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Direct rainfall, runoff-routing and FFA in an urban setting - what can we trust?

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ABSTRACT

Direct rainfall is often a controversial approach to hydrologic determination, particularly where calibration is not possible. The effects of human bias and data precision have potential to propagate uncertainty to sensitive areas. To address these concerns, we chose to implement a combination of artificial intelligence (AI) and rigorous calibration and validation to forge a solution for the Bundaberg Township.

The township itself is characteristically flat and highly impervious with multiple locations of cross-catchment connectivity – above and below ground. Due to these complexities, a direct rainfall model (TUFLOW SGS) was developed alongside a detailed (900+ subcatchments) XP-RAFTS semi-distributed model for hydrologic determination.

AI was used to delineate features such as building extents, roads and vegetation with high precision with minimal bias at a whole-of-catchment scale. Critically, the project team developed a novel approach that uses x-ray vision (literally) and point cloud data science to dependably estimate vegetation density below the canopy. For each feature delineated using AI, a fraction impervious was also assigned and used to assign a precise value for each XP-RAFTS subcatchment and TUFLOW grid cell.

Both hydrologic and hydraulic models were separately calibrated to gauged hydrographs for two significant historic events, with the TUFLOW model also being compared to recorded peak flood heights at almost 100 locations across the township. Results (hydrograph shape, volume and peak) across other key locations were then compared to quantify correlation and divergence. Finally, Australian Rainfall and Runoff 2019 (ARR19) flood quantiles for each method were plotted against Flood Frequency Analysis (FFA) to clearly quantify uncertainty using either approach.

This paper will discuss the methods and new technologies used to develop each model, achieve a defendable calibration to two historic events and the comparison of results between methods. It will also share near-future opportunities for the broader industry regarding continuous improvement of urban hydrologic and hydraulic modelling practice.

CONTEXT

Modelling flood risk in urban environments is complex – modelling approaches vary, and data often limits what can be achieved. Beyond limitations, the effects of human bias can also propagate uncertainty in sensitive areas that demand confidence. In the case of Bundaberg's Overland Flow Path Study, traditional approaches weren't quite enough.

The Bundaberg landscape is known for its gentle overland gradients and clayey soils; together these result in a large overland flood footprint in response to frequent rain events. Urban development since the mid-late 20th century has seen most creek tributaries 'upgraded' to concrete in efforts to maximise conveyance and developable area. Most urban catchments demonstrate some degree of cross-connectivity, whether through surface or subsurface drainage.

In recent decades, Bundaberg's built environment has seen:

- Increasing fraction impervious due to driveways, sealed shoulders and urban densification.
- Many high-set Queenslanders built-in underneath.
- A significantly larger portion of runoff captured and conveyed by subsurface systems.

Consequently, the Township's expsoure to flash flooding has become increasingly apparent which was highlighted through the Bundaberg Regional Council (BRC) Stormwater Management Strategy (SMS) (AECOM 2020).

BRC recognised an immediate need to understand flash flood behaviour within overland flow paths and use this information to effectively manage risk moving forward. To do this, BRC partnered with AECOM to commission a city-wide overland flow path model. Whilst the need for a direct rainfall approach was anticipated, it would need to be thoroughly justified and defended before the region placed confidence in its adoption. Inherent challenges of the past would need to be overcome by harnessing new approaches before we know what can be trusted.

OBJECTIVES

The objectives of this paper are to:

- Discuss the specific approach adopted, particularly where these extend beyond traditional practice.
- Compare merits and limitations of each approach.
- Share learnings and opportunities with the wider industry.

APPROACH

The project team adopted a 3-phased approach for delivery with Phases 1 and 2 discussed in this paper. Phase 1 focused on collecting, reviewing and preparing data. Phase 2 used the data prepared in Phase 1 to develop an FFA, hydrologic and hydraulic models to predict baseline flood behaviour within the Bundaberg Township. The overarching approach is shown in Figure 1.

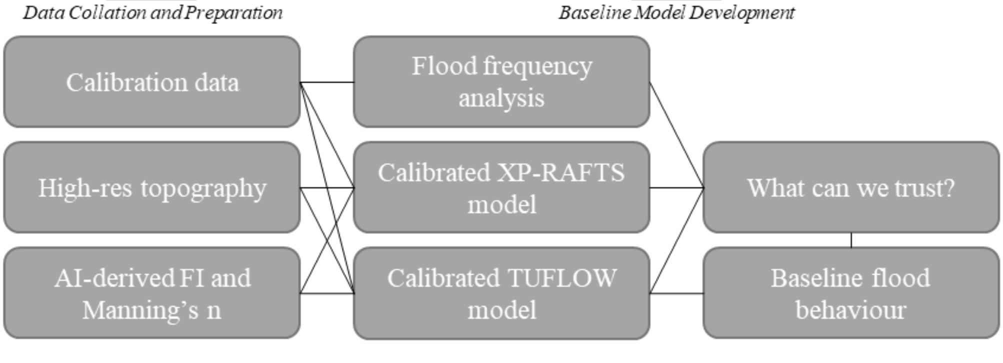

Figure 1. Technical Approach

TECHNICAL ACTIVITIES

Phase 1: Calibration Data

Phase 1 was set in place to establish an understanding of the data available and value which could be derived from it. Aspects of Phase 1 particularly relevant to this paper include:

Review of available rainfall, streamflow and calibration data. Pluviographic rainfall data was retrieved from two public and one private rainfall guages (all of which are calibrated). Two streamflow stations were identified, each covering a different period in time. Surveyed flood levels and extents were also provided by BRC at four locations within the township for the Oct 2017 event.

Analysis of the available data identified two events which would serve as calibration events:

1. Feb 1992 – a single peak flash flood event as a result of 265mm of rainfall over 20hrs. This event was captured by one pluviogprahic rainfall station and one streamflow station.
2. Oct 2017 – a triple peak flash flood event as a result of 288mm of rainfall over 10 hrs. This event was captured by three pluviogprahic rainfall stations and one streamflow station.

Rainfall and streamflow characteristics of each event are presented in Figure 2.

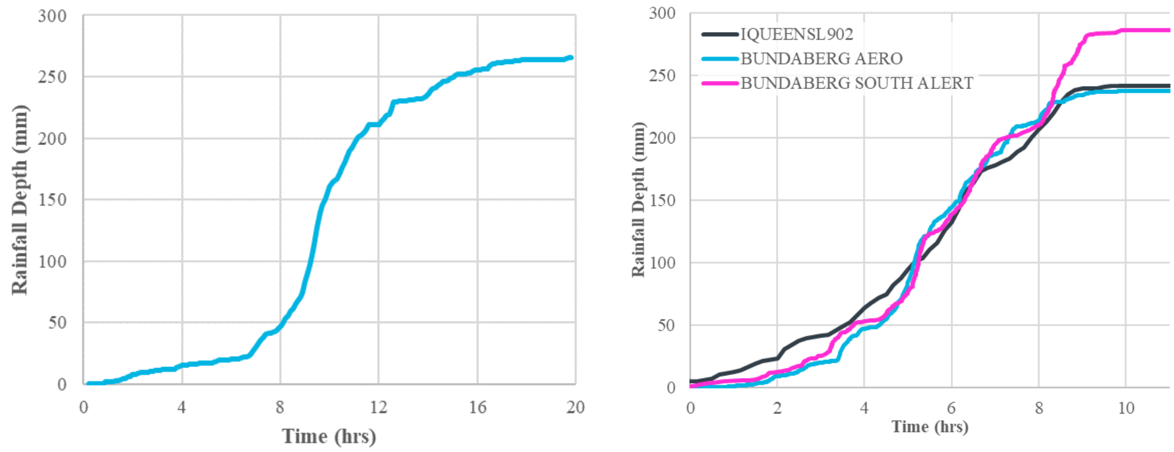

Figure 2. Calibration Event Rainfall Patterns (left – Feb 1992, right – Oct 2017)

The limited availability of calibration data (outside rainfall and streamflow stations) was highlighted as a risk to the study outcomes, as the model covered a large area (70km^2) and multiple catchments. To increase the volume of calibration data, approximately 300 community enquiries during the Oct 2017 were analysed for indications as to flood behaviour. This process identified:

1. 10 additional opportunities to retrieve surveyed heights and extents, 3 of which were able to be captured by BRC's registered surveyor.
2. 36 locations where a flood height could be estimated from timestamped, georeferenced photographs during and following the event. These locations were typically estimated from debris and water level marks using aerial imagery and LiDAR.
3. 38 points of anecdotal evidence where predicted flood behaviour could be checked qualitatively.

The distribution of the final Oct 2017 calibration database is presented in Figure 3.

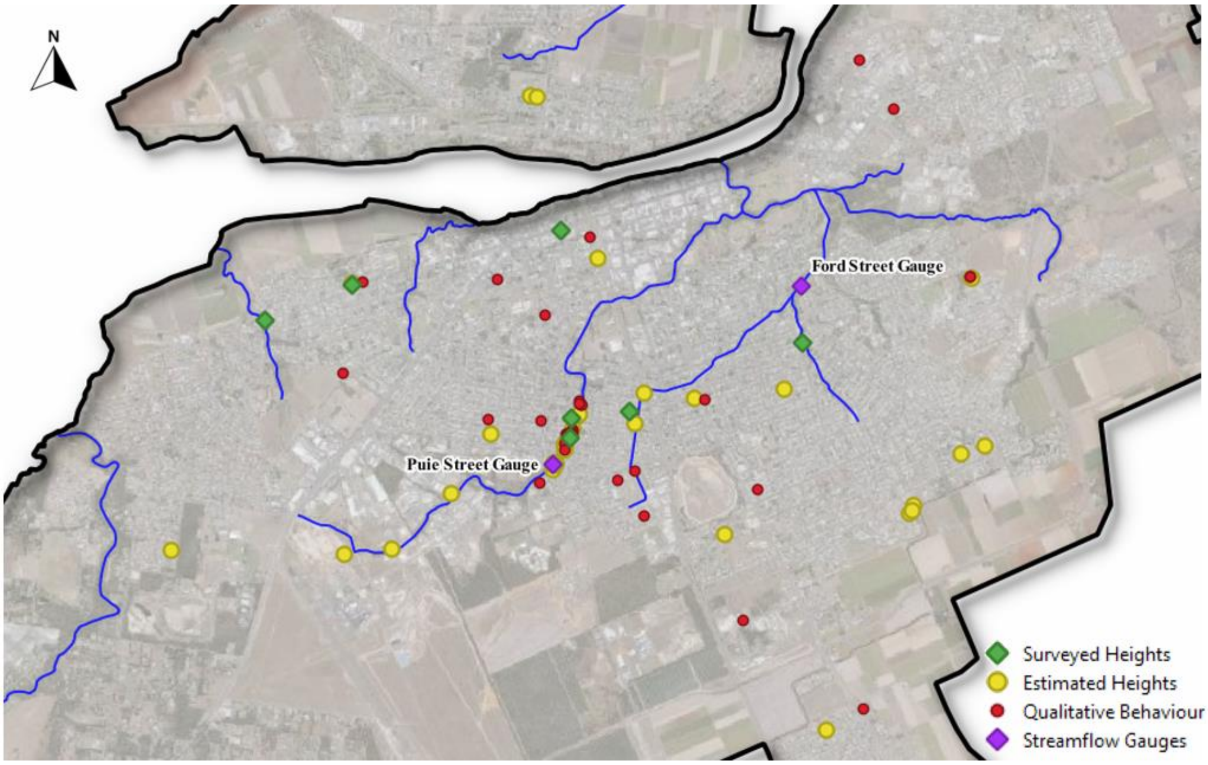

Figure 3. Oct 2017 Calibration Database

Phase 1: High-Res Topography

Prior to project commencement, BRC had surveyed major concrete channels throughout the study area. The regional 1m LiDAR DEM dataset was compared against available survey which revealed that flowpaths with a width of 2m of less were poorly represented in the 1m DEM. To overcome this challenge at the Township scale, the LiDAR point cloud was manipulated to reproduce a 0.5m TIN. A typical comparison between survey, 1m LiDAR DEM and 0.5m LiDAR DEM is presented in Figure 4. It can be seen that the 0.5m DEM better represents channel geometry.

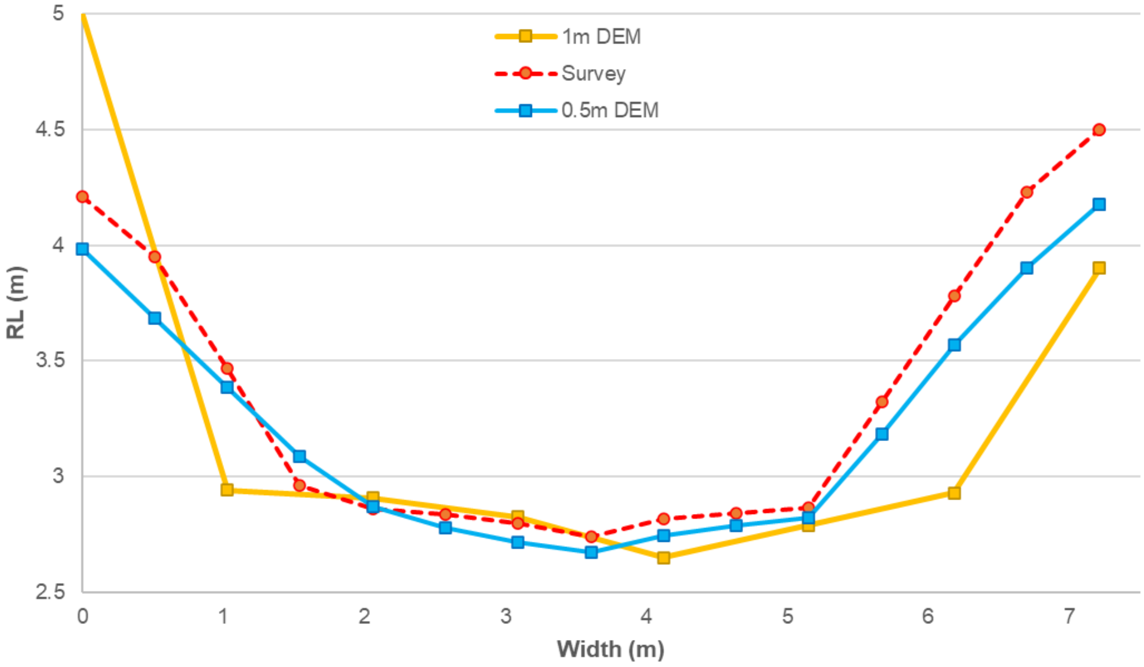

Figure 4. Topographic Dataset Comparison

Phase 1: AI-Derived Fraction Impervious and Manning’s n

A high-precision landuse database across the Bundaberg Township was constructed using AI and remote sensing. A Random Forest algorithm (supervised machine learning) was trained to interpret aerial imagery and topographic information to accurately define ground features (e.g. roads, buildings, vegetation and the like) at a 1m resolution.

An innovative approach was applied to better estimate vegetation density close to the ground where water flows. The logic behind the new approach drew on an intrinsic understanding of multi-return point cloud data. LiDAR is able to penetrate all but the densest of tree canopies and will return a number of locations throughout the vertical plane. For standalone trees, almost the full tree structure can be appreciated when viewing the LAS point cloud in a 3D workspace. Similarly, a dense understory will show a maze of points as they intersect low-profile branches and shrubs (see Figure 5).

To make best use of this valuable information, point cloud data science was employed to compare the quantity of low-lying (i.e. within 2m above ground) vegetation points against ground points in a specified area. Where most points in the point cloud profile were vegetation, it could be assumed the vegetation was medium to high density. Where most points in the area were ground, it could be assumed that the vegetation was low density or predominantly open space (which was the case for isolated trees with no underlying vegetation).

This landuse database was then used to derive a fraction impervious database, where each landuse class was assigned an appropriate % impervious (e.g. open space = 0%, concrete = 100%) and used to inform the XP-RAFTS and TUFLOW models. A depth-varying Manning’s n was then applied to each landuse class, taking into account the relative vegetation density, and used to inform materials files in the TUFLOW model. The final layers are presented in Figure 8.

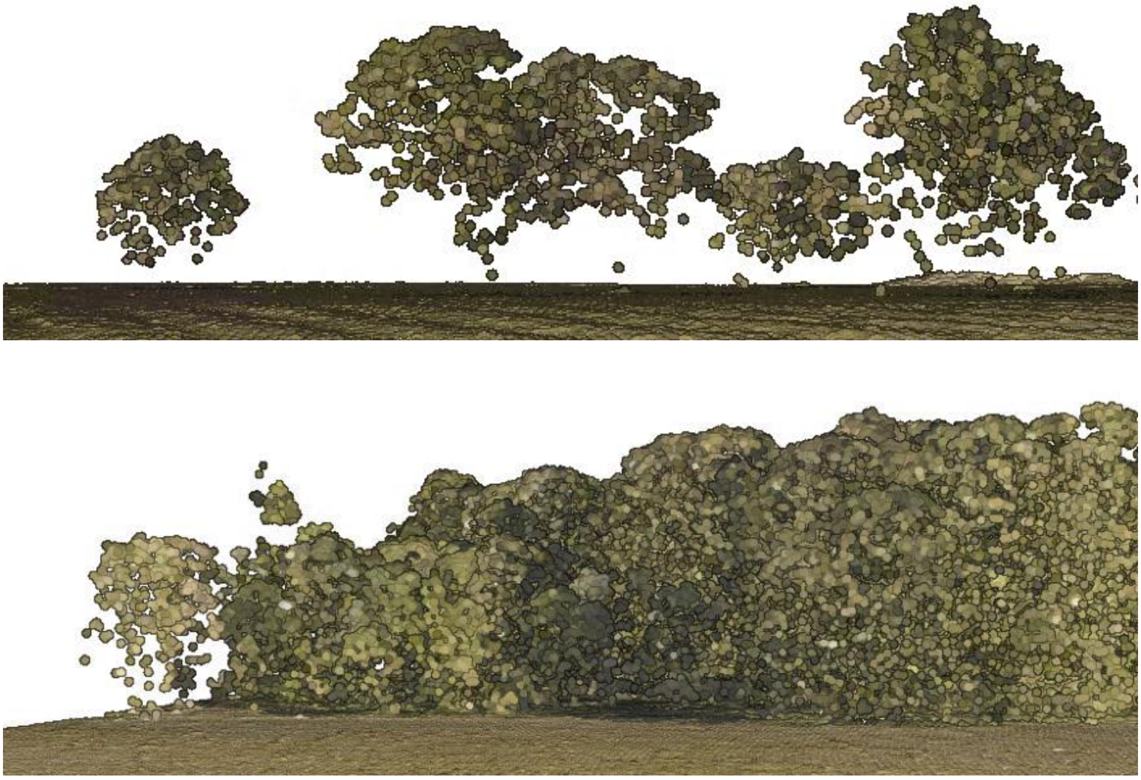

Figure 5. Point cloud data for standalone trees (top) and densely vegetated areas (bottom)

Phase 2: Hydrologic Model Calibration

An XP-RAFTS model was developed across the project extent with more than 900 subcatchments delineated to capture the level of detail required for the project. Subcatchments were typically in the order of 8ha in size and adopted a Muskingum-Cunge routing approach. Sensitivity testing of a simple lagging approach produced a poorly shaped hydrograph that was unable to be calibrated to gauged records. Fraction impervious and Manning's 'n' roughness were estimated using the AI-derived landuse database. The subcatchment layout and associated fraction impervious is shown in Figure 6.

The model was calibrated to the two historic events, with results of the calibration process shown in Figure 7. Manning's 'n' parameters were varied within ±15% of typical values to achieve a reasonable fit to peak, shape and volume at the Puie Street Gauge and Ford Street Gauge.

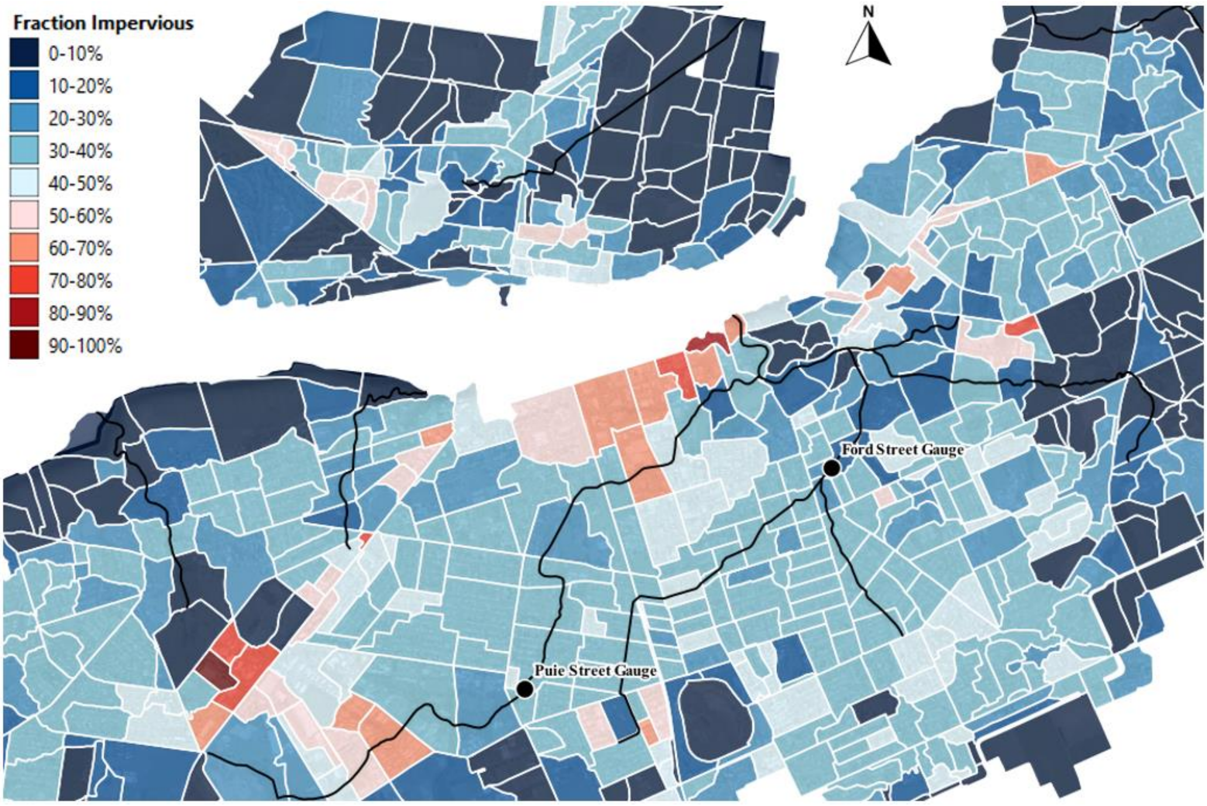

Figure 6. Subcatchment Layout and Fraction Impervious

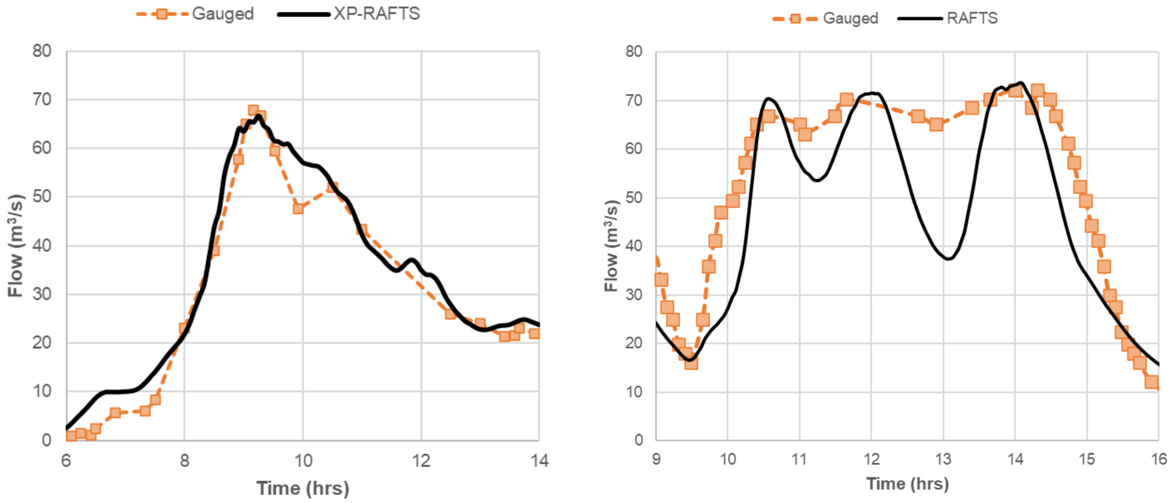

Figure 7. XP-RAFTS Calibration Results (left – Feb 1992 at the Puie Street Gauge, right – Oct 2017 at the Ford Street Gauge)

Phase 2: Hydraulic Model Calibration

A 1D/2D direct rainfall TUFLOW model was created to capture the 10,000ha township and utilised a model resolution convergence assessment, to demonstrate a 4m cell size with sub-grid sampling (SGS) was appropriate. Initially, a 1m SGS resolution was adopted, however, the connectivity of minor flow paths and artificial storage was identified as a limitation. Following generation of a 0.5m LiDAR TIN, a 0.5m SGS resolution was applied, facilitating better representation of channels smaller than 2m in width. Approximately 10,000 1D elements (including 375 mm diameter pipes and bigger) were included. Thousands of road crests were automatically enforced within the model surface in line with current best practice (TUFLOW 2021). Hydraulic roughness and material losses were applied using the 1m resolution landuse classifications (Figure 8).

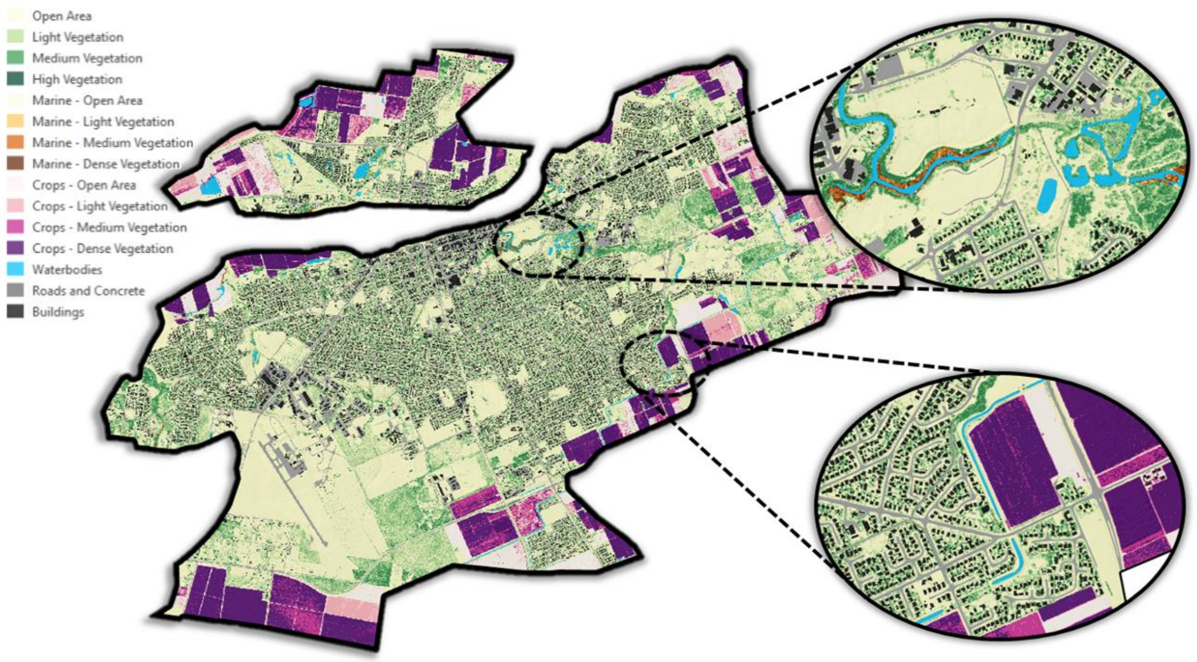

Figure 8. TUFLOW Model Hydraulic Roughness Distribution

Direct rainfall was applied for the Oct 2017 and Feb 1992 events using pluviographic rainfall data within the catchment (factoring in spatial variability where data permitted). Manning's 'n' values and major culvert loss parameters were adjusted to match peak flood heights, at 45 locations for the Oct 2017 event (including one streamflow gauge) and one location (the other streamflow gauge) for the Feb 1992 event. As seen in Figure 9, the Oct 2017 calibration achieved 100% of points within ±300mm and 85% within ±150mm. Comparison of discharge from the TUFLOW model at gauged locations to the XP-RAFTS and recorded hydrographs and are included in Figure 10. The comparison against gauge records again shows a reasonable fit to peak, shape and volume.

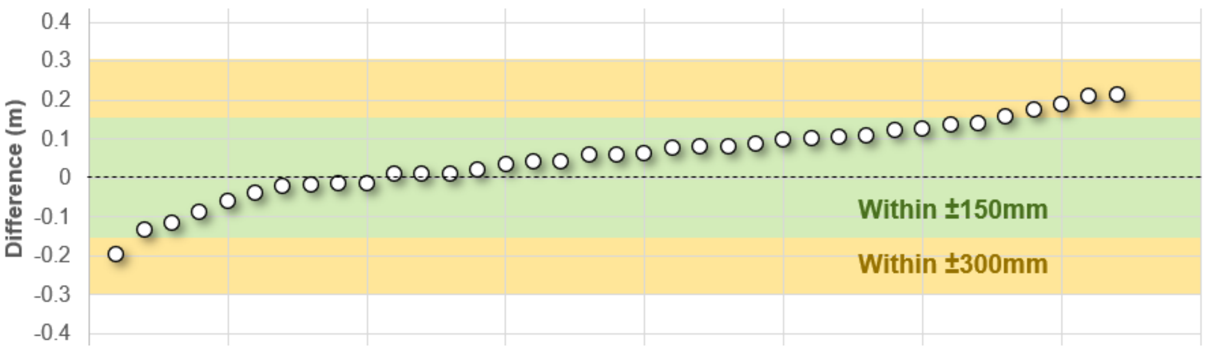

Figure 9. TUFLOW Oct 2017 Calibration Results

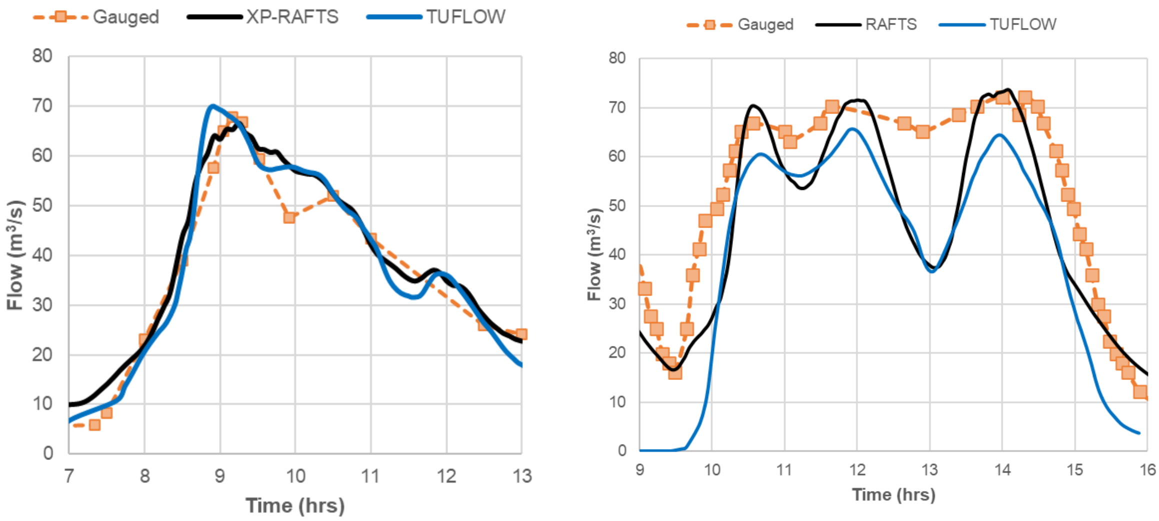

Figure 10. TUFLOW and XP-RAFTS Calibration Results (left – Feb 1992 at the Puie Street Gauge, right – Oct 2017 at the Ford Street Gauge)

Phase 2: Flood Frequency Analysis

A partial series was prepared for each of the streamflow gauging stations, noting that the periods of record were 14-years at the Puie Street gauge and 9-years at the Ford Street gauge. Whilst these durations of record are by no means reputable for a resoundingly confident FFA, they still serve as valuable comparisons. The FFA of best fit is plotted against modelled ARR19 quantiles in Figure 11.

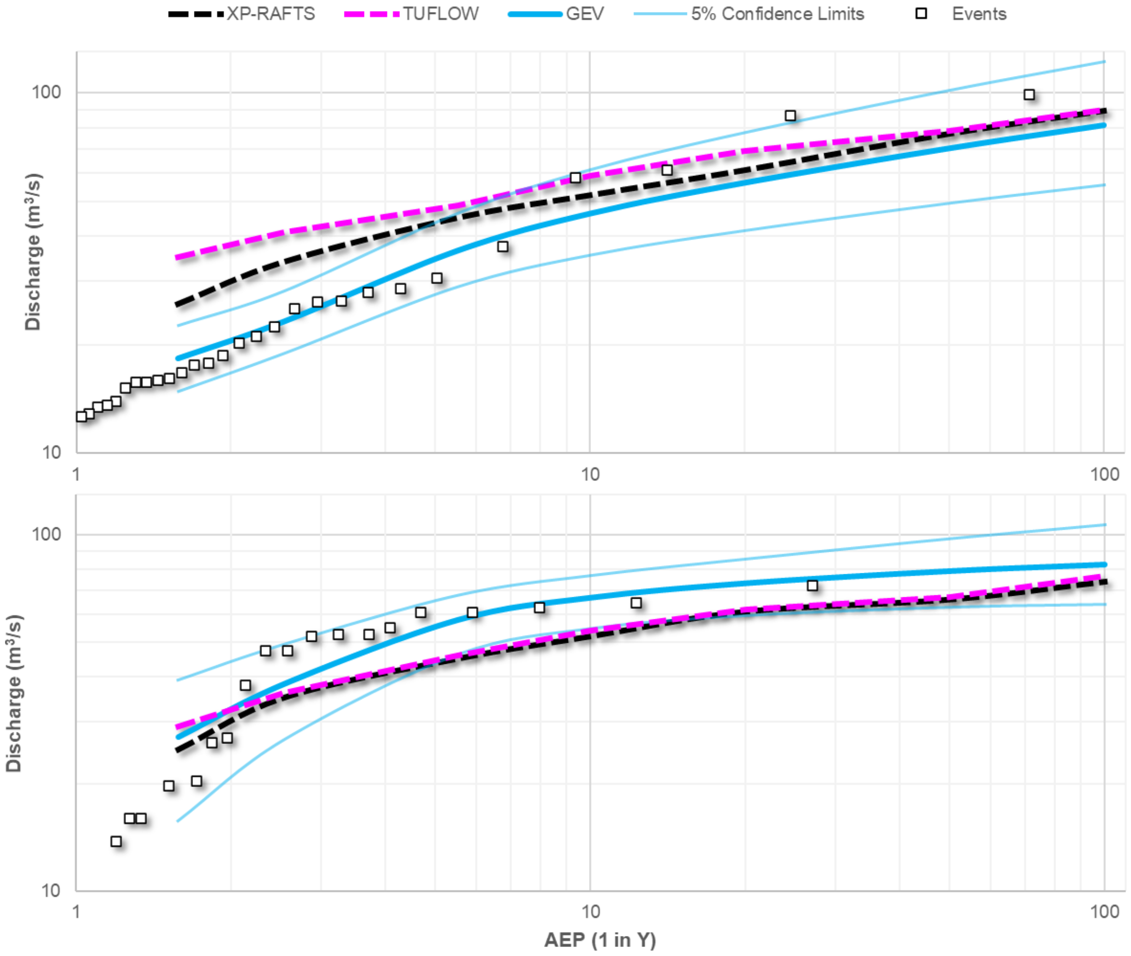

Figure 11. FFA vs Modelled ARR19 Quantiles (top – Puie Street Gauge, bottom – Ford Street Gauge)

WHAT CAN WE TRUST?

Figure 11 demonstrates that it is possible for runoff routing and direct rainfall approaches to converge in an urban setting. Predicted quantiles between XP-RAFTS and TUFLOW generally match within 3% at the Ford Street Gauge and within 10% at the Puie Street gauge (it is noted that conservative initial water level conditions adopted in the TUFLOW, but not adopted in the XP-RAFTS model contribute a portion of this discrepancy at the Puie Street gauge).

Observations regarding the comparison of XP-RAFTS and TUFLOW quantiles to FFA included:

- The quantile shape is generally similar, with convergence improving for rare events.
- The Ford Street gauge record captured several notable events within the previous decade which are expected to overestimate the frequency of a given flow.
- The Puie Street gauge record was captured before the diversion of a 140ha area from an adjoining catchment upstream of the gauge. Catchment diversion via surface or subsurface drainage is a surprisingly frequent occurrence which introduces non-stationarity in recorded data. Historic development and hints such as paleo ridge lines and geomoprhic instability should be investigated to inform data limitations.

Convergence between ARR19 quantiles for the modelling approaches was unforced and (we believe) achieved through:

1. Calibration to both frequent and rare historic flood events, ensuring parameters are appropriate for high and low stage flows.
2. Calibration to peak flood heights and extents at more than 40 locations throughout the Bundaberg township, which ensures model parameters and features are spatially appropriate for the range of flow paths and flood behaviour.
3. Precise, AI-derived fraction impervious (FI), which reduces uncertainty associated with traditional assumptions and approaches. Low density residential lots within Bundaberg showed significant variation in FI, with a mean value of 35% ±15% (1 standard deviation). Figure 12 demonstrates this variability in FI against lot size.

   QUDM recommends a FI between 40-75% for low density residential lots excluding roads (Table 4.5.1, QUDM 2017). Whilst this may be appropriate in some applications, only 24% of lots in the study area fell within this range. In contrast, Melbourne Water (2018) recommend a range of 10-40%, which is consistent with 76% of lots in the study area.

   Previous research with Moreton Bay Regional Council (MBRC) at Redcliffe highlighted a **10% change in fraction impervious resulted in a 20% change in peak flow and volume** (Maultby, Mosely 2021). The need for precise FI estimates in an urban setting must be appreciated given its typical influence on runoff. Traditional assumptions should be tested on a case-by-case basis to ensure calibration of other parameters (such as Manning's n) is not artificially skewed.
4. High-resolution topographic layers and 0.5m SGS coupled to a detailed 1D model. Modelled responsiveness and hydrograph shape was an important comparison between numerical methods and gauge results, highlighting the potential for a suitably detailed direct rainfall approach to model runoff behaviour in urban environs. Comparison of peak values alone may not be enough to demonstrate confidence, particularly in an urban setting.

Whilst a robust database and model calibration was achieved, there remained some surburbs with limited to no calibration data. How could confidence in the outcomes be established at these sites? Figure 13 compares TUFLOW and XP-RAFTS hydrographs at three separate locations for a given rainfall input. As can be appreciated, the modelled peaks and responsiveness is remarkably similar, with the total runoff volume predicted in TUFLOW within 7% of XP-RAFTS. Similarly, Tague (2001) confirms "the use of a non-grid-based method of partitioning is shown to be comparable to grid-based partitioning in terms of simulated soil moisture and runoff production".

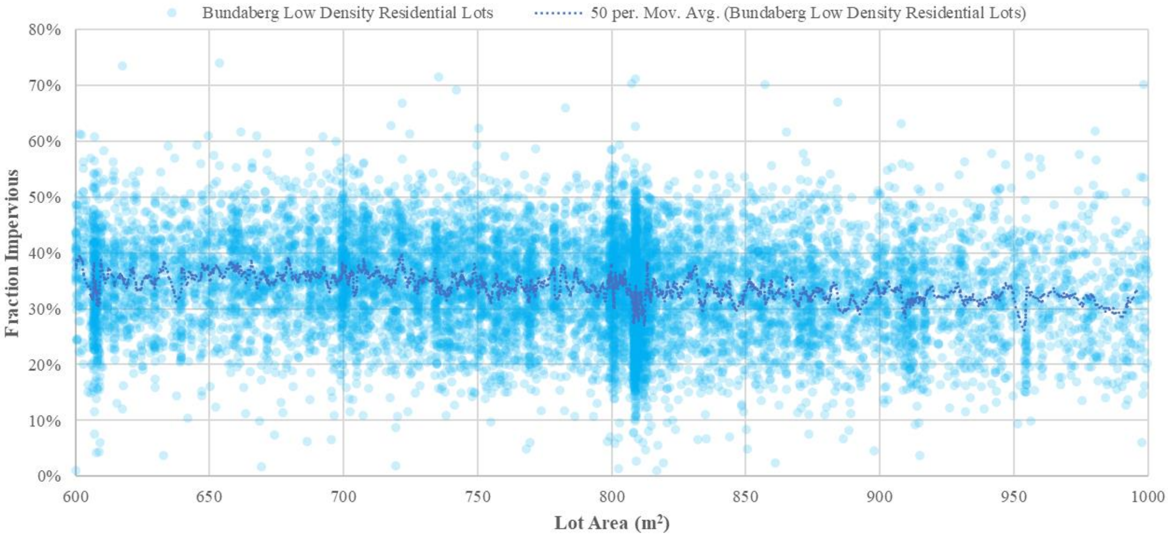

Figure 12. Low Density Residential Lot Fraction Impervious (Excluding Roads)

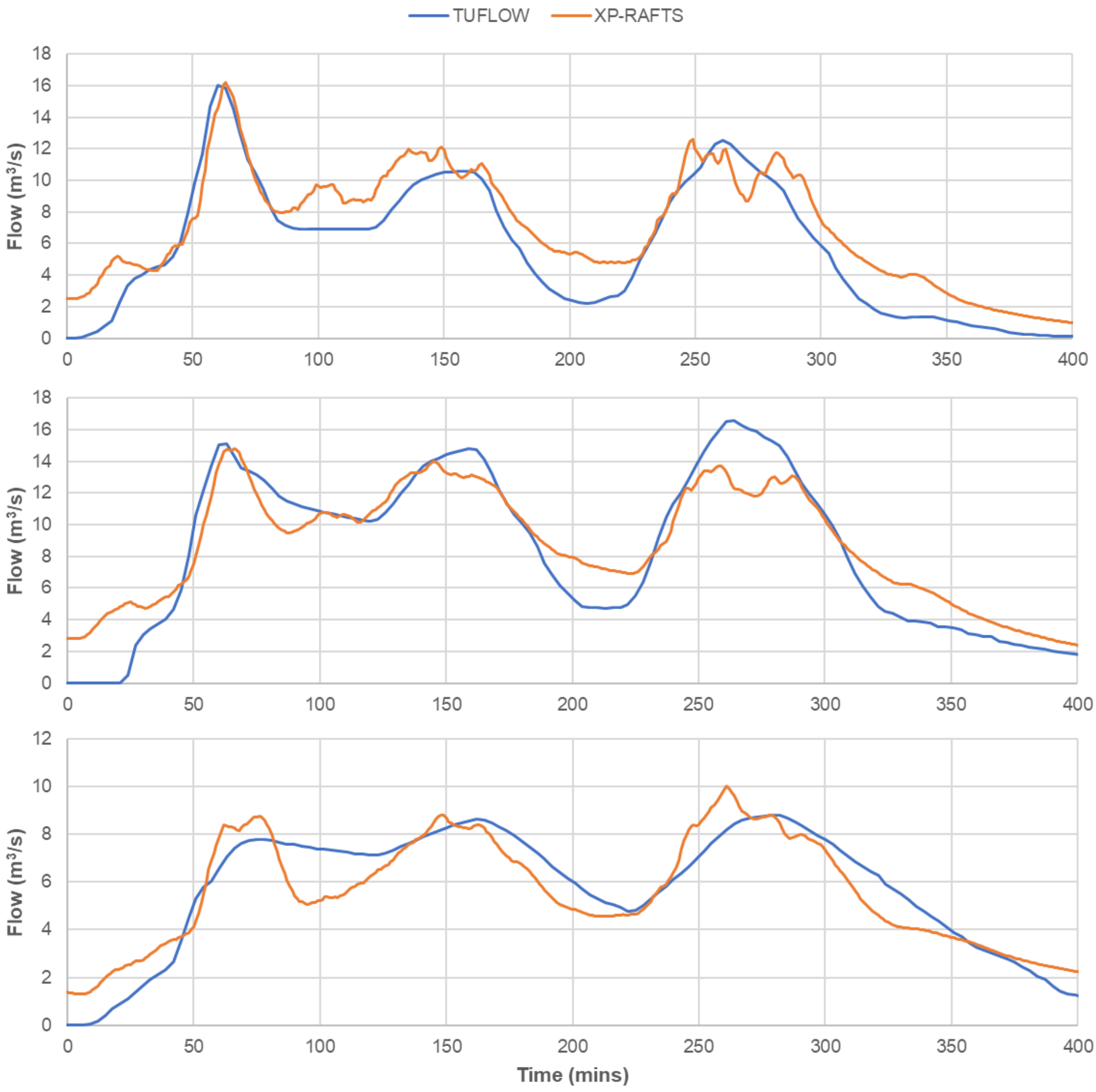

Figure 13. XP-RAFTS vs TUFLOW Validation at Low-Confidence Sites

CONCLUSIONS

So what can you trust? It all hinges on the data. No matter the method, data sets the limit for what we can defend and achieve. In this study, a specific focus was given to improving the availability, resolution and precision of underlying datasets. Efforts were focused on improving representation of minor overland flow paths, precision of fraction impervious and hydraulic roughness layers and availability of calibration data. Without these enhanced datasets we expect the modelling outcomes (for both XP-RAFTS and TUFLOW) would not have been possible. As Ball et al. (2019) note,

> *...greater detail in the representation of catchment physiography can only be expected to translate to greater accuracy of flood estimation results if this is accompanied by appropriate representation of hydrologic flood formation processes at the adopted special scale. (Chapter 6, ARR 2019)*

Direct rainfall can take the guesswork out of modelling poorly defined overland flow paths and surface-subsurface connectivity, particularly in complex urban settings. When done well, it can produce comparative outcomes to a traditional runoff routing approach. However, it can also increase modelling uncertainty when not given specialist attention (ARR 2019).

A direct rainfall approach in an urban setting makes sense where data is available, of suitable detail for model calibration and an independent method (such as runoff-routing) is used as validation in uncalibrated areas. An underlying runoff-routing model can also be used to refine selection of design storms, significantly reducing the computational effort required. Where data and time permit, direct rainfall is an advantegous approach in urban settings.

Where a run-off routing approach is proposed in an urban setting, we strongly recommend overland flow paths are informed by a high-level direct rainfall model. These results can then be used to support definition of subcatchment boundaries, ensuring enough detail is provided to capture key flow paths and cross-catchment connectivity.

Regardless of approach, the focus should be on data collection and preparation. Advancements in data quality and digital tools have framed a passageway for extracting new value from old data. Machine learning has the potential to apply human decision making capabilities at supermassive scale. Vegetation density can be quantitatively classified, removing human error and bias. Traditional assumptions can be tested and tailored to better represent local nuances. Hydrologic and hydraulic model base layers can be developed semi-automatically, allowing us to re-invest our valuable time towards the things that matter; things like calibration and validation.

Whilst models are invaluable tools, they're too often limited by the quality of their inputs. As George Fueschel coined, 'a computer just processes what it is given – garbage in, garbage out' (TechTarget, 2008). Whether we realise or not, our industry is rapidly advancing to make more with less. We're part of a 'quest for quality' and each have a distinct opportunity to create new value from data.

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BIOGRAPHY

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Jordan is the Water Resources Team Lead for AECOM Australia Pty Ltd in Rockhampton. Jordan brings collaborative delivery to complex water resources projects throughout Queensland. Beyond water his speciality lies in digital engineering, particularly Artificial Intelligence and GIS, for which he is consulted internationally. Jordan is passionate about connecting new and improved pathways with industry to deliver a better world for future generations.

Ben McMaster

Ben is the Water Infrastructure Sector Leader – Australia & New Zealand for AECOM Australia Pty Ltd. Ben brings his 15 years' experience to water projects and initiatives throughout Australia, with a core capability in hydrologic determination and strategy. As an industry leader, Ben is passionate about pairing early professionals with opportunities for digital advancement.