UNIVERSITY OF SOUTHERN QUEENSLAND

FACULTY OF HEALTH, ENGINEERING & SCIENCES

Comparison of direct rainfall and lumped-conceptual rainfall runoff routing methods in tropical North Queensland – a case study of Low Drain, Mount Low, Townsville.

A dissertation submitted by

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Abstract

As rain falls on a catchment, some of it will soak into the ground, some will be stored in small depressions, leaving the remainder to run along the surface as runoff. Flood modellers use a variety of software to analyse the way in which runoff behaves across a surface. Modelling has traditionally been undertaken in two components, hydrologic and hydraulic analysis. Hydrologic analysis enables the analyst to quantify the flow of water within a watercourse, by typically using lumped-conceptual runoff routing models. The hydraulic analysis uses the flow predictions of the hydrologic model to define the mechanisms of flow along watercourses and across floodplains. Within the last 10 years, 2D hydraulic modelling has become more popular with increasing flexibility, robustness and computational power. Its ability to apply rain directly to a 2D grid, known as the direct rainfall method (DRM), has provided for explicit modelling of catchments. Despite its popularity, there are differences between the models that are yet to be confirmed and explored by the industry.

Traditional lumped-conceptual models are broadly accepted in the industry due to their long history of use, and their successful calibration in a wider selection of gauged catchments. It is therefore unreasonable for one to assume that traditional lumped-conceptual approaches are being superseded by the DRM, despite it having increased popularity. Research is unfortunately limited for the popular growing DRM. Poor understanding of its intricacies have resulted in uncertainties toward its use. Parameters from traditional methods, such as rainfall losses, are being used to conceal uncertainties in the DRM. This project is important to the stormwater industry, as it provides practical value on the use of the DRM. Its findings extend on previous research by exploring the effects of catchment parameters, and also build on research, by investigating further effects for various storm durations.

A series of flood models were tested on a catchment, and three of its internal sub-catchments. The peak magnitude and timing of runoff results were compared between the DRM and lumped-conceptual models, being MIKE FLOOD and XP-RAFTS respectively. These analyses were explored over a range of storm duration events. Sensitivity testing of rainfall losses, catchment roughness, and wetting & drying, were undertaken so as to understand the effects of each of these parameters in the DRM.

Modelling and analysis were made possible through the use of both traditional and leading-edge engineering techniques, methods, and software tools. This project successfully highlights the components responsible for differences in catchment runoff behaviour between the DRM and lumped-conceptual model. The findings illustrate the effect storage has on reducing and attenuating runoff within the DRM, especially for short duration storm events, when compared to the lumped-conceptual model. These findings are unique, being the first known to be presented to this extent to the engineering industry. The sensitivity testing on the DRM complimented previous research, showing that lower rainfall losses, and roughness values, result in higher runoff.

Further investigations into the effect of storages, fraction impervious and slope, as well as many other components, are yet to be expanded by the industry.

This project contributes to the much needed insight into the DRM, when compared to lumped-conceptual models. The sensitivity analyses provide for practical awareness of

parameters, whilst the modelling over a variety of storm durations indicates major differences of runoff peaks and times when compared to lumped-conceptual models. It is unreasonable to say one method is superior to the other, as it is known that both methods have been successfully calibrated and verified to actual events. This project rather reveals the differences that modellers may encounter during use of the models, and justifies some of the reasons for them.

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14 October 2013

Date

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Contents

1.0 Introduction

This report chiefly outlines the background, objectives, methodologies, results and conclusions pertaining to the review of conventional lumped-conceptual runoff methods, and the more recent direct rainfall method. The review is centred on a case study of Low Drain, located in Townsville, North Queensland. The project aims to supplement previous research findings, as well as provide engineering guidance on the use of the direct rainfall method for various duration storm events.

1.1 Background – Hydrologic & Hydraulic Routing

Flood modelling has traditionally been undertaken in two components, hydrologic and hydraulic analysis. Hydrologic analysis 'enables the analyst to quantify the flow of water within a watercourse during any particular rainfall event' (Caddis et al. 2008, p. 1). The hydraulic analysis uses the flow predictions of the hydrologic model to 'define the mechanisms of flow along watercourses and across floodplains' (Caddis et al. 2008, p. 1).

There are numerous hydrologic models available to define the land phase of the hydrological cycle (Rehman 2011, p. 372). The most common and well established method of hydrologic analysis is performed using lumped runoff-routing models such as XP-RAFTS, RORB, and URBS. These models divide the catchment into a network of sub-catchments. They 'perform rainfall runoff routing by representing the catchment as one or more conceptual storages through which rainfall excess is routed' (Clark et al. 2008, p. 2497). In the early stages of the analysis the catchment is divided into sub-catchments, and values are given to each catchment variable as model inputs. Typically runoff hydrographs obtained from these models are input into hydraulic models, and routed through their domain. The lumped-conceptual approaches have been 'extensively verified and applied against gauged catchments, and are therefore generally considered appropriate tools for hydrological modelling' (Caddis et al. 2008, p. 1).

Hydraulic modelling has extensively evolved over the last twenty years (Rehman 2011, p. 372), of which improvements in data availability, numerical methods and computational power have been noticeable. The emerging availability of floodplain topographic data such as LIDAR and synthetic aperture radar has resulted in a transformation from data-poor to data-rich floodplain flood modelling (Tayefi et al. 2007, p. 3191). Bradbrook et al. 2004 claim that this has made two dimensional (2D) flood modelling an increasingly practical flood analysis tool. A feature of 2D modelling that has increased in popularity in recent years is the direct rainfall method.

The direct rainfall method (DRM), also known as the 'rainfall on grid' approach, is a relatively new technique that entered into the 2D modelling industry over the last 10 years (AR&R Project 15 2012, p. 11-184). The DRM model can cover an entire catchment, or simply an isolated area with the addition of source inflows known as boundary conditions. The DRM applies rainfall directly to the 2D grid of a hydraulic model for the duration of a designated storm event. At each timestep water is transferred between the grid cells, hence simulating runoff in the catchment. The DRM approach eliminates the need for a separate hydrological model such as the lumped-conceptual, purely using the 2D hydraulic model.

A component universal to both DRM and lumped-conceptual approaches are loss models. Not all rainfall falling on a catchment will result in flow at the catchment outlet, as losses such as infiltration, evaporation and storages occur. Both approaches account for such losses by subtracting a depth of rainfall from the hyetograph prior to their application. A difference in the two approaches is that lumped-conceptual models incorporate some storage losses into their rainfall loss, whereas the grid terrain of the 2D model incorporates some aspect of the catchment storage. This means that 'initial loss of the initial and continuing loss model should be lower in a direct rainfall model when compared with a traditional hydrological model' (AR&R Project 15 2012, p. 11-191).

Despite its increased popularity, limited research has been undertaken into the use of the DRM (AR&R Project 15 2012, p. 11-184). As the DRM is a fairly new technique, its approach has not superseded lumped-conceptual models (Taaffe et al. 2011, p. 434). Rehman et al. 2011 claim that in theory, hydraulic models provide a better definition of flow routing as their flow equations are derived from conservation of mass and momentum. Rehman et al. 2011 however conclude that rather than replace traditional hydrologic models, the DRM is another modelling technique with its own limitations. It was also found that 'there is as much difference in discharge time series between two different traditional hydrological models, as there is between direct rainfall and traditional hydrological models' (AR&R Project 15 2012, p. 11-184).

The research provided to date generally centres on case studies in New South Wales and Victoria. There has been no research found to date by the author relating to tropical locations such as North Queensland. It is envisaged that this research project will provide practical value on the use of the direct rainfall method in a tropical climate.

1.2 Background – Project Location

The location of the project case study is in the suburb of Mount Low, situated approximately 15 kilometres to the northwest of Townsville, forming part of Townsville's Northern Beaches. Northern Beaches is one of the most rapid growing suburban populations in Queensland. It is anticipated that by 2031, the Northern Beaches area is forecast to be home to 70,000 people, signifying growth of around 9% per annum (Townsville City Council 2012, p. 5). With this fast growing land development comes the need for informative flood studies to indicate flood prone areas, and develop flood mitigation measures.

Townsville City Council acquired the services of engineering consultant AECOM to produce a flood study of the Lower Bohle, which incorporates a portion of the Northern Beaches, inclusive of Low Drain. This flood study is currently within its final draft stage, and is being modelled using a 2D hydrodynamic software package MIKE FLOOD. The general model setup of this study was obtained for purposes of this research project.

1.3 Site Characteristics

The site of interest is in the catchment of Low Drain. The catchment slope is generally flat grading floodplain, and is covered by moderately dense bushland trees and sparse vegetation. Traditionally the land has remained largely vacant, however recent years has seen the increase of residential development. The general fall of the land is toward the coastal reach of Halifax Bay, with most of its runoff captured by Low Drain. Referring to Figure 1.1, Low Drain extends from the north of the Bruce Highway, travelling adjacent to Mount Low Parkway, before meandering its way to converge with Black River.

The land generally exhibits slopes of under 0.5%. It is noted that on the most upstream segments of the catchment, a mountainous hill exists with slopes between 15% and 20%. The total catchment contributing to Low Drain is approximately 1310 hectares. The catchment can be considered as having three main flow paths, hence three sub-catchments for this project. A large overland sub-catchment to the westernmost of the Mount Low area eventually pushes its way to the east, joining together with a central catchment, to then finally form a union with the eastern catchment over Low Drain.

The runoff from the westernmost sub-catchment experiences an interruption to its flows by a series of storage dams. The sub-catchment directly upstream of this on the southern side of the Bruce Highway also exhibits a storage detention basin. The depression in this storage basin was formed naturally, with the road embankment of the Bruce Highway as the artificial control for this basin. Likewise, the most upstream sub-catchment to Low Drain experiences a storage detention basin to the immediate upstream of the Bruce Highway. This basin was formed as part of a Council residential development and assists in mitigating flows in Low Drain. The raised level of the Bruce Highway in both instances was part of providing some extent of flood immunity to traffic users. All storage basins are represented in Figure 1.2.

Culverts that exist under the Bruce Highway, that offer relief to the detention storages, were included in each model to accurately represent their effect on the runoff routing.

This research project focuses on the three abovementioned main sub-catchments, as well as a total combined catchment of all of these sub-catchments.

Figure 1.1: Low Drain

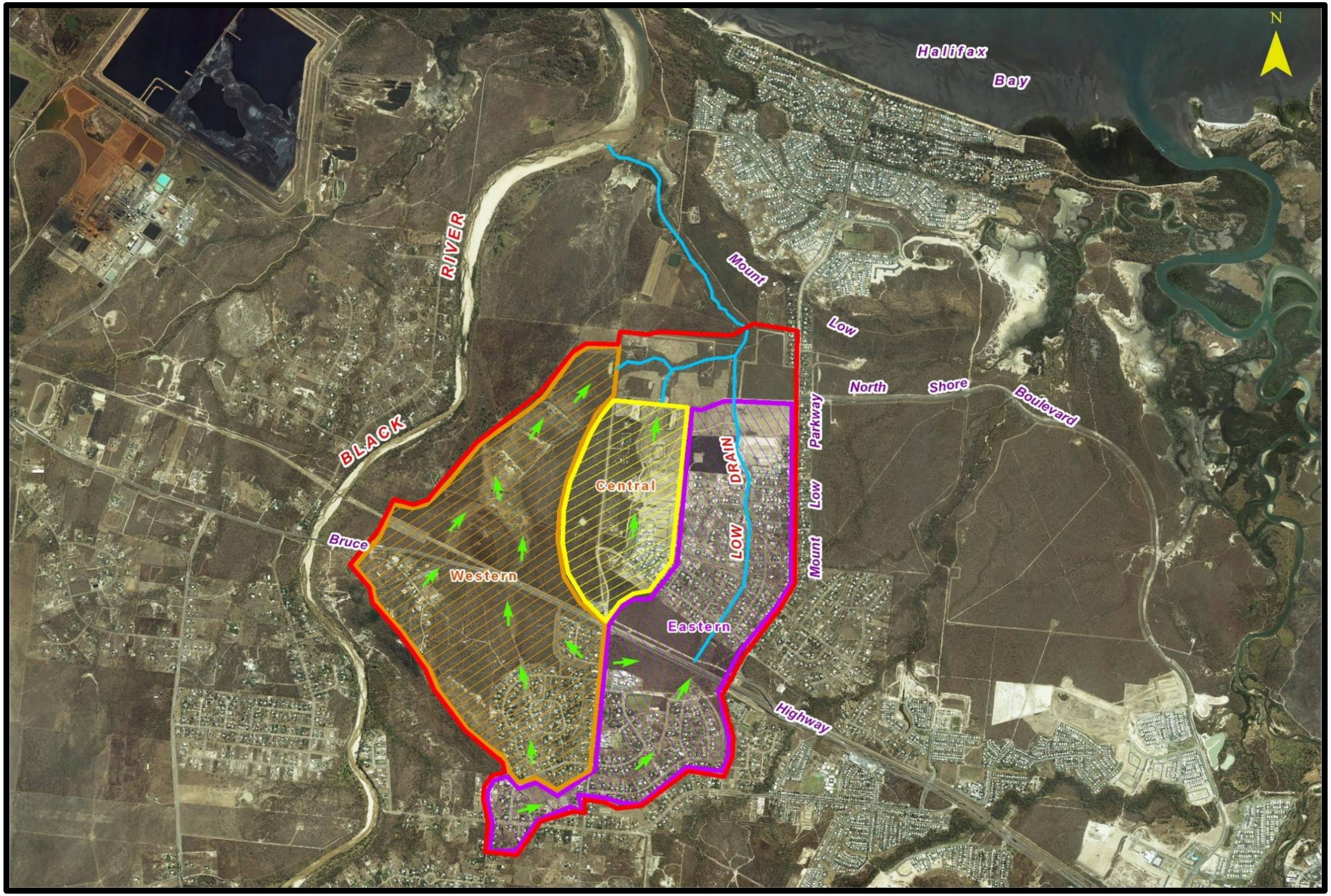
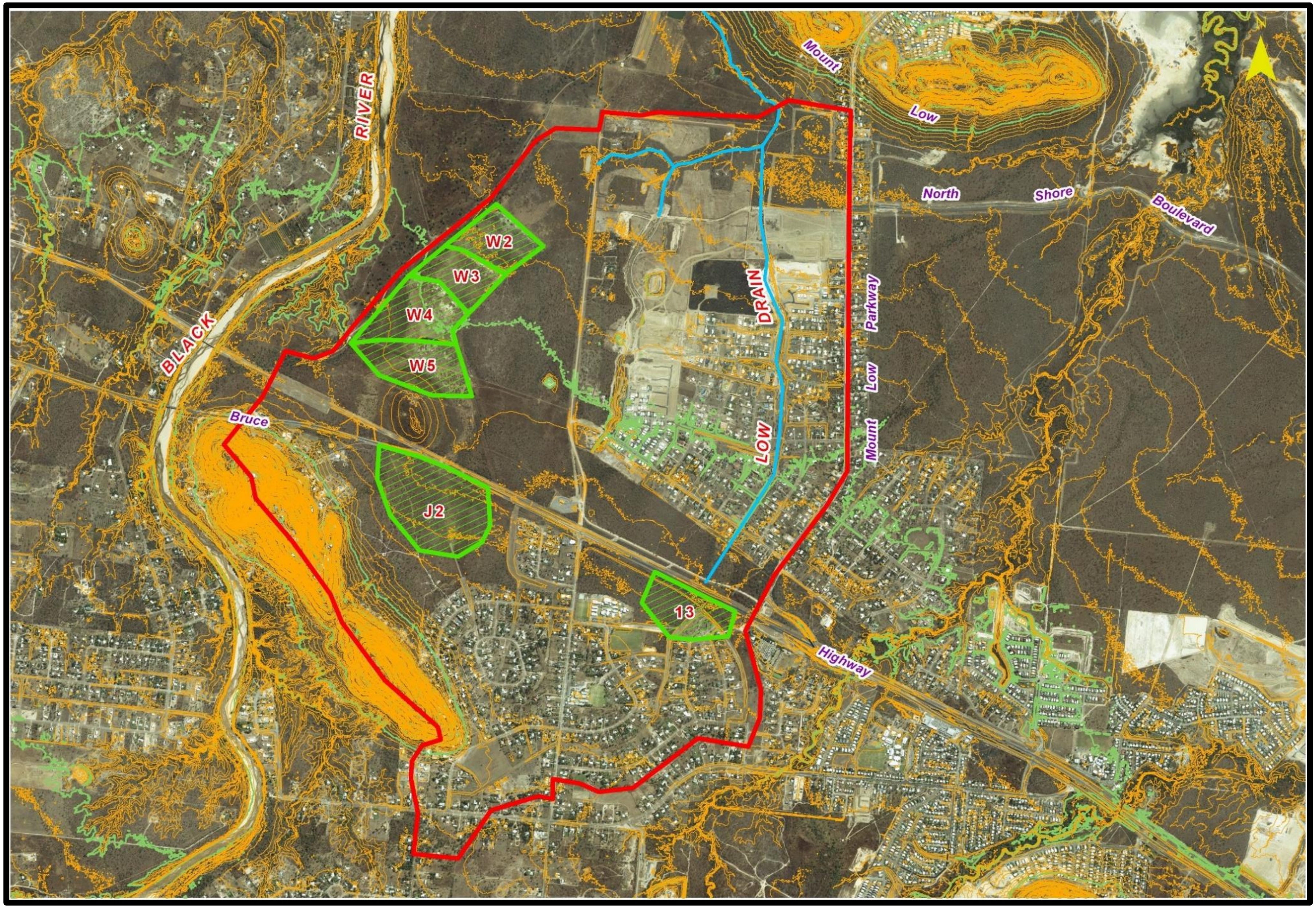


Figure 1.2: Storage Basins within the Low Drain Catchment



1.4 Project Objective

The ultimate project objective is to provide engineering guidance on the use of the direct rainfall method for various duration storm events, in tropical North Queensland. As the catchment is ungauged, results of the DRM are compared to a conventional lumped-conceptual model. The project seeks to outline duration events that are suitable for use by the DRM by comparing runoff results over a range of short and long durations. Through sensitivity analysis of rainfall losses, surface roughness, and wetting and drying on the DRM, it is possible to present guidance on the impact of these parameters in supplementing the DRM model for improvements in runoff.

The project outlines differences in runoff magnitude and timing between the two models, and presents reasons for attenuation in the DRM by exploring storage effects within it and the lumped-conceptual model.

1.5 Project Structure

The project dissertation is structured with the following elements:

- Literature Review
- Methodology
- Results and Discussion
- Conclusions and Recommendations

Literature Review

Relevant literature to the topic of runoff routing, in particular lumped-conceptual and direct rainfall approaches, is assembled to provide an informative briefing of the subject. It presents some of the current findings and opinions of professionals, as a result of their investigative work on the comparison of the two models. The literature review also details mechanisms of each approach.

Methodology – Hydrologic & Hydraulic Routing

This section describes how each model is set up, as well as parameters chosen. The sensitivity testing methods are defined here, as well as the final extraction of model findings for results.

Results and Discussion

A compilation of results are presented to compare the findings of the two runoff routing approaches.

Conclusions & Recommendations

A final summary of the conclusions are presented in this section, providing educational guidance on the use of the direct rainfall method. Recommendations of future research are also discussed.

1.6 Project Resources

This project required the collection of data, and the use of licenced software. Data such as surface contours, asset infrastructure (roads, culverts, bridges etc.), and previous flood study information were used. This information was supplied by Townsville City Council, and made readily available.

Townsville City Council have software licences to MIKE FLOOD, XP-RAFTS, ArcGIS and AutoCAD Civil 3D, all of which were made readily available for the purposes of this project.

Licenced software that was used is as follows:

- MIKE FLOOD – 2D modelling software, developed by the Danish Hydraulic Institute (DHI).
- XP-RAFTS – Hydrologic runoff model, developed by XPsolutions.
- ArcGIS – GIS mapping software, developed by Esri.
- AutoCAD Civil 3D – diverse software application, suitable for working with terrain models.
- Microsoft Excel – data analysis and chart production software.

1.7 Project Tasks

The project consisted of specific tasks to be undertaken. The tasks of the project consists chiefly of:

- *Compilation of Data:* Prior to any modelling, all relevant information such as contour data, asset infrastructure listings, previous studies, catchment characteristics and rainfall data are collaborated.
- *Testing:* Testing is undertaken on both models under a base-line case, as well as sensitivity cases with losses, roughness, and wetting and drying.
- *Data Extrapolation & Generation of Results:* Data is extrapolated from the software outputs, and results are then generated in the form of hydrographs and volumes.
- *Results:* The results of the models are compared and discussed
- *Dissertation:* The final dissertation is prepared, consisting of report writing, plots, tables, and graphs etc.

2.0 Literature Review

2.1 Current Industry Research

The direct rainfall method has been in practice for approximately ten years (AR&R Project 15 2012, p. 11-184). Its first application became evident to Rehman (2011) in the early 2000s, where traditional hydrologic modelling was not suitable for the design of flood escape routes in Sydney's western regions. Prior to the implementation of the DRM, 2D hydraulic models were developed for the prediction of hydrodynamic flow behaviour in watercourses and floodplains. With increasing flexibility, robustness and computational power in recent years, 2D hydraulic models have seen a 'shift away from their original application area' (Clark et al. 2008, p. 2499) by incorporating the rainfall-runoff routing component.

Despite the DRM having increased popularity, it would be unreasonable for one to assume that it is superseding traditional lumped-conceptual approaches. Traditional lumped-conceptual models are broadly accepted in the industry due to their long history of use, and their successful calibration in a wider selection of gauged catchments (AR&R 2012, p. 11-195). It is also noted that there is as much difference in runoff hydrographs between 'two different traditional hydrologic models, as there is between direct rainfall and traditional hydrologic models' (AR&R 2012, p. 11-184). Subsequently 'calibration to any hydrological model would not necessarily validate the results of the RFOG (rainfall-on-grid) approach' (Rehman 2011, p. 377). A comparison to a traditional lumped-conceptual approach is nonetheless worthy in ungauged catchments, and testing to gain appreciation of the behaviour of the DRM valuable to industry professionals.

One of the earlier pieces of research completed by Muncaster et al. (2006) investigated the application of the DRM. The research focused on the role of hydraulic roughness within the study catchment, comparing the effects of varied roughness to the runoff hydrographs. Being one of the early studies into the use of the DRM, Muncaster etl al. (2006) did not extend their research into the effects of losses, rather maintaining uniform losses for the purposes of their modelling. Caddis et al. (2008) tested both roughness and loss parameters in their research, finding that the DRM compared better to lumped-conceptual model results when roughness and loss values were lower than the traditional values. AR&R (2012) conclude further on these findings, stating that 'the impact that losses had on the flow hydrograph were overshadowed by the impacts that roughness had on the flow hydrograph' (AR&R 2012, p. 11-191).

Rehman et al. (2003) discovered that the DRM typically resulted in longer runoff times than lumped-conceptual models, and this finding was mostly consistent in the studies of Caddis et al. (2008) and Clark et al. (2008). Clark et al. (2008) discovered that its lumped-conceptual model began to drain almost immediately, whilst the DRM models appeared to 'exhibit significant delays prior to the commencement of runoff' (Clark et al. 2008, p. 2505). Another finding of Clark et al. (2008) was the differences between the traditional hydrologic and DRM were more pronounced for smaller ARI events.

The volume of water entering a catchment, either by rainfall or inflows, must equal the volume of water leaving it, minus losses and storages within the model. Volume errors are generally present in 2D models, especially when the DRM is applied (AR&R 2012). Generally if errors exceed five percent, numerical instabilities in the 2D model are considered to be a problem (AR&R 2012). Clark et al. (2008) found that its traditional hydrologic model drained almost all of its rainfall excess upon completion of its run simulation, whereas the 2D hydraulic models consistently estimated lower discharge volumes. Reasons for this were inconclusive and outside the scope of this research.

One of the most recent studies by Taaffe et al. (2011) focused on the effect of pit cells in the DEM (digital elevation model). Pit cells are cells in the DEM that are lower in elevation than surrounding cells, hence cannot route flow. The authors describe pit cells as being either authentic or spurious. Authentic pits are those representing depressed areas of the catchment, whereas spurious pits are artefacts in the construction of the DEM which arise from data errors and limited horizontal and vertical resolution (Taaffe et al. 2011). Taaffe et al. (2011) discovered that pit cells act as a second loss mechanism to the initial loss element, resulting in severe attenuation of the peak discharge at the outlet.

To date it has been common practice to apply the DRM in the same manner as traditional hydrologic models by subtracting an initial loss from the rain hyetograph prior to its application. By incorporating traditional loss approaches in the DRM, it assumes no significant losses are occurring within the routing of the 2D domain. The authors describe this practice as one that has arisen

> *due to poor understanding of the direct rainfall method's intricacies, meaning traditional loss models are being used to supplement uncertainties in the method (i.e. how it treats losses)*. (Taaffe et al. 2011, p. 440)

In an investigation on five catchments, Taaffe et al. (2011) found that pit cells removed a significant depth of rainfall, retaining between 4 and 10mm of rainfall for spurious pits. This retention from spurious pits is much similar to the initial loss value of 10mm prescribed by AR&R (Taaffe et al. 2011). The initial loss-continuing loss values of lumped-conceptual models are used to capture depression storages within a catchment, however Taaffe et al. (2011) claim that these cannot be associated to pit cells. Taaffe et al. (2011) found literature that describes depression storages as being of the centimetre scale in size. Grid sizes of 10m x 10m are not exactly small depressions in this instance, hence why Taaffe et al. (2011) describes depressed cells as pit cells.

At fine grid resolutions, Taaffe et al. (2011) found that spurious pits were frequently present, whereas their existence diminished at coarser resolutions such as 10m and 16m. It was discovered the 'depths of pits, and hence their effect as a losses mechanism, diminishes with a coarser grid resolution' (Taaffe et al. 2011, p. 439). Hence a model with a high resolution DEM cannot be considered to be essentially accurate with respect to the DRM.

As every catchment is different, their subsequent effect of pit cell storage will vary, and will be unique to its catchment's terrain. Thus 'any particular catchment requires a degree of familiarity and DEM analysis before it can be used in the direct rainfall model' (Taaffe et al. 2011, p. 441).

Caddis et al. (2008) conclude that the DRM has provided for improved representation of minor overland flowpaths than traditional models. It is recommend further research be undertaken to establish appropriate surface roughness values for various land use types (Caddis et al. 2008).

Conclusions from Clark et al. (2008), Caddis et al. (2008) and Muncaster et al. (2006) express the need for further research into the understanding of parameter interactions of the DRM. Current research has shown to evolve over the past ten years in regard to the DRM, and with anticipation for more to be undertaken, it is expected that guidance into the use of the DRM will become clearer for industry professionals. It would be ideal for such further testing to be conducted on a catchment with observed data for a range of events, so that the DRM can be verified to real physical data (Clark et al. 2008). 'Until further research is undertaken, thorough checking of direct rainfall models should be undertaken' (AR&R 2012, p. 11-184).

2.2 Conventional Hydrologic Lumped-Conceptual Model

XP-RAFTS is a runoff routing model that simulates both urban and rural catchments of various sizes. It is a non-linear model that is used extensively throughout Australasia and the Asia Pacific Region. It can model up to 2000 nodes, with each node having any size sub-catchment (XP-RAFTS 2012). It has capabilities of simulating storage basins and retention structures. The model generally requires data input such as catchment area, slope, roughness, loss rates and rainfall.

XP-RAFTS uses the Laurenson non-linear runoff routing procedure to develop runoff hydrographs by considering time-area and sub-catchment shape. This procedure was previously pioneered in early 1964 and was primarily aimed at rural catchments, but modified by Aitken in 1975 for use on urban catchments. The modified procedure eventually became the basis for the RAFTS software in 1980 (Goyen et al. 1991). XP-RAFTS relies on a storage equation with the non-linear storage function, which is given as:

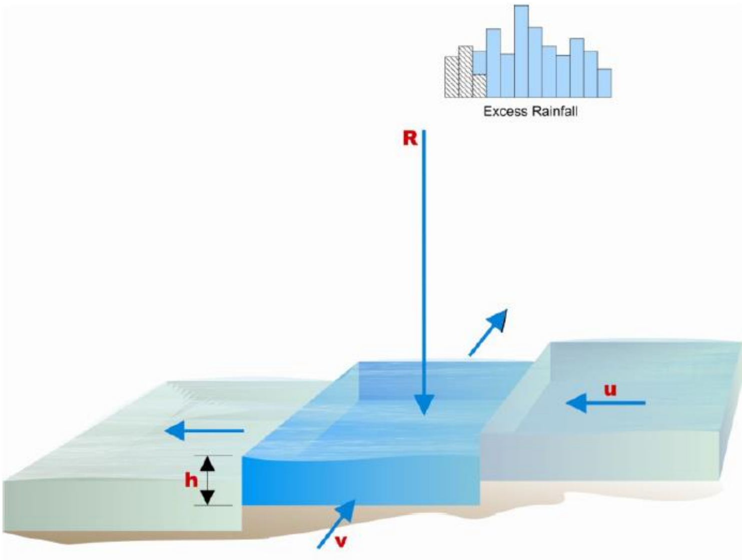
$$S = BQ^{n+1}$$

where S is storage which is related to outflow Q, where B is the storage delay time coefficient and n is the storage non-linearity exponent. The storage delay time coefficient B was developed by Aitken, and is a function of catchment area, slope, and degree of urbanisation in a catchment. Both of the B and n coefficients are empirically derived.

2.3 2D Fully Dynamic Hydraulic Model

The direct rainfall approach is regarded as relatively quick and easy to build, with a comprehensive suite of tools available in the MIKE software. Other 2D software exist such as TUFLOW and SOBEK, and are well accepted by the industry. It is a method for assessing broad-scale flood risk for areas on a catchment scale (AECOM 2012, p. 17). It applies rainfall directly on the 2D grid, minimising the need for hydrologic models like XP-RAFTS. Figure 2.1 represents a cell in a 2D grid, which plays a part in both receiving direct rainfall, and consequently routing overland flow.

Figure 2.1: Variables of 2D overland flow



(Rehman et al. 2011, p. 374)

The cell in Figure 2.1 represents a cell within a catchment domain consisting of multiple cells. Once the rainfall is applied to the grid cells of a catchment domain, accurate overland flow routing is possible within the 2D fully dynamic hydraulic model, using shallow water equations.

The 2D shallow water equations for overland flow comprise of both the conservation of mass, and conservation of momentum. They are:

Conservation of Mass:

$$\frac{\partial h}{\partial T} + \frac{\partial h}{\partial x}(uh) + \frac{\partial}{\partial y}(vh) = R$$

Conservation of Momentum (in both x and y directions):

$$\frac{\partial}{\partial t}(uh) + \frac{\partial}{\partial x}\left(u^2 h + \frac{1}{2} g h^2\right) + \frac{\partial}{\partial y}(uvh) + \frac{gu(u^2+v^2)^{1/2}}{c^2} = 0$$

$$\frac{\partial}{\partial t}(uh) + \frac{\partial}{\partial y}\left(v^2 h + \frac{1}{2} g h^2\right) + \frac{\partial}{\partial x}(uvh) + \frac{gv(u^2+v^2)^{1/2}}{c^2} = 0$$

Where *R* is the rainfall excess ($m^3/m^2/s$), *u* and *v* are velocities in orthogonal directions, *h* is the depth of water, *g* is the gravitational constant and *c* is the Chezy coefficient for bed friction.

A tool within the MIKE FLOOD software called 'wetting and drying' can be applied to the grid of the DEM. When a wet depth is specified to the grid domain, flow calculations only start computing when the rising water level becomes greater than this specified depth. When a dry depth is defined, flow calculations within grid cells cease to compute only when the falling water level reaches this specified dry depth. This type of testing is usually undertaken in tidal locations or complex floodplains. When the wetting and drying values used are considerable enough, the software utilises less grid cells, hence increasing computational run times. This method suppresses instabilities the software may encounter when attempting to simulate flow between adjacent cells that are either wet or dry.

The implication of wetting and drying is that it ceases the flow of water in the model until the defined depths are reached, also leaving much of the rainfall volume to remain in the model. Consequent to the cessation of flow, runoff experiences attenuation. It is common practice in flood models that the coarser the grid cells, the larger the wet & dry depth. For example, on large coastal mud flats, where usually modelling is of coarse grid scale, wetting depths are sometimes defined as 0.2m. This depth would not be appropriate in the Low Drain catchment where such depth would result in excessive attenuation.

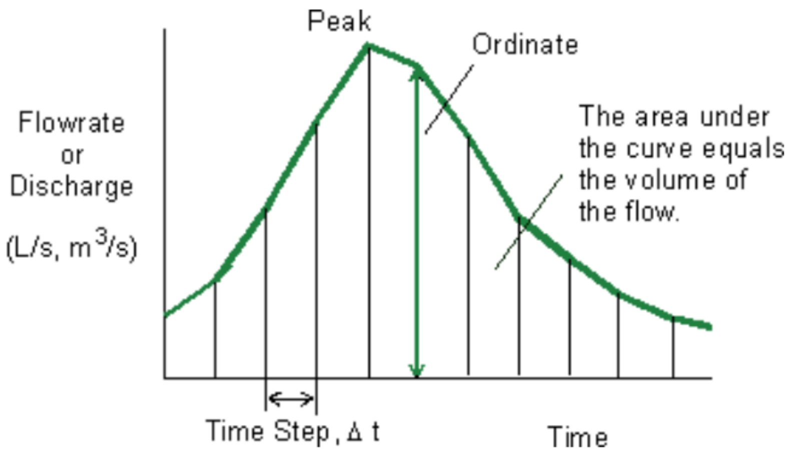
MIKE FLOOD recommends wetting and drying depths of 0.05 and 0.005m respectively.

3.0 Methodology

3.1 Overview

Both lumped-conceptual and DRM models require certain parameters and inputs that define a catchment in order for them to simulate runoff. The runoff results are usually in the form of a hydrograph, which describes the magnitude of the flow, and also how quickly the catchment responds to its time of peak. The area under the hydrograph is representative of the volume of water discharged from the catchment, as shown below in Figure 3.0.

Figure 3.0: Hydrograph



(O'Loughlin et al. 2012)

The duration of a storm event impacts the shape of the hydrograph. A short duration event will generally result in its peak to occur quicker than that of a longer duration storm of the same rainfall. However the magnitude of this peak may vary, and potentially be smaller than that of the longer duration. How a catchment responds to rainfall, and subsequently how its hydrograph is shaped, is also characterised by each model's definition of physical data such as, but not limited to, land use, roughness, slope, storages and losses.

The software used in this project for the conventional lumped-conceptual approach is XP-RAFTS. The hydraulic model used for the direct rainfall method is MIKE FLOOD.

After simulating both the DRM and lumped-conceptual models, results were compared and sensitivity tests were then undertaken on the DRM to indicate their effects on the catchment runoff. Due to the absence of streamgauge and flood height data, calibration of the DRM to recorded data was not possible. Hence results were compared to the lumped-conceptual approach by comparing flow hydrographs and volume checks at key locations in the catchment.

3.2 Testing Applications

Testing was undertaken on a total of four sub-catchments. These are:

1. Western sub-catchment
2. Middle sub-catchment
3. Eastern sub-catchment
4. Total of sub-catchments

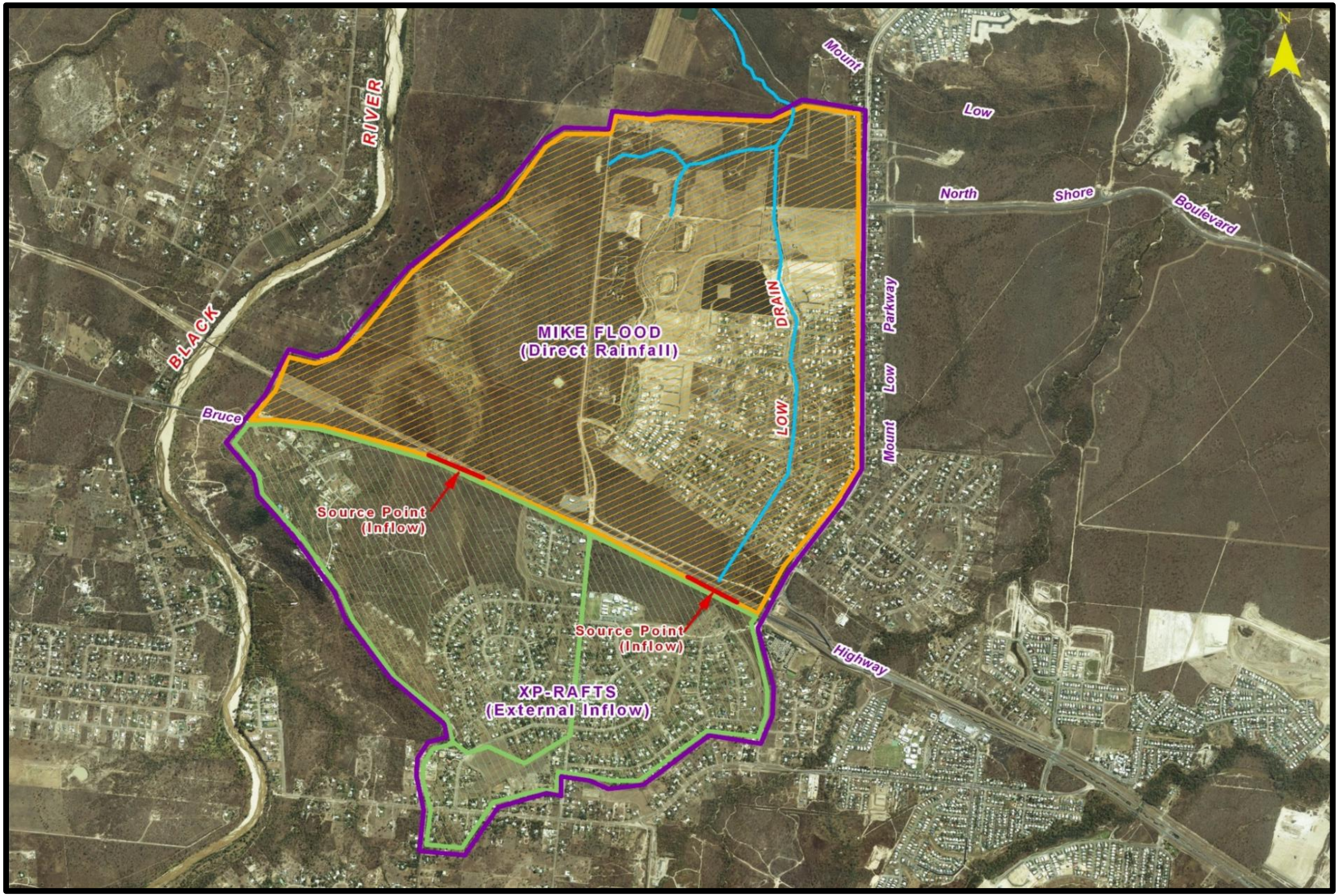
These areas are shown previously in Figure 1.1 of the section *1.0 Introduction*. Testing on these catchments was undertaken using design storms of 0.5, 1, 1.5, 2, 3, 6 and 24 hour storm durations, as outlined below in section *3.3 Setting Up the Models*.

The application of the DRM was undertaken over a major portion of the catchment, with runoff contributions for the remainder portions provided from the XP-RAFTS model. This application is defined further:

- External inflow catchments – MIKE FLOOD applied direct rainfall to a large portion of the Western and Eastern sub-catchments. Runoff contributions from upstream areas of these Western and Eastern sub-catchments were determined from the XP-RAFTS model. These source points are shown in Figure 3.1.
- Enclosed catchments – MIKE FLOOD applied direct rainfall to the entire Middle sub-catchment. The Middle sub-catchment is unique in that it does not experience external inflows from an upstream source.

The application method described here is commonly used in practice, and is recognised by the Australian Rainfall and Runoff (AR&R Project 15 2012, p. 11-187). This application was adopted in a similar study by Muncaster et al. (2006), which also investigated the direct rainfall method.

Figure 3.1 – Application Methods of the DRM

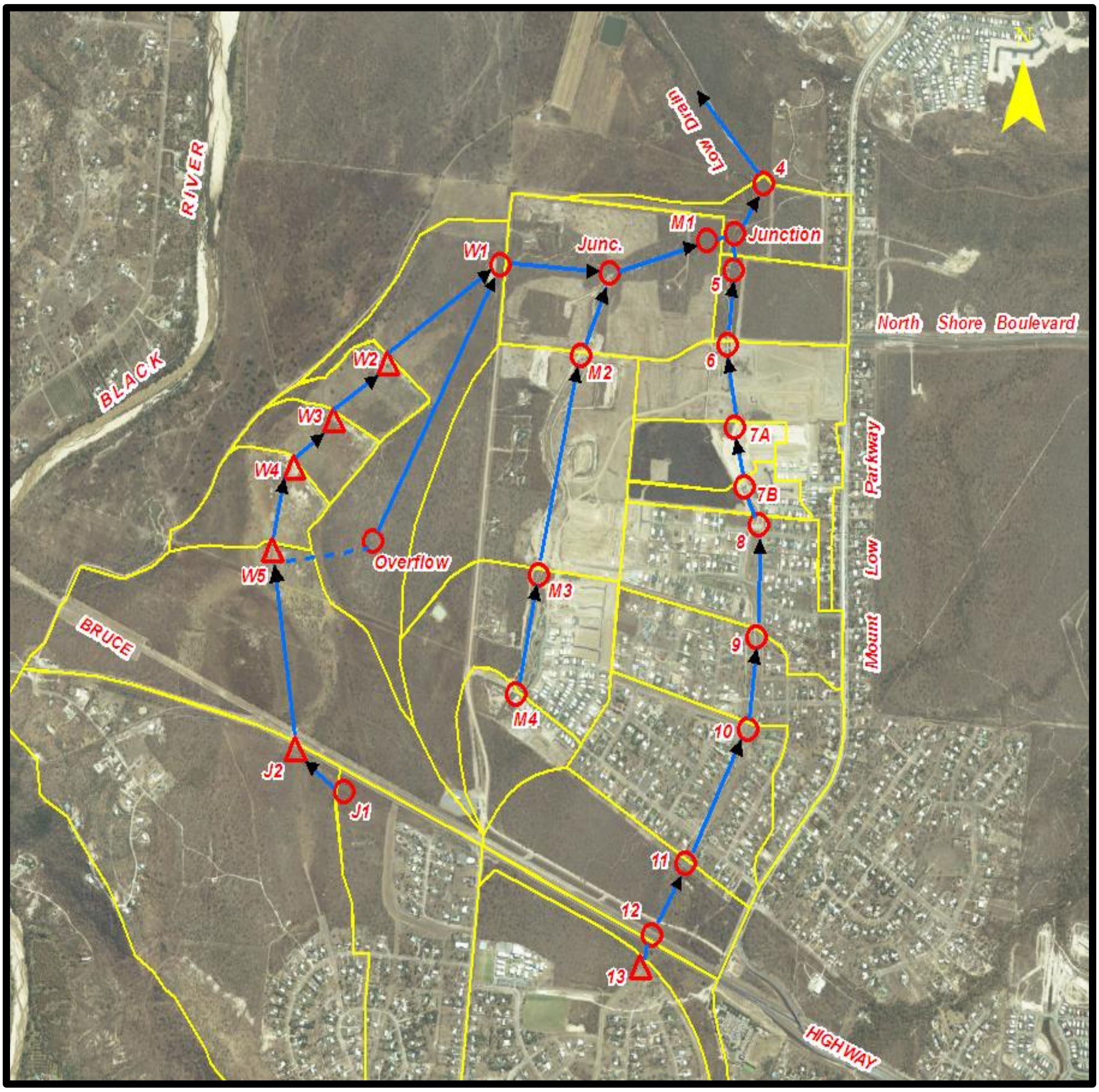


3.3 Setting up the Models

The following hydrologic data, parameters, and assumptions were used for the Mount Low site in both model approaches. It is noted that the original setup of the MIKE FLOOD DRM model was previously undertaken by AECOM, as part of the draft Lower Bohle Flood Study (2012). The XP-RAFTS model was prepared by the author.

The XP-RAFTS model is shown below in Figure 3.2. Here it is obvious that the three main sub-catchments were divided into smaller sub-catchments for more accurate detail and simulation of the catchment. The characteristic of these catchments are detailed in Appendix F.1.

Figure 3.2: The XP-RAFTS model



Rainfall Data

Intensity Frequency Duration (IFD) data was extracted from the *Australian Rainfall and Runoff* (Pilgrim, 1987). Standard techniques from AR&R were used to determine rainfall intensities for durations up to 72 hours and up to a 100-yr ARI event. These are shown below in Table 3.0.

Table 3.0: IFD Table

Duration	1 Year	2 Years	5 Years	10 Years	20 Years	50 Years	100 Years
5min	120.29	154.29	195.94	220.05	252.31	294.62	326.79
6min	113.77	145.90	185.22	207.97	238.41	278.34	308.68
10min	95.61	122.55	155.39	174.36	199.78	233.09	258.40
15min	81.84	104.87	132.82	148.95	170.58	198.91	220.43
20min	72.64	93.04	117.74	131.98	151.10	176.12	195.12
30min	60.69	77.70	98.20	110.01	125.87	146.62	162.37
45min	50.12	64.13	80.95	90.61	103.62	120.62	133.52
1hour	43.51	55.65	70.17	78.51	89.73	104.41	115.53
1.5hour	34.42	44.15	56.05	62.94	72.16	84.25	93.44
2hour	29.05	37.33	47.64	53.63	61.62	72.13	80.13
3hour	22.81	29.39	37.78	42.69	49.21	57.80	64.36
4.5hour	17.89	23.12	29.92	33.95	39.25	46.27	51.65
6hour	15.06	19.50	25.37	28.86	33.44	39.52	44.19
9hour	11.83	15.35	20.12	22.97	26.70	31.67	35.49
12hour	9.97	12.96	17.07	19.54	22.77	27.07	30.39
18hour	7.91	10.29	13.60	15.60	18.19	21.67	24.35
24hour	6.69	8.72	11.55	13.26	15.49	18.46	20.76
30hour	5.87	7.65	10.15	11.67	13.64	16.27	18.31
36hour	5.26	6.86	9.12	10.48	12.26	14.64	16.48
48hour	4.40	5.74	7.65	8.80	10.31	12.32	13.88
72hour	3.35	4.39	5.86	6.76	7.93	9.50	10.72

Design Event & Durations for Modelling

Townsville City Council's defined flood event is a 50 year average recurrence interval (ARI). All urban developments are to have a flood immunity from such event, and Townsville City Council require all habitable floor levels of dwellings to be a minimum of 450mm above the 50 year ARI. The primary event for comparison in this project is a 50 year ARI.

The 0.5, 1, 1.5, 2, 3, 6 and 24 hour storm durations for the 50 year ARI storm was simulated for both models.

Topographic Information

LiDAR surface contour data, accurate to 0.25m, was accessible from Townsville City Council. Accurate level data of structures was also obtained from Townsville City Council through the asset database and as-constructed drawings. Such information was useful as some of the catchments consisted of storage basins, which are crucial in runoff routing analysis.

Rainfall Losses
Rainfall losses do not contribute to runoff, and are abstractions from rainfall producing rainfall excess. Rainfall excess is the rainfall remaining after losses have been removed from the rainfall hyetograph. Rainfall excess is calculated by applying initial and continuing losses to the design rainfall for pervious and impervious surfaces. These losses represent infiltration and storage of runoff in surface depressions. The losses used are described in the testing methods section of this dissertation.

Roughness
Surface roughness is a measure of the resistance to flow and is primarily dependent on land use. Roughness coefficients are defined by a Manning's 'n' value. The values used for XP-RAFTS and MIKE FLOOD are described in the testing methods section. Typical roughness values, as outlined in the Townsville City Council Guidelines – Flood Studies and Reports (2010), are:

Land Use	Roughness Value (Manning's n)
Natural Watercourse	0.02 – 0.05
Riparian Corridor	0.06 – 0.12
Open Grassland	0.03 – 0.05
Low Density Vegetation	0.04 – 0.06
Medium Density Vegetation	0.05 – 0.08
High Density Vegetation	0.06 – 0.12
Roads	0.02 – 0.04
Open Channels	0.02 – 0.04
Rural Residential	0.04 – 0.07
Urban Residential	0.04 – 0.1
Parks	0.03 – 0.08

Fraction Imperviousness
A catchment consists of pervious and impervious surfaces. Impervious areas are typically surfaces such as roads, carparks, and roof dwellings. Pervious surfaces consist of lawns, gardens, parklands and undisturbed floodplains. The fraction impervious for surfaces of each model was established and made consistent for both XP-RAFTS and MIKE FLOOD. The fraction impervious of the MIKE FLOOD model had previously been setup by AECOM as part of the Lower Bohle Flood Study (2012). This had been setup by assigning values to all grid cells within a .dfs2 file. Fraction impervious values were assigned in the node sub-catchment data in the XP-RAFTS model. Fraction impervious values modelled are detailed in Appendix F.1 and I.1 for XP-RAFTS and MIKE FLOOD respectively.

Boundary Conditions
The XP-RAFTS model did not require boundary conditions as it is a runoff routing model where all catchments were included within it. The MIKE FLOOD model is a combined hydrologic and hydraulic model, therefore upstream and downstream boundary conditions were setup for its simulation.

Hydrographs were extracted from the XP-RAFTS model so they could be input into the MIKE FLOOD model as an upstream boundary condition. The MIKE FLOOD grid extended to the coastal reach of Halifax Bay where a downstream fixed water level of 1.254m AHD, being the mean high water springs (MHWS) for Townsville, was adopted as the downstream boundary condition. This downstream boundary condition is more tailored toward the hydraulic response, rather than the hydrologic run of the simulation.

Storages
As mentioned in section 1.3, detention storages exist within areas of the Low Drain catchment. During the simulation of the DRM in MIKE FLOOD, these storages are directly accounted for by the model by its DEM.

XP-RAFTS requires storage data to be user defined in its model. Software package AutoCAD Civil3D was used to determine storages at various water level elevations, and these were correlated over to the XP-RAFTS. The volume of storage at varying water elevations is detailed in Appendix G.1.

Structures
Road culvert structures exist under the Bruce Highway, and these offer relief to the above storage retention basins. These structures provide outflow through the culverts, as well as overtopping weir flow over the road crown. Details of the culverts and overflow were input into XP-RAFTS for modelling.

Grid Cell Size (MIKE FLOOD model)
The grid cell size of the DEM used in the MIKE FLOOD model is 10m x 10m. This size provides for satisfactory modelling, and has been adopted as a suitable resolution by Townsville City Council.

3.4 Model Testing Methods

3.4.1 Base-Line Testing

This test simulates the catchment runoff using consistent parameters in each model, and ones that are most representative of reality. These parameters are those that are normally adopted by the industry in typical flood modelling exercises.

The losses in each model were set as:

- Pervious Areas: Initial loss - 24mm, Continuing Loss - 2.5mm/h
- Impervious Areas: Initial loss – 1mm, Continuing Loss – 0mm/h

Losses were adopted as per suggestions outlined in AR&R Volume 1 (Pilgrim, 1987) for the east coast of Australia.

The roughness defined in each model was kept largely consistent. Site inspection and interpretation of aerial imagery provided guidance as to the type of roughness to be adopted within the catchment. The roughness values adopted for the XP-RAFTS and MIKE FLOOD models are detailed in Appendices F.1 and H.1 respectively.

Wetting and drying parameters were defaulted at 0.002 and 0.001 respectively.

The DRM and lumped-conceptual approaches were simulated, and analysis was undertaken on the following results:

- Runoff peak magnitude and timing to peak
- Storage Effect of 2D Hydraulic Model
- Storage Effect of lumped-conceptual XP-RAFTS
- Catchment volume check (mass balance)

These are described in the below in section *3.5 Review of Testing Results*.

3.4.2 Sensitivity Testing

The MIKE FLOOD model was found to have lower peak magnitude runoffs to that of XP-RAFTS, hence sensitivity testing was undertaken to determine if adjustments to model parameters had a compensating effect for MIKE FLOOD's lack of comparison. The XP-RAFTS model parameters were kept consistent with that of the base-line case for all sensitivity tests. Testing on the MIKE FLOOD model was initially carried out in a base-line test (consistent parameters between models), followed by the subsequent sensitivity tests to the MIKE FLOOD DRM:

- Losses
- Roughness
- Wetting and Drying

By reviewing alterations of the above parameters in MIKE FLOOD, their influences in comparison to the lumped-conceptual model were established. Subsequently, their effects over a series of storm durations were able to be recognised. The recognition of all of these influences consequently presents understanding of the behaviour of the DRM for a catchment in tropical North Queensland. It is noted once again that neither of the models supersedes the other, and the comparison of the DRM to the lumped-conceptual model was undertaken in attempts to give guidance on its use.

Losses

Alterations to the initial loss parameter were made to the pervious areas of the DRM within MIKE FLOOD, whilst keeping continuing losses unchanged throughout testing. The initial loss parameter was altered in descending values of millimetres, so as to follow recommendations outlined by AR&R (AR&R Project 15 2012, p. 11-191). These alterations were made in attempts to reach some level of congruency with the XP-RAFTS results.

Tests were modelled under the following losses (MIKE FLOOD only):

- IL 24mm (Base-line test)
- IL 10mm
- IL 5mm
- IL 0mm

The series of varying initial loss values were run for the 0.5, 1, 1.5, 2, 3, 6 and 24 hour durations. The roughness remained identical to that of the base-line test, as did the wetting and drying parameters.

Roughness

Alterations to the roughness parameters were made to the MIKE FLOOD model. An overall decrease in Manning's 'n' values were undertaken to the catchment in an attempt to smooth the surface out. Adjustments to the roughness were undertaken so as to reach similarity with the results of the XP-RAFTS model.

Roughness tests were modelled under the following scenarios:

- Base-line Case (roughness values pertinent to real catchment surface characteristics). Refer to Appendix H.1 for values used.
- Base-line Roughness Values –10%
- Base-line Roughness Values –20%
- Base-line Roughness Values –30%

The altered roughness values were run for all storm durations. The losses remained identical to that of the base-line test, as did the wetting and drying parameters.

Wetting and Drying

The wetting and drying depths were adjusted in the MIKE FLOOD model. Their impact on the results of the runoff were compared to the XP-RAFTS results.

Tests were undertaken as follows:

- Base-line Case – Wetting 0.002m, Drying 0.001m
- WD01 – Wetting 0.001m, Drying 0.0005m
- WD02 – Wetting 0.004m, Drying 0.002m

The altered wetting and drying values were run for all storm durations. The losses and roughness parameters remained identical to that of the base-line test.

3.5 Review of Testing Results

3.5.1 Review of Hydrographs

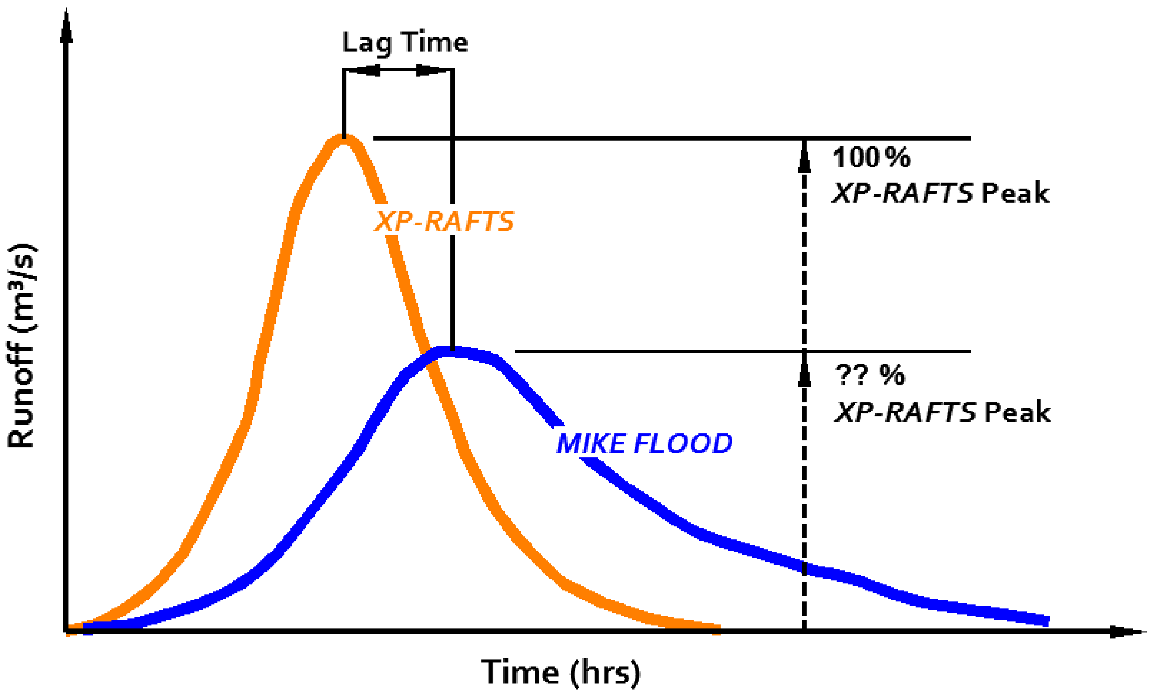
Hydrographs from the MIKE FLOOD model required undertaking discharge calculations for the four sub-catchments described in section 3.2. This involved setting up and running discharge calculations in the hydrodynamics section of the MIKE 21 toolbox. A total of 252 discharge calculation files were batched for this process. The hydrographs from the XP-RAFTS model were more easily obtained through the software's results section. Hydrograph data from each approach was collated in Microsoft Excel for all duration events, and for all testing methods.

To compare the two models, the peak magnitude of each model's hydrographs were tabulated. The peak runoffs from the MIKE FLOOD hydrographs were then taken as a percentage of the XP-RAFTS peaks, and this method is shown in Figure 3.3 below. The percentage flow data was plotted graphically over the numerous storm durations.

The time lag was compared in a similar fashion. The time to peak was tabulated for both models, and the time lag of the DRM (relative to a leading XP-RAFTS hydrograph as shown in Figure 3.3 below) was determined. XP-RAFTS hydrographs generally peaked much earlier, hence why the DRM peak times were considered a lag.

The runoff magnitude and timing were compared for trends across the duration of events modelled.

Figure 3.3: Analysis methods for peak flow magnitude and time lag



3.5.2 Storage Effect of 2D MIKE FLOOD

Unlike XP-RAFTS, the MIKE FLOOD model simulates flow across its 2D grid, most of which consists of depressions of varying magnitude acting as storage pockets throughout the grid domain. Storage generally results in both attenuation of runoff times and lowering of its peak magnitude. Storage effects are magnified when their storage characteristics are sizeable in comparison to the volume and rate of runoff arriving to them. Hence lower volumes from smaller duration events will be impacted by storages far more than those of larger volumes from longer duration events.

The effect of storage had not been the main focus of this project from the onset, with the majority to be done on sensitivity. However analysis of results presented too remarkable of an effect to not investigate in detail. Time constraints of the project did however limit in depth investigation. It was found that the runoff peak magnitudes and times of the DRM were subjected to signs of the above storage effects, especially in the lower duration events. The mass volume stored in the 2D model at the end of each run simulation were compared to the mass volume of rainfall applied to each catchment. A short duration event was compared to a longer duration event over multiple catchments to seek clarity of the storage effects.

3.5.3 Storage Effect of XP-RAFTS

XP-RAFTS treats storages within its model using a non-linear function of discharge. This function relies on a storage delay time coefficient, whose behaviour within a catchment will also alter depending on its fraction impervious.

The fast occurring and high peaking runoff of XP-RAFTS was found to be a direct result of little treatment of storages within its model, and this was more evident in a high fraction impervious catchment. The way in which XP-RAFTS treats storage differs to that of MIKE FLOOD, hence the difference in its volume of storages found. The storage function of XP-RAFTS was investigated, and the scale of its impact compared to MIKE FLOOD. Originally this component of analysis was outside the scope of the project, however its significance was too obvious to discard for discussion.

3.5.4 Catchment Volume Checks

A volume check was undertaken to ensure both models were conserving mass. To confirm this, the volume of rainfall dumped onto a catchment for a designated storm event should be equal or similar to the runoff and storage volumes combined.

From the MIKE FLOOD model, the 'calculate statistics' tool was used to obtain the intensity of rain at each timestep for the duration of the storm event. This data, in conjunction with the area over which it was applied, derived a volume at each timestep. The total volume was then calculated as the sum of water on the catchment at each timestep. For the XP-RAFTS model, an average intensity was extracted from the results file, and volumes were determined in a much similar fashion as the MIKE FLOOD model.

The total volume as a result of outflow was determined by the area under the outflow hydrographs. Stored volume for the MIKE FLOOD model was obtained through it's 'calculate statistics' tool at the last time step of the simulation.

Volume checks were undertaken on all sub-catchments, for two design duration events. Testing under two durations was sufficient for volume checking.

3.5.5 Sensitivity Analysis

Percentage peak flow magnitudes and time lags were compiled and compared in a similar fashion to that described in section 3.5.1 above. As losses, roughness and wetting and drying parameters are mutually exclusive, their effects are compared for impact on the DRM. Their ability to compensate for MIKE FLOOD's lack of similarity to XP-RAFTS is investigated.

Results across all catchments were averaged for overall effect. Runoff and time lag comparisons, along with their suitability over duration were made.

3.5.6 Suitability of Duration Events

The runoff results varied over the duration of events, with some durations giving more desirable comparison between the two models than others. This project was aimed at not only investigating the effects of the DRM, but providing guidance on its use.

This analysis combines the results of all tests, and analyses their impact over all durations. The durations where the DRM was of suitable comparison to XP-RAFTS were identified as part of this project.

4.0 Results and Discussion

4.1 General

This section will examine the base-line case tests between the two models, followed by the sensitivity testing. Results showing peak discharges and corresponding times to peak, along with their quantitative comparison with XP-RAFTS, are tabulated for all tests in Appendices B.1 and B.2.

4.2 Model Simulation Periods & Run Times

A total of 63 MIKE FLOOD models were run under the DRM, comprising of all base-line and sensitivity tests under the 7 durations. The actual run times for each model varied between 8 and 21 hours for each run, at much computational expense. The XP-RAFTS is much far more advantageous in this sense, with its simulations taking only a matter of minutes.

Almost all MIKE FLOOD models were setup for a simulation period of 10 hours, except for the 24hour duration event which was setup for 24 hours. When setting up the models it was not evident if these simulation periods would capture full hydrographs. Upon review of the hydrographs it was observed longer simulation periods would have been desirable to capture fully drained hydrographs for volume analysis. This analysis was originally outside the scope of the project, and re-running all models was not feasible within the time constraints of the project. Sufficient data was available for runoff analysis.

4.3 Base-line Testing

This sub-section is discussed by examining firstly some of the runoff hydrographs, followed by a comparison of peak flows, time lag and a discussion on effect of 2D hydraulic and lumped conceptual model storages.

4.3.1 Hydrographs

In general the XP-RAFTS hydrographs peaked earlier, and at a higher magnitude, when compared to the MIKE FLOOD DRM. This was more evident in the short duration storm events. Figures 4.1, 4.2, 4.3 and 4.4 below are hydrographs representing the Eastern, Middle, Western, and Total sub-catchments for the 2 hour storm event. They provide for a general feel of the magnitude and behaviour of the runoff.

It is noted here that the Western sub-catchment exhibits different shaped hydrographs between the two models, most likely a result of the way in which the flows are routed through the series of connected storage basins (refer to Figure 1.2 – storage basins W2-W5). XP-RAFTS simulates runoff through these basins using the user defined elevation-storage and elevation-outflow relationships. The elevation-storage data was kept largely consistent with that described in the MIKE FLOOD model, as both models used the same topographic data. The elevation-outflow relationship in the XP-RAFTS was also established from the topographic data, and derived using Manning's flow equations.

An additional overflow route from sub-catchment storage basin W5 (see Figure 3.2) to the outlet of the Western sub-catchment was also established and represented in XP-RAFTS. It is assumed the variance in hydrograph shape between the models is linked to each having their own unique way of treating storages and dealing with flows in this rather complex scenario. The 2D hydraulic model distributes flows across grid cells, and stores water in depressions. The lumped-conceptual model routes flows according to characteristics defined by the user, and stores water using its non-linear function. Despite the difference in shape, a positive to this situation is that the magnitude of peak flows were generally the same. Intricate investigation into the effects of large storage basins in the model was outside the scope of this project.

Figure 4.1: Eastern Sub-Catchment 50year 2hour Hydrographs

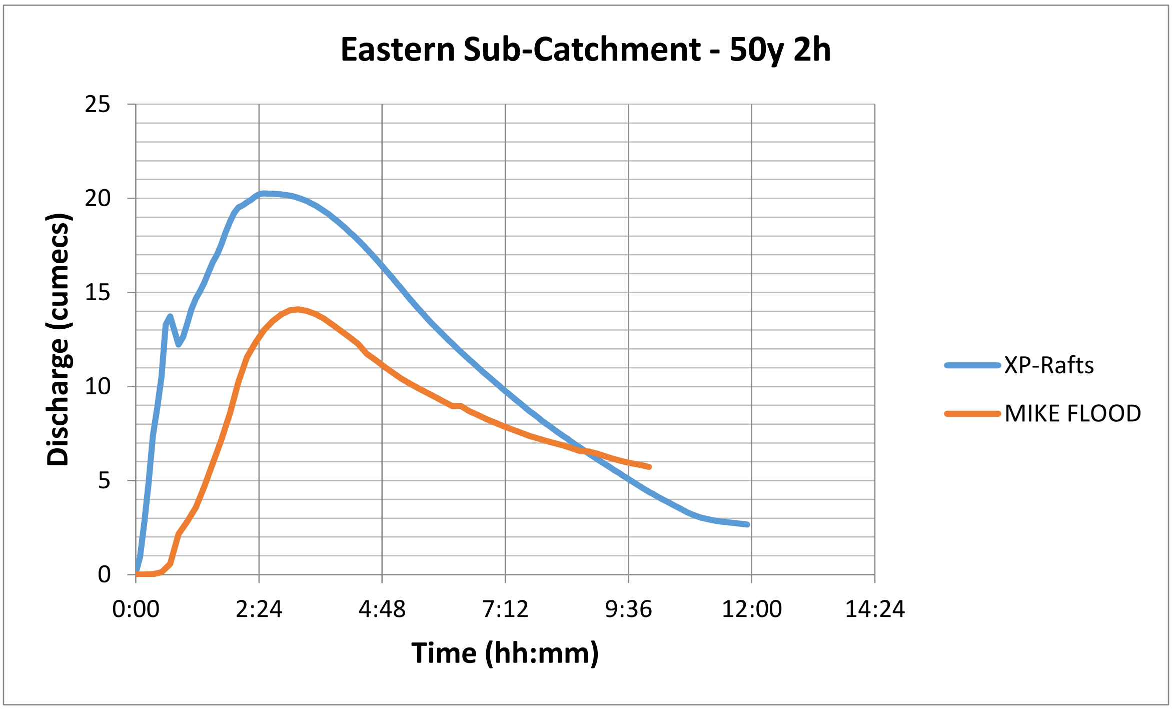


Figure 4.2: Middle Sub-Catchment 50year 2hour Hydrographs

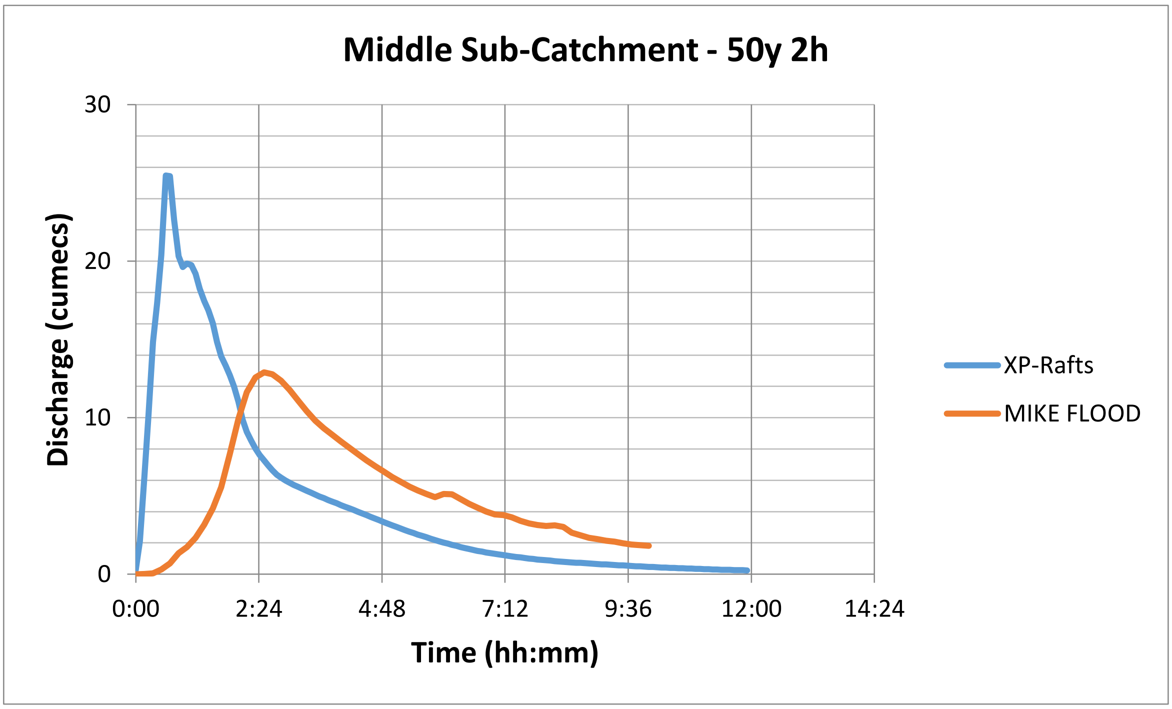


Figure 4.3: Western Sub-Catchment 50year 2hour Hydrographs

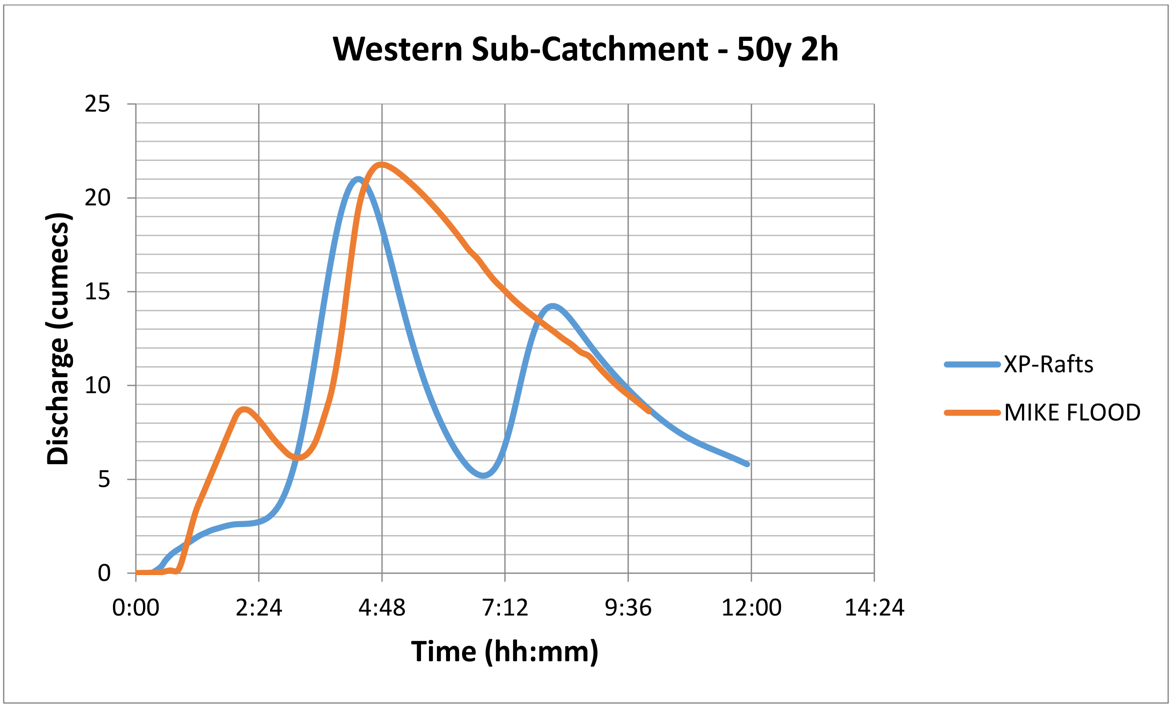
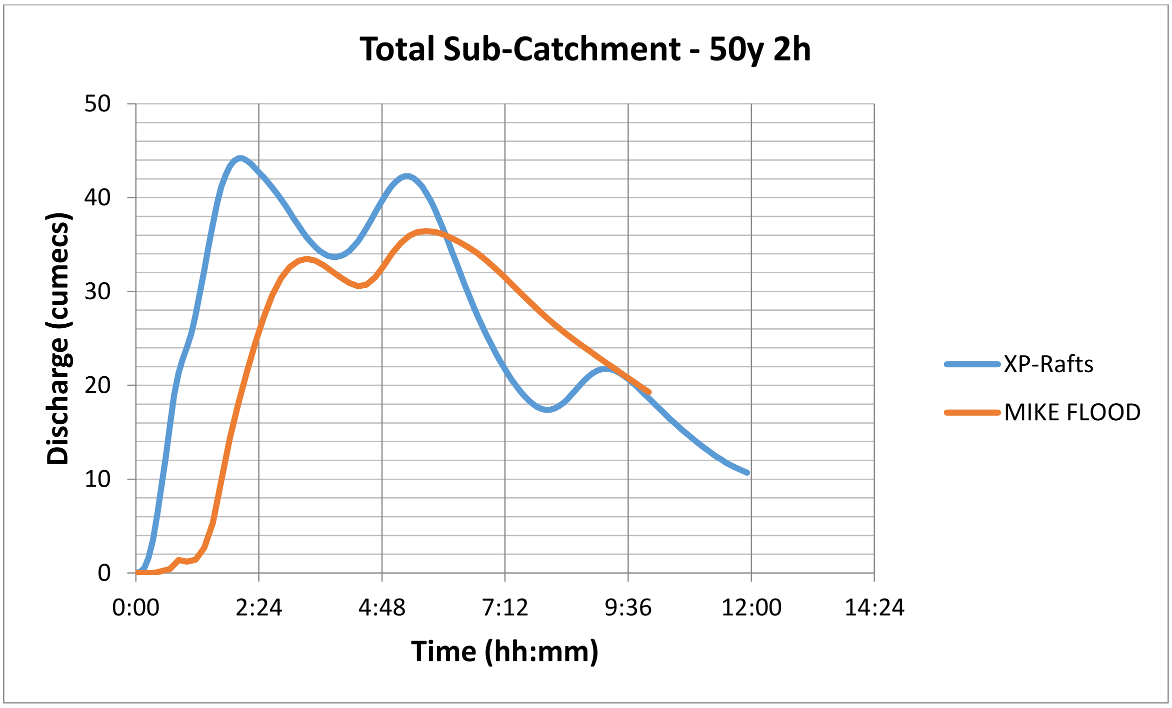


Figure 4.4: Total Catchment 50year 2hour Hydrographs

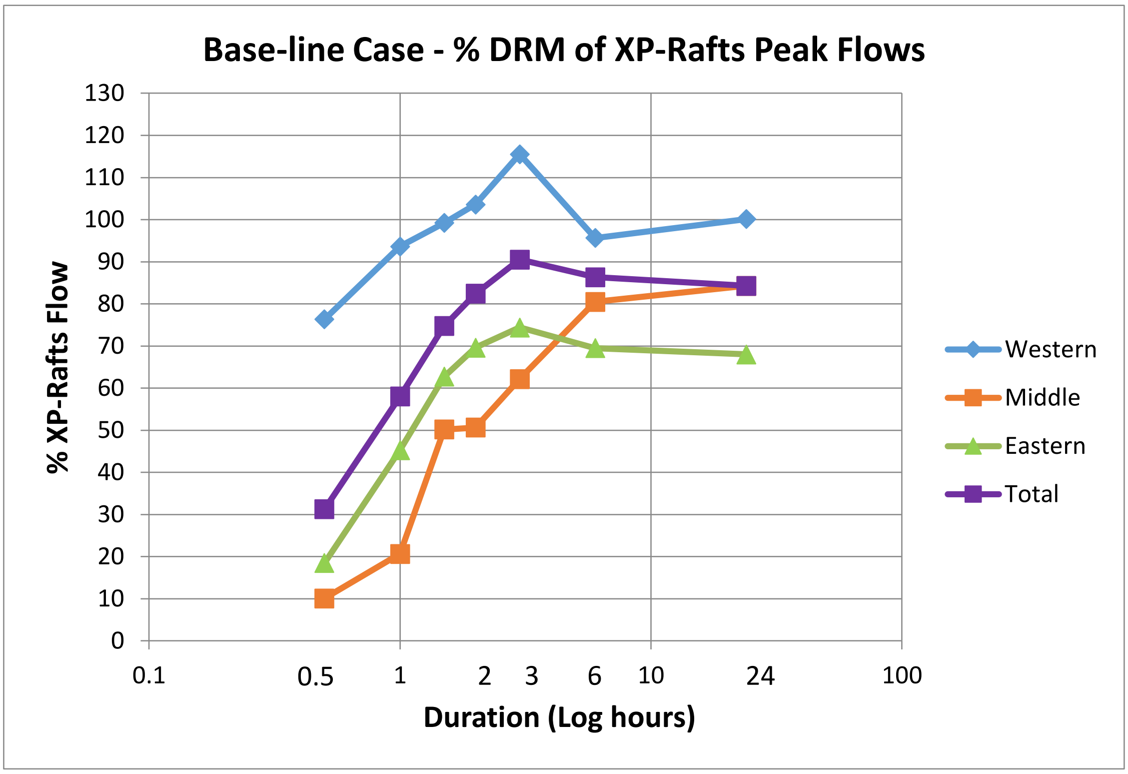


The hydrographs above are representative of only one storm event (2 hour). To analyse how the DRM behaves over a range of storm durations, the peak magnitude and timing to peak are detailed graphically below.

4.3.2 Base-line Peak Flows & Lag Times

The plot in Figure 4.5 below shows the MIKE FLOOD peak runoff magnitudes as a percentage of the XP-RAFTS runoff peaks, for representative sub-catchments. The x-axis signifies the event duration, in units of hour duration on a logarithmic scale.

Figure 4.5: Comparison of MIKE FLOOD (DRM) Runoff Peaks to XP-RAFTS



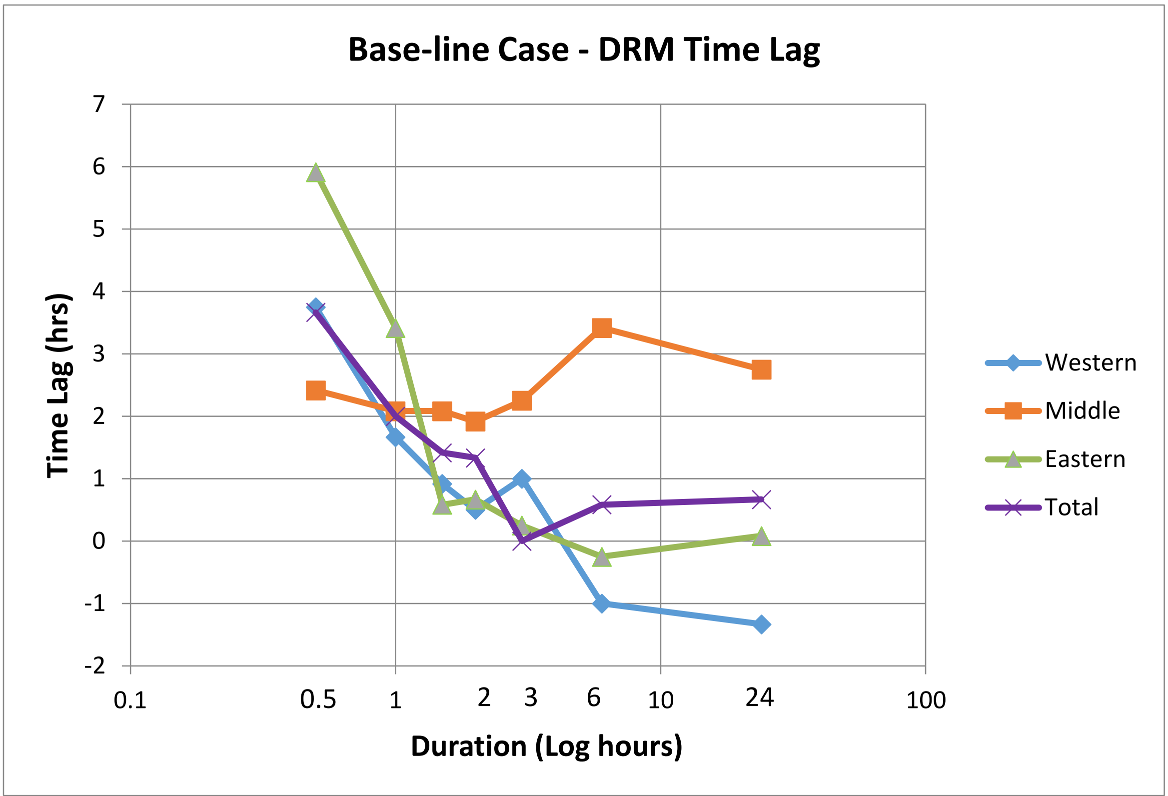
Across all sub-catchments analysed in Figure 4.5, a trend was established that showed as the duration increased so did the MIKE FLOOD peak flows in comparison to XP-RAFTS. This trend followed for up to a 3 hour duration for the Total, Western and Eastern sub-catchments, and up to a 6 hour duration for the Middle sub-catchment. For example, at an event duration of 3 hours for the Total catchment the peak flow was approximately 90% that of XP-RAFTS, compared to 31% for the 0.5 hour duration. Further explanation of this trend is discussed below in section *4.3.3 – Storage Effect of 2D Hydraulic Model*. From here it is observed that the percentage peak flows flattened out toward the 24 hour duration event for the majority of the catchments, with the exception of the Middle sub-catchment.

The flows within the DRM of the Middle sub-catchment differed to all others by being the least similar to the lumped-conceptual XP-RAFTS. The XP-RAFTS peak flows of the Middle sub-catchment are much higher than those of MIKE FLOOD in comparison to the other catchments, and also occur much quicker. As seen in Figure 4.5 above, this highly fraction impervious sub-catchment gave quite low percentage comparative flows of between 10% and 60% for the 0.5 hour and 3 hour durations respectively

In contrast, the Western sub-catchment showed almost matching flows to XP-RAFTS. Reasons for these are detailed below in sections *4.3.3* and *4.3.4*.

The plot below in Figure 4.6 displays the time lag of the MIKE FLOOD peak flow when compared to XP-RAFTS.

Figure 4.6: Time Lag of MIKE FLOOD (DRM) relative to XP-RAFTS



As seen above, the time lag of the DRM can be quite large for small duration events. For example, the 0.5 hour duration of the Eastern sub-catchment had a time lag of 5.9 hours. The general trend of the Eastern, Western and Total catchments showed a decrease in time lag as the duration event increased. These catchments showed close comparison to XP-RAFTS in time of peak for durations over 1.5 hours. Most time lags past this duration event were below 1.5 hours, with some exceptions where the DRM did the opposite and peaked before XP-RAFTS. The Western sub-catchment was one of these, peaking 1.3 hours prior to XP-RAFTS. As noted earlier, this sub-catchment is affected by a series of storage basins, and the shape of the hydrographs are different between models. Similar to the peak flow comparison, the time lag of the catchment runoffs tended to flatten out as they approached the 24 hour duration.

The Middle sub-catchment was the only catchment here to increase and maintain its time lag in higher duration events such as the 3, 6 and 24 hour. This finding is considered to be impacted more so by XP-RAFTS' treatment of storage in response to a highly fraction impervious land use, and this is discussed further in section *4.3.4* below.

Storage in a hydrologic or hydraulic system generally results in both attenuation of runoff times and lowering of its peak magnitude, most of which is occurring for the smaller duration events and less in the larger events of the DRM when compared to the lumped-conceptual XP-RAFTS. This effect is further investigated in the following section.

4.3.3 Storage Effect of MIKE FLOOD

Storages within the MIKE FLOOD model were found to be the cause of lower flows and increased time lags discussed in the previous section. By looking at the volume of water stored as a percentage of that received by rain after an event has been simulated, it is possible to grasp the severity of its effect on the runoff hydrograph. If the capacity of available storage is quite large in comparison to the volume of rainfall applied, it is obvious that less runoff is experienced by a catchment. Consequently the magnitude of flow will be attenuated, and the time to its peak will be lagged.

Figures 4.7 and 4.8 below represent results of the DRM for large catchments and smaller internal sub-catchments respectively. For purposes of this section of the dissertation, large catchments are those of the Eastern, Middle, Western and Total catchments. Small catchments are described as sub-catchments M4, W4, 9 and 7A, and are of exact dimension and location to that shown in the XP-RAFTS model of Figure 3.2. Figures 4.7 and 4.8 show the volume of water stored in the 2D grid domain (at the end of the simulation) as a percentage of the volume of rainfall applied to their respective catchments. They compare this percentage for the 1 and 24 hour durations.

It is noted that MIKE FLOOD applies initial and continuing losses prior to it being simulated as rain on the 2D grid. Losses used in the tests of Figures 4.7 and 4.8 below were an initial loss of 24mm and continuing loss of 2.5mm/h for pervious surfaces, and 1mm and 0mm/h for initial and continuing losses of impervious surfaces respectively.

Figure 4.7: Percentage Volumes of Storage to Rainfall for Large Catchments

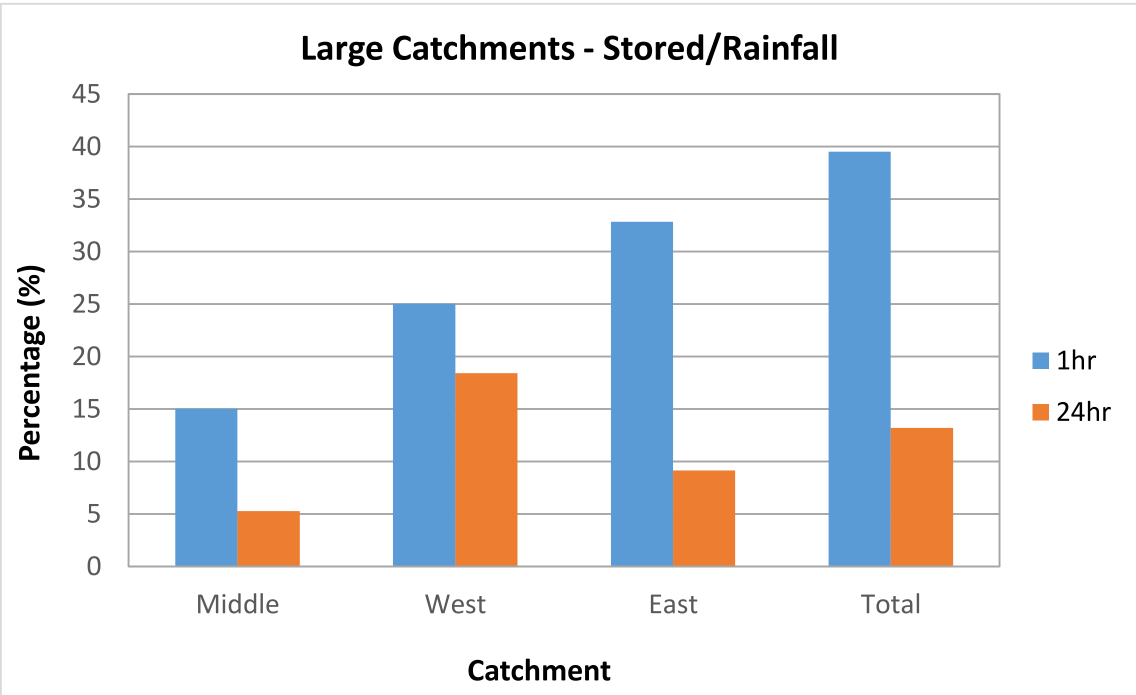
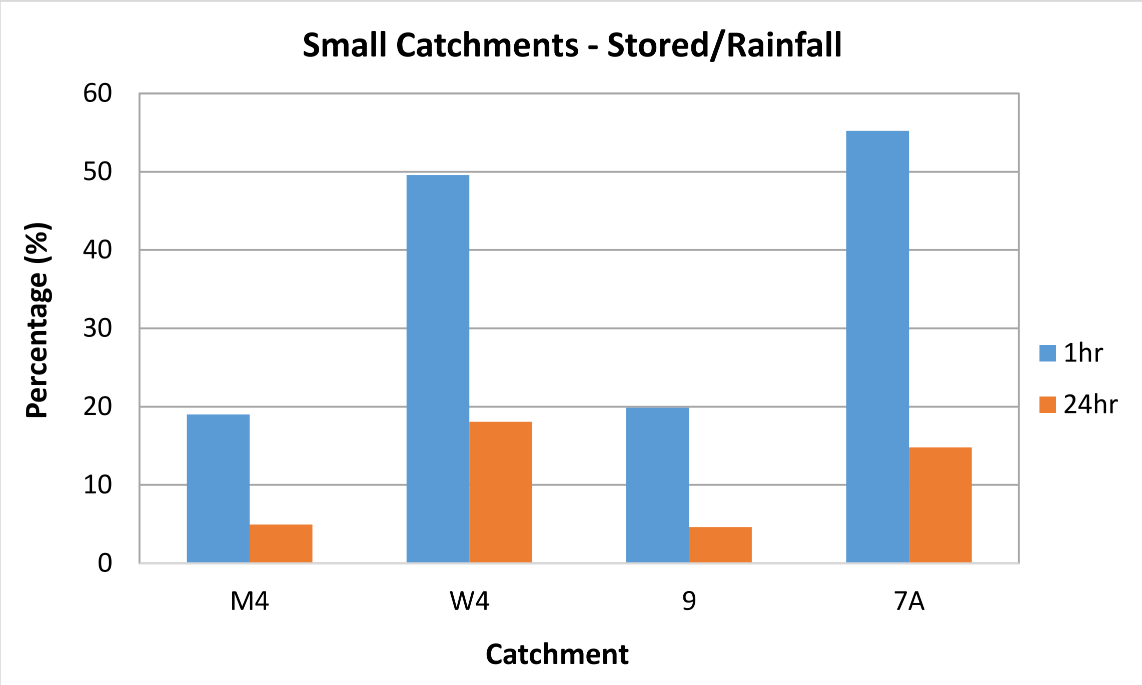


Figure 4.8: Percentage Volumes of Storage to Rainfall for Small Catchments



It is evident here that for all catchments analysed within the MIKE FLOOD model, the 1 hour storm duration stored a greater proportion of its received rainfall than the 24 hour duration. The Total catchment of Figure 4.7 shows that the model stored 39.5% of rainfall it received in the 1hour event, compared to 13.2% for the 24 hour duration. This trend indicates that storages within the 2D Hydraulic model have a greater effect on shorter duration events than longer ones. As storage has a direct relationship with peak flow and time, these effects are subsequently evident in the previous section of 4.3.2. Thus the reason for the DRM having peak flow attenuation and lag times in the results of section 4.3.2 above can be linked to the effect of storages within its 2D grid terrain.

An analysis of this relationship over all durations modelled as part of this project would have been desirable, particularly to identify trends similar to that of Figures 4.5 and 4.6. Unfortunately the simulation period setup for the initial runs of the models were not sufficient enough to capture fully drained hydrographs (where all runoff has left catchments), and data for the above had to be re-run for longer simulation periods. These models took a computation run time of 35-45 hours each, and a further allotment of time for manual extraction of data from the models. Due to time constraints of the project it was not possible to compare all duration storm events, however the findings above suffice for purposes of the project.

The Western sub-catchment, and one of its internal sub-catchments W4 (Figures 4.7 and 4.8 respectively) showed the highest percentage of all catchments for the 24 hour duration. This is a consequence of the storage basins capturing and retaining a majority of the runoff. Referring back to 4.3.2, it was noted that the Western sub-catchment's flows of the DRM closely matched those of XP-RAFTS. Such close comparison is believed to be from the inclusion of storages in the XP-RAFTS model. The basins W5, W4, W3, and

W2 behaved as, and accommodated for, storages in the same way the MIKE FLOOD DRM did. Besides the hydrograph shapes and time of peaks differing, the peak flows were nonetheless similar. Whilst the hydrograph shape may have differed between the two models, these findings suggest that inclusion of storages in the XP-RAFTS model provide for almost matching flows. It also points out the potential lack of storage in XP-RAFTS, when compared to MIKE FLOOD, and this is discussed below in section 4.3.4.

It is observed that the Middle catchment and one of its smaller sub-catchments M4 had the lowest percentage of stored to rainfall volume within the MIKE FLOOD model. The 1 hour durations had stored less than 20%, and the 24 hour durations approximately 5%. The low storages are a consequence of this catchment having a high fraction impervious land use. High fraction impervious surfaces are usually smoother and have little depression storages, thereby increasing volume runoff because infiltration is reduced (U.S Department of Transportation – Federal Highway Administration 2001).

A further point of emphasis noteworthy to the storage effects of MIKE FLOOD, but outside the scope of this project, is the influence of slope. Runoff is related to slope, and as slope becomes steeper the rate of flow increases. Much of the Low Drain catchment consists of grades below 0.5%, and as a consequence the 2D MIKE FLOOD grid model will attenuate flows to a greater extent than that of a catchment with steeper grades.

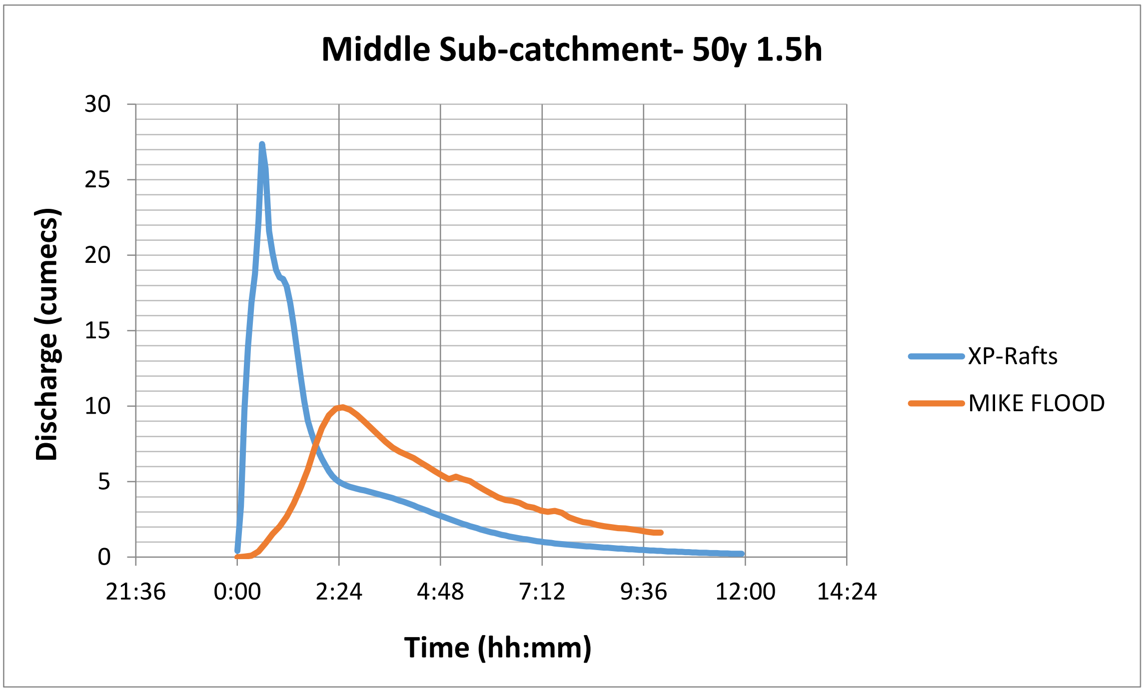
4.3.4 Storage Effect of XP-RAFTS

The above section outlined the behaviour of the MIKE FLOOD model in relation to how its storages are affected. This section investigates how XP-RAFTS treats storages, and why they are quite different to MIKE FLOOD. The below discussion highlights why XP-RAFTS stores little volume in comparison to MIKE FLOOD, and why this is more evident in higher fraction impervious surfaces.

Referring to Appendices F.1 and I.1, the fraction impervious of the Middle sub-catchment for each model was the highest among all sub-catchments, having values up to 60% fraction impervious. These high values were previously defined as part of the AECOM model (AECOM, 2012) for reasons particular to its flood study, and not defined as part of this project. A catchment with a high fraction impervious results in a fast occurring and higher peaking runoff hydrograph when compared to lower fraction impervious.

Looking at the hydrograph of Figure 4.9 below the peak in the XP-RAFTS model is large and occurs quite quickly, as it does in almost all results of this project. Although both models were prepared with similar fraction impervious for all catchments, it appears as though XP-RAFTS was far more sensitive with its response, also peaking much higher.

Figure 4.9: Middle sub-catchment 50year 1.5hour duration hydrograph



To investigate this further, the time of peak flows from the Middle sub-catchment were compared to the time at the peak of the temporal patterns from AR&R (Pilgrim, 1987). These temporal patterns relate to Zone 3, for ARI > 30 years, and define the behaviour of the storm. Figure 4.10 shows the 1.5 hour duration as an example.

Figure 4.10: AR&R Temporal pattern for 1.5 hour duration

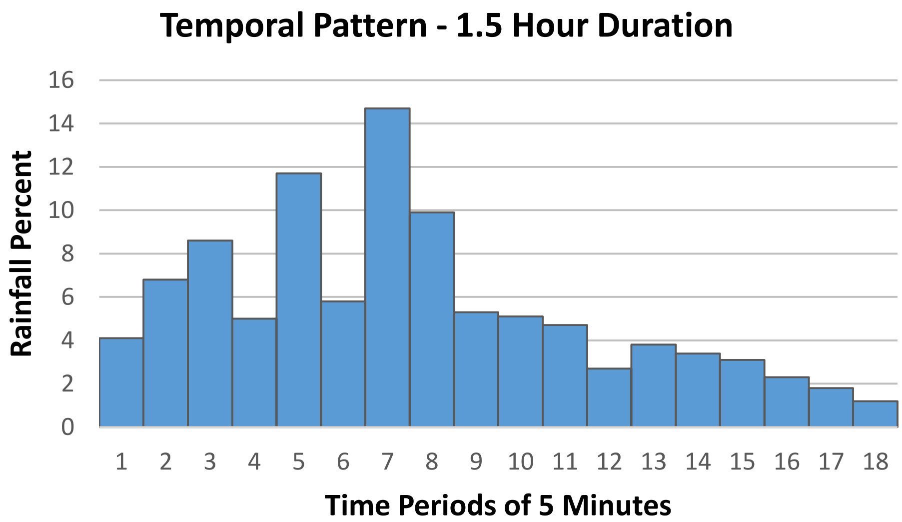


Table 4.1 below compares the runoff and temporal pattern peak times for all durations tested.

Table 4.1: Middle sub-catchment peak runoff times & temporal pattern peak times

Middle Catchment Duration (h)	Temporal Pattern Peak Time (hh:mm)	XP-RAFTS Runoff Peak Time (hh:mm)
0.5	0:15	0:15
1	0:25	0:25
1.5	0:35	0:25
2	0:35	0:35
3	1:00	0:55
6	1:15	1:25
24	2:00	1:55

As you can see, the peak runoffs for all durations occurred almost instantaneously with the storm burst peak of the temporal pattern. If XP-RAFTS is peaking at the same time as the temporal pattern, then it is assumed that very little storage is being accounted for in the model. To investigate this effect, the treatment of storage within XP-RAFTS is considered in further detail below.

As outlined in Section 2.2 the storage equation is given as:

$$S = BQ^{n+1}$$

where S is storage, B is the storage delay time coefficient and n is the storage non-linearity exponent. Using this function it is possible to examine the storage at a particular point in time of a catchment.

It is noted that,

$B = 0.285 \times A^{0.52} \times (1+U)^{-1.97} \times S_c{}^{-0.50}$, where A is the area in kilometres squared, U is the fraction of the catchment that is urbanised, and S_c is the main drainage slope.

$$n = -0.285\ (default\ XP\text{-}RAFTS\ value)$$

The Middle sub-catchment at the peak discharge of the 1.5 hour duration event was selected for inspection. Two cases were investigated, one being that modelled as part of the testing (approximately 50% fraction impervious), and the other scenario where no urbanisation occurs. Below are the results in Table 4.2 for storages based on the above equations. The storage in the MIKE FLOOD model at this same location and instance in time for the 1.5 hour duration is listed in Table 4.2 below for comparison.

Table 4.2: Storages of Middle Catchment using XP-RAFTS non-linear function

Case	Area (km^2)	U	Sc (%)	B	Q (m3/s)	Storage, S (m^3)
50% Impervious (Modelled)	1.5977	1	0.313	0.165906	27.371	**6,365**
0% Impervious	1.5977	0	0.313	0.649965	27.371	**24,938**
MIKE FLOOD	-	-	-	-	-	**156,022**

The MIKE FLOOD model at its peak runoff time stores 156,022m^3, much greater than 6,365m^3 of XP-RAFTS. XP-RAFTS' storage volume is only 5% that of MIKE FLOOD here. As the XP-RAFTS storage is a function of runoff, if this value was tripled for argument sake (82.1m^3/s), this would in turn see storages only double that of above.

As seen in Table 4.2 above, when the fraction impervious in XP-RAFTS is reduced to a rural scenario of 0%, the storage is increased to almost four times that of the 50% fraction impervious case. However, regardless of the degree of urbanisation in XP-RAFTS, the storages that it calculates are overshadowed by those in the MIKE FLOOD model. The 0% fraction impervious was compared in the above scenario so as to point out the influence that degree of urbanisation has on XP-RAFTS itself.

XP-RAFTS' non-linear function produces low storage volumes compared to MIKE FLOOD, and illustrates why peak flow magnitude and time are affected. Its low account for storage is why runoff is almost instantaneous with the temporal pattern described above. The results in section 4.3.2 Figure 4.6, where the DRM lag times were approximately 2 hours or greater for the Middle catchment for all duration events, are a consequence of the low storage in XP-RAFTS, in combination with a high fraction impervious surface, resulting in a fast occurring XP-RAFTS peak.

Going back to the previous discussion on the Western sub-catchment in section 4.3.3, through user defining storages within XP-RAFTS, peak flows are more closely matched between the models. Supplementing the XP-RAFTS model with additional storage, the volume retained in its model was able to be more appropriately matched to that of MIKE FLOOD.

The investigation of the storage effect of XP-RAFTS was not originally within the scope of the project, however its influence on results are noteworthy. Unfortunately its effect could not be investigated in entirety through sensitivity analysis due to the time constraints of the project.

4.4 Volume Checks

Both models were found to adequately conserve mass, with only minor errors in volumes encountered. Volume checks were undertaken for the 3 hour and 24 hour duration events over all catchments. The rainfall volumes of both models detailed below are representative of those after losses (initial and continuing) have been applied.

The MIKE FLOOD volumes are below in Tables 4.3 and 4.4 for the 3 hour and 24 hour durations respectively. It is noted here that the runoff volumes represent only as much of the hydrographs that were captured as part of the model simulation. Some catchments required further simulation time for a fully draining hydrograph, however this does not affect the mass calculations set out below. As shown the MIKE FLOOD model adequately conserved mass with all errors below 5%, except for the 24 hour duration of the Eastern catchment, which had an error of 6.251%.

Table 4.3: MIKE FLOOD Volume Checks for 3 hour Duration

Catchment	Stored (m^3)	Runoff (m^3)	Runoff+Stored (m^3)	Rainfall (m^3)	% Error
Western	267929.5	41538.8	309468.4	313329.0	1.247
Middle	63537.4	176431.9	239969.3	237159.2	1.185
Eastern	163529.3	158201.3	321730.6	307401.1	4.661
Total	665623.6	366745.1	1032368.7	1008409.3	2.376

Table 4.4: MIKE FLOOD Volume Checks for 24 hour Duration

Catchment	Stored (m^3)	Runoff (m^3)	Runoff+Stored (m^3)	Rainfall (m^3)	% Error
Western	334404.4	371293.9	705698.3	700337.0	0.766
Middle	101694.1	427806.0	529500.1	527754.3	0.331
Eastern	189190.1	539098.9	728289.0	685443.2	6.251
Total	834255.1	1485652.5	2319907.7	2248380.3	4.557

The XP-RAFTS results log file only provides rainfall data, thus any stored volume left after the simulation was determined by subtracting the runoff volume from the rainfall volume. The storage volume was compared as a percentage of the total rainfall. In tables 4.5 and 4.6 below, the 3 hour and 24 hour durations volumes are given respectively.

Table 4.5: XP-RAFTS Volume Checks for 3 hour Duration

Catchment	Rainfall (m^3)	Runoff (m^3)	Stored (m^3)	% Stored
Western	723352	292350.6	431001.4	59.6
Middle	250305.2	244221.6	6083.631	2.4
Eastern	663627.9	604482.5	59145.41	8.9
Total	1791986	1436204	355782.6	19.9

Table 4.6: XP-RAFTS Volume Checks for 24 hour Duration

Catchment	Rainfall (m^3)	Runoff (m^3)	Stored (m^3)	% Stored
Western	1830945	1452506	378438.9	20.7
Middle	637540.3	621792	15748.28	2.5
Eastern	1682281	1555249	127032.8	7.6
Total	4544146	3902498	641648.1	14.1

As seen above, the Western sub-catchment had the largest volume left stored in the model after simulation, with 59.6% and 20.7% for the 3 hour and 24 hour durations respectively. This is due to the storage basins capturing much of the applied rainfall volume. The Total catchment displayed a considerable amount also, having 19.9% and 14.1% of the total rainfall volume being stored within the model after simulation. Upon inspection of hydrographs it was visible that all runoff had not left the model at the end of the simulated period, due to the short run simulation period. It is suggested that runs in the future are simulated long enough to capture the full hydrograph, so that results can be interpreted adequately. The storage basins of the Western sub-catchment would also be adding to the percent storages of the Total catchment.

It is noted here volumes are different between the two models as MIKE FLOOD consisted of a mass balance over only its direct rainfall on grid area, and not the source inflows from the XP-RAFTS.

4.5 Sensitivity Testing

As discussed previously, sensitivity testing was undertaken to determine if adjustments to model parameters in the MIKE FLOOD model had a compensating effect for its lack of runoff comparison to XP-RAFTS. It is reiterated here that the XP-RAFTS model parameters remained constant throughout all sensitivity tests. Testing methodologies are discussed in section *3.4.2* above, along with the methods for results analysis in section *3.5.5*.

4.5.1 Losses

The results of this test are shown in Appendix C.1 and C.2 for the percentage peak flows and time lags respectively. They represent the MIKE FLOOD peak runoff magnitudes as a percentage of the XP-RAFTS runoff peaks. Similarly they show the time lag of the MIKE FLOOD model. The x-axis in these appendices signifies the event duration, in units of hour duration on a logarithmic scale.

The tabulated results of the peak runoff results are in Appendix B.1 and B.2. Across all catchments it was observed that by decreasing the initial loss values of the MIKE FLOOD model, its peak runoff magnitudes subsequently increased. By taking the average percentage of these results across all catchments, this can be seen in Table 4.7 below.

Table 4.7: Average of Percentage Flows (m^3/s) of MIKE FLOOD to XP-RAFTS - Losses

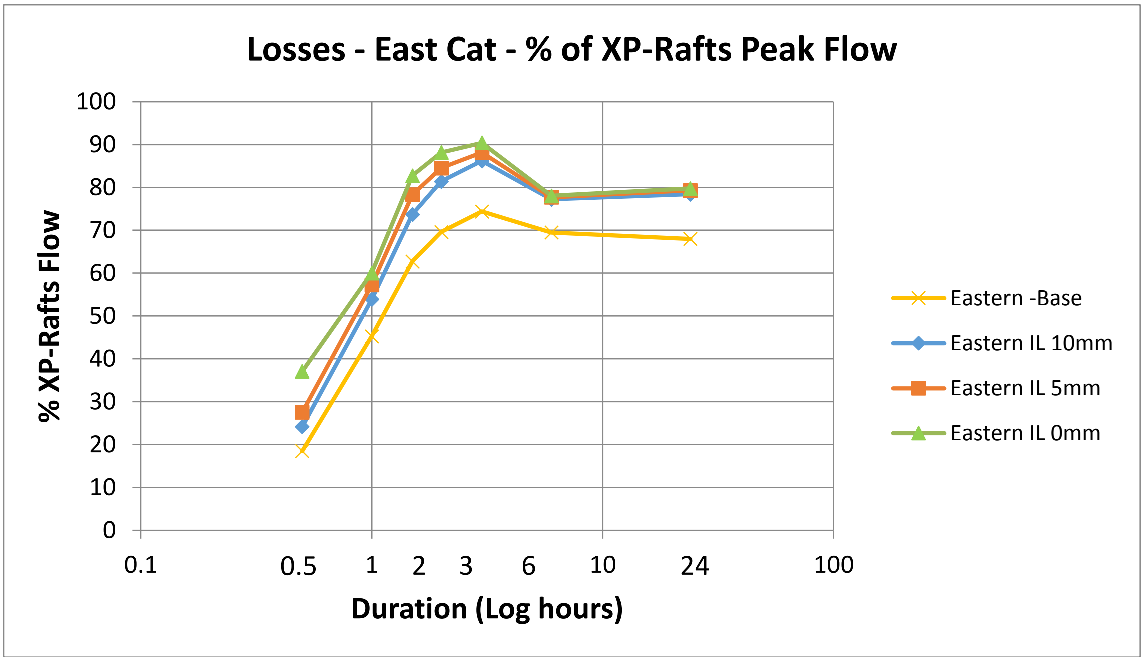
	0.5	1	1.5	2	3	6	24
IL Base (24mm)	34.0	54.4	71.7	76.6	85.7	83.0	84.2
IL 10mm	46.0	62.0	75.7	85.5	95.1	91.5	95.6
IL 5mm	50.1	65.1	78.6	88.5	96.7	92.2	96.5
IL 0mm	56.2	67.7	82.2	91.4	98.7	92.8	97.0

Looking at the Eastern Catchment in Figure 4.11 below (refer also Appendix C.1), the percent peak flow of the 0.5 hour duration MIKE FLOOD base-line case was 18.5%, and this value improved to 37.1% for the initial loss of 0mm. The time lag for this catchment in Appendix C.2 showed an improvement in the MIKE FLOOD model of 2.2 hours for this same duration. The time lag improved and converged with that of the base-line test in the longer duration events.

The Middle and Total Catchments exhibited similar effects from the losses tests. The 0.5 hour duration saw increased percentages of 6.9% and 19.7% from the base-line test to the 0mm initial loss test, for the Middle and Total catchments respectively. For the 24 hour duration this was 27.3% and 10.7%.

For the MIKE FLOOD DRM flows to be of similar magnitude to the XP-RAFTS lumped-conceptual model, not only do losses have to be reduced but the event duration must be large. For purposes of sensitivity testing comparison, values within 10% of each model are considered acceptable for similarity by the author. Thus, from the results shown in Table 4.7, the DRM is similar for initial loss values of 10mm or less for durations of 3 hours or greater. The minor exception of the 2 hour event with an initial loss of 0mm exists. Whilst altering the loss values shows improvements for all duration events, on a grander scale it appears as though the storage effect of section 4.3.3 has more of an impact on the DRM.

Figure 4.11: Eastern Catchment – Losses Test – MIKE FLOOD peak flows as a percentage of XP-RAFTS



An average of all the time lags are below in Table 4.8 across all durations for each test are shown below. As the initial losses decreased, so did the time lags. In a similar fashion to the flow comparison above, the time lags improved as the duration event was greater.

Table 4.8: Average of Time Lags (hours) - Losses

	0.5	1	1.5	2	3	6	24
IL Base (24mm)	5.4	3.1	2.0	1.7	0.9	0.6	0.5
IL 10mm	3.4	1.8	1.0	0.9	0.3	0.2	0.2
IL 5mm	2.9	1.8	0.9	0.8	0.2	0.1	0.1
IL 0mm	2.9	1.6	0.9	0.9	0.2	0.1	0.1

4.5.2 Roughness

The results of this test are shown in Appendix D.1 and D.2 for the percentage peak flows and time lags respectively. They represent those of the MIKE FLOOD model, in comparison to XP-RAFTS. The tabulated results of these are in Appendix B.1 and B.2. Across all catchments it was observed that a decrease in roughness values resulted in an increased peak runoff magnitude. Looking at the Western, Eastern and Total catchments in Appendix D.1, it is seen that the effects of roughness are most evident in the 3 hour duration event. For example, the Total catchment had an increase from 90.5% to 109.5% as the roughness was altered from the base-line case to the -30% roughness for the 3 hour duration. It is noted here this duration had the closest match to XP-RAFTS for all but the Middle sub-catchment.

The average of the percentage flows from all catchments are show below in Table 4.9.

Table 4.9: Average of Percentage Flows (m^3/s) – Roughness

	0.5	1	1.5	2	3	6	24
Roughness Base	34.0	54.4	68.3	76.6	85.7	83.0	84.2
Roughness -10%	36.2	56.3	71.1	80.3	89.4	84.8	85.8
Roughness -20%	37.5	56.6	74.3	84.9	94.1	86.9	87.6
Roughness -30%	39.0	59.7	78.1	90.0	99.9	89.3	89.8

As seen above in Table 4.9, not many situations exist where the DRM is at 90% that of XP-RAFTS. Those that do are roughness values that are 30% smoother than the base-line case, but this only occurs in the higher durations above the 2 hour event. Roughness values for the -10% and -20% cases do provide close match above 80%, but again this only occurs in longer durations, over 2 hours.

Looking at the plots in Appendix D.1, all catchments except for the Western were not greatly affected by decrease in roughness for durations of 0.5, 1 and 1.5 hours. For example, the Eastern sub-catchment increased only slightly from 45.3% to 50.1% from the base-line test to the -30% roughness for the 1 hour duration. Compare this to the 6 hour duration where it jumped from 86.3% to 99.3%.

A summary of the average time lags across all catchments is below in Table 4.10.

Table 4.10: Average of Time Lags (hours) - Roughness

	0.5	1	1.5	2	3	6	24
Roughness Base	5.4	3.1	2.0	1.7	0.9	0.6	0.5
Roughness -10%	5.0	2.9	1.8	1.4	0.4	0.5	0.4
Roughness -20%	5.2	2.7	1.6	1.2	0.3	0.2	0.3
Roughness -30%	4.8	2.4	1.3	1.2	0.0	-0.5	0.1

The table above shows similar trends to that of losses. For both the losses and roughness test it is clear that flows and lag times improve in the longer durations. This was the same finding of the storage effect in section 4.3.3. As both peak flow and its timing are related to storage, its influence remains to be of significance, even when losses and roughness are altered to values at the brink representing reality.

4.5.3 Wetting and Drying

The results of this sensitivity test are shown in Appendix E.1 and E.2 for the percentage peak flows and time lags respectively. They represent those of the MIKE FLOOD model, in comparison to XP-RAFTS. The tabulated results of these are in Appendix B.1 and B.2. Wetting and Drying had little to no effect on the results, and the average values from all catchments are below in Tables 4.11 and 4.12 for the percentage flow and time lags.

Table 4.11: Average of Percentage Flows (m^3/s) – Wetting & Drying

	0.5	1	1.5	2	3	6	24
Base	34.0	54.4	68.3	76.6	85.7	83.0	84.2
WD01	36.4	53.8	67.4	75.8	85.5	82.1	83.1
WD02	34.7	53.2	68.2	77.0	86.4	83.4	84.5

Table 4.12: Average of Time Lags (hours) – Wetting & Drying

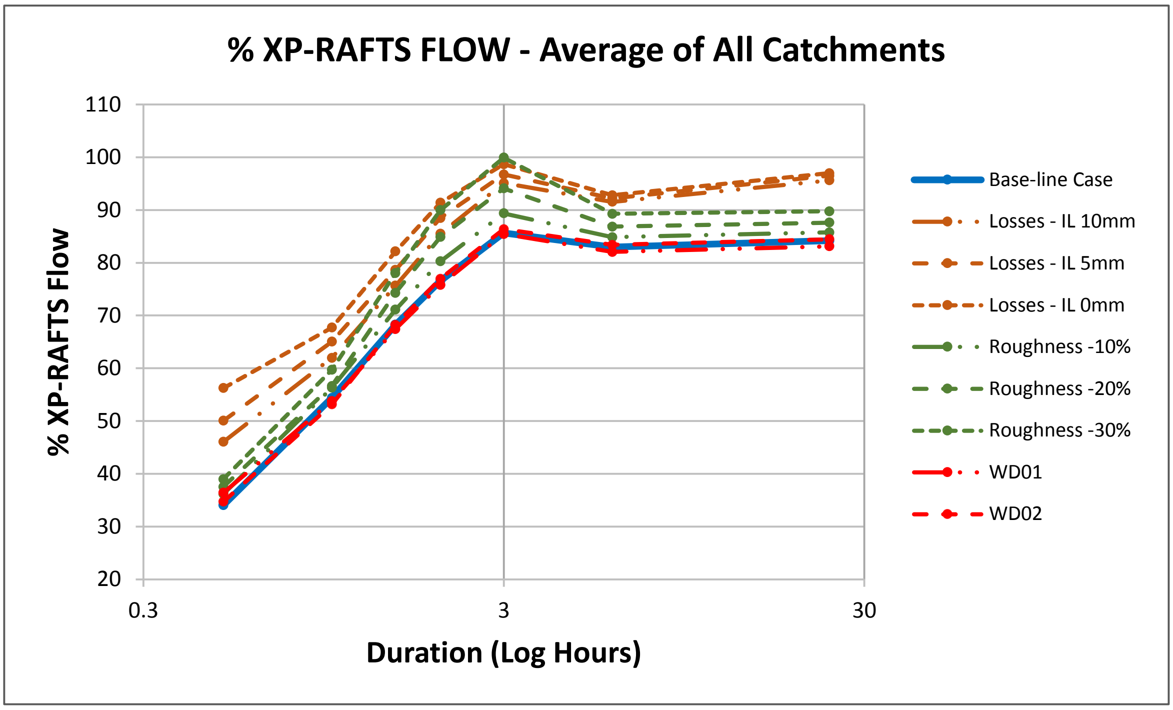
	0.5	1	1.5	2	3	6	24
Base	5.4	3.1	2.0	1.7	0.9	0.6	0.5
WD01	5.3	3.4	2.0	1.7	0.9	0.5	0.6
WD02	5.2	3.1	2.0	1.6	0.8	0.6	0.5

If the wetting and drying values were altered greater than 0.005m this may have resulted in a more sensitive outcome of this test. However, for this particular catchment this would not be practical from an engineering perspective to model values larger than 0.005m, largely due to too much attenuation beyond the realms representative to that of a real storm event. Although this test had little effect on the DRM, it was nonetheless worthy to undertake its analysis. The author did not find any research on the effects of wetting and drying on an actual catchment model. It is envisaged this finding will provide further insight into its impact on flood models for engineering professionals.

4.5.4 Summary of Sensitivity Testing

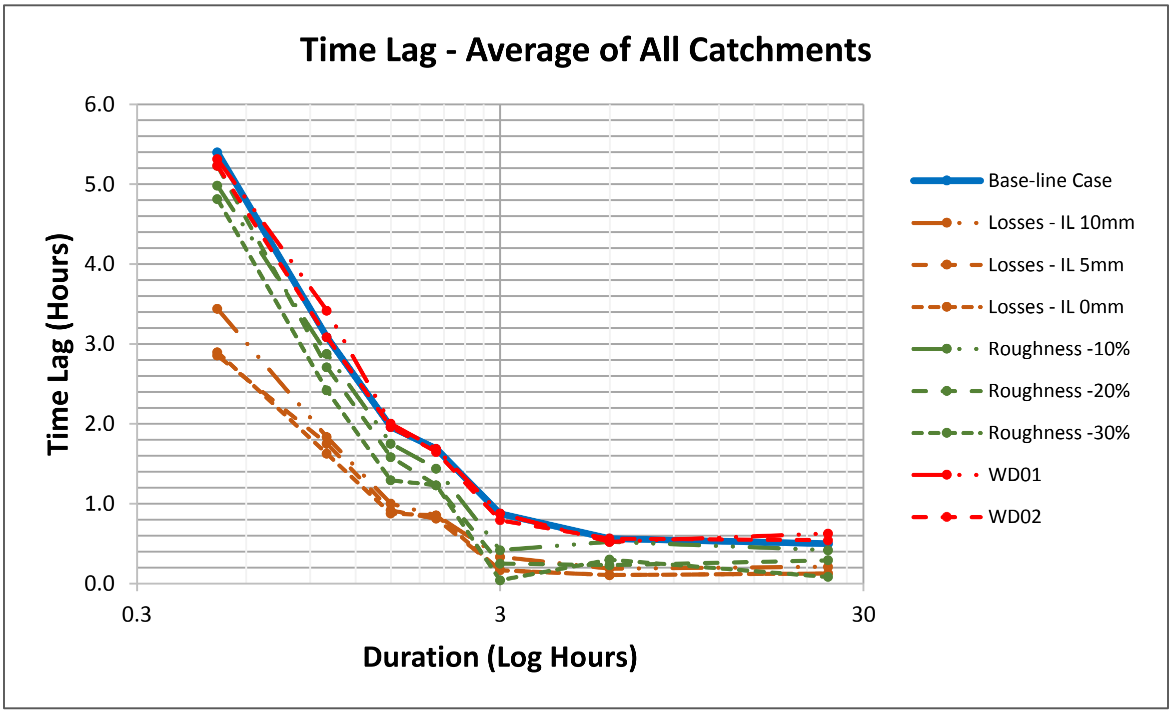
Below are plots summarising the results of the sensitivity for both percent flow comparison and time lag in Figures 4.12 and 4.13 respectively. They consist of results from Tables 4.7, 4.8, 4.9, 4.10, 4.11 and 4.12, and it is noted that these are average values from the catchments modelled. These figures assist in providing a grasp of the entire effect of all sensitivity testing on the models.

Figure 4.12: MIKE FLOOD Flows (as % of XP-RAFTS) Averaged Over All Catchments



The above figure shows that the losses tests had the greatest impact on the DRM. This is not to say that altering the roughness did not have a notable effect. Altering the roughness to -30% of the base-line case at the 3 hour duration showed a marginally better flow comparison than the IL 0mm. The roughness testing showed improved percent flows in the 2 and 3 hour duration events. The roughness alterations of -10%, -20% and -30% were clearly observed, as the percent flows showed obvious increases for each graduation. This was similar for the losses testing, however little graduation occurred in the 6 and 24 hour duration as losses changed from IL 10mm, 5mm and 0mm.

Figure 4.13: Time Lags as Averages of All Catchments



The time lags of the above figure show almost a mirror image of the flow percentage comparison, as one would expect. The shorter duration events leading up to 3 hours show a steep decline in time lag. The time lags after this duration flatten out at values between 0 and 0.8 hours. It is interesting to note that not only does the time lag flatten out, but so too does the percent flows in Figure 4.12.

As a final general statement, pertinent not only to sensitivity but all testing, the above figures suggest the DRM is more suited to the lumped-conceptual XP-RAFTS for durations inclusive and greater than the 3 hour event. The volume of runoff for durations of 3 hours and larger are assumed to outweigh that of its storage volume within the model, thus providing closer matching hydrographs with that of XP-RAFTS. The 3, 6 and 24 hour durations showed generally consistent flow percentages and lag times. Section *4.3.3 Storage Effect of MIKE FLOOD* is consistent with this assumption.

To compensate for the lack of peak runoff similarity to XP-RAFTS, the MIKE FLOOD DRM must be of duration 3 hours or greater, and undergo initial losses of 10mm or less. Adjusting the roughness to 30% less of what is assumed suitable to the catchment would be deemed practically unreasonable in most cases. Hence adjusting roughness to compensate for the DRM model seems an unlikely choice.

The findings from this section consist of averaged data across the catchment, and is not to say that other cases exist due to a range of varying situations of fraction impervious, detentions basins etc.

4.6 Suitability of Duration Events

This project was aimed at providing guidance on the use of the DRM, part of which would review suitability of duration events to the lumped-conceptual XP-RAFTS. This project encountered a combination of factors such as storages and fraction impervious, making it difficult to comment on what duration events are suitable. The findings of this project are nonetheless worthy of documenting.

Base-line Test Results

It is commonly accepted by the industry that results of flow calculations in hydrological methods can vary between 20-30%, however this finding was not found in any publications by the author. Perhaps this may be why analysis of stormwater flooding is coined the term “the black arts”. For these reasons, flows within 30% will be considered of similarity for comparative purposes in the base-line test.

Thus the event durations deemed suitable when compared to XP-RAFTS, along with their defined fraction impervious, are listed below in Table 4.13.

Table 4.13: Event durations of DRM suitable with XP-RAFTS

Catchment	Duration ≥ 70% XP-RAFTS	Fraction Impervious
Western	≥ 0.5 hour	0 – 2%
Total	≥ 1.5 hour	16 – 20%
Eastern	≥ 3 hour	14 – 20%
Middle	≥ 6 hour	35 – 42%

These findings do not give much clear indication as to what duration events of the DRM are more suitable with lumped-conceptual models. The storage and fraction impervious vary across the catchment, subsequently resulting in variable comparative runoffs between the models. The findings do however show that high fraction impervious catchments are more suited in longer duration events within the DRM, when compared to lumped-conceptual models. This is related to findings of Section 4.3.4.

Sensitivity Test Results

It isn't until all test results are averaged across all catchments that a clearer picture of the effects across duration are obvious. Figures 4.12 and 4.13 illustrate this, indicating the significant, yet differing, relationships for durations smaller and larger than the 3 hour event.

As discussed above, for durations of 3 hours and larger, the volume of rainfall outweighs the volume stored providing more complementary runoff results between the models. Even though some results from sensitivity tests show flows within 30% for the 2 hour duration, the trend of these plots suggest the 3 hour duration as a cut-off. It is advised durations below this are used with care in modelling. It is suggested that durations above and inclusive of 3 hours are suitable for modelling.

5.0 Conclusions and Recommendations

The testing of both the MIKE FLOOD direct rainfall method and lumped-conceptual XP-RAFTS were successful, and all models showed to conserve mass adequately. Modelling and analysis were made possible through the use of both traditional and leading-edge engineering techniques, methods, and software tools. Verification of modelling results would have been valuable if rainfall gauging stations and flood levels were available for the catchment area studied. Despite the absence of this data, findings were made possible for purposes of the research project.

The original scope of the project was to investigate the effects of losses, roughness and wetting and drying. To date this had mostly been the forefront of research by Muncaster (2006), Caddis et al. (2008), Clark et al. (2008) and Rehman (2011).

It wasn't until recent years where Taaffe et al. (2011) focused on the effect of storage within grid cells of the 2D hydraulic model. The research undertaken by Taeffe et al. (2011) presented valuable findings, such that pit cells were the cause of peak flow attenuation. The study centred on pit cells as loss mechanisms that were of similar magnitude of initial loss values of traditional loss models. The study however focused only on a 2 hour storm duration.

At the analysis stage of this project on Low Drain, it became evident that storages within the 2D grid domain of the DRM had a significant influence on the results, hence the requirement for further investigation as part of the project.

This project expands on the findings of Taaffe et al. (2011), exploring storage effects within the 2D model for a number of duration storm events. As storage influences runoff, its impact on the DRM when compared to the lumped-conceptual model was recognized. This project established that when rainfall was applied to the 2D grid domain, storages in the model impacted the lower volumes of the short durations more greatly than the higher volumes of the longer durations. Consequently results showed more prominent effects of peak runoff attenuation and time lag for short durations. This finding is the first known to industry, bringing much value to flood analysts. Short durations were found to be those of the 0.5, 1, 1.5 and 2 hour events. Long durations were those of the 3, 6 and 24 hour events, and their runoff peak magnitudes showed improved match to the lumped-conceptual model.

XP-RAFTS treats storages differently to that of the DRM MIKE FLOOD model. XP-RAFTS uses its non-linear function of discharge to develop a conceptual storage. Therefore as discharge increases so too does the storage. Other parameters such as fraction impervious will affect runoff response, as found by the highly urbanised Middle sub-catchment where storage was a factor of four times that of a hypothetical rural scenario.

This report established the large difference in storages calculated by each model through inspection of an internal sub-catchment. Here the storage at the time of peak for one duration was calculated, showing differences of 95% in volume between the models. This is consistent with the effect of storage on the runoff hydrographs, where the DRM model attenuated flows significantly more than the lumped-conceptual model. XP-RAFTS stored very little of the rainfall applied, hence why its runoffs were considerably higher and occurring rapidly. As mentioned above, it wasn't until rainfall volumes were large that MIKE FLOOD runoffs showed closer comparison with XP-RAFTS.

The effect of storage can explain the results of Clark et al. (2008), where it was discovered that their lumped-conceptual model began to drain almost immediately, whilst the DRM models appeared to 'exhibit significant delays prior to the commencement of runoff' (Clark et al. 2008, p. 2505). Research by Rehman et al. (2003), Caddis et al. (2008) and Clark et al. (2008) observe the DRM as experiencing longer runoff times. AR&R (2012) attribute some of the longer runoff times of the DRM to 'the impact of hydraulic controls such as bridges and culverts along the routing flowpath, which are absent in a traditional hydraulic model' (AR&R 2012, p. 11-188). Whilst this statement is true to some extent, this project reveals that it would rather be a case of bulk storages being absent in the traditional model. AR&R (2012) do go further to say that the DRM has been known to result in longer runoff times when in a simple terrain without structures. Documented reasons for lag times had not been explored until the time of this research project.

Confirming the abovementioned impacts of storages further, inspection of the Western sub-catchment showed similar runoff results between the models. Although hydrograph shapes differed between models, the magnitude of peak runoffs were comparable. Large storage basins of the sub-catchment were defined in XP-RAFTS, thus supplementing this model with storage of similar degree to that within the 2D hydraulic model. Whilst providing user-defined storages within XP-RAFTS delivered desirable runoff peak magnitude with MIKE FLOOD, such modelling replication in XP-RAFTS is not practical for scenarios like that of floodplains where small depressions are spatially scattered throughout a catchment.

Differences in storages are attributed to the way each model treat them. The DRM accommodates for storages by depressed grid cells in its 2D grid terrain. XP-RAFTS uses a function of discharge. There is no suggestion that one method is more suitable than the other, with both methods recognised for their successful calibration to gauged catchments. The implications of this project are that further research is required into the effect of storages between the models, in an attempt to provide confidence in the use of each model.

It is noted that catchment slope would contribute to the effect of storage in each model. Low Drain is mostly flat grading, exhibiting grades mostly below 0.5%, and this would no doubt have a more extreme outcome on the results when compared to a steeper catchment. The flat grades of the Low Drain catchment would have slowed flows and resulted in more attenuation, and this would be more evident in the MIKE FLOOD model where many depression pockets exist. As such investigation was outside the scope of the project, future analysis is suggested. Another component to be explored is the 'storage coefficient multiplication factor' in XP-RAFTS. This factor can be applied to uniformly alter the storage delay time coefficient 'B' over the entire catchment. Catchments with lower grades may warrant the use of this factor to accommodate for attenuation. However such use would need to be calibrated to a gauged catchment for verification.

Flood modellers practicing stormwater engineering, particularly in tropical North Queensland, can expect inherently different runoff magnitudes and times with DRM and lumped-conceptual models. This project found this will be particularly noticeable in storm events lower than a 3 hour duration. This is consistent with the findings of Clarke et al. (2008) where differences between models were more pronounced for smaller duration events. For this reason it is suggested that care is exercised when modelling durations less than 3 hours with the DRM. Further to this, modellers should apply extra attention where lumped-conceptual models are used in conjunction with DRM models, i.e. source and boundary inflows to the DRM. For durations inclusive and greater than 3 hours, modellers can expect runoffs from the DRM to be within 80% or greater than that of XP-RAFTS.

It is recognised that rainfall intensities and catchment characteristics will vary across study areas, therefore it is recommended to modellers that comparison of storages at the end of simulations are checked against rainfall volumes, for multiple durations, to grasp a feel of volume attenuation in the model. The magnitude and timing of runoff can be verified to that of a lumped-conceptual model. Flood modellers are suggested to be mindful of fast occurring and higher peaking runoff in high fraction impervious catchments of lumped-conceptual models, as a result of low accountability of storage within their models.

Looking at sensitivity testing of losses, roughness and wetting and drying, their effect on improving the DRM to compensate for its lack of similarity to that of the lumped-conceptual models demonstrate that their efforts are chiefly outweighed by storage attenuation in the 2D grid domain. Whilst this is the case, their influences on runoff within the DRM are noteworthy.

As durations below 3 hours are considered unsuitable, the sensitivity results above and inclusive of this duration are considered of more substance. The results of Section *4.5 – Sensitivity Testing* found that initial losses of 10mm or less for durations for 3 hours and longer gave best matching magnitude of runoff results within 10% of XP-RAFTS. Roughness values within this same range are only possible when it is smoothed to -30% of the base-line case, and in durations 2 hours or longer. These findings differ to those of AR&R (2012), where it was described that roughness overshadowed the impacts of losses. Wetting and drying had little to no effect on peak runoff magnitude in all its tests.

The purpose of sensitivity testing was to indicate the extent parameters were to be altered for suitable comparison to the lumped-conceptual model. Altering values to achieve model suitability does sometimes come at the price of losing representation of reality. For example, smoothing roughness values to -30% provided desirable results, but what this means is the physical roughness of, say a parkland, is now being described as something much smoother to that of a sealed road.

In a similar fashion, lowering initial losses to 10mm may result in a desirable comparison of results, however this may not be representative of its catchments losses from vegetation interception, soil infiltration, and evaporation. These may in practice total to 90mm.

As a further note, Goyen et al. (1991) states that models used by Aitken and Laurenson, which then became the basis for XP-RAFTS, have developed regression relationships from large (greater than 100 square kilometres) catchments and thus are not particularly suited to smaller sub-catchment work. The traditional intention of XP-RAFTS was to model flows of large rivers and creeks of gauged catchments, rather than small overland areas. Some may also argue that study over a range of catchments was limited by Aitken prior to its use as a basis for XP-RAFTS. Regardless of these beliefs, there is much confidence in the use of XP-RAFTS due to its wide commercial use and successful calibration to gauged catchments.

This project has successfully expanded on previous research, as well as provided new findings to the engineering industry. Whilst these findings deliver practical value and insight, behaviour of the direct rainfall method and lumped conceptual models are to be further explored. Thorough checking of direct rainfall models should be exercised until further research is undertaken. The following suggestions and recommendations for such study are outlined below:

- Investigation of storage effects are to be explored and compared between the DRM and lumped-conceptual models over the following scenarios. Link findings to the range of short and long durations in attempt to seek suitability of duration events for the DRM.
    - Volume stored as a percentage of rainfall dumped on a catchment should be tested over a range of storm durations so as to extend on findings of this project. It is suggested modellers undertake preliminary checks to ensure that the simulation periods are long enough to capture fully draining hydrographs.
    - Test a variety of land uses to explore the effect fraction impervious has on the DRM and lumped-conceptual models in terms of storage as well as runoff.
    - Test a variety of different slopes (i.e flat and steep).
    - Test a variety of average recurrence intervals such as 2, 5, 10, 20, 50, 100, 200 years to determine effects, if any, with variance in ARI.
    - Analyse the effect of storage on altering the grid size for a variety of resolutions such as 1m, 2m, 5m, 10m and 20m grids.
    - Undertake a comparison of runoff and storage effects by modelling a plethora of catchments. For example, the effects over a variety of catchments specific to a region in Northern Queensland could be analysed. Alternatively catchments along the eastern coast of Queensland could be tested for their variability.
- Compare a 2D hydraulic DRM and lumped-conceptual model for differences in runoff for catchments consisting of large storages such as retention basins and dams. Explore differences in hydrograph shape and storage.

- Where possible, attempt to model and analyse gauged catchments so as to calibrate flood models to recorded data, hence verify flows and water levels to actual rain events.

Whilst research of flood models such as the DRM lumped-conceptual can be complex, tedious and computationally expensive, the consequent results and findings of them are rewarding and their value magnified over the engineering industry. It is envisioned that the findings of this project will assist in the continued evolving research of the direct rainfall method.

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APPENDICES

Appendix A.1 – Project Specification

University of Southern Queensland

FACULTY OF ENGINEERING AND SURVEYING

ENG4111/4112 Research Project

PROJECT SPECIFICATION

FOR: **PETER JOHNSON**

STUDENT NO: 0050056776

TOPIC: Comparison of direct rainfall and lumped-conceptual rainfall runoff routing methods in tropical North Queensland – a case study of Low Drain, Mount Low, Townsville.

SUPERVISORS: Dr Ian Brodie - USQ
Wesley Bailey, Stormwater Planning Engineer - Townsville City Council

PROJECT AIM: To provide engineering guidance on the use of the direct rainfall method for various duration storm events, in tropical North Queensland.

PROGRAMME: Issue B, 19 August 2013

1. Undertake a literature review relating to lumped-conceptual runoff-routing and direct rainfall models.
2. Review user manuals for MIKE FLOOD & XP-RAFTS and become acquainted with both software.
3. Setup both models for the Low Drain catchment under a 50 year ARI (Average Recurrence Interval), for 0.5, 1, 1.5, 2, 3, 6 & 24 hour durations.
4. Undertake base-line and sensitivity tests using MIKE FLOOD for a number of duration storm events for comparison to the XP-RAFTS base-line case.
5. Compare the results of each model (hydrograph peaks and time to peak).
6. Check the model is conserving mass (volume checks).
7. Present findings and develop conclusions, highlighting the components responsible for differences in catchment runoff between the DRM and lumped-conceptual model.
8. Provide guidance on the use of the DRM, as a result of this project's findings as a case study in tropical North Queensland.

As time permits:

9. Undertake analysis under other ARI's, for example the 10, 20, and 100 year ARI.

AGREED:

_______________(student) 29/8/13 (date)

_______________(supervisor) 20/8/13 (date)

_______________(supervisor) 29-8-13 (date)

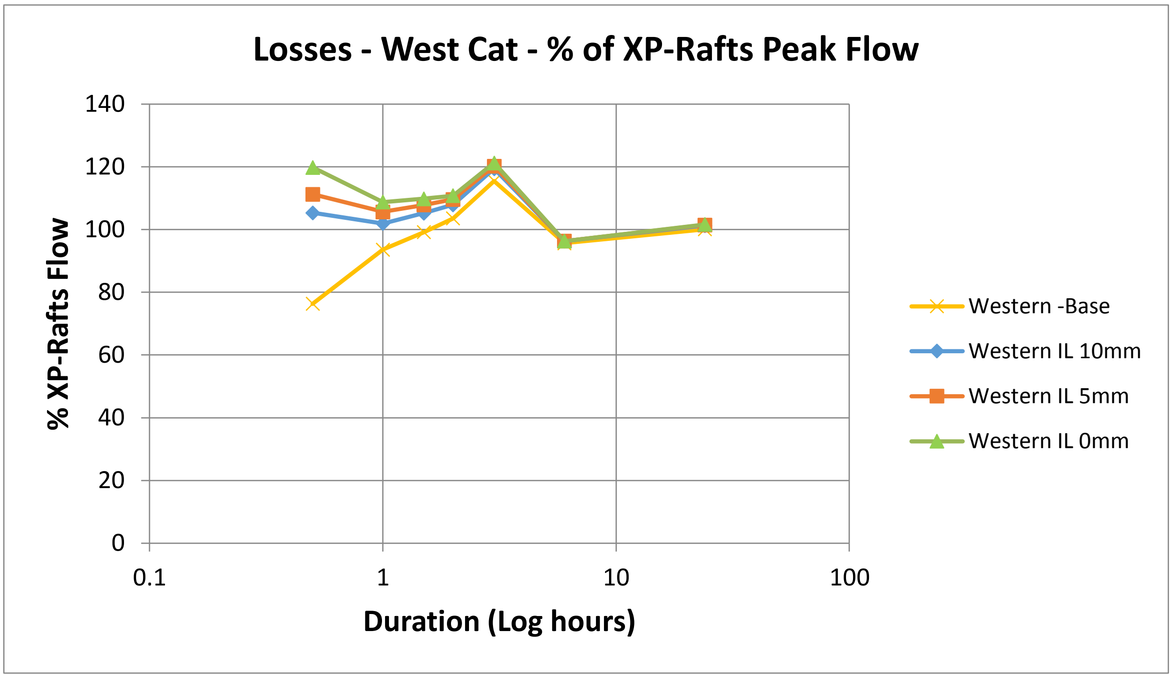
Appendix B.1 – Peak flows (incl. percentage MIKE FLOOD to XP-RAFTS)

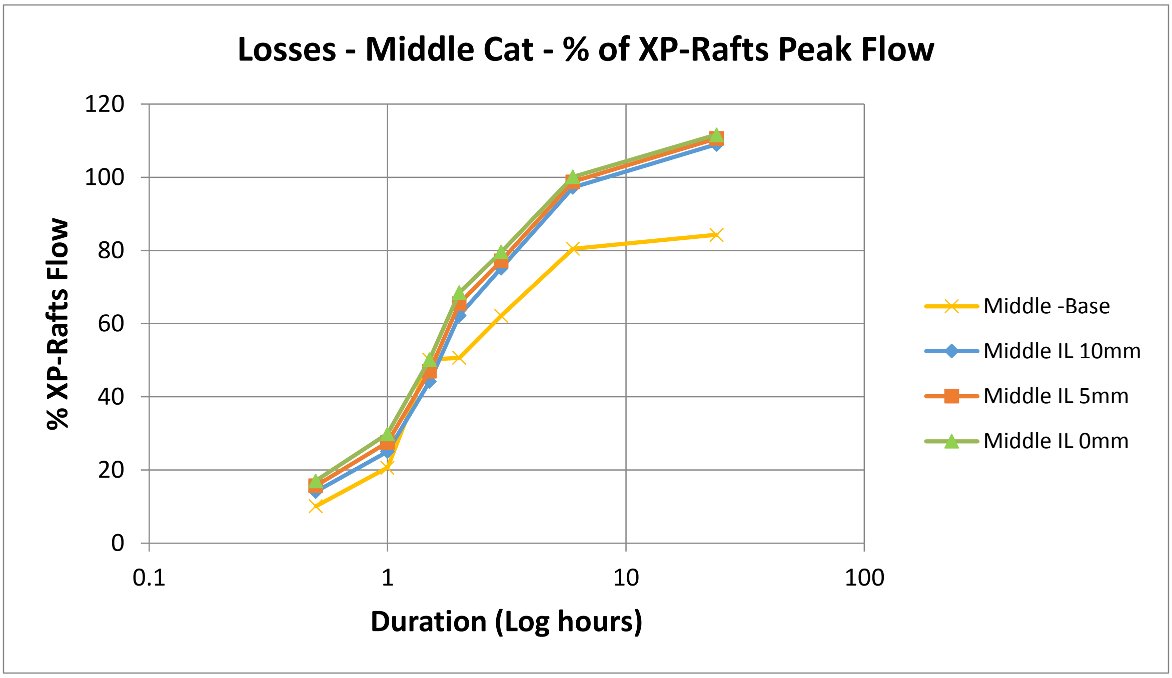
		0.5h	% XP-Rafts	1h	% XP-Rafts	1.5h	% XP-Rafts	2h	% XP-Rafts	3h	% XP-Rafts	6h	% XP-Rafts	24h	% XP-Rafts
XP-Rafts	Western	6.190	100.0	13.420	100.0	18.290	100.0	21.001	100.0	23.181	100.0	35.220	100.0	35.639	100.0
	Middle	28.685	100.0	29.742	100.0	27.371	100.0	25.465	100.0	25.650	100.0	21.473	100.0	20.847	100.0
	Eastern	16.775	100.0	15.945	100.0	17.140	100.0	20.265	100.0	25.677	100.0	34.082	100.0	34.755	100.0
	Total	26.235	100.0	34.507	100.0	40.711	100.0	44.176	100.0	52.115	100.0	73.699	100.0	77.045	100.0
Base Case (MIKE FLOOD)	Western	4.725	76.3	12.567	93.6	18.146	99.2	21.754	103.6	26.781	115.5	33.693	95.7	35.686	100.1
	Middle	2.897	10.1	6.139	20.6	13.736	50.2	12.897	50.6	15.947	62.2	17.285	80.5	17.568	84.3
	Eastern	3.104	18.5	7.218	45.3	10.755	62.7	14.106	69.6	19.105	74.4	23.681	69.5	23.639	68.0
	Total	8.199	31.3	20.016	58.0	30.424	74.7	36.412	82.4	47.173	90.5	63.622	86.3	64.927	84.3
Losses (MIKE FLOOD)	Western IL 10mm	6.522	105.4	13.679	101.9	19.250	105.2	22.666	107.9	27.686	119.4	33.925	96.3	36.103	101.3
	Middle IL 10mm	4.055	14.1	7.449	25.0	12.091	44.2	15.849	62.2	19.281	75.2	20.883	97.3	22.724	109.0
	Eastern IL 10mm	4.055	24.2	8.590	53.9	12.637	73.7	16.496	81.4	22.133	86.2	26.325	77.2	27.259	78.4
	Total IL 10mm	10.631	40.5	23.150	67.1	32.375	79.5	39.923	90.4	51.894	99.6	70.285	95.4	72.236	93.8
	Western IL 5mm	6.889	111.3	14.181	105.7	19.724	107.8	23.032	109.7	27.875	120.2	33.932	96.3	36.161	101.5
	Middle IL 5mm	4.498	15.7	8.192	27.5	12.862	47.0	16.674	65.5	19.800	77.2	21.213	98.8	23.061	110.6
	Eastern IL 5mm	4.619	27.5	9.127	57.2	13.424	78.3	17.130	84.5	22.633	88.1	26.489	77.7	27.564	79.3
	Total IL 5mm	11.996	45.7	24.071	69.8	33.123	81.4	41.640	94.3	52.849	101.4	70.747	96.0	72.855	94.6
	Western IL 0mm	7.418	119.8	14.597	108.8	20.096	109.9	23.268	110.8	28.114	121.3	33.933	96.3	36.226	101.6
	Middle IL 0mm	4.886	17.0	8.892	29.9	13.736	50.2	17.442	68.5	20.416	79.6	21.508	100.2	23.270	111.6
	Eastern IL 0mm	6.223	37.1	9.577	60.1	14.181	82.7	17.867	88.2	23.213	90.4	26.602	78.1	27.721	79.8
	Total IL 0mm	13.368	51.0	24.874	72.1	34.944	85.8	43.306	98.0	53.930	103.5	71.188	96.6	73.129	94.9
Roughness (MIKE FLOOD)	Western -10%	5.083	82.1	12.992	96.8	18.780	102.7	22.748	108.3	27.653	119.3	33.893	96.2	35.877	100.7
	Middle -10%	3.013	10.5	6.456	21.7	10.585	38.7	13.671	53.7	16.592	64.7	17.568	81.8	17.913	85.9
	Eastern -10%	3.236	19.3	7.426	46.6	11.189	65.3	14.721	72.6	19.966	77.8	24.262	71.2	24.161	69.5
	Total -10%	8.600	32.8	20.757	60.2	31.670	77.8	38.162	86.4	49.905	95.8	66.436	90.1	67.003	87.0
	Western -20%	5.281	85.3	12.846	95.7	19.612	107.2	24.155	115.0	29.217	126.0	34.210	97.1	36.302	101.9
	Middle -20%	3.143	11.0	6.793	22.8	11.263	41.1	14.595	57.3	17.338	67.6	17.857	83.2	18.210	87.4
	Eastern -20%	3.334	19.9	7.798	48.9	11.620	67.8	15.374	75.9	20.730	80.7	24.764	72.7	24.622	70.8
	Total -20%	8.917	34.0	20.402	59.1	32.948	80.9	40.340	91.3	53.183	102.0	69.631	94.5	69.673	90.4
	Western -30%	5.523	89.2	13.384	99.7	20.540	112.3	25.530	121.6	31.150	134.4	34.621	98.3	36.658	102.9
	Middle -30%	3.277	11.4	7.243	24.4	12.133	44.3	15.562	61.1	18.061	70.4	18.324	85.3	18.536	88.9
	Eastern -30%	3.364	20.1	7.991	50.1	12.167	71.0	16.237	80.1	21.932	85.4	25.282	74.2	25.167	72.4
	Total -30%	9.226	35.2	22.272	64.5	34.443	84.6	42.878	97.1	57.043	109.5	73.196	99.3	73.089	94.9
Wetting/Drying (MIKE FLOOD)	Western 01	5.191	83.9	12.225	91.1	17.704	96.8	21.381	101.8	26.715	115.2	32.872	93.3	34.555	97.0
	Middle 01	2.887	10.1	5.758	19.4	9.865	36.0	12.796	50.2	15.936	62.1	17.310	80.6	17.602	84.4
	Eastern 01	3.029	18.1	7.276	45.6	10.851	63.3	14.119	69.7	19.114	74.4	23.621	69.3	23.586	67.9
	Total 01	8.826	33.6	20.370	59.0	29.940	73.5	35.959	81.4	46.904	90.0	62.658	85.0	64.158	83.3
	Western 02	4.811	77.7	11.937	88.9	18.160	99.3	21.822	103.9	26.930	116.2	34.069	96.7	35.960	100.9
	Middle 02	2.853	9.9	6.090	20.5	9.972	36.4	12.968	50.9	16.030	62.5	17.333	80.7	17.651	84.7
	Eastern 02	3.418	20.4	7.458	46.8	10.793	63.0	14.193	70.0	19.353	75.4	23.711	69.6	23.635	68.0
	Total 02	8.066	30.7	19.470	56.4	30.201	74.2	36.635	82.9	47.646	91.4	63.792	86.6	64.934	84.3

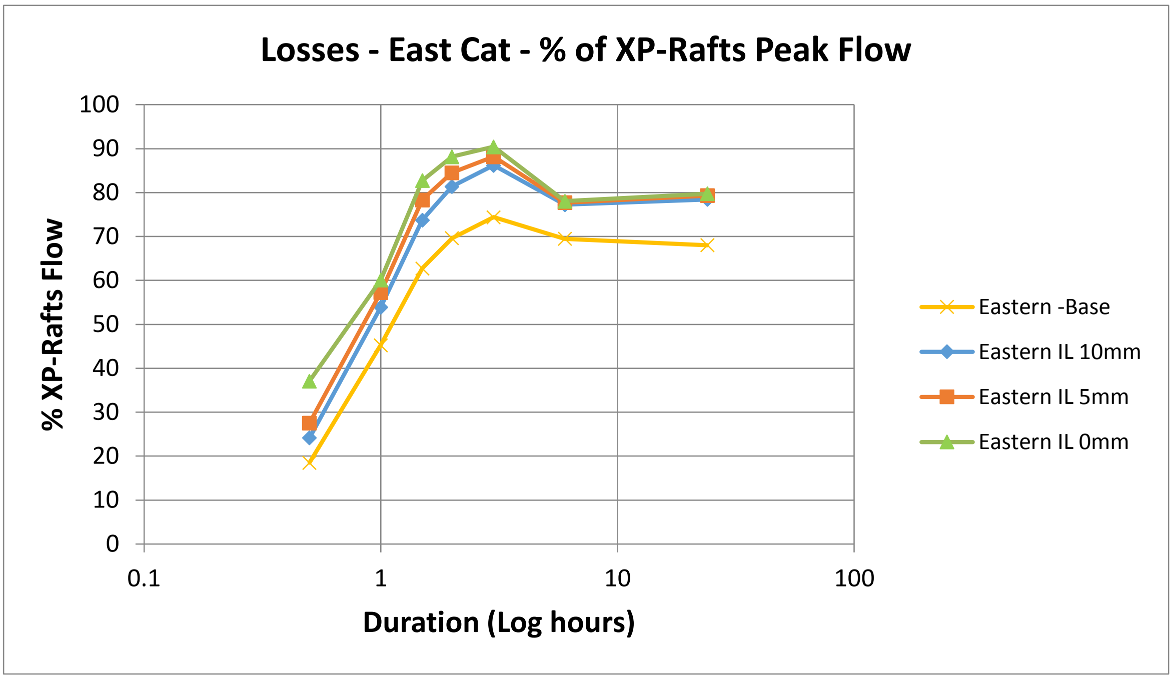
Appendix B.2 – Time to peak (incl. time lag relative to XP-RAFTS)

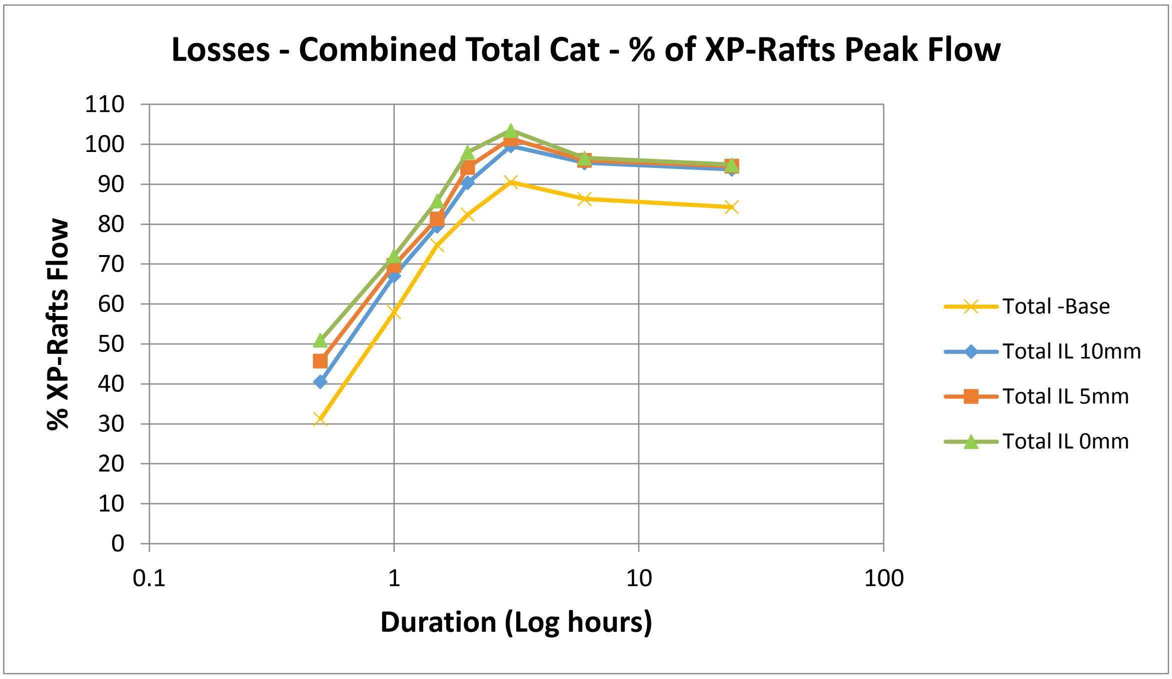
		0.5h	Lag (h)	1h	Lag (h)	1.5h	Lag (h)	2h	Lag (h)	3h	Lag (h)	6h	Lag (h)	24h	Lag (h)
XP-Rafts	Western	4:55	0.000	4:20	0.000	4:15	0.000	4:20	0.000	4:40	0.000	8:10	0.000	7:50	0.000
	Middle	0:15	0.000	0:25	0.000	0:25	0.000	0:35	0.000	0:55	0.000	1:25	0.000	1:55	0.000
	Eastern	0:15	0.000	0:25	0.000	2:35	0.000	2:30	0.000	3:25	0.000	5:05	0.000	4:55	0.000
	Total	0:30	0.000	1:40	0.000	1:45	0.000	2:00	0.000	5:30	0.000	6:05	0.000	6:00	0.000
Base Case	Western	8:40	3.750	6:00	1.667	5:10	0.917	4:50	0.500	5:40	1.000	7:10	-1.000	6:30	-1.333
	Middle	2:40	2.417	2:30	2.083	2:30	2.083	2:30	1.917	3:10	2.250	4:50	3.417	4:40	2.750
	Eastern	6:10	5.917	3:50	3.417	3:10	0.583	3:10	0.667	3:40	0.250	4:50	-0.250	5:00	0.083
	Total	4:10	3.667	3:40	2.000	3:10	1.417	3:20	1.333	5:30	0.000	6:40	0.583	6:40	0.667
Losses	Western IL 10mm	7:30	2.583	5:30	1.167	4:50	0.583	4:30	0.167	4:40	0.000	7:10	-1.000	6:30	-1.333
	Middle IL 10mm	4:10	3.917	2:30	2.083	2:20	1.917	2:20	1.750	3:00	2.083	4:10	2.750	4:20	2.417
	Eastern IL 10mm	4:10	3.917	3:00	2.583	2:50	0.250	2:50	0.333	3:20	-0.083	4:30	-0.583	4:20	-0.583
	Total IL 10mm	3:50	3.333	3:10	1.500	3:00	1.250	3:10	1.167	4:50	-0.667	5:40	-0.417	6:20	0.333
	Western IL 5mm	7:10	2.250	5:30	1.167	4:50	0.583	4:30	0.167	4:30	-0.167	7:10	-1.000	6:30	-1.333
	Middle IL 5mm	2:40	2.417	2:20	1.917	2:10	1.750	2:20	1.750	2:50	1.917	4:00	2.583	4:10	2.250
	Eastern IL 5mm	3:50	3.583	2:50	2.417	2:40	0.083	2:40	0.167	3:10	-0.250	4:30	-0.583	4:10	-0.750
	Total IL 5mm	3:40	3.167	3:10	1.500	3:00	1.250	3:10	1.167	4:40	-0.833	5:30	-0.583	6:20	0.333
	Western IL 0mm	6:50	1.917	5:20	1.000	4:40	0.417	4:30	0.167	4:30	-0.167	7:10	-1.000	6:30	-1.333
	Middle IL 0mm	2:40	2.417	2:20	1.917	2:10	1.750	2:20	1.750	2:50	1.917	4:00	2.583	4:10	2.250
	Eastern IL 0mm	4:00	3.750	2:40	2.250	2:40	0.083	3:00	0.500	3:10	-0.250	4:30	-0.583	5:00	0.083
	Total IL 0mm	4:00	3.500	3:00	1.333	3:00	1.250	3:00	1.000	4:40	-0.833	5:30	0.583	6:20	0.333
Roughness	Western -10%	8:10	3.250	5:40	1.333	5:00	0.750	4:40	0.333	4:40	0.000	7:10	-1.000	6:30	-1.333
	Middle -10%	2:30	2.250	2:30	2.083	2:20	1.917	2:20	1.750	3:00	2.083	4:30	3.083	4:30	2.583
	Eastern -10%	5:40	5.417	3:40	3.250	3:00	0.417	3:00	0.500	3:30	0.083	4:50	-0.250	4:50	-0.083
	Total -10%	9:30	9.000	6:30	4.833	5:40	3.917	5:10	3.167	5:00	-0.500	6:20	0.250	6:30	0.500
	Western -20%	7:50	2.917	5:20	1.000	4:40	0.417	4:20	0.000	4:30	-0.167	7:00	-1.167	6:30	-1.333
	Middle -20%	2:20	2.083	2:40	2.250	2:20	1.917	2:20	1.750	3:00	2.083	4:20	2.917	4:20	2.417
	Eastern -20%	8:00	7.750	3:30	3.083	3:00	0.417	2:50	0.333	3:20	-0.083	4:50	-0.250	4:40	-0.250
	Total -20%	8:40	8.167	6:10	4.500	5:20	3.583	4:50	2.833	4:40	-0.833	5:30	-0.583	6:20	0.333
	Western -30%	7:30	2.583	5:00	0.667	4:20	0.083	4:10	0.167	4:10	-0.500	4:50	-3.333	6:30	-1.333
	Middle -30%	2:10	1.917	2:30	2.083	2:10	1.750	2:20	1.750	2:50	1.917	4:10	2.750	4:00	2.083
	Eastern -30%	7:10	6.917	3:20	2.917	2:40	0.083	2:50	0.333	3:10	-0.250	4:30	-0.583	4:20	-0.583
	Total -30%	8:20	7.833	5:40	4.000	5:00	3.250	4:40	2.667	4:30	1.000	5:20	-0.750	6:10	0.167
Wetting/Drying	Western 01	8:40	3.750	6:10	1.833	5:10	0.917	4:50	0.500	5:40	1.000	6:50	-1.333	7:00	-0.833
	Middle 01	2:40	2.417	3:40	3.250	2:30	2.083	2:30	1.917	3:10	2.250	4:50	3.417	4:40	2.750
	Eastern 01	6:10	5.917	3:50	3.417	3:10	0.583	3:10	0.667	3:40	0.250	5:00	-0.083	4:50	-0.083
	Total 01	9:40	9.167	6:50	5.167	6:10	4.417	5:40	3.667	5:30	0.000	6:10	0.083	6:40	0.667
	Western 02	8:40	3.750	6:00	1.667	5:10	0.917	4:50	0.500	5:30	0.833	7:00	-1.167	6:30	-1.333
	Middle 02	2:40	2.417	2:40	2.250	2:30	2.083	2:30	1.917	3:10	2.250	4:50	3.417	4:40	2.750
	Eastern 02	5:40	5.417	3:40	3.250	3:10	0.583	3:00	0.500	3:30	0.083	5:00	-0.083	5:00	0.083
	Total 02	9:50	9.333	6:50	5.167	6:00	4.250	5:40	3.667	5:30	0.000	6:10	0.083	6:40	0.667

Appendix C.1 – Sensitivity Testing of Losses-Flows

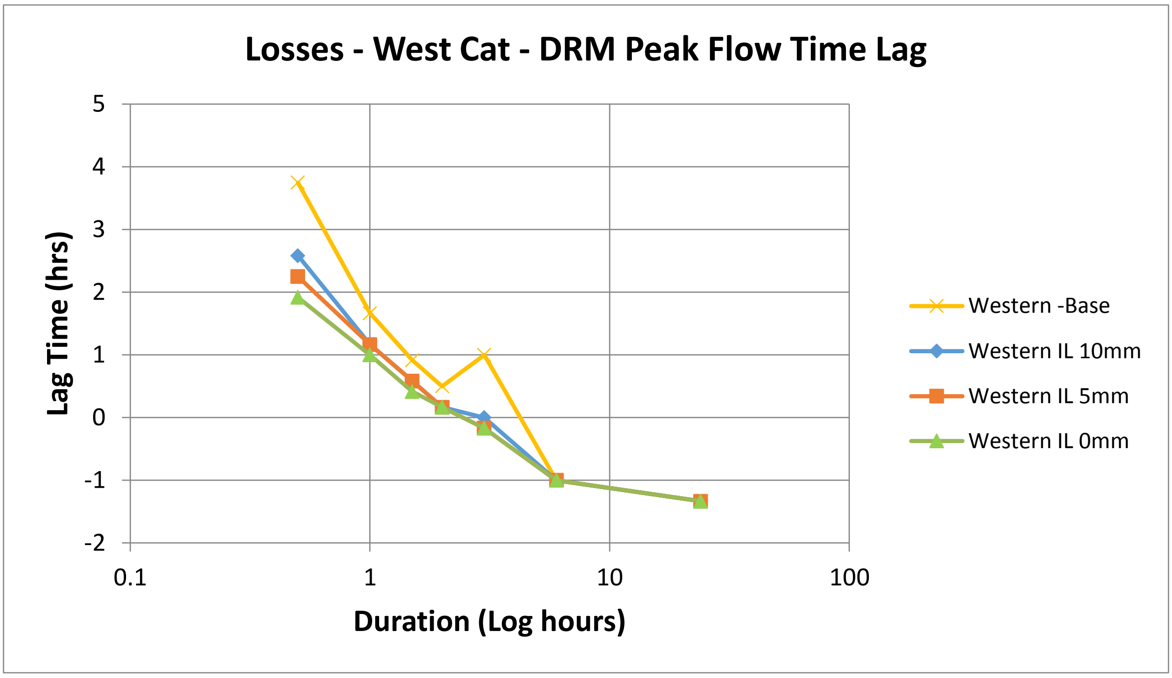


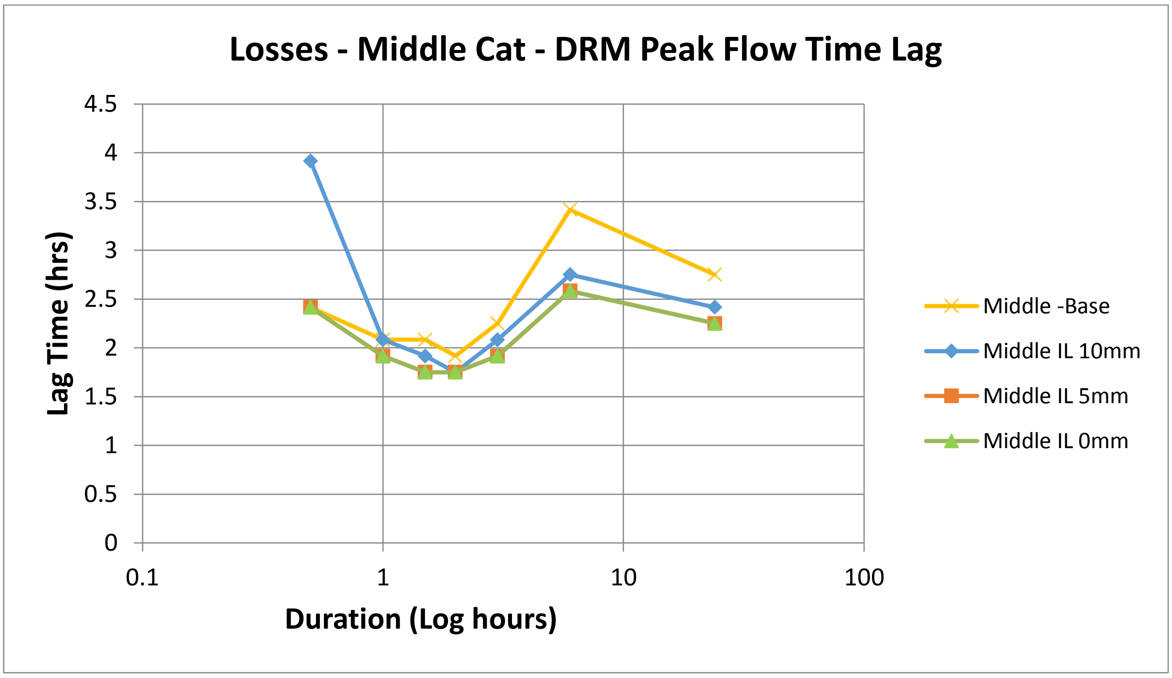


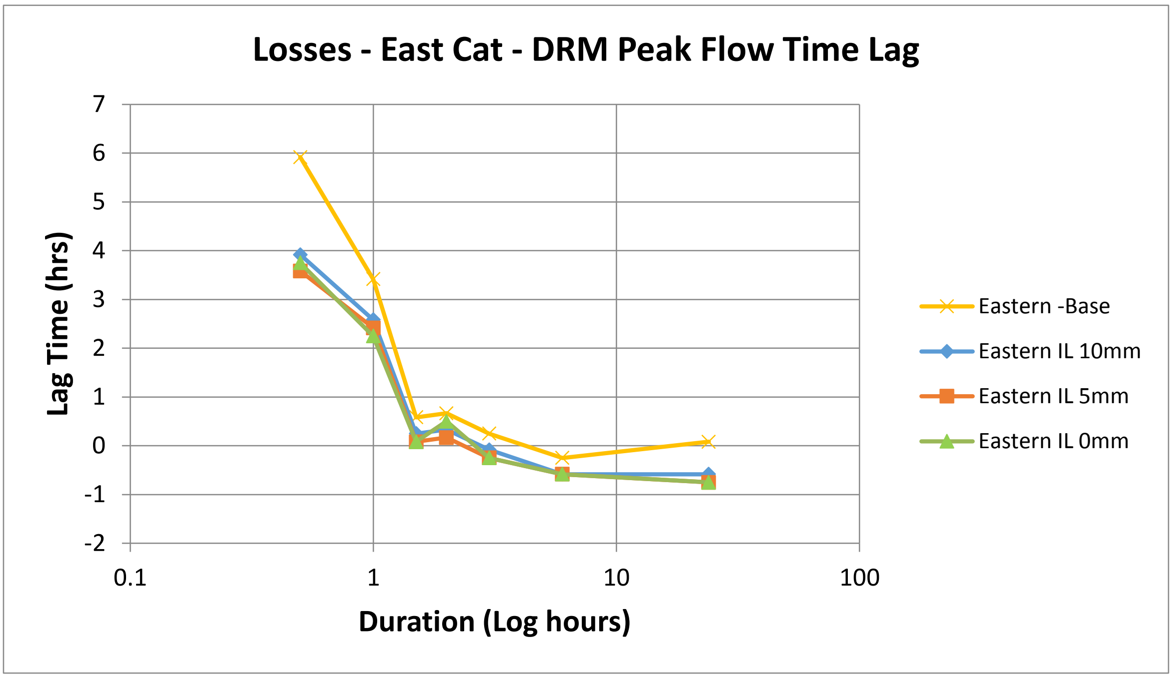

Losses - East Cat - % of XP-Rafts Peak Flow
% XP-Rafts Flow
100
90
80
70
60
50
40
30
20
10
0
0.1
1
10
100
Duration (Log hours)
Eastern -Base
Eastern IL 10mm
Eastern IL 5mm
Eastern IL 0mm

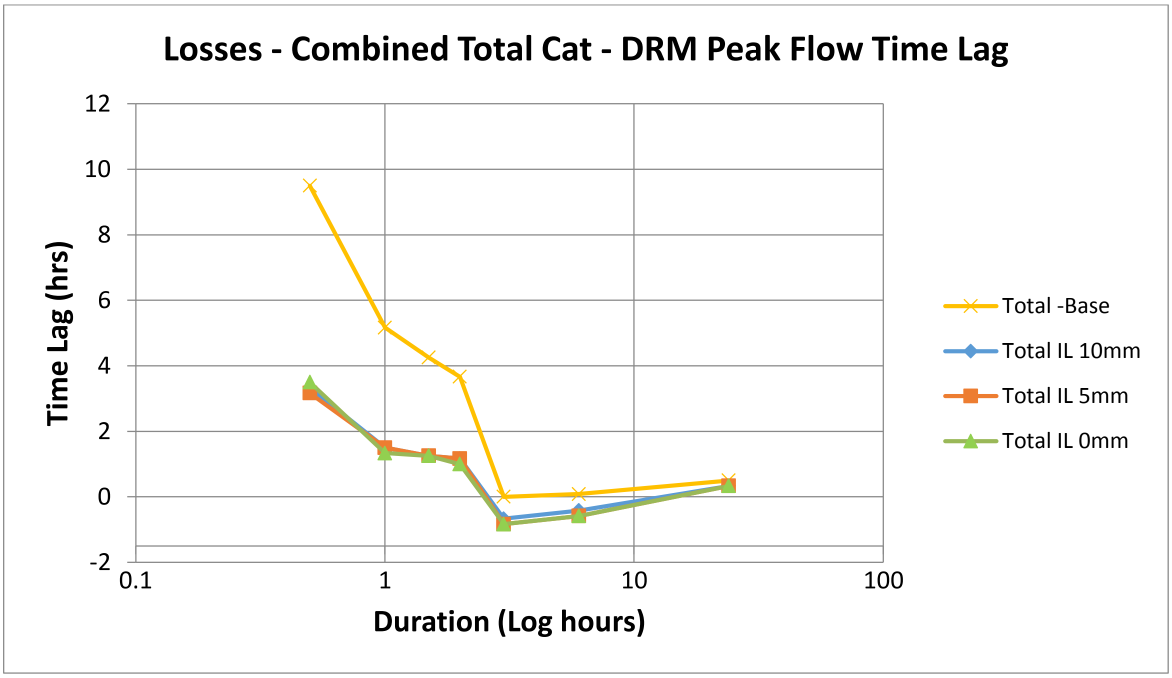

Losses - Combined Total Cat - % of XP-Rafts Peak Flow
% XP-Rafts Flow
110
100
90
80
70
60
50
40
30
20
10
0
0.1
1
10
100
Duration (Log hours)
Total -Base
Total IL 10mm
Total IL 5mm
Total IL 0mm

Appendix C.2 – Sensitivity Testing of Losses-Time Lag

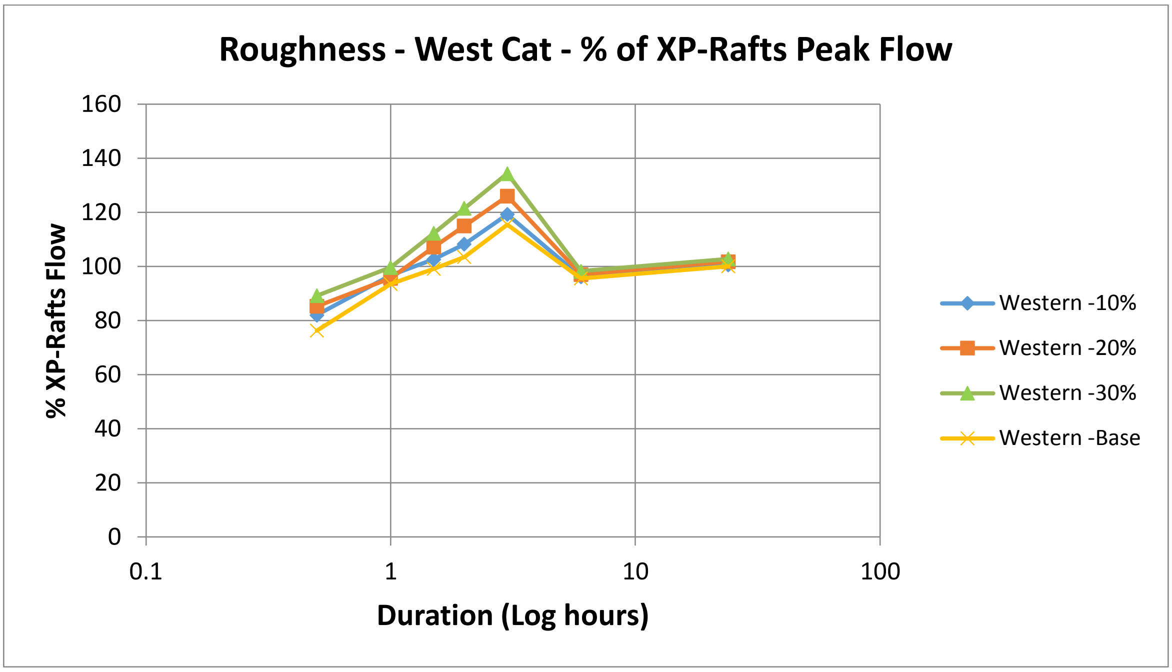


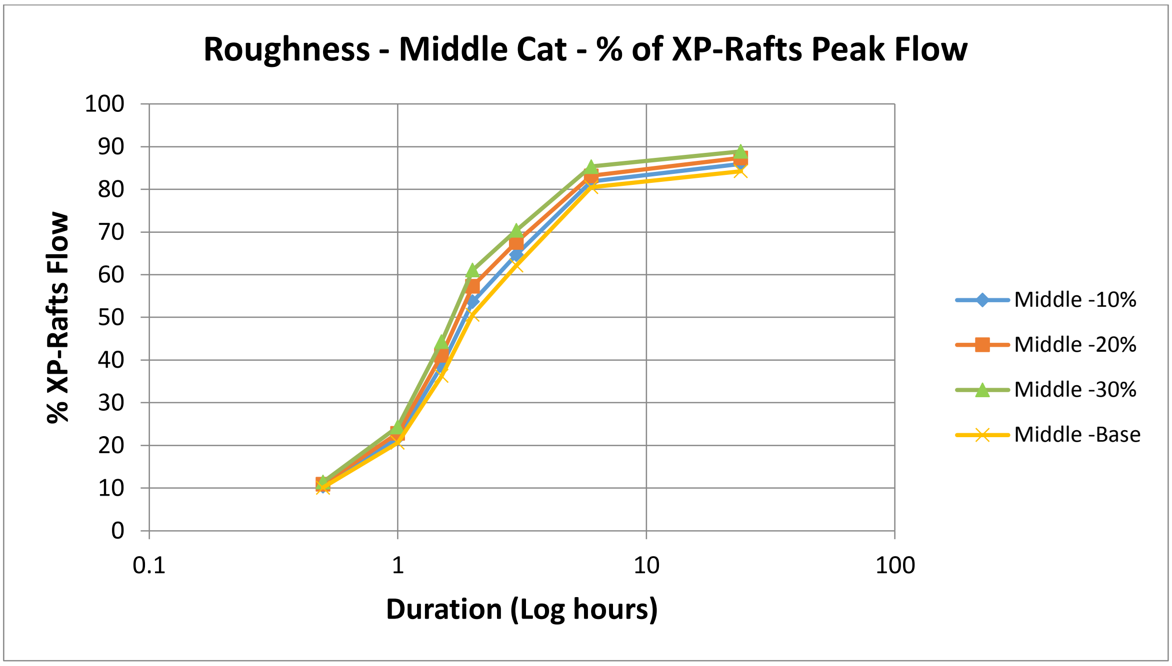


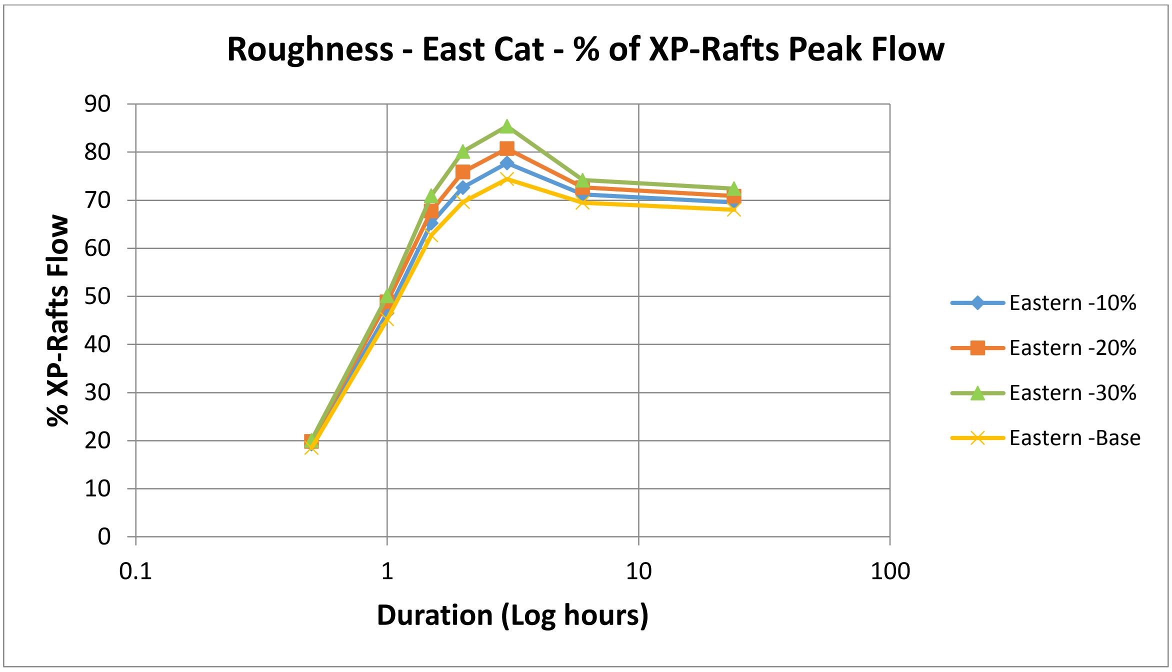

Losses - East Cat - DRM Peak Flow Time Lag
Lag Time (hrs)
7
6
5
4
3
2
1
0
-1
-2
0.1
1
10
100
Duration (Log hours)
Eastern -Base
Eastern IL 10mm
Eastern IL 5mm
Eastern IL 0mm

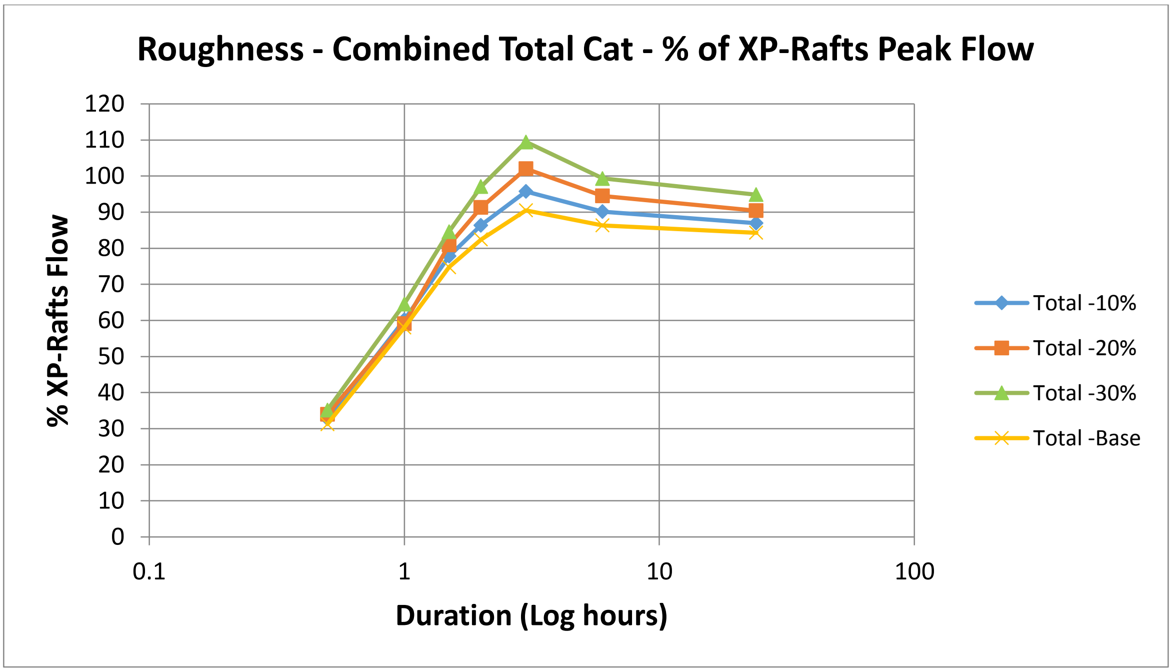

Losses - Combined Total Cat - DRM Peak Flow Time Lag
Time Lag (hrs)
12
10
8
6
4
2
0
-2
0.1
1
10
100
Duration (Log hours)
Total -Base
Total IL 10mm
Total IL 5mm
Total IL 0mm

Appendix D.1 – Sensitivity Testing of Roughness-Flows






Roughness - East Cat - % of XP-Rafts Peak Flow
% XP-Rafts Flow
0
10
20
30
40
50
60
70
80
90
0.1
1
10
100
Duration (Log hours)
Eastern -10%
Eastern -20%
Eastern -30%
Eastern -Base


Roughness - Combined Total Cat - % of XP-Rafts Peak Flow
% XP-Rafts Flow
0
10
20
30
40
50
60
70
80
90
100
110
120
0.1
1
10
100
Duration (Log hours)
Total -10%
Total -20%
Total -30%
Total -Base

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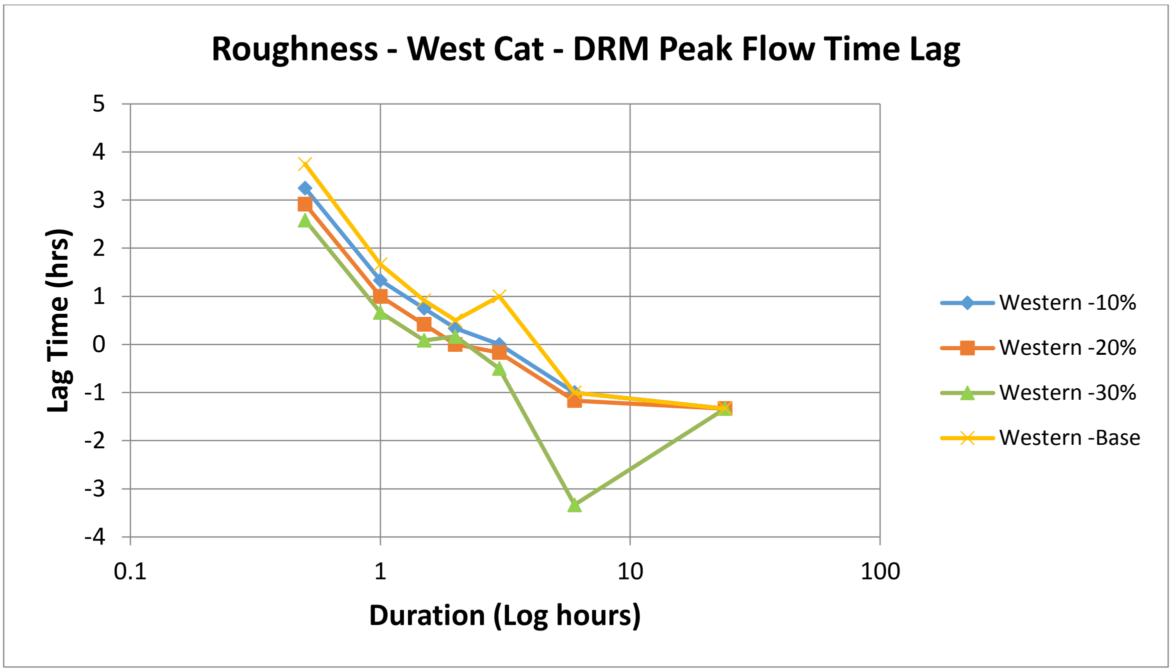
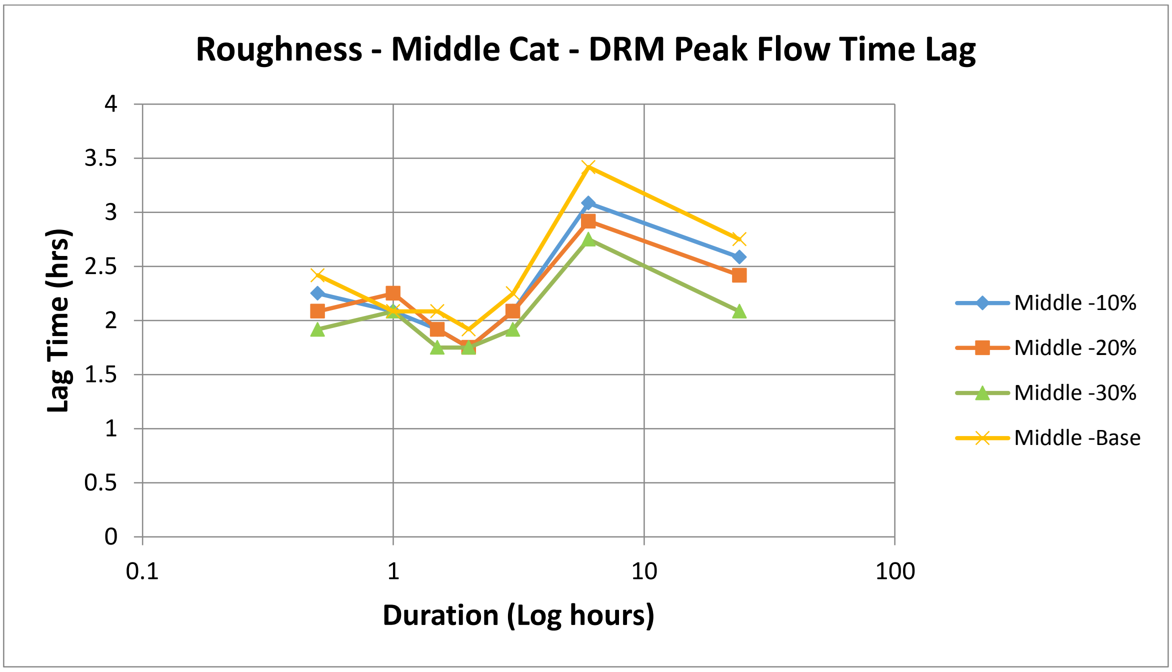
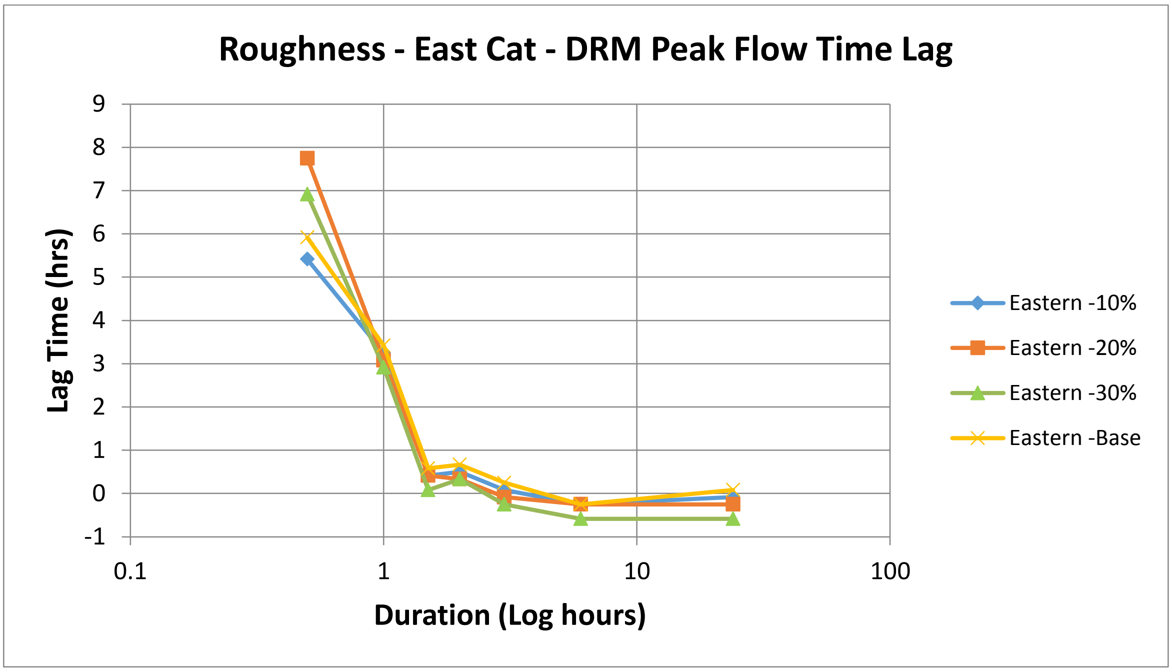
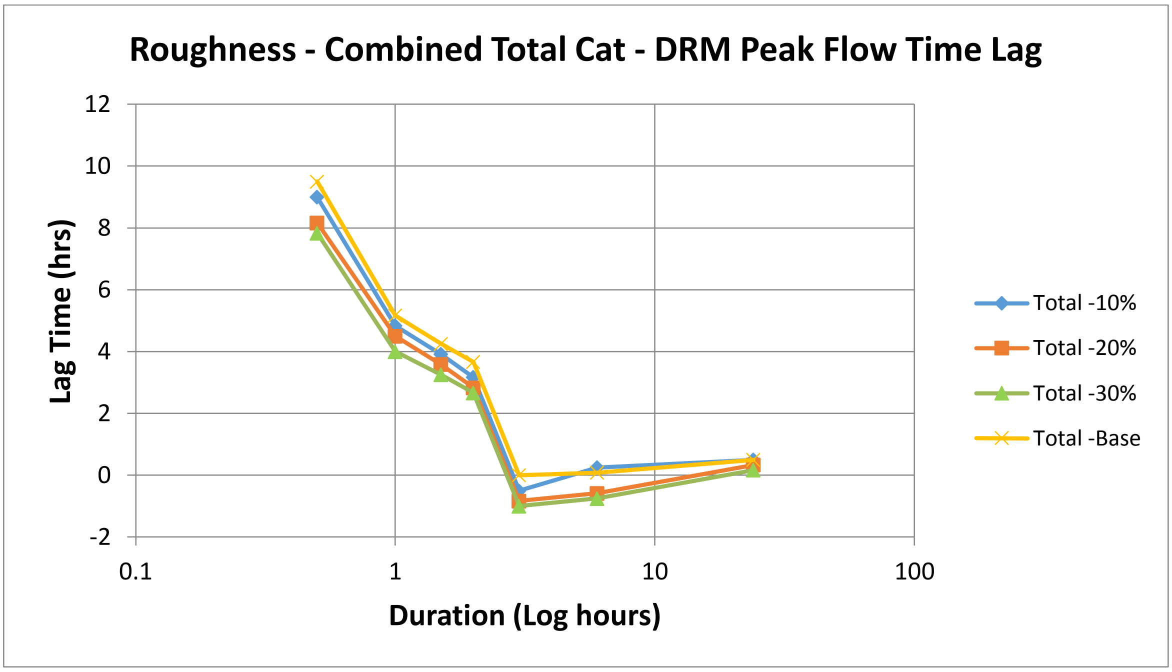
Appendix D.2 – Sensitivity Testing of Roughness-Time Lag

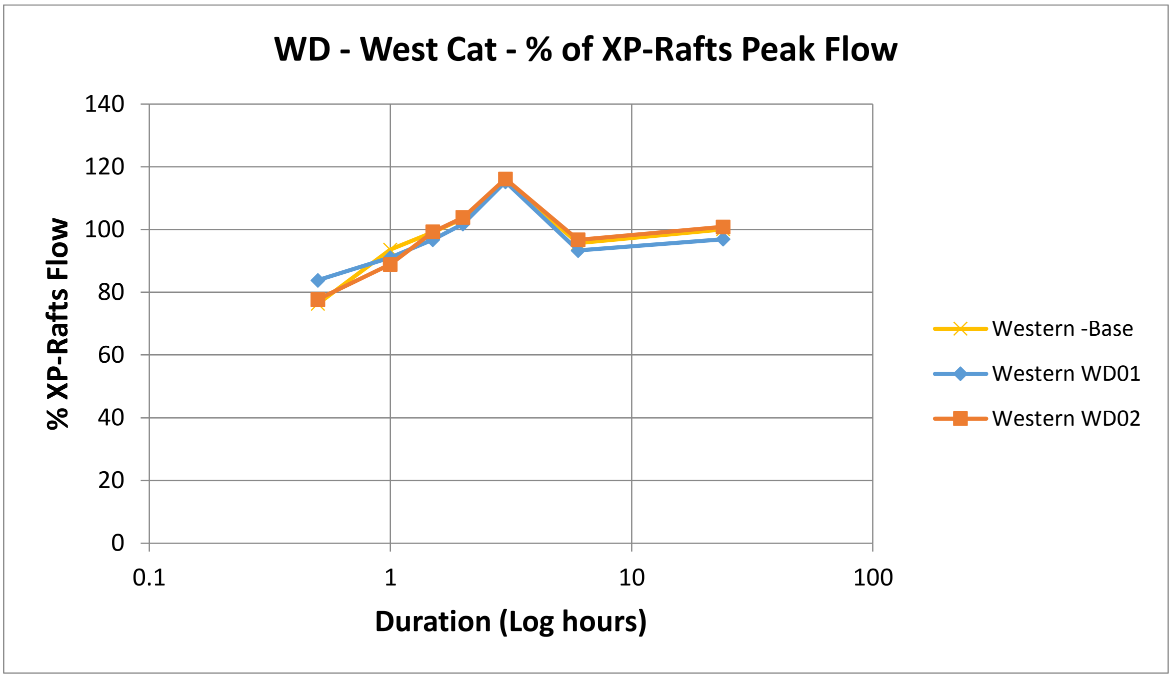


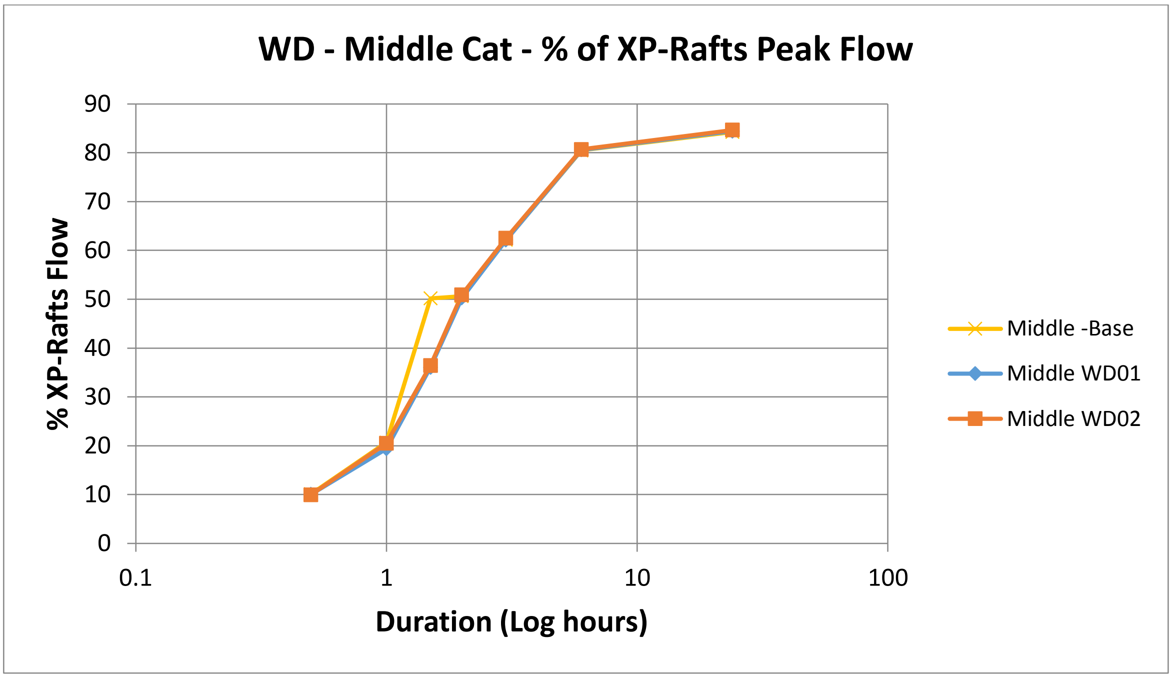


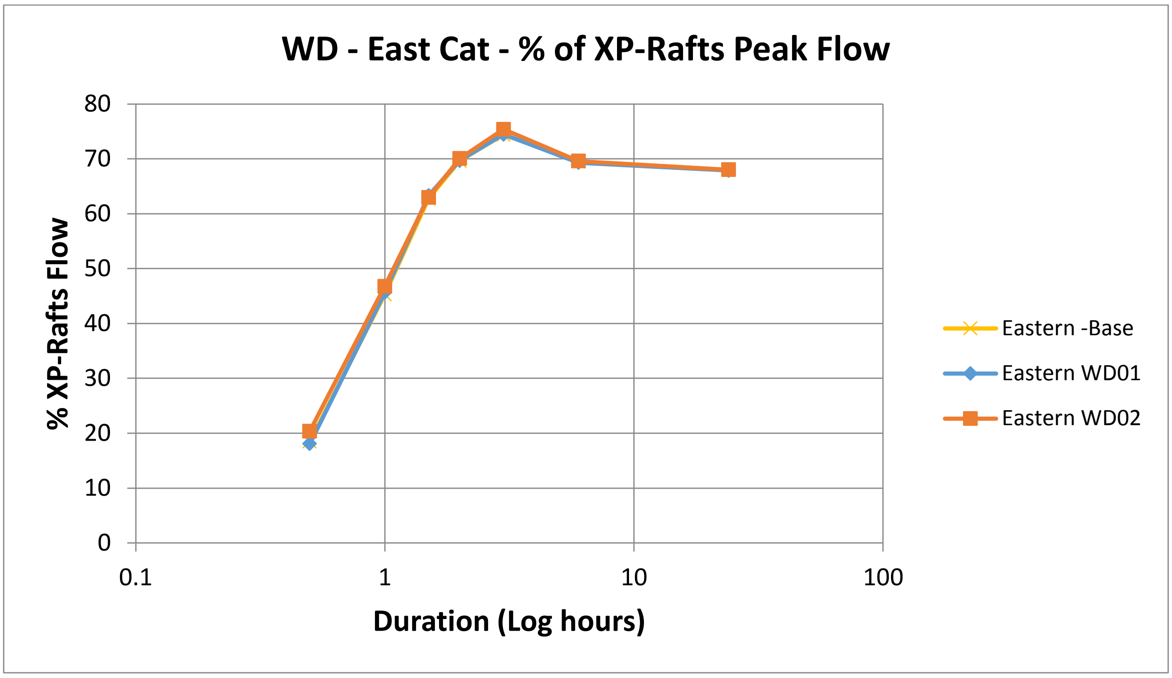

Roughness - East Cat - DRM Peak Flow Time Lag
Lag Time (hrs)
Duration (Log hours)
9
8
7
6
5
4
3
2
1
0
-1
0.1
1
10
100
Eastern -10%
Eastern -20%
Eastern -30%
Eastern -Base


Roughness - Combined Total Cat - DRM Peak Flow Time Lag
Lag Time (hrs)
Duration (Log hours)
12
10
8
6
4
2
0
-2
0.1
1
10
100
Total -10%
Total -20%
Total -30%
Total -Base

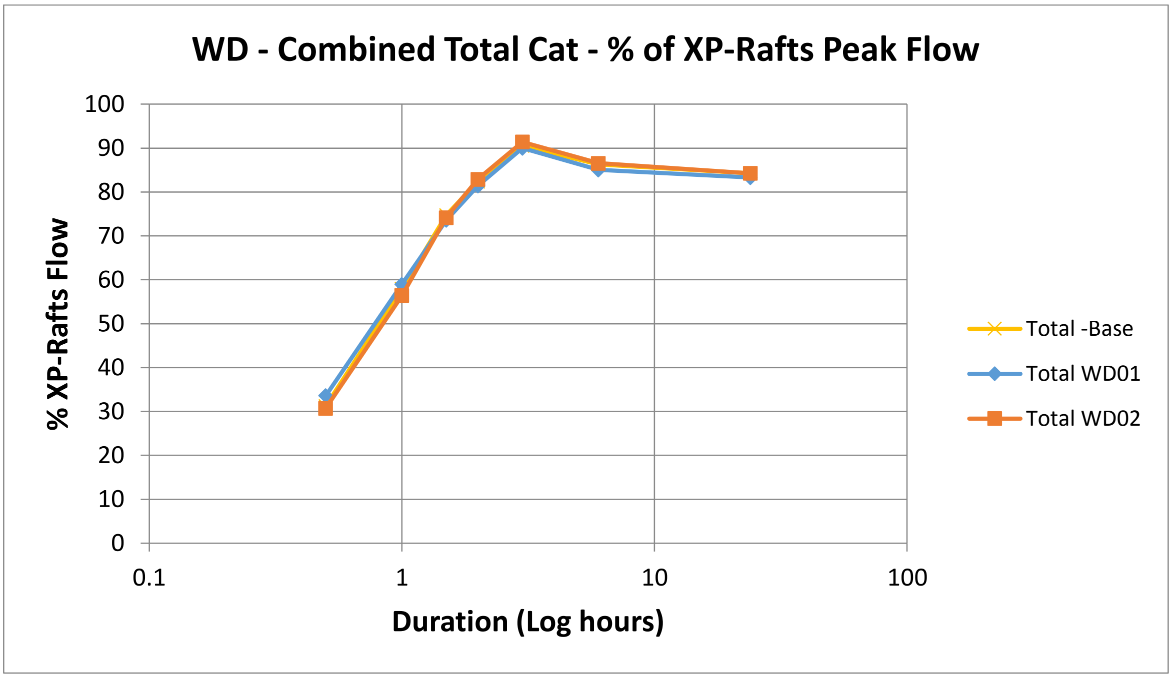
Appendix E.1 – Sensitivity Testing of Wetting & Drying-Flows





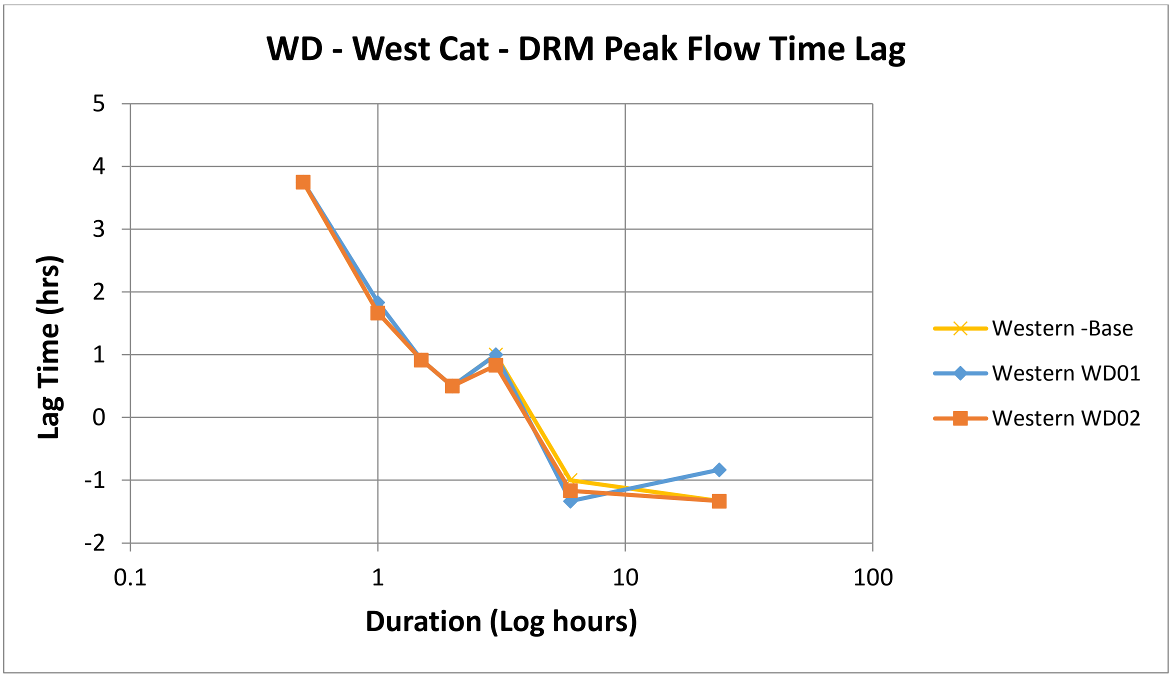


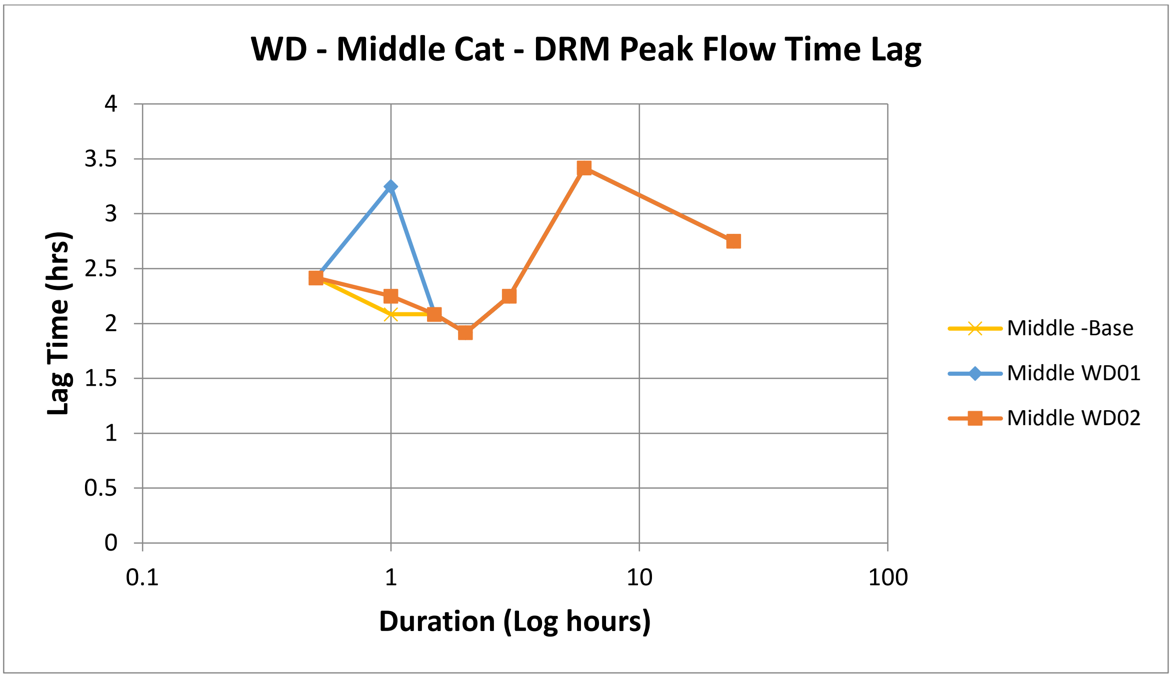
WD - East Cat - % of XP-Rafts Peak Flow
% XP-Rafts Flow
80
70
60
50
40
30
20
10
0
0.1
1
10
100
Duration (Log hours)
Eastern -Base
Eastern WD01
Eastern WD02

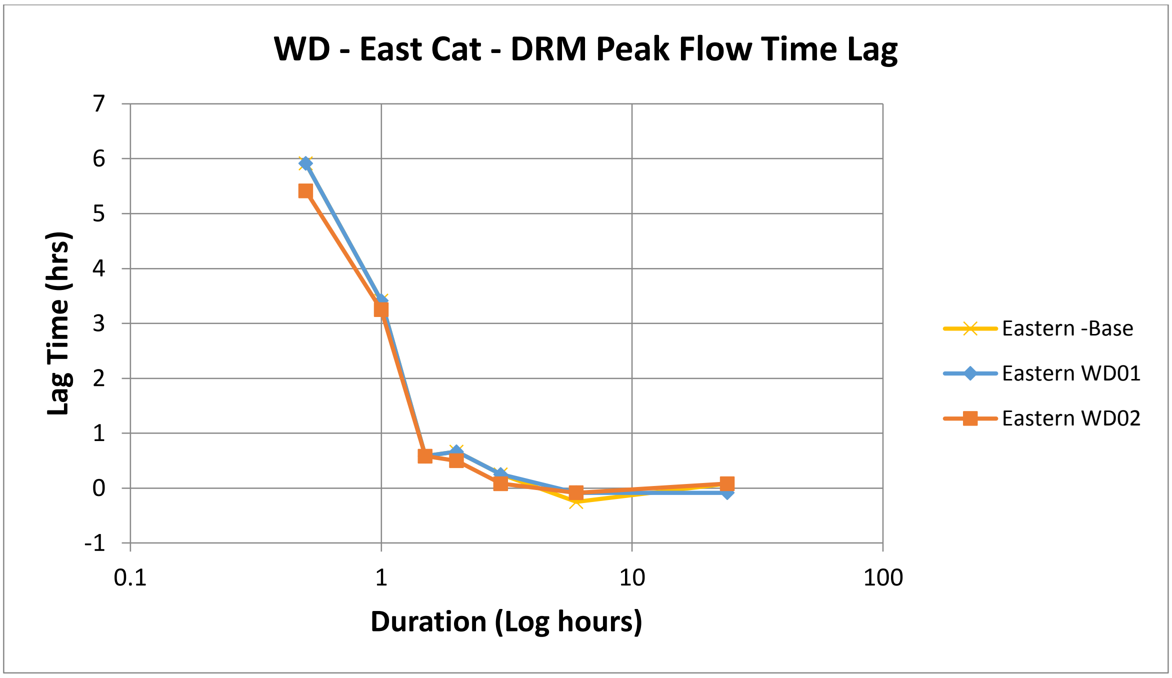


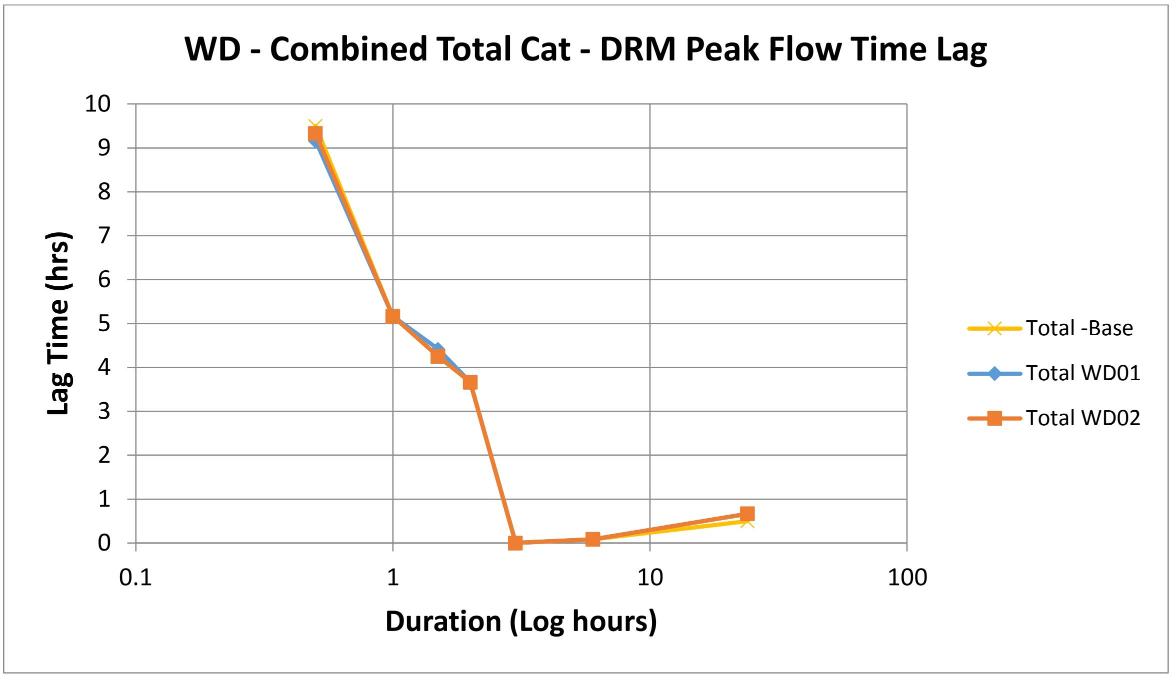
WD - Combined Total Cat - % of XP-Rafts Peak Flow
% XP-Rafts Flow
100
90
80
70
60
50
40
30
20
10
0
0.1
1
10
100
Duration (Log hours)
Total -Base
Total WD01
Total WD02

Appendix E.2 – Sensitivity Testing of Wetting & Drying-Time Lag




WD - Middle Cat - DRM Peak Flow Time Lag
Lag Time (hrs)
4
3.5
3
2.5
2
1.5
1
0.5
0
0.1
1
10
100
Duration (Log hours)
Middle -Base
Middle WD01
Middle WD02


WD - East Cat - DRM Peak Flow Time Lag
Lag Time (hrs)
7
6
5
4
3
2
1
0
-1
0.1
1
10
100
Duration (Log hours)
Eastern -Base
Eastern WD01
Eastern WD02


WD - Combined Total Cat - DRM Peak Flow Time Lag
Lag Time (hrs)
10
9
8
7
6
5
4
3
2
1
0
0.1
1
10
100
Duration (Log hours)
Total -Base
Total WD01
Total WD02

Appendix F.1 – XP-RAFTS Catchment Details

Catchment	Fraction Impervious %	Sub-catchment Type	Catchment Slope (%)	Manning's 'n'	Area (ha)
J2	10	Perv	9.21	0.07	165.02
		Imp	1.52	0.03	18.34
W5	0	Perv	0.4	0.07	104.56
W4	0	Perv	0.34	0.07	20.36
W3	0	Perv	0.33	0.07	14.2
W2	0	Perv	0.21	0.07	13.56
W1	0	Perv	0.22	0.07	72.69
M1	60	Perv	0.26	0.06	23.89
		Imp	0.26	0.03	35.84
M3	45	Perv	0.24	0.06	30.91
		Imp	0.24	0.03	25.3
M2	60	Perv	0.32	0.06	32.99
		Imp	0.32	0.03	49.48
M4	1	Perv	0.38	0.07	20.88
		Imp	0.38	0.03	0.21
J1	15	Perv	5.19	0.07	77.66
		Imp	0.25	0.03	13.71
13	10	Perv	0.28	0.06	147.73
		Imp	0.28	0.03	26.07
12	0	Perv	0.2	0.06	15.15
11	0	Perv	0.29	0.07	48.2
10	10	Perv	0.29	0.06	47.68
		Imp	0.29	0.03	5.3
9	10	Perv	0.33	0.06	41.88
		Imp	0.33	0.03	4.65
8	17	Perv	0.2	0.06	37.86
		Imp	0.2	0.03	7.76
7B	5	Perv	0.25	0.065	9.3
		Imp	0.25	0.03	.49
7A	5	Perv	0.23	0.065	16.35
			0.23	0.03	0.86
6	60	Perv	0.21	0.06	16.45
		Imp	0.21	0.03	24.68
5	0	Perv	0.2	0.07	20.85

Appendix G.1 – XP-RAFTS Storage Basin Details

Catchment 13	
RL	Storage (m³)
11.3	2
11.4	6
11.5	11
11.6	25
11.7	44
11.78	78
11.8	96
11.9	227
12	462
12.1	2,997
12.2	6,230
12.25	8,089
12.3	11,126
12.4	18,095
12.5	26,369
12.6	38,639
12.7	52,597
12.8	71,292
12.9	95,653
13	123,044
13.25	219,339
13.5	348,649
13.75	503,414
14	684,087
14.25	894,106
14.5	1,133,780

Catchment J2	
RL	Storage (m³)
11.5	0
11.6	558
11.7	1,621
11.8	3,927
11.9	7,583
12	12,030
12.1	20,852
12.2	31,239
12.3	45,015
12.4	62,488
12.5	81,961
12.6	108,016
12.7	136,008
12.8	167,534
12.9	202,855
13	240,597
13.25	363,095
13.5	515,236
13.75	694,051
14	898,130
14.25	1,127,413
14.5	1,381,887

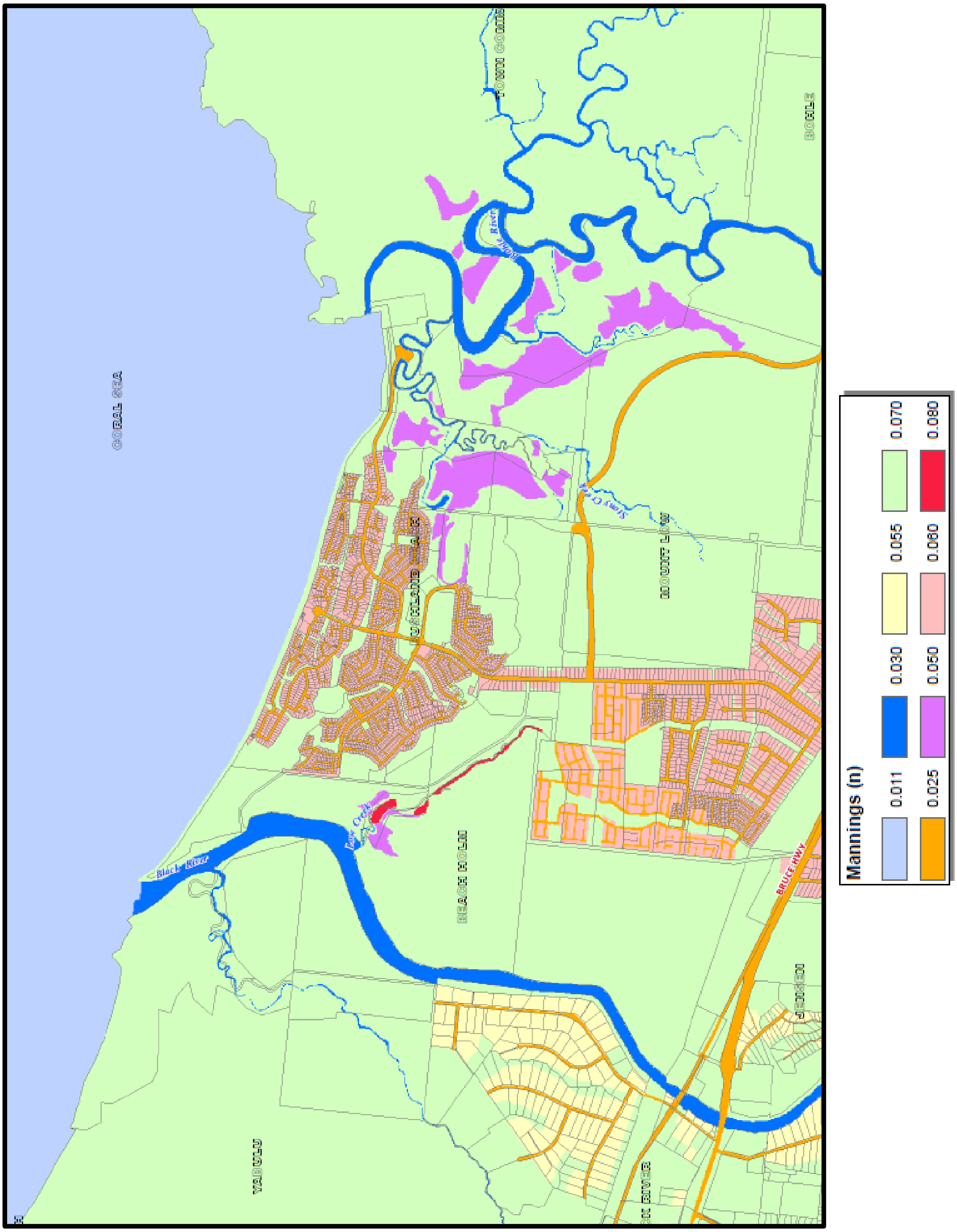
Catchment W5	
RL	Storage (m³)
10	0
10.1	8
10.2	23
10.3	1,814
10.4	6,426
10.5	12,571
10.6	24,303
10.7	37,865
10.8	54,506
10.9	74,505
11	96,847
11.25	167,599
11.5	261,837
11.75	377,875
12	527,150
12.25	704,109
12.5	901,515
12.75	1,115,991
13	1,341,931

Catchment W4	
RL	Storage (m³)
9.75	0
9.8	491
9.9	2,798
10	6,787
10.1	13,992
10.2	22,099
10.3	31,947
10.4	43,408
10.5	55,683
10.6	69,627
10.75	91,957
11	133,218
11.25	178,343
11.5	227,788
11.75	280,432
12	333,267
12.25	386,112
12.5	438,959

Catchment W3	
RL	Storage (m³)
9	0
9.1	1,032
9.2	3,107
9.3	7,081
9.4	12,636
9.5	18,980
9.6	28,457
9.7	38,494
9.8	49,379
9.9	61,064
10	73,243
10.25	106,041
10.5	141,290
10.75	177,353
11	213,497
11.25	249,643
11.5	285,788
11.75	321,933
12	358,078

Catchment W2	
RL	Storage (m³)
8.5	0
8.6	682
8.7	2,209
8.8	5,788
8.9	11,302
9	17,890
9.1	28,641
9.2	39,867
9.3	51,704
9.4	61,064
9.5	76,268
9.6	89,042
9.75	108,615
10	142,813
10.25	177,613
10.5	212,503
10.75	247,394
11	282,284
11.25	317,174
11.5	352,064
11.75	386,954

Appendix H.1 – MIKE FLOOD Base-line Testing Roughness



Appendix I.1 – MIKE FLOOD Base-line Testing Fraction Impervious