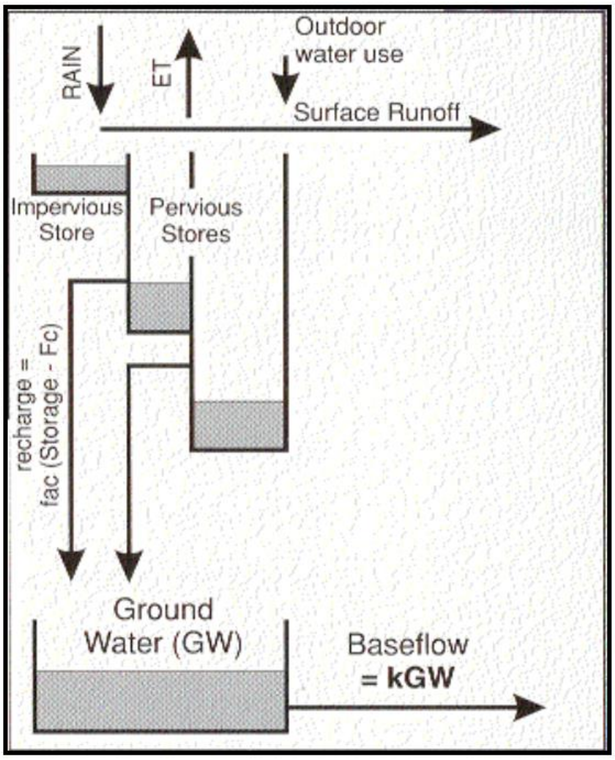

Figure 3: The model adopted within MUSIC for modelling catchment hydrology (Chiew et al., 1997).

There are several stormwater treatment nodes within the both software's as highlighted in Gold Coast City Council (2006) and Rossman (2010). The correct use of each of these treatment nodes is vital in the modelling process. Both SWMM and MUSIC use treatment nodes such as these in their treatment train when developing a drainage network (Peterson & Wicks, 2006).

Dickinson and Huber (1992) defined SWMM as a numerical model software obtainable from the Environmental Protection Agency. The software is designed for the simulation of flow quality and quantity of urban runoff. As a result the quality and quantity are a representation of the urban stormwater runoff and sewer overflow phenomena.

Peterson & Wicks (2006) completed a study into the importance of conduit geometry and physical parameters utilising SWMM as the software. Within this study there was a comparison of SWMM to other modelling techniques. It was deduced that in the studies case, it was good software for the application and it provided valuable information about the local flow of the system. This is extremely beneficial to the requirements of this project.

This information shows that both SWMM and MUSIC are both similar software packages which are suitable for the modelling of urban stormwater.

2.3.3 Meteorological Data

The selection of appropriate rainfall data is a vital step in any sort of hydrological modelling. The intensity-frequency-duration (IFD) is the commonly used tool when performing rainfall analysis (Koutsoyiannis, Kozonis & Manetas, 1998). It can take the form of Q1, Q5, Q10, Q20, Q50 and Q100 depending on the scale of the rain event. A Q1 event is common where as a Q100 event is only meant to occur every one hundred years or so

(Bureau of Meteorology, 2014). This data is available from the Bureau of Meteorology (2013) who has recently updated all of their IFD data to provide more accurate rainfall data. Normal rainfall data showing the amount of rainfall that fell in a certain area can also be obtained from the Bureau if required.

2.4 Conclusion

This chapter has provided an extensive insight into the literature available regarding important aspects of this project and its objectives. The chapter has gone into detail about airborne LiDAR including its history, systems and accuracy capabilities. The data collected from these airborne surveys was then discussed and its capabilities to be used in DEMs shown. The use of the DEMs for characteristic analysis was also highlighted with examples of other research using similar techniques shown. Finally some of the available hydrological software packages available including SWMM and MUSIC were shown, broken down and compared. The application of meteorological data within these hydrological modelling software packages was also emphasised. The information and knowledge gained from the research undertaken in this chapter will now be applied. This will be shown in the methodology undertaken to meet the objectives of the project in the following chapter.

Chapter 3 Methodology

3.1 Introduction

After gaining a large amount of theoretical information and analysing past works, a methodology had to be determined to meet the objectives. A study area had to be selected and LiDAR data over the study area required collection. After the data had been collected a DEM was generated from the ground points of the study area. Slope analysis was then performed on the DEM to highlight any areas of interest within the study area and to deduce the flood plain. Hydrological processing was also completed to identify catchments and streams within the area. Hydrological modelling was then performed utilising SWMM to highlight areas where mitigation may be implemented around the catchment and stream network.

3.2 Study Area

3.2.1 West Creek Location

The study area is West Creek, which forms part of the Gowrie Creek catchment. West Creek starts within southern Toowoomba, running north through Toowoomba meeting with East Creek near the CBD. The two creeks then merge to become one creek carrying on through Toowoomba in a northern direction. The layout of the creeks within the Gowrie Creek catchment is highlighted in figure 4.

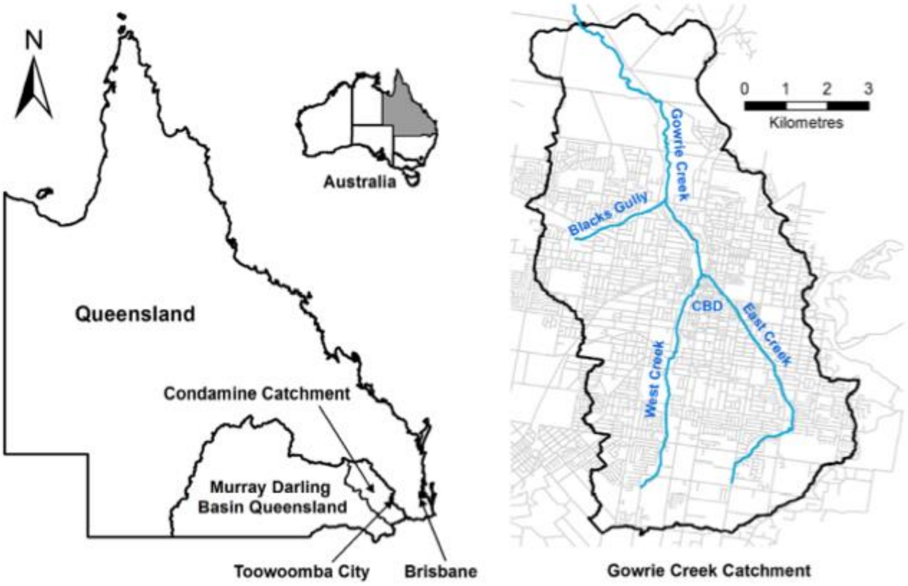

Figure 4: The location of the Gowrie Creek catchment within Queensland (left) and the approximate locations of the creeks within Toowoomba (right) (Liu, McDougall & Zhang, 2011).

West Creek played a major role in the floods that occurred in 2011 and is therefore an area of major interest (SKM, 2011). It is the largest creek within the catchment containing an area of water of approximately 16.2 km^2 (ICA, 2011). This makes it one of the most important catchments when it comes to determining a flood plain.

3.2.2 West Creek Urbanisation

All of the creeks within the Gowrie Creek catchment, including West Creek have been subject to heavy urbanisation due to constant expanding of Toowoomba (ICA, 2011). This has resulted in structures such as bridge crossings and housing right up to the edge of the creek, affecting the catchment. These bridge crossings restrict the flow of the water by funnelling the water under the road and have the capability of becoming blocked due to debris. An example of a bridge crossing can be seen in figure 5. Refer to Appendix E for other pictures related to the urbanisation of West Creek. These pictures are being used as a representation of the urbanisation and may not be a 100 % accurate representation of what West Creek was like in January 2011 before the flooding event occurred.

Figure 5: The bridge crossing over West Creek along Stenner Street in South Toowoomba as of August 2014.

West Creek has been heavily modified with the inclusion of concrete lined channels, detention basins, piped drainage systems and various other structures to manage stormwater. These have been included to help manage the damage around the bridges running over the creek. Other man-made structures such as concrete footpaths, shade structures and recreational structures have also been recently included for the use of the public. These structures all affect the natural flow of the water in the creek creating a different surface for it to run over and altering its path. An example of concrete lining being used in West Creek can be seen in figure 6.

Figure 6: Concrete lining on the lowest part of West Creek in between Spring Street and Stenner Street in South Toowoomba as of August 2104.

West Creek also contains a combination of varying grass types, shrubs and trees at moderate grade changes. The trees and shrubs within the catchment area are of varying type and density. The type and density of the nature within the catchment has a strong effect on the water the water flows within the catchment. It can help slow the flow of water and hold the ground together. However these trees and shrub can also become debris to block the pipe ways and road crossings. An example of the type of nature within West Creek can be seen in figure 7.

Figure 7: The types of trees and shrubbery along West Creek as of August 2014.

This study area is an excellent example of a watercourse located within an urbanised area that contains many varying factors including ground cover, trees, grade and manmade features. Each of these factors contributes and affects the way the water flows and meets with the rest of the catchment further downstream.

The study area, particularly near the CBD has undergone heavy man-made changes in the previous year due to recommendations from the Toowoomba

Regional Council for their flood mitigation program. Due to this the creek is not as it was in some areas when the data was collected at the end of 2010. However for the purpose of this research project West Creek will be treated as close as possible to how it was in 2010.

3.3 Airborne LiDAR Data

3.3.1 Data Collection

It was decided that collecting new LiDAR data would be majorly time consuming and too expensive for the purpose of this project. Also as the flooding event occurred over four years ago, new data over West Creek would not be a good representation of the flood plain. Instead LiDAR data was found of the Toowoomba area from another source.

The LiDAR data was sourced from the Toowoomba Regional Council who had Schlencker Mapping Pty Ltd conduct a Toowoomba wide airborne LiDAR survey covering 2760 km in 2010. The data collection was undertaken utilising an ALTM Gemini ALS scanner on a fixed wing aircraft. The Meta data for the LiDAR survey can be seen in table 2 below. The entire report can be viewed in Appendix D.

Table 2: The Meta data of the survey completed for the Toowoomba Regional Council (Schlencker Mapping Pty Ltd, 2010).

Acquisition Start Date	29th June 2010
Acquisition End Date	16th July 2010
Device Name	Optech 'ALTM Gemini'
IMU	Applanix 'Litton 510'
Flying Height (AGL)	1200m
No. of Runs	242
Swath Width	1000m
Side Overlap	30 %
Horizontal Datum	GDA94
Vertical Datum	AHD
Map Projection	MGA Zone56
Control	302 surveyed GPS control points
Vertical Accuracy	±0.15m @ 1σ
Horizontal Accuracy	±0.22m @ 1σ
Surface Type	Ground and DTM
Average Point Separation	1.0m
Laser Return Types	1st through to 4th

It can be seen from table 2 that the survey was completed late June and early July placing it approximately six months before the flooding event occurred. The plane flew at a height of 1200 m completing two hundred and forty two runs in total. The swath width of the laser scanner was 1000 m and there was a 30 % overlap for the survey. Of note within the Meta data is the average point separation, which is 1 m. This shows that the LiDAR data collected is of extremely high density allowing greater accuracy. The metadata also shows that the horizontal accuracy of the data is 0.15 m and the vertical accuracy is 0.22 m, both at the first standard deviation. These accuracies are within an expected range for an airborne LiDAR survey making the data suitable for analysis (BC-CARNS, 2006).

3.3.2 Data Validation

The same surveying company, through the use of a vehicle mounted GPS survey, validated the collected data. The GPS units utilised were Trimble R8

GNSS receivers collecting data at 50 m intervals. The survey covered a total of 218 km along bitumen and gravel roads collecting six thousand three hundred and thirty two points at an accuracy of ± 0.05 m. This GPS survey highlighted that 94 % of the LiDAR points collected are within 0.15 m of their true points.

The data provided had the ground points and non-ground points already separated in a binary LAS file format. There was no mention of the technique utilised to separate the ground and non-ground points.

3.4 Digital Elevation Model Generation

The generation of the DEM required the use of ArcGIS 10.2 software. Liu (2008) highlights that one of the most critical aspects of DEM generation with LiDAR data is the separation of ground and non-ground points. However in this case the LiDAR data had been provided already separated, taking out this step of the process. Thirty-five text files were utilised which were each approximately 1 km^2 in size. These files stretched far enough to give an accurate representation of the catchment area.

3.4.1 Inverse Distance Weighted Interpolation Technique

The generation of the DEM could be completed utilising multiple different tools. In the study completed by Liu, McDougall and Zhang (2011) the DEM was generated by the IDW interpolation technique. The technique is mathematical that uses a linearly weighted combination of points to determine cell values. The method assumes that the influence of the variable being mapped decreases as its distance from the sample location grows (Phillip & Watson, 1985). This is highlighted in figure 8.

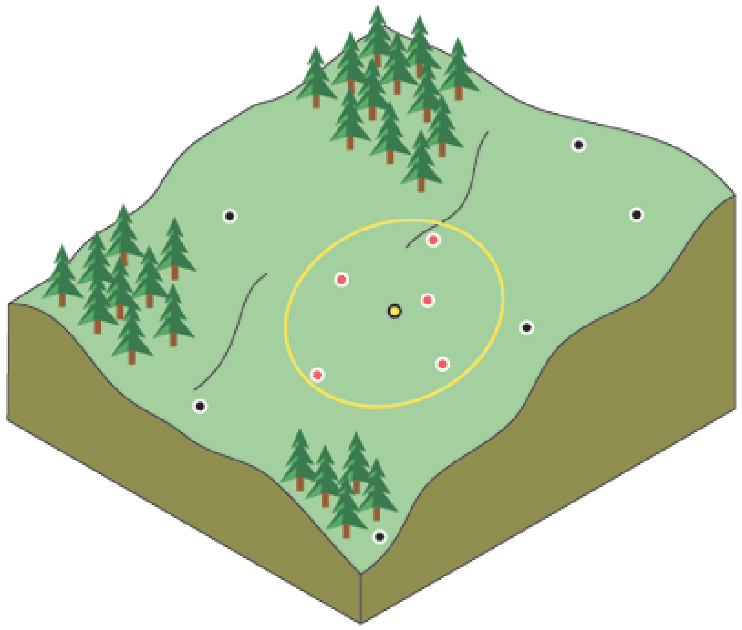

Figure 8: The Inverse Distance Weighted sample location used when processing the points whilst generating a DEM (ESRI(a), 2014).

The range of values used to interpolate limits the output of a cell using this technique. Due to the results being a weighted distance average, sudden rises or falls cannot be generated unless they already have data collected over them. To get the best results from the method dense data sampling is required, if not the results may not be a true representation of the surface (Phillip & Watson, 1985). In the case of the data over West Creek there are no sudden rises or falls with consistent grade changes throughout. The data has also been densely collected as mentioned in section 3.3.1 at a ground separation distance of 1 m. As a result the IDW technique would present an accurate representation of the actual surface.

3.4.2 Topo to Raster Interpolation Technique

Another technique that may be utilised to generate a DEM is the Topo to Raster interpolation tool. The Topo to Raster tool is one that has been designed for the generation of DEMs that are correct in a hydrological sense. This tool is based on the ANUDEM program, which was developed by Michael Hutchinson (Hutchinson, 1988). The technique imposes constraints while it interpolates the elevation values of a raster surface to ensure that the final outcome has a true representation of drainage, ridges and streams. The interpolation technique used within this method is an interactive finite difference technique. It utilises the knowledge of landscapes having multiple hilltops and minimal sinks to generate a connected drainage pattern. The drainage conditions that are imposed upon the surface help generate an output that is best for hydrological work and requires little to no post processing (ESRI(c), 2014).

A choice had to be made between the two techniques as to which should be utilised. The Topo to Raster interpolation tool was chosen to generate the DEM. The IDW tool requires one surface to be input, which can then be created into a DEM. This means that other tools such as the merge tool would be required to generate the DEM, increasing the chances of error. Whereas the Topo to Raster tool allows multiple input files and generates the surface from each individual input. This technique is also specifically made to generate DEMs that are hydrologically accurate, making it the clear choice for this analysis.

To generate the DEMs the Topo to Raster interpolation technique was utilised. The text files had to be displayed with the appropriate Map Grid Australia 1994 (MGA1994) projection. In Toowoomba the correct map grid correction is zone fifty-six. Each tile once displayed was then exported into a shape file to allow generation of the DEM.

To generate the DEM the individual shape files were inputted and the output cell size was set at two. This generated a DEM with a resolution of 2 m. A second DEM was also generated with the same input shape files with an output cell size of five. This allowed for the generation of a DEM with a resolution of 5 m. The two different resolutions were chosen to observe the differences in the generation of the stream networks and catchment size in later modelling.

3.5 Hydrological Analysis

Once the DEMs were generated the hydrological analysis was completed. The initial steps of the analysis were completed in Arc Hydro to perform hydrological analysis of the catchments and drains. Following the hydrological analysis a slope map was generated to determine the flood plain.

Liu, McDougall and Zhang (2011) and Liu & Zhang (2010) completed a characteristic analysis and extracted drainage networks from DEMs previously. Both studies showed that that the extraction of drainage networks is based on the widely used D8 algorithm. Within this algorithm the correct choice of threshold values is vital to the accuracy of the stream network. To complete this extraction in both instances the Arc Hydro extension within the

ArcGIS 10.2 software was utilised. This extension of the software can be utilised to perform several forms of analysis after performing multiple steps.

3.5.1 Arc Hydro Pre Processing

The steps involved in the pre-processing for Arc Hydro are extremely important and must be completed in the correct order for the processing to work. The first step involves reconditioning the DEM by imposing linear features onto it. This step is an optional one and does not need to be completed. The second step involves filling all of the sinks within the DEM. If there is a cell in the DEM that has multiple high cells around it, the water will not flow causing issues in the modelling. This step fills those cells to ensure that this does not occur (ESRI, 2011).

Once filled the direction of flow for each cell is determined from the steepest descent values within the cells. The next step involves determining the flow accumulation. The flow accumulation creates a grid showing the number of cells, upstream of a cell. Following the flow accumulation the stream must then be defined. Within this step there is a stream threshold that must be input. It originally displays 1 % of the maximum flow accumulation, but this may be changed. The result is a grid that shows all of the cells from the input flow accumulation that has a value greater than the threshold entered (ESRI, 2011).

The next step is stream segmentation where each steam is given a unique identifier. Following the segmentation the catchment grid delineation is created. This step creates a grid where each cell carries a value that is an indication of which catchment it belongs to (ESRI, 2011). After this multiple steps may be completed to generate the polygon lines for the stream and the catchment, making a better representation. The adjoining catchments can also be generated which show any catchment that is not a head catchment. Finally the drainage points can be generated which shows the point where water would be expected to drain from each stream. Once these have been determined further analysis can be completed including determination of surface area, shape indices and the creek profile (ESRI, 2011).

The Arc Hydro pre-processing analysis was completed on both the 2 m DEM and the 5 m DEM. The pre-processing for each of the DEMs followed the same steps except for the input of the threshold value in the stream definition step. The 2 m DEM had thresholds of 0.1970 that is the minimum 1 %, 0.3, 0.5, 0.75 and 1. Each of these and the corresponding number of cells can be seen in figure 9.

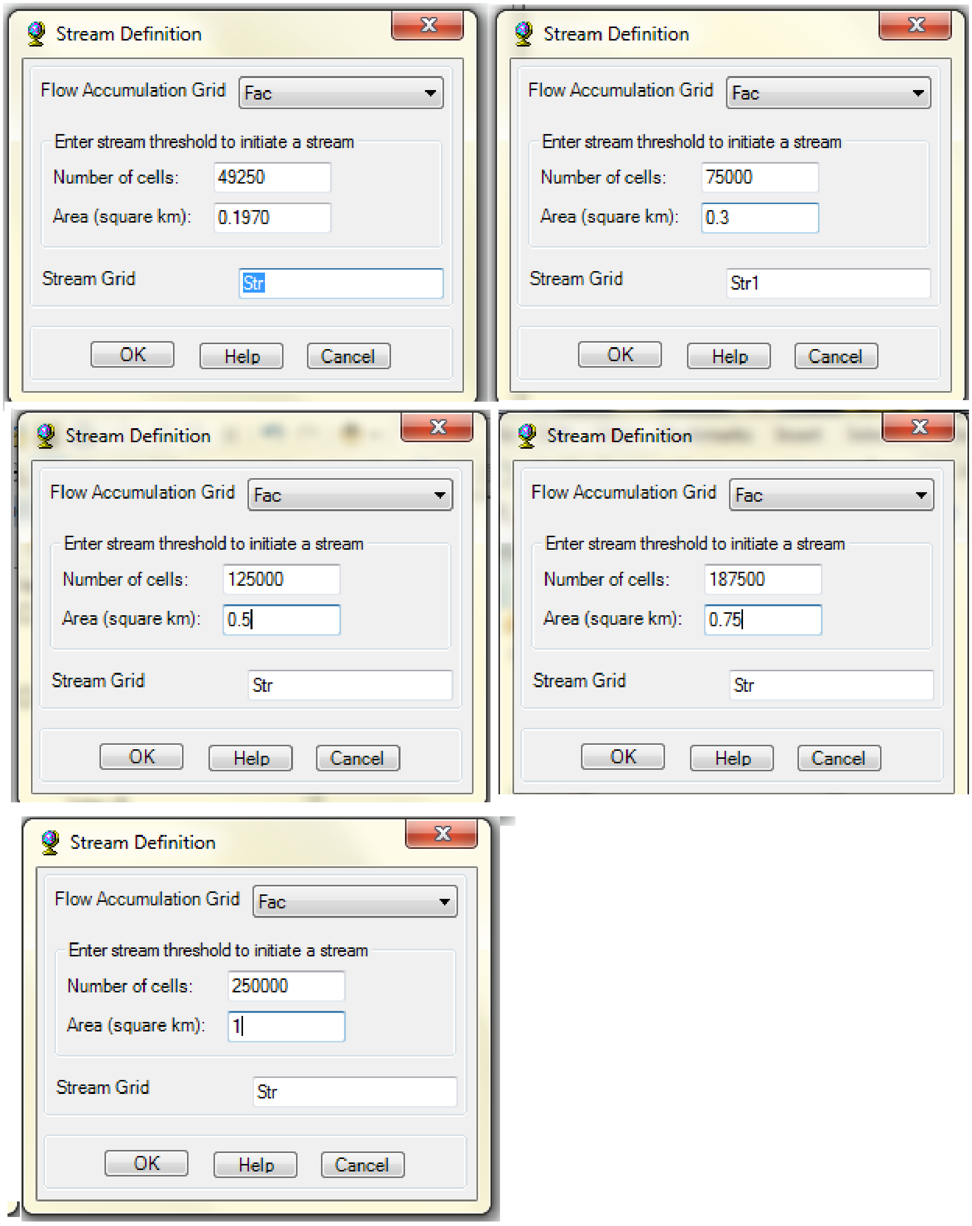

Figure 9: The multiple inputs for each of the stream definitions during pre-processing of the 2 m DEM.

The same process was followed with the 5 m DEM. The threshold inputs for the 5 m DEM were 0.1975 which was the minimum 1 %, 0.3, 0.5, 0.7 and 1. The threshold inputs and their corresponding number of cells can be seen in figure 10.

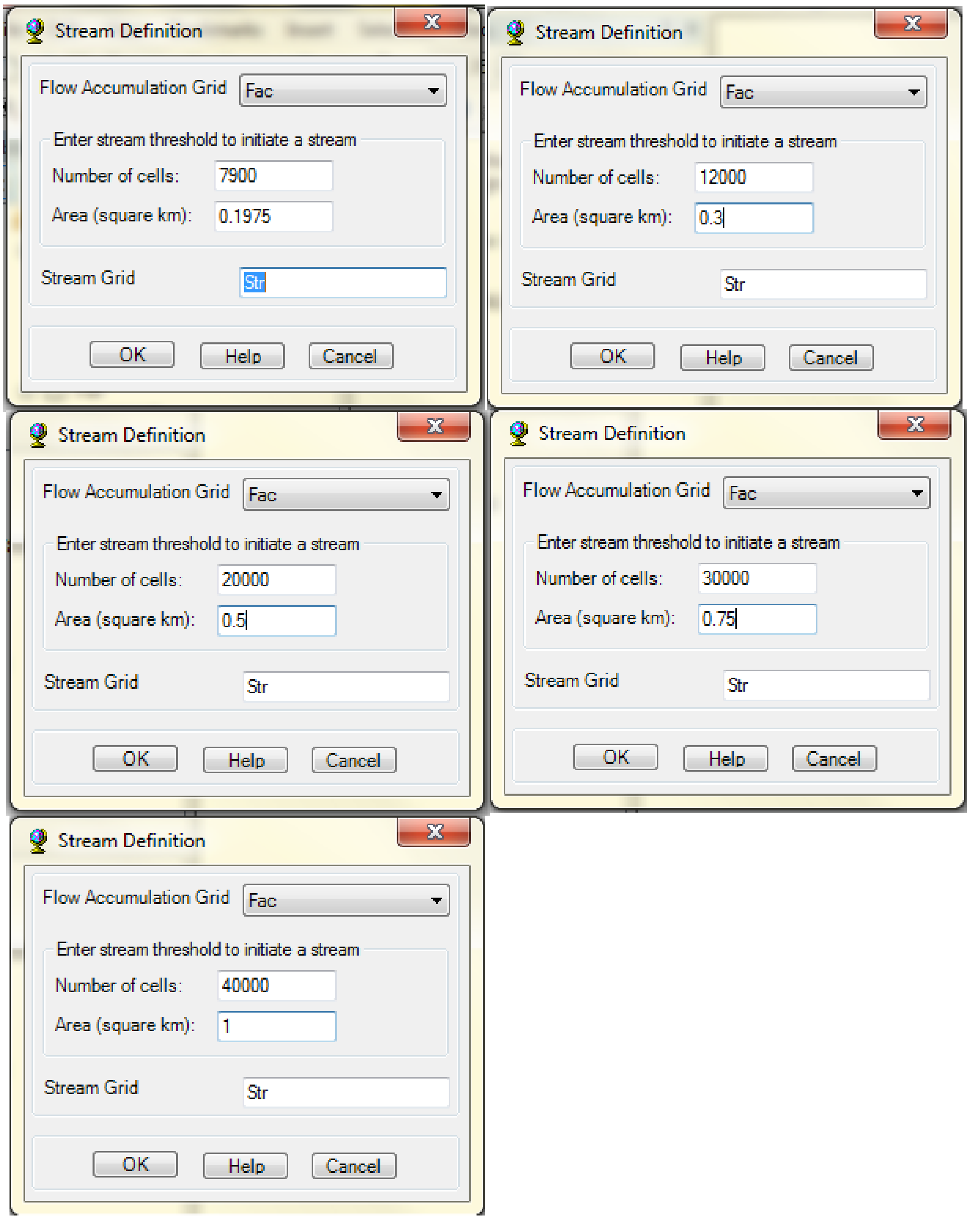

Figure 10: The multiple inputs for each of the stream definitions during pre-processing of the 5 m DEM.

Once the streams and catchments were generated analysis was completed on each of the maps to identify the stream networks and the size and shape of the catchment for West Creek.

3.5.2 Slope Analysis

The slope tool works by identifying the gradient or rate of maximum change in the z value of each individual cell compared to its neighbours. The steepest downhill descent for the cell is then determined by finding the maximum change in elevation between the eight surrounding cells and the cell itself. If there is no data within a cell then it is left as having no data within it (Burrough & McDonnell, 1998). An example of how the cells works can be seen in figure 11.

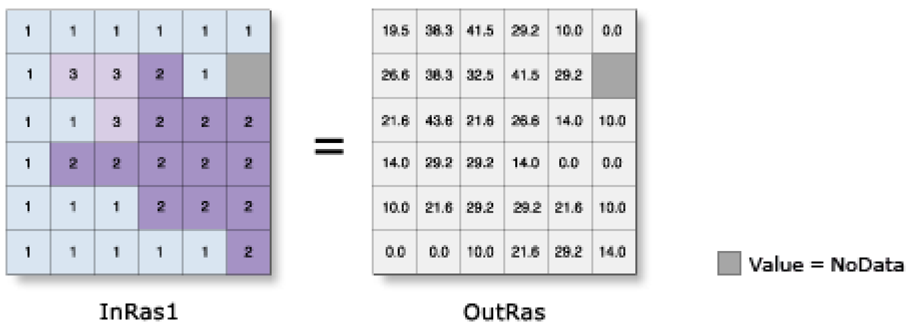

Figure 11: The way the cells are worked within a slope analysis (ESRI(b), 2014).

The generation of the slope analysis surface was completed on the 5 m DEM created through the Topo to Raster technique. The generation of slope analysis on both the 2 m and 5 m DEM was deemed meaningless and was not completed, as the results were almost identical. The surface was generated with a percentage representation instead of a degree representation. The Z factor for both slope surfaces was kept as default which was 1. Once generated the surfaces were reclassified to 0 - 2 %, 2 - 5 %, 5 - 10 %, 10 - 20 %, 20 – 30 % and 30 – 44 %. The reclassification allowed for a better representation of the slopes within the creek highlighting the areas which may be the flood plain. The resulting slope map was then analysed with the areas that fell within the 0 - 2 % and 2 - 5 % deemed a chance of being a flood plain.

3.6 Hydrological Modelling

To perform the hydrological modelling software had to be chosen. The choice was between MUSIC and SWMM. It was decided that since both software packages offer similar analysis, SWMM would be utilised for the analysis. SWMMs ability for free download and use with online guides and tutorials compared to MUSICs restrictive access and paid tutorials made it the obvious choice.

To begin the analysis the treatment train had to be drawn over the study area. SWMM has multiple different forms of hydrological components that can be utilised to represent the system on the ground. These components can be generally broken into nodes or links. Within each of these, the main components that were utilised in this model were sub catchments, storage units, conduits, junctions, outlets and rain gages (Rossman, 2010). Each of these was drawn over a background image of the West Creek DEM to ensure relative positioning.

3.6.1 Rain Gages

To determine the approximate locations of the rain gages the maps provided in ICA (2011) were utilised in conjunction with the background image. The image utilised to gain the rain gages location can be seen in Appendix G. The location of the rain gages in the model can be seen in figure 12.

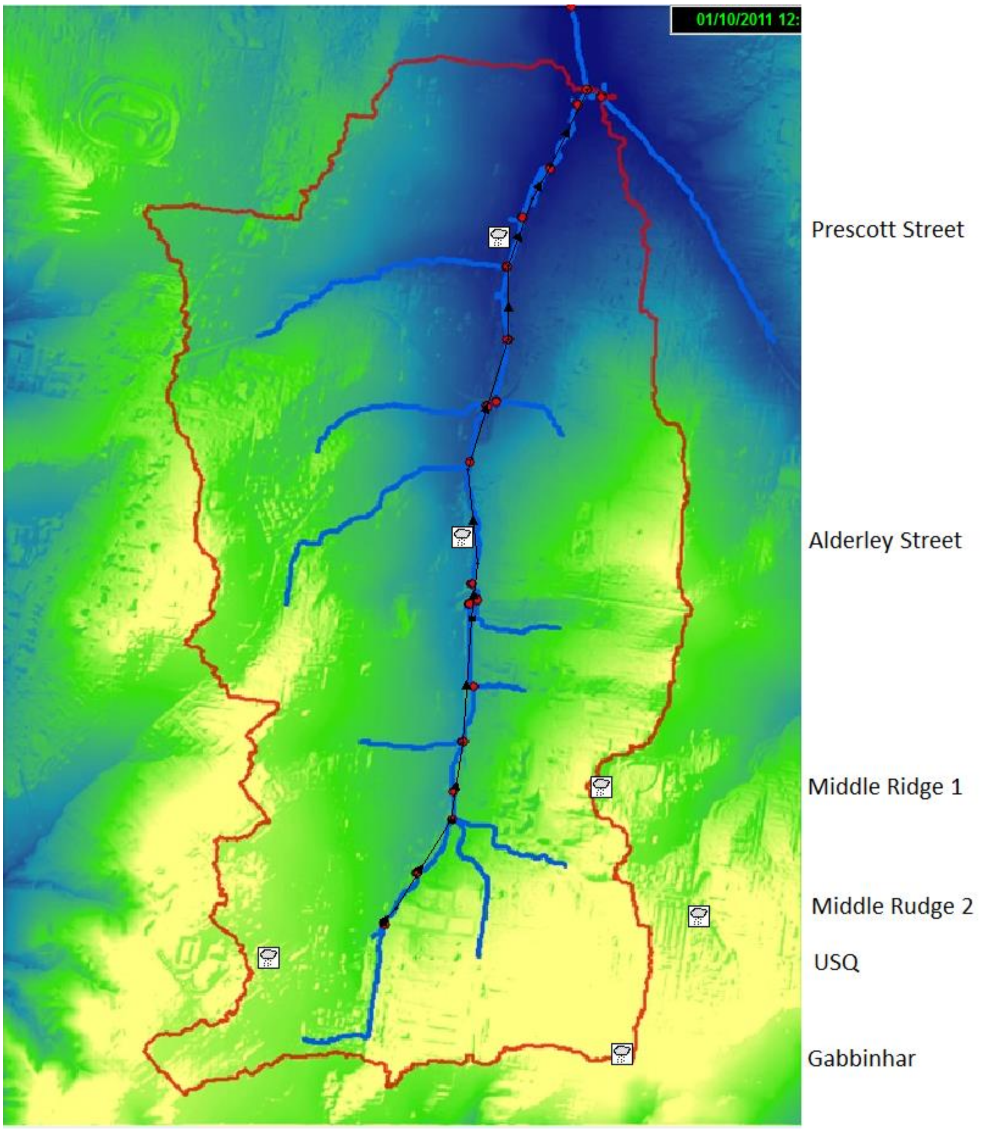

Figure 12: The location of the rain gages on the study area within the model.

Once placed the rain gages required rainfall data to be input. The rainfall data for each of the rain gages was also obtained from ICA (2011) who had access to the 15-minute rainfall data from the Bureau of Meteorology. It was decided to run a 2 hour 15 minute simulation with rainfall data at every 15 minutes. This length for the simulation would cover both before the main rainfall occurred and after. The software required a specific format to input as rainfall data, which can be seen in the following figure. The other files utilised can be seen in Appendix G. The file requires the name of the rain gage, the year, month, day, hour, minute and rainfall amount in either millimetres or inches. In this case millimetres were utilised.

USQ Rainfall - Notepad

File Edit Format View Help

USQ	2011	1	10	12	0	1
USQ	2011	1	10	12	15	2
USQ	2011	1	10	12	30	1
USQ	2011	1	10	12	45	3
USQ	2011	1	10	13	0	4
USQ	2011	1	10	13	15	8
USQ	2011	1	10	13	30	13
USQ	2011	1	10	13	45	27
USQ	2011	1	10	14	0	18
USQ	2011	1	10	14	15	14

Figure 13: The format of the rainfall data file that is used in the rain gages for the simulation.

3.6.2 Storage Units and Junctions

After the rain gages are input the treatment train itself may be created. The four components that were utilised in the model included storage units, conduits, outlets and junctions. The storage units represented the detention basins along West Creek capable of storing water during a flooding event. These are shown in figure 14 by the nodes SU6, SU7 and SU8. Each of the storage units required the input of a maximum depth, surface area and invert level (Rossman, 2010). The approximate surface area of each storage unit was determined though measurement from an aerial photograph and maximum depth was assumed to be 2 m for each of the storage units. The invert level of the original storage unit was gained from the DEM. A slope of -1.46 % was then applied to each node by measuring the distance between the two nodes, multiplying it by the slope value, and taking it away from the previous nodes level. This allowed a constant downward slope of 1.46 % throughout the model.

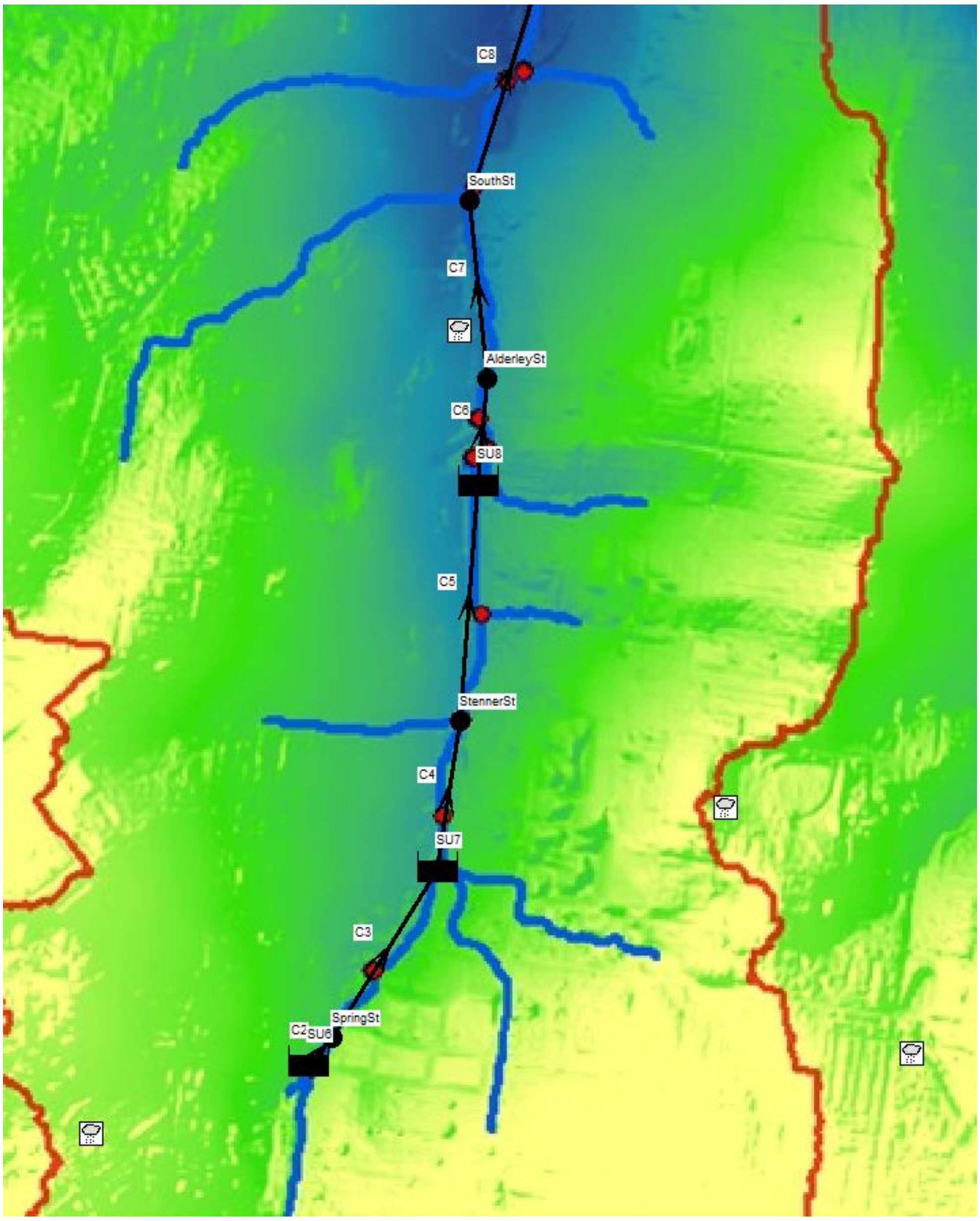

Figure 14: The southern half of the treatment train showing the storage units, conduits and junctions.

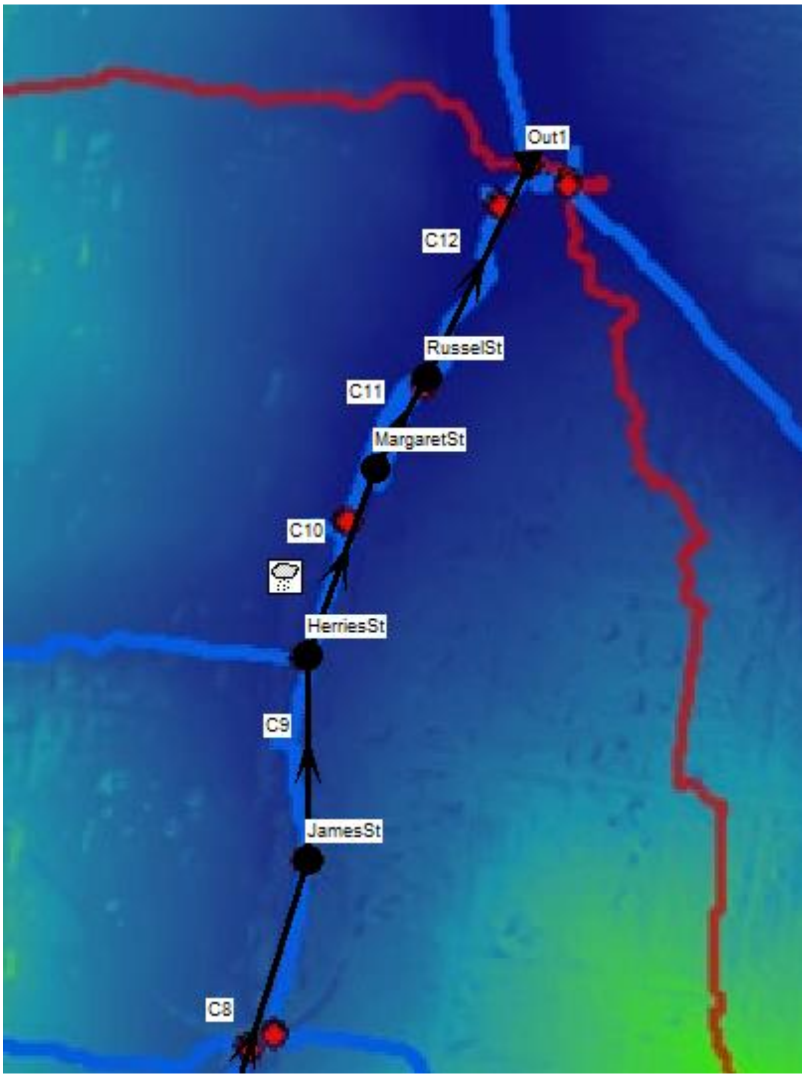

Figure 15: The northern half of the treatment train showing the conduits, junctions and outlet.

Junctions were placed at each of the major street crossings over West Creek. These junctions are connectors allowing the conduits to continue through the model (Rossman, 2010). The junctions had inputs of maximum depth, assumed to be 1 m and invert level. These can be seen in figures 14 and 15 with the street names beside them.

3.6.3 Conduits

The conduits are the main part of this model as they represent the shape of the creek as it flows through Toowoomba. There are multiple shapes that may be utilised for the conduit, however in this case an irregular shape was chosen. The irregular shape allows for a user-defined conduit drawn within the software (Rossman, 2010). Two shaped conduits were utilised, one wider than the other. The wider conduit represented the creek shape further away from the CBD and then the smaller shape was used as it approached the CBD. In the models case the smaller conduit was utilised from South Street onwards. Though this is not a 100 % true representation of West Creek, it was one of the assumptions that had to be made for the purpose of this analysis. The two sized conduits can be seen in figures 16 and 17. The length of the conduit, measured from aerial photograph was also input with the remaining inputs left as default.

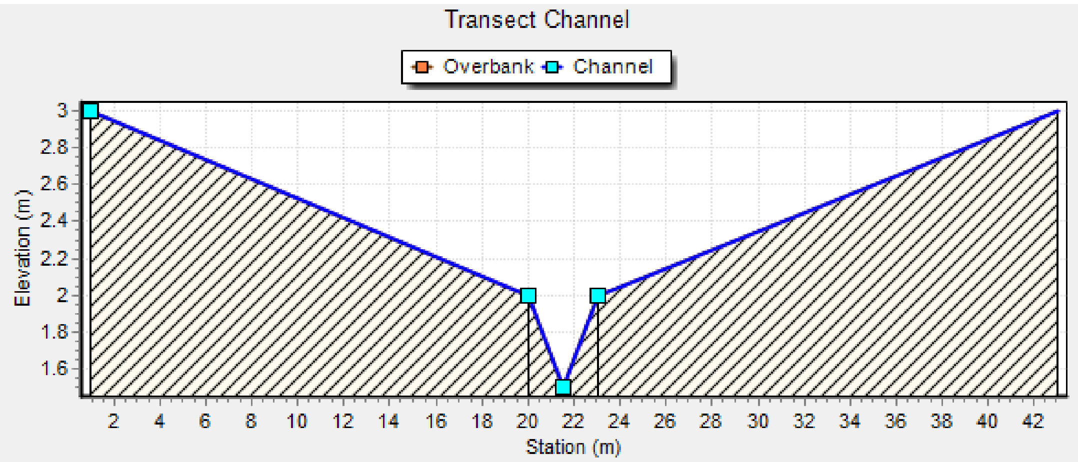

Figure 16: The transect view of the wider conduit utilised in the treatment train before South Street.

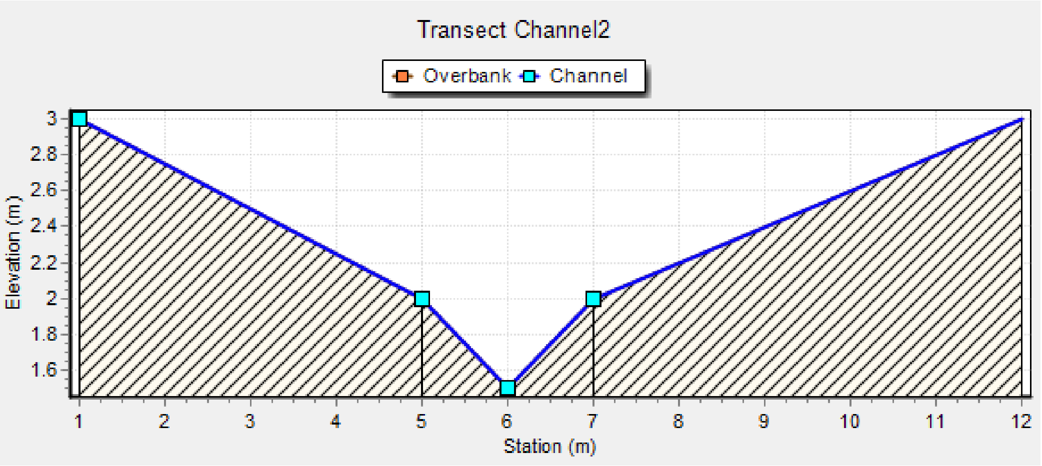

Figure 17: The transect view of the smaller conduit utilised in the treatment train after South Street.

3.6.4 Sub Catchments

The final requirement of the model is the sub catchments. The sub catchment nodes are areas of land within the model that direct surface runoff to a certain point of discharge chosen by the user (Rossman, 2010). The sub catchments have multiple inputs that may be specified, however for the purposed of this model only the area, slope, width, outlet, rain gage and imperviousness were specified and the rest of the properties were left as default. The shapes of the sub catchments for the model can be seen in figure 18.

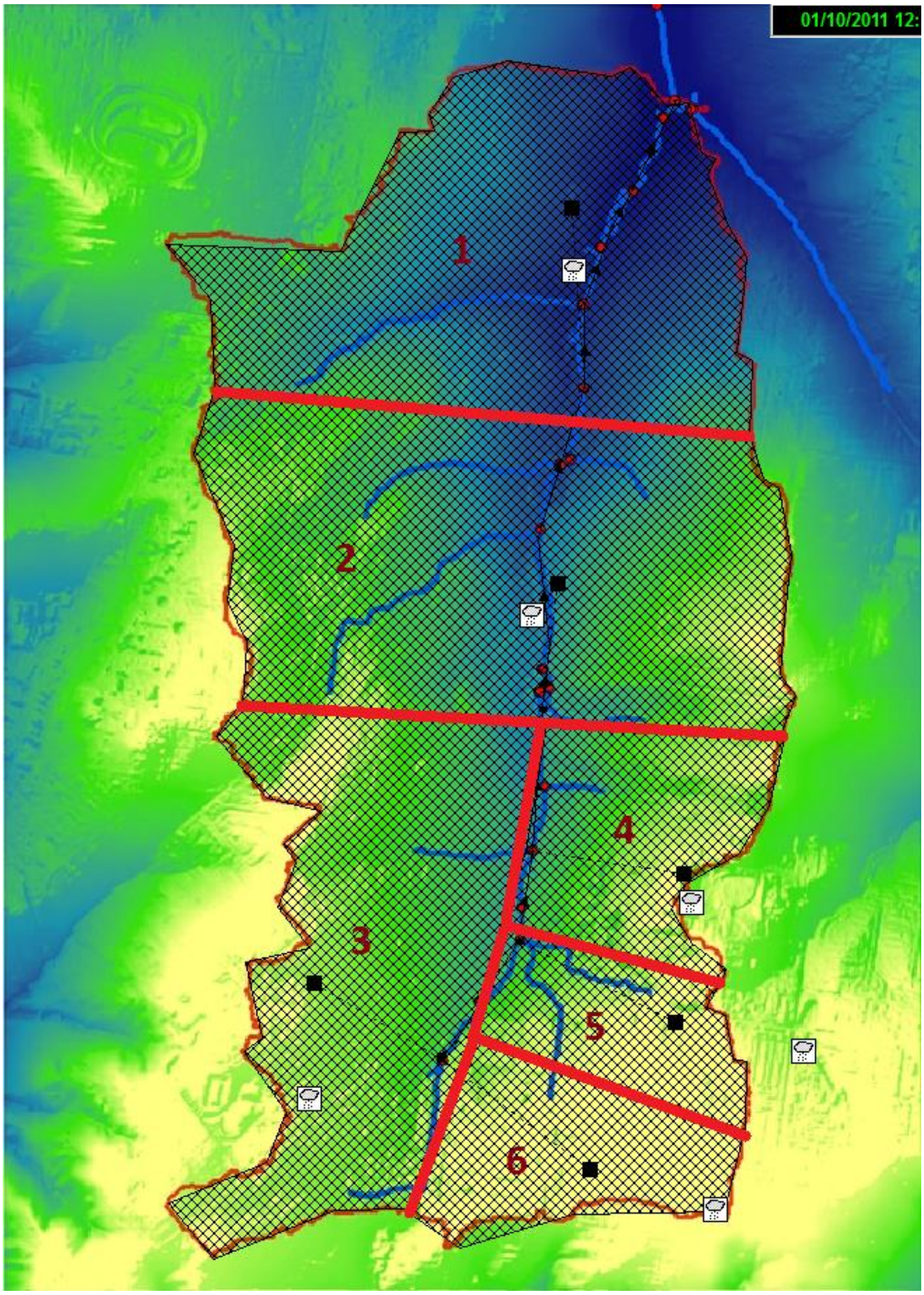

Figure 18: The sub catchments within the model highlighting their location and shape.

It can be seen that the study area was broken down into six sub catchments. The sub catchments are the hatched area separated by the red lines and following the catchment area generated from the Arc Hydro analysis. Each sub catchment requires a specified rain gage so that it may determine where the rain is coming from. As a result of there being six rain gages within the study area, six sub catchments were created. The sub catchments also require multiple other inputs. The properties utilised for the first sub catchment can be seen in figure 19.

Subcatchment S1

Property	Value
Name	S1
X-Coordinate	5859.544
Y-Coordinate	8398.409
Description	...
Tag	
Rain Gage	Prescott
Outlet	JamesSt
Area	629.754
Width	100
% Slope	1.46
% Imperv	50
N-Imperv	0.01
N-Perv	0.1
Dstore-Imperv	0.05
Dstore-Perv	0.05
%Zero-Imperv	25
Subarea Routing	OUTLET
Percent Routed	100
Infiltration	HORTON
Groundwater	NO
Snow Pack	
LID Controls	0
Land Uses	0
Initial Buildup	NONE
Curb Length	0

Optional comment or description

Figure 19: The values input for the required properties of the first sub catchment.

It can be seen that the rain gage for the first sub catchment was the Prescott Street gage. The outlet specified was the James Street junction. The area of the sub catchment in hectares was also measured utilising the on screen-measuring tool. The width value, which is the average width of the overland flow for the runoff was estimated by dividing the area by the length of the longest drainage point as specified in Rossman (2010). The average slope of the sub catchment was input as the slope value of West Creek determined in the slope analysis. Finally the imperviousness of the ground was assumed at 50 % to represent an area that is affected by urbanisation. The rest of the values were left as default. The input values for the other sub catchments can be seen in Appendix G. Once all information was input correctly the simulation could then be run.

3.7 Conclusion

This chapter has provided an overview of the methods utilised to meet the objectives of the project. The study area was analysed where the effects of urbanisations were clearly defined. The method utilised to collect the LiDAR data was also demonstrated and the techniques utilised to validate the data's accuracy were also expressed. The generation of the DEMs was also expressed with the choice of the Topo to Raster technique highlighted. The steps utilised to perform the hydrological analysis including the Arc Hydro pre-processing; slope analysis and flood plain analysis were also highlighted. Finally the methods utilised in the hydrological modelling software package SWMM were also demonstrated, showing the treatment train nodes and links and their required properties. The results of the methods mentioned in this chapter will now be highlighted and discussed.

Chapter 4 Results and Discussion

4.1 Introduction

This chapter will present the results of the methodology presented in the previous chapter and discuss them. The results of the DEM generation will be shown and discussed. The analysis from Arc Hydro will also be presented with the slope analysis and flood plain map also shown and discussed. Finally the results of the hydrological modelling will be presented and discussed.

4.2 Digital Elevation Model Generation

The DEMs were generated utilising the Topo to Raster interpolation technique. The model generated at a resolution of 2 m can be seen in figure 20.

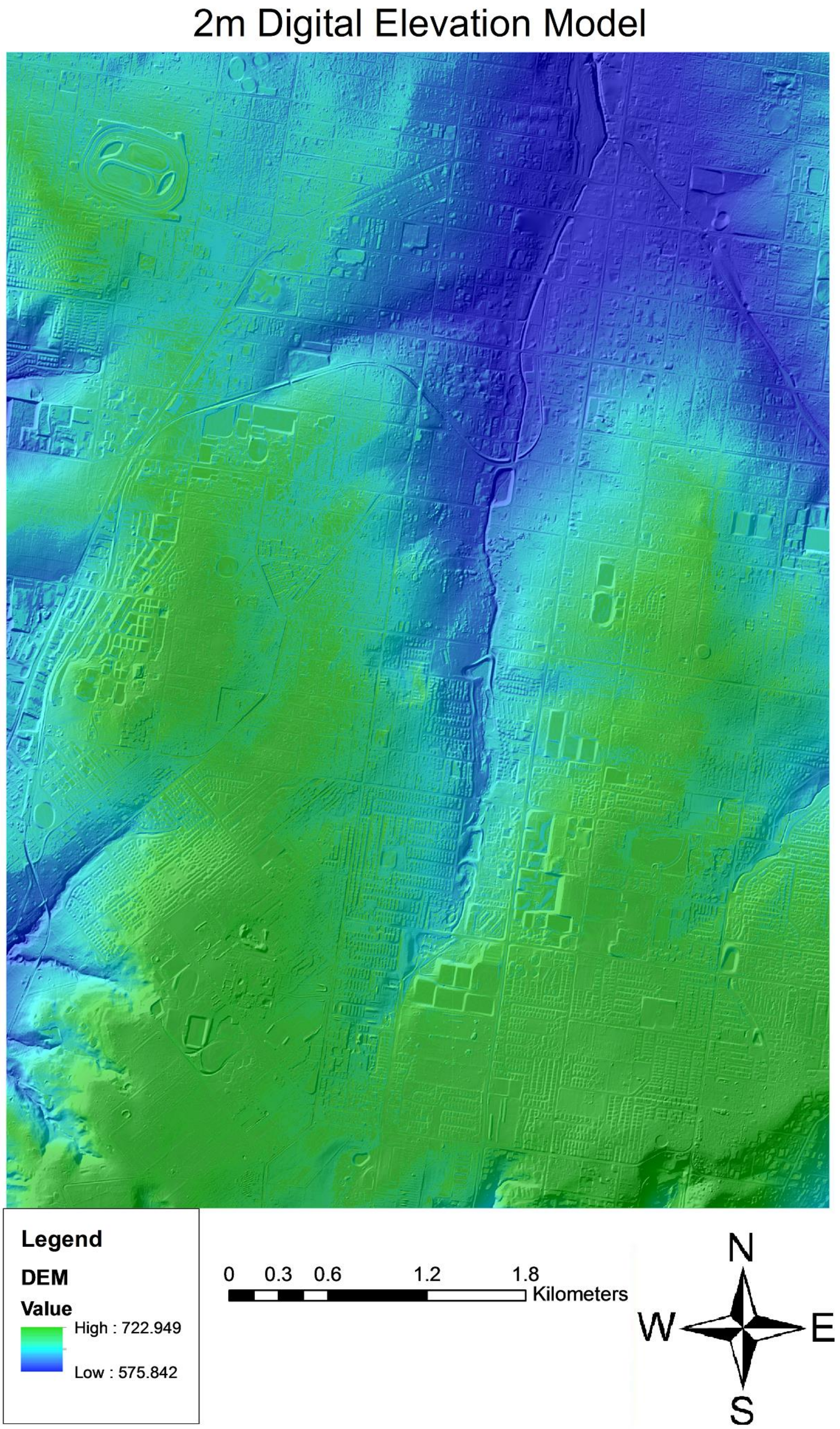

Figure 20: The DEM generated using the Topo to Raster technique at a 2 m resolution.

The dark blue of the DEM highlights the areas which are of a lower elevation and may be at risk of flooding. An area of interest is where West Creek meets East Creek to merge and become one, clearly visible in the top right hand corner of the DEM. It can be seen from the maximum and minimum heights within the DEM that there is a vertical difference of 174.107 m. The extreme heights at either end of the scale are also in the areas of interest with the start of West Creek highest and the end of West Creek lowest. With such a large elevation difference between the highest and lowest points, there will be a high chance of fast flowing water within the creek.

As well as a DEM at a resolution of 2 m, a DEM at a resolution of 5 m was also generated. The DEM generated at the resolution of 5 m can be seen in figure 21.

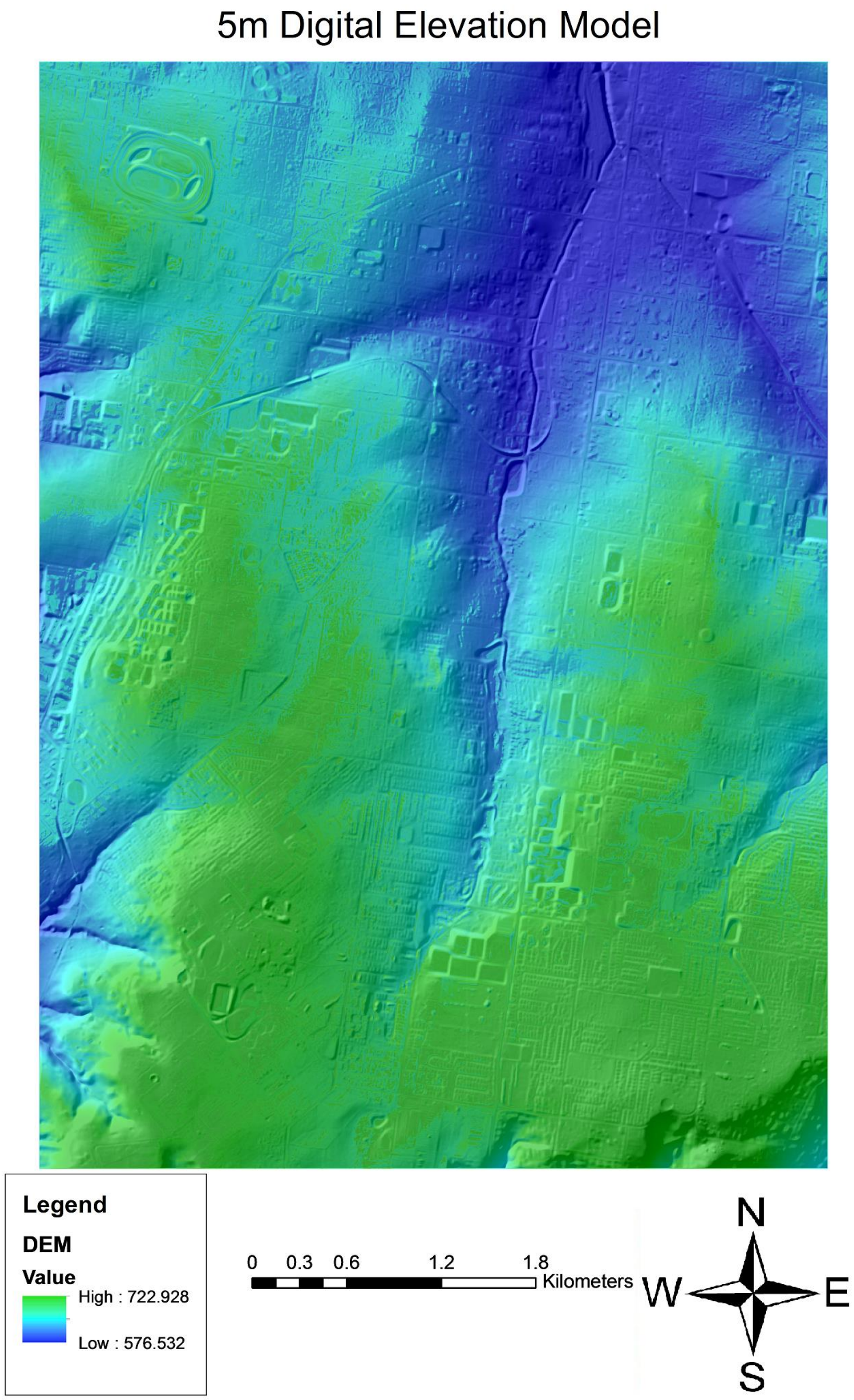

Figure 21: The DEM generated using the Topo to Raster technique at a resolution of 5 m.

The DEM generated at this resolution is another good representation of the interest area. The change in resolution only had a minor effect on its appearance but will have a major effect on the hydrological analysis.

4.3 Hydrological Analysis

4.3.1 Arc Hydro Results

The hydrological analysis was completed in the Arc Hydro software. There were multiple per-processing steps involved. These steps worked towards generating multiple streams and catchments. Different threshold values defined in the pre-processing steps were utilised on each DEM. The streams and catchments were generated on both the 2 m and 5 m DEMs. The results of the 5 m DEM at a threshold value of 0.3 can be seen in figure 22.

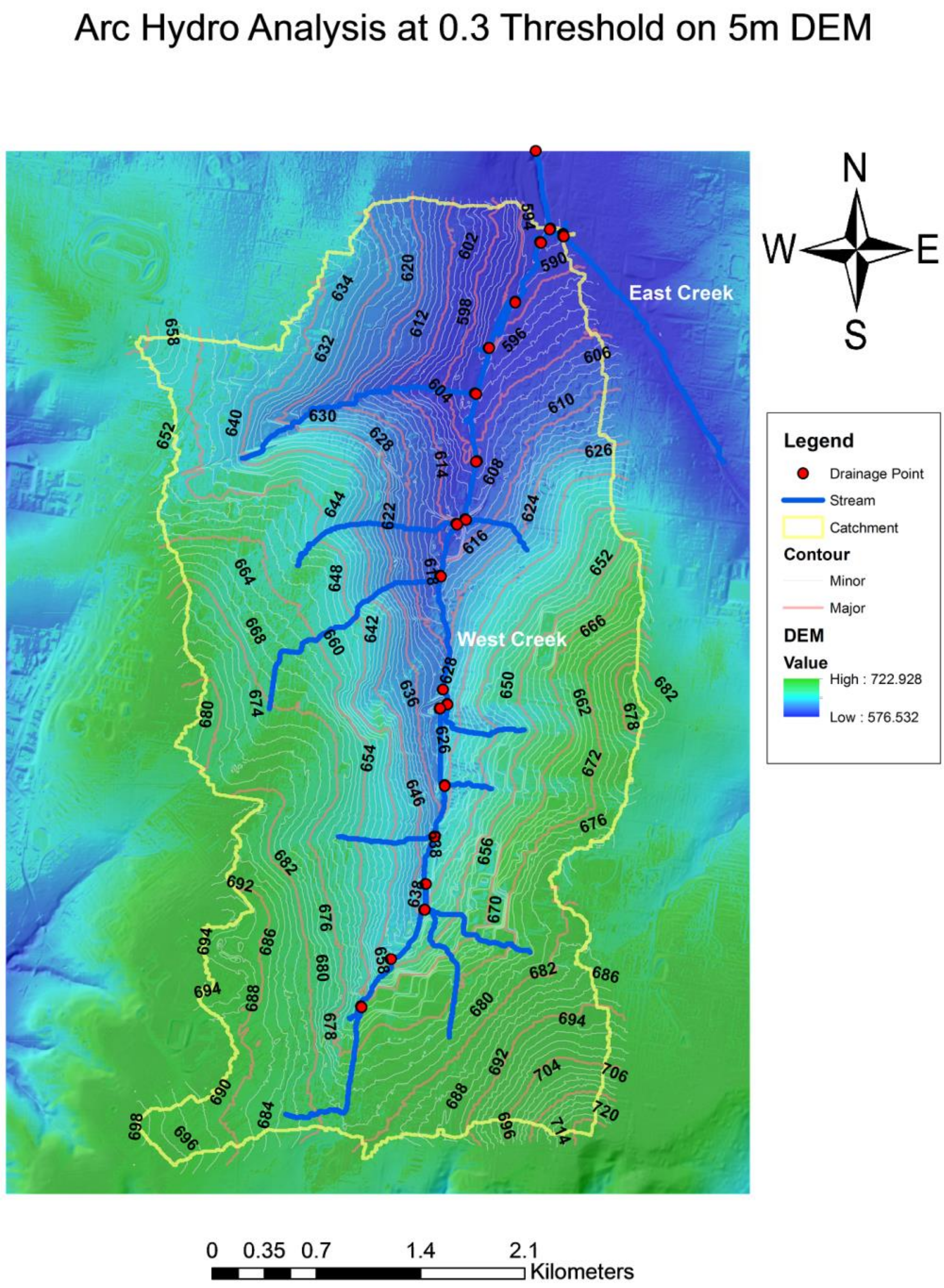

Figure 22: The results of the Arc Hydro analysis on the 5 m DEM at a threshold value of 0.3m

It can be seen within figure 22 that both West Creek and East Creek are mapped in dark blue and their area of intersection is shown in the top right hand corner. This area of intersection is one of interest as the two creeks are both meeting at their lowest points to merge. This would result in large amounts of water meeting and forming one large water body. The area after the intersection of these two creeks resulted in a large amount of the flooding in 2011 (ICA, 2011). This is an area highlighted from this analysis that requires mitigation. The network after the area of intersection would have to be mitigated to handle the combined waters of both creeks when the rainfall is at its highest.

Sub streams that run into West Creek are also shown running generally in an East-West direction. The catchment area generated within the software is shown in yellow. Any rain that falls within this catchment would be expected to flow to West Creek either through the sub streams or along the ground. The drainage points are also highlighted in red showing areas where water is expected to drain. These are located at areas where sub streams meet West Creek and where East and West Creek meet. The areas where sub streams meet West Creek are of interest, as water velocity would be expected to increase as more water is added in the main stream. These may be areas that require further analysis and possible mitigation.

The other maps showing the results of the analysis at the different threshold values on the 2 m and 5 m DEMs can be seen in Appendix G. It can be seen from the maps that the minimum threshold created the denser stream network. As the threshold increased the stream network thinned out and the catchment made subtle changes in shape. Also the networks generated in the 2 m DEM were denser than those generated in the 5 m DEM at each threshold value. Even though a denser network may seem better, it may not be a true representation of what is actually on the ground. As noted in Liu & Zhang

(2010) the highly accurate DEM with a small threshold value provides extremely detailed networks which are useful for detailed descriptions of the drainage network. Whereas a higher threshold value is best at representing the overall pattern of the network.

In this analysis an overall pattern of the network is more important than detailed information on each sub stream. As a result an estimation had to be made on which value generated the most accurate stream network and catchment shape. After viewing much of the creek and considering the effects of urbanisation, it was decided that the 5 m DEM at a 0.3 threshold was the best representation of the network on the ground. This was due to the other results showing either too detailed a stream network or too simple a network. The dense results of the 2 m DEM with the minimum threshold would be best for highly detailed analysis of each stream. Whereas the results of the 5 m DEM with a threshold value of 1 would be best for analysis of West Creek only with no other contributing factors.

4.3.2 Arc Hydro Validation

To validate the shape of the catchment and streams generated a comparative map was utilised. This can be seen in figure 23.

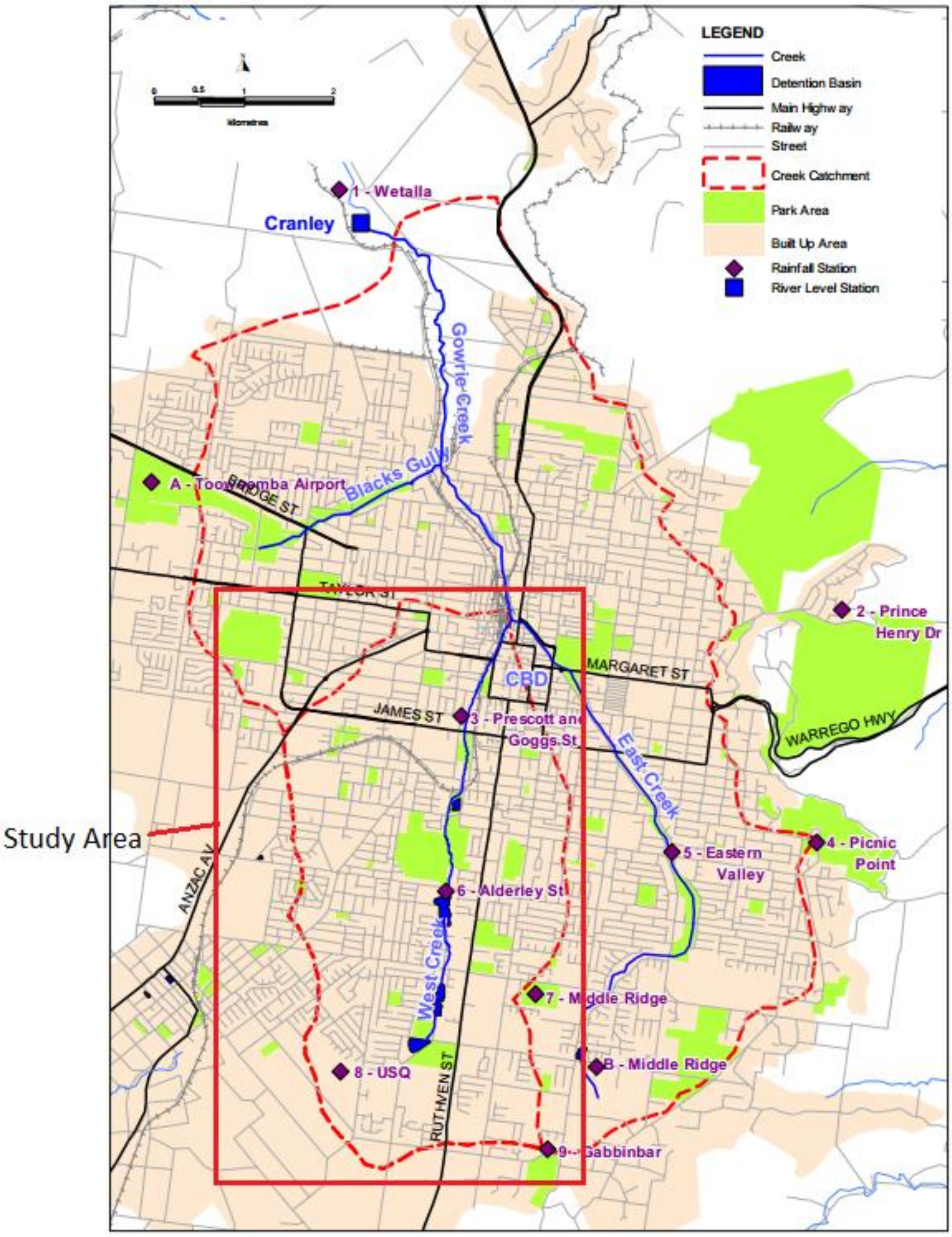

Figure 23: The map generated by the ICA hydrology Panel in reaction to the flooding event in 2011 (ICA, 2011).

This map in figure 23 was created in reaction to the flood in 2011 and shows the entirety of the Gowrie Creek catchment. The whole map is not applicable to this analysis with the red square box highlighting study area of the DEM generated in this analysis. There was no mention of the technique or methods utilised to create this map but it serves as a comparison to ensure validity. It can be seen from this map and the one generated utilising Arc Hydro in figure 22 that they are extremely similar. The catchment shape is extremely similar with the Arc Hydro analysis showing a more detailed shape. The main difference is in the stream network with the stream generated from the DEM highlighting multiple sub streams joining in with West Creek. This is a result of the accuracy of the DEM utilised and also the threshold chosen to represent the network. However the general shape of the West Creek itself is similar and provides assurance that the results gained are accurate.

4.3.3 Slope Analysis and Flood Plain Map

After generating the stream networks and catchment area a slope analysis was completed. The results of the initial analysis of the elevations can be seen in figure 24.

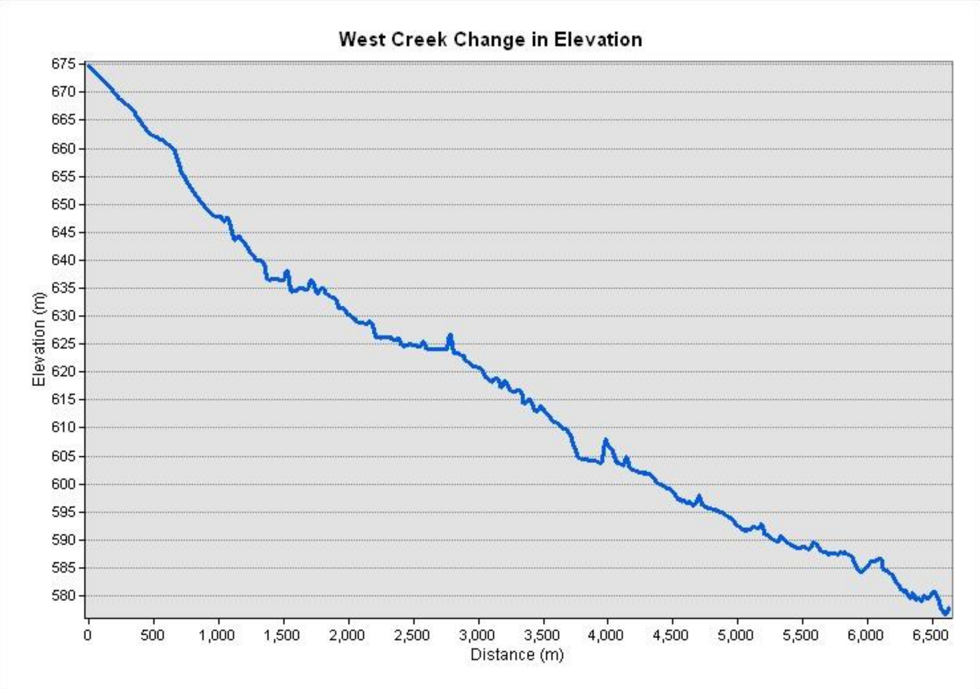

Figure 24: The change in elevation over the length of West Creek starting in the south and running northeast.

This graph shows that over 6.5 km there is a drop of 95 m from the beginning of West Creek until where it meets with East Creek. It can be seen that the downgrade of 1.46 % is fairly consistent throughout the entire creek. Water flowing down this creek would be expected to gain constant speed and volume depending on the shape and size of the creek.

It can be seen that within the graph there are some spikes in elevation. These spikes are caused by the crossings of East-West running streets along West Creek. As a result there is no LiDAR data under these crossings. To improve the accuracy of the slope results and the stream analysis terrestrial spatial data could be collected under these crossing to create a better representation of the stream. However for the purpose of this analysis no further data was collected.

The slope tool was utilised to generate a percentage slope map with classifications of 0 - 2 %, 2 - 5 %, 5 - 10 %, 10 - 20 %, 20 – 30 % and 30 – 44 %. This map also contributes to generating the flood plain. The resulting slope analysis for the 5 m DEM can be seen in figure 25.

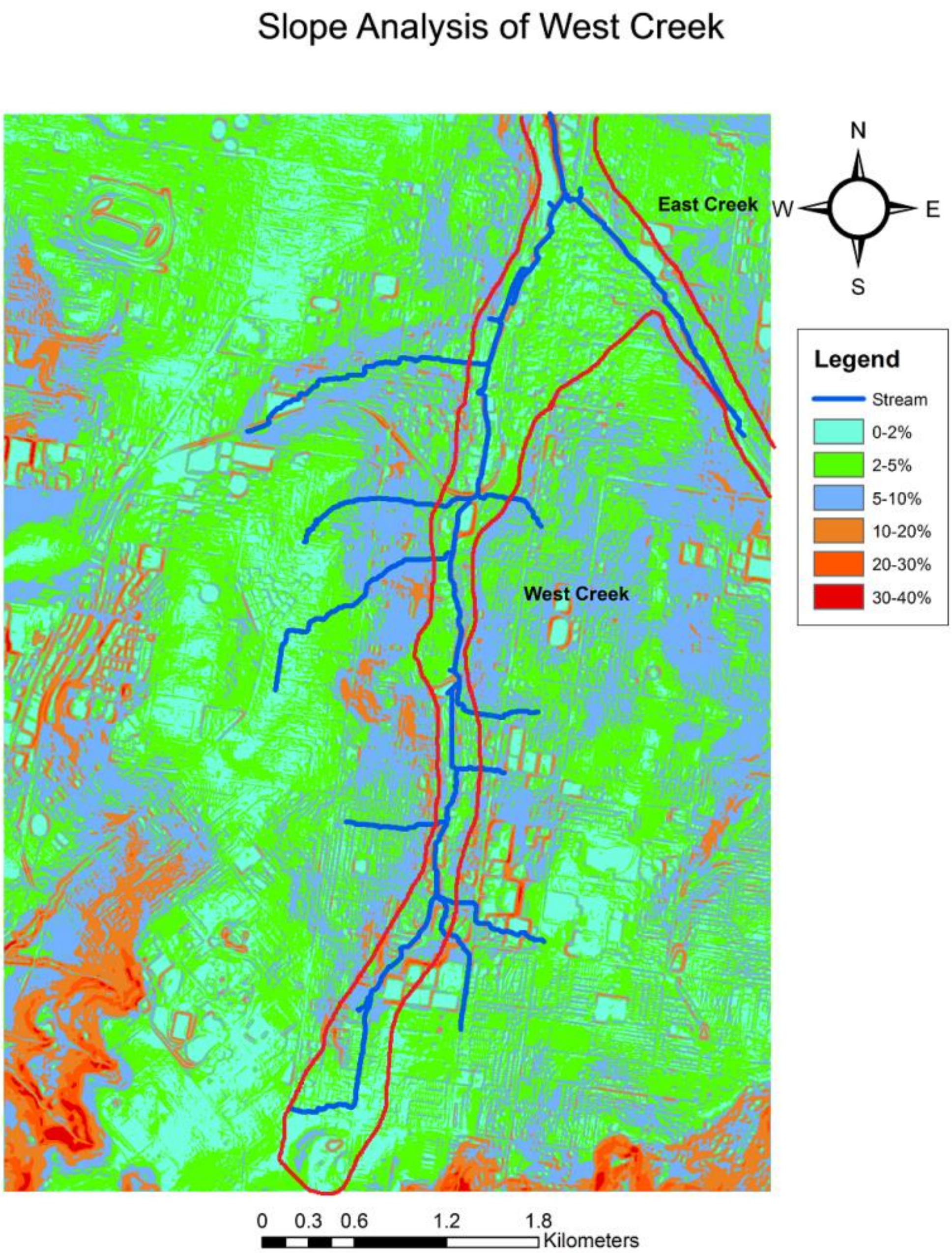

Figure 25: The map generated from the slope analysis tool showing the different slopes and flood plain.

The slope map shows that along West Creek there are fairly steep slopes generally in the green 2 – 5 % slope. However most of the ground surrounding West Creek is at a slope value of 5 - 10 %. This shows that as water falls within the previously defined catchment, it will travel quickly to West Creek. Then as it meets with West Creek the water will continue to accumulate and gain speed as it travels through the system at the average downward slope of 1.46 %. It can also be seen that the area where East and West Creek meet is classified as 0 – 2 % slope. This in combination with the two creeks meeting will increase water velocities and increase the chance of flooding. This area has been highlighted in both analyses so far and is one that will require major mitigation.

The expected flood plain is drawn in red around West and East Creek in figure 25. It can be seen from the slope analysis that there are fairly step banks along West Creek working in combination with the general downward slope. This means that the water will flow through the catchment quickly until it finds a flatter place to spread out. This area is what would be expected to be the flood plain. It can be seen from the shape of the flood plain running South to North, that it is quite small at a width of approximately 100 m. The narrow nature of the area surrounding the creek restricts the waters ability to spread out. However it can be seen that near where West Creek meets East Creek there is a significantly large area that is fairly flat falling in the 0 – 2 % and 2 – 5 % area. This is where the flood plain widens as it is the first chance the floodwaters have had to spread out. There is also the water coming in from East Creek that would further increase the chance of flooding in this area. In a high rain event this area would be at greatest risk of flooding and may require mitigation in the future.

The urbanisation of West Creek will also affect the flood plain. Manmade features such as fences which can catch debris and buildings minimise the ability of the waters to spread across the terrain. As a result a heavily urbanised area may have a smaller flood plain, but have higher water levels moving at faster velocities (Booth, 1991). The urbanisation along West Creek further contributes to the small width of the flood plain. However though the flood plain is small, its width increases its ability to gain speed and volume. This will have negative effects further downstream, especially when it meets other streams with the same issues.

4.3.4 Flood Plain Validation

To validate the shape of the flood plain created, it can be compared to the actual size of the flood plain that occurred in the 2011 flood. This map was also generated by ICA (2011) showing the extent of the flood occurring over the entire Gowrie Creek catchment. The area of interest is only West Creek with the study area highlighted by the red square box. This can be seen in figure 26.

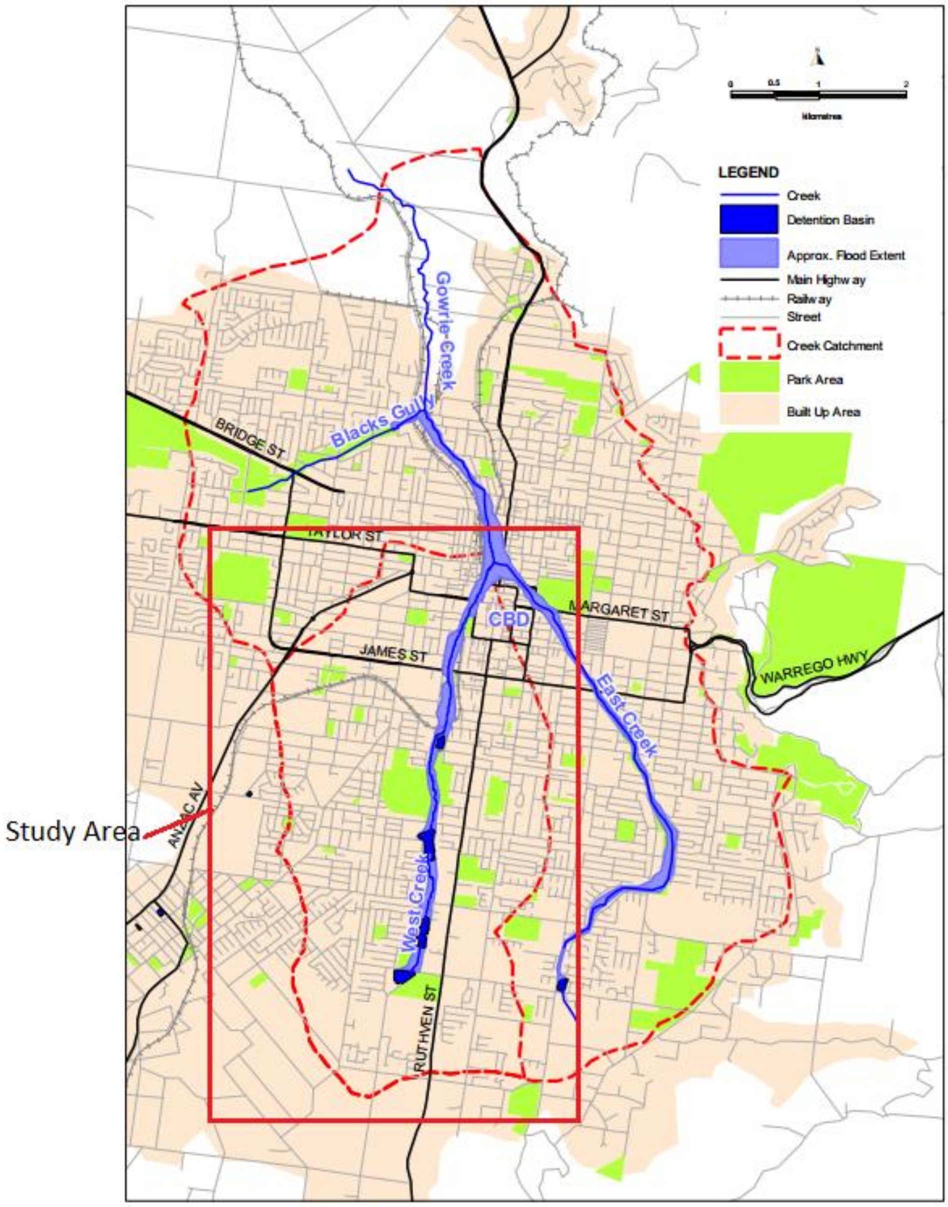

Figure 26: The approximate extent of the flooding that occurred in 2011 over the Gowrie Creek catchment (ICA, 2011)

It can be seen from this map that the flood extent of the event was extremely narrow. Along most of West Creek the extent was approximately 100 m and in spots was as wide as 300 m. The extent then became quite larger where East and West Creek meet. This would be expected due to the flatter nature of the terrain in combination with the two creeks meeting. This map shows a flood plain which is extremely similar to the one generated from the slope analysis. As a result the information gained from the slope analysis can be seen as accurate and validated.

4.4 Hydrological Modelling

The hydrological modelling of West Creek required the input of multiple parameters within the software SWMM. From this modelling multiple pieces of information such as water heights, volumes, flows and velocities were generated. This modelling process required multiple assumptions to be made throughout due to lack of availability to specific data. However the parameters utilised still provide a good representation of West Creeks hydrological behaviour.

4.4.1 Water Elevation

The graph shown in figure 27 represents the elevation of the water as it flows through the system. In this figures case the graph is representing the amount of water in the system at the end of the simulation. The water in the system is shown in blue and the maximum amount of water it can handle is the line above the water.

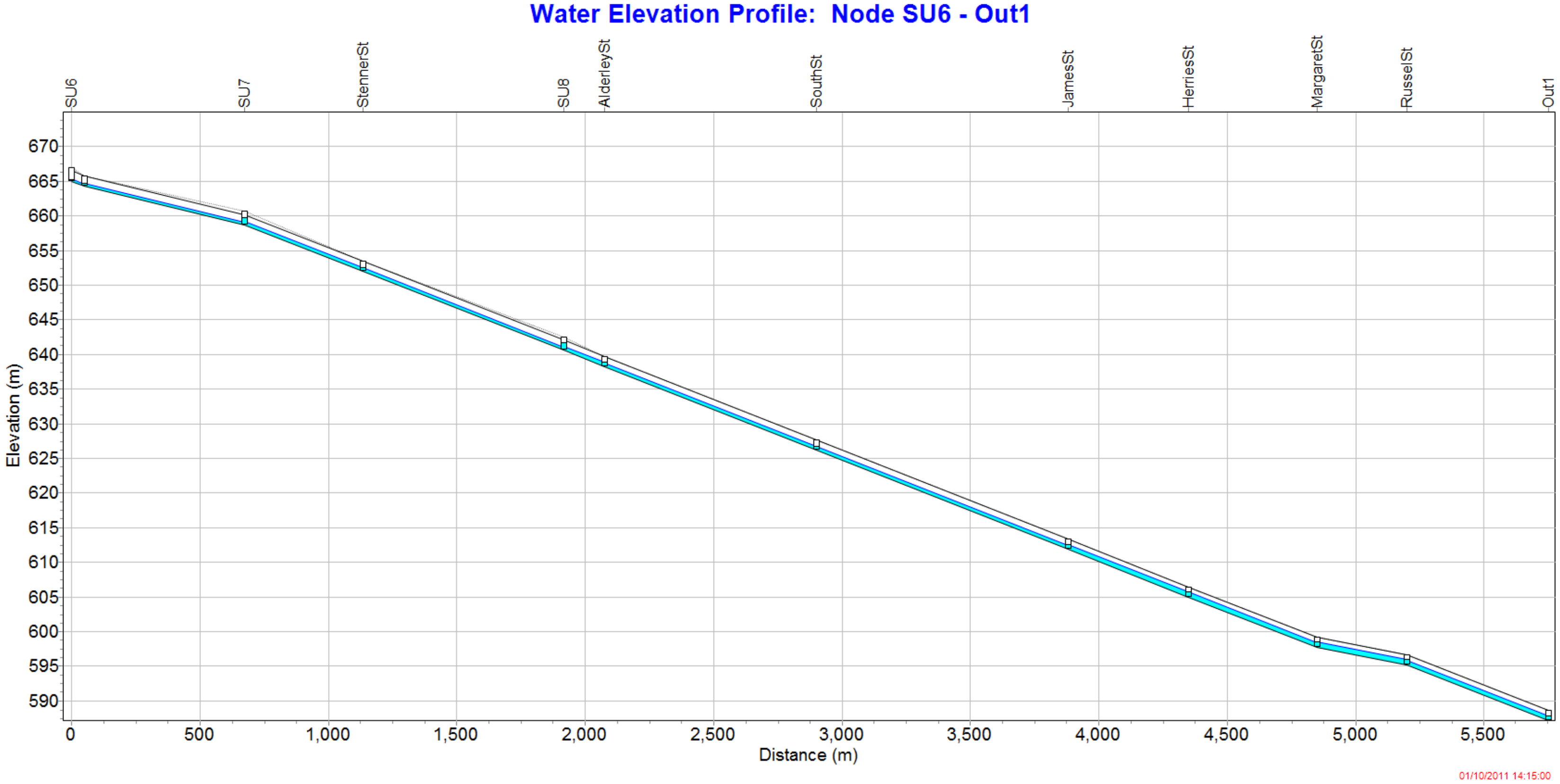

Figure 27: The water elevation profile from beginning to end of the model showing water depth at the end of the simulation time.

It can be seen from figure 27 that the model utilised is capable of holding the amount of water generated from the rainfall event. As progress is made through the system the water elevation rises, but not to or above the maximum. In an actual flooding event it would be expected that the system elevation would rise above the maximum height. This happened in the flood in 2011 but has not happened in this model.

There are several factors that may have contributed to the model not showing the expected height of water from the rainfall event. In the model there were several assumptions made and multiple parameters left as default. These assumptions and default parameters will have an effect on the accuracy of the model. Also when the flooding event occurred in early 2011 there had been extensive drenching rain falling for an extended period beforehand (ICA, 2011). As a result there was water already in the system and the absorbability of the soil was minimal. This would have resulted in nearly all of the water becoming runoff. However in the model generated there was water absorption in the soil, resulting in an unrealistic representation of the system at the time of the event. It would be expected that the actual flood in 2011 was worse than what is shown here.

4.4.2 Water Velocities

The model also generated the velocity and flow rate of the water in the conduits of system. The flow rates can be seen in Appendix G. The velocities of the water in the conduits can be seen in figures 28 and 29.

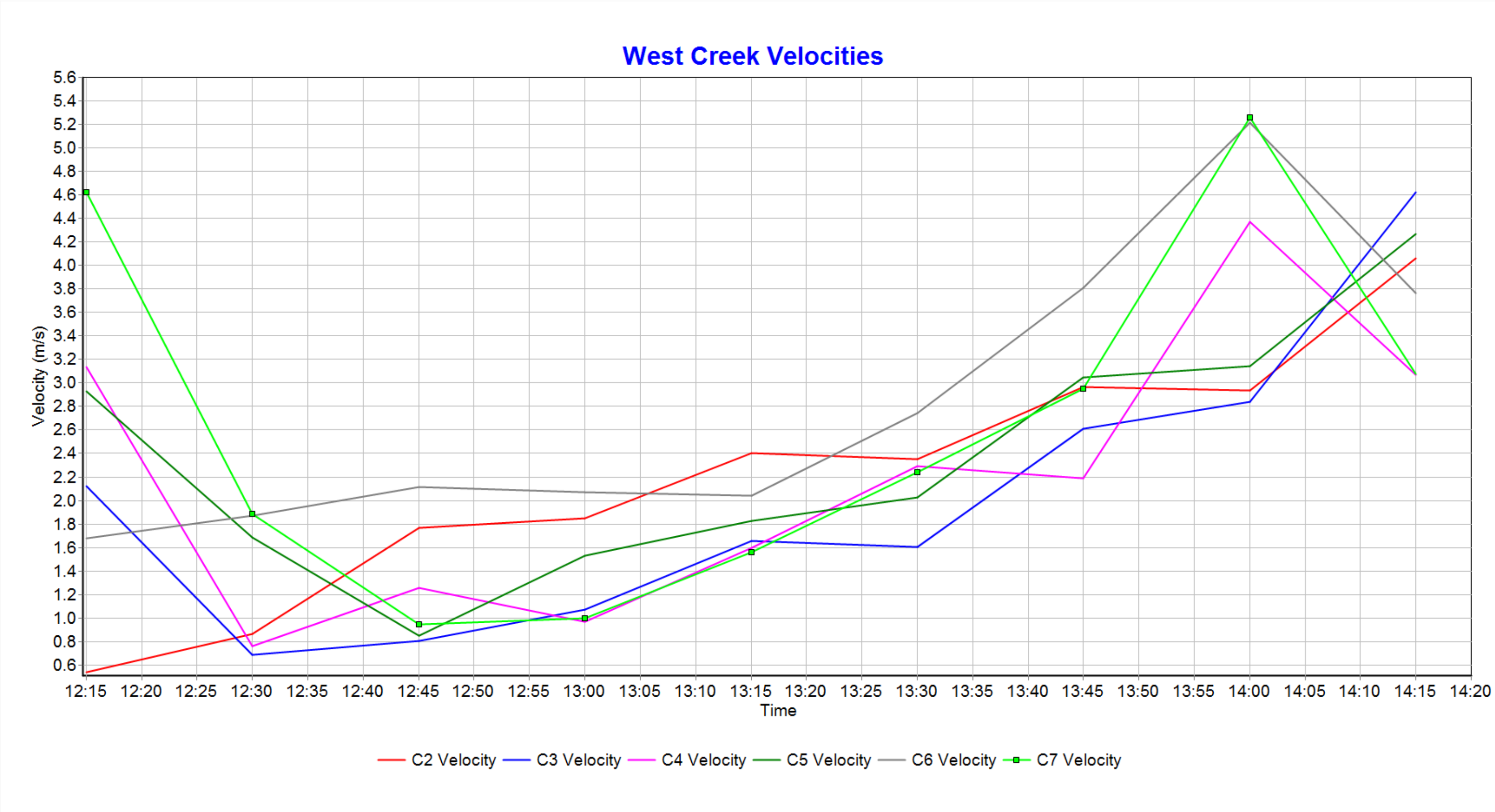

Figure 28: The velocities of the first six conduits between the junctions of the model.

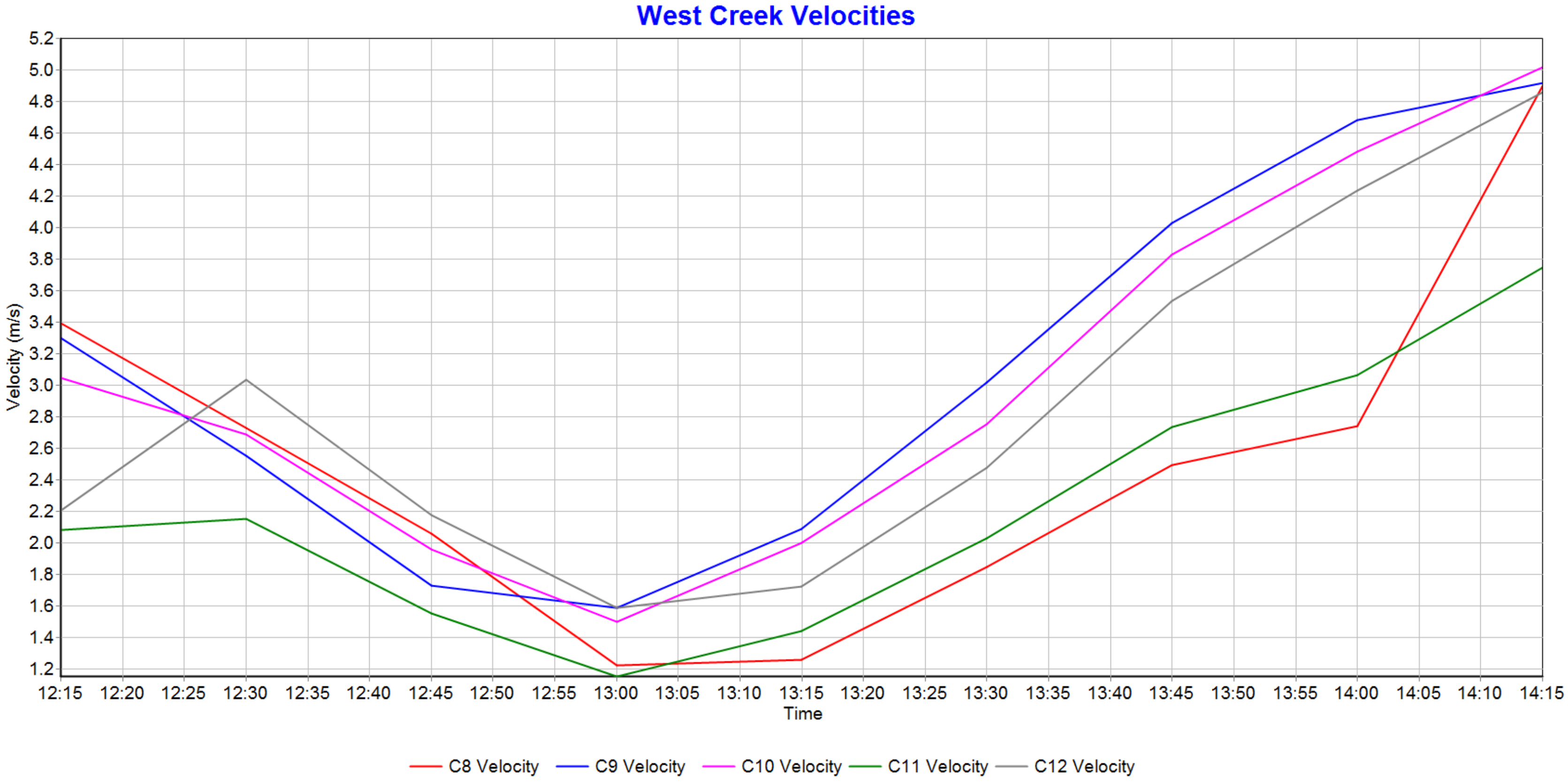

Figure 29: The velocities of the last five conduits between the junctions of the model.

The velocities in figure 28 show the conduits that had the wider conduit size. It can be seen from the velocities that as progression is made further down the model in both time and distance, velocity increases. The first conduit starts at a low velocity and gradually rises as the rainfall increases. Then as progress is made down the treatment train, the initial velocities gradually increase. This would be expected as each conduit has the water running into it from earlier in the model plus its own influx of rainfall. Each of the conduits then shows a decrease in velocity before gradually increasing again. The final velocities of the conduits vary between 4.6 m/s and 3.0 m/s.

The velocities of the C4, C6 and C7 conduits are slightly out of pattern with the other conduits. They start with a high surge of water and then slow before surging again at approximately 1:45 pm to around 5.0 m/s and falling afterwards. The surge at 1.45 pm is explained by the required selection of an outlet point for the sub catchments. The sub catchments are draining a large portion of the rainfall into the specified junction. The rainfall then runs from this junction through the conduits. This then causes an increase in water and velocity. This is not a true representation, as the rain falling in the sub catchment would fall according to the shape of the terrain. This water would then flow somewhat evenly into the conduits, not into an individual junction.

The velocities in figure 29 show the conduits with the smaller sized conduit. This graph shows consistent results with each conduit beginning at approximately the same velocity. Each then slows before gradually increasing in speed by the end of the simulation. The final velocity of the C8, C9, C10 and C12 conduits at the end of the simulation time is approximately 4.8 m/s.

The results for these conduits are of most importance as they have to deal with the most amount of water. They are also the final stages before West Creek meets East Creek. From these results it can be expected that when the flood waters merge with East Creek, they will be travelling at approximately 4.8 m/s. at the worst of the rainfall. To decrease the damage caused by the flowing water when it meets East Creek, the water needs to be slowed earlier in the creek. Mitigation would be required along West Creek to try and slow the water flow before it reaches East Creek.

As mentioned previously in section 4.4.1, there were many assumptions made when creating the model. These results however still give a good understanding of the type of water velocities that would be expected in a flood of this size. However it would be expected that the actual flood in 2011 generated faster velocities than shown here.

4.4.3 Water Volume

The volume of water flowing through the conduits at each stage of the simulation was also generated. The graphs of each conduits volume can be seen in figures 30 and 31.

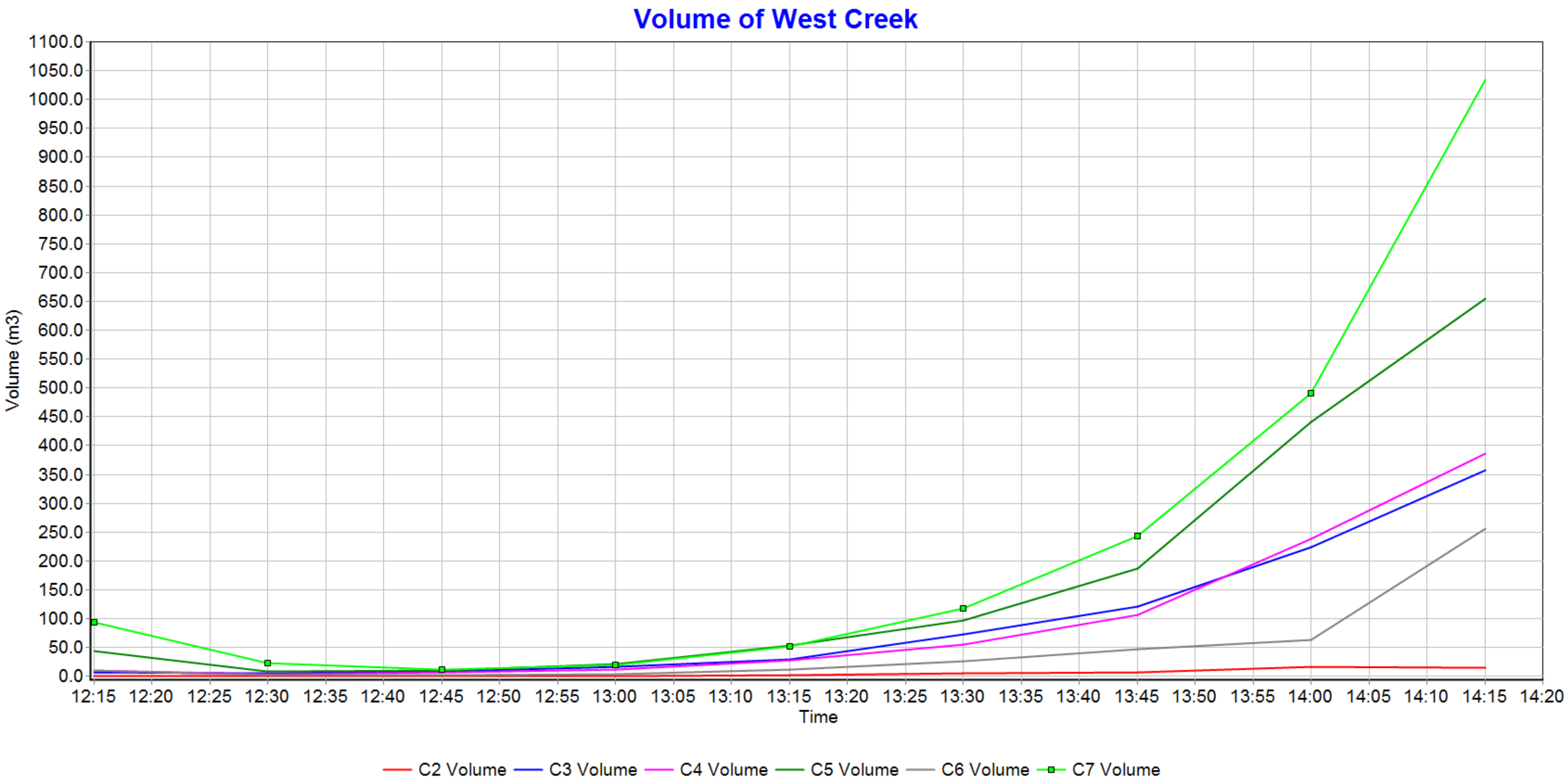

Figure 30: The volume of water in the first six conduits between the junctions of the model.

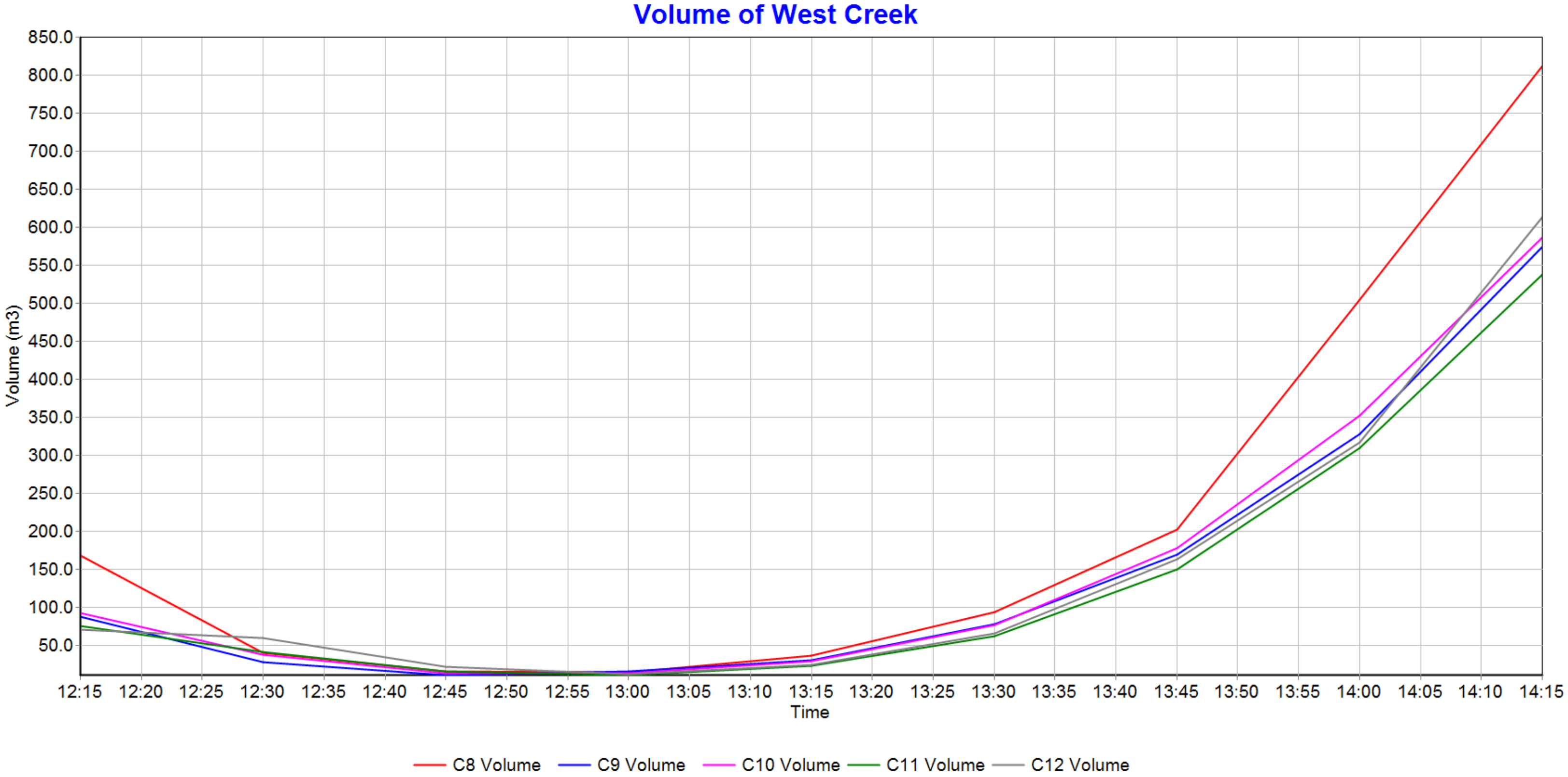

Figure 31: The volume of water in the last five conduits between the junctions of the model.

Each of the figures highlights a similar pattern with the volume of the conduits during the simulation. There is a small amount of water in the system before reducing in volume and then gradually increasing by the end of the simulation. The overall amount of volume also gradually increases as progress is made down the treatment train. The final conduit in figure 31 shows that there is approximately 600 m^3 of water in the conduit at the end of the simulation. This shows that by the end of the simulation there was 600 m^3 of water in the system when it meets East Creek. This is a large amount of water and further highlights that mitigation is required along West Creek to reduce velocities and volume.

An outlier in this data is the conduit C7. This conduit has a much larger volume of water through it than the other conduits. This may be caused by the sub catchment influx however this conduit has been highlighted as an irregularity in both velocity and volume. This shows that there may be something wrong with the model or an issue in the area itself. This area may be one that requires mitigation to make it consistent with the other conduits.

As well as the multiple assumptions made there were also several other factors that were not considered in the model. These include inflow of water from roads, sub streams and urbanisation. There is a stormwater system along the roads running through West Creek and they all feed into the system. This large amount of water will change the outcome of a simulation. The sub streams generated in the Arc Hydro analysis were also not included in the model. These would have further contributed to the amount of water flowing into system. Finally urbanisation was not considered entirely in the model. It was assumed that the rainfall was all landing on the ground. However in reality there are multiple buildings with roofs that have the capability to catch the rainfall and store it in tanks or other storage devices. These effects of urbanisation will also have major effects on the results of the simulation.

4.5 Conclusion

This chapter has highlighted the results of the methodology and discussed the importance of the results. The results of the DEM generation were highlighted and discussed. The hydrological analysis was also presented showing the stream network and catchment definition generated from Arc Hydro. The area where East and West Creek meet was highlighted as requiring mitigation. The results from Arc Hydro were also compared and validated against another stream network and catchment. The results of the slope analysis were presented highlighting the general downward slope of 1.46 % of West Creek. A slope classification map also helped define areas of interest and the flood plain. A flood plain was mapped in areas that fell in the 0 – 2 % and 2 – 5 % slope classification. This flood plain was thin along West Creek and then spread out near where East and West Creek meet. The negative affect that urbanisation has on the flood plain was also discussed with areas requiring mitigation highlighted. The generated flood plain was compared against the actual flood plain for 2011 with multiple similarities shown. Finally the hydrological modelling results generated from SWMM were presented. West Creeks water elevations, velocities and volumes were each highlighted and discussed. The hydrological information was also discussed and its application to flood mitigation highlighted. Multiple assumptions and information left out of the analysis were also highlighted and discussed. This information will now be summed up and further recommendations regarding the research discussed in the following chapter.

Chapter 5 Conclusion

5.1 Introduction

The chapters up until now have gone through the objectives of this research project, the background information relevant to these objectives, the techniques utilised to reach them and the results of these methods. This information will now be summed up and further recommendations will be made.

5.2 Conclusions

Overall each of the objectives based on the projects aim have been met. Information and methods relating to airborne LiDAR data in hydrological analysis, modelling and flood plain mapping have been highlighted. A large amount of background data regarding airborne LiDAR systems, accuracy and application was presented in the literature review. Multiple techniques and studies were also presented relevant to the extraction of stream networks and catchment boundaries. Hydrological modelling software packages were also compared and the relevance of MUSIC and SWMM was highlighted.

Two DEMs at resolutions of 2 m and 5 m were created using the Topo to Raster interpolation technique. The two DEMs were generated to show the difference in stream network generation. These DEMs were then used in the hydrological analysis. From this multiple maps were created utilising thresholds of minimum, 0.3, 0.5, 0.75 and 1 in the Arc Hydro pre processing steps. It was found that as the threshold value was increased, the stream density decreased. The 2 m DEM also resulted in denser stream networks than the corresponding threshold values of the 5 m DEM. The catchment boundary shapes changed in small amounts with each changed threshold value and DEM resolution. It was discussed that a denser stream network is not always a true representation of the network on the ground. The stream network and catchment boundary created from the 5 m DEM at a threshold value of 0.3 was chosen to best represent the stream on the ground. The map highlighted the area of intersection of West and East Creek for future flood mitigation. This map was then validated by comparing the catchment and creek shape to a model generated by ICA (2010).

A slope analysis was also completed on the 5 m DEM. This resulted in the determination of the overall downward slope of West Creek. It was found that over 6.5 km West Creek dropped 95 m at a consistent downward slope of 1.46 %. The slope tool was also utilised to generate a percentage slope map with classifications of 0 - 2 %, 2 - 5 %, 5 - 10 %, 10 - 20 %, 20 - 30 % and 30 - 44 %. This map was then utilised to determine the expected flood plain with areas falling in the 0 - 2 % and 2 - 5 % expected to flood. It was found that the flood plain was fairly narrow along West Creek before spreading when meeting East Creek. The flat area around the intersection of East and West Creek was highlighted again as requiring mitigation. This generated plain was then validated by comparison to the actual flood plain from 2011.

The software SWMM was then utilised to perform hydrological modelling. From this process water heights, flow rates, velocities and volumes were gained. It was found that at the end of 2 hour and 15 minute long simulation there would be water flowing at approximately 4.8 m/s. At the end of the simulation there was also 600 m^3 of water in the system when it met East Creek. The results also highlighted that at the end of the simulation there was no excess water flowing out of the system. It was deduced that mitigation is required along West Creek to reduce the amount of water in the system when it meets East Creek. Further mitigation would also be required where the two creeks meet to ensure the downstream system can handle both creeks floodwaters.

Within the modelling process there were several assumption and factors that were discussed. The assumptions made in the modelling process, the factors of urbanisation and the inability to represent the drenched ground resulted in values less than expected. There were also many other factors highlighted which were not be considered in the model such as road stormwater and roof catchment. Each of these may result in changes to the final outcome of the model.

5.3 Further Research and Recommendations

The information gained from the results can be used as a tool in future flash flood mitigation. It has been highlighted through the use of Airborne LiDAR data, DEM generation, hydrological analysis and modelling that when used in conjunction, a proactive solution can be reached. By applying each of the above techniques to West Creek, problems with urbanisation, stream alignment and catchment shape were highlighted. To prevent such major flooding events occurring in the future, this analysis should be completed ensuring that the Q100 rainfall information is utilised. This will ensure that the mitigation measures in place are able to deal with the worst case scenario in the future. By putting more effort into a proactive solution a large amount of money and lives may be saved in the future.

In the slope analysis of the DEM it was highlighted that there were several elevation rises due to road crossings across West Creek. To further increase the accuracy of the model it is recommended to collect terrestrial spatial data underneath these crossings. This will allow for a greater representation of the study area and also assist in better creation of the stream networks and boundary.

Within the hydrological modelling process utilising SWMM, due to time restrictions, there were multiple assumptions made when creating the treatment train. These included many of the parameters and the shapes of the conduits. Several other factors were also not included in the model such as road stormwater runoff systems, absorbability of the ground and urbanisation. As a result the outputs gained from the modelling were not entirely accurate.

There is a much more detailed application of SWMM in flood modelling than highlighted in this analysis. As a result it is recommended furthering research into the application of this software to model floods. By correctly applying all of the assumptions made in this particular model, a more accurate result will be gained. This result will then be more useful in flood mitigation. The greater result can be used in conjunction with the other steps to further increase the accuracy and usefulness of the analysis.

It is also recommended to further research into flood mitigation techniques. This study has helped highlight a method to identify problems with the waterway. However further analysis may be input into the mitigation techniques utilised. Particular techniques to be researched may revolve around dealing with urbanisation, the shape of the creek and the effect of long term rainfall followed by a large downpour.

5.4 Conclusion

This chapter has provided the conclusions gained from the methods utilised to reach the projects objectives. The objectives have each been reached with the application of airborne LiDAR data, DEMs, hydrological analysis and modelling all highlighted. Recommendations have also been made with regards to future work on the topic. Overall a proactive solution has been highlighted in this project that may be used in the future to reduce flood damage and save lives.

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Appendices

Appendix A - Project Specification

University of Southern Queensland

FACULTY OF ENGINEERING AND SURVEYING

ENG 4111/4112 Research Project
PROJECT SPECIFICATION

TOPIC: LiDAR DATA FOR DEM GENERATION AND FLOOD PLAIN MAPPING

SUPERVISORS: Xiaoye Liu

PROJECT AIM: This project seeks to utilise airborne LiDAR data to generate high quality digital elevation models (DEM) for characteristic analysis of West Creek catchment area to facilitate future flash flooding mitigation.

PROGRAMME: **(Issue A, 13 March 2014)**

1. Research the background information relating to LiDAR data high resolution DEM generation and flood analysis software.
2. Analyse current software methods utilised for characteristic analysis and select one suitable for the analysis.
3. Collect LiDAR data of West Creek catchment suitable for the generation of selected quality DEM.
4. Implement the selected software with the collected data to produce a characteristic analysis and other necessary outputs.
5. Produce a map of the area showing all characteristic analysis.
6. Submit an academic dissertation on the topic.

As Time Permits:

7. Utilise a software package to perform an urban storm water analysis on the catchment.
8. Design practical ways to reduce the effects of flash flooding in the future.

AGREED:

____________________ (Student) _______________(Supervisor)

Date: / / 2014 Date: / / 2014

Appendix B - Resource Analysis, Project Timeline and Consequential Effects

B.1 Resource Analysis

The resources required for this dissertation are relatively simple with all of them readily available for use. The physical resources that will be required include a powerful enough computer to process large amounts of LiDAR data. A computer of such capability is already available within the Universities Engineering and Surveying computer labs. These computers or a personal computer will also be required to utilise the software required to write the dissertation. The non-ground and ground LiDAR data for the Toowoomba region will also be required. The University of Southern Queensland who gained the data from the Toowoomba Regional Council provided this data.

The software requirements include Arc GIS with the Arc Hydro and Arc Map package. This software package is already installed and available for use on the University computers. The software package SWMM will also be required for the hydrological modelling. This software was gained for free online from The United States Environmental Protection Agency. Finally the Microsoft package of Word, PowerPoint and Excel will be required for the analysis, presentations and final completion of the dissertation. These were self-provided and are also available on the Universities computers.

Each of these resources are already available and therefore do not require a budget for purchases. The critical items of the resources are the University computers, the LiDAR data and the Arc GIS and SWMM software for the mapping, analysis and modelling. If these were to fail or become unavailable the project would not be able to go ahead. There are no measures that can be used to reduce this vulnerability other than performing safe computer measures to reduce the chances of data corruption and software failure. Loss of the written dissertation due to data corruption or damage to computer is also a major threat. To counter this multiple copies of the dissertation are kept across multiple computers, USB's and online storage services such as email and backup.

B.2 Project Timeline

The timeline followed on the way to finishing the dissertation can be seen below in figure 32.

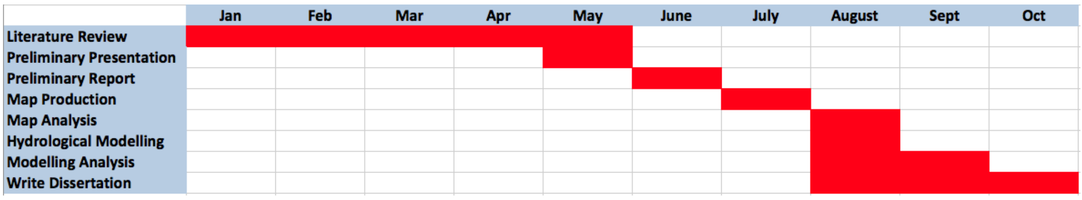


Figure 32: The timeline for the project covering both semesters.

B.3 Consequential Effects of the Project

Within any major technical activity there are possibilities for effects to the community in both positive and negative ways. These consequences can affect people in three areas including sustainability, safety and ethical issues. Critically analysing a project identifying all of the possible effects is a vital step, ensuring that the best interest of the community is maintained.

B.3.1 Sustainability

This project is aimed at analysing waterways to determine areas for flood mitigation in the future. Performing such a task will provide a means of maintaining the waterways in their natural state, reducing the severity of flooding. If hydrological analysis is not performed then severe manmade changes may be implemented to the waterway affecting the natural flow of water and the ecosystems that rely on the system. The environmental sustainability of the waterways can therefore be maintained while still mitigating flood damage.

The analysis of creeks also increases the sustainability and suitability of living for residents near the creek. Residents living near creeks can be placed in severe danger when flooding occurs. Analysing the characteristics of creeks and finding ways to mitigate the damage caused by flooding can make the living environment far more sustainable. This allows more people to live within the city, feeling safe from flooding. This increase in social sustainability will result in continued growth of the region and the communities with it.

Residents are also affected economically by the damage that occurs to the infrastructure with multiple businesses closing to rebuild after flood damage. By reducing the severity of the damage to the infrastructure the community will experience less rebuild costs and shorter times of reduced business hours. This improves the economic sustainability of the region and the government having positive effects for the entire country.

Finally this project may also have effects on the surveying profession itself. The collection of LiDAR data isn't a common traditional survey method but with the possibility of such importance as flood mitigation, it may become a highly desired data type. If this were the case then data would have to be collected often to ensure up to date maps and models can be created. This will improve the sustainability of surveyors who work with LiDAR and all other aspects of its collection. The surveyors and the businesses they work for will find themselves with more consistent work in the years to come. This will also contribute to the social sustainability with secure work easily being found within the community for a professional.

B.3.2 Safety

With all survey work there is some form of safety issues that are linked to it. The collection of Airborne LiDAR data requires the use of a plane and ground control. There are many dangers that can occur with this including plane crash, being hit by a car and being electrocuted. Each of these dangers is unlikely but if airborne LiDAR becomes highly sought after, more flights will occur, increasing the risk of danger.

There are also positive safety factors that may result as an effect of this project. The safety of local residents living in flood prone areas will greatly increase with improved mitigation and prediction capabilities. The safety of those living downstream will also increase with mitigation measures in place.

B.3.4 Ethical

As with any action completed by a professional with expertise there is a possibility of ethical issues. In the case of this project the major issue that may occur revolves around incorrect analysis produced from the LiDAR data. If incorrect analysis were to be completed and deaths or major infrastructure damage were to occur, the blame falls directly on the analyser and the individual who created the process. Therefore there is a significant amount of responsibility on the project for safety of residents within the community.

Appendix C - Risk Assessment

All of the work for this project will be completed within the University of Southern Queensland. As the data has been provided and no fieldwork is required, there are minimal possibilities of risk. However there are still risks associated with the computer work of the project and these are highlighted below. The risk assessment is the most up to date Risk Management Plan utilised within the University of Southern Queensland at the time of creation.

University of Southern Queensland

Generic Risk Management Plan

Workplace (Division/Faculty/Section):

Engineering and Surveying

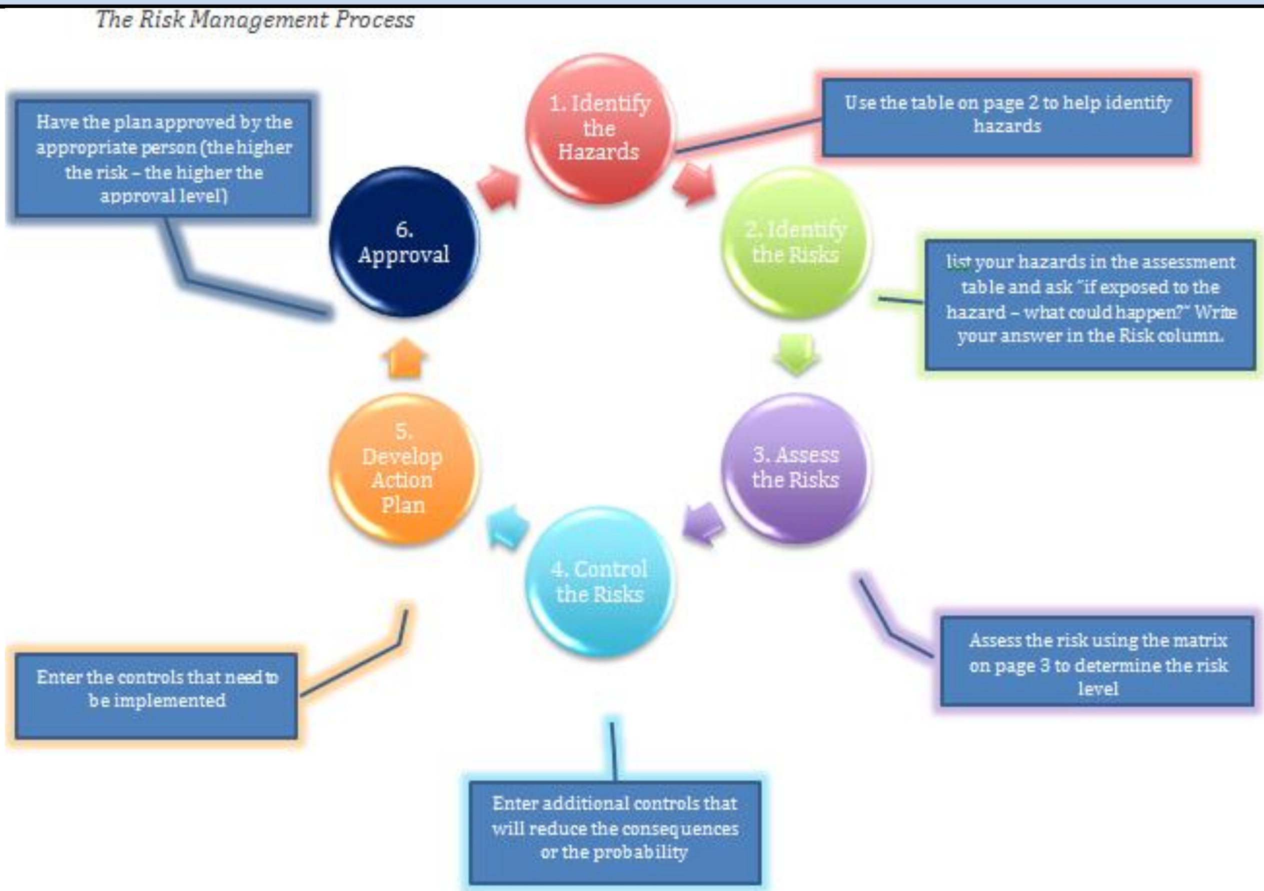
Assessment No (if applicable):	Assessment Date:	Review Date: (5 years maximum)
	4/06/2014	-/-/-

Context: What is being assessed? Describe the item, job, process, work arrangement, event etc:

Create Digital Elevation Models (DEM) from airborne LiDAR data utilising Arc GIS. Then perform hydrological analysis on these DEM utilising the software program Arc Hydro. Finally perform hydrological modelling utilising the Storm Water Management Model (SWMM). Steps include:

1. **Input data into ArcGIS software.**
2. **Generate DEMs.**
3. **Utilise DEM in Arc Hydro for hydrological analysis**
4. **Use SWMM to generate a treatment train and model the creek**
5. **Analyse results**

Assessment Team – who is conducting the assessment?



Step 1 - Identify the hazards (use this table to help identify hazards then list all hazards in the risk table)

General Work Environment		
☐ Sun exposure	☐ Water (creek, river, beach, dam)	☐ Sound / Noise
☐ Animals / Insects	☐ Storms / Weather/Wind/Lightning	☐ Temperature (heat, cold)
☐ Air Quality	☐ Lighting	☐ Uneven Walking Surface
☐ Trip Hazards	☐ Confined Spaces	☐ Restricted access/egress
☐ Pressure (Diving/Altitude)	☐ Smoke	☐
Other/Details:		
Machinery, Plant and Equipment		
☐ Machinery (fixed plant)	☐ Machinery (portable)	☐ Hand tools
☐ Laser (Class 2 or above)	☐ Elevated work platforms	☐ Traffic Control
☐ Non-powered equipment	☐ Pressure Vessel	☐ Electrical
☐ Vibration	☐ Moving Parts	☐ Acoustic/Noise
☐ Vehicles	☐ Trailers	☐ Hand tools
Other/Details:		
Manual Tasks / Ergonomics		
☒ Manual tasks (repetitive, heavy)	☐ Working at heights	☐ Restricted space
☐ Vibration	☐ Lifting Carrying	☐ Pushing/pulling
☐ Reaching/Overstretching	☒ Repetitive Movement	☐ Bending
☒ Eye strain	☐ Machinery (portable)	☐ Hand tools
Other/Details:		
Biological (e.g. hygiene, disease, infection)		
☐ Human tissue/fluids	☐ Virus / Disease	☐ Food handling
☐ Microbiological	☐ Animal tissue/fluids	☐ Allergenic
Other/Details:		
Chemicals Note: Refer to the label and Safety Data Sheet (SDS) for the classification and management of all chemicals.		
☐ Non-hazardous chemical(s)	☐ 'Hazardous' chemical (Refer to a completed hazardous chemical risk assessment)	
☐ Engineered nanoparticles	☐ Explosives	☐ Gas Cylinders
Name of chemical(s) / Details:		
Critical Incident – resulting in:		
☐ Lockdown	☒ Evacuation	☒ Disruption
☐ Public Image/Adverse Media Issue	☐ Violence	☐ Environmental Issue
Other/Details:		
Radiation		
☐ Ionising radiation	☐ Ultraviolet (UV) radiation	☐ Radio frequency/microwave
☐ infrared (IR) radiation	☐ Laser (class 2 or above)	☐
Other/Details:		
Energy Systems – incident / issues involving:		
☒ Electricity (incl. Mains and Solar)	☐ LPG Gas	☐ Gas / Pressurised containers
Other/Details:		
Facilities / Built Environment		
☐ Buildings and fixtures	☐ Driveway / Paths	☐ Workshops / Work rooms
☐ Playground equipment	☐ Furniture	☐ Swimming pool
Other/Details:		
People issues		
☒ Students	☒ Staff	☐ Visitors / Others
☐ Physical	☐ Psychological / Stress	☐ Contractors

☒ Fatigue	☐ Workload	☐ Organisational Change
☐ Workplace Violence/Bullying	☐ Inexperienced/new personnel	☐
Other/Details:		
Step 1 (cont) Other Hazards / Details (enter other hazards not identified on the table)		

Risk Matrix

Eg 1. Enter Consequence

Eg 2. Enter Probability

Eg 3. Find Action

	Consequence				
Probability	**Insignificant** No Injury 0-$5K	**Minor** First Aid $5K-$50K	**Moderate** Med Treatment $50K-$100K	**Major** Serious Injuries $100K-$250K	**Catastrophic** Death More than $250K
Almost Certain 1 in 2	M	H	E	E	E
Likely 1 in 100	M	H	H	E	E
Possible 1 in 1000	L	M	H	H	H
Unlikely 1 in 10 000	L	L	M	M	M
Rare 1 in 1 000 000	L	L	L	L	L

Recommended Action Guide
E=Extreme Risk – Task ***MUST NOT*** proceed
H=High Risk – Special Procedures Required (See USQSafe)
M=Moderate Risk – Risk Management Plan/Work Method Statement Required
L=Low Risk – Use Routine Procedures

Risk register and Analysis

Step 1 (cont)	Step 2	Step 3			Step 4				
Hazards: From step 1 or more if identified	**The Risk:** What can happen if exposed to the hazard with existing controls in place?	**Risk Assessment** (use the Risk Matrix on p3) Consequence x Probability = Risk Level			**Additional controls:** Enter additional controls if required to reduce the risk level	**Risk assessment with additional controls** (use the Risk Matrix on p3 – has the consequence or probability changed?)			**Controls Implemented ? Yes/No**
		Consequences	**Probability**	**Risk Level**		**Consequences**	**Probability**	**Risk Level**	
Example									
Working in temperatures over 35^0 C	Heat stress/heat stroke/exhaustion leading to serious personal injury/death	catastrophic	possible	Mod	Regular breaks, chilled water available, loose clothing, temporary shade shelters, essential tasks only, close supervision, buddy system	catastrophic	unlikely	Low	Yes
Typing on computer	Repetitive Strain Injury from continuous use	Minor	Possible	Moderate	-Warm up hands before beginning using small hand movements. - Take breaks every 30-60mins to stretch out hands.	Minor	Unlikely	Low	Yes
Looking at computer screen	Eye dryness, Headaches, Neck Injury and Back Injury	Minor	Likely	High	- Take breaks from the screen every 30-60 minutes. - Ensure adequate amounts of blinking occur. - Ensure screen is at ideal distance and angle.	Minor	Possible	Moderate	Yes

Step 1 (cont)	**Step 2**	**Step 3**			**Step 4**				
Hazards: From step 1 or more if identified	**The Risk:** What can happen if exposed to the hazard with existing controls in place?	**Risk Assessment** (use the Risk Matrix on p3) Consequence x Probability = Risk Level			**Additional controls:** Enter additional controls if required to reduce the risk level	**Risk assessment with additional controls** (use the Risk Matrix on p3 – has the consequence or probability changed?)			**Controls Implemented?** Yes/No
		Consequences	**Probability**	**Risk Level**		**Consequences**	**Probability**	**Risk Level**	
Example									
Working in temperatures over 35^0 C	Heat stress/heat stroke/exhaustion leading to serious personal injury/death	catastrophic	possible	Mod	Regular breaks, chilled water available, loose clothing, temporary shade shelters, essential tasks only, close supervision, buddy system	catastrophic	unlikely	Low	Yes
					- Sit at a computer on a chair at correct height. - Sit with correct posture. - Take regular breaks to stretch out the body.				
Computer Lab Fire due to electrical malfunction	Serious Burns or Death	Catastrophic	Rare	Low	- Fire extinguishers within building. - Evacuation maps provided in all rooms - Fire wardens trained on evacuation procedure - Fire stairs available.	Major	Rare	Low	Yes

Step 1 (cont)	Step 2	Step 3			Step 4				
Hazards: From step 1 or more if identified	**The Risk:** What can happen if exposed to the hazard with existing controls in place?	**Risk Assessment** (use the Risk Matrix on p3) Consequence x Probability = Risk Level			**Additional controls:** Enter additional controls if required to reduce the risk level	**Risk assessment with additional controls** (use the Risk Matrix on p3 – has the consequence or probability changed?)			**Controls Implemented?** Yes/No
		Consequences	**Probability**	**Risk Level**		**Consequences**	**Probability**	**Risk Level**	
Example									
Working in temperatures over 35^{0} C	Heat stress/heat stroke/exhaustion leading to serious personal injury/death	catastrophic	possible	Mod	Regular breaks, chilled water available, loose clothing, temporary shade shelters, essential tasks only, close supervision, buddy system	catastrophic	unlikely	Low	Yes
Loss of data	Stress	Insignificant	Possible	Low	-Keep multiple copies of data and dissertation over multiple forms.	Insignificant	Unlikely	Low	Yes
		Select a consequence	Select a probability	Select a Risk Level		Select a consequence	Select a probability	Select a Risk Level	Yes or No

Step 5 – Action Plan (for controls not already in place)

Control Option	Resources	Person(s) responsible	Proposed implementation date

Step 6 – Approval

Drafter's Comments:

Drafter Details:

Name: Signature: Date: / /

Assessment Approval: (Extreme or High = VC, Moderate = Cat 4 delegate or above, Low = Manager/Supervisor)

I am satisfied that the risks are as low as reasonably practicable and that the resources required will be provided.

Name: Signature: Date: / /

Position Title:

Appendix D - LiDAR Report for: Toowoomba Regional Council 2010 LiDAR Capture Project

SCHLENCKER MAPPING PTY LTD

LiDAR Report for:

TOOWOOMBA REGIONAL COUNCIL

Toowoomba Regional Council
2010 LiDAR Capture Project

BRIEF:

Schlencker Mapping undertook data acquisition using Airborne Laser Scanning (ALS) techniques over a large portion of the Toowoomba Regional Council LGA area. In total more than 2760 square kilometers of data was collected.

ACQUISITION:

Data collection was undertaken using a fixed wing aircraft using the Optech "ALTM Gemini" ALS scanner. On board GPS and IMU systems were supplemented with ground GPS base stations running at all times during flight.

BASE STATIONS:

The airborne survey position was computed from the onboard Applanix dual frequency GPS receiver along with ground base stations and supplemented by corrections from the Applanix IMU. Base stations used were the D.E.R.M. Toowoomba Permanent Base (PM753327) and Toowoomba Regional Council Permanent Base.

GROUND CONTROL:

Ground control points were used as check points against the remotely sensed data. These points were measured using Rapid Static GPS methodologies and consisted of 302 locations throughout the project areas. Control around the urban area of Toowoomba was provided by Toowoomba Regional Council.

The residuals measured on the ground control when compared against the LiDAR surface were as follows:

Toowoomba (179 points)
Average dz 0.021
Average magnitude 0.073
Root mean square 0.101
Std deviation 0.099

Toowoomba South (12 points)
Average dz +0.017
Average magnitude 0.027
Root mean square 0.034
Std deviation 0.032

Oakey (19 points)
Average dz +0.012
Average magnitude 0.035
Root mean square 0.043
Std deviation 0.042

Dam Break Area (14 points)
Average dz 0.034
Average magnitude 0.052
Root mean square 0.065
Std deviation 0.058

Pipeline (6 points)
Average dz 0.031
Average magnitude 0.078
Root mean square 0.091
Std deviation 0.093

Haden (5 points)
Average dz +0.032
Average magnitude 0.041
Root mean square 0.051
Std deviation 0.043

Clifton (7 points)
Average dz -0.005
Average magnitude 0.051
Root mean square 0.060
Std deviation 0.065

Yarraman (6 points)
Average dz +0.028
Average magnitude 0.050
Root mean square 0.053
Std deviation 0.049

Cooyar (5 points)
Average dz +0.000
Average magnitude 0.034
Root mean square 0.039
Std deviation 0.044

Quinlow & Peranga (12 points)
Average dz -0.001
Average magnitude 0.073
Root mean square 0.081
Std deviation 0.084

Pittsworth (15 points)
Average dz +0.004
Average magnitude 0.056
Root mean square 0.068
Std deviation 0.070

Cecil Plains (8 points)
Average dz +0.004
Average magnitude 0.054
Root mean square 0.067
Std deviation 0.072

Tummaville (5 points)
Average dz +0.007
Average magnitude 0.021
Root mean square 0.033
Std deviation 0.036

Millmerran (8 points)
Average dz +0.009
Average magnitude 0.052
Root mean square 0.062
Std deviation 0.066

DATA SUPPLIED:

The following datasets have been supplied as part of the project:

- Ground Points in XYZ(Flight Line) format
- Non-Ground Points in XYZ(Flight Line) format
- 1m DTM in XYZ format
- 1m DTM in ASCII Grid format
- 0.25m Contours in SHP format
- All returns in LAS format

Data has been provided on a square 1km x 1km tile grid.

File naming conventions are based on the South-West corner of the tile and this is shown at the start of each file name. An example of naming for a tile of the 1m DTM is below:

394000_6955000_1k_1m_DEM.xyz - where 394000,6955000 is the South-West corner coordinate of the tile.

REFERENCE DATUM:

The horizontal datum for the project is Geodetic Datum Australia (GDA) and the projection Map Grid Australia (MGA) 1994, Zone 56. The vertical datum is the Australian Height Datum (AHD) based on the ground base stations.

LIDAR METADATA:

Acquisition Start Date	29th June 2010
Acquisition End Date	16th July 3010
Device Name	Optech 'ALTM Gemini'
IMU	Applanix 'Litton 510'
Flying Height (AGL)	1200m
No. of Runs	242
Swath Width	1000m
Side Overlap	30 %
Horizontal Datum	GDA94
Vertical Datum	AHD
Map Projection	MGA Zone56
Control	302 surveyed GPS control points
Vertical Accuracy	± 0.15m @ 1σ
Horizontal Accuracy	± 0.22m @ 1σ
Surface Type	Ground and DTM
Average Point Separation	1.0m
Laser Return Types	1^{st} through to 4^{th}

DATA VALIDATION:

As LiDAR scanning is a predominately a remote process, data validation is required to confirm the captured data. This is accomplished by comparing field survey data to the remotely sensed data.

Field survey for data validation was undertaken using Trimble R8 GNSS GPS receivers, using continuous topo recording mode with measurements at 50 meter intervals, along gravel and bitumen roads, using a car mounted receiver. During measurement some difficulties were experienced, including loss of lock due to terrain or vegetation, and this may cause some erroneous measurements in the RTK operation, and not necessarily in the laser scanned ground data.

Measurement was made from separate PSM's in each area that had been used to establish the ground control:

At each PSM, the set up was confirmed by check measurements to other existing PSM's as well as ground control targets established for the project and additional points measured by RTK methods that would be suitable for checking using the mobile RTK system.

At each of the check areas the following kilometers of road were measured:

Cecil Plains	8.7 kilometers	261 points
Clifton	20.1 kilometers	568 points
Crows Nest	10.8 kilometers	321 points
Esk	13.5 kilometers	361 points
Goombungee	16.0 kilometers	540 points
Gowrie	14.4 kilometers	458 points
Highfields	10.7 kilometers	300 points
MacLagen	14.3 kilometers	383 points
Millmerran	12.2 kilometers	355 points
Oakey	20.6 kilometers	730 points
Pittsworth	14.8 kilometers	466 points
Toogoolawah	26.3 kilometers	813 points
Toowoomba	21.2 kilometers	457 points
Yarraman	13.7 kilometers	319 points

By measuring along roads, a variety of areas can be verified as well as obtaining validation across different scanning swaths. This is a more effective validation than the traditional method of measuring a lot of points in a restricted area such as a sports field.

A total of 218 kilometers of roads were measured recording 6332 points to an accuracy of +/- .05 meters.

The areas and PSM's used as bases for the validation measurement and the results obtained were as follows:

Cecil Plains From PSM 70770
8 kilometers of roads
261 points
Average magnitude: .052
RMS: .070
Standard Deviation: .058
Points falling outside .15 meters: 13
Percentage within .15 meters: 95.0%

Clifton From PSM 46598
8 kilometers of roads
568 points
Average magnitude: .036
RMS: .046
Standard Deviation: .045
Points falling outside .15 meters: 1
Percentage within .15 meters: 99.8%

Crows Nest From PSM 42419
8 kilometers of roads
321 points
Average magnitude: .067
RMS: .091
Standard Deviation: .089
Points falling outside .15 meters: 32
Percentage within .15 meters: 90.0%

Esk From PSM 32719
35 kilometers of roads
361 points
Average magnitude: .096
RMS: .110
Standard Deviation: .100
Points falling outside .15 meters: 61
Percentage within .15 meters: 83.1%

Goombungee From PSM 70731
22 kilometers of roads
540 points
Average magnitude: .071
RMS: .085
Standard Deviation: .059
Points falling outside .15 meters: 34
Percentage within .15 meters: 93.7%

Gowrie From PSM 4059
20 kilometers of roads
458 points
Average magnitude: .064
RMS: .081
Standard Deviation: .069
Points falling outside .15 meters: 32
Percentage within .15 meters: 93.0%

Highfields From PSM 44129
36 kilometers of roads
300 points
Average magnitude: .082
RMS: .094
Standard Deviation: .050
Points falling outside .15 meters: 16
Percentage within .15 meters: 94.7%

MacLagen From PSM 44037
7 kilometers of roads
383 points
Average magnitude: .046
RMS: .063
Standard Deviation: .063
Points falling outside .15 meters: 15
Percentage within .15 meters: 96.0%

Millmerran From PSM 111709
13 kilometers of roads
355 points
Average magnitude: .036
RMS: .048
Standard Deviation: .048
Points falling outside .15 meters: 2
Percentage within .15 meters: 99.4%

Oakey From PSM 114608
13 kilometers of roads
730 points
Average magnitude: .078
RMS: .091
Standard Deviation: .080
Points falling outside .15 meters: 50
Percentage within .15 meters: 93.2%

Pittsworth From PSM 71157
13 kilometers of roads
466 points
Average magnitude: .049
RMS: .062
Standard Deviation: .052
Points falling outside .15 meters: 4
Percentage within .15 meters: 99.1%

Toogoolawah From PSM 1808
13 kilometers of roads
813 points
Average magnitude: .071
RMS: .087
Standard Deviation: .069
Points falling outside .15 meters: 50
Percentage within .15 meters: 93.8%

Toowoomba From PSM 5337
13 kilometers of roads
457 points
Average magnitude: .076
RMS: .100
Standard Deviation: .083
Points falling outside .15 meters: 55
Percentage within .15 meters: 87.9%

Yarraman From PSM 80996
13 kilometers of roads
319 points
Average magnitude: .057
RMS: .073
Standard Deviation: .058
Points falling outside .15 meters: 7
Percentage within .15 meters: 97.8%

Overall, on the total area verified, the accuracy achieved was over 94% of points within .15 meters, well within the accuracy specifications for the project.

Appendix E - West Creek Photos

Toowoomba is a city that is growing and as a result is constantly expanding to fit more people. Due to this the natural waterways and catchments within the city are being heavily affected by urbanisation. West Creek is one of these affected waterways, containing many different manmade features. Some of these features can be seen below in the following figures. Please note that the pictures within the following figures were taken in August 2014 and may not be a 100 % true representation of what the creek was like in January 2011. The photos are simply being used as a tool to highlight the effects of urbanisation on the waterway and not as an analysis tool.

Figure 33: A detention basin located along West Creek in between Spring Street and Stenner Street taken in August 2014.

Figure 34: A major power line running along West Creek with the power pole situated directly next to the creek taken in August 2014.

Figure 35: Concrete footpaths built along West Creek for recreational use affecting the natural flow of the creek taken in August 2014.

Figure 36: A toilet block built within the catchment of West Creek used for recreational purposes taken in August 2014.

Figure 37: A public shade structure and barbeque built next to West Creek near Stenner Street taken in August 2014.

Figure 38: Housing built approximately 30 metres from West Creek affecting the natural flow of the water into the catchment and in danger of flooding from the creek taken in August 2014.

Figure 39: The piped drainage system used under the Spring Street road crossing funnelling the water in and out again taken in August 2014.

Figure 40: An example of the types of tress situated along West Creek taken in August 2014.

Figure 41: An example of some of the shrubbery along West Creek taken in August 2014.

Appendix F - Arc Hydro Maps

The Arc Hydro analysis required multiple steps. The step which had an effect on the stream and catchment output was the threshold. As the threshold was increased the density of the streams were reduced and the catchment made slight changes in its shape and size. The following figures contain the maps generated from the 2 m DEM.

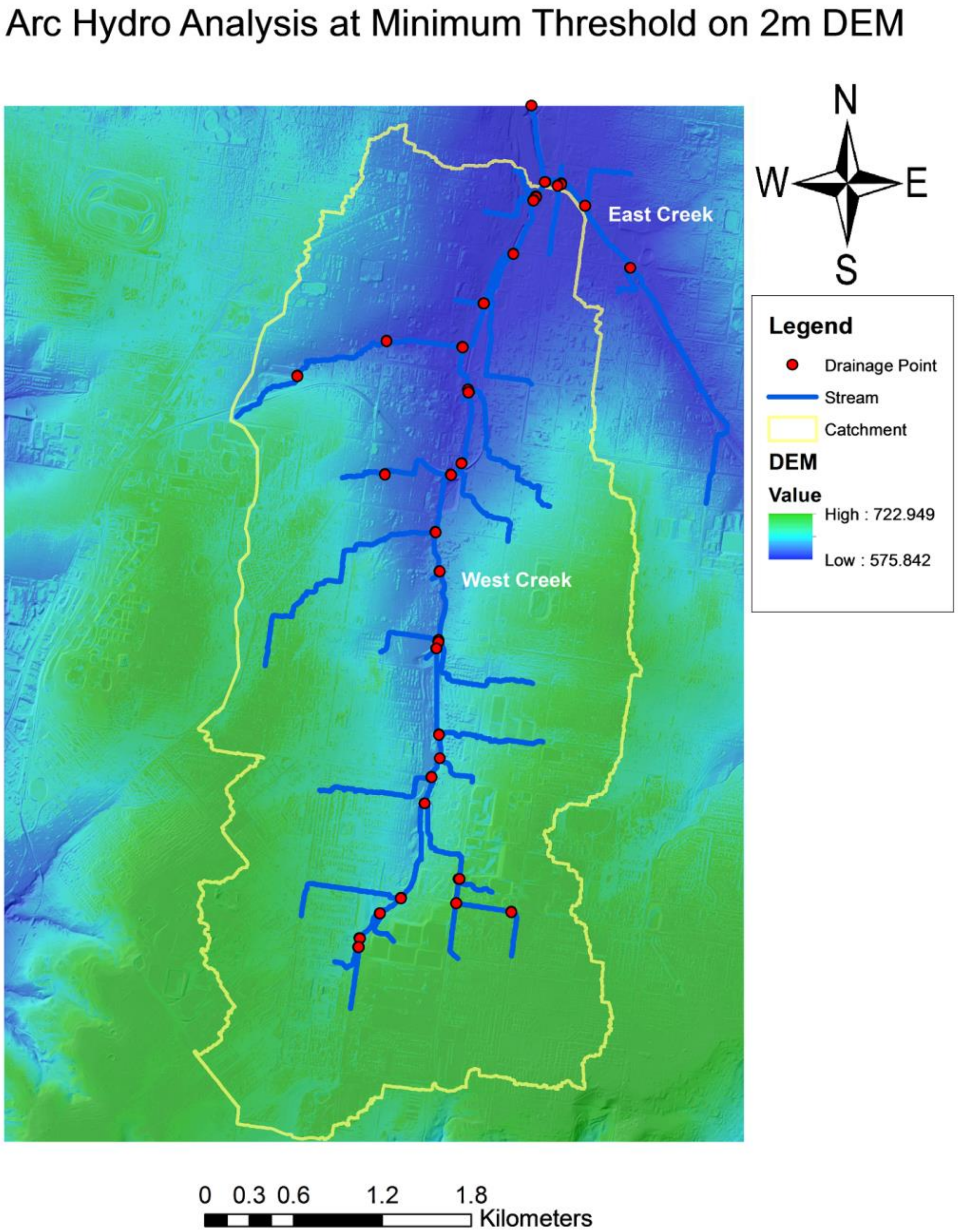


Figure 42: The results of the Arc Hydro analysis on the 2 m DEM showing the stream, catchment and drainage points utilising the minimum threshold.

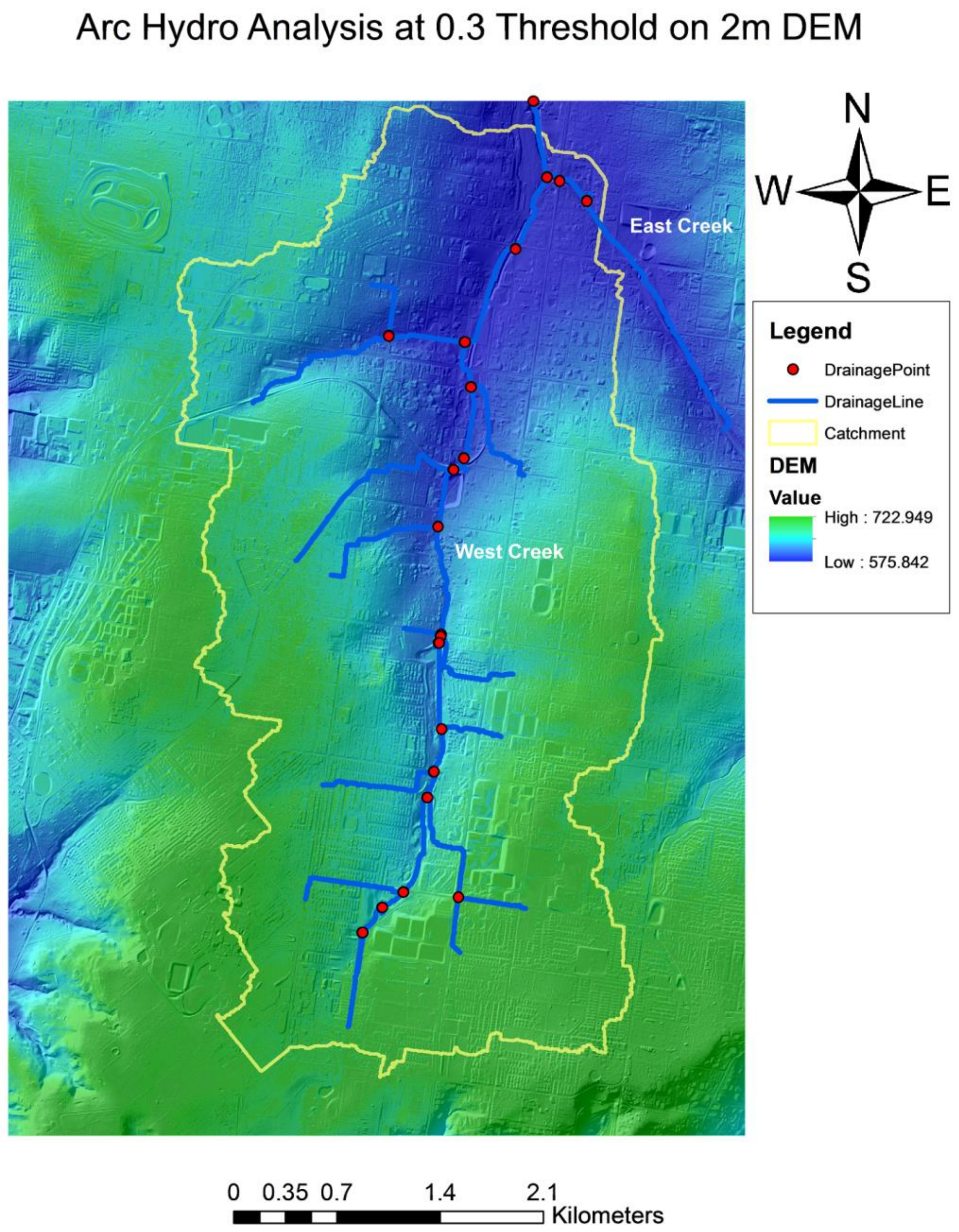


Figure 43: The results of the Arc Hydro analysis on the 2 m DEM showing the stream, catchment and drainage points utilising a threshold of 0.3.

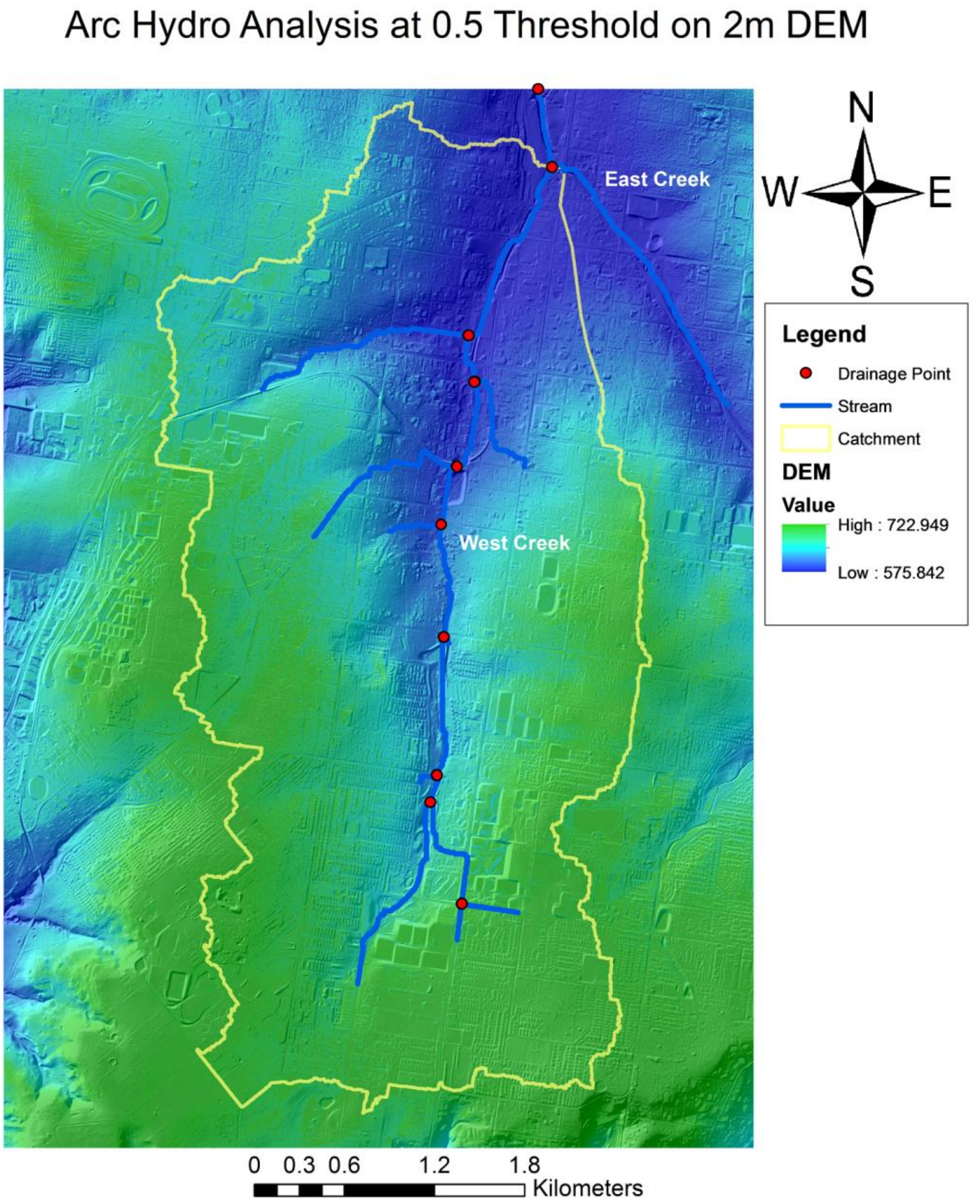


Figure 44: The results of the Arc Hydro analysis on the 2 m DEM showing the stream, catchment and drainage points utilising a threshold of 0.5.

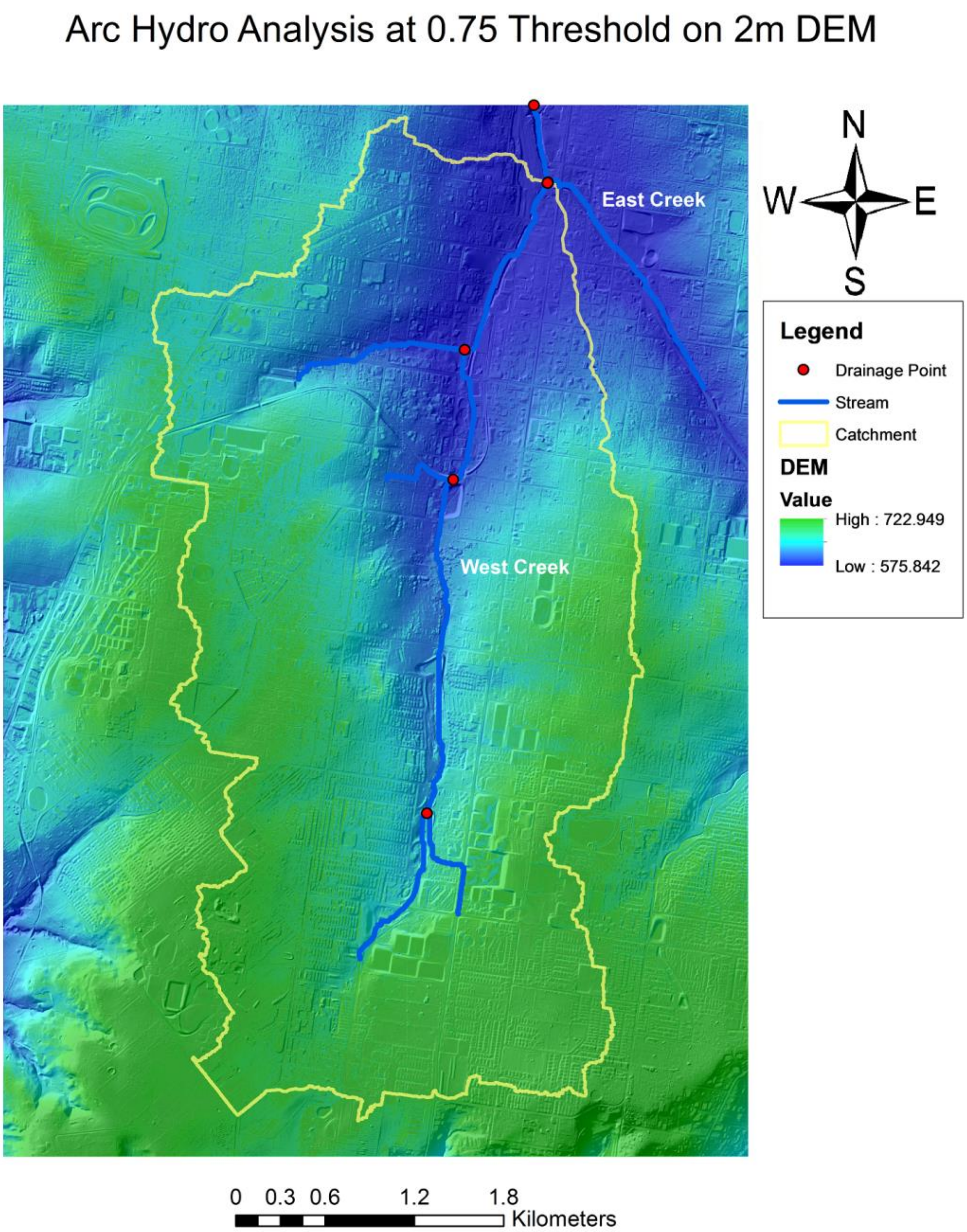


Figure 45: The results of the Arc Hydro analysis on the 2 m DEM showing the stream, catchment and drainage points utilising a threshold of 0.75.

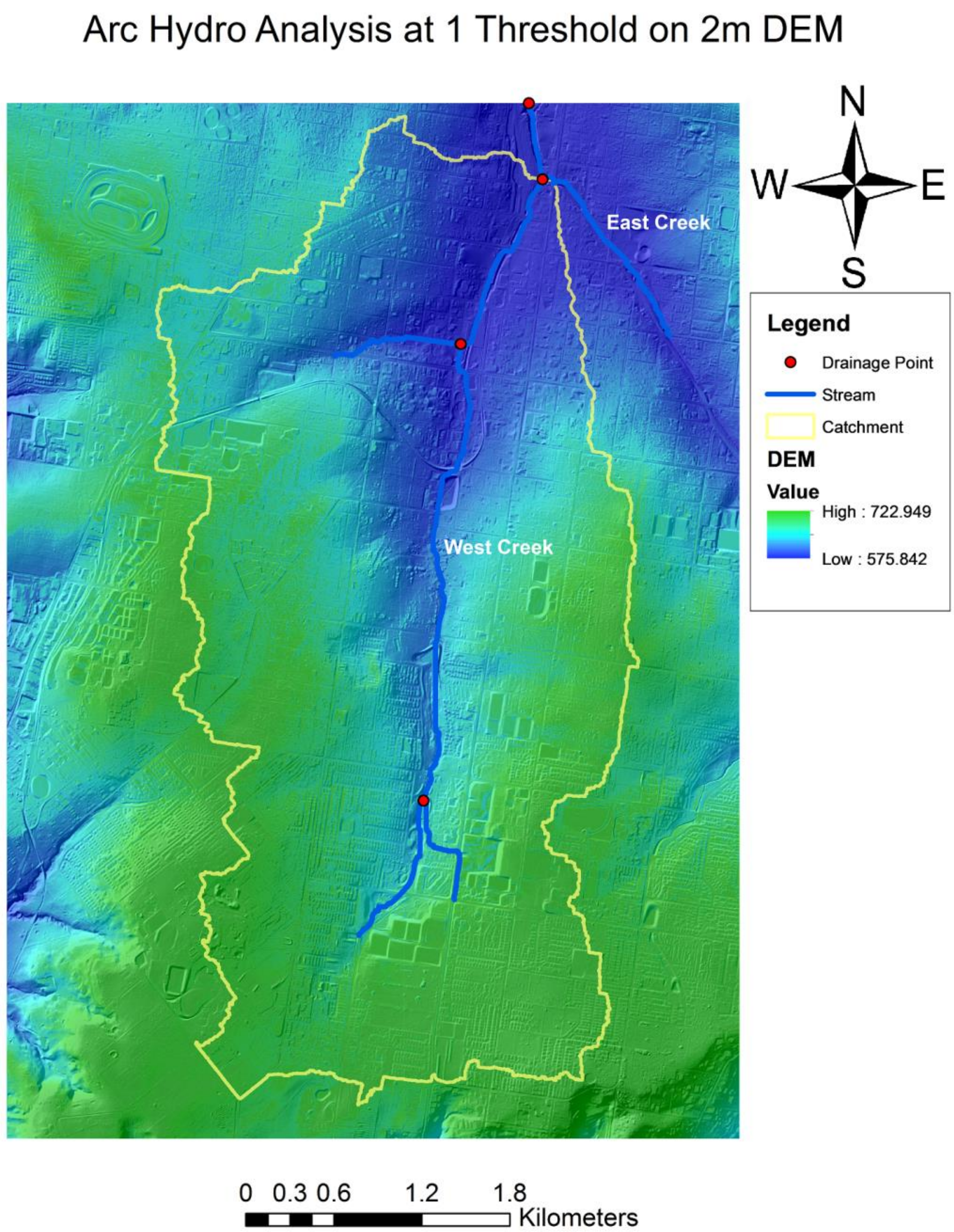


Figure 46: The results of the Arc Hydro analysis on the 2 m DEM showing the stream, catchment and drainage points utilising a threshold of 1.

The same process was followed with the 5 m DEM. The same thresholds were inputted on a DEM with a lower resolution to see the differences in the representation of the streams and catchment. The maps from this analysis can be seen in the following figures.

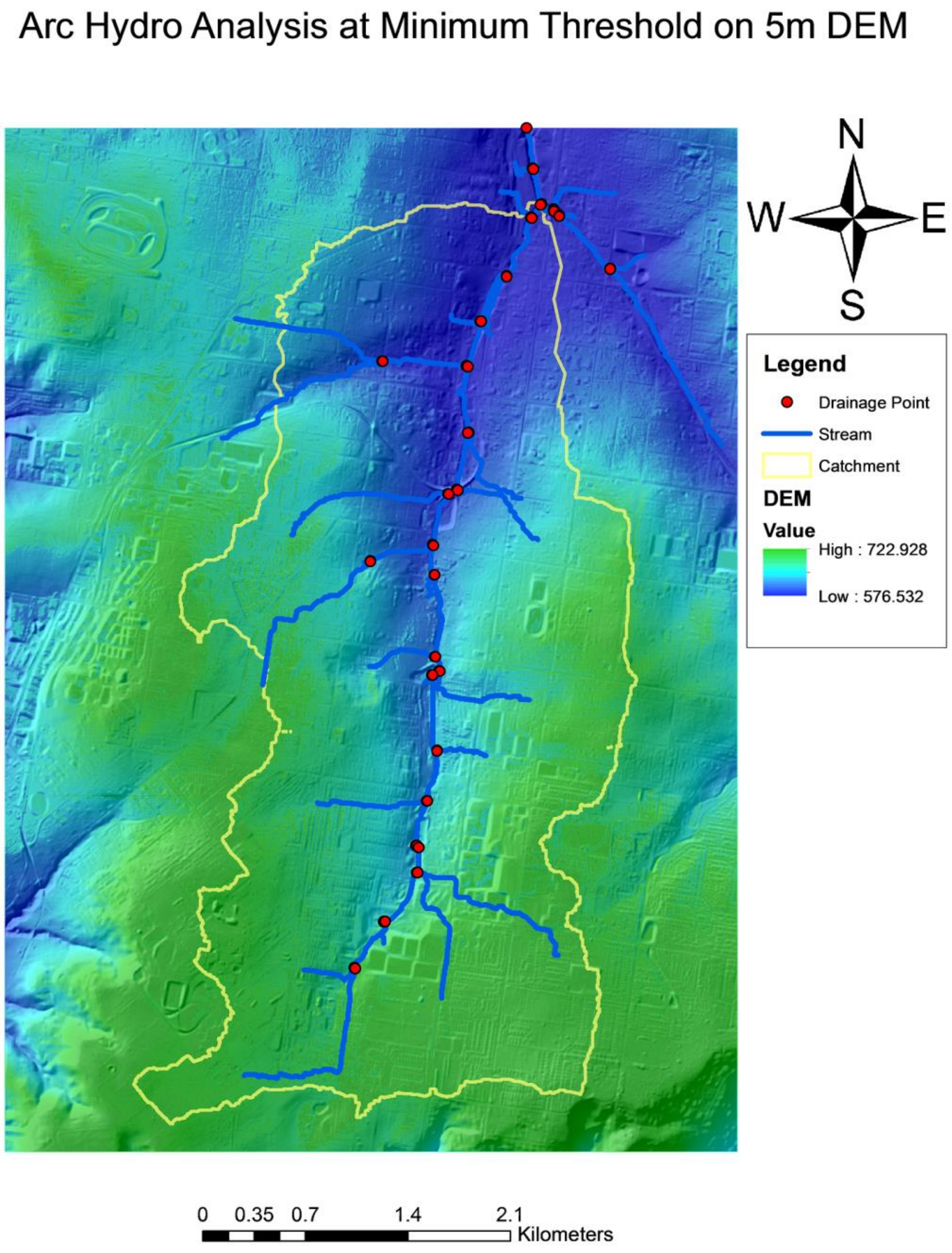


Figure 47: The results of the Arc Hydro analysis on the 5 m DEM showing the stream, catchment and drainage points utilising the minimum threshold.

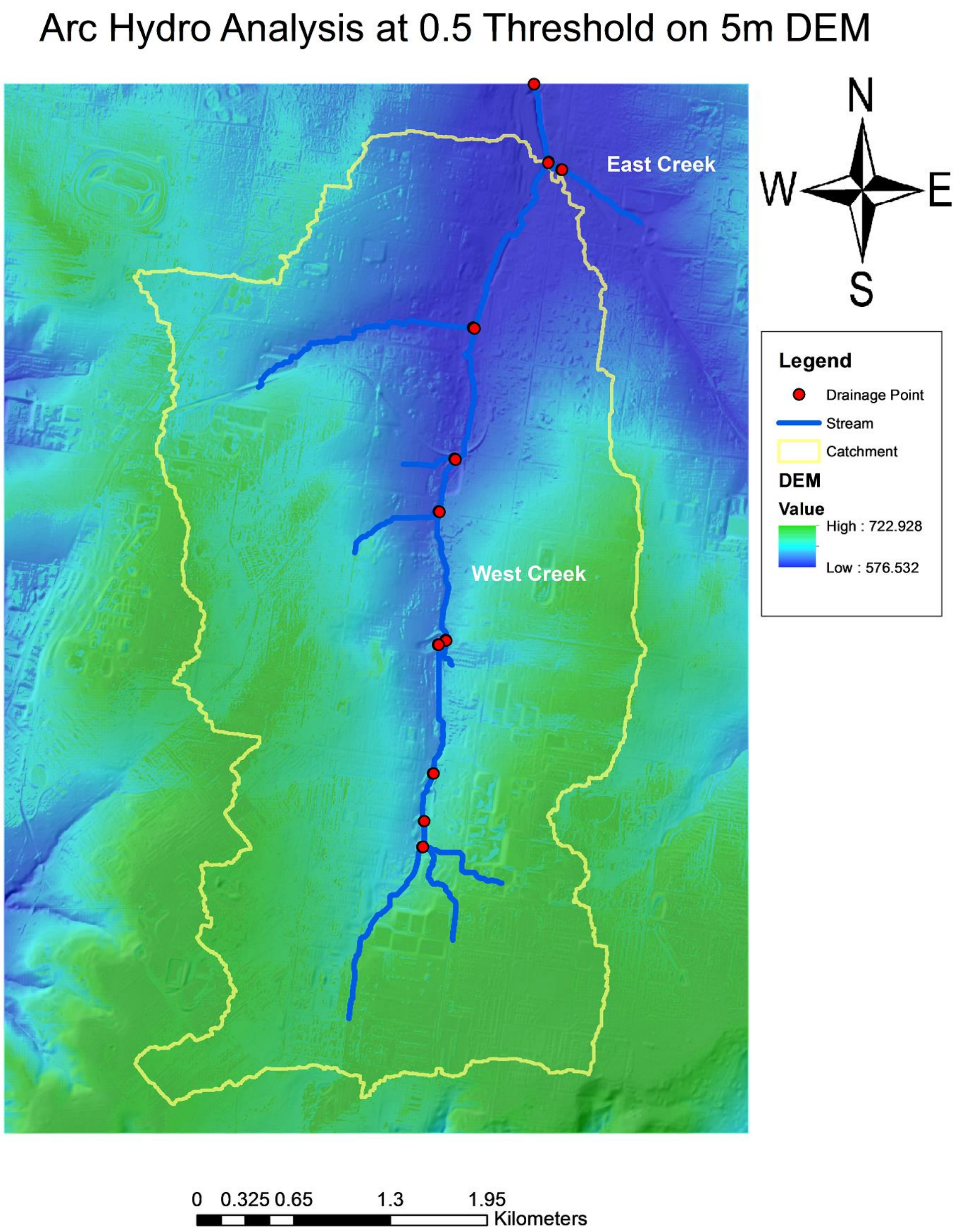


Figure 48: The results of the Arc Hydro analysis on the 5 m DEM showing the stream, catchment and drainage points utilising a threshold of 0.5.

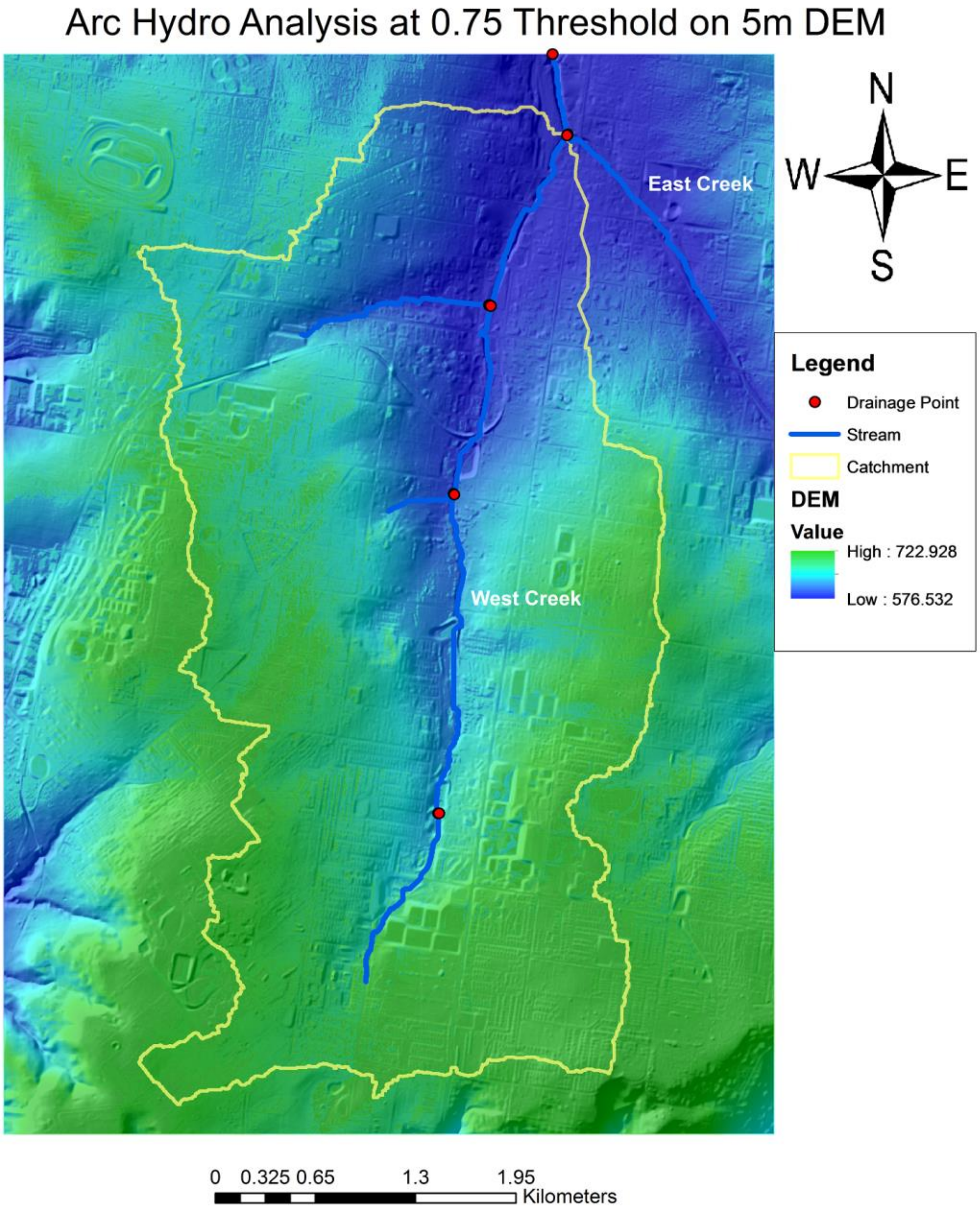


Figure 49: The results of the Arc Hydro analysis on the 5 m DEM showing the stream, catchment and drainage points utilising a threshold of 0.75.

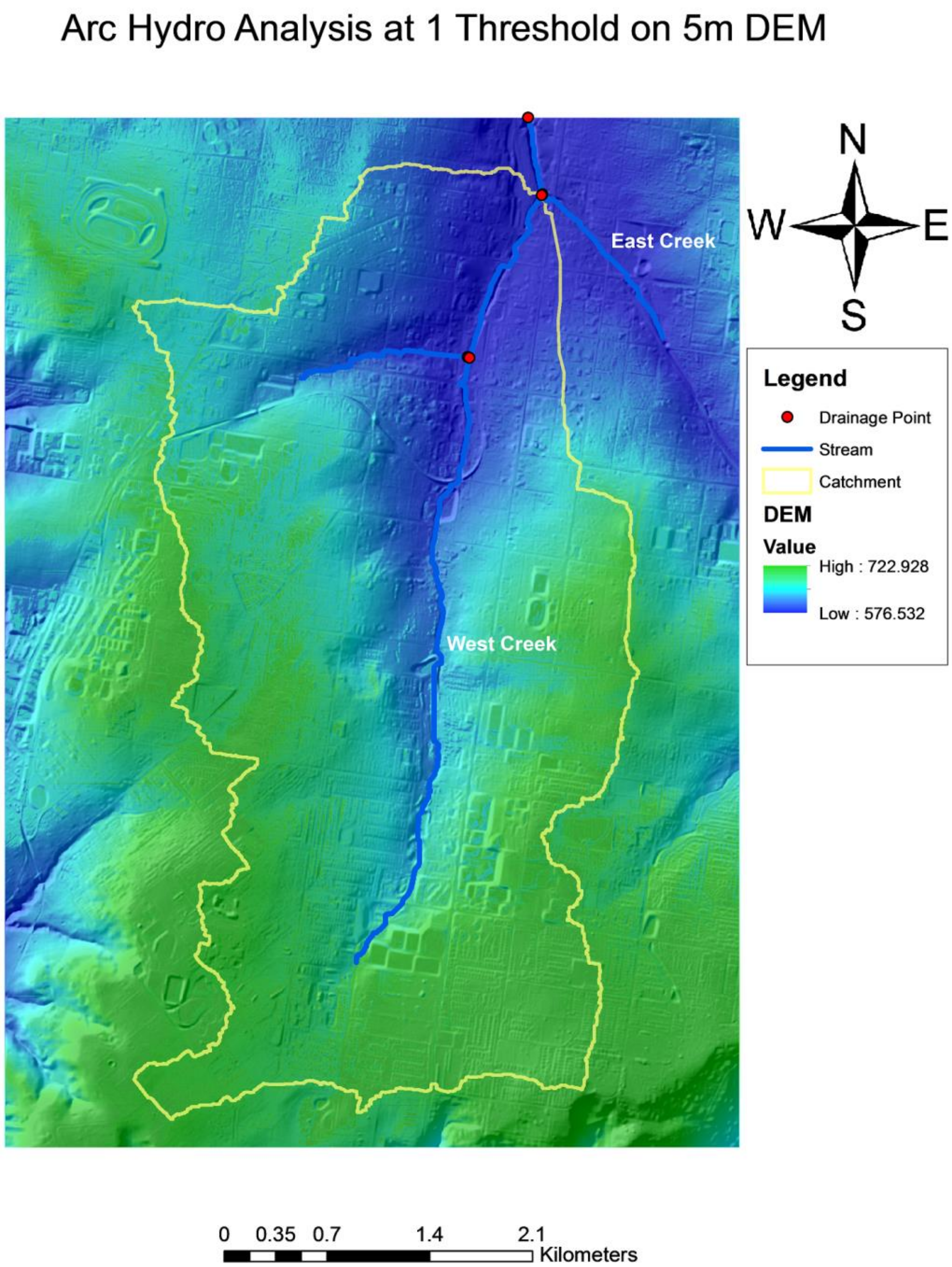


Figure 50: The results of the Arc Hydro analysis on the 5 m DEM showing the stream, catchment and drainage points utilising a threshold of 1.

Appendix G - Hydrological Modelling Information and Outputs

The hydrological modelling process involved the creation of a treatment train representing West Creek. As a result there were several inputs including sub catchments, conduits, rain gages and junctions. The extra information utilised within the creation of the treatment train is presented in the following figures. The simulation also resulted in many outputs regarding the behaviour of the rainfall. The extra results are also presented in the following figures.

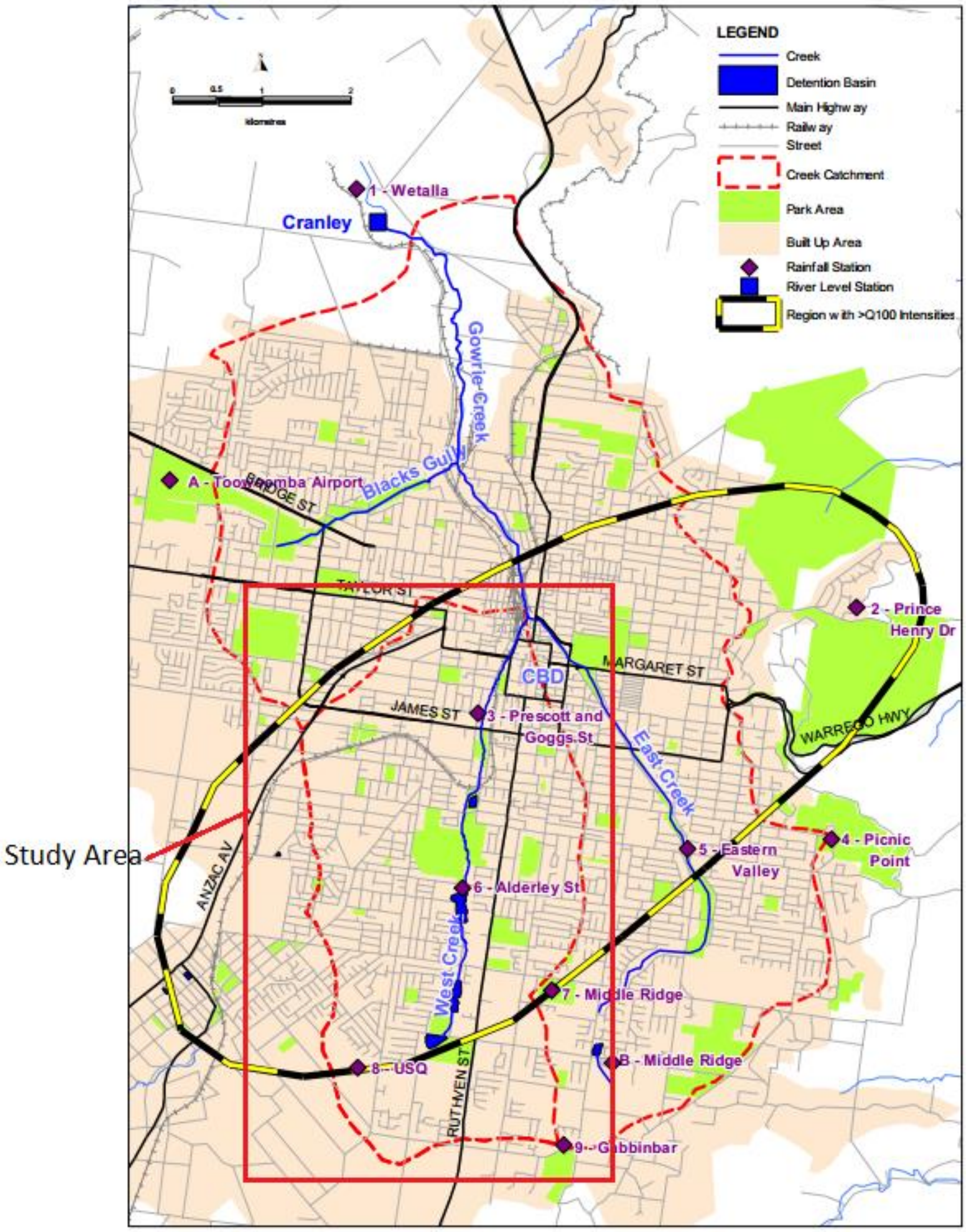


Figure 51: The Gowrie creek catchment showing the area which was affected by rainfall categorised at Q>100 intensity and the location of the rain gages (ICA, 2011).

Alderley Rainfall - Notepad

Alderley	2011	1	10	12	0	0
Alderley	2011	1	10	12	15	2
Alderley	2011	1	10	12	30	1
Alderley	2011	1	10	12	45	2
Alderley	2011	1	10	13	0	4
Alderley	2011	1	10	13	15	7
Alderley	2011	1	10	13	30	12
Alderley	2011	1	10	13	45	22
Alderley	2011	1	10	14	0	30
Alderley	2011	1	10	14	15	7

Gabbinhar Rainfall - Notepad

Gabbinhar	2011	1	10	12	0	1
Gabbinhar	2011	1	10	12	15	2
Gabbinhar	2011	1	10	12	30	1
Gabbinhar	2011	1	10	12	45	2
Gabbinhar	2011	1	10	13	0	3
Gabbinhar	2011	1	10	13	15	7
Gabbinhar	2011	1	10	13	30	11
Gabbinhar	2011	1	10	13	45	17
Gabbinhar	2011	1	10	14	0	14
Gabbinhar	2011	1	10	14	15	9

Middle Ridge 1 Rainfall - Notepad

Middle1	2011	1	10	12	0	1
Middle1	2011	1	10	12	15	2
Middle1	2011	1	10	12	30	1
Middle1	2011	1	10	12	45	4
Middle1	2011	1	10	13	0	8
Middle1	2011	1	10	13	15	6
Middle1	2011	1	10	13	30	17
Middle1	2011	1	10	13	45	32
Middle1	2011	1	10	14	0	21
Middle1	2011	1	10	14	15	5

Middle Ridge Rainfall - Notepad

Middle2	2011	1	10	12	0	1
Middle2	2011	1	10	12	15	2
Middle2	2011	1	10	12	30	1
Middle2	2011	1	10	12	45	4
Middle2	2011	1	10	13	0	8
Middle2	2011	1	10	13	15	6
Middle2	2011	1	10	13	30	17
Middle2	2011	1	10	13	45	32
Middle2	2011	1	10	14	0	21
Middle2	2011	1	10	14	15	5

Prescott Rainfall - Notepad

Prescott	2011	1	10	12	0	0
Prescott	2011	1	10	12	15	1
Prescott	2011	1	10	12	30	1
Prescott	2011	1	10	12	45	7
Prescott	2011	1	10	13	0	6
Prescott	2011	1	10	13	15	14
Prescott	2011	1	10	13	30	23
Prescott	2011	1	10	13	45	25
Prescott	2011	1	10	14	0	19
Prescott	2011	1	10	14	15	7

Figure 52: The rain gage files utilised within the hydrological model showing the amount of rainfall every 15 minutes.

Subcatchment S2

Property	Value
Name	S2
X-Coordinate	5749.819
Y-Coordinate	5489.516
Description	
Tag	
Rain Gage	Alderley
Outlet	SU8
Area	734.538
Width	100
% Slope	1.46
% Imperv	50

Subcatchment S3

Property	Value
Name	S3
X-Coordinate	3859.622
Y-Coordinate	2394.381
Description	
Tag	
Rain Gage	USQ
Outlet	SU6
Area	499.151
Width	100
% Slope	1.46
% Imperv	50

Subcatchment S4

Property	Value
Name	S4
X-Coordinate	6726.681
Y-Coordinate	3245.119
Description	
Tag	
Rain Gage	Middle1
Outlet	StennerSt
Area	201.170
Width	50
% Slope	1.46
% Imperv	50

Subcatchment S5

Property	Value
Name	S5
X-Coordinate	6655.821
Y-Coordinate	2093.275
Description	
Tag	
Rain Gage	Middle2
Outlet	SU7
Area	135.043
Width	50
% Slope	1.46
% Imperv	50

Subcatchment S6

Property	Value
Name	S6
X-Coordinate	5993.182
Y-Coordinate	951.348
Description	
Tag	
Rain Gage	Gabbinhar
Outlet	SU6
Area	185.395
Width	50
% Slope	1.46
% Imperv	50

Figure 53: The parameters utilised in each of the sub catchments within the hydrological model.

```
EPA STORM WATER MANAGEMENT MODEL - VERSION 5.1 (Build 5.1.006)
--------------------------------------------------------------

WARNING 02: maximum depth increased for Node SpringSt
WARNING 02: maximum depth increased for Node StennerSt
WARNING 02: maximum depth increased for Node AlderleySt
WARNING 02: maximum depth increased for Node JamesSt
WARNING 02: maximum depth increased for Node SouthSt
WARNING 02: maximum depth increased for Node HerriesSt
WARNING 02: maximum depth increased for Node MargaretSt
WARNING 02: maximum depth increased for Node RusselSt

*********************************************************
NOTE: The summary statistics displayed in this report are
based on results found at every computational time step,
not just on results from each reporting time step.
*********************************************************

****************
Analysis Options
****************
Flow Units ............... CMS
Process Models:
  Rainfall/Runoff ........ YES
  RDII ................... NO
  Snowmelt ............... NO
  Groundwater ............ NO
  Flow Routing ........... YES
  Ponding Allowed ........ NO
  Water Quality .......... NO
Infiltration Method ...... HORTON
Flow Routing Method ...... KINWAVE
Starting Date ............ JAN-10-2011 12:00:00
Ending Date .............. JAN-10-2011 14:15:00
Antecedent Dry Days ...... 0.0
Report Time Step ......... 00:15:00
Wet Time Step ............ 00:05:00
Dry Time Step ............ 01:00:00
Routing Time Step ........ 60.00 sec


*********************
Rainfall File Summary
*********************
Station    First        Last         Recording   Periods    Periods    Periods
ID         Date         Date         Frequency  w/Precip    Missing    Malfunc.
-------------------------------------------------------------------------------
USQ        JAN-10-2011  JAN-10-2011     15 min        10          0          0
Alderley   JAN-10-2011  JAN-10-2011     15 min        10          0          0
Prescott   JAN-10-2011  JAN-10-2011     15 min        10          0          0
Middle1    JAN-10-2011  JAN-10-2011     15 min        10          0          0
Middle2    JAN-10-2011  JAN-10-2011     15 min        10          0          0
Gabbinhar  JAN-10-2011  JAN-10-2011     15 min        10          0          0


**************************        Volume         Depth
Runoff Quantity Continuity     hectare-m            mm
**************************     ---------       -------
Total Precipitation ......        51.492        21.589
Evaporation Loss .........         0.000         0.000
```

```
Infiltration Loss ........         1.962         0.823
Surface Runoff ...........         1.613         0.676
Final Surface Storage ....        48.054        20.148
Continuity Error (%) .....        -0.267


**************************        Volume        Volume
Flow Routing Continuity         hectare-m     10^6 ltr
**************************     ---------     ---------
Dry Weather Inflow .......         0.000         0.000
Wet Weather Inflow .......         1.265        12.648
Groundwater Inflow .......         0.000         0.000
RDII Inflow ..............         0.000         0.000
External Inflow ..........         0.000         0.000
External Outflow .........         0.672         6.722
Internal Outflow .........         0.000         0.000
Evaporation Loss .........         0.000         0.000
Seepage Loss .............         0.000         0.000
Initial Stored Volume ....         0.041         0.412
Final Stored Volume ......         0.598         5.977
Continuity Error (%) .....         2.770


********************************
Highest Flow Instability Indexes
********************************
Link C4 (85)
Link C6 (84)
Link C2 (79)
Link C7 (78)
Link C3 (75)


*************************
Routing Time Step Summary
*************************
Minimum Time Step           :     60.00 sec
Average Time Step           :     60.00 sec
Maximum Time Step           :     60.00 sec
Percent in Steady State     :      0.00
Average Iterations per Step :      1.40
Percent Not Converging      :      0.00


***************************
Analysis begun on:  Tue Oct 07 10:51:18 2014
Analysis ended on:  Tue Oct 07 10:51:18 2014
Total elapsed time: < 1 sec
```

Figure 54: The summary report generated by the software SWMM after running the simulation.

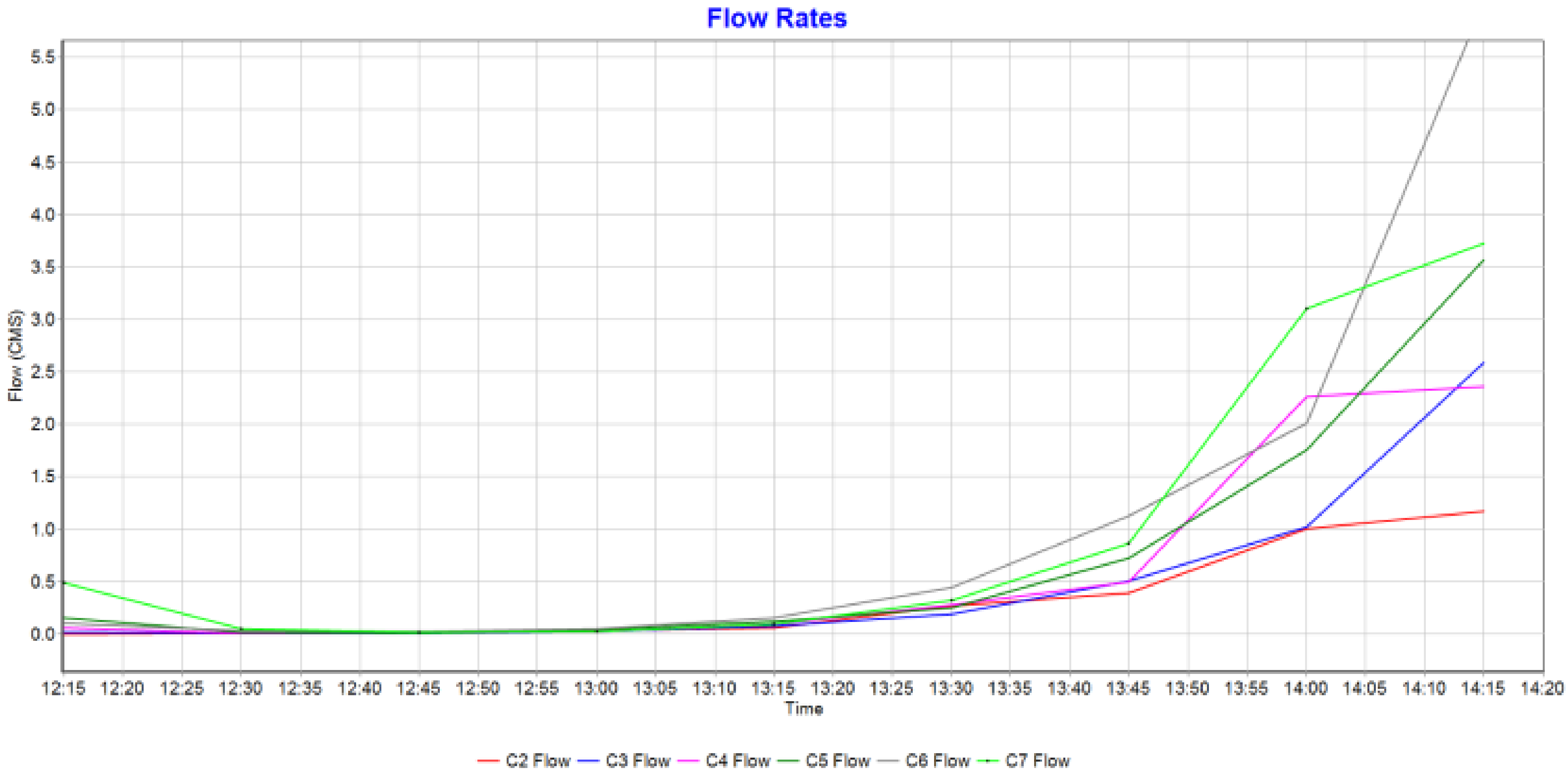


Figure 55: The flow rate of water in the first six conduits between the junctions of the model.

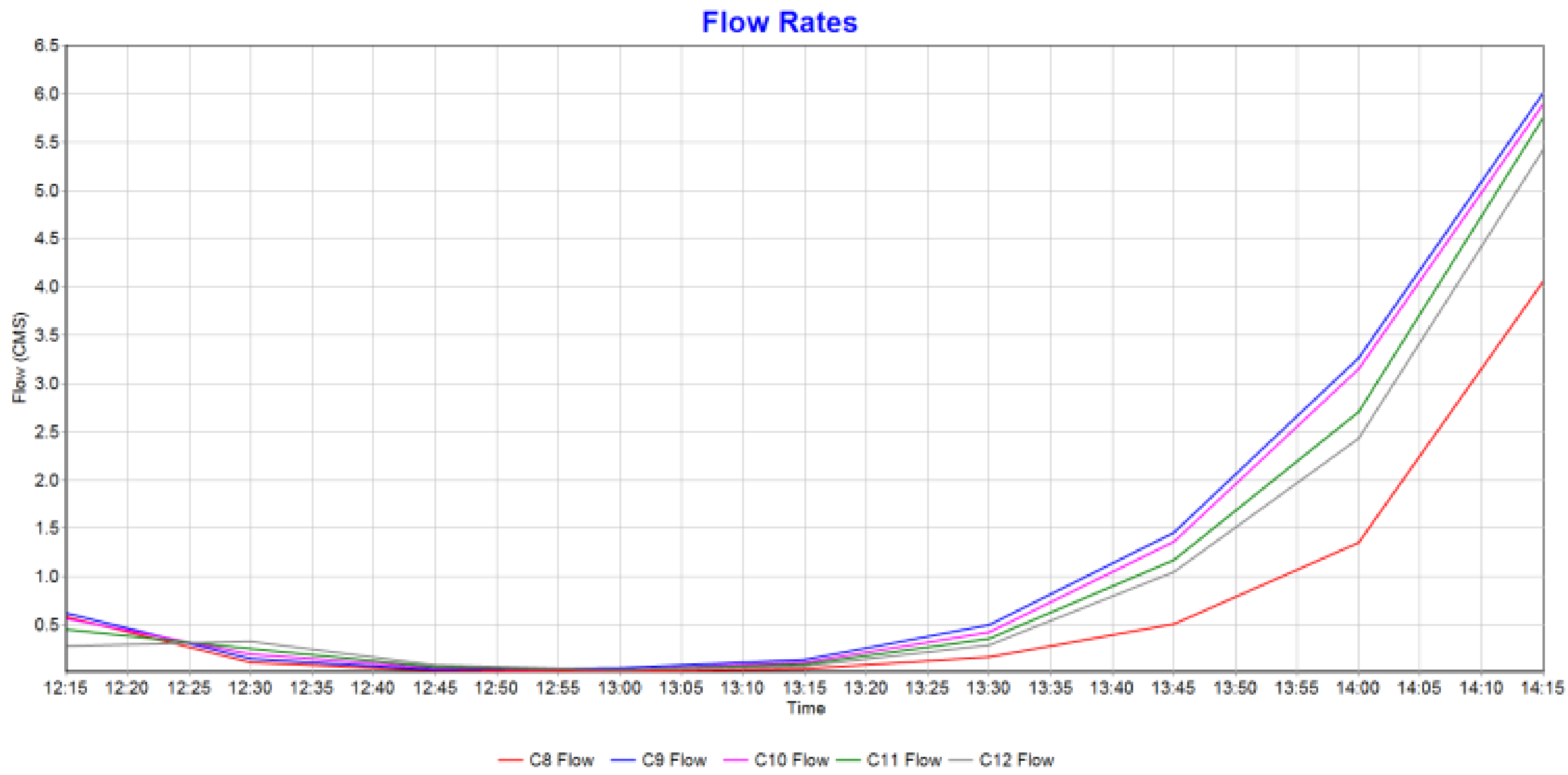


Figure 56: The flow rate of water in the last five conduits between the junctions of the model.