COMPARISON OF DIRECT RAINFALL AND LUMPED-CONCEPTUAL RAINFALL RUNOFF ROUTING METHODS IN TROPICAL NORTH QUEENSLAND – A CASE STUDY OF LOW DRAIN, MOUNT LOW, TOWNSVILLE.

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Abstract

Traditional lumped-conceptual models are broadly accepted in the industry due to their long history of use, and their successful calibration in a wide selection of gauged catchments. However, within recent years two-dimensional hydraulic modelling has become more popular with increasing flexibility, robustness and computational power. Its ability to apply rain directly to a two-dimensional 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 within the industry. In addition, poor understandings of intricacies with the DRM have resulted in uncertainties toward its use.

Research is limited for the DRM, with published findings focusing predominantly on case studies in New South Wales and Victoria. Published research by Rehman et al. (2003), Caddis et al. (2008), Clark et al. (2008), and Taaffe et al. (2011) indicate considerable differences in peak runoff between DRM and lumped conceptual models.

In this paper, 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 model, being MIKE FLOOD and XP-RAFTS respectively. These analyses were explored over a range of rainfall event durations, and present new findings associated with storage effects in the DRM. Sensitivity testing of rainfall losses, catchment roughness, and wetting & drying were additionally undertaken to assess their effects in the DRM, and expand on current published research. The findings in this paper are expected to not only provide practical value to the stormwater industry, but also assist in guidance on the use of the DRM in tropical North Queensland.

Keywords

Catchment modelling, hydrologic routing, direct rainfall method, two-dimensional hydraulic modelling

Introduction

Flood analysts have conventionally used lumped conceptual runoff-routing models as a prediction for flows, and used these results as inputs into the 2D hydraulic model at relevant locations. Runoff is subsequently routed through the 2D hydraulic model, simulating hydraulic flow behaviour as it passes over the topographical grid cells within the 2D grid domain.

Hydraulic modelling has extensively evolved over the last twenty years, and a feature that has increased in popularity in recent years is the direct rainfall method (DRM). The DRM, also known as the ‘rainfall-on-grid’ approach, applies rainfall directly to the 2D grid cells of a hydraulic model for the duration of a designated rain event. The DRM approach eliminates the need for a separate hydrological model such as the lumped-conceptual. Despite its popularity, the DRM has not superseded lumped-conceptual models. Each are considered valid modelling tools with lumped-conceptual models having a successful history of calibration to gauged catchments (Engineers Australia 2012, p. 11-195).

Whilst the DRM model can cover an entire catchment, it is common for flood analysts to cover an isolated study area with the addition of source inflows from traditional lumped conceptual models (combined DRM and lumped-conceptual) to reduce computational run times. Flood analysts, whether using the DRM solely or in conjunction with lumped-conceptual models, are yet to fully understand the practical behaviour of the DRM and its differences from traditional models.

The forefront of current research has focused on the effect roughness and rainfall losses have on hydrographs. Caddis et al. (2008) tested these 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. Engineers Australia (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’ (Engineers Australia 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).

In recent years Taaffe et al. (2011) focused on the effect of storage within depressed grid cells of the 2D hydraulic model, described as ‘pit cells’. The research undertaken by Taaffe et al. (2011) presented valuable findings, such that pit cells were the cause of peak flow attenuation. Pit cells are cells in the DEM that are lower in elevation than surrounding cells, hence cannot route flow. The study’s main focus was on pit cells acting as a second loss mechanism to the initial loss values of rainfall. All research to date has been limited to investigating hydrograph effects from a single storm duration only. This paper expands on all research, and presents new findings across numerous storm durations.

Background

Lumped-conceptual & 2D Fully Dynamic Hydraulic Models

Lumped Conceptual Model

XP-RAFTS is a lumped-conceptual model that 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 non-linear storage function, which is given as:

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

where S is storage which is related to outflow Q, with B as the storage delay time coefficient and n the storage non-linearity exponent. Both of the B and n coefficients are empirically derived.

2D Fully Dynamic Hydraulic Model

MIKE FLOOD is a coupled 2D/1D model, used for flood modelling of rural and urban catchments. It comprises of a component that applies rainfall directly on the 2D grid, minimising the need for hydrologic models like XP-RAFTS. Figure 1 represents a cell in a 2D grid, which plays a part in both receiving direct rainfall, and consequently routing overland flow.

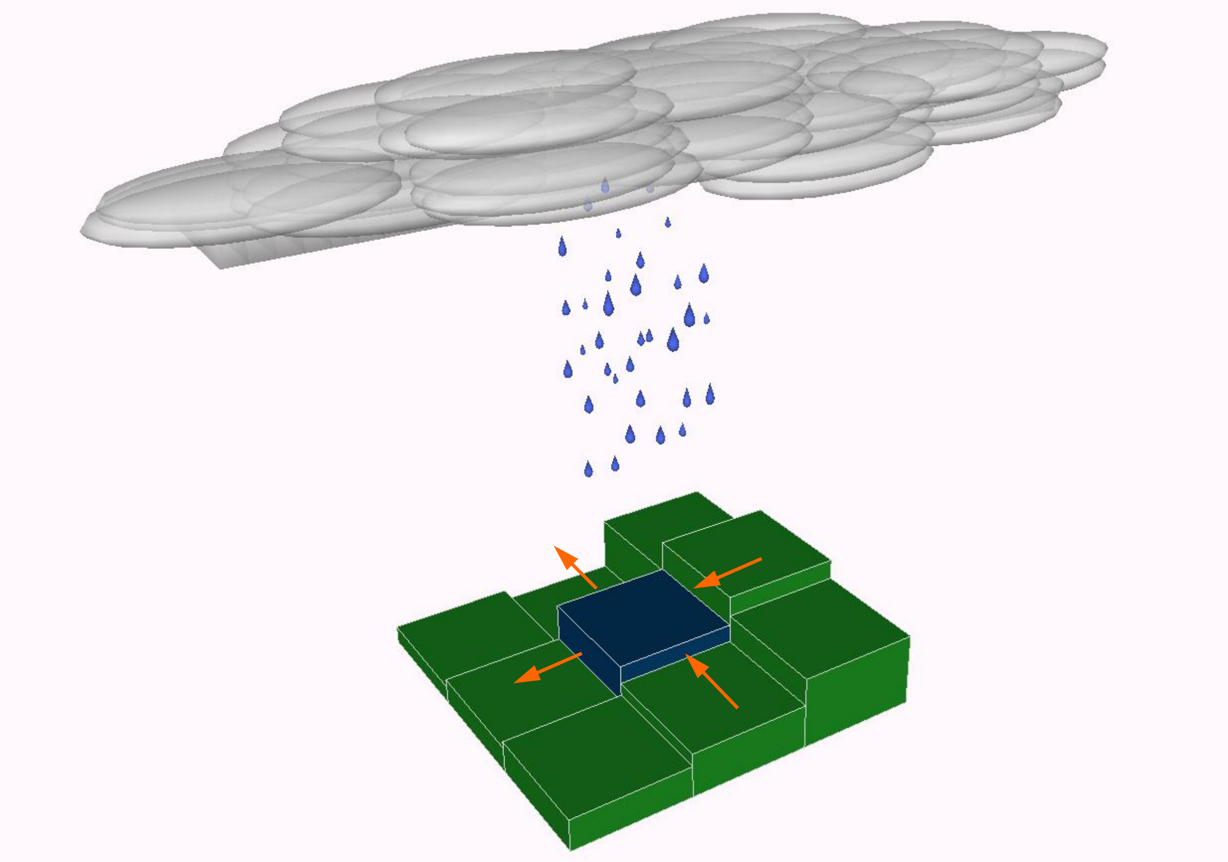

Figure 1: 2D overland flow

The cell in Figure 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 conservation of mass and conservation of momentum.

Study Area Location & Characteristics

The location of the case study is in the suburb of Mount Low, situated approximately 15 kilometres to the northwest of Townsville. 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. The general fall of the land is northward toward Halifax Bay, with most of its runoff captured by Low Drain. Low Drain extends from the north of the Bruce Highway, travelling adjacent to Mount Low Parkway, before meandering its way to a confluence with Black River.

The land generally exhibits slopes of under 0.5%. It is noted that in the most upstream segments of the catchment is Mount Kulburn, 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, which are the 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 middle catchment, to then finally the eastern catchment of Low Drain. This paper focuses on the three abovementioned main sub-catchments, as well as a total combined catchment of all of these sub-catchments.

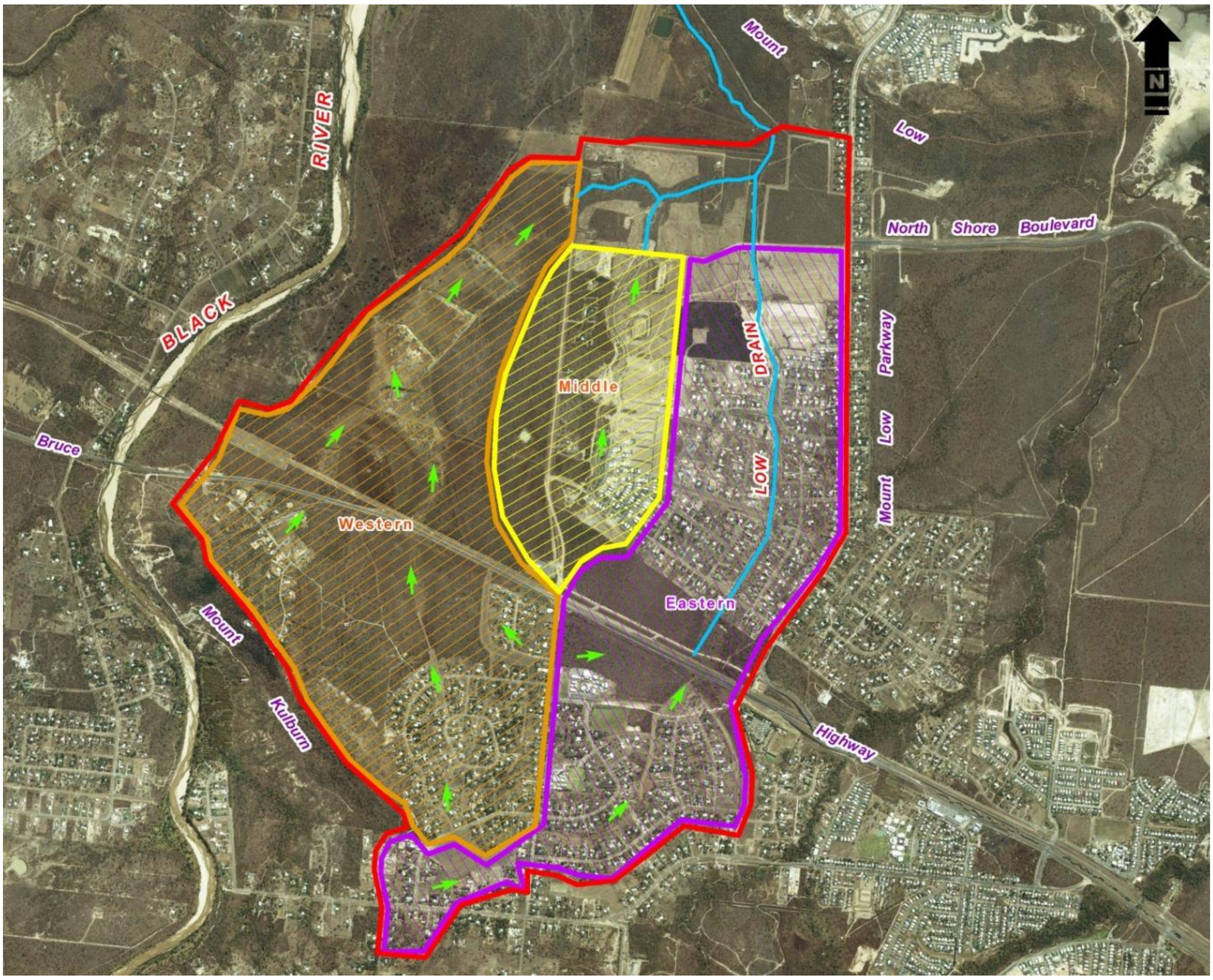

Figure 2: The Low Drain Catchment

Methodology

Testing Applications

Testing was undertaken on a total of four sub-catchments, being the western, middle, eastern, and a total of these sub-catchments. Testing on these catchments was undertaken for a 50 year ARI, using 0.5, 1, 1.5, 2, 3, 6 and 24 hour storm durations. A large computational effort of 63 model runs was made including base-line, and sensitivity testing on losses, roughness, and wetting & drying. The application of the DRM was undertaken over a major portion of the catchment to the north of the Bruce Highway, with runoff contributions for the upstream portions provided from the XP-RAFTS model. The grid cell size of the DEM used in the MIKE FLOOD model was 10m x 10m.

Due to the absence of gauging and flood height data, calibration of the models to recorded data was not possible. The XP-RAFTS catchments within this paper were modelled as localised catchments within a larger XP-RAFTS model of Black River. It is important to note that whilst the localised catchments of this study were not calibrated, the Black River XP-RAFTS model of which they were nestled within had been calibrated to recorded data. As a secondary check, runoff values were validated against the rural Rational Method, which is a well-recognised practice within the industry.

Model Testing Methods

The methods and results are separated into two sections. The first section examines the models in a base-line case (original and standard parameters), and the second section describes the effects of sensitivity testing on the MIKE FLOOD model.

PART ONE: Base-Line Testing

This test simulates the catchment runoff using consistent parameters in each model, and ones that are most representative of reality (i.e. what would typically be used in flood studies). 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 MIKE FLOOD

Initial and continuous rainfall loss values of 24mm / 2.5mm/h and 1mm / 0mm/h were applied to the pervious and impervious areas respectively. The roughness was kept largely similar between each model for consistency, and was reflective of ground conditions from on-site investigation. Wetting and drying parameters were defaulted at 0.002m and 0.001m respectively.

PART TWO: Sensitivity Testing

Sensitivity testing was undertaken to determine if adjustments to model parameters in MIKE FLOOD had an effect on the magnitude and timing of the peak runoffs, when compared to XP-RAFTS. The XP-RAFTS model parameters were kept consistent with that of the base-line case for all sensitivity tests. The following sensitivity tests were undertaken on the MIKE FLOOD DRM:

- *Losses* – the initial loss parameter was lowered from 24mm to 10mm, 5mm and 0mm for pervious areas in the DRM. Impervious losses and continuing losses remained unchanged.
- *Roughness* – roughness values were altered by factors of -10%, -20% and -30% of that of the base-line case.
- *Wetting and Drying* – as a further test to the base-line scenario, two more alterations were made being: WD01 (Wetting 0.001m, Drying 0.0005m) and WD02 (Wetting 0.004m, Drying 0.002m).

The above sensitivity tests were carried out for all 0.5, 1, 1.5, 2, 3, 6 and 24 hour storm durations.

Results & discussion

Part One: Base-Line Testing

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. Both models were found to adequately conserve mass, with only minor errors in volumes encountered.

Peak Flow & Lag Times

To compare the two models, the peak runoffs from the MIKE FLOOD hydrographs were taken as a percentage of the XP-RAFTS peaks, and this method is shown in Figure 3 below. The time lag of the DRM (relative to a leading XP-RAFTS hydrograph) was determined.

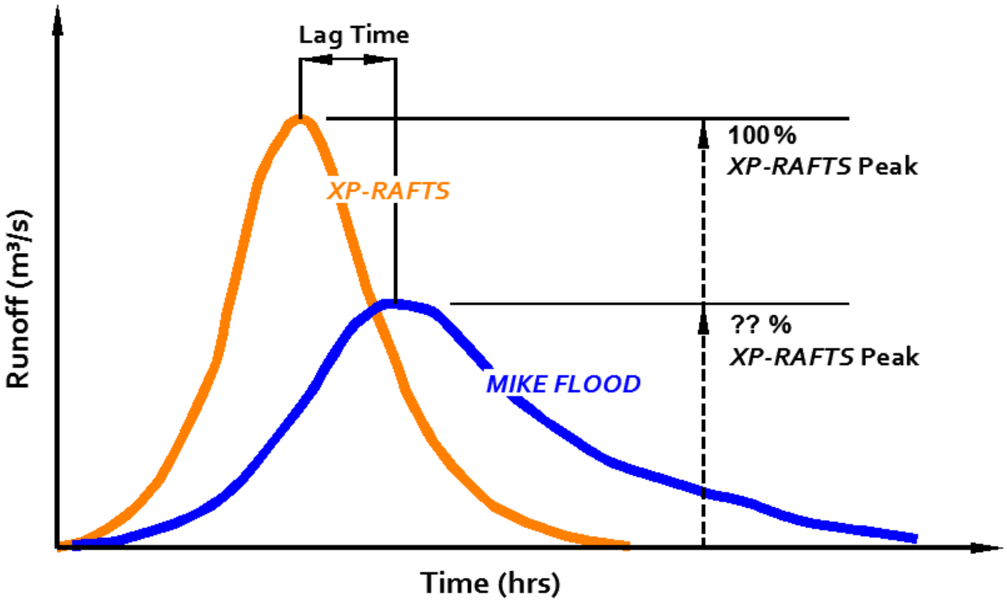

Figure 3: Analysis methods for peak flow magnitude and time lag

The percentage flow data, for representative sub-catchments, was plotted graphically over the numerous storm durations, illustrated below in Figure 4. The x-axis is in units of log-hours.

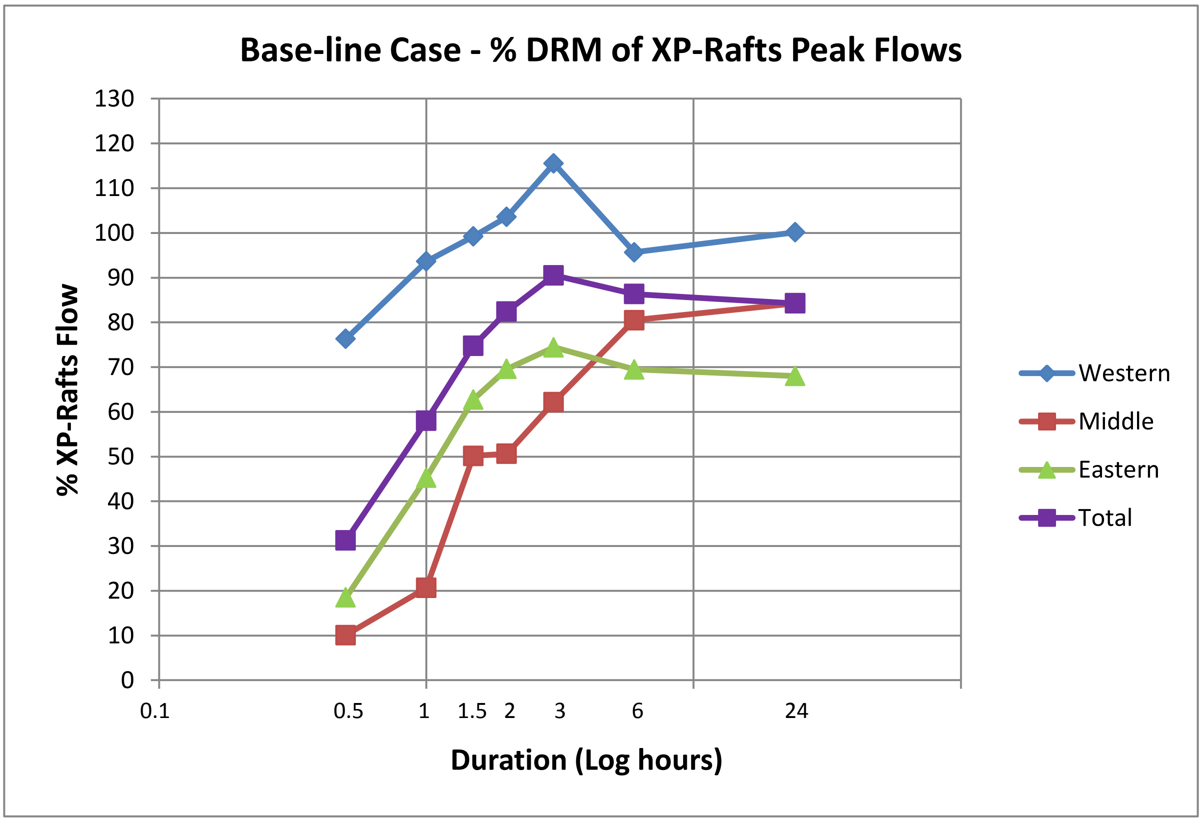

Figure 4: Comparison of MIKE FLOOD (DRM) Runoff Peaks to XP-RAFTS

Across the sub-catchments analysed in Figure 4, a trend was established that showed the MIKE FLOOD DRM had least similar peak flows to XP-RAFTS in durations less than 3 hours. 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. The Middle sub-catchment consists of the greatest overall fraction impervious over the entire study area. In many instances the XP-RAFTS peak flow of this sub-catchment coincided with the storm burst peak of the temporal pattern, suggesting a high sensitivity to fraction impervious.

In contrast to the Middle sub-catchment, the Western sub-catchment showed almost matching flows to XP-RAFTS. XP-RAFTS was supplemented with user-defined storages for large detention basins within the Western sub-catchment. This resulted in XP-RAFTS accommodating for storages similar to that of those within the 2D grid domain of MIKE FLOOD. Consequently the peak flows of the models were of best similarity, as seen in Figure 4.

The plot below in Figure 5 displays the time lag of the MIKE FLOOD DRM peak flow when compared to XP-RAFTS.

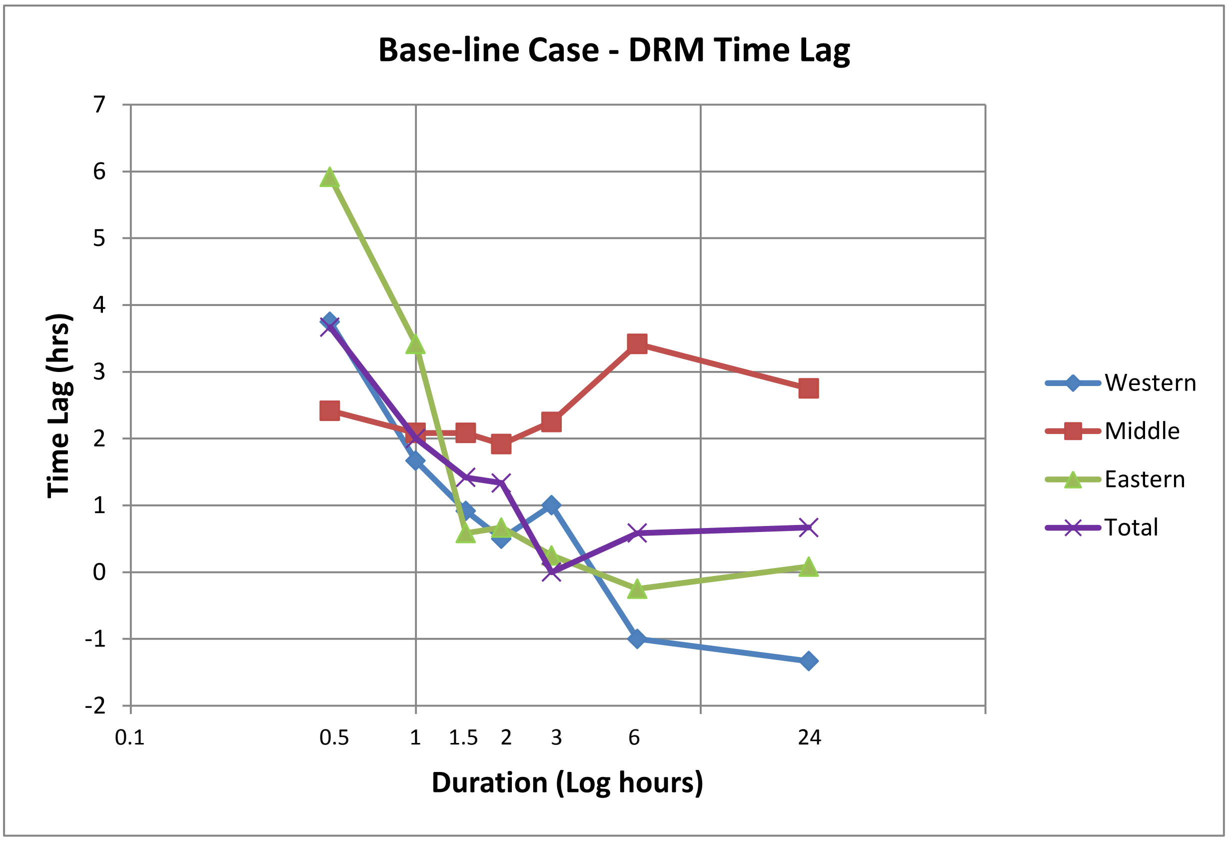

Figure 5: Time Lag of MIKE FLOOD (DRM) relative to XP-RAFTS

The time lag of the DRM can be quite large for small duration events less than 3 hours. The Middle sub-catchment was the only catchment here to maintain larger time lags in higher duration events such as the 3, 6 and 24 hour. This finding is considered to be impacted more so by XP-RAFTS' rapid response to a greater overall fraction impervious within the sub-catchment, however further investigation into fraction impervious was outside the scope of this paper. The Western sub-catchment was the only exception to peaking before XP-RAFTS (see Figure 5 - 6 & 24 hour durations). This sub-catchment consists of a series of storage basins, and the hydraulic treatment of these features differs between the two models. Whilst such differences exist, investigation of peak runoff time-lag in catchments consisting of storage basins was not explored further.

Storage effect of MIKE FLOOD

Storage generally results in both attenuation of runoff times and lowering of its peak magnitude. 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. 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 storage 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.

Figure 6 shows 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 respective catchments. It compares this percentage for the 1 and 24 hour durations.

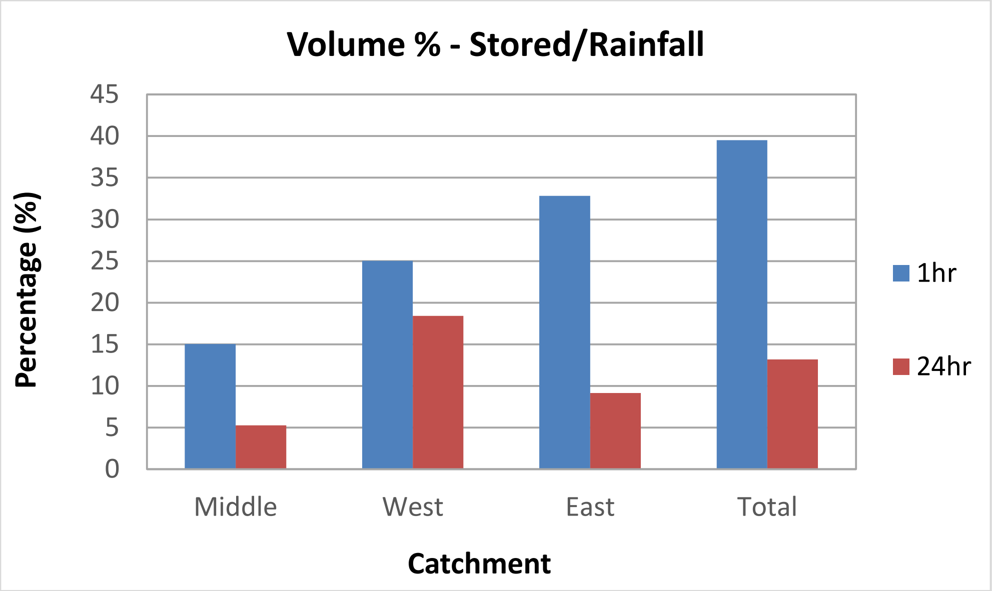

Figure 6: Percentage Volumes of Storage to Rainfall for Large Catchments

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. This finding was confirmed during analysis of additional internal sub-catchments not listed in this paper. This trend indicates that lower rainfall volumes from smaller duration events will be impacted by storages far more than those of larger volumes from longer duration events. Hence, the high peak flow attenuation and lag times in smaller duration events (< 3 hours) in the results of section *Peak Flow & Lag Testing*, can be attributed to the effect of storages within the DRM 2D grid terrain.

An analysis of this relationship over all durations would have been desirable. Unfortunately the simulation periods for some models were not sufficient in capturing fully drained hydrographs (where all runoff has left catchments). Re-running the models, and further data extraction, was decided against due to time constraints.

Part Two: Sensitivity Testing

Losses, roughness and wetting & drying parameters in the MIKE FLOOD model were altered to explore for compensating factors that may improve the DRM's similarity in runoff to the lumped-conceptual model. Testing and model comparison to XP-RAFTS similar to above was made for all catchments, totalling to over 500 pieces of data. These results were averaged across all catchments for overall effect. Plots relating to peak runoff and time lag are shown below.

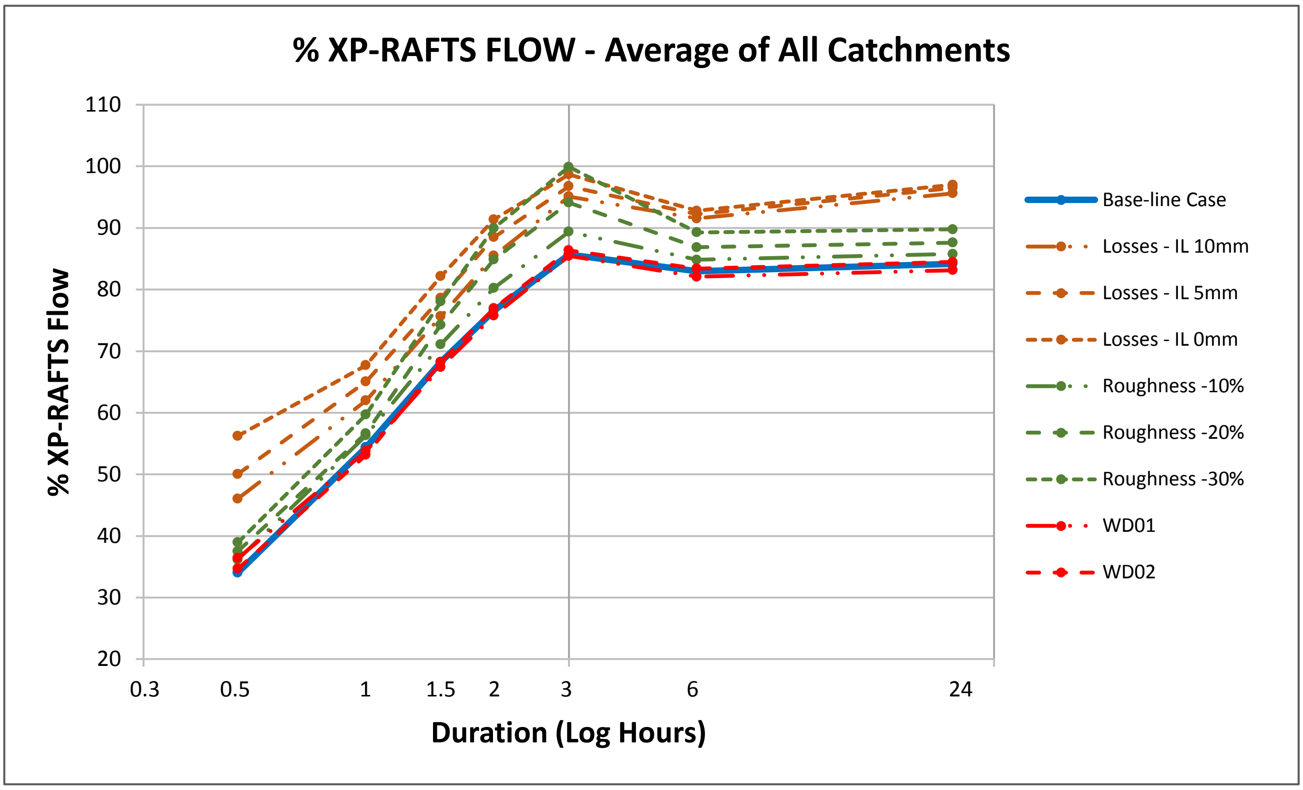

Figure 7: MIKE FLOOD Flows (as % of XP-RAFTS) Averaged Over All Catchments

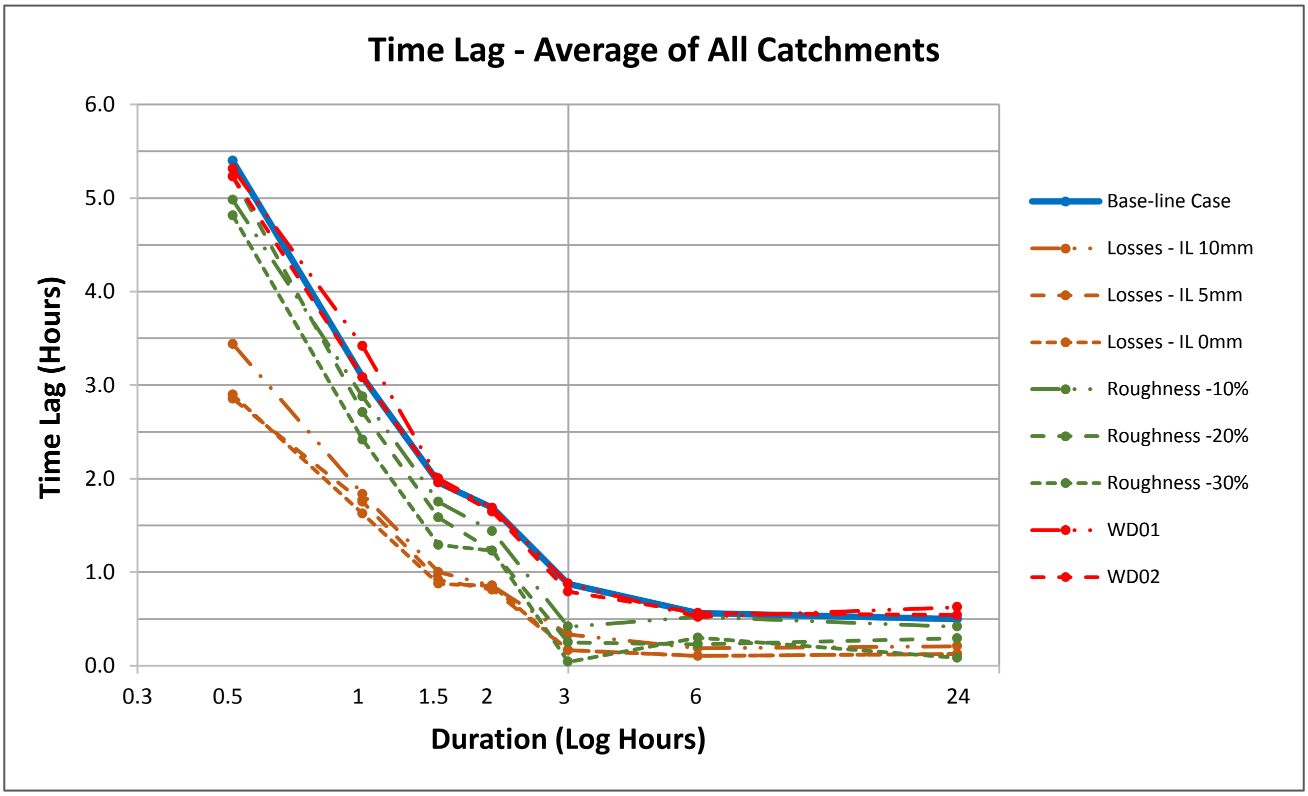

Figure 8: MIKE FLOOD Time Lags Averaged Over All Catchments

Figure 7 indicates the losses tests had the greatest impact on the DRM in terms of improving flow similarity to XP-RAFTS. 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 displayed improved percent flows in the 2 and 3 hour duration events.

The time lags of Figure 8 illustrate almost a mirror image of the flow percentage comparison. Adjustments to losses indicate greater sensitivity when compared to roughness and wetting & drying. Sensitivity testing of wetting & drying showed little to no impact in comparison to the base-line test in regards to flow and time lag.

The most striking finding in the above figures, pertinent to all testing, is the DRM is more suited to the lumped-conceptual XP-RAFTS for durations inclusive and greater than the 3 hour event. The findings from this section consist of averaged data across the catchment, and are not to say that other cases exist due to a range of varying situations of fraction impervious, detentions basins etc.

Conclusion

This paper establishes that storages in the DRM model impact the lower rainfall volumes of the short durations more greatly than the higher volumes of the longer durations. Consequently there are more prominent effects of peak runoff attenuation and time lag for short durations. This brings new findings to the engineering industry, and much practical value to flood analysts. In this case study, short durations were found to be those of the 0.5, 1, 1.5 and 2 hour events, and long durations were those of the 3, 6 and 24 hour events.

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. Engineers Australia (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’ (Engineers Australia 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. Engineers Australia (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 paper.

Taaffe et al. (2011) discovered severe attenuation of the peak discharge at the outlet, attributing this to pit cell storage within the 2D domain. This research focused on comparing losses retained from pit cells to that of initial loss depths from the rainfall hyetograph. Whilst this research diverges slightly to that of this paper, its finding related to attenuation is comparable.

Supplementing XP-RAFTS with user-defined storage basins that are present in the grid domain of the 2D model delivered desirable runoff peak magnitudes with MIKE FLOOD, as seen by the Western sub-catchment in Figure 4. It is noted that such modelling replication in XP-RAFTS is not practical for scenarios resembling that of floodplains where small depressions are spatially scattered throughout a catchment. Whilst magnitudes of runoff were similar in this catchment, cases existed where the XP-RAFTS peak runoff occurred after that of MIKE FLOOD. It is recommended additional investigation of runoff behaviour in large storage basins for each model is undertaken.

The highly fraction impervious Middle sub-catchment displayed fast runoff response in the XP-RAFTS model, recognising a requirement for further research into the effects of fraction impervious between the DRM and lumped conceptual models.

This paper has identified through sensitivity testing, that whilst altering parameters such as losses, roughness and wetting & drying have an impact on runoff, these factors are outweighed by storage attenuation in the 2D grid domain. This was more evident in durations less than 3 hours. As a further note to sensitivity testing, altering parameters to achieve model suitability does sometimes come at the price of losing representation of reality.

Alterations to XP-RAFTS parameters such as catchment roughness and the storage coefficient multiplication factor was outside the scope of this project, and is suggested as a further avenue for further research. Another component worthy of exploring is grid cell size of the direct rainfall model. Clark et al. (2008) discovered that the peak runoff of their direct rainfall models converged closer to that of their lumped conceptual model when the grid size was decreased. However in another published article, Taaffe et al. (2011) found that decreasing the grid size will increase the abundance of ‘pit cells’, describing these as ‘potentially severely attenuating the peak discharge at the catchment outlet’ (Taaffe et al. 2011, p. 434). It is recommended further investigation into grid sizes is undertaken to clarify their impacts. It is noteworthy that smaller grid sizes in large catchments may be a limitation due to their large computational demands and potential instabilities. Furthermore, the Low Drain catchment is generally flat grading (mostly <0.5%), and poor slope would undoubtedly have a more extreme outcome on results when compared to a steeper catchment.

For flood modellers practicing stormwater engineering, particularly in tropical North Queensland, 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 of that of XP-RAFTS.

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 paper are that further research is required to be undertaken on lumped-conceptual and direct rainfall models so as to improve guidance and confidence in their use. Where possible, it is recommended this research attempt to model and analyse gauged catchments that are calibrated to recorded data.

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