



University of
**Southern
Queensland**

UNDERSTANDING THE HYDRAULIC IMPACT OF HYDROLOGIC UNCERTAINTY IN THE URBAN GOWRIE CREEK CATCHMENT

A thesis submitted by

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ABSTRACT

Estimating peak flow rates from a catchment has long been a focus of engineering hydrologists and is fundamental to the design of flood protection infrastructure. Understanding the uncertainty associated with peak flow estimation is, however, often neglected by practitioners. Without a detailed understanding of uncertainty, the risks associated with major flooding in urban catchments cannot be completely understood. In January 2011, Toowoomba experienced one of its worst floods on record with Gowrie Creek breaking its banks in multiple locations, resulting in at least four deaths. Peer review of subsequent hydrologic modelling of the catchment recommended gaining a better understanding of the loss parameters adopted and the resulting uncertainty associated with these parameters. The industry popular design event method uses the traditional initial/continuous loss model. Adopting a dynamic loss approach within a continuous simulation model overcomes this limitation, while allowing for the simulation of multiple rainfall iterations and in turn a better understanding of hydrologic uncertainty. This research first calibrated a continuous simulation hydrologic model by simulating 11 selected storm events (with peak flows ranging from as low as 9 m³/s and as high as 600 m³/s). By disaggregating 100 years of daily rainfall to sub-daily (six minute) rainfall multiple times using the method of fragments and simulating these within the calibrated continuous simulation hydrologic model, it was possible to produce multiple iterations of 100 years of stream flows. Flood frequency analysis of these stream flows produced peak flows at the outlet of the catchment for various annual exceedance probabilities with uncertainty. Finally, this research developed a two-dimensional hydraulic model of the Gowrie Creek catchment and simulated hydrographs correlating to the peak flows for each hydrologic model iteration to determine the impact hydrologic uncertainty has on the flood extent within the urban Gowrie Creek catchment. The hydraulic impact of hydrologic uncertainty was found to be significant and would have a direct impact on urban planning.

CERTIFICATION OF THESIS

I, Iain Brown, declare that the PhD Thesis entitled *Understanding the hydraulic impact of hydrologic uncertainty in the urban Gowrie Creek catchment* is not more than 100,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references, and footnotes.

This thesis is the work of Iain Brown except where otherwise acknowledged, with the majority of the contribution to the journal papers presented as a Thesis by Publication undertaken by the student. The work is original and has not previously been submitted for any other award, except where acknowledged.

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Iain Brown contributed 75% to this journal paper. Collectively, Kevin McDougall, Sreeni Chadalavada, Md Jahangir Alam and Rezaul Chowdhury contributed the remainder.

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Iain Brown contributed 75% to this journal paper. Collectively, Kevin McDougall, Sreeni Chadalavada and Md Jahangir Alam contributed the remainder.

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Iain Brown contributed 75% to this journal paper. Collectively, Kevin McDougall, Sreeni Chadalavada and Md Jahangir Alam contributed the remainder.

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CHAPTER 1: INTRODUCTION

1.1 Background

Understanding the hydrologic response of urban catchments to extreme rainfall events is fundamental to making informed engineering and planning decisions around development extents, flood mitigation and disaster management (Pathiraja et al., 2012) and is fundamental to the design of flood protection infrastructure (Ball et al., 2019; Hossain et al., 2019; Kastridis et al., 2021; Segura-Beltrán et al., 2016). The need for an accurate hydrologic model and understanding the uncertainty in the results cannot be overstated.

In January 2011, Toowoomba experienced one of its worst floods on record, with Gowrie Creek breaking its banks in multiple locations. In addition to inundation, the floodwaters proved hazardous, with high velocities resulting in dangerous conditions for pedestrians and motorists at major road crossings, resulting in at least four deaths. As a result of the January 2011 flooding, a peer review panel was established to review the hydrologic and hydraulic models developed. The peer review recommended gathering further site-specific data and simplifying/gaining further understanding of the loss parameters adopted to understand the uncertainty in the modelling undertaken. These two factors, loss and uncertainty, have formed the basis of the research.

To understand how an urban catchment responds to a rainfall event, many methodologies have been developed. Peak flow estimations using the Rational Method (Kuichling, 1889; Mulvaney, 1851) have been used extensively in urban and rural catchments as it allows for a simplistic transformation of average rainfall intensity to peak flow. However, the subjective nature of the time of concentration estimation means that it is often difficult for two practitioners to produce the same answer. To overcome this issue, the development of hydrologic models using design hydrographs with a single temporal pattern (Australian Institution of Engineers, 1987)

or an ensemble of temporal patterns (Ball et al., 2019) has been the recommended methodology in urban catchments in Australia.

With all urban stormwater models, several input parameters are required, many of which are based on regional approximations or assumptions. Rarely are catchment specific parameters available and are often time consuming to obtain. Computer processing capability has also limited which methodology can be used in urban areas, however, recent technological advancements mean that more complex methodologies can now be utilised.

One such hydrologic parameter which leads to a high uncertainty in hydrologic modelling outcomes is the rainfall loss approach (Ball et al., 2019). Rainfall loss can be defined as the amount of rainfall that does not appear as immediate runoff (Hill et al., 1998). Rainfall losses are often accounted for by separating the losses into two categories: the initial loss (interception and infiltration prior to saturation or antecedent moisture conditions) and the continuing loss (infiltration post saturation) (Phillips et al., 2014). Most initial loss/continuing loss models greatly simplify the condition of the catchment prior to the event (Cameron et al., 1999). Rainfall losses in the catchment can vary because of geography, antecedent moisture conditions, and the intensity of the rainfall event (Ball et al., 2019). The most commonly used approach for simulating a catchment's runoff response to rainfall in Australia is the design event method (Ball et al., 2019). This method uses the widely adopted initial loss/continuing loss model. While it is simple to implement in practice, it assumes that the transformation of rainfall to runoff is probability neutral, i.e., the annual exceedance probability of the design rainfall data will always result in a flood of the same annual exceedance probability (Kavetski et al., 2006). The literature offers minimal guidance on the adoption of appropriate loss values (Rahman et al., 2002; Tularam and Ilahee, 2007), therefore rural catchment based initial loss/continuing loss parameter assumptions continue to be used for pervious urban areas even though the suitability of the parameters for use in urban catchments is not well understood (Ball et al., 2019).

Dynamic loss models differ from initial loss/continuing loss models as they account for the interaction between periods of wetting and drying through direct simulation of the physical processes occurring in the catchment (Cameron et al., 1999; Kavetski et al., 2006; Muncaster et al., 1999). The impact that each loss model has on the estimated rainfall excess is demonstrated in the hyetographs in Figure 1-1

Impact loss model has on rainfall excess. (a) Rainfall excess (white area) from the commonly used fixed Initial Loss/Continuing Loss model, with the darker hatch representing initial loss and the lighter hatch representing the fixed continuing loss, and (b) Rainfall excess (white area) from a dynamic infiltration loss model with the lighter hatch representing the loss (drawn based on the concept of O'Loughlin et al. (1996)). Rainfall losses to the catchment vary by geography, antecedent moisture conditions, the intensity of the rainfall event, and spatial distribution within the

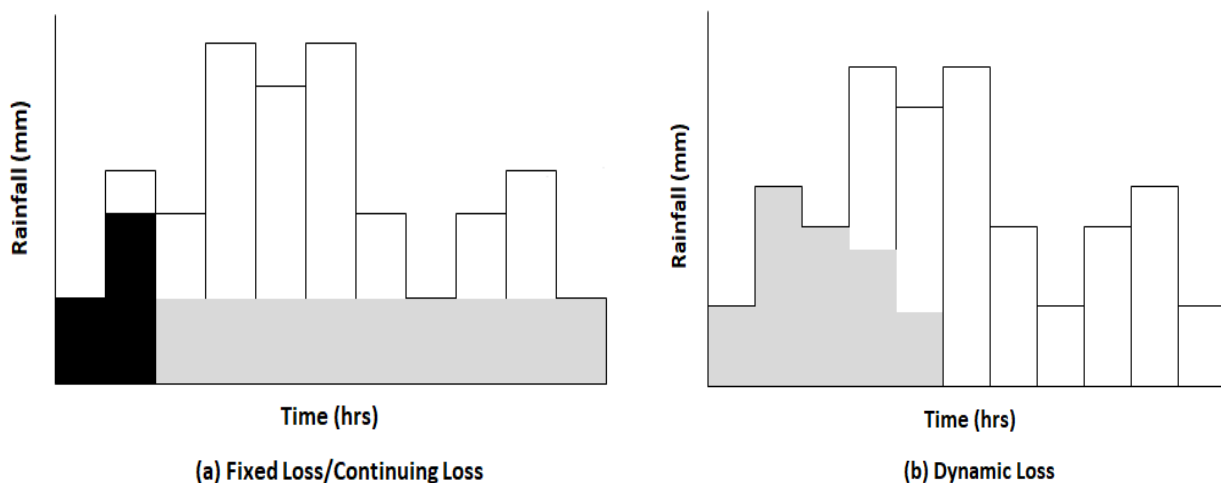


Figure 1-1 Impact loss model has on rainfall excess. (a) Rainfall excess (white area) from the commonly used fixed Initial Loss/Continuing Loss model, with the darker hatch representing initial loss and the lighter hatch representing the fixed continuing loss, and (b) Rainfall excess (white area) from a dynamic infiltration loss model with the lighter hatch representing the loss (drawn based on the concept of O'Loughlin et al. (1996)).

catchment, which is often overlooked (Phillips et al., 2014). However, without catchment specific data, hydrologic modelling cannot be calibrated. So regional based parameter assumptions continue to be adopted due to the limited guidance of appropriate values to use (Phillips et al., 2014).

Continuous simulation models seek to overcome the issue of assumed antecedent moisture conditions by modelling a complete sequence of rainfall data over a much longer duration than that of a typical design temporal pattern (Blazkova

and Beven, 2009; Calver et al., 2009; Camici et al., 2011). It also removes the need to simulate 'design' storm temporal patterns as it simulates recorded rainfall events and translates them to a hydrograph. By simulating a sufficient length of recorded rainfall, a flood frequency analysis can be undertaken to determine the flow rate corresponding to a given exceedance probability, and the hydrograph relating to the flow rate can also be determined.

The availability of a sufficient length of rainfall with a small enough time step to accurately model the catchment of interest is a key limitation to continuous simulation modelling (Viviroli et al., 2009). Government monitored rain gauges are often recorded on a daily timestep only and may have periods of incomplete data. The availability of pluviograph data, which provides sub-daily data sufficient for an analysis of this nature, is limited both domestically and internationally (Lewis et al., 2019; Seth Westra et al., 2012), and may only be available for relatively short periods of time. However, the recent development of synthetic rainfall generators and appropriate methodologies to calibrate the results has somewhat overcome this limitation.

There is a level of uncertainty associated with all hydrologic models. The level of uncertainty reduces with the increased degree of calibration and by reducing the number of assumed parameters. It is important to understand the uncertainty in the model results as the factors of safety and design freeboards can be reduced if the model is able to adequately simulate a range of flood events (Ball et al., 2019).

1.2 Research Aim and Objectives

The aim of this research is to investigate the predictive accuracy and uncertainty of hydrologic and hydraulic modelling of the Gowrie Creek catchment in Toowoomba by obtaining a better understanding of the loss parameters through continuous simulation. To understand the accuracy in the results obtained from the predictive hydrologic modelling, an uncertainty analysis of the key input parameters

will be undertaken. The impact hydrologic uncertainty has on hydraulic modelling will then be determined.

This research will develop a continuous simulation urban hydrologic model for the Gowrie Creek catchment and calibrate the model with both available rainfall and stream gauge data. By developing a continuous simulation model, the limitation of assuming antecedent moisture conditions will be overcome. Based on literature reviewed to date, no continuous hydrologic simulation of the Gowrie Creek catchment has been undertaken, and a limited number of urban catchments worldwide have adopted this methodology. By evaluating the hydraulic impact of hydrologic uncertainty, the impact that key hydrologic parameters have on flood extents within a catchment can be assessed.

The research objectives are to:

- 1) Develop a continuous simulation hydrologic model for the Gowrie Creek catchment in Toowoomba and calibrate the catchment losses to historical rainfall and streamflow data.
- 2) Generate and simulate sub-daily rainfall to produce a long series of continuous streamflow to allow a flood frequency analysis.
- 3) Undertake an uncertainty analysis of the key continuous simulation modelling parameters to understand the uncertainty of the flood frequency analysis.
- 4) Develop and simulate the extent of uncertainty within a hydraulic model to determine the impact hydrologic uncertainty has on the flood extent within the Gowrie Creek catchment.

The key research questions explored in this thesis are:

- 1) Does continuous simulation hydrologic modelling offer a more complete understanding of hydrological processes and can it replicate historical stream flows.

- 2) Can the uncertainty in the peak flows be determined using continuous simulation, and how do the results compare to other approaches, including the design event method.
- 3) What impact does hydrologic uncertainty have on the estimation of flood extents.

This research provides new insight into the impact of hydrologic uncertainty on the estimation of flood extents in an urban catchment. By comparing this to other methods popular in the industry, it offers an alternate method that may improve the understanding of uncertainty and its impact on urban planning. This provides an advancement in hydrologic and hydraulic modelling and allows industry professionals and decisions makers alike to make more informed decisions.

1.3 Thesis structure

Chapter 1 introduces the research undertaken within this thesis by first providing context to why this research was initiated and why the Gowrie Creek catchment was chosen as the subject site. By highlighting the importance of understanding uncertainty in hydrologic modelling and its corresponding impact on flood extents, the scene has been set to illustrate the importance of this research and leads to the development of the research objectives and research questions that will be addressed within this thesis.

Chapter 2 provides a review of literature regarding continuous simulation modelling and the advantages it has in understanding hydrologic uncertainty. In this chapter, a review of industry popular hydrologic modelling approaches is undertaken which subsequently leads to the selection of the hydrologic modelling approach for this research. However, to enable an uncertainty analysis to be undertaken, additional concepts are introduced, including synthetic rainfall generation and the use of flood frequency analyses, with this chapter concluding with the review of hydraulic modelling approaches.

Chapter 3 summarises the overall methodology used to complete all three journal papers and meet the research objectives. This chapter is critical in highlighting how the research was undertaken after the detailed review of literature, and documents how all three journal papers are linked.

Chapters 4 to 6 present the original research that has been carried out as part of this thesis by publication. The first journal paper in Chapter 4 presents the calibration of a continuous hydrologic simulation model in the urban Gowrie Creek catchment in Toowoomba, Australia and provides calibrated loss model parameters for an urban catchment. The calibrated continuous simulation hydrologic model is then used in the second journal paper presented in Chapter 5, which simulates multiple iterations of disaggregated rainfall data within the model to estimate peak flows for various annual exceedance probabilities and validates these against both the design event method and the available stream gauge data. The third and final journal paper in Chapter 6 extracts multiple iterations of design hydrographs from the model developed in journal paper 2 for the 1-in-100-year annual exceedance probability event and simulates them in a two dimensional hydraulic model to show the impact hydrologic uncertainty has on flood extents within the Gowrie Creek catchment.

In Chapter 7, the key findings are discussed, and future research directions are summarised. The key research questions that were originally presented in Chapter 1 are answered in detail, with reference to the journal papers published as part of this research.

The overall thesis structure is schematically shown in Figure 1-2 **Thesis Structure.**

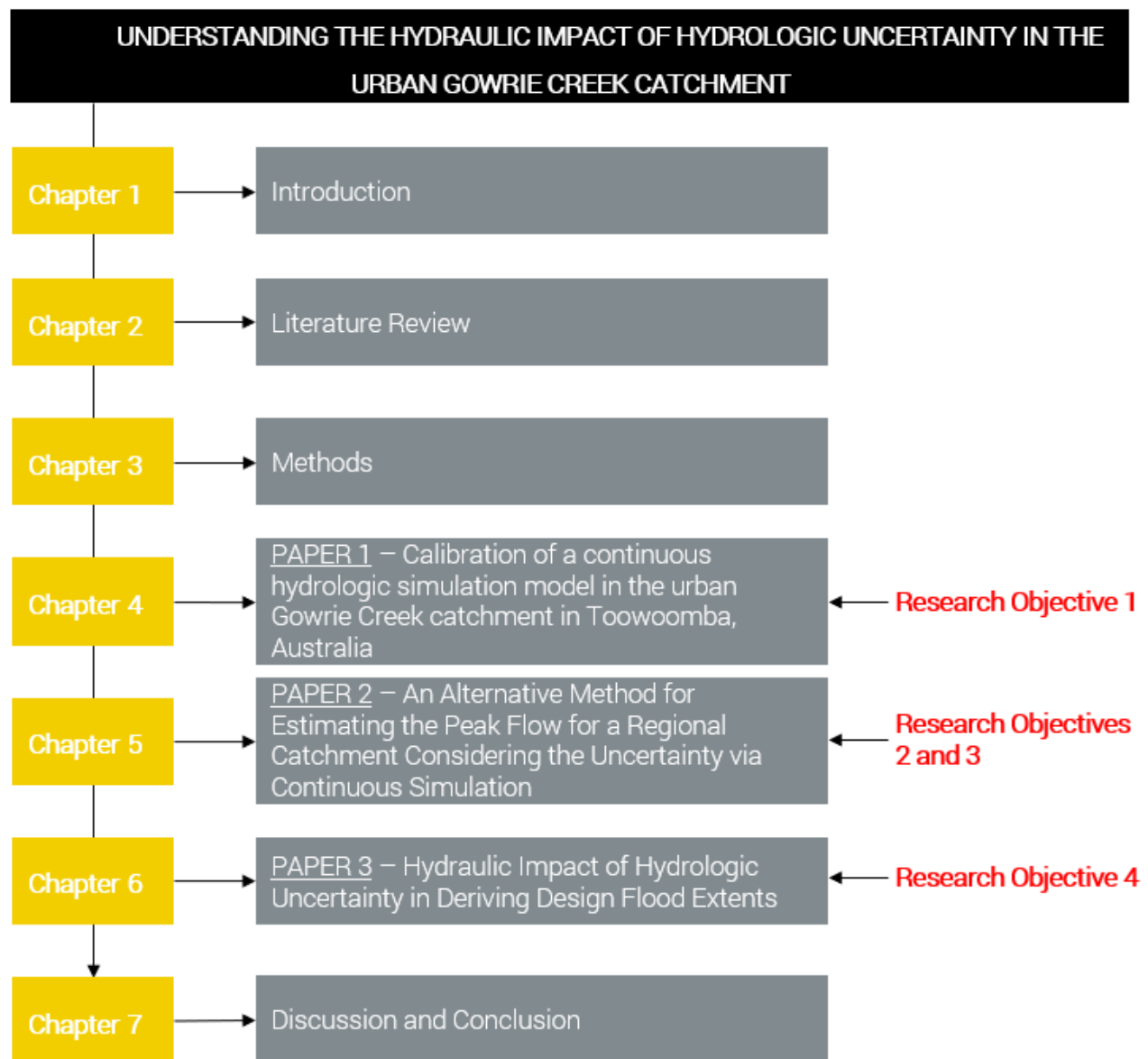


Figure 1-2 Thesis Structure

1.4 Research Scope and Limitations

This research had the following limitations:

- All hydrologic and hydraulic modelling was limited to the Gowrie Creek catchment in Toowoomba, Australia only. Only data available at the commencement of this research was utilised as the focus was to model a past event. This data included aerial survey, land use data, rainfall and stream flow.
- The hydrologic and hydraulic modelling was limited to a point in time, which results in a static interpretation of the underlying terrain and land use within the catchment.

- This calibration of both the hydrologic and hydraulic models was limited by the number of recorded flood events. In particular, only one major event (January 2011) was suitable for the hydraulic model calibration due to the amount of data collected in that event. No other recorded flood event had suitable hydraulic model calibration data.
- The hydrologic model uncertainty was limited by the computational time. This issue has been discussed extensively in journal paper 2.

1.5 Conclusion

Chapter 1 of this thesis has provided a detailed background to the research. The aftermath of major flooding in Toowoomba in 2011 highlighted the importance of understanding the hydrologic response of an urban catchment. Of particular importance in understanding a catchments response to rainfall is the amount of hydrologic loss to the catchment, with this parameter leading to significant uncertainty in the conversion of rainfall to runoff. The concept of adopting a probability neutral conversion of rainfall to runoff has also been introduced, which is a common assumption made in popular hydrologic modelling techniques. This research seeks to overcome this assumption, while also understanding the uncertainty associated with key hydrologic parameters, through continuous simulation. The aims and objectives this research intends to achieve and the research questions it will answer have also been detailed, highlighting the contribution this research will make to both academia and industry.

Chapter 2 provides a comprehensive review of literature relating to the research aims and objectives to highlight the research gap that this research has attempted to fill.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter provides a comprehensive review of the literature relating to the research objectives and provides further detail on the gap in literature that this research is seeking to fill. To allow an investigation into the predictive accuracy of hydrologic modelling, an understanding of the hydrologic modelling approaches used in literature is obtained. This review then leads to the hydrologic modelling approach to be adopted in this research (continuous simulation).

To allow the uncertainty analysis to be undertaken within the continuous simulation hydrologic model, a long series of sub-daily rainfall is required. The various methods used in literature to disaggregate daily rainfall to a sub-daily timestep are reviewed and a robust method chosen. Simulating the long series of sub-daily rainfall only provides a long series of streamflow and as a result, flood frequency analysis methods to convert streamflow to peak flow are investigated. How uncertainty can be incorporated into the hydrologic modelling has also been reviewed.

Finally, a review of hydraulic modelling techniques was undertaken to allow the hydraulic impact of hydrologic uncertainty to be understood.

2.2 Historical Approach to Peak Flow Estimation

A commonly used approach for simulating a catchment's runoff response to rainfall is the design event method (Ball et al., 2019). The design event method transforms a design rainfall with a given temporal pattern and an assumed antecedent moisture condition of the catchment based on regional loss parameters, into a hydrograph when routed through a hydrologic model. While this method is simple to implement in practice, it greatly simplifies the condition of the catchment prior to the event (Cameron et al., 1999) and assumes the transformation is probability neutral, meaning that the annual exceedance probability of the design rainfall data will always result in a flood of the same annual exceedance probability

(Kuczera et al., 2006). Making this assumption requires the model parameters to be 'optimised' through the calibration process (Pathiraja et al., 2012).

As a majority of urban catchments are ungauged, calibration of the loss parameters using the design event method is often not possible. There is limited guidance on appropriate loss values to adopt in literature (Rahman et al., 2002; Tularam and Ilahee, 2007). The Australian Rainfall and Runoff guideline is typically quoted in lieu of site-specific information, however the suitability of the parameters for use in urban catchments is not well understood (Ball et al., 2019).

Increased computational capacity, and the availability (or ability to generate) sub-daily rainfall data, has allowed for more complex models with improved representation of the complex physical processes within a catchment to be developed (Boughton and Droop, 2003). An example, and the focus of this research, is continuous simulation modelling which has become a viable method to overcome the assumptions made in the design event method (Cameron et al., 1999). It is seen as the most rigorous modelling approach for understanding the interaction between variables with joint probability as it directly simulates a long period of climatic conditions (Kavetski et al., 2006). Continuous simulation modelling removes the need for arbitrary assumptions of the antecedent moisture conditions of the catchment and allows for an accurate account of the hydrologic losses (Boughton et al., 2002). By producing a time series of flow rates, a Flood Frequency Analysis (FFA) can be undertaken to determine the peak flow rate corresponding to a given annual exceedance probability, and the uncertainty can be quantified to understand the accuracy of the peak flow estimations for a given annual exceedance probability (Cameron et al., 1999).

2.3 Continuous Simulation

Continuous simulation modelling involves modelling long periods of rainfall data to produce a long series hydrograph (Boughton et al., 2002). The key advantages of continuous simulation modelling over other methods are that it rejects the concept

of probability neutrality, and more importantly, it removes the need for hydrologists to make assumptions on the condition of a catchment prior to a rainfall event. While continuous simulation modelling has typically been applied to rural catchments as they are more often gauged, it can be transitioned to urban catchments that also have sufficient data available.

The output of continuous simulation modelling is a long continuous flow series, meaning for the period of rainfall data available, a corresponding discharge at the outlet of the catchment can be produced. This offers two key advantages:

- 1) It is possible to achieve an improved model calibration, as the volume of the hydrograph can be considered both during storm events and over the long term.
- 2) The uncertainty in the result can be estimated, as opposed to a typical sensitivity analysis, as the impact of rainfall patterns can be assessed without the need to alter the loss parameters.

Linsley and Crawford (1974) were early adopters of continuous simulation modelling in urban catchments and went on to develop a computer based continuous simulation model (the Stanford Watershed Model) in the 1960s. Rangari et al. (2015) described the plethora of stormwater modelling software available to analyse an urban catchment using both the design event and continuous simulation, however there still seems to be limited published applications or case studies using continuous simulation. Ling et al. (2015) compared various methods used to estimate peak flows for various catchments, however continuous simulation was excluded from the urban catchment case study. More recently, Grimaldi et al. (2021) proposed a step forward for the practical use of their continuous simulation approach in an ungauged catchment, however the catchment used in the assessment was less than 25% urban.

While the documented use of continuous simulation modelling in urban catchments is limited, its use in rural catchments dates to at least the 1990s. Boughton and Hill (1997) compared the results of a continuous simulation model for the Boggy Creek catchment in Victoria, Australia against the available stream gauge

and found good agreement for rare and extreme events. A subsequent study by Boughton et al. (2002) for the Avon River and Spring Creek catchments in Victoria, Australia found that limited rainfall and stream gauge data offered minimal opportunity for calibration. For the Moore River catchment in Western Australia, Newton and Walton (2000) achieved good agreement with both a flood frequency analysis of the stream gauge and design event modelling. Each of the studies mentioned adopted a rainfall excess model, the Australian Water Balance Model (Boughton, 2004), and routed the excess rainfall through a hydrologic model (Boyd et al., 1996). Industry practitioners tend to use hydrologic models with a graphical interface that determine and route the rainfall excess, including XP-Rafts (XPSolution, 2008), SWMM (EPA, 2015) and URBS (Carroll, 1994). The hydrologic model platform used in this research is discussed in the next section.

2.4 Hydrologic Modelling

Due to the complex, data intensive and potentially long computational times associated with continuous simulation modelling, it is important to select a suitable modelling platform. Boughton and Droop (2003) have successfully applied continuous simulation modelling to both the RORB and WBNM models, however they were both used as a routing tool only, with the runoff depth pre-calculated in a separate loss model (Australian Water Balance Model). It is likely that this approach was adopted due to the limited selection of dynamic infiltration loss models available within the RORB and WBNM models.

This research reviewed a range of hydrologic models and software to determine a suitable system for this study. The widely used urban stormwater management tool XP-Rafts platform was chosen for its capability to undertake both design event and continuous simulation modelling (Innovyze, 2018). XP-Rafts has the ability to model all key continuous simulation hydrologic processes, including rainfall/runoff, losses through both infiltration (ARBM or initial/continuing loss models), as well as evaporation from standing water bodies. XP-Rafts is extensively

used in consulting engineering, however, is not as common in research, likely due to the associated licensing costs. Through undertaking this research using XP-Rafts, it was possible to build on the research undertaken by Boughton and Droop (2003) by identifying another modelling platform capable of undertaking continuous simulation modelling. In addition, XP-Rafts is the model of choice of the industry funding source for this research (TRC).

The pervious area loss within this software is represented by the ARBM dynamic loss approach adapted from the research of Chapman (1968) and Chapman (1970) and is summarised in Figure 2-1 **Graphical representation of the ARBM loss model, which forms the basis of runoff generation in the XP-Rafts model, with supporting equations for key components of the runoff generation process (drawn based on the concept of XPSolution (2008))**. This loss approach can be visualised as a series of interconnected buckets of varying sizes. Rainfall that isn't intercepted by trees or plants (Interception Storage Capacity (ISC)) may be captured in minor surface depressions (Depression Storage Capacity (DSC)). If the rainfall is intense enough, runoff may result from the DSC, otherwise infiltration to the Upper Soil Capacity (USC) occurs. Water is redistributed between the USC and the Lower Storage Capacity (LSC) depending on the capacity available within the bucket. Water from the LSC can then be drained into the Groundwater Storage Capacity (GSC) which contributes to baseflow. The ARBM allows for the simulation of soil moisture depletion through evaporation between rainfall events (Fleming, 1974) with evapotranspiration depleting the ISC, DSC, USC and LSC. Any excess rainfall is routed to the catchment outlet based on the non-linear runoff-routing method developed by Laurenson (1964).

The ARBM has 15 input parameters. Goyen (1981) found that nine of these are consistent across all land use types, four have a negligible impact on runoff during extreme rainfall events, and two parameters within the infiltration function are highly sensitive: sorptivity (S_0) and hydraulic conductivity (K_0). As sorptivity is a component of hydraulic conductivity, the two parameters are degenerate, meaning they cannot

be solved in isolation and, therefore, one of the two parameters has to be fixed to allow the infiltration function to be optimised. For this reason, sorptivity was fixed in line with the results of Goyen (1981) at $10 \text{ mm/min}^{0.5}$. In addition to the infiltration function's sensitivity, it is logical that the DSC would be sensitive given that it directly controls the initial conversion of rainfall to runoff. An increasing DSC allows more rainfall to transfer to the USC. Direct measurement of the ARBM parameters is

difficult, uncertain, costly and impractical (Mein and McMahon, 1982) and, as a result, was not attempted as part of this research.

2.5 Synthetic Rainfall Generation

To produce a long series of continuous streamflow, a continuous simulation

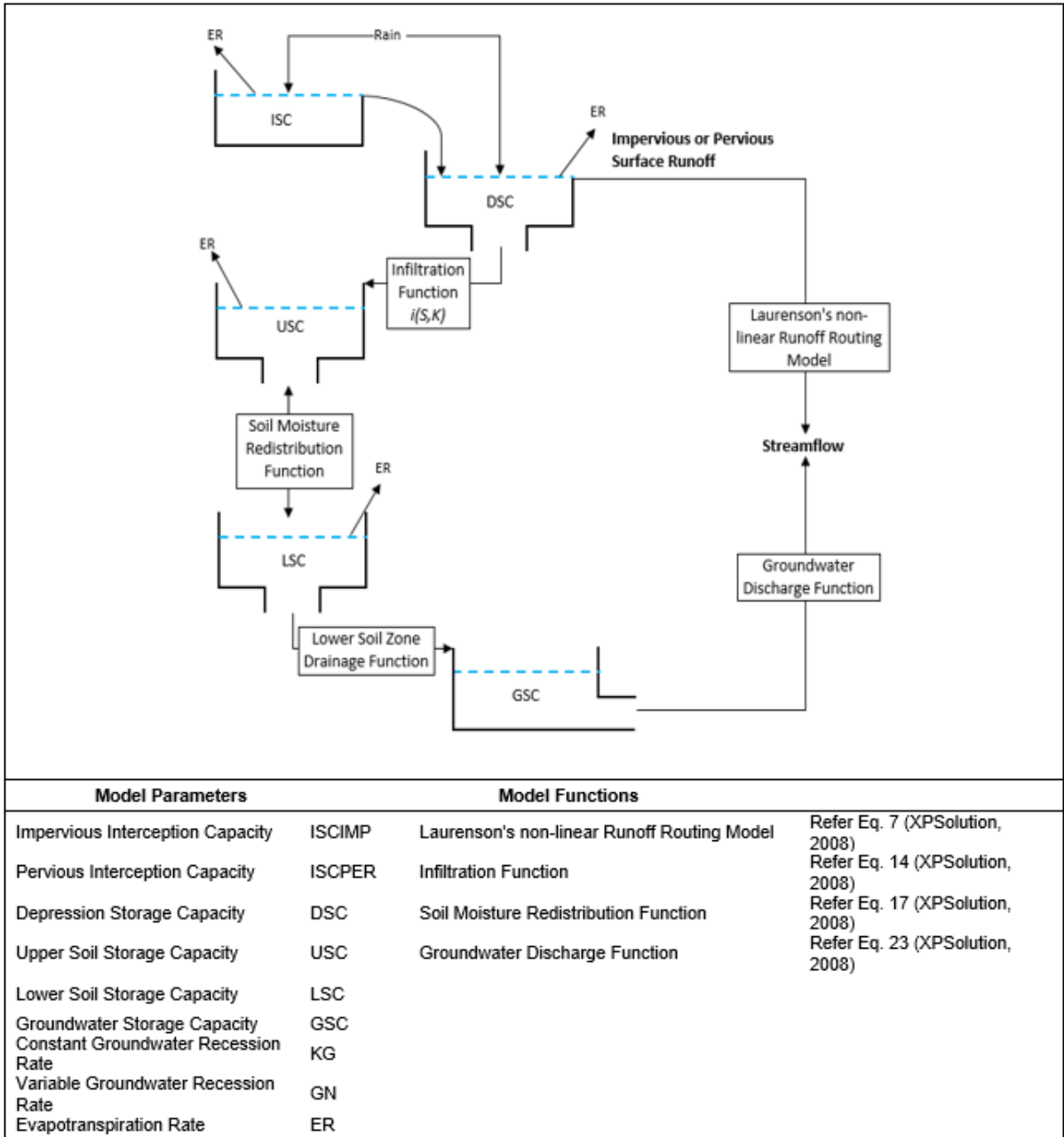


Figure 2-1 Graphical representation of the ARBM loss model, which forms the basis of runoff generation in the XP-Rafts model, with supporting equations for key components of the runoff generation process (drawn based on the concept of XPSolution (2008))

model requires an extended period of recorded rainfall at a suitable time step for the

size and level of urbanisation of the catchment (Linsley and Crawford, 1974). In the case of a relatively small urban catchment, rainfall at a sub-hourly interval is required. Obtaining a recorded rainfall series of sufficient length over this time scale is extremely challenging given the lack of sub-daily rainfall gauges available, not only globally (Lewis et al., 2019), but more relevant to this research, in sparsely populated countries such as Australia (Seth Westra et al., 2012). This contrasts with recent reviews of global precipitation data, with some locations offering sub-daily rainfall that spans multiple decades (Sun et al., 2018). The availability of sub-daily rainfall data has supported recent advancements in the use of continuous simulation hydrologic modelling (Grimaldi et al., 2021); however, this research is unique in that the lack of availability of site-based sub-daily rainfall data requires alternate considerations. To address this issue, sub-daily rainfall can be generated from coarser timescale (daily) rainfall records via disaggregation (Li et al., 2018) if historical daily rainfall data for at least 100 years is available for the site (Jeffrey et al., 2001).

The most commonly used rainfall disaggregation approaches are summarised in the literature (Li et al., 2018), including parametric sampling methods, such as the Poisson-cluster models and the random scale models, as well as nonparametric sampling methods, such as the method of fragments. They concluded that the method of fragments, first proposed as a method to disaggregate streamflow (Svanidze, 1964), was more flexible for operational use. At its core, the method of fragments simply disaggregates daily rainfall by selecting the pattern or 'fragments' of a known sub-daily event. The process of selection of suitable sub-daily events varies across the literature. This includes the use of the previous and subsequent day wetness to limit the sample size (S Westra et al., 2012) or adding classes based on rainfall magnitude to ensure the daily rainfall was disaggregated based on sub-daily rainfall of a similar magnitude, as well as limiting the selection to events that occurred in the same month as the disaggregated rainfall (Li et al., 2018). While a long series of sub-daily rainfall data was produced, neither study used their dataset for continuous hydrologic modelling to estimate flood frequency.

An important consideration when using the method of fragments is the storm class. The storm class defines how the daily and sub-daily rainfall data sets are related, as the daily rainfall data are only disaggregated to storms within the same storm class. It was initially suggested that only four storm classes be selected based on the rainfall before and after the day of interest (S Westra et al., 2012). However, this has several limitations including the potential for not considering important storms based on their insignificant pre/post-day rainfall total. In addition, large daily rainfall totals could be disaggregated into high-intensity, short-duration, and low-depth storms based on the same pre/post-rainfall conditions, rather than basing them on the magnitude of rainfall on the day of interest. The latter issue is of particular interest if the disaggregated rainfall is to be used in a hydrological model. As a result, dividing the rainfall data into several storm classes was subsequently suggested, with an interval of 5 mm being adopted (Li et al., 2018).

2.6 Peak Flow Estimation via Continuous Simulation

Once disaggregated, the sub-daily rainfall data can be simulated within the continuous simulation hydrologic model. To estimate peak flows from a continuous simulation model, the data should normally follow a flood frequency distribution similar to gauged streamflow records. A model that can replicate a long series of streamflow (i.e., continuous simulation) can assist in overcoming the shortcomings of stream gauge data, most noticeably the impact of urbanisation (Ball et al., 2019). A flood frequency analysis can be undertaken using one of two sampling approaches: annual maximum series and peaks over threshold (also known as partial series) (Swetapadma et al., 2021). The annual maximum series, while easier to identify independent flood events, produces fewer data points than the peaks over threshold series (Karim et al., 2017), but also prioritises the maximum annual flood over multiple larger floods that may have occurred in the same year. In contrast, the peaks over threshold approach offers added complexity due to the requirement of selecting an appropriate threshold flow. Some researchers found the best results of their flood

frequency analysis occurred when the number of data points (m) equalled the years of data (n) (Jayasuriya and Mein, 1985; McDermott, G.E. and Pilgrim, 1982; Swetapadma et al., 2021), while others recommended a ratio of 1 m :3 n (Dalrymple, 1960). Both sampling approaches rely on a long series of continuous streamflow, with at least 50 years of data recommended to be used (Kobierska et al., 2018).

2.7 Uncertainty

Understanding the level of hydrologic uncertainty allows design and planning decisions associated with the results obtained to be optimised. Uncertainty modelling deals with two broad categories of uncertainty (Ball et al, 2016):

- 1) Aleatory (or inherent) uncertainty, which refers to uncertainty attributed to natural randomness or natural variability observed in nature, and
- 2) Epistemic (or knowledge-based) uncertainty, which refers to uncertainty attributed to incomplete/imperfect knowledge of a physical system (hence its model), and the inability to measure it precisely (if at all).

Epistemic uncertainty can be reduced through the development of a model based on physically verified parameters and calibrated to observed rainfall events (Gupta and Govindaraju, 2023). However, to understand the impact of aleatory uncertainty, an analysis of the impact of varying input parameter sets is required. As most of the input parameters, including losses, can be calibrated from historical rainfall events, a key varying parameter set is the rainfall data. Assessing the peak flow from multiple iterations of disaggregated rainfall data allows for the understanding of this uncertainty.

2.8 Hydraulic Modelling

Accurate flood mapping is an important process undertaken by planning authorities to ensure sustainable land use planning and protection of human property and life (Grimaldi et al., 2013). The role of flood mapping in building resilient communities increases as the urban population grows and the uncertain nature of

rainfall becomes more evident (Fischer and Stanchev, 2022). Flood maps are a direct output of complex, two-dimensional hydraulic models that require either direct rainfall input (rain on grid) or hydrographs produced from hydrologic models (fluvial). This research focusses on the fluvial approach to flood plain mapping, given the lack of benchmarking of hydraulic models using rain on grid (Costabile et al., 2021).

HEC-RAS 2D is a two-dimensional hydraulic routing model that performs unsteady flow analysis and allows the modelling of open channels, floodplains, levees, culverts and bridges (Brunner, 2020). It enables the user to choose from one of three numerical solvers; 2D Diffusion wave, Shallow Water Equation with an Eulerian-Lagrangian approach to solve for advection (SWE-ELM), or more recently (Version 6.0), a Shallow Water Equation that uses an Eulerian approach to solve advection (SWE-EM). The equations that drive the above numerical solvers are detailed in the HEC-RAS Hydraulic Reference Manual Version 6.3 (Brunner, 2020).

Benchmarking of the SWE-ELM numerical solver was undertaken (Baker, 2018) and was found to perform extremely well across all eight tests when compared to the models used in the original benchmarking study (Neelz and Pender, 2013). This included popular industry models like TufLOW (TufLOW, 2018) and Mike Flood (DHI, 2021). In addition, when benchmarking the different numerical solvers, the SWE-EM option did not provide any additional benefit over the default SWE-ELM, despite the increased computational time required (Costabile et al., 2021). Based on the above, this research adopted the SWE-ELM numerical solver within HEC-RAS 2D for all results shown.

2.9 Conclusion

Chapter 2 of this thesis has provided a comprehensive review of literature relating to the research aims and objectives. In particular, Chapter 2 has reviewed the hydrologic modelling approaches that are popular with industry practitioners and has highlighted the assumptions made in the design event method that simplify the condition of the catchment prior to rainfall events. Continuous simulation hydrologic

modelling has been highlighted as a more comprehensive method to evaluate the conversion of rainfall to runoff.

As continuous simulation hydrologic modelling requires a long series of rainfall to convert to streamflow, sourcing rainfall of this nature has been investigated. The lack of recorded sub-daily rainfall has resulted in the need for various rainfall disaggregation methods that can convert a long series of recorded daily rainfall to a sub-daily timestep. The method of fragments has been identified as a robust method to achieve this research objective, however careful interrogation of the storm class will be needed.

Simulating the long series of disaggregated rainfall will result in a long series of stream flow that will need to be converted to peak flows. Review of flood frequency analysis techniques has identified both the annual maxima and the peaks over threshold sampling methods are valid, leading to both methods being used in this research.

To understand the uncertainty in peak flow, the sources of uncertainty have been reviewed. Given the epistemic sources can be reduced through calibration, the focus of the research will be on aleatory sources, in particular rainfall variation. Simulating multiple iterations of the disaggregated rainfall within the continuous simulation hydrologic model will allow the uncertainty to be understood. Reviewing hydraulic modelling techniques will allow the impact hydrologic uncertainty has on flood extents to be understood.

By undertaking this review, a gap in literature whereby continuous simulation has not been used in an urban catchment has been identified. Adopting continuous simulation to determine peak flows for various annual exceedance probabilities has rarely been used in literature, with minimal evidence of its use in an urban catchment with a short response time.

Chapter 3 continues on from Chapter 2 by presenting the methods used in undertaking this research.

CHAPTER 3: Methods

3.1 Introduction

The review of literature presented in Chapter 2 has highlighted that the industry popular design event method leads to assumptions being made that greatly simplify a catchments conversion of rainfall to runoff. A key research gap identified is that continuous simulation, a more rigorous method that overcomes this simplification, has rarely been used in literature in an urban catchment. In addition, the understanding of hydrologic uncertainty associated with varying rainfall patterns is not well understood, and the subsequent impact hydrologic uncertainty has on hydraulic modelling is not documented.

As a result, this research proposes to fill this gap by first developing a continuous simulation hydrologic model for the Gowrie Creek catchment in Toowoomba and calibrating the catchment losses to historical rainfall and streamflow data. To allow an uncertainty analysis to be undertaken, multiple iterations of disaggregated sub-daily rainfall will be simulated in the continuous simulation hydrologic model, resulting in multiple iterations of stream flow being produced. A flood frequency analysis of the stream flow will result in multiple iterations of peak flow with various annual exceedance probabilities and in turn gaining an understanding of the uncertainty in the result. Simulating these flows in a hydraulic model will highlight the impact hydrologic uncertainty has in deriving design flood extents.

This thesis culminates in a series of three journal papers that investigate hydrologic uncertainty through continuous simulation hydrologic modelling and uses the results to ultimately evaluate the hydraulic impact of hydrologic uncertainty. The modelling approach is summarised in Figure 3-1 **Summary of modelling approach to this research**. The study area and detailed methodology used to achieve the research objectives is presented in the following sections.

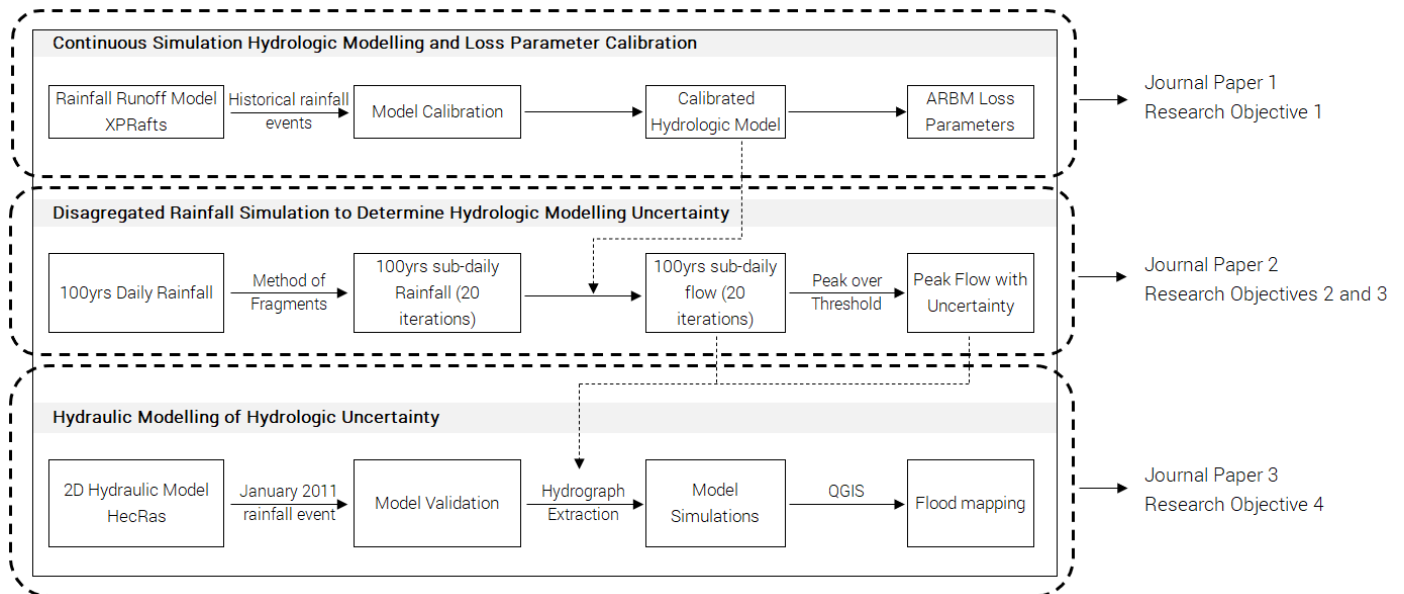


Figure 3-1 Summary of modelling approach to this research

3.2 Study Area

The Gowrie Creek catchment is a heavily urbanised catchment in the city of Toowoomba, in the state of Queensland, Australia. Toowoomba is sub-tropical with an average annual rainfall of 700 mm, the majority of which falls over the wet season from November to March. The 51 km² catchment, shown in Figure 3-2, is twice as long as it is wide, and has a well-defined, heavily modified creek line. Elevations within the catchment range from 750m Australian Height Datum (AHD) at the southern and eastern extents, to 550m AHD at the catchment outlet to the north. This significant height difference across the catchment results in sub-catchment areas varying in slope from 3% near the valley, to 9% at higher elevations.

The tributaries within the catchment, namely East and West Creeks, contain a series of detention basins installed to help reduce flood risk. After the major flooding in 2011, additional flood mitigation measures and monitoring stations were installed as shown in Figure 3-2. Fifteen rain gauges and one stream gauge currently monitor the catchment, however only six of these were in operation during the 2011 flood event. Since 2016, 11 gauges have been found to provide reliable measurements. The data available and methods used to develop the three journal papers are summarised in the following sections.

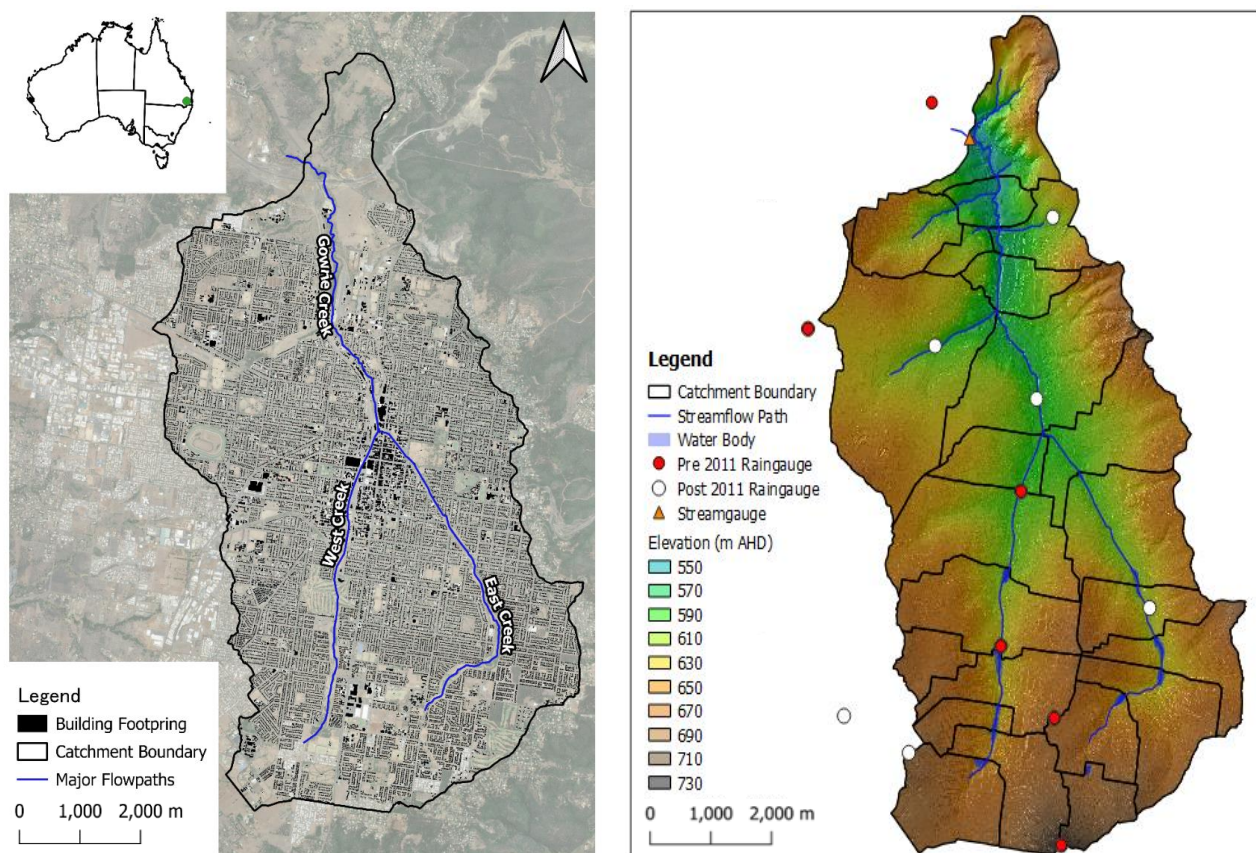


Figure 3-2 Gowrie Creek catchment in Toowoomba with key catchment features shown

3.3 Study Data and Quality

Development of the hydrologic and hydraulic models for this research required data to be sourced from three key agencies namely: Toowoomba Regional Council, the Bureau of Meteorology (BOM) and the Queensland Government. The data types, source and details are presented in Table 3.xx, and discussed below.

Sub-daily rainfall data was sourced from Toowoomba Regional Council operated rain gauges across the study catchment. During the major rainfall and flood event in 2011, only six gauges were in operation. Since 2016, 11 additional gauges were added across the catchment, however, only six were found to provide reliable measurements. Whilst the quality of the data could not be guaranteed by the Toowoomba Regional Council, the gauge data was cross checked against more reliable sources, including data provided by the Bureau of Meteorology, to validate the data and remove outlier values where necessary. In addition to the sub-daily rainfall, the Toowoomba Regional Council provided a 1m digital elevation model (DEM) developed from aerial LiDAR survey captured in 2010 ($\pm 150\text{mm}$ accuracy), landuse planning data that highlighted the existing and future land use in the catchment area, and details of the hydraulic structures within the catchment. This data was instrumental in developing the hydrologic and hydraulic models for the study area.

Sub-daily rainfall data from four gauges near to the catchment was obtained from the BOM. The sub-daily rainfall from this source was considered more reliable and of a higher quality, particularly for longer durations due to the quality control completed after the initial data capture. The Bureau data is screened for errors, using an automated technique, and makes use of quality control using a climate database. Full quality control is completed some weeks after the end of the most recent month of capture. Any extreme values are confirmed by written reports, and the data are compared with those of nearby stations (BoM, 2024).

Daily rainfall, with up to 100 years of data, was sourced from the Queensland Government SILO database. The SILO database uses mathematical interpolation techniques to construct spatial grids to infill gaps in time series datasets. Given the length of data sourced, more recent data (i.e. within the last 50 years), is considered to be of higher quality than older data. In addition to the daily rainfall data, a continuous stream gauge level located at Cranley at the outlet of the study area catchment since 1969 was sourced. The stream gauge converts the measured water level to a flow rate based on a rating curve developed for the site. The levels

measured are considered accurate, however, the conversion to flow is considered an estimate only due to the reliance on a rating curve that has not been verified during any significant flood event.

Table 3-1 Data used within this research

Data Type	Source	Detail
Sub-daily Rainfall Gauge		Wet Season with Reliable Rainfall Data
Wetella	Toowoomba Regional Council	2010/11, 2016 – 2019
Dwyer	Toowoomba Regional Council	2016 – 2019
Toowoomba Airport	Toowoomba Regional Council	2010 – 2019
Black Gully	Toowoomba Regional Council	2016 – 2019
Gowrie Creek	Toowoomba Regional Council	2016 – 2019
Prescott and Goggs	Toowoomba Regional Council	2010/11, 2016 – 2019
Alderley	Toowoomba Regional Council	2010/11, 2016 – 2019
Eastern Valley	Toowoomba Regional Council	2016 – 2019
Drayton	Toowoomba Regional Council	2016 – 2019
Platz	Toowoomba Regional Council	2016 – 2019
Middle Ridge	Toowoomba Regional Council	2010/11, 2016 - 2019
Gabbinbar	Toowoomba Regional Council	2010/11, 2016 – 2019
Oakey Airport	Bureau of Meteorology	2003 – 2021
UQ Gatton	Bureau of Meteorology	2010 – 2021
Dalby Airport	Bureau of Meteorology	2011 – 2021
Warwick	Bureau of Meteorology	2011 – 2021
Daily Rainfall Gauge		
Catchment centroid	SIL0, Queensland Government	1920 - 2020
Water Level Gauge		
Cranley	Queensland Government	1969 - present

Digital Elevation Model	Toowoomba Regional Council	1 m digital elevation model derived from an aerial survey captured in 2010
Landuse	Toowoomba Regional Council	Landuse cadastre within the catchment extent
Hydraulic structure details	Toowoomba Regional Council	GIS layer of culvert / pipe sizes and lengths.

3.4 Methodology for Calibration of a Continuous Hydrologic Simulation Model in the Urban Gowrie Creek Catchment in Toowoomba, Australia - Journal Paper 1

Journal Paper 1 is titled Calibration of a Continuous Hydrologic Simulation Model in the Urban Gowrie Creek Catchment in Toowoomba, Australia and is published in the Journal of Hydrology: Regional Studies. It discusses the approach used for the development and calibration of the continuous simulation hydrologic modelling of the study area. The methods used in this journal paper are summarised below in Section 3.3.1 and 3.3.2. The methods and journal paper address Research Objective 1: Develop a continuous simulation hydrologic model for the Gowrie Creek catchment in Toowoomba and calibrate the catchment losses to historical rainfall and streamflow data. The journal paper and its outcomes are detailed in Chapter 4.

3.4.1 Hydrologic Model Development

An XP-Rafts semi-distributed hydrological model was used to represent the Gowrie Creek system. XP-Rafts was chosen as the preferred software platform for this research as it was able to be used for continuous simulation modelling and has the dynamic loss model ARBM already built in. The software outputs runoff hydrographs at defined points throughout a catchment based on a user-defined set of catchment characteristics and rainfall data. Key user defined catchment characteristics include sub-catchment area, impervious area and loss.

The pervious area loss within this software is represented by the ARBM dynamic loss approach as presented earlier. The total Gowrie Creek catchment was delineated into 23 sub-catchments based on a 1m digital elevation model derived from an aerial survey captured in 2010. This data, drainage infrastructure data, and overland flow mapping completed in 2018, were supplied by the Toowoomba Regional Council. The urban nature of the catchment required manual catchment delineation as automatic methods could not accommodate the hydraulic impact of roads and underground drainage infrastructure.

3.4.2 *Hydrologic Model Calibration*

A two-stage calibration approach, as performed by Dayaratne (2000) and Broekhuizen et al. (2020), was utilised. Stage 1 calibrated small historic storm events resulting in runoff from impervious areas only. This was followed by Stage 2, in which larger historic storm events that included pervious area runoff, were calibrated.

For the Stage 1 calibration, hydraulic conductivity (K_o) and storage capacities (DSC, USC and LSC) were adjusted until there was no runoff from the pervious area. This effectively set a lower limit for these parameters. For the Stage 2 calibration, K_o and DSC were adjusted with the aim of making the model's output hydrograph match the observed. The parameters determined via calibration were then used to run the model for several validation events to ensure that parameter performance was consistent across a range of observed events.

3.5 Methodology for An Alternative Method for Estimating the Peak Flow for Regional Catchment Considering the Uncertainty via Continuous Simulation - Journal Paper 2

Journal Paper 2 is titled An Alternative Method for Estimating the Peak Flow for a Regional Catchment Considering the Uncertainty via Continuous Simulation and is published in the Journal of Hydrology: Regional MDPI Water. It discusses the approach used to develop multiple iterations of sub-daily rainfall to be simulated in

the continuous simulation hydrologic model to determine the uncertainty in peak flow estimations for various annual exceedance probabilities.

The methods used in this journal paper are summarised below in Sections 3.4.1 and 3.4.2. The methods and journal paper address Research Objective 2: Generate and simulate sub-daily rainfall to produce a long series of continuous streamflow to allow a flood frequency analysis, and Research Objective 3: Undertake an uncertainty analysis of the key continuous simulation modelling parameters to understand the uncertainty of the flood frequency analysis. The journal paper and its outcomes are detailed in Chapter 5.

3.5.1 Rainfall Disaggregation

The method of fragments approach used six major steps to disaggregate historical daily rainfall based on sub-daily rainfall data from multiple representative rainfall stations (Li et al., 2018). A key difference in this research was the exclusion of the need to only disaggregate daily rainfall using sub-daily storms that occur at a similar time of year or have similar rainfall on the day before or after the target day. To best represent the range of storms possible and to understand the impact various storm patterns have on the catchment response to rainfall, it is important that a larger quantity of storms is available for use in the disaggregation. When reviewing the sub-daily rainfall data used in this research, it was clear that as the rainfall amount increased, the number of storms decreased significantly. Previous studies that used the method of fragments approach (Li et al., 2018; Pathiraja et al., 2012; Seth Westra et al., 2012) constrained the storm selection by incorporating seasonality, whereby the range of storms available for disaggregation was limited to those within a preset window around the day of rainfall being disaggregated. These previous studies did not, however, use the disaggregated rainfall in a hydrology model nor did they compare the results to IFD data.

The key steps adopted in this research to disaggregate historic daily rainfall from sub-daily rainfall were:

- 1) Assign a storm class to both the historic daily and sub-daily rainfall series.
- 2) Assign a unique storm number to each historic sub-daily storm.
- 3) For a given day 'x' in the daily rainfall series, select a sub-daily storm with the same Storm Class.
- 4) Disaggregate the daily rainfall based on the pattern of the sub-daily storm.
- 5) Repeat Steps 3 and 4, ensuring the sub-daily storms are chosen uniformly to create an ensemble of disaggregated rainfall.
- 6) Repeat all steps multiple times to create multiple iterations of disaggregated rainfall to understand the uncertainty.

3.5.2 *Peak Flow with Uncertainty*

The method of fragments was used on 100 years of daily rainfall to 100 years of sub-daily (6 minute) rainfall. This was repeated 20 times to produce 20 unique iterations of 100 years of sub-daily rainfall that was then simulated within the calibrated continuous simulation hydrologic model. A flood frequency analysis of all 20 iterations of 100 years of continuous flow was undertaken on the peaks over threshold series using a Bayesian fit of the Log Pearson Type 3 (LPIII) distribution (Ball et al., 2019). Given the relatively narrow range of peak flow results, simulating more than 20 iterations was found to have minimal impact of the result.

3.6 Methods for Hydraulic Impact of Hydrologic Uncertainty in Deriving Design Flood Extents - Journal Paper 3

Journal Paper 3 is titled Hydraulic Impact of Hydrologic Uncertainty in Deriving Design Flood Extents, submitted to Journal of Hydrologic Engineering. It discusses the development of a hydraulic model for the study area and the modelling of the continuous simulation hydrologic model results to determine the impact hydrologic uncertainty has on deriving design flood extents.

The methods used in this journal paper are summarised below in Section 3.5.1 and 3.5.2. The methods and journal paper address Research Objective 4: Develop and

simulate the extent of uncertainty within a hydraulic model to determine the impact hydrologic uncertainty has on the flood extent within the Gowrie Creek catchment. The journal paper and its outcomes are detailed in Chapter 5

3.6.1 *Hydraulic Modelling*

A hydraulic model was developed using the SWE-ELM numerical solver within HEC-RAS 2D. A one metre digital elevation model, derived from an aerial survey captured in 2010, was supplied by the Toowoomba Regional Council and used as the base terrain model for the hydraulic model. The roughness, or Manning's 'n', of the terrain was modified within the hydraulic model to reflect the changes in the surface conditions. Buildings were represented by the building block technique, increasing the terrain within the footprint of buildings to be significantly higher than that of the predicted flood to ensure no flow or storage occurred within the footprint of the building. The hydraulic structures were represented using a storage area/2D flow area connection. The 2D hydraulic model simulated 20 iterations of hydrographs that equated to the one in 100-year annual exceedance probability peak flow determined via the flood frequency analysis.

3.7 Conclusion

Chapter 3 of this thesis has provided an overview of the methodology of this research and detailed how each component fits together to achieve the research objectives. The study area is also presented, being the heavily urbanised Gowrie Creek catchment in Toowoomba.

The methodology required to produce journal paper 1 and in turn achieve research objective 1 is presented. The methodology includes the development of a continuous simulation hydrologic model using the modelling software XP-Rafts. The continuous simulation hydrologic model is then calibrated to various historical rainfall events using a two-stage approach.

The methodology required to produce journal paper 2 and in turn achieve research objectives 2 and 3 is then presented. The methodology includes the

disaggregation of 100 years of daily rainfall to a sub-daily timestep using the method of fragments. By producing and simulating 20 unique iterations of the sub-daily in the continuous simulation hydrologic model, peak flow estimates for various annual exceedance probabilities were determined with uncertainty.

Finally, the methodology required to produce journal paper 3 and in turn achieve research objective 4 is presented. The methodology includes the development of a 2D hydraulic model of the study area, and simulation of the hydrologic model results produced in journal paper 2. By simulating the hydrologic model results, it was possible to determine the impact hydrologic uncertainty has on deriving design flood extents.

The next chapter presents the first journal paper published as part of this research and discusses how it has met research objective 1.

CHAPTER 4: PAPER 1: CALIBRATION OF A CONTINUOUS HYDROLOGIC SIMULATION MODEL IN THE URBAN GOWRIE CREEK CATCHMENT IN TOOWOOMBA, AUSTRALIA

4.1 Introduction

Deriving design storms for an urban catchment requires a determination of the conversion of rainfall to runoff. The commonly used initial loss/continuous loss model uses parameters that have been calibrated for gauged rural catchments and applies them to the pervious component of the urban catchment. Dynamic loss models, such as the Australian Representative Basin Model (ARBM), aim to better represent the physical interaction between periods of wetting and drying through direct simulation of the physical processes occurring in the catchment. The availability of suitable ARBM parameters is, however, limited. In this research, loss model parameters suitable for use in the dynamic loss ARBM for the Gowrie Creek catchment in Toowoomba, Australia, through the two-stage calibration of a continuous simulation hydrologic model was derived. The model offered a satisfactory fit (Nash Sutcliffe Efficiency > 0.5) for 9 of the 11 selected storm events, with seven events exceeding a Nash Sutcliffe Efficiency of 0.75. Events used in the calibration/validation included peak flows as low as 9 m³/s and as high as 600 m³/s. A comparison was made between the derived parameters to those published in the literature, with the results highlighting the need to develop a database of calibrated loss parameters for urban catchments was then compared.

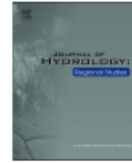
4.2 Published Journal Paper

Brown et al. (2022), "Calibration of a continuous hydrologic simulation model in the urban Gowrie Creek catchment in Toowoomba, Australia", is published in the Journal of Hydrology: Regional Studies, Volume 40, April 2022.



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Calibration of a continuous hydrologic simulation model in the urban Gowrie Creek catchment in Toowoomba, Australia

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Keywords:

Continuous simulation
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ABSTRACT

Study region: Toowoomba, Queensland, Australia

Study focus: In this study we derive loss model parameters suitable for use in the dynamic loss Australian Representative Basin Model (ARBM) through the calibration of a continuous simulation hydrologic model. We compare the derived parameters to those published in the literature, and our results highlight the need to develop a database of calibrated loss parameters for urban catchments.

New hydrological insights: The development of design storms for flood modelling commonly uses the initial loss/continuous loss model to estimate the conversion of rainfall to runoff. This loss model, when applied to pervious areas, uses parameters that have been calibrated for gauged rural catchments. These same parameters are often applied to the pervious component of ungauged urban catchments with minimal understanding of the resulting impact on runoff. This research uses a continuous simulation modelling approach to calibrate parameters suitable for use in the ARBM loss model built into the hydrological modelling software XPRAFTS. Through a two-stage calibration approach, the model offered a satisfactory fit (Nash Sutcliffe Efficiency > 0.5) for 9 of the 11 selected storm events, with seven events exceeding a Nash Sutcliffe Efficiency of 0.75. Events used in the calibration/validation included peak flows as low as 9 m³/s and as high as 600 m³/s. Developing these loss model parameters offers new insights into the suitability of a dynamic loss model approach in an urban catchment in regional Australia and provides an alternative to the parameters already available in the literature which were found to overestimate the peak flow in frequent events.

1. Introduction

Understanding the hydrologic response of urban catchments to extreme rainfall events is fundamental to making informed engineering and planning decisions around urban development, flood mitigation and disaster management (Pathiraja et al., 2012). The need for an accurate hydrologic model and an understanding of the uncertainty associated with the model's results cannot be overstated. In January 2011, Toowoomba, a regional town in the state of Queensland, Australia, experienced its worst flood on record with Gowrie Creek breaking its banks in multiple locations. In addition to inundation, the floodwaters proved hazardous, with high

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velocities resulting in dangerous conditions for pedestrians and motorists at major road crossings, resulting in the death of at least four people. Following this major flooding, a design event hydrologic model was developed as part of the Gowrie Creek Flood Risk Management Study undertaken for the Toowoomba Regional Council. A subsequent peer review panel highlighted the need to understand the uncertainty in flood hydrographs being produced by the hydrologic modelling.

A critical hydrologic parameter that leads to a high level of uncertainty in hydrologic modelling is rainfall loss (Ball et al., 2019). Rainfall loss can be defined as the amount of rainfall that does not appear as immediate runoff (Hill et al., 1998). Rainfall losses are often accounted for by separating the losses into two categories: the initial loss (interception and infiltration prior to saturation or antecedent moisture conditions) and the continuing loss (infiltration post saturation) (Phillips et al., 2014). Most initial loss/continuing loss models greatly simplify the condition of the catchment prior to the event (Cameron et al., 1999). Rainfall losses in the catchment can vary as a result of geography, antecedent moisture conditions, and the intensity of the rainfall event (Ball et al., 2019). The most commonly used approach for simulating a catchment's runoff response to rainfall in Australia is the design event method (Ball et al., 2019). This method uses the widely adopted initial loss/continuing loss model. While it is simple to implement in practice, it assumes that the transformation of rainfall to runoff is probability neutral, i.e. the annual exceedance probability of the design rainfall data will always result in a flood of the same annual exceedance probability (Kavetski et al., 2006). The literature offers minimal guidance on the adoption of appropriate loss values (Rahman et al., 2002; Tularam and Ilahe, 2007), therefore rural catchment based initial loss/continuing loss parameter assumptions continue to be used for urban pervious areas even though the suitability of the parameters for use in urban catchments is not well understood (Ball et al., 2019).

Dynamic loss models differ from initial loss/continuing loss models as they account for the interaction between periods of wetting and drying through direct simulation of the physical processes occurring in the catchment (Cameron et al., 1999; Kavetski et al., 2006; Muncester et al., 1999). The impact each loss model has on the estimated rainfall excess is demonstrated in the hyetographs in Fig. 1.

Increased computational capacity and the availability of (or ability to generate) sub daily rainfall data has allowed for more complex modelling with improved representation of the complex physical processes within a catchment (Boughton and Droop, 2003). Continuous simulation models seek to overcome the issue of assumed antecedent moisture conditions by modelling a complete sequence of rainfall data over a much longer duration than that of a typical design temporal pattern (Blazkova and Beven, 2009; Boughton, 2005; Calver et al., 2009; Camici et al., 2011), thereby rejecting the concept of probability neutral conversion of rainfall to runoff. Continuous simulation modelling removes the need for assumptions of the antecedent moisture conditions of the catchment, and allows for a more accurate accounting of the hydrologic losses (Boughton and Droop, 2003; Muncester et al., 1999). While continuous simulation modelling is no less complex than design event methods, it provides a more realistic 'design hydrograph' in terms of volume and duration that has a variety of applications (Grimaldi et al., 2021).

Linsley and Crawford (1974) were one of the early adopters of continuous simulation modelling in an urban catchment with their discussion on a computer based continuous simulation model (the Stanford Watershed Model) they developed in the 1960 s and later modified for other applications. More recently, Rangari et al. (2015) described a number of urban stormwater models available to undertake continuous simulation, however there still appears to be limited published applications or case studies in urban catchments. Ling et al. (2015) compared various design flood estimation methods for both urban and rural catchments, however excluded continuous simulation modelling from the urban catchment case study. Grimaldi et al. (2021) proposed a step forward and testing for the practical use of their continuous simulation approach in an ungauged catchment, however the catchment used in the assessment was less than 25% urban.

Several continuous simulation models of rural catchments have been documented in literature. The study of the Moore River catchment in Western Australia, completed by Newton and Walton (2000) using continuous simulation modelling, achieved good agreement with both a flood frequency analysis of the stream gauge and design event modelling. Boughton and Hill (1997) compared the results of a continuous simulation model for the Boggy Creek catchment in Victoria, Australia against the available stream gauge and found good agreement for rare and extreme events. Boughton et al. (2002) followed up this study with an assessment of the Avon

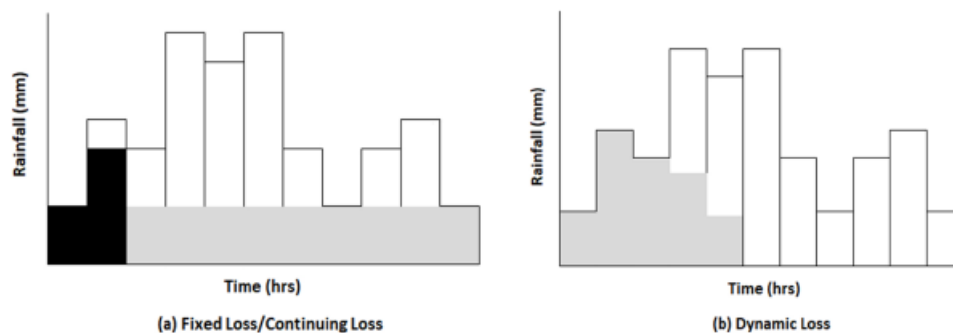


Fig. 1. (a) Rainfall excess (white area) from the commonly used fixed Initial Loss/Continuing Loss model, with the darker hatch representing initial loss and the lighter hatch representing the fixed continuing loss, and (b) Rainfall excess (white area) from a dynamic infiltration loss model with the lighter hatch representing the loss (drawn based on the concept of O'Loughlin et al. (1996)).

River and Spring Creek catchments in Victoria, Australia and found that limited rainfall and stream gauge data offered minimal opportunity for calibration. The availability of a sufficient length of continuous rainfall data with a small enough time step to accurately model the catchment of interest is a key limitation of continuous simulation modelling (Viviroli et al., 2009). However, if data is available, continuous simulation modelling is seen as the most rigorous modelling approach for understanding the interaction between variables with joint probability as it directly simulates a long period of climatic conditions (Kavetski et al., 2006).

While there is agreement that continuous simulation models should be used where data permits, there is a disconnect between the modelling software used in the literature and the modelling used by practitioners. The abovementioned studies all adopted the rainfall excess model, the Australian Water Balance Model (Boughton, 2004), and routed the rainfall excess through the this model (Boyd et al., 1996). However, industry practitioners generally use software models that have a graphical user interface, including XPRAFTS

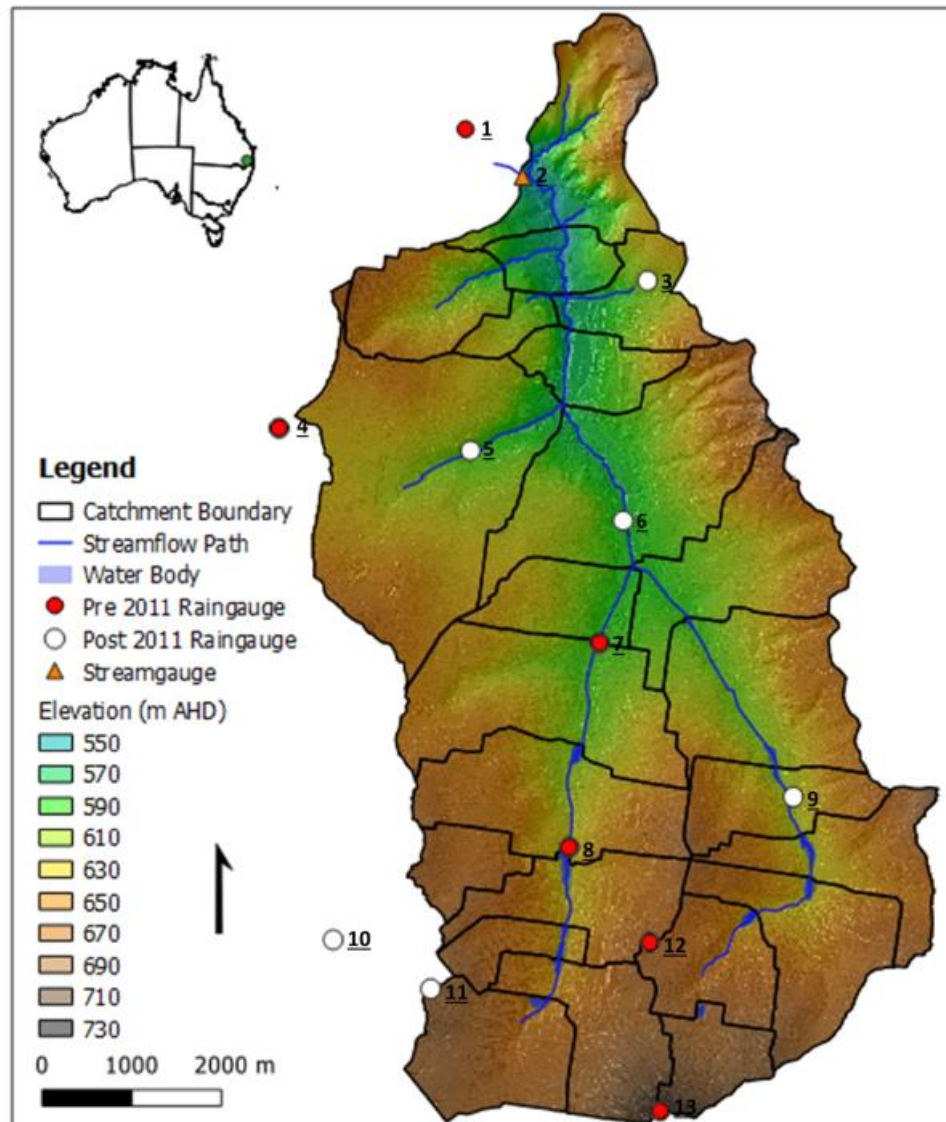


Fig. 2. Gowrie Creek catchment in Toowoomba with key catchment features shown.

(XPSolution, 2008), SWMM (EPA, 2015) or URBS (Carroll, 1994). XPRAFTS is a non-linear runoff routing model used extensively throughout Australia and the Asia Pacific region and is recommended by Australian modelling guidelines (i.e. Australian Rainfall and Runoff (Ball et al., 2019)) for use in catchment hydrologic modelling. Despite its widespread use, the documentation of suitable loss parameters for the ARBM dynamic loss model is limited to a set of parameters presented by Goyen (1981) and another documented in the Australian Capital Territory stormwater design guidelines (Department of Urban Services, 2021), herein referred to as the 'ACT guidelines'. This is a significant gap in research given Australia's tropical, temperate, arid and alpine habitats and climate regimes; all of which have high variability (Head et al., 2014). Limiting practitioners to either the initial loss/continuing loss model or the ARBM model, with parameters based on Goyen's research, leads to increased uncertainty, especially in ungauged catchments where calibration is not possible.

Using continuous simulation models in urban catchments presents several challenges in addition to the lack of documented input loss parameters. The spatial distribution of available rainfall data, as well as the connection of impervious area and hydraulic controls, all influence the timing and volume of runoff at the catchment outlet. For example, Dayaratne and Perera (2004) modelled the urban Giralang catchment in Canberra and found variations in time to peak with a lag of up to one hour between the modelled and observed event as a result of adopting a single representative rain gauge despite a catchment area of only 94 ha. While there is uncertainty in all hydrologic modelling approaches, the level of uncertainty declines with model calibration.

The development of a catalogue of suitable ARBM loss parameters would be a significant achievement for the hydrologic community and would be of particular importance to applied hydrologists working with similar simulation models. The new contribution being offered by this paper is the development of loss parameters for a regional urban catchment and highlight the need for a catalogue of parameters that can be used more broadly by applied hydrologists across other catchments. This research aims to: 1) develop a continuous simulation hydrologic model for an urban catchment, 2) calibrate the ARBM parameters for the Gowrie Creek catchment, and 3) compare these model results to existing documented model parameters to assess the need for further cataloguing of region-specific parameters both within Australia and internationally. Materials and methods used to develop the model are described in Section 2, Section 3 presents the calibration results which are then compared to other documented parameters in Section 4. Finally, our conclusions are presented in Section 5.

2. Materials and methods

2.1. Study area

The Gowrie Creek catchment is a heavily urbanised catchment in the city of Toowoomba, in the state of Queensland, Australia. Toowoomba is considered to be sub-tropical with an average annual rainfall of 700 mm, the majority of which falls over the wet season from November to March. The 51 km² catchment, shown in Fig. 2, is twice as long as it is wide, and has a well-defined, heavily modified creek line. Elevations within the catchment range from 750 m Australian Height Datum (AHD) at the southern and eastern extents, to 550 m AHD at the catchment outlet to the north. This significant height difference across the catchment results in sub-catchment areas varying in slope from 3% near the valley, to 9% at higher elevations.

The tributaries within the catchment contain a series of detention basins installed to help reduce flood risk. After the major flooding in 2011, additional flood mitigation measures and monitoring stations were installed. Fig. 2 shows the gauge locations, and Table 1 provides additional details for each gauge. Fifteen rain gauges and one stream gauge currently monitor the catchment, however only six of these were in operation during the 2011 flood event. Since 2016, 11 gauges have been found to provide reliable measurements.

Table 1
Details of the gauges located within the Gowrie Creek catchment and used in this research.

Gauge Details						
Number	Name	Type	Owner	Location		Wet Season with Reliable Rainfall Data
				Easting (m)	Northing (m)	
1	Wetalla	Rain	Toowoomba Regional Council	394414	6957064	2010/11, 2016–2019
2	Cranley	Level	Queensland Government	395431	6955810	1969 - present
3	Dwyer	Rain	Toowoomba Regional Council	396805	6954647	2016–2019
4	Toowoomba Airport	Rain	Toowoomba Regional Council	392716	6952996	2010–2019
5	Black Gully	Rain	Toowoomba Regional Council	394846	6952747	2016–2019
6	Gowrie Creek	Rain	Toowoomba Regional Council	396532	6951986	2016–2019
7	Prescott and Goggs	Rain	Toowoomba Regional Council	396151	6950321	2010/11, 2016–2019
8	Alderley	Rain	Toowoomba Regional Council	395935	6948336	2010/11, 2016–2019
9	Eastern Valley	Rain	Toowoomba Regional Council	398433	6948899	2016–2019
10	Drayton	Rain	Toowoomba Regional Council	393314	6947305	2016–2019
11	Platts	Rain	Toowoomba Regional Council	394404	6946760	2016–2019
12	Middle Ridge	Rain	Toowoomba Regional Council	396868	6947225	2010/11, 2016–2019
13	Gabbinbar	Rain	Toowoomba Regional Council	396983	6945342	2010/11, 2016–2019

2.2. XPRAFTS model description

An XPRAFTS semi-distributed hydrological model was used to represent the Gowrie Creek system. The software outputs runoff hydrographs at defined points throughout a catchment based on a user-defined set of catchment characteristics and rainfall data. Key user defined catchment characteristics include sub-catchment area, impervious area and loss.

The pervious area loss within this software is represented by the ARBM dynamic loss approach adapted from the research of Chapman (1968, 1970), and is summarised in Fig. 3. This loss approach can be visualised as a series of interconnected buckets of varying sizes. Rainfall that isn't intercepted by trees or plants (Interception Storage Capacity (ISC)) may be captured in minor surface depressions (Depression Storage Capacity (DSC)). If the rainfall is intense enough, runoff may result from the DSC, otherwise infiltration to the Upper Soil Capacity (USC) occurs. Water is redistributed between the USC and the Lower Storage Capacity (LSC) depending on the capacity available within the bucket. Water from the LSC can then be drained into the Groundwater Storage Capacity (GSC) which contributes to baseflow. The ARBM allows for the simulation of soil moisture depletion through evaporation between rainfall events (Fleming, 1974) with evapotranspiration depleting the ISC, DSC, USC and LSC. Any excess rainfall is routed to the catchment outlet based on the non-linear runoff-routing method developed by Laurenson (1964).

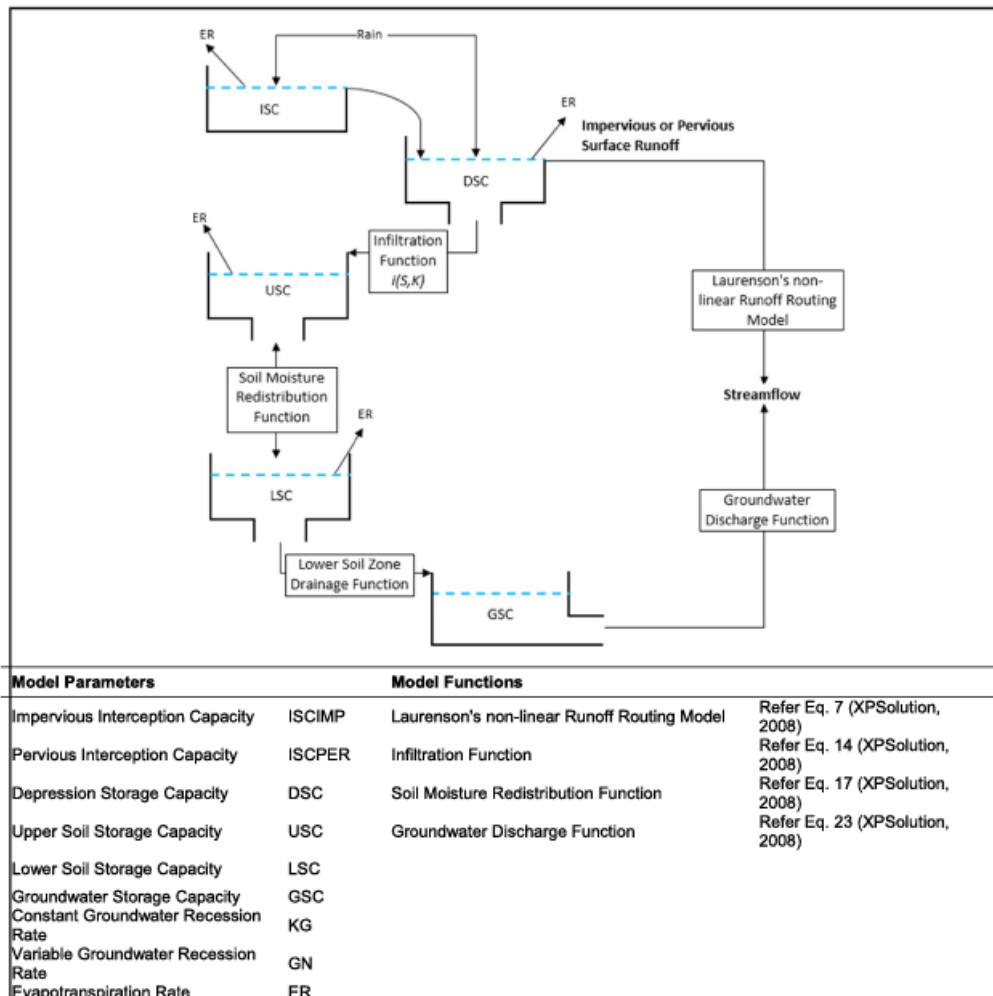


Fig. 3. Graphical representation of the ARBM loss model, which forms the basis of runoff generation in the XPRAFTS model, with supporting equations for key components of the runoff generation process (drawn based on the concept of XPSolution (2008)).

The ARBM has 15 input parameters. Goyen (1981) found that nine of these are consistent across all land use types, four have a negligible impact on runoff during extreme rainfall events, and two parameters within the infiltration function are highly sensitive: sorptivity (S_0) and hydraulic conductivity (K_0). As sorptivity is a component of hydraulic conductivity, the two parameters are degenerate, meaning they cannot be solved in isolation and, therefore, one of the two parameters has to be fixed to allow the infiltration function to be optimised. For this reason, we fixed sorptivity at $10 \text{ mm/min}^{0.5}$, in line with the results of Goyen (1981). In addition to the infiltration function's sensitivity, it is logical that the DSC would be sensitive given that it directly controls the initial conversion of rainfall to runoff. An increasing DSC allows more rainfall to transfer to the USC. Direct measurement of the ARBM parameters is difficult, uncertain, costly and impractical (Mein and McMahon, 1982) and, as a result, was not attempted as part of this research.

2.3. Sub-catchment delineation

The total Gowrie Creek catchment was delineated into 23 sub-catchments (as shown in Fig. 2) based on a 1 m digital elevation model derived from an aerial survey captured in 2010. This data, drainage infrastructure data and overland flow mapping completed in 2018, were supplied by the Toowoomba Regional Council. The urban nature of the catchment required manual catchment delineation as automatic methods could not accommodate the hydraulic impact of roads and underground drainage infrastructure.

While further delineation to increase the number of sub-catchments could have been undertaken, Boyd (1985) showed that for natural catchments of this size, the number of sub-catchments should be at the lower end of the 9–45 range. As the catchment being assessed is urban, a number closer to the middle of the range was targeted. In addition, Rezaei-Sadr (2020) showed that delineating sub-catchments to a size less than 3% of overall catchment offered no improvement in modelling accuracy. The area of the Gowrie Creek sub-catchments is approximately 5% of the overall catchment size.

2.4. Rainfall data and spatial distribution

The hydrologic model requires rainfall data to be applied to each of the delineated sub-catchments. The rainfall data for all 11 rain gauges shown in Fig. 2 was supplied by the Toowoomba Regional Council as a cumulative rainfall total in five-minute increments with the accumulation resetting at the end of each day. There were some clear errors in the rainfall data, including increments of rainfall significantly higher than would be expected, such as rainfall intensities greater than 500 mm/hr with no corresponding stream gauge record. In addition, one of the gauges showed an annual period of no rainfall, suggesting that it had malfunctioned. Periods of erroneous data were removed from the datasets to allow the data to be used.

The rain gauge data needs to be spatially distributed via interpolation to the sub-catchment centroid. Many schemes with varying degrees of complexity have been proposed for the spatial interpolation of rainfall (Thiessen, 1911; Shepard, 1968; Delhomme, 1978). Statistical approaches, such as Kriging, have been found to perform better than interpolation methods such as Thiessen or Inverse Distance Weighted (IDW) to estimate monthly and annual totals (Tabios III and Salas, 1985; Bussi res and Hogg, 1989; Creutin and Obled, 1982). However, these previous studies or reviews have focussed on sites with an order of magnitude lower spatial density of rain gauges (0.01–0.001 per km^2) than the Gowrie Creek catchment (0.12–0.22 per km^2). Dirks et al. (1998) conducted a comparison study of three interpolation methods (Thiessen, IDW and Areal-mean) and a statistical method (Kriging) for Norfolk Island, a small catchment with high gauging density similar to the Gowrie Creek catchment. All methods were performed in a comparable manner, and Dirks et al. (1998) concluded that the IDW method was the most appropriate choice for practical use due to its minimal computational effort.

The IDW interpolation method proposed by Shepard (1968), and represented in Eq. 1, assumes that the rainfall observations closer to a position at which rainfall is to be estimated will have a greater influence on the value.

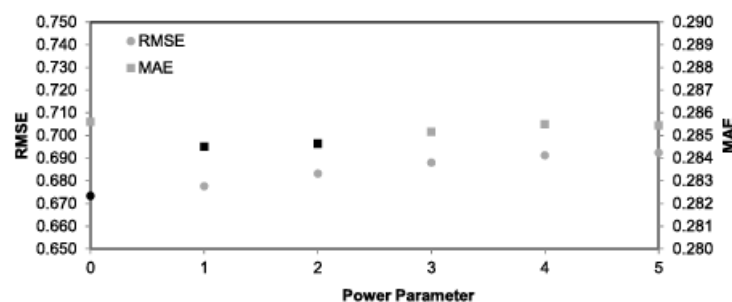


Fig. 4. Error associated with the adoption of a different power parameter in the IDW function, with the best performing variable highlighted in black.

$$Z_p = \frac{\sum_{i=1}^n \left(\frac{Z_i}{d_i^p} \right)}{\sum_{i=1}^n \left(\frac{1}{d_i^p} \right)} \quad (1)$$

where, Z_p = interpolated rainfall value at location of interest (mm), Z_i = known rainfall value at i rainfall station, d_i = distance to i rainfall station from location of interest, p = power parameter.

The adopted power parameter compounds the influence of the nearest observation and, as the power parameter approaches infinity, the IDW interpolation approaches that proposed by Thiessen (or nearest neighbour) interpolation. The optimum power parameter was determined using the leave one out or fictitious point method, where a known observation point (we used gauge number 11, Drayton) is left out and the surrounding gauges are used to estimate its rainfall series. The interpolated and observed rainfall series for Drayton were evaluated for their Root Mean Squared Error (RMSE) and the Mean Absolute Error (MAE), with a lower error identifying a better fit. Fig. 4 shows that the error decreases with a reduction in the power parameter. The magnitude of the error, however, is not significant enough to suggest that the estimated series is sensitive to the power parameter adopted, and the difference in annual rainfall between a power parameter of one and a power parameter of six is only 60 mm. Dirks et al. (1998) reached a similar conclusion, and suggested that the default power parameter of two would be suitable. Due to the high density of rainfall gauges and the known rainfall variability in the catchment, only the nearest three gauges were used for the interpolation in this research.

2.5. Impervious area

Runoff in a hydrologic model is highly sensitive to the impervious fraction of the catchment (Alley and Veenhuis, 1983) as a greater impervious fraction results in a higher conversion of rainfall to runoff. The Total Impervious Area (TIA) is generally determined using land use mapping and the use of impervious fractions to convert the total area of different land uses to impervious areas only. The fraction of the TIA that is directly connected to stormwater infrastructure, including urban roads and rooves, is known as the Effective Impervious Area (EIA) (Hartcher and Chowdhury, 2017), and it is well established that the EIA is of greater importance than the TIA (Cherkauer, 1975; Beard and Chang, 1979). In this research, the EIA was determined using both a regression analysis and land use mapping.

2.5.1. Determining EIA via regression analysis

The EIA of the Gowrie Creek catchment was estimated through the analysis of rainfall and streamflow records using the method described by Miller (1978). This estimation method has been used extensively in research (Boyd et al., 1993; Chiew and McMahon, 1999). The assessment involves calculating the gradient of the regression between runoff and rainfall, excluding events with runoff from pervious areas as rainfall is linearly proportional to impervious runoff. Rainfall events suitable for the regression analysis were chosen by adopting an inter-event time (as proposed by Lloyd, 1990; Aryal et al., 2007 and Rodríguez-Blanco et al., 2012) of two hours to separate individual storms, and were then further filtered to consider a minimum rainfall depth of 2 mm and a maximum rainfall duration of 10 h. A regression analysis of the remaining events is shown in Fig. 5. The gradient of the line indicates an EIA fraction of 0.18 or 18%.

2.5.2. Determining EIA via land use mapping

Catchment planning mapping was used to estimate the Total Area (TA) of different land uses, including Urban Areas (UA), commercial, roads, other development types and open space. With the TA of each land use known, ratios of TA to TIA and TIA to EIA for each land use, as detailed in the Queensland Urban Drainage Manual (IPWEAQ, 2016) and presented in Table 2, were used to determine the overall catchment EIA of 41%. This is significantly higher than the regression-based EIA (18%) and is likely due to the relatively unknown EIA to TIA ratio of differing road types as well as a likely overestimation of the EIA to TIA ratio of UAs due to the age of catchment development. The land use mapping method also found the EIA to be 87% of the UA, which doesn't reflect the

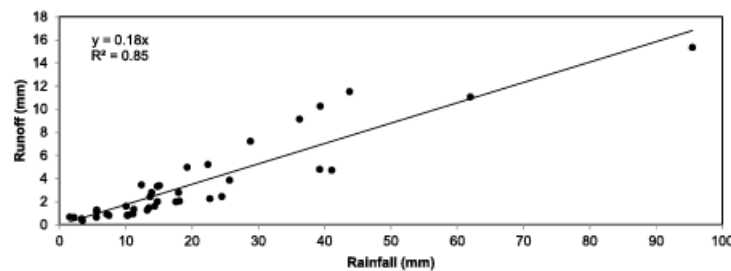


Fig. 5. Runoff vs Rainfall for over 40 storms selected (represented by the dots) using the method of Miller (1978) to determine the effective impervious area as indicated by the gradient of the line (0.18). The regression line indicates a good level of fit.

Table 2

Ratios of Total Area to Total Impervious Area, and Total Impervious Area to Effective Impervious Area for each land use within the Gowrie Creek catchment, used to determine the Effective Impervious Area via land use mapping.

Land use	TA (ha)	TIA/TA (%)	TIA (ha)	EIA (ha)	EIA/TIA (%)
Urban Area (UA)	2417	65	1571	864	36
Commercial	369	90	333	283	77
Road Reserve	979	70	685	685	70
Other Development	523	50	262	262	50
Open Space	811	0	0	0	0
Total	5099		2850	2095	41

findings of Phillips et al. (2014) who found that across eight catchments it was consistently around 35% of the UA. This compares well to the regression-based method which was 38% of the UA. The land use mapping method is therefore overestimating the EIA for the catchment and the regression analysis best represents the effective impervious area of the catchment.

While the land use mapping method overestimated the EIA, it did allow disaggregation to a sub-catchment level. We, therefore, adopted the impervious area ratios for each sub-catchment from the land use mapping method while achieving an overall EIA equivalent to the regression analysis (18%). The results of this analysis for each sub-catchment was used as the impervious component of the hydrologic model and is shown in Fig. 6.

2.6. Calibration and validation

2.6.1. Principles

A two-stage calibration approach, as performed by Dayaratne (2000) and Broekhuizen et al. (2020), was utilised. Stage 1 calibrated small historic storm events resulting in runoff from impervious areas only. This was followed by Stage 2, in which larger historic storm events that included pervious area runoff were calibrated.

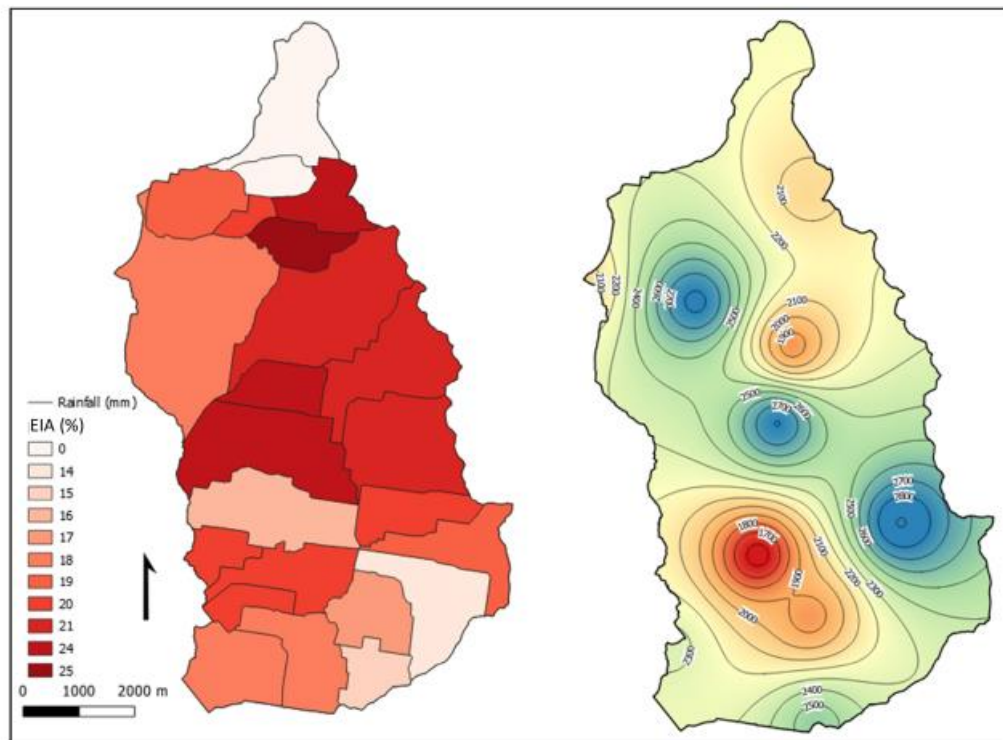


Fig. 6. Spatial variation of impervious area throughout the Gowrie Creek catchment (left) and total rainfall isohyets from 2016 to 2019 (right).

For the Stage 1 calibration, hydraulic conductivity (K_0) and storage capacities (DSC, USC and LSC) were adjusted until there was no runoff from the pervious area. This effectively set a lower limit for these parameters. For the Stage 2 calibration, K_0 and DSC were adjusted with the aim of making the model's output hydrograph match the observed. The parameters determined via calibration were then used to run the model for several validation events to ensure that parameter performance was consistent across a range of observed events.

To determine calibration appropriateness, the performance statistics detailed by Moriasi et al. (2007) and summarised in Table 3 were used. The Nash-Sutcliffe Efficiency (NSE) is a coefficient commonly used to determine the predictive power of a hydrologic model (McGuen et al., 2006), with a coefficient of 1.0 representing a perfect fit. The RMSE-observation standard deviation Ratio (RSR) is a measure of the spread of model results relative to the observed results. RMSE values less than half the standard deviation are generally considered to indicate good model prediction (Singh et al., 2005), therefore the lower values of both RMSE and, in turn, RSR represented a good model fit. The percentage of bias (PBIAS) is a measure of the tendency of the modelled result to be above or below the observed result (Of et al., 1999), with a PBIAS of 0 representing a perfect fit. Peak flow and volume difference were also assessed. Peak flow is an important hydrologic criterion and a key input for hydraulic design.

2.6.2. Historic storm events

The continuous simulation model was run for the complete series of available and reliable historic rainfall data, and individual storm events were selected for calibration/validation. The selected storm events included 13 events during the 2010/11 wet season as well as the wet seasons between 2016 and 2019, as summarised in Table 4.

There was a distinct lack of large (Stage 2) calibration/validation flood events for the study catchment. Inspection of the stream gauge data at the outlet of the catchment highlighted that the 2010/11 wet season was the last significant wet season for the catchment. There were no subsequent wet seasons with events exceeding the peak flow of Event 13. No reliable rainfall data prior to the 2010/11 wet season was available for use.

3. Calibration/validation results and discussion

3.1. Stage 1 calibration

Eleven events were assessed as part of the Stage 1 calibration/validation process, ranging in observed peak flow from $9 \text{ m}^3/\text{s}$ to $79 \text{ m}^3/\text{s}$. The calibration process confirmed that the DSC was a key calibration parameter as the volume of runoff was sensitive to this parameter. This is evident in Fig. 7, which shows the difference (%) between the volume of modelled runoff to the volume of observed runoff with an increasing DSC. The results also show that Events 3 and 4 were suitable for use in the calibration process due to the notable change with increasing DSC.

Comparing the performance statistics of NSE, PBIAS, peak flow difference and RSR for Events 3 and 4 (Fig. 8), a DSC of 7 mm clearly resulted in the best fit. Visual inspection of the model discharge against the observed discharge at the catchment outlet (Fig. 10) also suggests the model is representing the observed flows well. The DSC of 5 mm performed best for Event 4 in terms of PBIAS and RSR, but performed very poorly in NSE and peak flow difference for Event 3, suggesting that it is not suitable for other events. When calibrating the DSC, a K_0 of 0.3 mm/min was adopted. The sensitivity of the model to K_0 was also investigated, with the results (presented in Fig. 9) showing that 0.3 mm/min is optimum.

When adopting a DSC of 7 mm and K_0 of 0.3 mm/min for the nine validation events, six performed satisfactorily, with NSE values ranging from 0.50 to 0.92 (NSE results for all events are presented in Fig. 13). While NSE is considered a key performance indicator, peak flow and volume were also critical to further justify the impervious fraction and spatial distribution of rainfall. Of the three Stage 1 events that performed unsatisfactorily, all produced peak flows within 20% of the observed, and two produced volumes within approximately 30% of the observed. These results suggest that the adopted impervious fraction is representative of the catchment, as a higher impervious fraction would result in a higher peak flow and increased volume. In addition, visual inspection of the Stage 1 calibration results showed that the shape of the modelled hydrograph matched the observed, suggesting the interpolated rainfall is representing the ungauged rainfall.

It was expected that, given the relatively small magnitude of observed flow used in the Stage 1 events, some results would be unsatisfactory. Smaller flow events often correspond to localised storms that may only fall over some sub-catchments but are intense enough to produce runoff from those sub-catchments. Distributing the recorded rainfall (if it did in fact fall over the rain gauge) over the entire sub-catchment may, therefore, not reflect the nature of the event. Despite this, the relatively small number of unsatisfactory

Table 3
Performance ratings for different model statistics, including the Nash-Sutcliffe Efficiency, the RMSE-observation standard deviation ratio, the Percentage of Bias, and the Peak flow/Volume difference as detailed in Moriasi et al. (2007).

Performance Rating	Model Statistic			
	NSE	RSR	PBIAS	Peak Flow/ Volume Difference
Very Good	0.75 – 1.0	0.0 – 0.5	< +– 10	
Good	0.65 – 0.75	0.5 – 0.6	+ –10 – + –15	
Satisfactory	0.50 – 0.65	0.6 – 0.7	+ –15 – + –25	+ –20
Unsatisfactory	< 0.5	> 0.7	> +– 25	> +– 20

Table 4
Chosen Calibration and Validation events.

Event Number	Start Date	Start Time (hrs)	End Time (hrs)	Calibration	Validation
Stage 1					
1	December 16, 2010	1400	1800		x
2	December 11, 2010	1000	2100		x
3	December 19, 2010	0900	2030	x	
4	January 2, 2011	1800	2230	x	
5	October 2, 2017	1230	0500		x
6	October 15, 2017	1230	2100		x
7	October 21, 2017	0730	1830		x
8	October 26, 2017	1700	1930		x
9	October 12, 2018	1700	0400		x
10	October 21, 2018	1300	1800		x
11	October 24, 2018	1900	2200		x
Stage 2					
12	December 27, 2010	1000	1530	x	
13	January 10, 2011	1230	1700		x

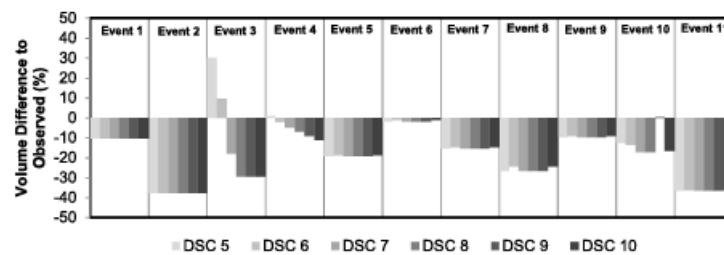


Fig. 7. Difference in volume between modelled and observed Stage 1 events with increasing DSC (in mm). The large variability in volume difference shown in Event 3 and Event 4 make them suitable for calibration.

validation results suggests that the model represents the hydrologic response of the catchment well.

3.2. Stage 2 calibration

As expected, the Stage 2 calibration was sensitive to both DSC and K_0 . However, through the Stage 2 calibration, it was found that the impact of DSC and K_0 on the calibration process was similar; a decreasing DSC or K_0 value resulted in an increase in peak flow. The K_0 value of 0.3 mm/min adopted as part of the Stage 1 calibration to limit pervious area runoff, provided the lower limit for calibration as part of Stage 2.

The DSC parameters assessed as part of Stage 1 were also assessed in Stage 2. The results in Fig. 12 show that the NSE and peak flow generally increased with decreasing DSC, however, Event 12 appeared to reach a maximum NSE when DSC was near 7 mm, and the peak flow increase plateaued when DSC approached 5 mm. In addition, the Stage 1 calibration highlighted that a DSC less than 6 mm resulted in a very poor calibration for Event 3, suggesting that the relatively improved performance of Event 12 with decreasing DSC may be overstated.

Given that the results presented in Fig. 11 show that the model generally underestimated the recorded peak flow, increasing the K_0 value above 0.3 mm/min would only serve to reduce the peak flow further. Comparing the modelled hydrographs to the observed flows (Fig. 12) further highlights how both events, while visually achieving the hydrograph shape, underestimated both volume and peak flow. Event 13 seems to show an observed second smaller peak approximately one hour after the initial peak that wasn't apparent in the model. While the model did show a second peak, it was much closer to the first peak, resulting in a broadening out of the hydrograph. It is known that during this event, the stream gauge malfunctioned, and the results were interpolated from field observations after the event. It is likely that this interpolation overestimated the nature of the event and was the cause of the discrepancies shown.

3.3. Other ARBM parameter sensitivity

The ARBM parameters of DSC and K_0 were identified by both the literature and this research as the most sensitive in estimating the pervious area loss. A sensitivity analysis of the other ARBM parameters, as defined in Fig. 3, was undertaken to ensure that they were also optimised as part of the two-stage calibration approach. The sensitivity analysis reduced the other ARBM parameters by 20%, while keeping the DSC and K_0 at their calibrated values, with the results presented in Fig. 13 (Stage 1 calibration events) and Fig. 14

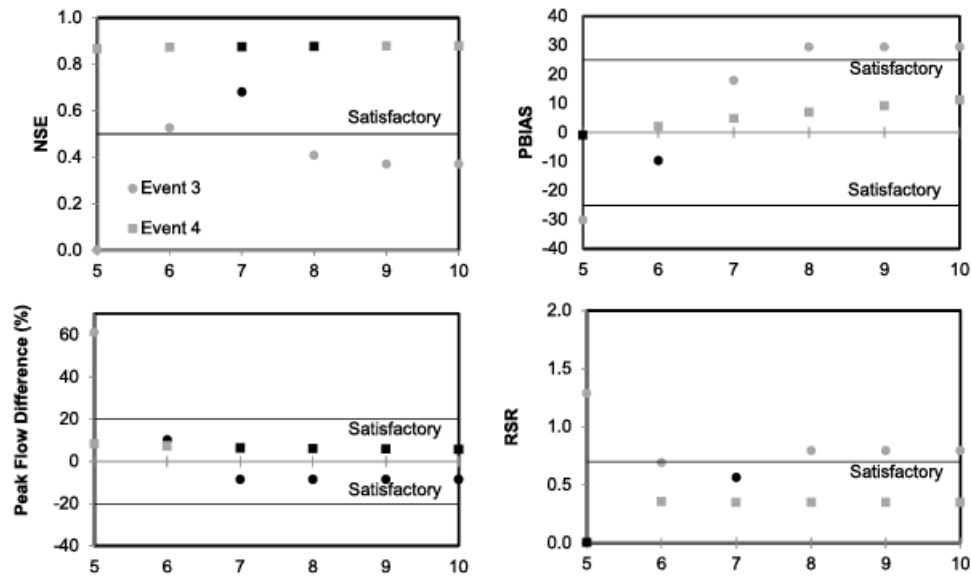


Fig. 8. Statistical performance of Events 3 and 4 with increasing DSC (in mm). The optimum DSC for each statistic is highlighted in black, and shows that a DSC of 7 mm performed best in terms of NSE and RSR, while still performing satisfactorily in both peak flow difference and PBIAS. The satisfactory text is located either above or below the line to show where the satisfactory limits are.

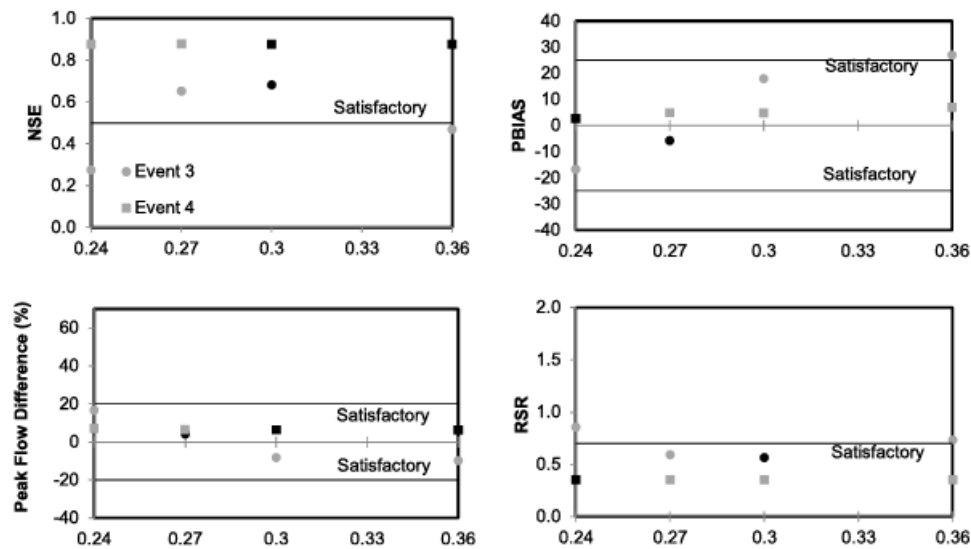


Fig. 9. Statistical performance of Events 3 and 4 with increasing K_p . The optimum K_p for each statistic is highlighted in black, and shows that a K_p of 0.3 mm/min performed best in terms of NSE and RSR, while still performing satisfactorily in both peak flow difference and PBIAS. The satisfactory text is located either above or below the line to show where the satisfactory limits are.

(Stage 2 calibration event). The sensitivity analysis confirmed that the other ARBM parameters were optimised, as one of the Stage 1 calibration events (Event 4) produced pervious area runoff. In addition, there was an insignificant increase in the peak flow/volume in the Stage 2 calibration event. It is also worth noting that increasing the sensitivity of the other ARBM parameters was not needed as the

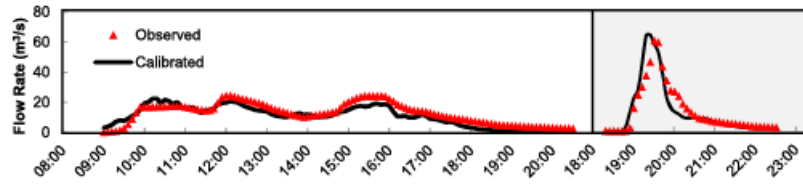


Fig. 10. Comparison of modelled hydrograph to observed values for Stage 1 calibration Event 3 (left) and Event 4 (right).

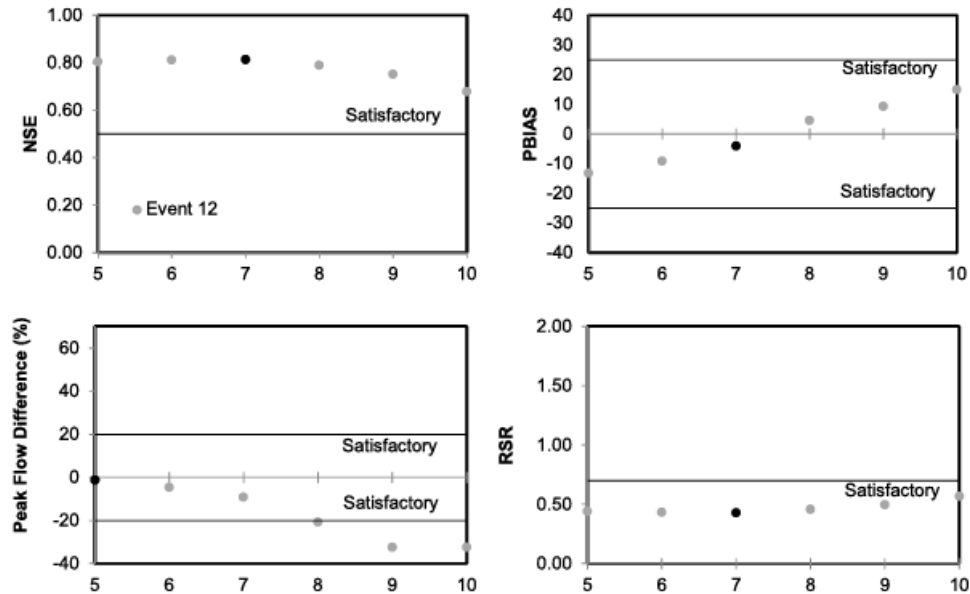


Fig. 11. Statistical performance of Event 12 with increasing DSC. The optimum DSC for each statistic is highlighted in black. The satisfactory text is located either above or below the line to show where the satisfactory limits are.

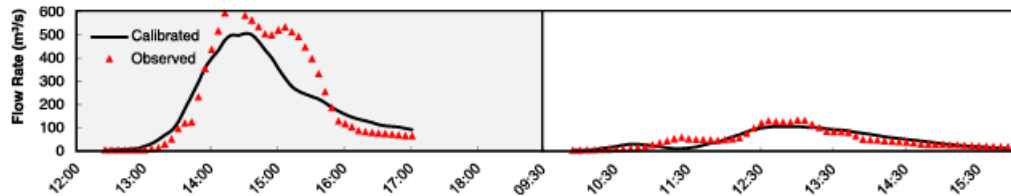


Fig. 12. Comparison of modelled hydrograph to observed values for Stage 2 calibration Event 13 (left) and validation Event 12 (right). The calibration performed well with the modelled peak flow within 10% of the observed.

parameters had already been reduced to ensure no previous area runoff from the Stage 1 events. Increasing the other ARBM parameters by 20% would produce the same result as the calibrated parameters for the Stage 1 events, while potentially reducing the peak flow/volume in the Stage 2 events. (Fig. 15).

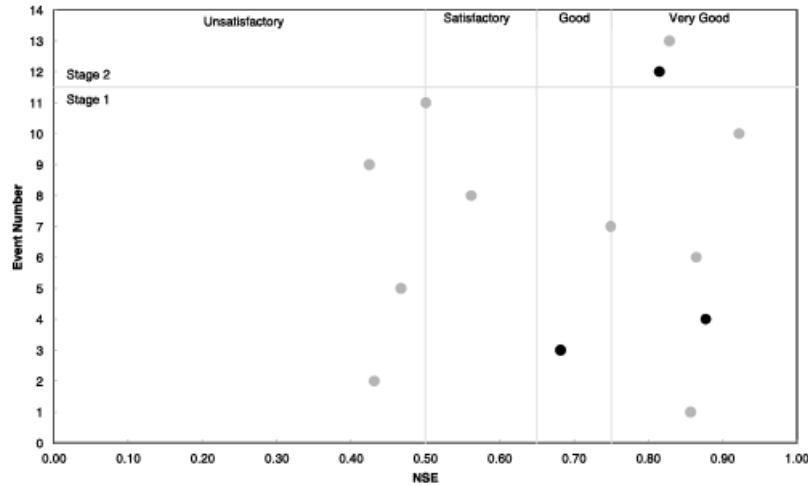


Fig. 13. NSE performance of all 13 storm events with calibration events highlighted in black.

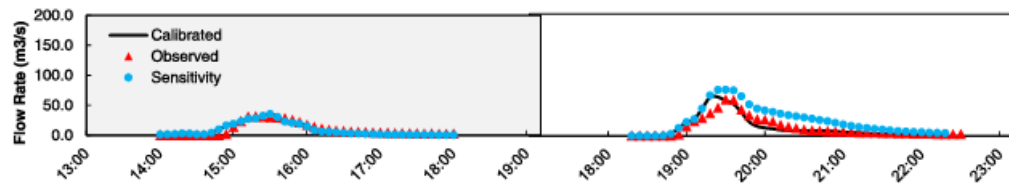


Fig. 14. Hydrographs comparing the calibrated and sensitivity ARBM parameters to the observed flow for Event 1 (left) and Event 4 (right). The results showed that while Event 1 was no sensitive to the change in ARBM parameters, Event 4 was highly sensitive, with a noticeable increase in both peak flow and volume. The volume increase is likely the result of pervious area runoff that wasn't evident in the observed hydrograph based on the steeper gradient of the falling limb.

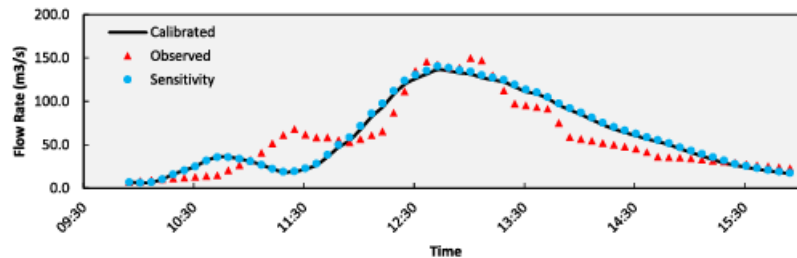


Fig. 15. Hydrograph comparing the calibrated and sensitivity ARBM parameters to the observed flow for Event 12. The results showed that Event 12 was not sensitive to the change in ARBM parameters.

4. Discussion on loss parameters and calibration challenges

4.1. Loss model parameter comparison to literature

The calibrated ARBM parameters determined from this study are presented in Table 5. The parameters recommended by Goyen (1981) for residential lawns, determined through calibration of a number of catchments in Canberra, along with parameters documented in the ACT guidelines (Department of Urban Services, 2021) are also shown. While the infiltration parameters (S_0 and K_0) are somewhat comparable, the storage capacities are significantly different, most notably the DSC. This result is surprising as Goyen's

Table 5
Calibrated ARBM parameters for the Gowrie Creek catchment and Comparative Values from Goyen (1981) and the ACT guidelines.

Parameter	Description	Gowrie Creek	Comparative Value		Unit
			Goyen (1981)	ACT guidelines	
Storage Capacities					
CAPIMP	Impervious	2	0.5	0.5	mm
ISC	Interception	3	1.0	1.0	mm
DSC	Depression	7	1.0	1.0	mm
USC	Upper Soil	40	12.5	25	mm
LSC	Lower Soil	70	25	50	mm
GSC	Groundwater	0	0	0	mm
Infiltration					
S ₀	Dry Sorptivity	10	10	3	mm/min ^{0.5}
K ₀	Hydraulic Conductivity	0.3	0.84	0.33	mm/min
LDF	Lower Soil Drainage Factor	0.1	0.05	0.05	–
KG	Constant Groundwater Recession Rate	0.94	0.94	0.94	–
GN	Variable Groundwater Recession Rate	1.0	1.0	1.0	–
ER	Evapotranspiration	7.0	10	10	mm/hr

parameters are based solely on pervious area, whereas our study has some impervious areas included in the pervious area component of the model due to the impervious area component reflecting EIA only. This is a key contribution of this research and illustrates the need to develop a catalogue of ARBM parameters that can be used by applied hydrologists when investigating catchments with similar geographical or climatic conditions.

Adopting values in line with Goyen (1981) or the ACT guidelines resulted in runoff from the pervious areas in the Stage 1 events, and given the high proportion of pervious area within the catchment, the discharge flow rate and volume at the outlet of the catchment were significantly higher, as highlighted in Fig. 16.

4.2. Overcoming calibration challenges

Currently continuous simulation modelling in urban catchments is rarely undertaken in practice or reported in the literature. The challenges faced in the development of our continuous simulation model for the Gowrie Creek catchment demonstrate the reasons for its limited use.

Rainfall data provided for the catchment seemed reasonable on paper however, the rainfall isohyets provided in Fig. 4 show the significant spatial variation across what would be considered a relatively small catchment. The use of the IDW method of interpolation seemed to overcome this issue as the shape and magnitude of the hydrographs presented generally reflected the observed. However, to achieve the results presented, a lag of 30 min had to be applied to the modelled output. It is believed that this lag is not uncommon given the previously mentioned issues faced by Dayaratne and Perera (2004). Inspection of the input data highlighted that the lag is likely to be a combination of rainfall being recorded regularly (five minutes) while stream gauge records can have timesteps of up to 30 min. In addition, the hydrologic model's response to rainfall, on impervious areas in particular, may not represent real conditions, especially for small events.

The amount of impervious area, in particular EIA, is a vital input to an urban hydrological model. While it is difficult to directly source this data, the methods detailed in the study seem to have produced a value that represents the catchment well, given that 10 of the 11 Stage 1 calibration events produced peak flows within 20% of the observed. The lack of significant rainfall events in the catchment within the period of data available suggests that smaller, impervious runoff only events may form a critical part of a flood frequency analysis.

It is recognised that the lack of rainfall events does impact the validity of the Stage 2 calibration. Investigation of the stream gauge data shows that a peak flow above that of calibration Event 12 has only been recorded seven times, with all but two of these occurring prior to 2010, and one being validation Event 13. There was an event recorded early in January 2011, unfortunately the rain gauge

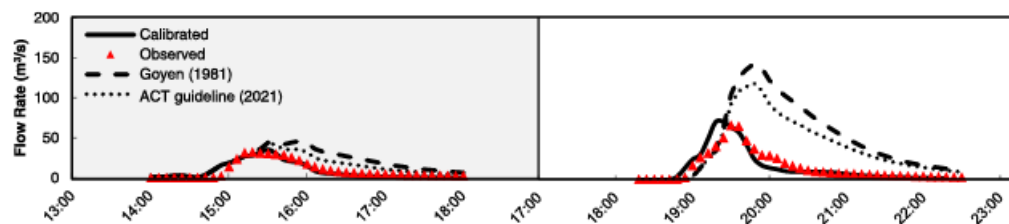


Fig. 16. Hydrographs comparing the calibrated, Goyen (1981) and the ACT guidelines ARBM parameters to the observed flow for Event 1 (left) and Event 4 (right).

data provided did not cover the full extent of the event and was, therefore, not used in the calibration. However, this does not detract however from the findings of this research and highlights the need for further cataloguing of ARBM parameters for wider adoption of continuous simulation modelling by applied hydrologists.

5. Conclusions

Predicting the hydrologic response of urban catchments to extreme rainfall events is fundamental to making informed engineering and planning decisions associated with urban development, flood mitigation and disaster management. Improving the uncertainty in all hydrologic modelling requires careful model calibration including the utilisation of appropriate model parameters for the specific catchment.

This paper focussed on determining catchment specific loss parameters for the Gowrie Creek catchment in Toowoomba, Australia as part of the model calibration. It developed and calibrated a continuous simulation hydrologic model for an urban catchment and then determined the ARBM parameters suitable for the Gowrie Creek catchment. These parameters have been documented within this paper and offer new values for the possible use by applied hydrologists dealing with similar catchment and climatic conditions. We then simulated other documented ARBM parameters to highlight the need for further cataloguing of suitable parameters both within Australia and internationally.

Despite the challenges discussed, this research effectively calibrated an urban continuous simulation model using modelling software widely used in industry. The performance of the model, in particular the NSE and peak flow, showed that the model could produce suitable design hydrographs for the catchment if a sufficient length of rainfall data was available. It also showed that loss model parameters available in the literature, in particular those provided by Goyen (1981), may significantly overestimate peak flows for small events. This research has provided industry with an additional set of loss parameters that may be applicable to other urban catchments whilst highlighting the gap that is preventing widespread industry adoption of continuous simulation models like XPRAFTS. By documenting a new set of parameters, this research may help improve confidence in the modelling of similar ungauged catchments, or at least highlight the variability likely to be experienced in urban catchments throughout Australia. This research also highlights that assumptions around impervious fractions and catchment losses may be overestimating urban catchment runoff.

CRedit authorship contribution statement

I.W. Brown – Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. K. McDougall – Conceptualization, Resources, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition. Md. Jahangir Alam – Conceptualization, Methodology, Validation, Writing – original draft, Writing – review & editing, Supervision. R. Chowdhury – Methodology, Validation, Writing – original draft, Supervision. S. Chadalavada – Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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4.3 Links and Implications

This journal paper focussed on determining catchment specific loss parameters for the Gowrie Creek catchment in Toowoomba, Australia, as part of the model calibration. It developed and calibrated a continuous simulation hydrologic model for an urban catchment and then determined the ARBM parameters suitable for the Gowrie Creek catchment. By undertaking this component of work, research objective 1 was achieved: *“Develop a continuous simulation hydrologic model for the Gowrie Creek catchment in Toowoomba and calibrate the catchment losses to historical rainfall and streamflow data”*.

Other documented ARBM parameters were simulated to highlight the need for further cataloguing of suitable parameters both within Australia and internationally. The parameters provided could pave the way for other studies to add to the growing catalogue of ARBM parameters or provide an alternative to the commonly used initial loss/continuing loss model. Significant contribution to the knowledge was offered as the research question that *“continuous simulation hydrologic modelling offers a more complete understanding of hydrological processes and can replicate historical stream flows”* was answered by showing that the continuous simulation hydrologic model could replicate a range of storm events from small to large without the need to modify the input losses. The loss model parameters have been documented in this journal paper and offer new values for the possible use by applied hydrologists dealing with similar catchment and climatic conditions. This is important as continuous simulation removes the need for an arbitrary assumption of antecedent moisture conditions in the catchment and opens the door for a more detailed understanding of hydrologic uncertainty.

This research sets the scene for ultimately achieving the research aim, as the calibrated hydrologic model could be used for the estimation of design hydrographs for the Gowrie Creek catchment, which is the focus of journal paper 2.

Chapter 4 of this thesis presented the first journal paper published as part of this research. This journal paper set the foundation for the subsequent journal papers, in particular the second journal paper that is presented in the next chapter.

CHAPTER 5: PAPER 2 – AN ALTERNATIVE METHOD FOR ESTIMATING THE PEAK FLOW FOR A REGIONAL CATCHMENT CONSIDERING THE UNCERTAINTY VIA CONTINUOUS SIMULATION

5.1 Introduction

Estimating peak flow for a catchment is commonly undertaken using the design event method, however, this method does not allow for the understanding of uncertainty in the result. Continuous simulation can understand the uncertainty, however, relies on a long series of rainfall data at a time-step that suits in the scale of the catchment. This research first presents a simplified method of fragments approach to rainfall disaggregation that ignores the need to consider seasonality, offering a greater diversity in storm patterns within the resulting sub-daily rainfall. By simulating 20 iterations of the disaggregated sub-daily rainfall within a calibrated continuous simulation hydrologic model, multiple long series of streamflow at the outlet of the catchment was produced. With this data, the use of both the annual maximum and peaks over threshold approaches to flood frequency analysis was investigated and it was found that for a one in 100-year annual exceedance probability peak flow, the peaks over threshold method was significantly less uncertain than the annual maximum method. For the one in 100-year annual exceedance probability, the median peak flow from the peaks over threshold method produced an outcome comparable to the design event method peak flow, indicating that this research offers an alternative approach to estimating peak flow, with the additional benefit of understanding the uncertainty in the estimation. Finally, this journal paper highlighted the impact that length and period of streamflow has on peak flow estimation and noted that previous assumptions around the minimum length of gauged streamflow required for flood frequency analysis may not be appropriate in particular catchments.

5.2 Published Journal Paper

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Article

An Alternative Method for Estimating the Peak Flow for a Regional Catchment Considering the Uncertainty via Continuous Simulation

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Abstract: Estimating peak flow for a catchment is commonly undertaken using the design event method; however, this method does not allow for the understanding of uncertainty in the result. This research first presents a simplified method of fragments approach to rainfall disaggregation that ignores the need to consider seasonality, offering a greater diversity in storm patterns within the resulting sub-daily rainfall. By simulating 20 iterations of the disaggregated sub-daily rainfall within a calibrated continuous simulation hydrologic model, we were able to produce multiple long series of streamflow at the outlet of the catchment. With these data, we investigated the use of both the annual maximum and peaks over threshold approaches to flood frequency analysis and found that for a 1-in-100-year annual exceedance probability peak flow, the peaks over threshold method ($333 \text{ m}^3/\text{s} \pm 50 \text{ m}^3/\text{s}$) was significantly less uncertain than the annual maximum method ($427 \text{ m}^3/\text{s} \pm 100 \text{ m}^3/\text{s}$). For the 1-in-100-year annual exceedance probability, the median peak flow from the peaks over threshold method ($333 \text{ m}^3/\text{s}$) produced an outcome comparable to the design event method peak flow ($328 \text{ m}^3/\text{s}$), indicating that this research offers an alternative approach to estimating peak flow, with the additional benefit of understanding the uncertainty in the estimation. Finally, this paper highlighted the impact that length and period of streamflow has on peak flow estimation and noted that previous assumptions around the minimum length of gauged streamflow required for flood frequency analysis may not be appropriate in particular catchments.

Keywords: uncertainty; flood frequency; rainfall disaggregation; peak flow continuous simulation



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1. Introduction

Estimating peak flow rates from a catchment has long been a focus of engineering hydrologists and is fundamental to the design of flood protection infrastructure [1–4]. Understanding the uncertainty associated with peak flow estimation is, however, often neglected by practitioners, despite the acceptance that many sources of uncertainty exist [1,5–7]. The commonly used design event method requires antecedent moisture conditions to be adjusted to ensure a probability-neutral conversion of rainfall to runoff [4,8–10]. Ref. [11] detailed the benefits of continuous simulation over the design event method with their development of a calibrated hydrologic model in a regional town in the state of Queensland, Australia. This paper expands on the research undertaken by the authors [11], whose focus was the calibration of the continuous simulation hydrologic model to historical events, with the aim of deriving flood frequency estimates with a greater understanding of uncertainty.

To estimate peak flows from a continuous simulation model, the data should normally follow a flood frequency distribution similar to gauged streamflow records. A model that can replicate a long series of streamflow (i.e., continuous simulation) can assist in

overcoming the shortcomings of stream gauge data, most noticeably the impact of urbanisation [1]. A flood frequency analysis (FFA) can be undertaken using one of two sampling approaches: annual maximum series and peaks over threshold (also known as partial series) [12]. The annual maximum series, while easier to identify independent flood events, produces fewer data points than the peaks over threshold series [13] but also prioritises the maximum annual flood over multiple larger floods that may have occurred in the same year. In contrast, the peaks over threshold approach offers added complexity due to the requirement of selecting an appropriate threshold flow. Some researchers found the best results of their FFA occurred when the number of data points (m) equalled the years of data (n) [11,14,15], while others recommended a ratio of 1 m :3 n [16]. Both sampling approaches rely on a long series of continuous streamflow, with at least 50 years of data recommended to be used [17].

To produce a long series of continuous streamflow, a continuous simulation model requires an extended period of recorded rainfall at a suitable time step for the size and level of urbanisation of the catchment [18]. In the case of a relatively small urban catchment, rainfall at a sub-hourly interval is required. Obtaining a recorded rainfall series of sufficient length over this time scale is extremely challenging given the lack of sub-daily rainfall gauges available not only globally [19] but more relevant to this research in sparsely populated countries such as Australia [20]. This contrasts recent reviews of global precipitation data, with some locations offering sub-daily rainfall that spans multiple decades [21]. The availability of sub-daily rainfall data has supported recent advancements in the use of continuous simulation hydrologic modelling [22]; however, this research is unique in that the lack of availability of site-based sub-daily rainfall data requires alternate considerations. To address this issue, sub-daily rainfall can be generated from coarser timescale (daily) rainfall records via disaggregation [23] if historical daily rainfall data for at least 100 years are available for the site [24].

The most commonly used rainfall disaggregation approaches are summarised in the literature [23], including parametric sampling methods such as the Poisson-cluster models and the random scale models, as well as nonparametric sampling methods such as the Method of Fragments (MoF). They concluded that the MoF, first proposed as a method to disaggregate streamflow [25], was more flexible for operational use. At its core, the MoF simply disaggregates daily rainfall by selecting the pattern or ‘fragments’ of a known sub-daily event. The process of selection of suitable sub-daily events varies across the literature, including the use of the previous and subsequent day wetness to limit the sample size [26] or adding classes based on rainfall magnitude to ensure the daily rainfall was disaggregated based on sub-daily rainfall of a similar magnitude, as well as limiting the selection to events that occurred in the same month as the disaggregated rainfall [23]. While a long series of sub-daily rainfall data was produced, neither study used their dataset for continuous hydrologic modelling to estimate flood frequency.

This research offers new insight via the presentation of an alternate method for estimating peak flow in a small regional urban catchment. Via the inclusion of associated uncertainty, this method also offers practical insight into how accurate regional authorities should consider their hydrological assessments to be. The results of this research also contribute significantly to the understanding of hydrologic uncertainty, especially in an urban catchment where the reliance on accurate hydrologic modelling is at its greatest. By assessing the impact that the length and period of streamflow series has on peak flow estimation, we highlight the limitations associated with peak flow estimations from gauged catchments.

In particular, this research aims to develop a long series of sub-daily (6 min) rainfall data for use in a continuous simulation model using a simplified version of the MoF and a long series of continuous flow data using the calibrated hydrologic model developed by the authors [11]. It will also estimate, with uncertainty, the peak flow for a range of annual exceedance probabilities and compare the results of this research to other methods. The

materials and methods used in this research are described in Section 2, while Section 3 presents and discusses the results. Finally, our conclusions are presented in Section 4.

2. Materials and Methods

2.1. Continuous Simulation Model

A continuous simulation model was used in this research to estimate the peak flow for different annual exceedance probabilities. The model was developed by the authors [11] for the Gowrie Creek catchment, a heavily urbanised 50 km² catchment in the regional city of Toowoomba, in the state of Queensland, Australia. Toowoomba is considered to be sub-tropical with an average annual rainfall of 700 mm, the majority of which falls over the wet season from November to March. The extent of the catchment and its location in Australia are shown in Figure 1. The following two paragraphs summarise the hydrologic model and the key calibrated loss parameters.

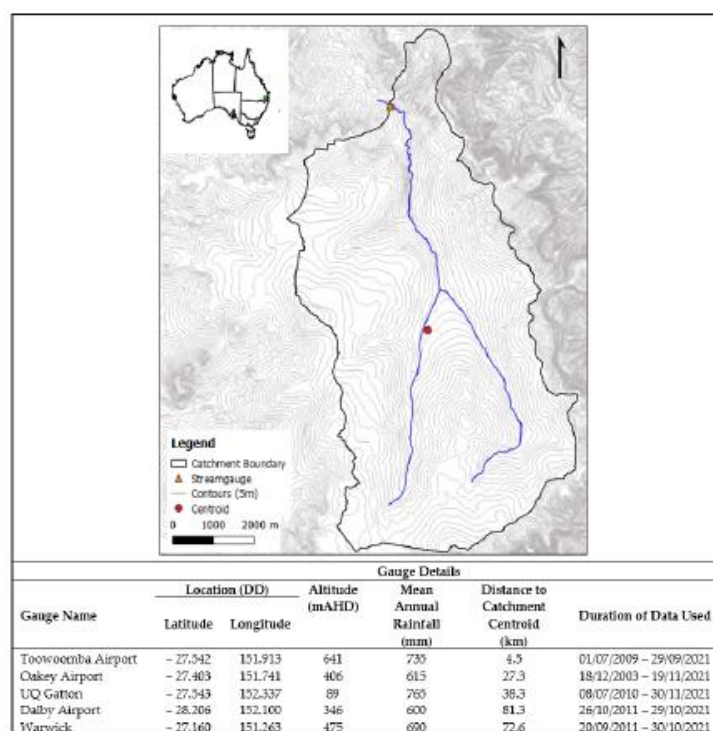


Figure 1. Location of the Gowrie Creek catchment and details of the sub-daily rainfall data used in the rainfall.

An XPRAFTS semi-distributed hydrological model was used to represent the Gowrie Creek system. The overall catchment was delineated into 23 sub-catchments, with each sub-catchment having a unique impervious fraction determined via regression analysis. The previous area loss within this software is represented by the ARBM dynamic loss approach [27,28]. This loss approach can be visualised as a series of interconnected buckets of varying sizes. Rainfall that is not intercepted by trees or plants (Interception Storage Capacity (ISC)) may be captured in minor surface depressions (Depression Storage Capacity (DSC)). If the rainfall is intense enough, runoff may result from the DSC, otherwise infiltration to the Upper Soil Capacity (USC) occurs. Water is redistributed between the USC and

the Lower Storage Capacity (LSC) depending on the capacity available within the bucket. Water from the LSC can then be drained into the Groundwater Storage Capacity (GSC), which contributes to baseflow. The ARBM allows for the simulation of soil moisture depletion via evaporation between rainfall events [29] with evapotranspiration depleting the ISC, DSC, USC, and LSC. Any excess rainfall is routed to the catchment outlet based on the non-linear runoff-routing method [30]. The model was calibrated using the two-stage calibration approach [31,32]. The model offered a satisfactory fit (Nash Sutcliffe Efficiency > 0.5) for 9 of the 11 selected storm events, with seven events exceeding a Nash Sutcliffe Efficiency of 0.75. Events used in the calibration/validation included peak flows as low as $9 \text{ m}^3/\text{s}$ and as high as $600 \text{ m}^3/\text{s}$. The calibrated ARBM parameters are shown in Table 1.

Table 1. Calibrated ARBM loss model parameters for the Gowrie Creek catchment [11].

Parameter	Description	Calibrated Parameter	Unit
Storage Capacities			
CAPIMP	Impervious	2	mm
ISC	Interception	3	mm
DSC	Depression	7	mm
USC	Upper Soil	40	mm
LSC	Lower Soil	70	mm
GSC	Groundwater	0	mm
Infiltration			
S_0	Dry Sorptivity	10	$\text{mm}/\text{min}^{0.5}$
K_0	Hydraulic Conductivity	0.3	mm/min
LDF	Lower Soil Drainage Factor	0.1	-
KG	Constant Groundwater Recession Rate	0.94	-
GN	Variable Groundwater Recession Rate	1.0	-
ER	Evapotranspiration	7.0	mm/h

A challenge identified in the calibration approach was the lag present when comparing the model simulations to the available streamflow data. This issue is not uncommon [33] and was noted to be likely due to the simplified way the hydrologic model responds to rainfall and can vary with changing rainfall intensity [34–36]. Despite this issue, the strong calibration achieved suggests the model adequately represents the magnitude of the runoff, which is the focus of this research.

While models for the catchment were calibrated to the historic rainfall and streamflow records, this research required additional steps to enable the continuous simulation model to be developed. Initially, daily rainfall data within the catchment for a 100-year period were obtained to allow the sub-daily rainfall disaggregation to be undertaken. This 100-year series of sub-daily rainfall data could then be simulated in a continuous simulation model to produce a 100-year time series of simulated streamflow. An FFA of this simulated streamflow was then undertaken to estimate peak flows of varying flood frequencies. This approach was repeated for 20 sub-daily rainfall disaggregation scenarios to facilitate the estimation of uncertainty in the results.

2.2. Daily Rainfall Data

Historical daily rainfall at the centroid of the catchment was sourced from SILO, a Queensland Government database containing continuous daily climate data for Australia from 1889 to the present day [24]. The 100 years of daily rainfall (year 1920 to 2020) used in this research are shown in Figure 2.

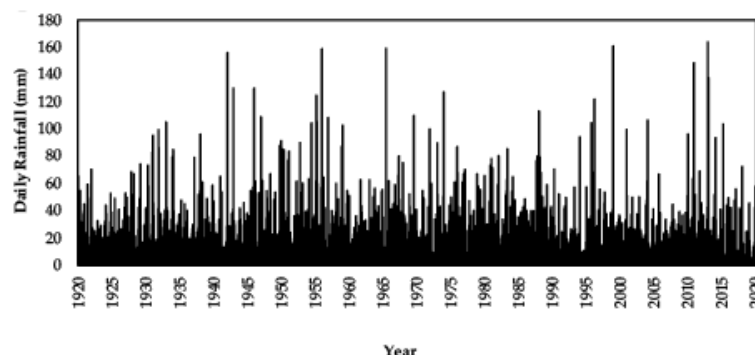


Figure 2. Graphical representation of the 100 years of daily rainfall data sourced for this research [24].

2.3. Sub-Daily Rainfall Data

A long, continuous series of historical sub-daily rainfall data with a timestep shorter than the intended disaggregated timestep is needed to disaggregate the daily rainfall using the MoF. Historical sub-daily rainfall data are, however, limited in Australia [20]. To extend the sub-daily rainfall data duration and allow a wider variety of storm temporal patterns to be used, shorter durations of data from multiple gauging stations surrounding the catchment were sourced and ‘stacked’ to create a single longer series. This approach was used by [23] and found to achieve similar results to adopting a single sub-daily rainfall dataset. For the Gowrie Creek catchment specifically, only 12 years of sub-daily rainfall data were available; therefore, data from rain gauges located outside the catchment were sourced. The location of the catchment and proximity and duration of the historical sub-daily rainfall were sourced from the Bureau of Meteorology and used in the rainfall disaggregation, as shown previously in Figure 1.

2.4. Daily Rainfall Disaggregation

2.4.1. Method of Fragments

The MoF approach used six major steps to disaggregate historical daily rainfall based on sub-daily rainfall data from multiple representative rainfall stations [23]. A key difference in this research was the exclusion of the need to only disaggregate daily rainfall using sub-daily storms that occur at a similar time of year or have similar rainfall on the day before or after the target day. The reasons for this are discussed further in Section 2.4.4.

The key steps adopted in this research to disaggregate historic daily rainfall from sub-daily rainfall were

1. Assign a storm class to both the historic daily and sub-daily rainfall series;
2. Assign a unique storm number to each historic sub-daily storm;
3. For a given day ‘x’ in the daily rainfall series, select a sub-daily storm with the same Storm Class;
4. Disaggregate the daily rainfall based on the pattern of the sub-daily storm.
5. Repeat Steps 3 and 4, ensuring the sub-daily storms are chosen uniformly to create an ensemble of disaggregated rainfall;
6. Repeat all steps multiple times to create multiple iterations of disaggregated rainfall to understand the uncertainty.

2.4.2. Storm Class

An important consideration when using the MoF is the storm class. The storm class defines how the daily and sub-daily rainfall data sets are related as the daily rainfall data are only disaggregated to storms within the same storm class. It was initially suggested that only four storm classes be selected based on the rainfall before and after the day

of interest [26]. However, this has a number of limitations including the potential for not considering important storms based on their insignificant pre/post-day rainfall total. In addition, large daily rainfall totals could be disaggregated into high-intensity, short-duration, and low-depth storms based on the same pre/post-rainfall conditions, rather than basing them on the magnitude of rainfall on the day of interest. The latter issue is of particular interest if the disaggregated rainfall is to be used in a hydrological model.

As a result, dividing the rainfall data into a number of storm classes was subsequently suggested, with an interval of 5 mm being adopted [23]. This method was initially utilised in this research; however, there were too few storms available for less frequent/more extreme daily rainfall totals. It was evident that multiple storm class options had to be considered and evaluated to determine the best approach.

2.4.3. Determination of the Number of Storm Classes

To ensure that the MoF produced sub-daily rainfall data suitable for the hydrologic assessment, the results from three storm class options, presented in Table 2, were validated against the intensity-frequency-duration (IFD) data for the catchment. The IFD data represent design storm rainfall depths developed by the Australian Bureau of Meteorology and are commonly used in design event modelling. These storm class options were evaluated to validate the iterative approach presented in Figure 3, which was used in an attempt to optimise the number of storm classes within each option.

Table 2. Storm class options assessed.

Class ID	Option 1		Option 2		Option 3	
	Min Rain (mm)	Max Rain (mm)	Min Rain (mm)	Max Rain (mm)	Min Rain (mm)	Max Rain (mm)
1	0.1	1	0.1	1	0.1	1
2	1.1	5	1.1	5	1.1	6
3	5.1	10	5.1	10	6.1	11
4	10.1	15	10.1	15	11.1	16
5	15.1	20	15.1	20	16.1	19
6	20.1	25	20.1	25	19.1	24
7	25.1	30	25.1	35	24.1	36
8	30.1	35	35.1	45	36.1	68
9	35.1	40	45.1	55	68.1	200
10	40.1	45	55.1	65		
11	45.1	50	65.1	75		
12	50.1	55	75.1	100		
13	55.1	60	100.1	200		
14	60.1	65				
15	65.1	70				
16	70.1	75				
17	75.1	80				
18	80.1	100				
19	100.1	200				

To directly evaluate the MoF results from the class options assessed, IFD data were developed from the generated sub-daily rainfall. The annual maximum series was first modelled to the Generalised Extreme Value (GEV) distribution, as per the Bureau of Meteorology methodology for generating IFD data from historical sub-daily rainfall data [37]. A direct comparison of the MoF-generated design rainfall depths to the Bureau of Meteorology-generated design rainfall depths for the same duration and annual exceedance probability for different storm class options is shown in Figure 4. From this comparison, it was clear that class option 2 produced the best fit due to its proximity to the 1 in 1 line and was subsequently used in this research. The results suggest when moderate (>25 mm/day) to extreme (>75 mm/day) rainfall depths are reached, the size of the class should be increased

to allow a greater range of storms to be selected. Providing a larger number of smaller classes (class option 1) resulted in fewer storms to choose from, thereby decreasing the representation of moderate to extreme rainfall events, while a smaller number of larger classes (class option 3) resulted in moderate daily rainfall depths being associated with more extreme storm patterns.

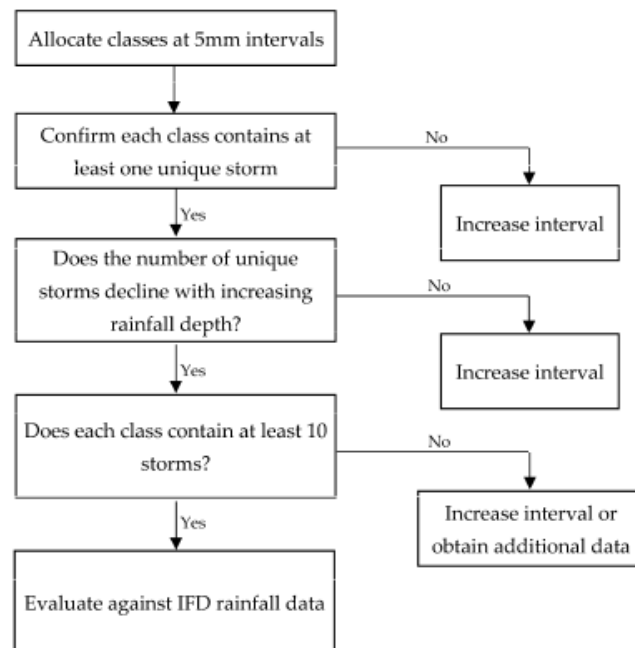


Figure 3. Iterative approach to determining optimal number of storm classes.

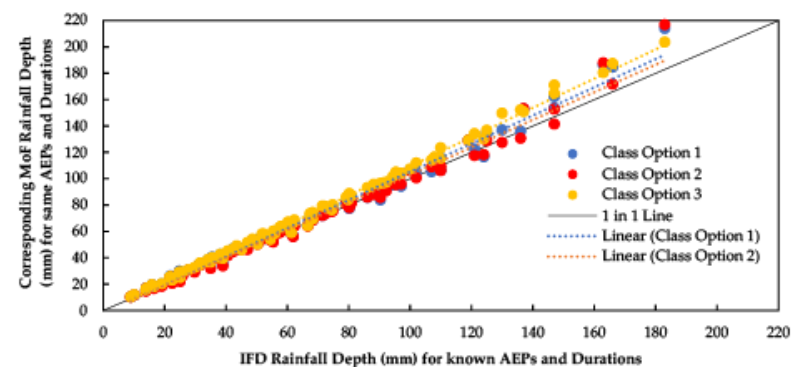


Figure 4. Comparison of the MoF generated rainfall depths with the Bureau of Meteorology generated rainfall depths for the same duration and annual exceedance probability for three storm class options. Class option 2 shows the best fit, with the 1 in 1 line representing a perfect fit.

As the disaggregated sub-daily rainfall covered the same time period as the recorded sub-daily rainfall, it was possible to directly compare the maximum rainfall from critical

storm durations for the size of the catchment, namely those from 30 min to 360 min, for each year. While the MoF is not intended to replicate recorded sub-daily rainfall nor be used for hindcasting [38–40] and in turn unlikely to replicate recorded rainfall, comparing the disaggregated rainfall to the nearby Toowoomba Airport gauge for these critical storm durations (refer to Figure 5) showed that it was able to maintain key statistics, including the median and mean. This result provided additional support for the use of the MoF and the adoption of class option 2.

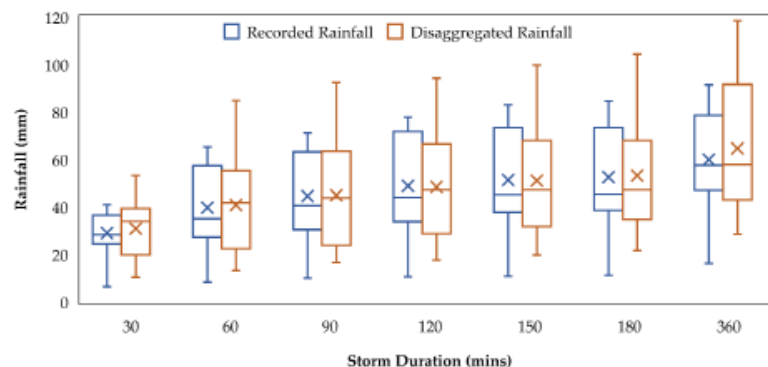


Figure 5. Comparison between the recorded rainfall at the Toowoomba Airport and the Disaggregated rainfall for the same time period (2009 to 2019) for key storm durations, highlighting that key statistics including the median and mean are preserved.

2.4.4. Seasonality

To best represent the range of storms possible and to understand the impact various storm patterns have on the catchment response to rainfall, it is important that a larger quantity of storms is available for use in the disaggregation. When reviewing the sub-daily rainfall data used in this research, it was clear that as the rainfall amount increased, the number of storms decreased significantly, as shown in Figure 6. Previous studies that used the MoF approach ([8,20,23]) constrained the storm selection by incorporating seasonality, whereby the range of storms available for disaggregation was limited to those within a preset window around the day of rainfall being disaggregated. These previous studies did not, however, use the disaggregated rainfall in a hydrology model nor did they compare the results to IFD data. If this was undertaken, they would likely have seen that the same storm patterns would have been chosen multiple times to disaggregate the more extreme daily rainfall totals, and therefore produced similar peak flows, volumes, and timing for multiple events, likely skewing any flood frequency analysis undertaken. To overcome this issue, this research excluded seasonality as a constraint on storm selection and instead adopted an approach whereby multiple iterations of disaggregated rainfall were simulated to better understand the uncertainty associated with storm selection.

2.5. Hydrologic Model Simulation

The calibrated continuous simulation hydrologic model developed by the authors [11] was used in this research. The hydrologic model was simulated for a period of 100 years (1920 to 2020) of disaggregated historical daily rainfall. Twenty iterations of the disaggregated rainfall were simulated to allow the uncertainty in the results to be determined. While the model run times made running additional iterations prohibitive, increasing the number of iterations would have minimal impact on the outcomes of the research due to the small number of unique iterations possible, in particular for larger daily rainfall totals (as presented in Figure 6). This issue is further explored in Section 3.3.

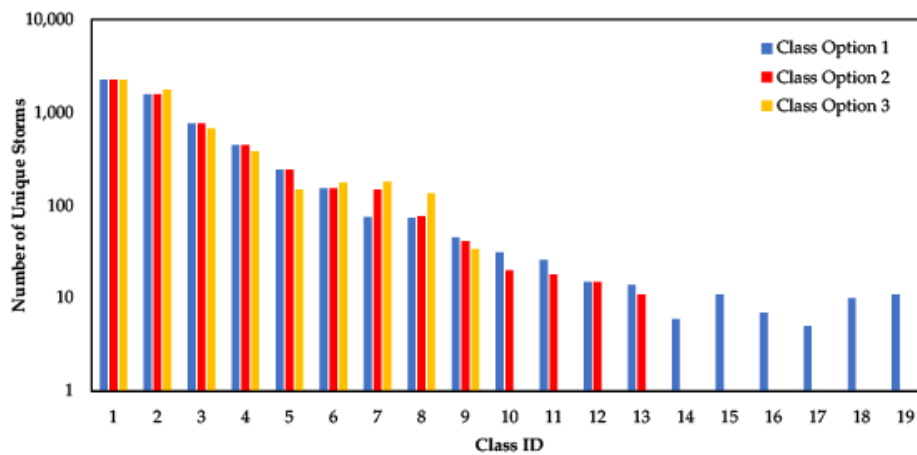


Figure 6. Number of unique storms available for selection within each class ID for each class option. Ignoring seasonality from the disaggregation process allowed for a much larger number of storms available for selection when using the MoFs. Class option 2 satisfies the iterative approach presented.

2.6. Determination of Threshold Value

To allow the peaks over threshold flood frequency analysis of the long series of flow rates determined via continuous simulation, a threshold value is required. The data series used to undertake the flood frequency analysis is the maximum monthly flows above the threshold value. A higher threshold value will result in fewer values in the data series, while a lower threshold value will result in the opposite. In this research, we proposed an alternate method where we graphically interrogated the peak monthly flow from the full 100 years of continuous flow ranked in ascending order to determine clear changes in trend. Figure 7 shows three clear changes in trend at $45 \text{ m}^3/\text{s}$, $70 \text{ m}^3/\text{s}$ and $110 \text{ m}^3/\text{s}$.

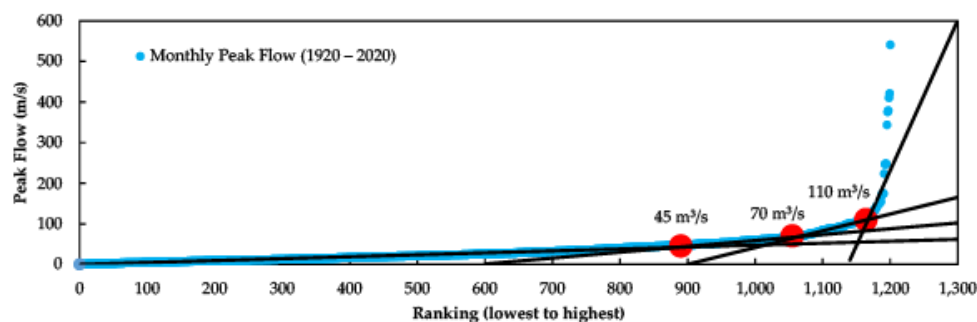


Figure 7. Peak monthly flow from 100 years of continuous flow ranked in ascending order with clear changes in trend highlighted by the red dots. A threshold value of $70 \text{ m}^3/\text{s}$ was used in this research based on this method.

Adopting the higher value of $110 \text{ m}^3/\text{s}$ resulted in a $0.5\text{m}:1\text{n}$ ratio, which was considered a data series too small for a flood frequency analysis [14]. Adopting the lower value of $45 \text{ m}^3/\text{s}$ resulted in a $3.2\text{m}:1\text{n}$ ratio, significantly higher than those documented in the literature [14,15]. In addition, the trend change noted at $45 \text{ m}^3/\text{s}$ was not as clear as the other two changes in slope. Adopting the middle value of $70 \text{ m}^3/\text{s}$ resulted in a $1.2\text{m}:1\text{n}$ ratio, which is in line with those documented in the literature [14,15], and graphically

represents a clear change in trend, suggesting the flows below $70 \text{ m}^3/\text{s}$ would have a very frequent recurrence interval.

3. Results

3.1. Flood Frequency Analysis

A flood frequency analysis of all 20 iterations of the continuous simulation model was undertaken on the peaks over threshold series using a Bayesian fit of the Log Pearson Type 3 (LPIII) distribution [1]. The same flood frequency analysis was also undertaken using the available stream gauge data with the combined results shown in Figure 8. As shown, all 20 simulations are within a relatively tight band. Given that all results are equally likely, we considered that the median would approximate the peak flow for a given Annual Exceedance Probability (AEP), with the range of possible results (or uncertainty bounds) being within the highest and lowest results of the simulation. This suggests that the 1-in-10-year AEP peak flow would be $166 \text{ m}^3/\text{s} \pm 20 \text{ m}^3/\text{s}$, while the 1-in-100-year AEP peak flow would be $333 \text{ m}^3/\text{s} \pm 50 \text{ m}^3/\text{s}$.

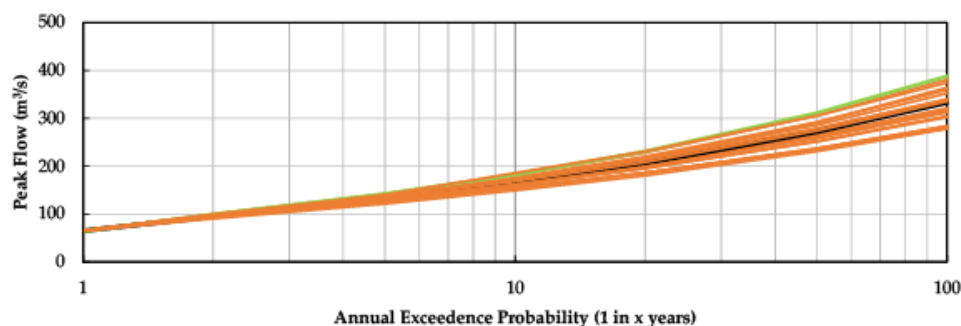


Figure 8. Flood frequency analysis of all 20 simulations (orange), with the median result shown in black and the same analysis of the stream gauge series shown in green. The simulated results show a relatively tight range suggesting there is limited uncertainty in the result.

In addition to the main finding above, the performance of the simulated results is also supported by the proximity of the same flood frequency analysis undertaken on the stream gauge. While the stream gauge result is at the upper end of the range of simulated results, it is posited that the shorter length of available stream gauge data (52 years), in comparison to the model simulations (100 years), potentially skews the stream gauge results. If the flood frequency analysis of the simulated results was undertaken for the same period and length of available stream gauge data (refer to Figure 9), the simulated results would better reflect the stream gauge data. What is also evident, however, is that the range of possible solutions increases significantly. Using the same approach as above, the 1-in-10-year AEP peak flow increases to $172 \text{ m}^3/\text{s} \pm 30 \text{ m}^3/\text{s}$, while the 1-in-100-year AEP peak flow would increase to $360 \text{ m}^3/\text{s} \pm 100 \text{ m}^3/\text{s}$. In practice, it is recommended that at least 50 years of data be used in a flood frequency analysis [17]. This research indicates that data of this length may, however, overestimate the result and increase the uncertainty significantly.

While the length of available data is a well-discussed criterion when undertaking a flood frequency analysis [17], the period of data adopted is often neglected. This issue is particularly evident in catchments such as the Gowrie Creek catchment, which may be considered to have a sufficient length of gauged data but recently experienced a flood event significantly larger than any others recorded. The impact of adopting the minimum of 50 years of streamflows over differing time periods (1920–1970, 1930–1980, 1940–1990, 1950–2000, 1960–2010, and 1970–2020) was undertaken using one of the model simulations and is shown in Figure 10. These results show the impact that large floods (or the lack

thereof) can have on the flood frequency analysis, with the 1-in-100-year AEP peak flow ranging from 308 m³/s to 432 m³/s.

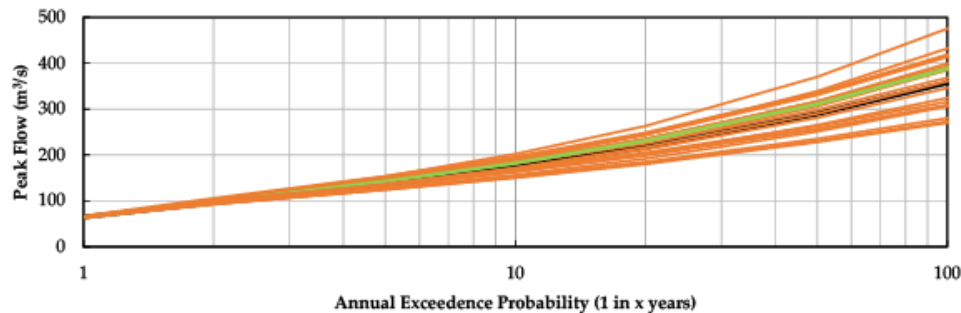


Figure 9. Flood frequency analysis of 52 years of all 20 simulations (orange) with the median result shown in black, and the same analysis of the stream gauge series shown in green. The simulated results show a relatively tight range, suggesting that there is limited uncertainty in the result.

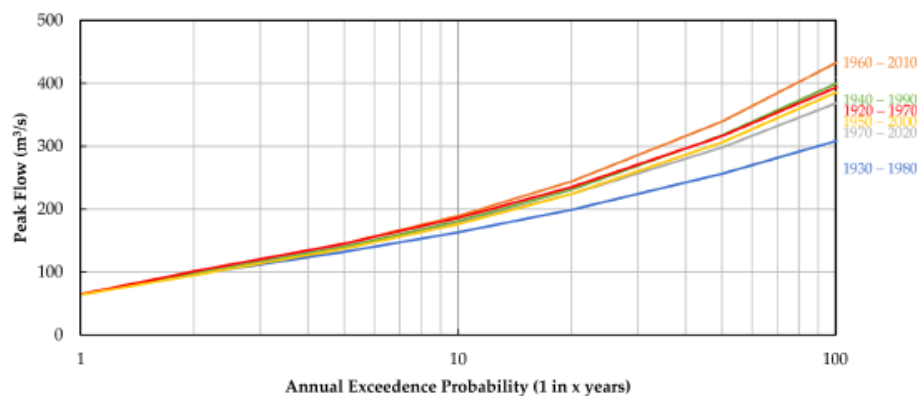


Figure 10. Flood frequency analysis of different 50-year time periods of one model simulation. The results show a significant difference in the estimated peak flows based on the period of data adopted.

3.2. Peaks over Threshold vs. Annual Maximum Series

As detailed in Section 1, the peaks over threshold method was used in this research to develop the data series for flood frequency analysis. However, the annual maximum series is still used by most practitioners, and it was therefore worth highlighting the impact of adopting the alternative option. The results presented in Figure 11 show that the annual maximum series results in significantly higher peak flows for AEPs less frequent than 1 in 5 years while also resulting in increased uncertainty in the result. For example, the 1-in-100-year AEP using the peaks over threshold approach was estimated to be 333 m³/s $\pm$ 50 m³/s, while using the maximum series approach, it was 427 m³/s $\pm$ 100 m³/s.

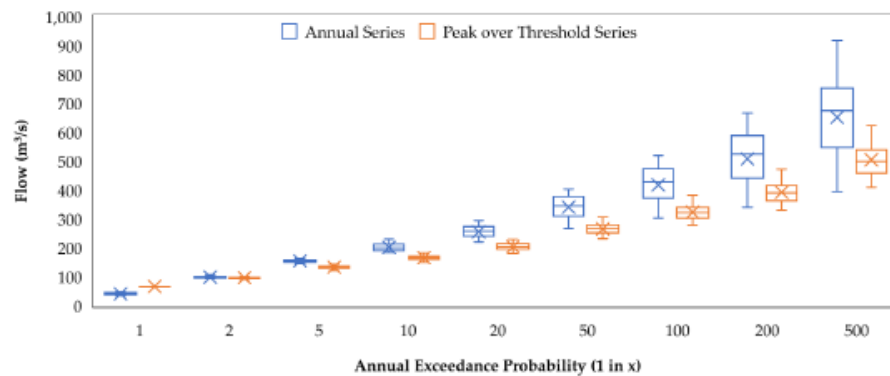


Figure 11. Flood frequency analysis of all 20 simulations using the peaks over threshold series (orange) and annual maximum series (blue). In general, the annual maximum series results in higher peak flows for the same AEP while also resulting in a wider range (or increased uncertainty) in the results.

3.3. Impact of the Number of Disaggregated Rainfall Iterations

While the software used in this research was limited due to the number of disaggregated rainfall iterations that could be simulated in a reasonable timeframe, the results shown in Figure 12 support the previous hypothesis that increasing the number of simulations beyond 20 would not have a significant impact. When viewing the change in the median peak flow for the 1-in-100-year AEP with each new iteration, it can be seen that there is a small variation in the result (between 320 m³/s and 340 m³/s), with an even tighter range (between 320 m³/s and 330 m³/s) forming beyond 11 iterations. This is likely due to the range of the results plateauing after the same number of iterations, suggesting that the upper and lower bounds of the 1-in-100-year AEP peak flow was reached based on the rainfall data used. Adding new sub-daily storms based on additional data collected over time would likely change this result. However, it is unlikely to be significant based on the narrow range of median peak flows.

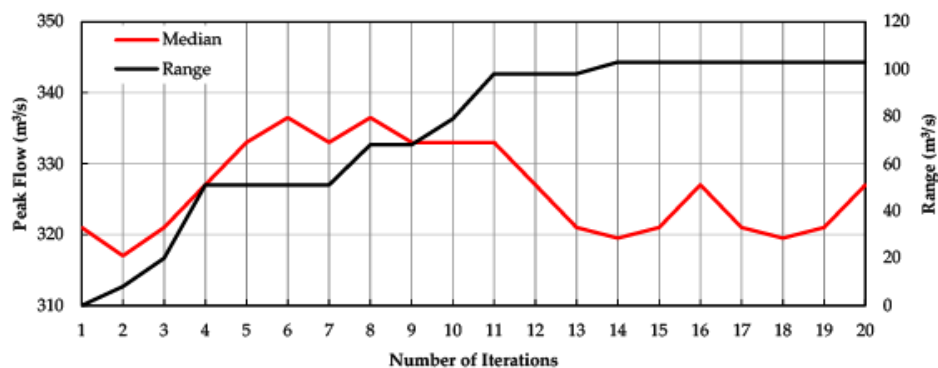


Figure 12. Change in median peak flow (red) and range (black) for the 1% AEP with an increase in the number of disaggregated rainfall iterations. There appears to be a trend change in both results after 11 iterations.

3.4. Comparison to Other Methods

Two previous hydrological assessments of the Gowrie Creek catchment were undertaken in the wake of the significant flooding in 2011. In 2013, the design event method was used to estimate the peak flow at the stream gauge for a range of AEPs from the 1-in-2-year to the 1-in-100-year AEPs (AECOM, 2013). An alternative approach to estimating peak flow was proposed by [41] who applied a Monte Carlo framework to the simplistic rational method (naming it the Rational Monte Carlo (RMC) method) to estimate peak flows for the same range. The results of these assessments in addition to the outcomes of this research are presented in Figure 13.

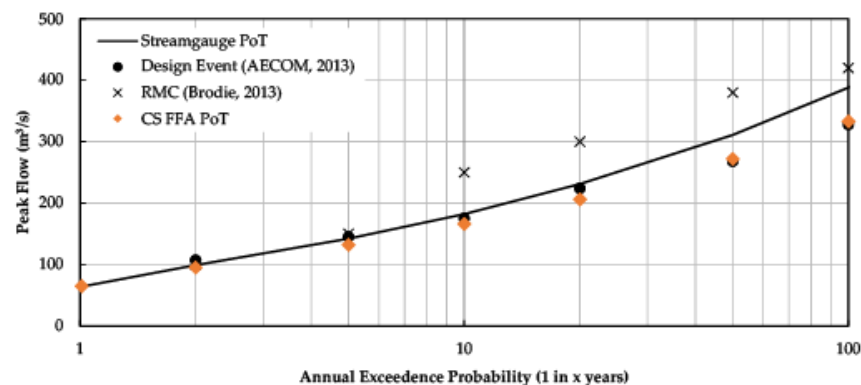


Figure 13. Comparison of the results of this research (diamond) against the design event method (circle), the Rational Monte Carlo framework (cross), and a flood frequency analysis of the stream gauge. The comparison shows a good agreement between this research and the design event method [41].

From this comparison, it is evident that the results of this research show a strong correlation with the design event method for all AEPs, while also showing good agreement with the RMC method for the 1-in-2 year and 1-in-5-year AEPs. It is noticeable, however, that there is a significant divergence from the RMC when the AEP becomes less frequent. This is likely due to the differing treatment of hydrologic losses, with this research adopting a dynamic loss model discussed in [11], while the RMC method adopts a simplistic runoff coefficient.

3.5. Review of an Individual Flood Event

While determining the peak flow for a given annual exceedance probability was the key outcome of this research, it was also interesting to compare the results of all scenarios simulated against the recorded streamflow for a given historical event. The major flooding that occurred in the Gowrie Creek catchment in January 2011 was an obvious candidate for comparison. The results shown in Figure 14 highlight that different rainfall temporal patterns were chosen to represent the same total daily rainfall. While the inconsistencies of the stream gauge during this event were documented by the authors [11]. It is still worth noting that all peak flows were less than the $\sim 600 \text{ m}^3/\text{s}$ recorded by the stream gauge, with a concentration of scenarios around a peak of $400 \text{ m}^3/\text{s}$. This suggests that a similar rainfall temporal pattern was chosen multiple times during the disaggregation process, which is consistent with the limited availability of large storm patterns as shown previously in Figure 6, and further supports the insignificant impact additional iterations would have on the result.

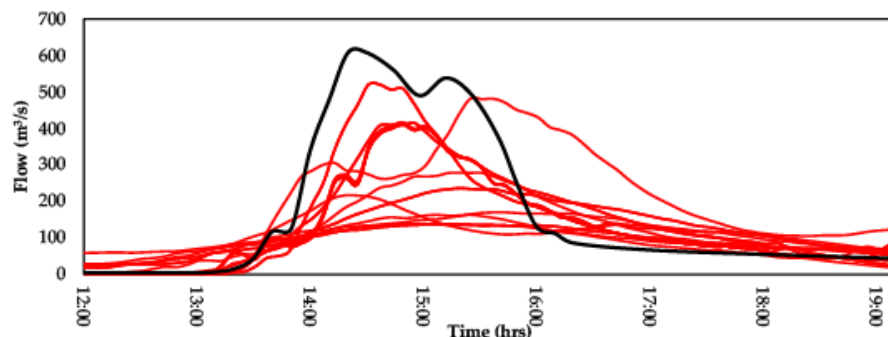


Figure 14. Hydrographs for all scenarios simulated (red) for the major January 2011 event in comparison to the recorded streamflow (black).

4. Conclusions

This research investigated the use of a calibrated continuous simulation model using the industry standard hydrology model XPRafts to estimate peak flows for a range of annual exceedance probabilities with uncertainty.

The need for a continuous series of sub-daily rainfall data for use in a continuous simulation model highlighted the requirement for a rainfall disaggregation model to disaggregate a long series of historic daily rainfall to a sub-daily scale. The use of a modified MoF that excluded seasonality and pre/post rainfall conditions allowed for a significant increase in the number of storms to be selected within a given class and allowed for the uncertainty to be better understood. The results of this method showed a strong correlation to the Bureau of Meteorology IFD design rainfall, justifying the use of this alternative method over those previously documented in the literature. This is a significant outcome, as it provides an alternate methodology to produce disaggregated rainfall better suited for continuous simulation modelling.

To understand the uncertainty in the result, 20 simulations of the calibrated hydrologic model with different disaggregated rainfall series were undertaken. A flood frequency analysis using the peaks over threshold method allowed the estimation of peak flows for different annual exceedance probabilities. The relatively tight range of results suggested there was limited uncertainty in the result, which is an important understanding when undertaking hydrologic modelling in an urban catchment.

This research further investigated the use of different flood frequency analysis methods and the use of different quantities and periods of streamflow data. When the flood frequency analysis of the model simulations (100 years of streamflow) was compared to the stream gauge (52 years of streamflow), it was evident that the stream gauge result was higher than all modelled results. If the flood frequency analysis of the model simulations was reduced to the same number of years and time period, the stream gauge result was close to the median of the modelled results. It was also shown that if 50 years of data were selected from differing time periods, the results of a flood frequency analysis could vary significantly. This result is of significance to practitioners who rely on flood frequency analyses of poorly gauged catchments to make informed decisions.

This research compared the peaks over threshold and the annual maximum series methods and showed that the use of the annual maximum series results in significantly more uncertainty in comparison to the peaks over threshold approach. Understanding the uncertainty of each method will assist practitioners who may seek to utilise alternative methods in evaluating the peak discharge in a catchment.

Finally, we were able to compare our result to other methods previously adopted for this catchment and found good agreement with the design event method. This result suggests the new methods being adopted within this research are comparable to other

methods whilst also providing an improved understanding of the uncertainty. This research can be extended to extract hydrographs to determine the impact hydrologic uncertainty has on hydraulic modelling.

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5.3 Links and Implications

This journal paper focussed on estimating the peak flow for various annual exceedance probabilities from the Gowrie Creek catchment in Toowoomba, Australia, using continuous simulation. Through the development of a simplified method of fragments rainfall disaggregation model, 100 years of daily rainfall data to sub-daily (6 minute) was able to be disaggregated and 20 unique iterations of the sub-daily rainfall was generated. While it wasn't possible to directly calibrate the sub-daily rainfall data to recorded rainfall, intensity-frequency-duration rainfall data was able to be calibrated then generated from the sub-daily rainfall to intensity-frequency-duration rainfall data generated by the Bureau of Meteorology. The strong calibration achieved allowed us to use the rainfall disaggregation model to achieve research objective 2, *"Generate and calibrate sub-daily (5 minute) synthetic rainfall with a sufficient duration for the continuous simulation model to produce an annual series of design flow rates for flood frequency analysis"*.

Simulating the 20 unique iterations of sub-daily rainfall through the continuous simulation model produced 20 iterations of 100 years of streamflow at the outlet of the catchment. A flood frequency analysis of each streamflow iteration allowed the estimation of peak flow for a range of annual exceedance probabilities, with the median result being adopted, and the minimum/maximum result providing the uncertainty bounds. This result allowed us to achieve research objective 3, *"Undertake an uncertainty analysis of the key continuous simulation modelling parameters to understand the uncertainty of the flood frequency analysis"*.

With this outcome, the result was compared to other peak flow estimates within the Gowrie Creek catchment, including the design event method, the rational Monte Carlo method and a flood frequency analysis of the existing stream gauge. This research highlighted that the approach adopted was able to replicate other commonly used methods (in particular the design event method) with the added benefit of showing the uncertainty in the result. This suggests that this approach could be applied to other catchments with the benefit of understanding uncertainty,

and answers research question 2 by showing that “*the continuous simulation hydrologic model was able to determine the peak flow with uncertainty and correlates strongly with other methods, including the design event method*”. This is a significant contribution to knowledge in this area as it provides applied hydrologists with a feasible alternative method to understanding peak flow estimates for an urban catchment. The modelling undertaken can be extended to allow hydrographs to be extracted, which could be modelled within a 2D hydraulic model to estimate the flood extent, with uncertainty, which is the focus of journal paper 3.

In the next chapter, the third journal paper is presented, which aims to develop a hydraulic model that can assess the impact that hydrologic uncertainty has on deriving design flood extents.

CHAPTER 6: PAPER 3 – HYDRAULIC IMPACT OF HYDROLOGIC UNCERTAINTY IN DERIVING DESIGN FLOOD EXTENTS

6.1 Introduction

Flood mapping is an essential input to urban planning. The commonly used design event method determines the flood extent from a single design hydrograph determined via a probability neutral conversion of rainfall to runoff. To understand the uncertainty in flood extent mapping for the Gowrie Creek catchment in Toowoomba, Australia, the use of the continuous simulation hydrologic model calibrated as part of the previous research was proposed. This allowed the extraction of multiple iterations of design hydrographs. By simulating each iteration in the 2D hydraulic model HEC-RAS, minimum, median and maximum flood extents likely within the catchment were determined. By comparing the results to the design event method, it was evident that the design event method closely correlated with the minimum continuous simulation iteration. Given the wide range between the minimum and maximum continuous simulation iterations, it is possible that the design event method was underestimating the flood extent. In addition to the flood extent, the critical time to peak parameter was also assessed for uncertainty and compared to the design event method. At the confluence of two major tributaries within the catchment, the time to peak was found to range between 30 minutes and 230 minutes, with the design event method producing a time to peak of 95 minutes, offering further insights into the potential uncertainty by utilising this alternate method. If the time to first inundation was considered over the time to peak, the time available for emergency response during an event would differ significantly. The research offered insight into the likely uncertainty in flood mapping and how the commonly used design event method may be underestimating the flood extent.

6.2 Submitted Journal Paper

Brown et al. (20xx), "Hydraulic Impact of Hydrologic Uncertainty in Deriving Design Flood Extents", submitted to Journal of Hydrologic Engineering on 27 January 2024.

Hydraulic Impact of Hydrologic Uncertainty in Deriving Design Flood Extents

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ABSTRACT:

Flood mapping is an essential input to urban planning. The commonly used design event method determines the flood extent from a single design hydrograph determined via a probability neutral conversion of rainfall to runoff. To understand the uncertainty in flood extent mapping for the Gowrie Creek catchment in Toowoomba, Australia, we proposed the use of a continuous simulation hydrologic model that allowed the extraction of multiple iterations of design hydrographs. By simulating each iteration in the 2D hydraulic model HEC-RAS, we determined minimum, median and maximum flood

extents likely within the catchment. Comparing the results to the design event method, it was evident that the design event method closely correlated with the minimum continuous simulation iteration. Given the wide range between the minimum and maximum continuous simulation iterations, it is possible that the design event method is underestimating the flood extent. In addition to the flood extent, the critical time to peak parameter was also assessed for uncertainty and compared to the design event method. At the confluence of two major tributaries within the catchment, the time to peak was found to range between 30 minutes and 230 minutes, with the design event method producing a time to peak of 95 minutes, offering further insights into the potential uncertainty by utilising this alternate method. If the time to first inundation was considered over the time to peak, the time available for emergency response during an event could differ significantly.

AUTHOR KEYWORDS (OPTIONAL): Uncertainty, Hydraulic Modelling, Flood Mapping.

1. Introduction

Accurate flood mapping is an important process undertaken by planning authorities to ensure sustainable land use planning and protect human property and life (Grimaldi et al. 2013). The role of flood mapping in building resilient communities increases as the urban population grows and the uncertain nature of rainfall becomes more evident (Fischer and Stanchev 2022). The importance of flood planning becomes evident when significant rainfall events happen, such as the event which occurred in the regional town of Toowoomba in Queensland, Australia in 2011. In this event, flash flooding resulted in floodwaters with high velocities causing dangerous conditions for pedestrians and motorists at major road crossings and resulted in the death of at least four people.

Flood maps are a direct output of complex two-dimensional hydraulic models that require either direct rainfall input (rain on grid) or hydrographs produced from hydrologic models (fluvial). This research focusses on the fluvial approach to flood plain mapping, given the lack of benchmarking of hydraulic

models using rain on grid (Costabile et al. 2021). To develop flood maps for a given annual exceedance probability, hydrographs from a hydrologic model for the same annual exceedance probability are required. The design event method, which adopts a probability neutral conversion of design rainfall to runoff with the help of a pre-determined hyetograph, is commonly used to develop these hydrographs and is popular amongst practitioners due to its relative simplicity (Grimaldi et al. 2013). This method does however come with significant limitations, particularly the adoption of a simplistic initial loss/continuing loss model that greatly simplifies the antecedent moisture conditions of the catchment prior to the event (Cameron et al. 1999) and is scaled to ensure a probability neutral conversion of rainfall to runoff. To overcome these limitations, continuous simulation hydrologic modelling can be utilised to provide a more realistic design hydrograph in terms of volume and duration (Grimaldi et al. 2021).

A continuous simulation hydrologic model was previously developed and calibrated for the Gowrie Creek catchment in Toowoomba by the authors (Brown et al. 2022). As rainfall loss is considered a critical hydrologic parameter that leads to a high level of uncertainty (Ball et al. 2019), a dynamic loss model was used to more comprehensively represent the wetting and drying through direct simulation of the physical processes occurring in the catchment (Cameron et al. 1999; Kuczera et al. 2006; Muncaster, Weinmann, and Boughton 1999). The model, once calibrated, offered a satisfactory fit (Nash Sutcliffe Efficiency > 0.5) for nine of the 11 selected storm events, with seven events exceeding a Nash Sutcliffe Efficiency of 0.75 (Brown et al. 2022). The same model was then used to estimate peak flows for different Annual Exceedance Probabilities (AEP) at the outlet of the catchment via a peak over threshold flood frequency analysis as part of a research paper by the same authors (Brown et al. 2023).

To allow the flood frequency analysis to be undertaken, a long time series of flow estimations are required. The continuous simulation hydrologic model can produce these estimations, however a long series of simulated rainfall data is also required (Kobierska, Engeland, and Thorarinsdottir 2018). Given

the relatively small size and the urban nature of the Gowrie Creek catchment, simulating daily rainfall would not provide the level of detail required. Using the modified method of fragments approach (Li et al. 2018), the disaggregation of 100 years of daily rainfall available for the site was completed and documented (Brown et al. 2023). Using this method, it was possible to produce 20 iterations of six-minute rainfall simulations for a 100-year period. Routing the sub-daily rainfall in a calibrated rainfall/runoff model produced 20 iterations of continuous flow over a 100-year period, well in excess of the 50 years recommended (Kobierska et al. 2018). The continuous flow series was used by the authors to estimate peak flows for a range of annual exceedance probabilities. The research identified that a continuous simulation model could effectively estimate the peak flow from a catchment with a low degree of uncertainty and with the median result correlating well with the design event method (Brown et al. 2023).

To develop a suitable hydraulic model, hydrographs for the time period within the full continuous flow series, which approximately matched the peak flow estimated via flood frequency analysis, were identified and extracted. This approach is similar to that proposed by (Grimaldi, Petroselli, and Serinaldi 2012), however as 20 iterations of 100 years of continuous rainfall was simulated (Brown et al. 2023), it was possible to extract 20 unique estimates of a design hydrograph, each of which would be considered equally likely to occur. By simulating each of the 20 iterations of design hydrographs through a 2D hydraulic model, it would be possible to understand the hydraulic impact of hydrologic uncertainty, in particular the impact on two key results; flood extent and time to peak.

Understanding the range of uncertainty in flood extents and time to peak within an urban catchment, and its comparison to the design event method, offers a significant contribution to the hydrologic community and engineers who report these results for government agencies and private entities. The new contribution being offered by this paper is the understanding of this uncertainty and to highlight the potential shortcomings of the design event method. This research aims to: i) provide an alternate

approach to estimate the uncertainty in flood extents, ii) estimate the range of times to peak at key locations within the catchment, and iii) compare the results to the design event method and highlight the uncertainty present in the design event method. The methods used to develop the model are described in Section 2, while Section 3 presents and discusses the results. Finally, conclusions are presented in Section 4.

2. Methodology

2.1 Study Area

The Gowrie Creek catchment is a heavily urbanised catchment in the city of Toowoomba, in the state of Queensland, Australia. Toowoomba is considered to be sub-tropical with an average annual rainfall of 700 mm, the majority of which falls over the wet season from November to March. The 51 km² catchment, shown in Figure 1, is twice as long as it is wide, and has a well-defined, heavily modified creek line. Elevations within the catchment range from 750m Australian Height Datum (AHD) at the southern and eastern extents, to 550m AHD at the catchment outlet to the north. This significant height difference across the catchment results in sub-catchment areas varying in slope from 3% near the valley, to 9% at higher elevations.

Gowrie Creek is formed at the confluence two creeks: East Creek and West Creek. Both East and West Creeks contain a series of detention basins, some of which were constructed after the major flooding that occurred in 2011.

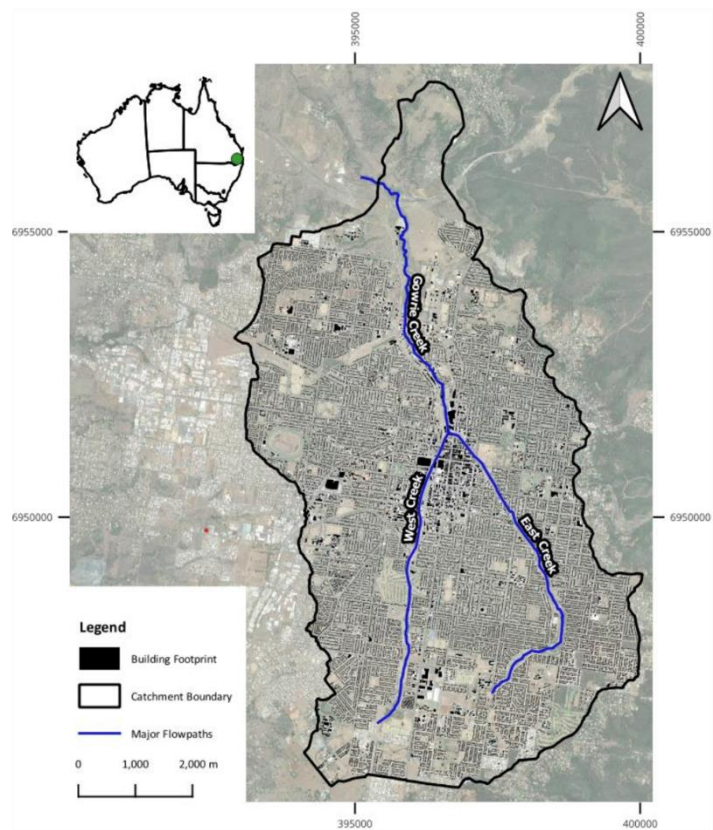


Figure 1 Location of the Gowrie Creek catchment with major tributaries highlighted.

2.2 Model Approach

This research builds on two previous investigations by the authors, where, the hydrologic loss parameters were firstly calibrated to historical events (Brown et al. 2022), and subsequently the uncertainty in peak flow estimates was determined for a range of annual exceedance probabilities (AEPs) (Brown et al. 2023). The model approach taken for this research, and how all the research papers fit together, is shown in Figure 2.

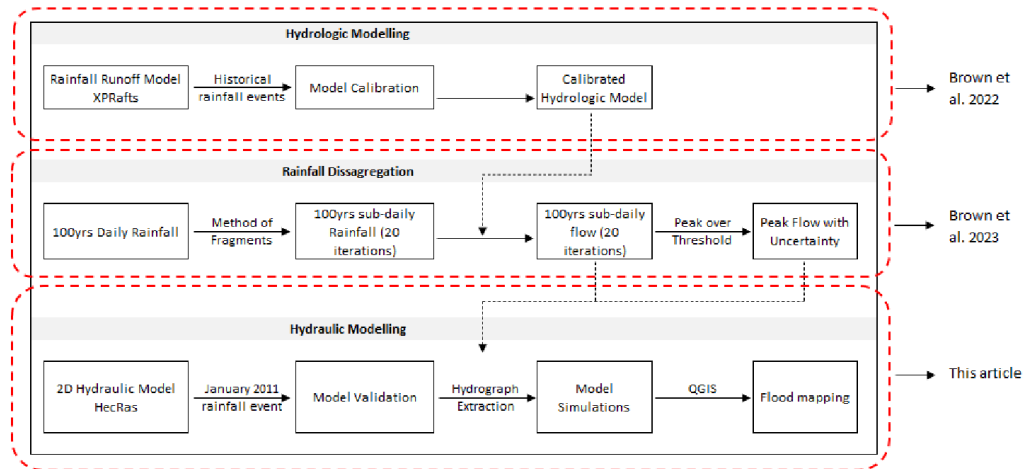


Figure 2 Hydraulic modelling approach and relationship with previous research. The tasks being documented in this research are highlighted in red.

2.3 HEC-RAS 2D Model Description

HEC-RAS 2D is a two-dimensional hydraulic routing model that performs unsteady flow analysis and allows the modelling of open channels, floodplains, levees, culverts and bridges (Brunner 2020). It enables the user to choose from one of three numerical solvers; 2D Diffusion wave, Shallow Water Equation with an Eulerian-Lagrangian approach to solve for advection (SWE-ELM), or more recently (Version 6.0), a Shallow Water Equation that uses an Eulerian approach to solve advection (SWE-EM). The equations that drive the above numerical solvers are detailed in the HEC-RAS Hydraulic Reference Manual Version 6.3 (Brunner 2020).

Benchmarking of the SWE-ELM numerical solver was undertaken (Baker 2018) and found to perform extremely well across all eight tests when compared to the models used in the original benchmarking study (Neelz and Pender 2013). This included popular industry models like TufLOW (TufLOW 2018) and Mike Flood (DHI 2021). In addition, when benchmarking the different numerical solvers, the SWE-EM

option did not provide any additional benefit over the default SWE-ELM, despite the increased computational time required (Costabile et al. 2021). Based on the above, this research adopted the SWE-ELM numerical solver within HEC-RAS 2D for all results shown.

2.4 Model Terrain

A one metre digital elevation model, derived from an aerial survey captured in 2010, was supplied by the Toowoomba Regional Council and used as the base terrain model for the hydraulic model. Due to the construction of additional detention basins within East Creek post 2010, the base terrain was modified to include an additional aerial survey which was captured in 2015. This combined data was used to create a flexible mesh model terrain that consisted of a three metre cell size within major flow paths (East, West and Gowrie Creeks) that transitioned over 20 metres to a 10 metre cell size within the remaining hydraulic model extent. Due to the steep catchment and well-defined channels, these cell sizes provided an accurate representation of the terrain within the flood extent while not creating an onerous simulation time. The hydraulic model extent is shown in Figure 3.

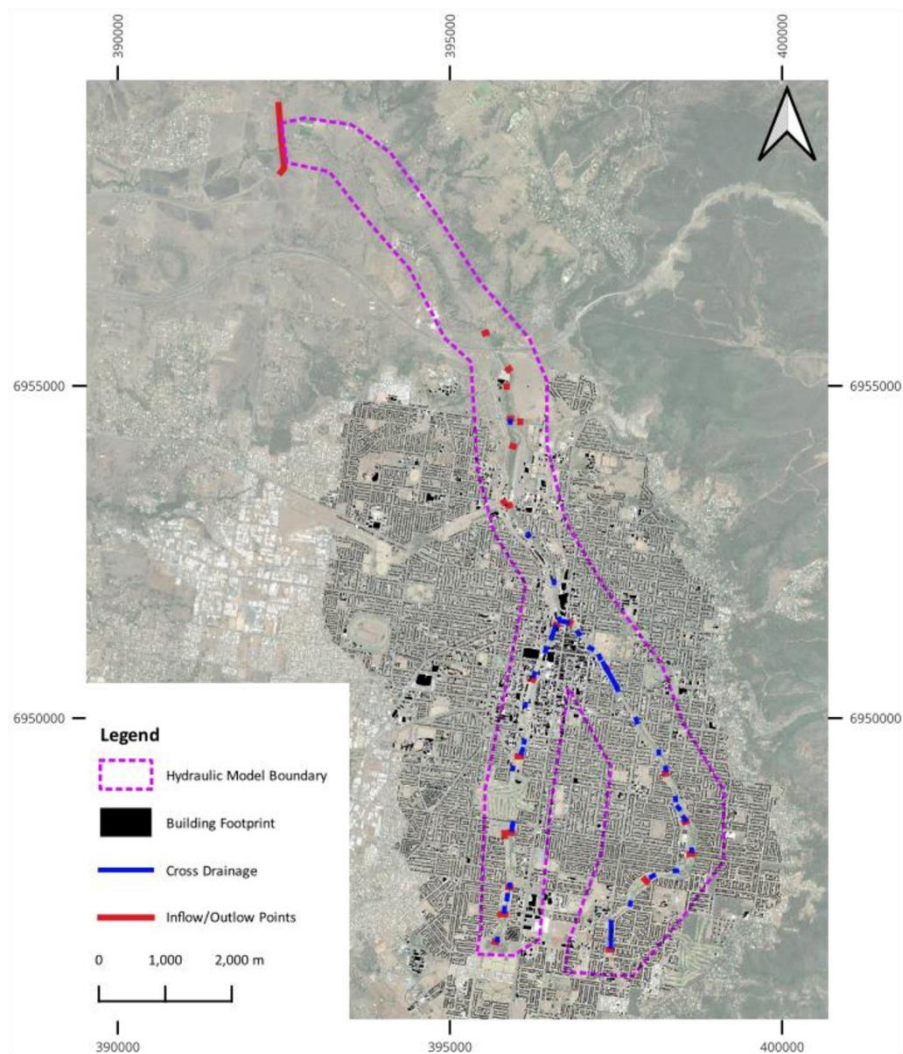


Figure 3 Hydraulic model extent (magenta), along with modelled hydraulic structures (blue) and inflow/outflow boundaries in red.

2.5 Roughness

The roughness, or Manning's 'n', of the terrain was modified within the hydraulic model to reflect the changes in the surface conditions. The open channels generally consisted of either grass, a composite of grass and a concrete invert/low flow channel, or full concrete across the entire cross section. The urban area consisted of grass verges, concrete paths and paved roads, and was therefore given a Manning's 'n' value slightly higher than a full concrete channel. A summary of the hydraulic model roughness parameters is shown in Table 1, noting that the representation of buildings is further discussed in Section 2.6. All values adopted are within the range of Manning's 'n' values recommended (Chow 1959) for the particular land cover types and were adjusted to achieve the model validation shown in Section 3.1.

Table 1 Hydraulic Model Roughness Parameters

Land Cover	Adopted Manning's 'n'
Concrete Channel	0.015
Composite Concrete and Grassed Channel	0.025
Grass	0.035
Urban Area	0.02
Buildings	Refer Section 2.6

2.6 Representation of Buildings

As the building height has been filtered out of the aerial survey provided, the impediment to flow created by the buildings needed to be reconsidered. Buildings are typically represented by either one of two techniques when using the hydraulic model; building block (terrain is raised within the building footprint) and building resistance (roughness is increased significantly within the building footprint). (Mustafa and Szydlowski 2021) compared hydraulic model results using HEC-RAS 2D to those recorded via a physical model and found the building block technique provided the best level of precision. This research adopted the building block technique, increasing the terrain within the footprint of buildings to

be significantly higher than that of the predicted flood to ensure no flow or storage occurred within the footprint of the building.

2.7 Design Hydrograph Selection

A key input to a fluvial hydraulic model, like the one used in this research, is the hydrograph. To allow the estimation of a design flood extent, a design hydrograph with the same AEP had to be extracted from the continuous simulation model. (Brown et al. 2023) determined the peak from the 1% AEP via a flood frequency analysis of a peak over threshold series for all 20 iterations simulated. With the peak flow known, it was possible to interrogate the individual peak monthly flows (over the 100 year series) and identify when an event occurred that was nearest to this peak. The hydrologic model was run continuously with outputs every six minutes. From this, a hydrograph was extracted. This corresponded to the peak monthly flow that best matched the annual exceedance probability. Figure 3 provides an example of the hydrographs extracted from the confluence of East and West Creeks (Figure 3a), and at the outlet of the Gowrie Creek catchment for each iteration (Figure 3b) shows that The shape and magnitude of the hydrographs are similar to one another which confirmed a previous finding by the authors that 20 iterations of hydrologic simulations were sufficient to estimate the range of results with minimal uncertainty (Brown et al. 2023). Local hydrographs were then extracted from each sub-catchment and input directly into the hydraulic model at the locations shown in Figure 4.

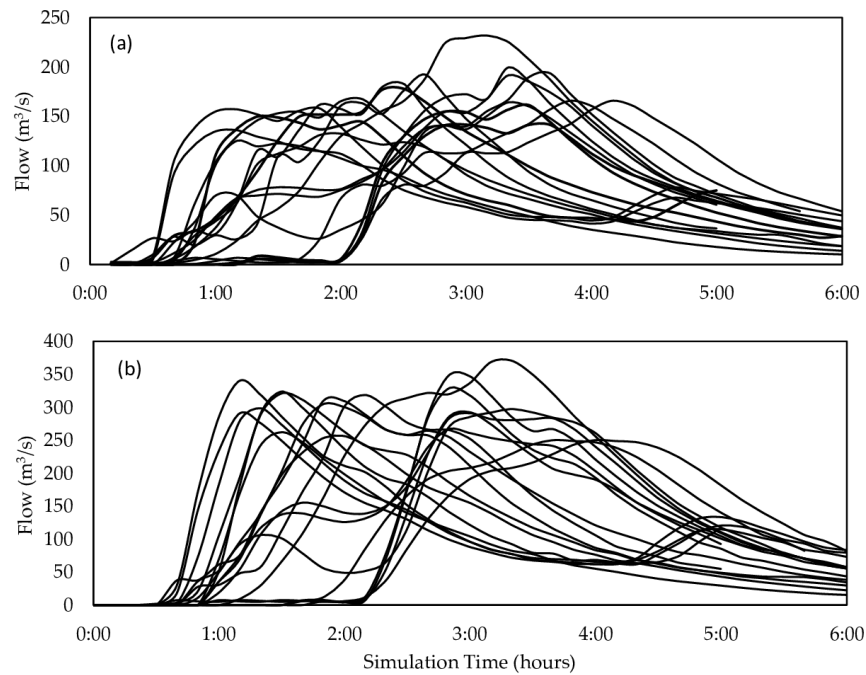


Figure 4 Total hydrographs at the confluence of East and West Creeks (a) and the outlet of the Gowrie Creek catchment (b) for all 20 iterations assessed.

2.8 Hydraulic Structures

Numerous hydraulic structures exist within the major flow paths at road crossings and the outlets of detention basins. The hydraulic structures are represented using a storage area/2D flow area connection. This connection type allowed the input of various connection types, including culverts (both rectangular and circular) and allowed the representation of all hydraulic structures within the model extent. The surface above the hydraulic structure was represented by model terrain. The location of the hydraulic structures within the model extent is shown in Figure 3.

2.9 Boundary Conditions

A normal depth downstream boundary, with a friction slope of 0.01 m/m, was adopted at the downstream end of the hydraulic model extent. The boundary condition adopted does not impact on the results of this research when the hydraulic model was extended by approximately five kilometres downstream of the extent of urban development within Toowoomba. The outlet boundary, located at the northern extent of the hydraulic model, is shown in Figure 3.

3. Results and Discussion

3.1 Hydraulic Model Validation

Prior to undertaking design simulations, validation of the hydraulic model was undertaken to ensure the input parameters adequately represented the flood response. As there were insufficient flood levels recorded within the extent of the hydraulic model, it was not possible to undertake detailed calibration, however, a debris survey and photographic evidence was used to approximate flood extents during the major flooding that occurred in January 2011 (the only flood event with this level of detail and the largest flood event on record). In addition, a hydraulic model developed by an engineering consulting firm, AECOM, for the Gowrie Creek 2015 Base Case Flood Model (AECOM 2015) used this same event to validate their model, and so it was possible to compare the results of this research to both data sets. The results of this research (blue) are compared to the observed extent (red line) and the previous study (AECOM 2015) at the confluence of East and West Creeks in Figure 5.

Figure 5 illustrates that the results of this research correlate closely with the flood extent observed during the January 2011 event. It also compares favourably with the previous study (AECOM 2015), with the main difference being at the confluence of the two tributaries. It is difficult to determine the exact reasons for this difference as the previous study (AECOM 2015) hydraulic model was not able to be interrogated. However, it is likely the result of how the different model types account for the complex

hydraulic situation, given the presence of a hydraulic structure located immediately downstream of the confluence. In addition, while the grid size adopted for each model was the same (3m), this research adopted a flexible mesh (versus the more traditional square grid), likely resulting in a smoother transition between the grids.

While there is a difference in flood extent between the two models, the results of this research align more closely with the observed flood event at this location. Therefore, it is considered that the input parameters and model methodology adopted in this research are adequately representing the flood behavior.



Figure 5 Comparison of the flood extent during the January 2011 flood event, with the results of this research (blue) agreeing closely with the observed extent (red line) and generally in line with the previous study (green).

3.2 Design Simulations

All 20 iterations of the 1% AEP event extracted from the continuous simulation model were simulated through the HEC-RAS 2D hydraulic model. The minimum, median and maximum result were extracted

and are presented in Figure 6, with three locations where the results vary significantly shown in insets 1 to 3. The insets illustrate that there are areas of significant uncertainty in the flood extent. Given that each iteration simulated is considered equally likely, the significant variation in the results suggest that care is needed when adopting a single design storm event, as would be the case when the design event method is used. To further highlight the uncertainty in the prediction of flood extent, a comparison was undertaken (refer Figure 6) between the minimum, median and maximum results determined through this research, and the design event flood extent (AECOM 2015). These results indicate that at some locations, like those highlighted in the insets, the design event method results in flood extents less than the minimum flood extent which has been determined by this research, and significantly less than the median and maximum flood extents. This is significant as these results are used when making decisions relating to urban planning and infrastructure upgrades and further highlights the need to understand hydraulic modelling uncertainty. In urban planning, instead of adopting the median result with a freeboard allowance applied, an alternative option could be used whereby the maximum is adopted (with little or no freeboard). When assessing the capacity of drainage infrastructure, or when designing new drainage infrastructure, the median result could be adopted, however the infrastructure would also be assessed against the maximum result to ensure there are no unintended impacts.

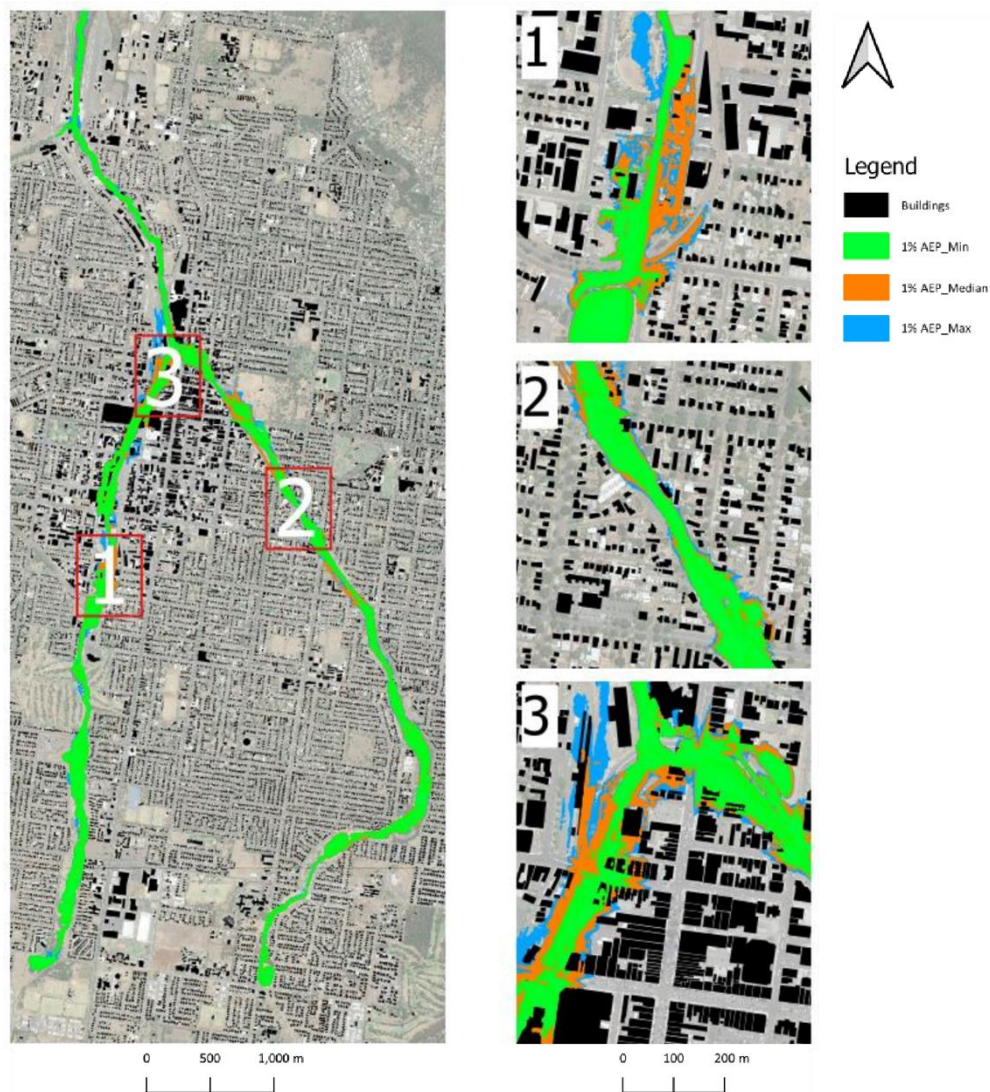


Figure 6 Minimum (green), Median (orange) and Maximum (blue) 1% AEP flood extents within the hydraulic model extent, with key locations of difference highlighted in insets 1, 2 and 3.

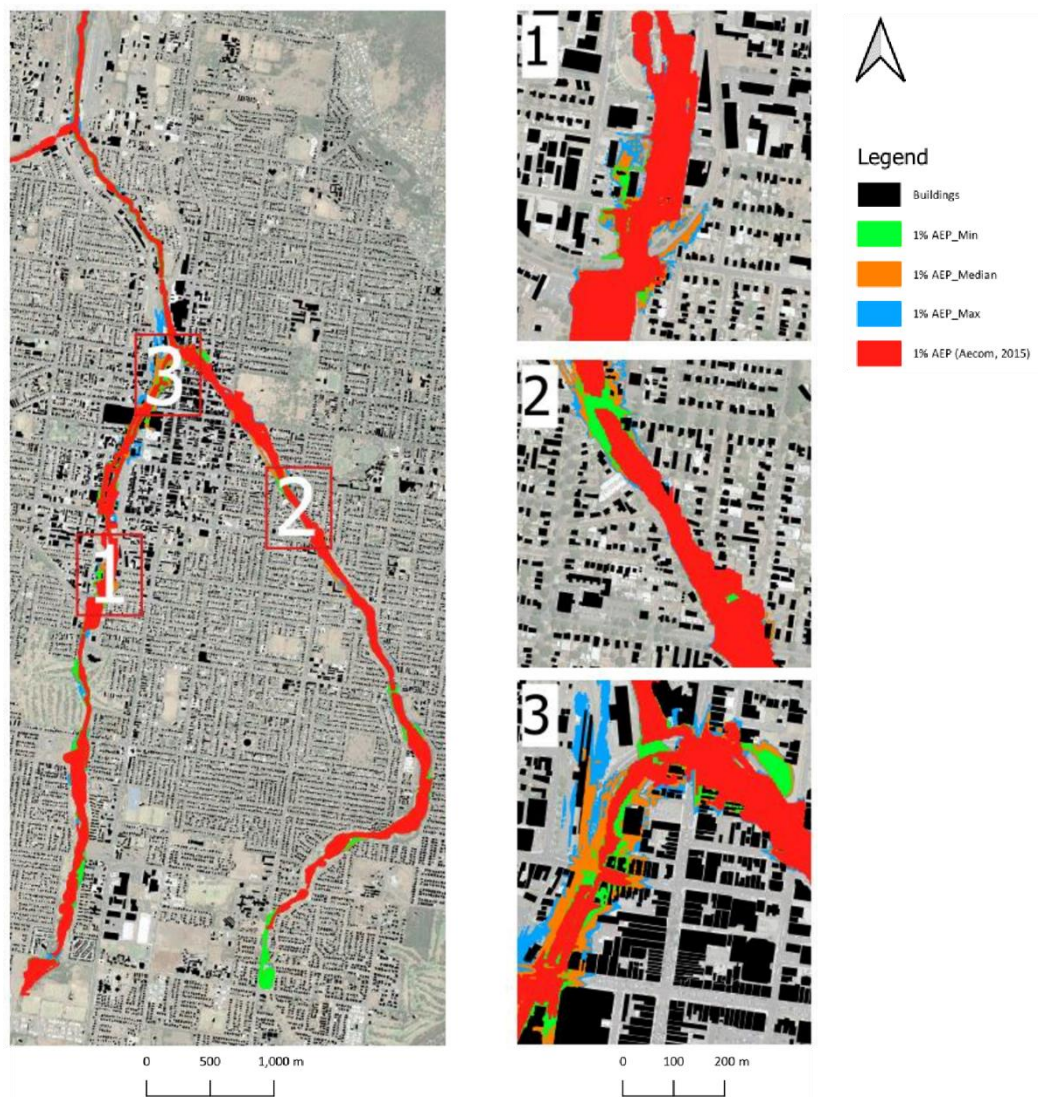


Figure 7 Minimum (green), Median (orange) and Maximum (blue) 1% AEP flood extents within the hydraulic model extent in comparison to the previous study 1% AEP flood extent (red) with key locations of difference highlighted in insets 1, 2 and 3.

3.3 Time to Peak

While the flood extent is critical in urban planning, hydraulic model results can also assist in disaster management planning, with a key result being the time to peak. The time to peak varies depending on the temporal pattern of the rainfall and the response time of the catchment. A key limitation of the design event method is the adoption of one critical storm, resulting in a single estimation of the time to peak. In this research, the time to peak was estimated for all 20 iterations (as shown in Figure 8), to highlight the uncertainty in the critical decisions being made by these assessments. At the confluence of East and West Creeks, the time to peak ranged from 30 minutes to 200 minutes, with the design event method suggesting a time to peak of 95 minutes.

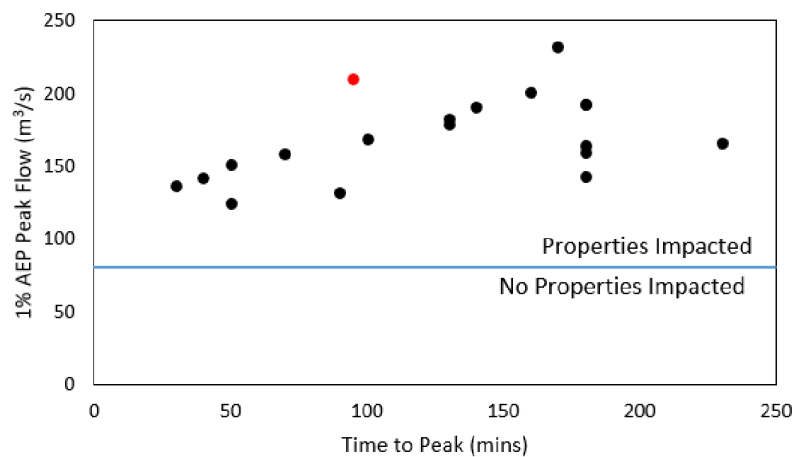


Figure 8 Peak flow estimates for all 20 iterations shown in black and the design event method (AECOM 2015) shown in red along with the threshold value at which point properties are.

While the time to peak is a significant consideration in disaster planning, the flood model extents for the catchment (as shown previously in Figure 6) suggest that the land parcels are likely to be inundated prior to the peak. Therefore, a more accurate representation of the time available to respond to a predicted flood would be the time to first inundation. Interrogation of the hydraulic model results at the confluence of East and West Creeks showed properties were inundated at a threshold flow of

approximately 80 m³/s. However, Figure 8 illustrates that the peak flow estimation for all 20 iterations assessed, as well as the design event method (AECOM 2015), are all significantly higher than this threshold. If the time to first inundation was used, the time available would reduce significantly as shown in Figure 9, with the range reducing from the previously quoted 30 minutes to 200 minutes, to between 10 minutes and 130 minutes. This significant reduction in response time would likely lead to changes in possible options available during an event of this nature.

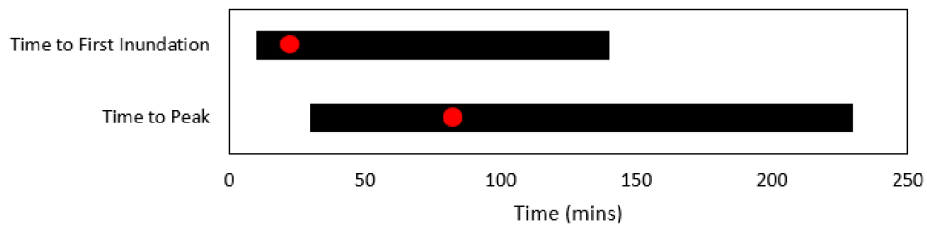


Figure 9 Range of time to peak and time to first inundation for the 1% AEP flood event at the confluence of East and West Creek (black), with the results of the design event method (AECOM 2015) shown in red.

4. Conclusions

Flood mapping is an essential decision-making tool used in urban planning. While the commonly used design event method aims to estimate the extent, it fails to provide an understanding of the likely uncertainty. To understand the uncertainty, this paper provides an alternate approach whereby design hydrographs are extracted from a continuous simulation hydrologic model and subsequently simulated in a 2D hydraulic model. As the previously developed continuous simulation hydrologic model provided 20 iterations of continuous flow, it was possible to estimate the flood extent for all 20 iterations and therefore gain an understanding of the range or uncertainty bounds of the results.

The detailed hydraulic mapping showed that the range of results were significant, in particular for areas near the confluence of East and West Creeks. It was also noticeable that the design event method, when compared to the range of results determined in this research, appeared to correlate best with the

minimum iteration, suggesting there is likely a significant level of uncertainty in the design event estimation.

In addition to the flood extent, the time to peak is also a key consideration in disaster planning and management. This research highlights that there is significant uncertainty in the time to peak, with a range of 30 minutes to 230 minutes found at the confluence of East and West Creeks. While the time to peak is commonly quoted, this research highlights the need to understand the time to first inundation, as it is likely more influential in disaster management decisions. By determining the flow rate after the first property was impacted, it is possible to estimate the time to first inundation, which is significantly lower than the time to peak, with the results ranging from 10 minutes and 130 minutes.

This research provides a significant contribution to the knowledge as it highlights the possible shortcomings of the design event method and illustrates why alternate methods such as continuous simulation can provide a greater understanding of the uncertainty associated with hydraulic modelling and mapping.

DATA AVAILABILITY STATEMENT:

Some or all data, models, or code generated or used during the study are proprietary or confidential in nature and may only be provided with restrictions (e.g., anonymized data). (List items and restrictions)

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AECOM, "Gowrie creek," 2015.

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6.3 Links and Implications

This journal paper culminates this research by taking the hydrologic outputs produced in journal paper 2 and running it through a 2D hydraulic model to estimate flood extents with uncertainty. This achieved research objective 4, *“Develop a hydraulic model and simulate the extent of uncertainty within the hydrologic model to understand the impact the uncertainty has on the flood extent within the Gowrie Creek catchment.”* By simulating the minimum, median and maximum hydrographs from the one in 100 year annual exceedance probability event, the detailed hydraulic mapping showed that the range of results was significant. It was also noticeable that the design event method, when compared to the range of results determined in this research, appeared to correlate best with the minimum iteration, suggesting there is likely a significant level of uncertainty in the design event estimation. This finding was significant, and answered research question 3, highlighting the *“impact that hydrologic uncertainty has on the estimation of flood extents.”* In addition to the flood extent, the time to peak at key locations within the catchment was evaluated, given its importance in disaster management. This research highlights that there is significant uncertainty in the time to peak, with a range of 30 minutes to 230 minutes found at the confluence of the two major tributaries within the catchment. While the time to peak is commonly quoted, this research highlights the need to understand the time to first inundation, as it is likely more influential in disaster management decisions. By determining the flow rate after the first property was impacted, it is possible to estimate the time to first inundation, which is significantly lower than the time to peak, with the results ranging from 10 minutes and 130 minutes. The overall results of this research go a long way to suggest that continuous simulation is a feasible alternative to the design event method as it not only correlates well, but it goes further to provide an understanding of uncertainty that the design event fails to provide.

The next chapter provides further discussion on the research undertaken, answers the research questions initially proposed in Chapter 1, and provides final conclusions while offering insight into further research directions.

CHAPTER 7: DISCUSSION AND CONCLUSION

7.1 Introduction

This thesis investigated the use of a continuous simulation hydrologic model coupled with a 2D hydraulic model to ultimately understand the impact hydrologic uncertainty has on the flood extent within the Gowrie Creek catchment in Toowoomba, Australia. The research showed that the continuous simulation hydrologic modelling approach was able to at least replicate the results of the more commonly used design event method and had the benefit of providing uncertainty bounds for the results. When the hydrographs were routed through the 2D hydraulic model, the research showed that the design event method correlated best with the minimum continuous simulation result, suggesting the design event method may be underestimating the flood potential within the Gowrie Creek catchment.

The key outcomes of this thesis with respect to the research aim and objectives will be firstly detailed in Section 7.2. Section 7.3 will then elaborate on the research questions initially posed and how these questions were answered in the context of the findings. Section 7.4 discussed the key contributions to knowledge particularly in the areas of uncertainty relating to hydrologic and hydraulic modelling. Finally, Section 7.5 outlines possible future research directions which have been identified through this research.

7.2 Achievement of Research Aim and Objectives

The aim of this research was to investigate the predictive accuracy and uncertainty of hydrologic and hydraulic modelling of the Gowrie Creek catchment in Toowoomba by obtaining a better understanding of the loss parameters through continuous simulation. This research aim was achieved through the successful completion of the four research objectives. The objectives and outcomes are briefly reviewed below.

7.2.1 Research Objective 1: Develop a continuous simulation hydrologic model for the Gowrie Creek catchment in Toowoomba and calibrate the catchment losses to historical rainfall and streamflow data

This research objective was addressed in journal paper 1, which developed and calibrated a continuous simulation hydrologic model, and then determined the ARBM parameters suitable for the urban Gowrie Creek catchment. The loss model parameters documented in this journal paper offer new values for the possible use by applied hydrologists dealing with similar catchment and climatic conditions. By undertaking this component of work, research objective 1: *"Develop a continuous simulation hydrologic model for the Gowrie Creek catchment in Toowoomba and calibrate the catchment losses to historical rainfall and streamflow data"*, was achieved. The continuous simulation hydrologic model developed to achieve research objective 1 formed the basis for research objective 2 and 3.

7.2.2 Research Objective 2: Generate and simulate sub-daily rainfall to produce a long series of continuous streamflow to allow a flood frequency analysis

This research objective was addressed in journal paper 2, which developed a simplified method of fragments rainfall disaggregation model to disaggregate 100 years of daily rainfall data to sub-daily rainfall (6 minute). While it wasn't possible to directly calibrate the sub-daily rainfall data to recorded rainfall, intensity-frequency-duration rainfall data was able to be calibrated then generated from the sub-daily rainfall to intensity-frequency-duration rainfall data generated by the Bureau of Meteorology. Simulating the disaggregated rainfall within the continuous simulation hydrologic model allowed research objective 2, *"Generate and calibrate sub-daily synthetic rainfall with a sufficient duration for the continuous simulation model to produce an annual series of design flow rates for flood frequency analysis"*, to be achieved. The rainfall disaggregation model was used to developed 20 unique iterations of sub-daily rainfall that could be simulated within the continuous simulation hydrologic model to achieve Objective 3.

7.2.3 Research Objective 3: Undertake an uncertainty analysis of the key continuous simulation modelling parameters to understand the uncertainty of the flood frequency analysis

This research objective was addressed in journal paper 2, which simulated the 20 unique iterations of sub-daily rainfall through the continuous simulation model to produced 20 iterations of 100 years of streamflow at the outlet of the catchment. A flood frequency analysis of each streamflow iteration allowed the estimation of peak flow for a range of annual exceedance probabilities, with the median result being adopted, and the minimum/maximum result providing the uncertainty bounds. This result allowed research objective 3, *"Undertake an uncertainty analysis of the key continuous simulation modelling parameters to understand the uncertainty of the flood frequency analysis"* to be achieved.

7.2.4 Research Objective 4: Develop and simulate the extent of uncertainty within a hydraulic model to determine the impact hydrologic uncertainty has on the flood extent within the Gowrie Creek catchment

This research objective was addressed in journal Paper 3, which culminated the research by taking the hydrologic outputs produced in journal paper 2 and running it through a 2D hydraulic model to estimate flood extents with uncertainty. By simulating the minimum, median and maximum hydrographs from the one in 100 year annual exceedance probability event, the detailed hydraulic mapping showed that the range of results was significant. It was also noticeable that the design event method, when compared to the range of results determined in this research, appeared to correlate best with the minimum iteration, suggesting there is likely a significant level of uncertainty in the design event estimation. This outcome achieved research objective 4, *"Develop a hydraulic model and simulate the extent of uncertainty within the hydrologic model to understand the impact the uncertainty has on the flood extent within the Gowrie Creek catchment."*

7.3 Review of Research Questions

This section reflects on the initial research questions that were posed and then discusses the answers to these questions in the context of the research findings.

7.3.1 Research Question 1: Does continuous simulation hydrologic modelling offer a more complete understanding of hydrological processes and can it replicate historical stream flows?

Journal paper 1 of this research developed and calibrated a continuous simulation hydrologic model for the Gowrie Creek catchment. When developing the hydrologic model, two key input parameters that directly impact the hydrological processes within the catchment were identified; loss and impervious area. The directly connected impervious area was determined through the calibration process and confirmed against traditional measuring methods. The ARBM dynamic loss model parameters were also determined through the calibration process.

A two-stage calibration approach was adopted in this research. The first stage involved calibrating the loss parameters to small rainfall events that likely resulted in runoff from impervious areas only. These rainfall events were typically small and were preceded by long periods of minimal rain, resulting in a relatively dry catchment. The second stage involved calibrating the loss parameters to larger rainfall events that likely resulted in runoff from both impervious and pervious areas. These rainfall events were typically larger and were preceded by periods of rainfall, resulting in a relatively wet catchment.

A broad range of historical events were used in the calibration process, with peak flows as low as 9 m³/s and as high as 600 m³/s. The model offered a satisfactory fit (Nash Sutcliffe Efficiency > 0.5) for nine of the 11 selected storm events, with seven events exceeding a Nash Sutcliffe Efficiency of 0.75.

This level of calibration and thorough evaluation of the runoff from the catchment highlighted that the continuous simulation model offered a more complete understanding of the hydrological processes. The ability of the continuous simulation model to replicate historical stream flow from small rainfall events suggested that the model was reflecting the challenging impervious area conditions experienced by an urban catchment. It showed that adopting a total impervious fraction would have significantly overestimated the runoff in small events as the total impervious area was significantly larger than the directly connected impervious area.

The ability of the continuous simulation hydrologic model to replicate historical stream flow from larger rainfall events suggested that the dynamic loss model was reflecting the impervious and pervious components of the catchment. Based on the research undertaken, it was concluded that continuous simulation hydrologic models do offer a more complete understanding of hydrological processes and they can replicate historical stream flows.

7.3.2 Research Question 2: Can the uncertainty in the peak flows be determined using continuous simulation, and how do the results compare to other approaches, including the design event method?

Journal paper 2 of this research developed a simplified rainfall disaggregation model to allow 100 years of sub-daily (6 minute) rainfall data to be simulated within the calibrated continuous simulation model. The simplified rainfall disaggregation model built on the method of fragments, however the constraint of seasonality commonly used, was removed to allow a greater number of storms to be used as fragments. By simulating the rainfall disaggregation model 20 times, it was possible to produce 20 unique sub-daily 100-year rainfall sequences. This was a significant change in methodology for the method of fragments as it allowed a larger number of unique storms.

Simulating the 20 unique sub-daily rainfall sequences within the continuous simulation hydrologic model resulted in 20 unique series of streamflow at the outlet

of the catchment for a 100-year period. A flood frequency analysis of the streamflow allowed the estimation of peak flows for a range of annual exceedance probabilities. Performing the flood frequency analysis on all 20 iterations allowed the minimum, median and maximum peak flow for each annual exceedance probability to be determined. It was considered that the median would approximate the peak flow for a given annual exceedance probability, while the minimum and maximum represented the uncertainty bounds.

It was possible to compare the median continuous simulation peak flow with three other methods previously used to estimate the peak flow at the outlet of the catchment; flood frequency analysis of the stream gauge, the design event method (GCFRM study) and the Rational Monte Carlo method (Brodie, 2013). Undertaking this comparison identified that the median continuous simulation peak flow correlated well with the design event method for all annual exceedance probabilities up to the one in 100. These results prove that the continuous simulation hydrologic model can estimate the peak flow from a catchment with uncertainty, and the results correlate well with other approach, including the design event method.

7.3.2 Research Question 3: What impact does hydrologic uncertainty have on the estimation of flood extents?

Journal paper 3 of this research provided an alternate approach to firstly deriving design hydrographs whereby hydrographs are extracted from a continuous simulation hydrologic model. The previously modelled 20 iterations of continuous flow allowed for the extraction of hydrographs that aligned with the peak flow estimated via the flood frequency analysis. Hydrographs from each of the 20 iterations were subsequently simulated in a 2D hydraulic model and it was then possible to estimate the flood extent for all 20 iterations, therefore gaining an understanding of the range or uncertainty of the results.

The detailed hydraulic mapping showed that the range of results were significant, in particular for areas near the confluence of East and West Creeks. It was

also noticeable that the design event method, when compared to the range of results determined in this research, appeared to correlate best with the minimum iteration, suggesting there is likely a significant level of uncertainty in the design event estimation.

In addition to the flood extent, the time to peak is also a key consideration in disaster planning and management. This research highlights that there is significant uncertainty in the time to peak, with a range of 30 minutes to 230 minutes found at the confluence of East and West Creeks. While the time to peak is commonly quoted, this research highlights the need to understand the time to first inundation, as it is likely more influential in disaster management decisions. By determining the flow rate after the first property was impacted, it is possible to estimate the time to first inundation, which is significantly lower than the time to peak, with the results ranging from 10 minutes and 130 minutes.

This journal paper highlighted the impact hydrologic uncertainty has on flood extents within the Gowrie Creek catchment, as well as other key hydraulic parameters such as time to peak and time to first inundation.

7.4 Contribution to Knowledge

This research contributed significantly to the understanding of hydrologic uncertainty and the impact it has on hydraulic mapping. A small catalogue of documented ARBM parameters was able to be increased through the calibration of ARBM parameters within a continuous simulation hydrologic model. This allows practitioners to consider whether these parameters could also be used in the catchment of interest, and at least offers an alternative to previously documented parameters, which were found to overestimate the peak flow in the historical events assessed. The impact different types of impervious area has on relatively small flows was also evaluated, and showed total impervious area would significantly overestimate these flows.

Secondly, the simplified method of fragments used in the disaggregation of daily rainfall to sub-daily rainfall offers an alternate approach to the method of fragments currently documented in literature. By excluding seasonality, a methodology was provided that resulted in a greater diversity of peak flow hydrographs and subsequently a greater understanding of the likely uncertainty in peak flow estimation. It was shown that the use of the peaks over threshold method resulted in a tighter range of possible results, suggesting it should be used instead of the traditional annual maximum series. By reviewing the impact of time periods used in the flood frequency analysis, the likely significant risk in undertaking a flood frequency analysis on gauged flows was highlighted, even if the typical minimum of 50 years was available.

Finally, simulating the range of peak flow hydrographs within a 2D hydraulic model showed hydrologic uncertainty has a significant impact on flood mapping. This finding was significant and contributes to industry knowledge by highlighting that uncertainty that likely exists in currently published flood mapping, and also highlights that the typically used design event method may be underestimating the flood extents within a catchment. It also showed that key disaster management parameters, including time to peak and time to first inundation, have significant uncertainty that needs to be evaluated.

The outcomes of this research provide new insight into an alternate methodology that should be considered when undertaking hydrologic and hydraulic studies in other urban catchments.

7.5 Future research directions

This research should provide the basis to further explore and utilise continuous simulation hydrologic models to understand the uncertainty in flood mapping within urban catchments. The future research directions resulting from this research are anticipated to include:

- 1) undertaking a similar assessment across urban catchment to evaluate and assess the variability of the ARBM parameters to determine their transferability between catchments. This is important as it will broaden the ability of the ARBM parameters to be used in practice, and in turn allow the use of continuous simulation hydrologic modelling in more catchments. Adopting this approach offers a more complete understanding of the hydrologic processes within a catchment and allows for a better understanding of uncertainty.
- 2) growing a catalogue of ARBM parameters to allow practitioners an alternative to the IL/CL loss model. It should be noted that the ARBM, while developed in Australia, is not limited to Australian applications. In this research it was shown that adopting the ARBM parameters currently documented in literature resulted in a significant overestimation of peak flow. This confirmed that the ARBM parameters are likely to vary geographically, and therefore growing a catalogue of parameters will allow their use in locations where model calibration is not possible.
- 3) reviewing existing flood maps within other urban catchments to understand how uncertainty is being considered. As this research showed the hydraulic impact of hydrologic uncertainty is significant, understanding how (if at all) uncertainty has been considered in flood mapping in other urban areas is critical to determining the flood resilience of the community. This review would be valuable irrespective of the hydrologic modelling approach (ie. continuous simulation vs design event method) or modelling platform.

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