University of Southern Queensland

Faculty of Health, Engineering and Sciences

Effects of On-Site Detention Systems on Urban Drainage Catchments

A dissertation submitted by

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ABSTRACT

Urban development can have a detrimental effect on the natural water cycle. This can primarily be attributed to the changes urban development can have on stormwater drainage catchment features. These changes result in an increase in rainfall runoff volume and discharge rate, and stormwater management controls are used to try to decrease these impacts.

On-site detention (OSD) is a stormwater drainage control technique used to mitigate the impact of development or re-development on individual sites (Phillips, et al., 2015) (DEWS, 2013). Within parts of south east Queensland local governments require OSD systems to be designed using a site based analysis, without consideration of the entire drainage catchment. The purpose of this project is to investigate the catchment wide effects of implementing OSD systems, that have been designed using a site based approach, using a Direct Rainfall Method (DRM) two-dimensional (2D) hydraulic model.

The research was completed within an urban drainage catchment of Coomera, QLD in the City of Gold Coast (CoGC) region. Within this region OSD systems are typically developed using a site based one-dimensional (1D) modelling approach. Existing research and studies have shown that OSD systems need to be implemented throughout at least 20% of a catchment to have any positive impact, and that these systems have the potential to increase flooding problems if they are not designed properly particularly during events outside of the critical duration.

The catchment selected contained 6 OSD systems, which have all been built within the last 10 years. Each of these systems were designed using a site based 1D analysis, without consideration of any external or downstream catchments, as per the requirements of the CoGC. As part of this study, 2D DRM modelling was completed for pre-developed, post-developed and post-developed with OSD scenarios using TUFLOW. This was compared to a traditional lumped hydrograph TUFLOW method and a 1D XP-RAFTS model.

The results show that the OSD systems did not mitigate post development flows to within the pre-developed level for any of the modelled events, this was due to the existing storage within the pre-developed catchment attenuating flows. Peak flows were slightly reduced for most events, although some of the low average recurrence interval (ARI) events saw an increase in peak discharges as a result of the various OSD systems and the timing of their discharges.

Although peak flows were only slightly reduced, the OSD systems were effective at reducing local flood depths, with the 100-year ARI critical design storm event achieving a reduction of 50 mm across roads within the catchment.

As a result of implementing OSD systems throughout the catchment stormwater discharges and velocities were locally increased around the OSD outlets, which also resulted in significant increase in hazard. At other locations throughout the catchment, depths, velocity and hazard were reduced. It is important to note that it is common for OSD systems within the CoGC region to be designed using a site based analysis, and they are typically positioned at the lowest point of a site, which is often adjacent a road (unlike the subject catchment). The modelling showed increases of flooding hazard (depth velocity product) of up to 0.05 during the 100 year ARI critical event. Slight increases in depth velocity product have a large impact on the categorisation of hazard, and with large increases in hazard around the OSD outlets, particularly in large ARI events, it should be considered by local authorities and designers how best to manage this.

This research has highlighted that different modelling approaches (1D and 2D) produce vastly differing results when analysing or designing detention systems. This confirms the need for engineers and practitioners to remain aware of the constraints, strengths and weaknesses of each approach, and additionally confirms the need for further research into the differences between these techniques.

This research has shown that implementing OSD using a site based analysis is not always an effective approach. It has been shown that the catchment wide effects of multiple OSD systems can be unpredictable and hard to calculate and that a site based approach to stormwater management can cause varying (sometimes negative) impacts throughout an entire catchment. This has further highlighted the need for local government policy reform to allow for more accurate engineering techniques and to move away from these site based approaches.

Engineers and practitioners have multiple tools and techniques at their disposal, to constrain them to a site based approach has been shown to be ineffective, especially when so much data is readily available to accurately and cheaply analyse an entire drainage catchment.

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Certification of Dissertation

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

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GLOSSARY OF TERMS

1D Model	*One Dimensional Hydraulic Model*
2D Model	*Two Dimensional Hydraulic Model*
AEP	*Annual Exceedance Probability*
AHD	*Australian Height Datum*
ARI	*Average Recurrence Interval of a rainfall event - the average, or expected, value of the periods between exceedances of a given*
ARR	*Australian Rainfall and Runoff*
BoM	*Australian Bureau of Meteorology*
BMP	*Best management practice*
Brownfield Site	*Urban sites for potential building development that have had previous development on them.*
CoGC	*City of Gold Coast Council*
Cumec	*Cubic metre per second*
DEHP	*Department of Environment and Heritage Protection*
DEM	*Digital Elevation Model*
DEWS	*Department of Energy and Water Supply*
DNRW	*Department of Natural Resources and Water*
DRM	*Direct Rainfall Method, Rainfall on Grid*
DTM	*Digital terrain model*
Greenfield	*Previously undeveloped site*
ha	*Hectare*
HIA	*Hydraulic Impact Assessment*
IEAust	*The Institution of Engineers, Australia*
IFD	*Intensity-Frequency-Duration*
IPWEA	*Institute of Public Works Engineering Australia*
LiDAR	*Light Detection and Ranging aerial survey*
LPD	*Lawful point of discharge.*
m	*Metre*
m^2	*Square metre*
m^3/s	*Cubic metre per second*
min	*Minutes*
OSD	*On site detention*
QUDM	*Queensland Urban Drainage Manual*
RAFTS	*Runoff Analysis and Flow Training Simulator*
RORB	*Runoff Routing program*
SMP	*Stormwater management plan*

Stormwater Quantity Management	*The management of stormwater discharge rates and volumes*
WSUD	*Water Sensitive Urban Design*
XP-RAFTS	*Software package for dynamic modelling of stormwater and river system. It is used for link-node (1D) models*
XP-SWMM	*Software package for dynamic modelling of stormwater and river system. It is used for both link-node (1D) and spatially distributed*

CHAPTER 1 – INTRODUCTION

Urban development can have a detrimental effect on the natural water cycle. This can primarily be attributed to the changes urban development can have on stormwater drainage catchment features. The main changes are summarised as follows:

- Urban development increases impervious areas within a drainage catchment which results in lower infiltration characteristics;
- With the establishment of stormwater conveyance networks rainfall runoff is more rapidly concentrated to creeks and drainage paths; and
- Urban development can also effect the existing natural storage within drainage catchments (Ladson, 2015).

These changes to the natural drainage catchment features can result in an increase in rainfall runoff volume and discharge rate. Stormwater management controls are used to attempt to decrease the potential impacts from these increases.

Stormwater detention is a form of drainage control and can be defined as; storing rainfall runoff for short periods of time to reduce peak discharge rates, and releasing the stored volume at a controlled rate (Phillips, et al., 2015). In areas where there is limited room for implementation of regional stormwater detention systems On-Site Detention (OSD) can be used as a discharge or flood control technique to mitigate the impact of development or redevelopment on individual sites (Phillips, et al., 2015) (DEWS, 2013).

The majority of local governments in Australia have protocols and guidelines in place, which must be considered when planning or designing stormwater drainage systems. State and federal planning and design guidelines also exist. However, local council guidelines typically take precedence over all other guidelines, as Councils are responsible for approval of the type of urban development discussed throughout this report. The City of Gold Coast (CoGC, Council), is a local government located on the south eastern coast of Queensland, Australia. This report investigates the impact of OSD systems on a catchment wide scale within the CoGC region.

A review of the CoGC guidelines and policies have shown that when sizing OSD systems within the region, analysis should be done of stormwater discharge generated within the subject site only, excluding any external catchments that are not included as part of the development application, and further research has shown that this concept is common throughout most parts of Queensland, this is discussed in detail below.

These Council requirements do not necessarily deliver sound community benefits. This is reflected in the CoGC requirement, even on brownfield and infill sites, to demonstrate no increase in peak discharge at the property boundary with the stated objective of non-worsening of flood heights and peak runoff to the adjacent property owner, without assessing the any other contributing catchments.

This approach to stormwater management adopted under the development codes mentioned above, unnecessarily limits the analysis to the portion of land being the subject of a planning application, which results in a short sited analysis that could potentially result in ineffective infrastructure. Therefore, the intention of this project is to research the effectiveness of these OSD systems especially when used in the brown field setting.

1.1 PURPOSE

The purpose of this project is to investigate the catchment wide effects of implementing OSD systems on an urban drainage catchment.

1.2 OBJECTIVES

In order to achieve the above mentioned purpose statement, the following objectives have been adopted for this research project:

- Conduct a review of CoGC stormwater quantity management policies and compare these with other local governments, and other Australian guidelines;
- Investigate an urban drainage catchment within the CoGC region, collecting information on all appropriate parameters, including any drainage network information that is available;
- Analyse the impact of implementing OSD systems that are designed to achieve the requirements of the CoGC, within an urban drainage catchment where existing drainage infrastructure is already in place;
    - Complete modelling using a Direct Rainfall Method (DRM) 2D hydraulic model (defined below);
    - Comparison of different modelling techniques, and investigation into modelling discrepancies.

1.3 MODELLING DEFINITIONS

Hydraulic modelling is a numerical modelling process that is used to replicate flow and fluid transport processes in natural systems, and it can also be used as tool to analyse hydraulic structures and machines (ASCE, 2000). As discussed previously, the main objective of this research is to investigate the catchment wide impacts of OSD systems using a DRM 2D model, additional modelling techniques were also used for methodology comparison. The following section defines the hydraulic modelling concepts that will be discussed throughout this report.

1.3.1 1D HYDRAULIC MODELLING

One-Dimensional (1D) flow models are numerical models that are based on the Saint Venant equations for solving gradually varying unsteady flow in one horizontal dimension (McCowan, 2015). 1D models require flow path cross sections to be defined or detailed, these flow paths are usually in the form of creeks, floodplains, riverbanks and pipes etc. Stormwater discharge is routed through these defined flow paths downstream through the catchment. 1D models are typically computationally quick, and are well suited to catchments with well defined flow paths (McCowan, 2015). The disadvantage of a 1D model is the estimation of flow path is made by the user. As the majority of catchments are made up of several contributing flow paths 1D models are not always suitable.

1.3.2 2D HYDRAULIC MODELLING

Two-Dimensional (2D) flow models are numerical models that are based on depth-averaged equations of conservation of mass and momentum in two horizontal dimensions. This method is based on the assumption that velocity direction and magnitude is uniform over the depth of water, this assumption is usually appropriate for the shallow flow depths found in flood plains and urban settings (McCowan, 2015). In a 2D model, the model surface is defined as a Digital Elevation Model (DEM) and this surface is divided into cells (or a grid). Across the boundaries of each grid element velocities are calculated and therefore flow and depth of flow. One of the main advantages of a 2D model is; flows are automatically conveyed across a surface and flow paths do not have to be estimated. 2D models are computationally intensive and can result in long model run times, they are also dependant on the quality of the DEM data, and models can easily become unstable where surfaces are poorly defined (McCowan, 2015).

CHAPTER 2 – BACKGROUND

2.1 Previous Related Studies

This section of the report analyses existing studies that have been completed on the effects of stormwater quantity controls on urban drainage catchments.

Studies and research in the field of stormwater quantity management has reduced in the last few years, with a surge in interest in Water Sensitive Urban Design (WSUD) principles and stormwater quality treatments. Figure 2-1 and Figure 2-2 below show the results of a USQ Library search for stormwater quantity and quality texts, these results show that there is a clear inclination towards the research field of stormwater quality management.

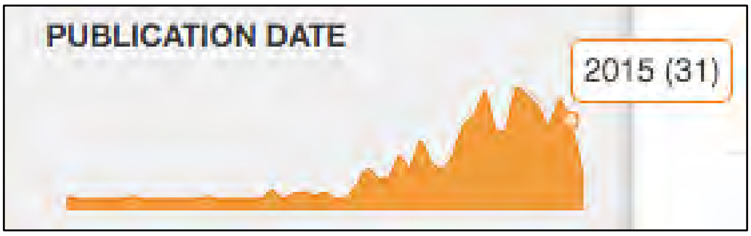

FIGURE 2-1 STORMWATER QUANTITY WRITINGS (USQ, 2016)

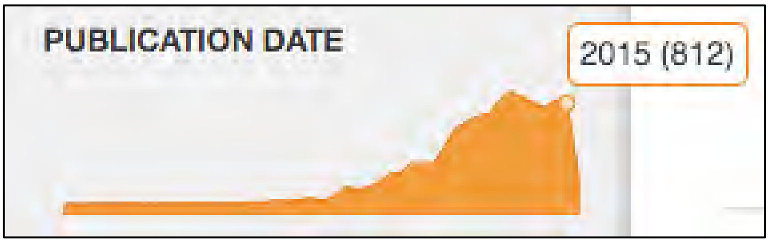

FIGURE 2-2 STORMWATER QUALITY WRITINGS (USQ, 2016)

Although a number of studies have been completed, it is widely acknowledged throughout the engineering industry that further research is required on the catchment wide effects of on-site detention systems, and this is outlined in the literature review below.

Previous methods of studying the impacts of implementing OSD solutions throughout urban drainage catchments utilised 1D link-node routing methods such as RAFTS (McPhail, et al., 1994). These types of catchment wide analysis typically yield varying results due to the differing features of drainage catchments, such as:

- Topography;
- Vegetation cover; and
- Rainfall Patterns; etc.

Therefore, the impact of OSD systems on catchment wide basis has typically been concluded to be site specific (Beecham, et al., 2005). This would suggest that a total catchment study is always required to properly assess the impacts of OSD systems.

These existing catchment wide studies show a trend in worsening of flood situations in events outside of the critical event (Beecham, et al., 2005). It is generally thought throughout the industry (and it is mentioned in QUDM) that detaining flows in the lower third of a drainage catchment should be avoided, due to the belief that delaying of downstream peak flows could cause the peak of the upstream flows to occur at the same time, which would result in higher peak flows and a worsening of flooding. Research has shown however that detaining of flows in the lower third of a catchment can be an effective form of drainage and flood control, this difference in behaviour is due to existing storage within the upper areas of the catchment (Beecham, et al., 2005). These unusual results further justify the requirement for catchment wide analysis when implementing any OSD system as each catchment presents individual constrains and features.

Beecham's study, *Modelling on-site detention on a catchment-wide basis,* showed that results can vary greatly depending upon how many OSD systems are implemented throughout the catchment. The study showed that when 9% of the catchment was re-development, and OSD measures were implemented within these re-developed areas, a reduction of only 2.4% of 100yr ARI peak discharges was achieved at the catchment outlet. A reduction of flood level of 0.5% was achieved for the 100yr ARI critical event, but an increase in flood level occurred for non critical events. The study also showed that if the catchment was re-developed up to 50%, and OSD was implemented throughout the catchment in this scenario, a reduction of peak discharge and flood depths of 30% could be achieved during the 100yr ARI, although an increase of flood level during non-critical events still occurred (Beecham, et al., 2005). These results suggest that for OSD to be an effective flood and discharge control technique at least 20% of the catchment needs to implement these systems, and even if this is achieved an increase in flood levels can still occur under certain circumstances. This shows that there is a need for further investigation into the impacts of these systems, particularly during regional flood events.

Studies have also been completed comparing OSD systems to regional detention systems, the OSD systems within these studies were implemented into each sub-catchment of a region (Sharman, 2002). These studies showed that regional detention systems were more efficient in required volume (as a percentage of catchment area) although the OSD systems were obviously more beneficial to alleviate local drainage problems immediately downstream of the control (Sharman, 2002). This study assumed ultimate development conditions and that each sub-catchment within the region has an OSD system. As will be discussed further in this report; the use of OSD systems in re-developed areas means that they will be implemented over time, in some circumstances it could be many years before an entire catchment is redeveloped (sometimes never), therefore as a regional flood control technique OSD would not be able to be compared to a regional detention solution. Although these studies show that OSD can be effective in reducing peak discharges within a drainage catchment, but as discussed above it is only so when a large portion of the catchment is being treated.

Further research into the benefits of distributed stormwater Best Management Practices (BMP's), such as detention basins, has found some benefits of controls that are well distributed throughout a catchment. (Loperfido, et al., 2014). As was the case with the research mentioned above (Sharman, 2002) it assumes that the detention storage required to mitigate the peak flows of the entire catchment is distributed throughout (Loperfido, et al., 2014). As discussed above, distribution of these systems achieves a more efficient reduction of peak flow in respect to storage volume, and again, this philosophy assumes that the entire catchment has implemented the solution.

In the case of re-development (or brownfield sites) councils typically employ the use of OSD systems to mitigate flooding and peak flows. As a result of this technique these solutions can only be implemented as each portion of a catchment is re-developed. The results of the above mentioned research show that OSD systems as a form of flood mitigation on the catchment scale is not suited for re-development scenarios, as it could potentially only be an effective solution once the entire catchment (or a large portion of it) is re-developed.

The latest issue of Australian Rainfall and Runoff acknowledges that catchment wide studies have been conducted at various scales throughout Australia (Phillips, et al., 2015). An example of a catchment based assessment was undertaken in the Fourth Edition of the OSD Handbook for the Upper Parramatta River Catchment (UPRCT, 2005). This handbook outlines the OSD requirements to be implemented on a lot scale within the catchment. The storage volume requirements and outlet configurations for the lot level OSD systems are a result of catchment wide calculations, which were completed using XP-RAFTS 1D modelling (1D and 2D modelling is discussed in detail below). The catchment wide modelling determined that an OSD storage volume of 455m^3/ha of development area was required with permissible discharges from both a low flow and high flow outlet

(UPRCT, 2005). This handbook is an example of a governing body implementing OSD systems that have been backed up by a catchment wide study, although alternative solutions (such as regional detention systems) have not been acknowledged, it can be assumed that OSD within this catchment was deemed to be the most suitable solution.

The site storage requirement of 455m^3/ha is considerably higher than the CoGC's experiential rule of thumb of 200m^3/ha, which would suggest there is a great need for catchment wide studies within the CoGC region. This high volume of site storage (455m^3/ha) also suggests that the simple approach of *non-worsening* of discharges for each individual development site was not enough to mitigate peak discharges or flooding on the catchment scale. The handbook states that "*This approach was used to determine the OSD parameters required to ensure no increase in flood peak flows under a plausible ultimate development scenario"* (UPRCT, 2005), which confirms that the site storage requirement was adopted as a catchment wide control, split between smaller areas, and not as a localised control. This study further justifies the requirements of a catchment wide analysis prior to implementing OSD measures throughout.

2.2 Policies and Guidelines

The following section of the report outlines the applicable policies and guidelines for urban development in regard to the management of stormwater quantity.

2.2.1 City of Gold Coast Policies

The Gold Coast City Plan (CoGC, 2016) makes reference to the *Guidelines for Stormwater Quantity Management (GCCC, 2013)* that are to be used in conjunction with the Queensland Urban Drainage Manual (QUDM) (DNRW, 2008) when designing and planning stormwater drainage controls for urban development within the region. When approached for verification on the location of the *Guidelines for Stormwater Quantity Management (GCCC, 2013)*, the CoGC informed that although these guidelines are referenced within the City Plan, they are currently in draft and not available for distribution outside of council.

Upon further consultation with CoGC officers it was established that the following guidelines are generally what is required of stormwater quantity management within the region (although they are not written in any document available to the public).

When assessing the need for of stormwater quantity controls, and during the design of these controls, only the local catchment is to be included in the calculations:

Pre and post-development peak flows are to be calculated assessing only the flows generated within the subject site, contributing sub-catchments external to the site are not to be included within the analysis. The design of any stormwater detention devices is to be completed to achieve a 'non-worsening' effect of site flows only, at the property boundary.

Non-worsening of site discharge is required:

As discussed above, a 'non-worsening' of site discharge is required. QUDM defines non-worsening as:

"discharge from a development will not create a worse situation for downstream property owners than that which existed prior to the development." (DEWS, 2013).

CoGC defines non-worsening as post development peak discharges not exceeding pre-development.

CoGC requires non-worsening of site discharges at the Lawful Point of Discharge (LPD). LPD is a point of discharge which is either under the control of a Local Authority or Statutory Authority, or at which discharge rights have been granted by registered easement in favour of the Local Authority or Statutory Authority.

As stated above CoGC considers a sites LPD as the point at which it leaves the site, therefore CoGC requires site peak flows to be mitigated to within pre-developed levels, with no consideration of the rest of the catchment. This concept is made further evident in the review of the number of Stormwater Management Plans within the CoGC region below.

The CoGC officers also made reference to the techniques that council uses to assess proposed stormwater quantity controls and calculations. The rational method is used as a comparison for hydraulic modelling and as a tool to check detention storage calculations. The CoGC also employ an experiential detention storage check of 200m^3 per hectare of development area on a greenfield site.

In some locations throughout the CoGC region, council officers also request for site flows to be mitigated to within pre-developed 2yr ARI levels. That is; post developed peak site flows up to the 100yr ARI must be detained to within pre-developed 2yr ARI levels. This is required to improve drainage problems in local networks.

2.2.2 Queensland Urban Drainage Manual

As discussed above, the CoGC City Plan refers to QUDM (2008) for guidelines on stormwater quantity management (CoGC, 2016) (DNRW, 2008).

Section 5.02 of QUDM discusses the potential problems associated with the design and implementation of stormwater quantity control devices in urban drainage catchments, and are summarised as follows (DNRW, 2008):

i. The creation of coincident flood peaks causing increased downstream flooding.
ii. Cumulative increases in flows downstream of several basins resulting from the overlapping of the extended falling limbs of the various outflow hydrographs.
iii. Increased potential for accelerated creek erosion downstream of the detention systems.
iv. Extended periods of inundation of the basin area especially during the more frequent flood events.
v. Potential salt intrusion of low-lying excavated basins.
vi. Safety risks associated with both the flooded basin and its outlet structure.

During the design of stormwater quantity control systems QUDM acknowledges that catchment wide analysis may not always be possible, and in an effort to simplify these design procedures for consultants, a simplified procedure was investigated (DNRW, 2008).

‘*Significant hydrologic modelling was carried out during the development of this edition of QUDM in order to establish a simple design procedure that would avoid the problems of overlapping discharge hydrographs; however, no procedure could be established.’* (DNRW, 2008)

In both QUDM (2008) and the updated provisional release of QUDM (DEWS, 2013), this simplified method is not established, and it is still acknowledged that a catchment wide analysis will not always be completed. In order to overcome the potential risks that arise from not completing catchment wide analysis when designing stormwater quantity controls, QUDM suggests that Water Sensitive Urban Design (WSUD) features, such as rainwater tanks or infiltration basins, can be used to reduce the potential for increased runoff volume (DEWS, 2013) (DNRW, 2008).

As discussed in Section 2.1 of this report, it has been made evident that catchment wide analysis should always be conducted when implementing any type of detention system.

For greenfield and infill developments where the design requirements of a stormwater quantity control system have not been determined from a total catchment study, QUDM recommends that sizing of these systems should be based on achieving the following minimum requirements (DNRW, 2008):

i. *No increase in flood levels on adjoining land where such an increase would cause damage to, or adversely affect either the "value" or "potential use" of the land.*
ii. *No increase in peak discharges immediately downstream of the development for a selected range of storm durations, for a selected range of ARIs up to the "Defined Flood Event".*

Technical Note 5.04.1:

- *Point (ii) above indicates that the peak discharge for each of the selected storm durations shall not increase even if that storm duration does not produce the highest peak discharge for the given ARI.*
- *It is recommended that the selected storm durations tested should include the 1-hour storm, 3-hour storm and a storm of duration at least three times the critical storm duration of the detention/retention basin.*

It should be noted that as is the case with any set of guidelines or recommendations, QUDM is open to interpretation. Point (ii) above could be interpreted as; no increase in site peak site discharges at the LPD, disregarding any other contributing upstream catchments. The recommendation could also be interpreted as; there should be no increase in total peak discharge at the LPD (which would include all contributing catchments). This difference in interpretation was made evident from advice given by CoGC officers as discussed above.

It can be concluded that there is an indication of potential risk in the implementation of OSD systems within urban drainage catchments, and that further investigation into these risks and potential impacts of these systems is required.

QUDM also discusses the techniques involved in the design of detention and retention systems. It recommends that the final sizing of these system be completed using computer routing models. OSD design requirements will be discussed in detail below.

2.2.3 AUSTRALIAN RAINFALL AND RUNOFF

The Australian Rainfall and Runoff (ARR) is a set of guidelines for flood estimation. These guidelines are greatly detailed and contain procedures and techniques for all types of flooding and drainage design, including urban development.

The first edition of ARR was released in 1958, and has undergone a number of revisions since. ARR is currently under revision (draft issue available at the time of completing this report), this latest revision is a result of ongoing projects and studies completed to refine flooding estimation (Ball, et al., 2015). The latest issue of *Book 9 – Runoff in Urban Areas* has undergone some major changes, including discussion on the limitations of the Rational method and the changes in approach necessary for consideration of volume-based problems rather than peak flow based problems (Ball, et al., 2015).

Historically the stormwater management of urban development was focussed on peak flow control. As discussed above, state and local guidelines require the mitigation of post developed peak flows to within the pre-developed level, typically using detention structures (Coombes & Roso, 2015).

ARR Book 9 discusses the current methodologies being employed for the mitigation of peak flows, and that a typical process includes the mitigation of site flows without consideration of the entire catchment, (as shown in CoGC guidelines and QUDM), although ARR goes on to say:

"*…if the peak discharge is the only aspect of flood behaviour that is managed, there is a likelihood that other characteristics of the changed hydrologic response, such as peak timing and flow duration, will not be adequately addressed."* (Coombes & Roso, 2015)

The new ARR guidelines also require the design of OSD systems to be completed based on a catchment wide assessment (although design techniques if such an assessment is not possible have also been included). Design of OSD systems as outlined in ARR will be discussed further below.

2.3 OSD DESIGN

As stated above the design and detail of OSD systems in Queensland is to be done in accordance with QUDM. The updated ARR also outlines techniques on the design of OSD systems. Sizing of the systems is to be completed with the aid of hydrological and hydraulic computer modelling (DNRW, 2008). The modelling process for determining the required detention storage volume and outlet configuration will be discussed in detail below.

Typically, an OSD system consists of a low flow outlet and a highflow weir, these outlets are designed to restrict outflows during a range of storm event. Storage volume is provided in the form of tanks or basins to temporarily store the excess water from the restriction of flows. Figure 2-3 below shows a typical OSD system with an outlet designed to throttle different storm events to within the pre-developed level.

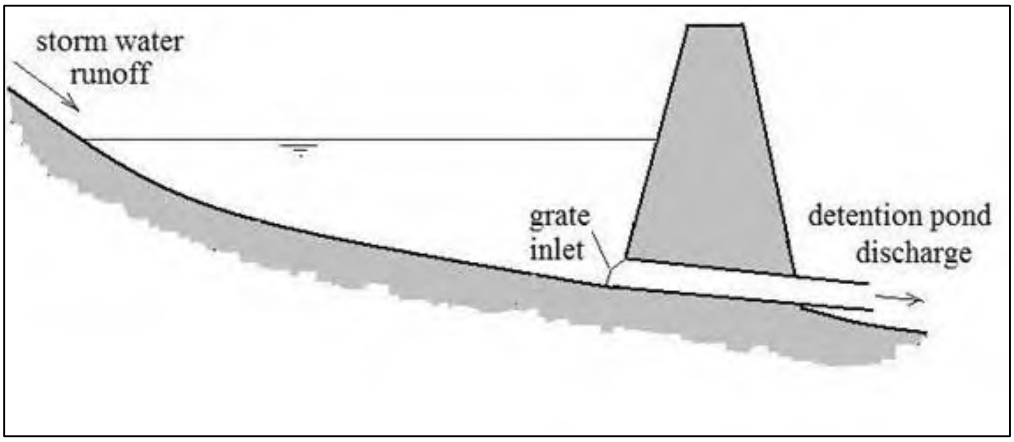

FIGURE 2-3 TYPICAL OSD SYSTEM (BRIGHT HUB INC., 2012)

OSD systems can also be in the form of above ground tanks, and incorporated into Stormwater Quality Treatment Devices (SQIDs) such as; above the extended detention depth of a bio-retention system. (DNRW, 2008). Due to constraints and features OSD shape, size and outlet configuration can differ between sites.

2.3.1 ISSUES WITH OSD SYSTEMS

Many issues exist with using OSD systems as a flood mitigation technique. The main issues of implementing multiple OSD systems within a catchment are:

- **Discrepancies between sites** – Different sites within a catchment may have been designed by different consulting engineers, and due to inconsistencies in council's examination of applications, due to time constraints and inconsistency of code and policy, differences in OSD systems between sites may occur. This can result in an overall ineffective control system (Still, 1999).

- **Discrepancy in construction** – Within some councils the inspecting officer may not be the same officer that approved the design documentation, this is also the same with engineering consultancies. Due to this difference in team members crucial design elements may be overlooked during construction, simply due to the team members not being aware of the design process or constraints (Still, 1999). As-Constructed survey does not always get completed properly, for the same reason that what may be a crucial design element to a designer may not be interpreted as such by a surveyor (Still & Bewsher, 1999). These construction issues highlight the problems with implementing a number of small (and sometimes complicated) systems as opposed to a regional one.
- **Maintenance** – The majority of OSD systems are privately owned, although some are owned by council. The maintenance of privately owned OSD systems is the responsibility of the property owner therefore it is not easy for council to monitor maintenance (Still, 1999). Due to the complicated outlet configuration that is typically incorporated into an OSD system maintenance is imperative to the effectiveness of the system, as these outlets may become blocked. OSD systems that are owned by the council are not always maintained effectively. As some systems within a catchment may be of a considerable age, council do not always have suitable records and systems can be overlooked and therefore not maintained.

2.4 HYDRAULIC MODELLING

As state above OSD systems are typically designed with the aid of hydrological and hydraulic computer models (DNRW, 2008). Runoff routing packages such as XP-RAFTS, XP-SWMM, DRAINS etc. use different hydrograph routing techniques to calculate discharge. The techniques typically included in these types of models are SWMM, Kinematic Wave, Laurenson's Method and Time Area Method. These methods can produce varying results depending on catchment features, local governments and state guidelines typically suggest which is the preferred technique (Fatema Akram, 2014). These type of programs typically include catchments that are routed through a physical element such as creeks, channels or pipes, this is what is referred to as 1D modelling. 1D models are best suited to modelling flows along well defined flow paths such as creeks or pipes, they are also computationally quick to run.

2 Dimensional (2D) modelling is defined as:

"2D flow models are based on the numerical solution of the depth-averaged equations describing the conservation of mass and momentum in two horizontal dimensions." (McCowan, 2015)

It is a dynamic modelling process that computes flows in multiple directions across a surface, or Digital Elevation Model (DEM). The model is split into a mesh or series of grids, and the 2D model equations are solved across each grid. Coupled 1D/2D models are used to integrate complex structures such as pipes into a 2D domain (McCowan, 2015), an example of a 1D/2D coupled modelling software program is TUFLOW.

2.4.1 1D Modelling – XP-RAFTS & XP-SWMM

As defined in Chapter 1 above, 1D hydraulic models typically consist of:

- Nodes which contain hydrological input parameters and calculations; and
- Links which route/convey runoff downstream through the catchment

XP-RAFTS and XP-SWMM are both forms of 1D hydraulic models from XP Solutions Inc. XP-RAFTS has been used in this study as a regional hydrological model for the comparison and validation of the 2D hydraulic models. XP-RAFTS is a non-linear runoff routing model that uses the Laurenson method of lumped impervious and pervious sub-catchments to develop runoff hydrographs from a catchment (XP Solutions Inc., 2016).

XP-SWMM uses the same runoff routing methodologies as XP-RAFTS, although it has the capabilities to model more complicated hydraulic structures (XP Solutions Inc., 2016), and has therefore been utilised in this study to model the 6 OSD systems within the catchment.

2.4.2 2D Modelling – TUFLOW

TUFLOW was originally developed in 1989 as a joint research and development project between WBM Pty Ltd and The University of Queensland (TUFLOW, 2015). It is a computer based program that simulates depth-averaged, 1D and 2D surface flows (TUFLOW, 2016). It works by solving depth averaged, momentum and continuity equations across a surface or DEM which is broken down into a mesh or grid The program does not have a graphical interface but operates through a geographical information system (GIS) and text editing software, which allows for ease of data management and presentation (TUFLOW, 2016).

TUFLOW and other 2d flood models normally require separate hydrological programs (such as XP-RAFTS) for hydrograph inputs, or alternatively Direct Rainfall Method (DRM) can be used in place of a separate hydrological model. Due to the complicated nature of the program, this report will not detail the computational processes involved, for further information refer to the TUFLOW manual (TUFLOW, 2016).

2.4.3 Direct Rainfall Method

Rainfall on grid, also known as DRM, is the process of applying rainfall directly onto the 2D domain, where the rainfall hyetograph is evenly distributed over the catchment area. Alternatively, the rainfall can be applied over a smaller polygon that represents the larger catchment area. The rainfall depth in each time-step is applied to each individual grid (or cell), the 2D model engine then applies its typical hydraulic calculations to determine runoff from each cell (Australian Rainfall and Runoff, 2016).

Rainfall on grid also has limitations, one of the main being that problems can occur where water gets trapped within depressions of the DEM as the rain is dropped directly on it. Also the simulation of a rain event being evenly distributed throughout a catchment is not reflective of real world events and can present some problems. It has been found that the storage effects of the depressions mentioned above may result in peak flow attenuation, particularly in low ARI events with low durations (Johnson, 2013).

Rainfall on grid can be useful for detailed urban studies, and is advantageous where catchment delineation and flow movement is unclear (Australian Rainfall and Runoff, 2016). Even though the technique has limitations, it is well suited for assessing hydraulic impacts, and not so much for detailed flood level investigation. Therefore, this technique may be applicable for the assessment of OSD systems on a catchment wide scale, providing the computational run times are not too extensive and that you consider the volume being stored in the model.

2.5 Need For Modelling Comparison

As discussed above there are a lot of differences between hydraulic modelling techniques that engineers and flood modellers need to be aware of. There are limited studies on the difference between 1D and 2D models, and particularly between DRM and lumped hydrograph methods (Johnson, 2013). As a result, there is a real need for further research into comparison of modelling methodology, particularly where DRM and lumped models are used in conjunction (Johnson, 2013).

2.6 SUBJECT CATCHMENT DETAILS

The stormwater drainage catchment of this research project is located in Coomera on the Gold Coast, Queensland. The catchment was chosen as the majority of development within the catchment has been within the last 10years, it has a central well defined drainage corridor, and is not located within the 100yr ARI regional flood extents, as defined by CoGC flood map and shown in Figure 2-4 below.

FIGURE 2-4 SURROUNDING FLOOD CONSTRAINTS (COGC, 2016)

Development applications are available for public review on CoGC's Planning and Development online database (PD Online) (CoGC, 2016). As a result, approved Stormwater Management Plans (SMP) and Hydraulic Impact Assessments (HIA) are available for review.

The subject site of this research has six (6) development sites that have been assessed and analysed. Each of these development sites was researched on PD Online, and these details made it possible to develop OSD parameters for each site, and analyse the impacts of site based assessments (CoGC, 2016). Figure 2-5 and Figure 2-6 below show aerial images of the pre-developed and post-developed catchments for this study, with the six (6) development sites mentioned above included as the post developed scenario and shown outlined in orange (Nearmap Ltd, 2016). These individual development sites are discussed in detail below.

FIGURE 2-5 PRE-DEVELOPED CATCHMENT (NEARMAP LTD, 2016)

In the pre-developed condition, shown in Figure 2-5, the existing development within the catchment is being serviced by detention and treatment systems located centrally along the drainage corridor running south to north, this development is known locally as Genesis (Belleng Pty Ltd, 2004).

It is understood that in the post-developed scenario, any additional catchments that were developed outside of the Genesis development that discharge into the central drainage corridor were required to provide their own stormwater quality and quantity management, i.e. these additional developments were not catered for in the Genesis design (Belleng Pty Ltd, 2004).

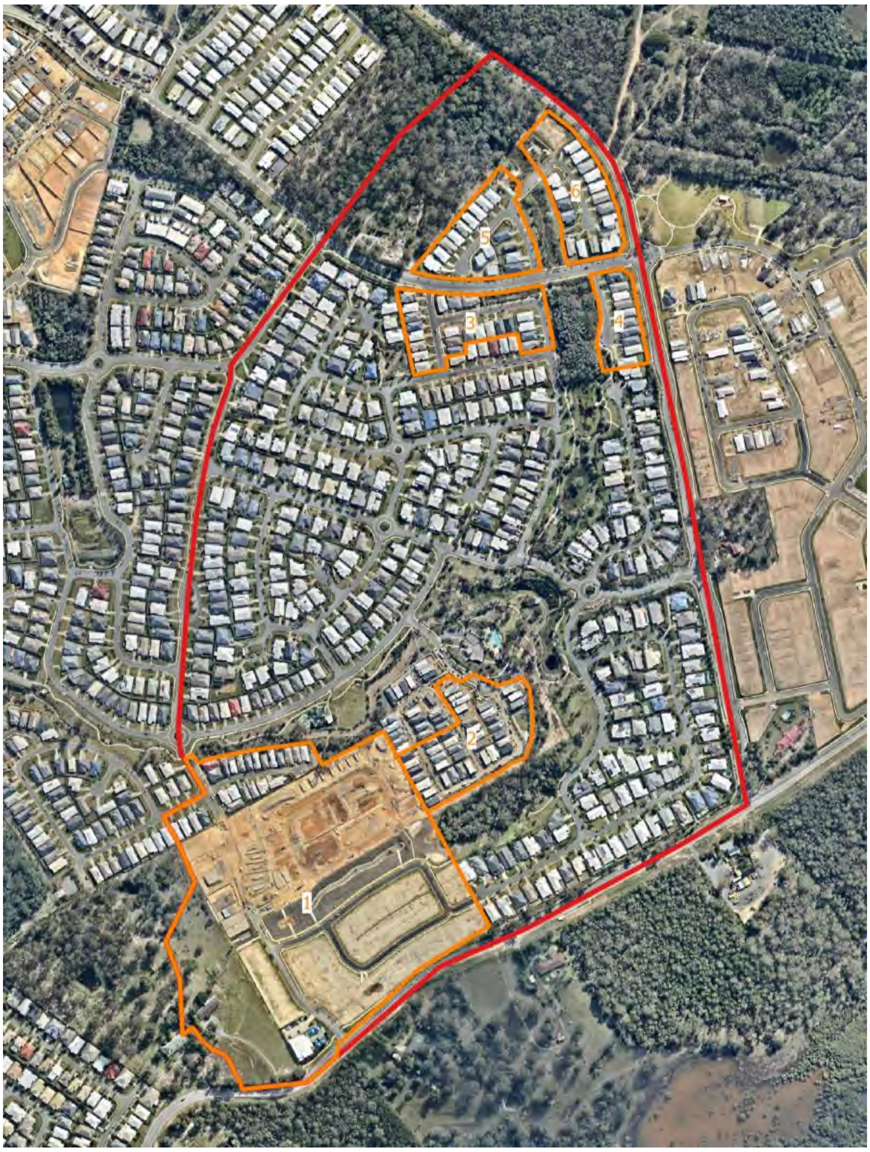

FIGURE 2-6 POST-DEVELOPED CATCHMENT (NEARMAP LTD, 2016)

2.6.1 Heritage Estate Flooding and Stormwater Report

A review of the Heritage Estate flooding and stormwater report, obtained from CoGC PD-Online, established the input parameters for the OSD system modelling, which is detailed in Chapter 3 below (CoGC, 2016). The document highlighted that the existing creek system adjacent to the eastern boundary of the development was established as the LPD and peak flows were non-worsened across this boundary using 1D modelling WBNM (Water Technology Pty Ltd, 2014). Figure 2-7 below shows these development sites at a larger scale, these sites will henceforth be referred to as development site 1.

The detention system is also depicted in Figure 2-7 below, and is mid-way through construction when this photograph was taken (Nearmap Ltd, 2016). The system is a central detention system that allows for conveyance of external catchments as well as mitigation of peak flows (Water Technology Pty Ltd, 2014). This basin will henceforth be referred to as Basin 1.

It should be noted that although Basin 1 was designed with 1D modelling techniques to mitigate peak flows, a 2D modelling analysis was also completed in this study to assess the velocities and flooding depths downstream of the development. The 2D analysis did not assess peak flows, and in particular did not mention the potential attenuation of peak flows caused by the existing dams on this site in the pre-developed condition. The 2D analysis was used to assess development impacts only (velocity and depths as mentioned above) (Water Technology Pty Ltd, 2014).

FIGURE 2-7 HERITAGE ESTATE DEVELOPMENT SITE (NEARMAP LTD, 2016)

FIGURE 2-8 HERMATIGE ESTATE CATCHMENTS (WATER TECHNOLOGY PTY LTD, 2014)

2.6.2 GENESIS STORMWATER MANAGEMENT PLAN

As discussed above, in the pre-developed scenario, the existing development within the subject catchment is known locally as Genesis. Stage 6A of the Genesis development contains additional development area to the original master plan, and as a result required on site stormwater quality and quantity management measures (Belleng Pty Ltd, 2004) (Biome Consulting Pty Ltd, 2014).

A review of the Genesis Stage 6A, Conceptual Stormwater Management Plan obtained from CoGC PD-Online highlighted that the LPDs of the development were established at the northern boundary and the eastern boundary, into the drainage corridor, and peak flows were non-worsened across this boundary using 1D modelling XP-STORM (CoGC, 2016) (Biome Consulting Pty Ltd, 2014). Figure 2-9 below shows these development site at a larger scale, these sites will henceforth be referred to as development site 2.

This study found that peak flows generated from the northern catchment (Catchment B in Figure 2-10) did not require mitigation due to the reduction in size of the contributing catchment to the LPD. As such only one detention system was found to be required and is located adjacent the eastern LPD, and will henceforth be referred to as Basin 2.

FIGURE 2-9 GENESIS STAGE 6A DEVELOPMENT SITE (NEARMAP LTD, 2016)

FIGURE 2-10 GENESIS 6A CATCHMENTS (BIOME CONSULTING PTY LTD, 2014)

2.6.3 AMITY ROAD STORMWATER MANAGEMENT PLAN

A review of the Amity Road stormwater management plan, obtained from CoGC PD-Online highlighted that the northern boundary of the development within the drainage corridor was established as the LPD for the development and flows were non-worsened across this boundary using 1D modelling XP-STORM (CoGC, 2016) (VDM Engineering Pty Ltd, 2012). Figure 2-11 below shows these development sites at a larger scale, these sites will henceforth be referred to as development sites 3 and 4.

The two detention systems within this development are incorporated on top of two bio-retention basins, and are depicted within Figure 2-12 below, the basin within the northeast corner of Catchment A1 will be referred to as Basin 3, and the basin within the southwest corner of Catchment B will be referred to as Basin 4. It should be noted that part of the development within this site to the west, is bypassing the basin, but peak flows are still mitigated at the LPD.

FIGURE 2-11 AMITY ROAD DEVELOPMENT SITE (NEARMAP LTD, 2016)

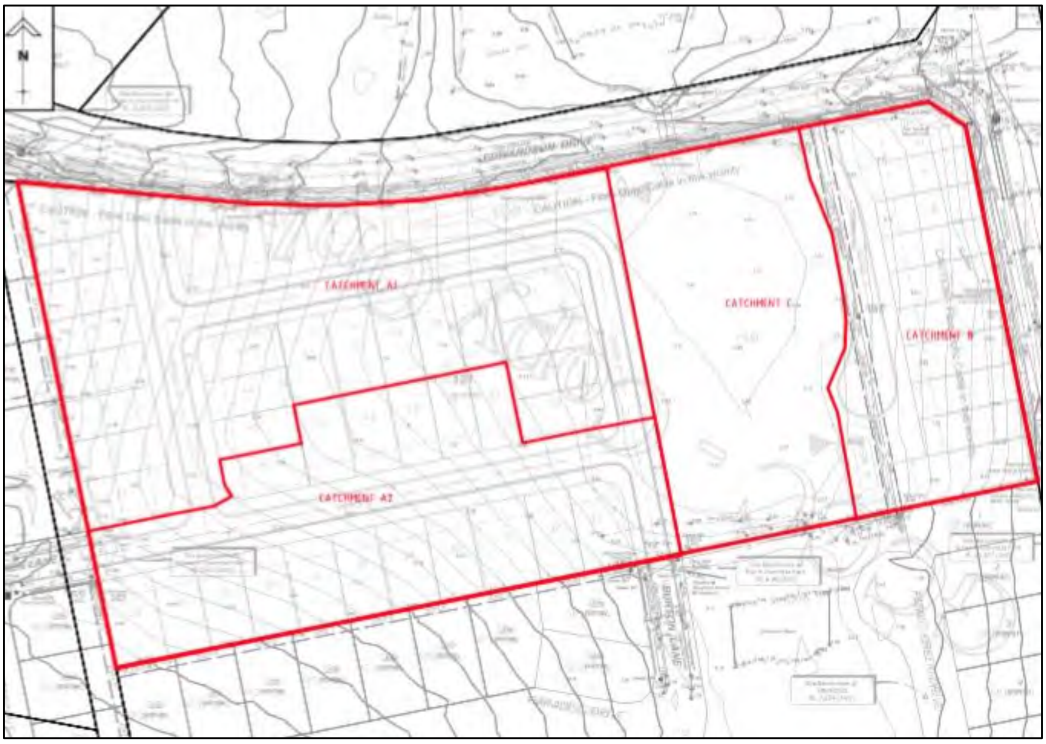

FIGURE 2-12 AMITY ROAD CATCHMENTS (VDM ENGINEERING PTY LTD, 2012)

2.6.4 EDWARDSONS LANE STORMWATER MANAGEMENT PLAN

A review of the Edwardsons Lane stormwater management plan, obtained from CoGC PD-Online highlighted that the north-western boundary of the development was established as the LPD for the development and flows were non-worsened across this boundary using 1D modelling XP-RAFTS (CoGC, 2016) (VDM Engineering Pty Ltd, 2012). Figure 2-13 below shows these development sites at a larger scale, these sites will henceforth be referred to as development sites 5 and 6.

The two detention systems within this development are incorporated on top of two bio-retention basins, and are depicted within Figure 2-14 below, the basin within the northeast corner of Catchment A will be referred to as Basin 5, and the basin within the northwest corner of Catchment B will be referred to as Basin 6.

FIGURE 2-13 EDWARDSONS LANE DEVELOPMENT SITES (NEARMAP LTD, 2016)

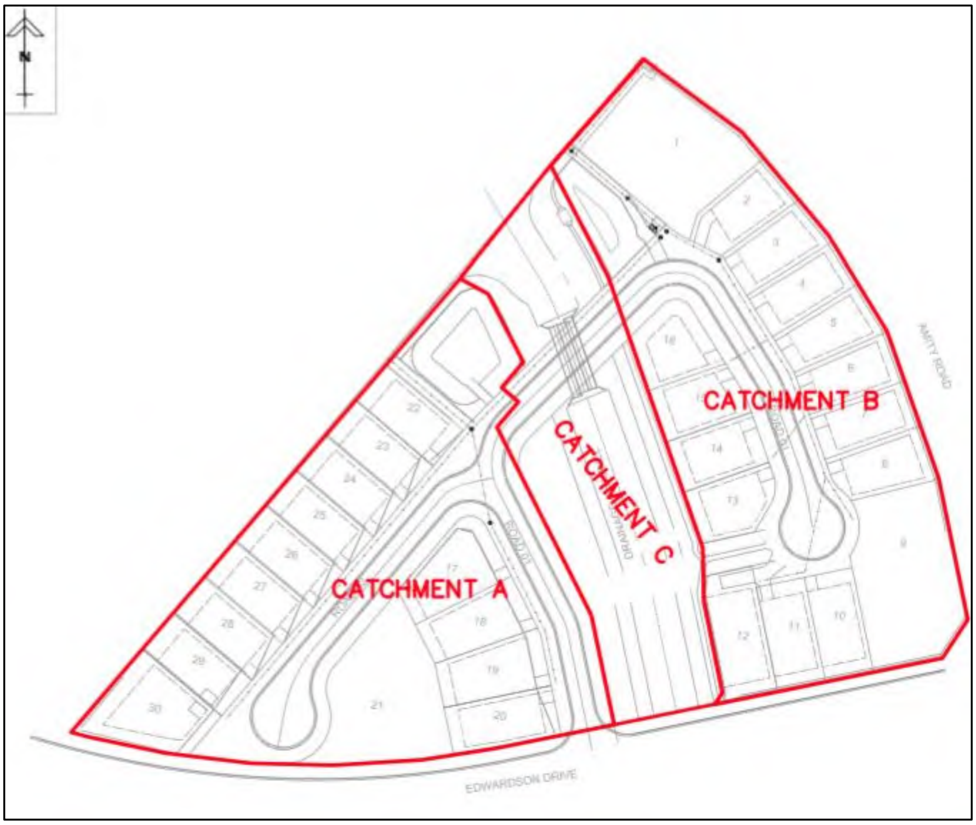

FIGURE 2-14 EDWARDSONS LANE SMP CATCHMENTS (VDM ENGINEERING PTY LTD, 2012)

2.7 Summary of Findings

The findings of the background research are summarised as follows:

- Studies show that effectiveness of stormwater quantity control approach is heavily dependent on catchment features;
- There is little investigation into the behaviour of small OSD systems implemented throughout a drainage catchment during regional flooding events;
- Studies show that OSD systems need to be implemented throughout at least 20% of the catchment to have any measurable positive outcome, even then a rise in flood levels can still occur under certain circumstances;
- There has been a numerous research undertaken in the behaviour of OSD systems on the catchment scale using 1D flood modelling techniques, but a limited amount has been done using 2D modelling;
- Previous studies and guidelines suggest that a total catchment study is always required to properly assess the impacts of OSD systems;
- UPRCT studies have shown that implementing OSD solutions throughout a catchment may not be as simple as *non-worsening* each site, and a larger OSD storage requirement may be necessary based on the catchment wide requirement. This shows that catchment wide analysis is vital;
- OSD systems are not always a reliable solution, as there can be faults in the design, construction and maintenance issues that causes the systems to be ineffective.
- A 2D flood modelling approach to analyse OSD solutions on a catchment wide scale can help to show the impacts of the system, particularly with respect to hazard and flow concentrations;
- Rainfall on grid 2D modelling technique could be an accurate way of assessing the impacts of OSD on a catchment scale. Provided the modeller/engineer is aware of its limitations.

Additionally, information and modelling parameters were gathered on each of the six development sites within the catchment.

CHAPTER 3 – METHODOLOGY

As discussed above the main objective of this research is to investigate the catchment wide impacts of OSD systems using the DRM 2D modelling technique. The following chapter outlines the methodology used to achieve this objective.

3.1 DEFINING CATCHMENT PARAMETERS AND PRELIMINARY HYDROLOGICAL CALCULATIONS

As discussed previously, a catchment within the Coomera area of the Gold Coast region was selected. This catchment was selected as it had a well defined catchment perimeter with no external catchments contributing runoff to the points of interest. The catchment was also small enough to allow for a reasonable grid size in a DRM model.

3.1.1 MODELLING SCENARIOS

The modelling scenarios adopted for this study were established based on the literature review outlined in Chapter 2 of this report. The 2-year, 20yr, and 100yr ARIs were chosen to establish the impacts of the OSD systems through their design limits, and the 200yr ARI was chosen to assess the impacts of these systems beyond their design limits.

The 20-minute, 45 minute, 60 minute, 90 minute, 120 minute and 180 minute were chosen to ensure a range of durations from what was defined in the literature as short, through to long.

3.1.2 CATCHMENT DELINEATION

The subject catchment was split into sub-catchments of similar size, impervious percentage, and land use. These sub-catchments were analysed and the following parameters gathered from aerial imagery and LiDAR data:

- Slope – using equal area slope method;
- Area;
- Impervious Percentage;
- Flow path lengths.

Delineation of the sub-catchments for both pre and post-developed scenarios is included within Appendix B.

3.1.3 HYDROGRAPH LAGS AND TIME OF CONCENTRATION

After the sub-catchment flow path length, slope and roughness were determined, hydrograph lagging was calculated using assumed stream velocities as advised by Table 4.06.5 of QUDM (DNRW, 2008). These lag times were used to route hydrographs within the XP-RAFTS model downstream through the catchment, to avoid having to delineate physical properties of the flow paths within the model. Time of concentrations of catchments were also calculated.

3.1.4 COLLECTION OF RAINFALL DATA

Rainfall data was collected from the Australian Governments Bureau of Meteorology in the form of Intensity Frequency Duration (IFD) data (Bureau of Meteorology, 2016). The IFD data detailed the intensity, in mm/hr, for the subject catchment for differing ARI events. The data obtained is included below in Figure 3-1.

Intensity-Frequency-Duration Table

Location: 27.850S 153.350E NEAR.. Coomera Issued: 10/5/2016

Rainfall intensity in mm/h for various durations and Average Recurrence Interval

Average Recurrence Interval

Duration	1 YEAR	2 YEARS	5 YEARS	10 YEARS	20 YEARS	50 YEARS	100 YEARS
5Mins	127	160	195	214	241	276	302
6Mins	119	150	183	201	226	259	284
10Mins	97.1	123	150	166	187	214	235
20Mins	71.3	90.3	111	123	139	159	175
30Mins	58.1	73.8	91.0	101	114	131	144
1Hr	39.3	50.0	62.2	69.1	78.6	91.0	100
2Hrs	25.2	32.2	40.6	45.4	52.0	60.5	67.0
3Hrs	19.1	24.5	31.2	35.1	40.3	47.1	52.3
6Hrs	11.8	15.3	19.8	22.4	25.9	30.6	34.2
12Hrs	7.53	9.78	12.8	14.6	17.0	20.2	22.7
24Hrs	5.00	6.51	8.61	9.90	11.6	13.8	15.5
48Hrs	3.35	4.38	5.83	6.72	7.87	9.43	10.6
72Hrs	2.54	3.34	4.46	5.17	6.07	7.28	8.23

(Raw data: 50.54, 9.74, 3.35, 90.39, 19.85, 7.19, skew=0.06, F2=4.41, F50=17.21)

© Australian Government, Bureau of Meteorology

FIGURE 3-1 SUBJECT SITE IFD (BUREAU OF METEOROLOGY, 2016)

Zone 3 temporal patterns were obtained from ARR (IEAust, 2003). These patterns outline incremental percentages of the intensity for the duration of a storm event. For the 1D models (XP-RAFTS and XP-SWMM), the temporal patterns are included in the software packages, and the IFD data is the only rainfall input. For TUFLOW DRM the temporal patterns were applied to the intensity for each event, and then converted to depth (mm). The 60min temporal pattern for Zone 3 is shown below in Table 3-1 as an example, and the resultant rainfall depth graph is included as Figure 3-2.

TABLE 3-1 ARR TEMPORAL PATTERN 60MIN DURATION (% AT 5MIN INCRIMENTS)

<30yrs	3.9	7	16.8	12	23.2	10.1	8.9	5.7	4.8	3.1	2.6	1.9
>30yrs	4.3	7.3	16.1	11.6	21.7	10	9	6	5.2	3.5	3	2.3

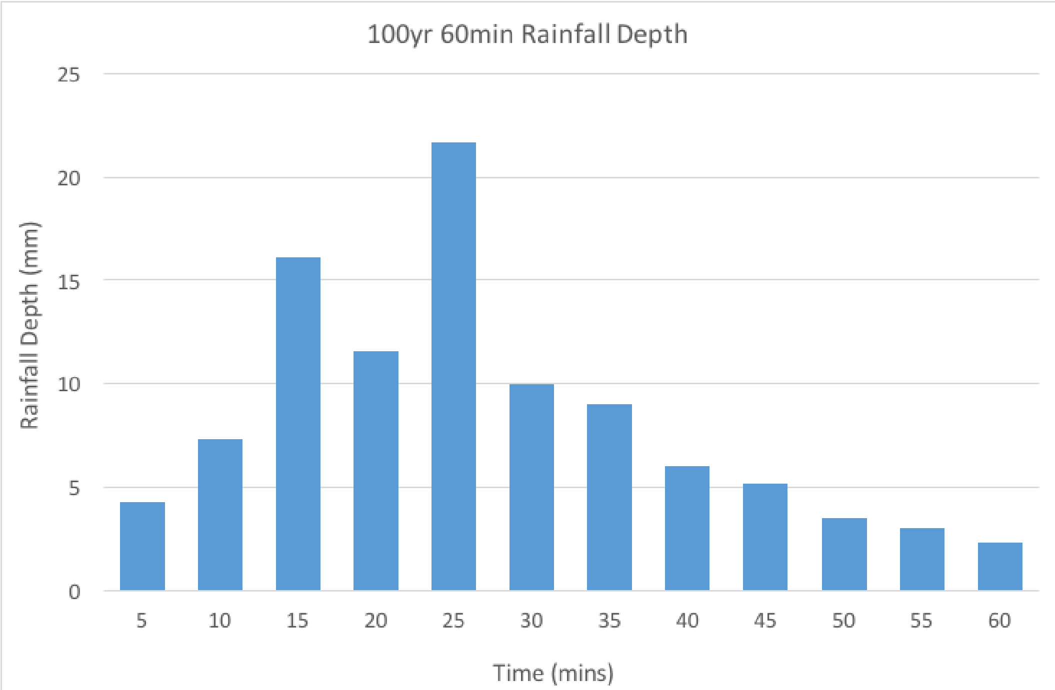

FIGURE 3-2 100YR 60MIN RAINFALL DEPTHS

3.1.5 200YR ARI PARAMETERS

As the 200yr ARI event is outside of the extents of normal IFD and ARR parameters, alternative methods for calculating the modelling parameters were utilised. The Probable Maximum Precipitation (PMP) was calculated for the subject site, utilising the methodology outlined in ARR (IEAust, 1987). In Australia short duration PMP is calculated using the Generalised Short Duration Method (GSDM) (XP Solutions Inc., 2016). This method uses mapping of Australia that categorises zones of duration limits, topography correction factors, elevation correction factors, and moisture correction factors. These correction factors are utilised to then calculate the PMP (Commonwealth Bureau of Meteorology , 2003). For the catchment the PMP is estimated to have an Annual Exceedance Probability (AEP) of 10^{-7} (Commonwealth Bureau of Meteorology , 2003).

From this the 200yr ARI intensity was estimated by linear interpolation. Once the intensity for the events was known the remainder or the process for determining modelling parameters was as per the other ARI's mentioned above.

3.1.6 RAINFALL LOSSES AND ROUGHNESS

Rainfall losses, and manning's roughness values for XP-RAFTS, XP-SWMM and the TUFLOW models have been adopted based on the suggested values of ARR, QUDM and the above mentioned literature (IEAust, 2003) (DNRW, 2008). The losses and roughness parameters applied to the TUFLOW models are summarised below in Table 3-2, and are similar to those adopted in the 1D models.

Depth varying manning's roughness can be adopted within DRM models to accurately represent roof areas within a catchment (Boyte, 2014) (Syme, 2008). The manning's roughness and depth variance adopted in this model were selected based on the above mentioned guidelines and the TUFLOW manual (TUFLOW, 2016).

TABLE 3-2 SUBJECT CATCHMENT LOSSES AND MANNINGS ROUGHNESS

Material	Roughness Parameters		Infiltration Parameters	
	Depth (mm)	Manning's n	Initial Loss (mm/hr)	Continuing Loss (mm/hr)
Grass	0.05	0.03	10	1
	0.1	0.02		
Road/path/ driveways	0.02	-	1	0
Roof	0.03	0.01	1	0
	0.05	3		
Dense vegetation	0.08	-	15	2.5
Water body	0.03	-	1	0

It should be noted that for both the TUFLOW models a boundary condition was applied with constant hydraulic grade i.e. downstream flooding or inundation was not considered as part of this study, only locally generated runoff.

3.2 XP-RAFTS MODELLING

As mentioned above the 1D modelling software XP-RAFTS (by XP Solutions Inc.) was utilised to develop input hydrographs for the lumped TUFLOW models, and to develop a regional 1D model . These models were developed to compare to the DRM results.

3.2.1 INPUT PARAMETERS

Areas, slopes, lag times etc. were input into the links and nodes within XP-RAFTS, the models were then set up using the 'storm generator' feature of the software, which allows for automatic implementation of events by selecting ARI's and durations (XP Solutions Inc., 2016).

A catchment storage parameter was applied to the XP-RAFTS model to try and calibrate the model to the DRM, to achieve comparable results. This was completed through trial and error and it was found that a storage multiplication parameter of 2 resulted in a XPRAFTS model and a lumped TUFLOW model that resembled the DRM the closest for the majority of events.

200yr ARI

The 200yr ARI events required the IFD parameters to be included within the software, as this event was beyond the capabilities of the automatic storm generator. This meant applying multipliers to the ARR temporal pattern for >30yr ARI, and creating a separate model for each duration.

OSD Scenario

For the post-development scenarios that included the OSD systems, hydrograph outputs from the XP-SWMM models (which are discussed below) had to be input manually into each of their respective catchments. As a result, a model file was required to be set up for each scenario. Figure 3-3 below shows a screen shot of the pre-developed scenario from the XPRAFTS model.

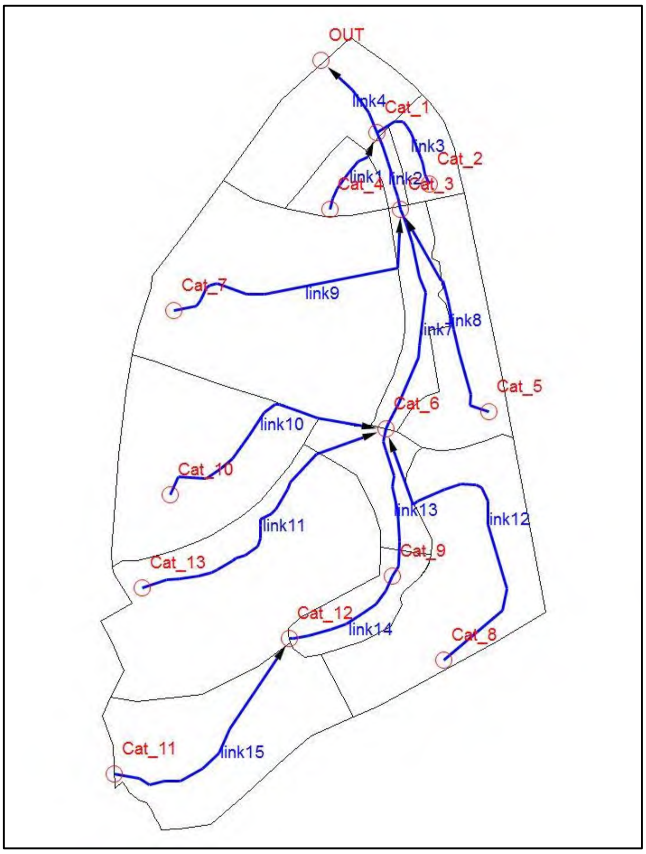

FIGURE 3-3 PRE-DEVELOPMENT XP-RAFTS MODEL

3.2.2 OUTPUT TO TUFLOW

The resultant hydrographs for each sub-catchment were exported from XP-RAFTS into CSV spreadsheets for input into the TUFLOW models. As there were 13 sub-catchments, 3 TUFLOW models (pre-development, post-development and post-development with OSD), and 24 scenarios approximately 940 hydrographs had to be exported and managed into a database for input into TUFLOW.

3.3 XP-SWMM ON-SITE DETENTION MODELLING

As mentioned above 1D modelling XP-SWMM (by XP Solutions Inc.) was utilised to model the six (6) OSD systems. This software is able to model complicated outlet structures, in the form of a stage vs discharge relationship curve, such as riser pits with multiple orifices.

3.3.1 BASIN INPUTS

As with XP-RAFTS catchment parameters such as areas, slopes roughness etc. were input into the nodes of the model. From the reports outlined in Section 2.6 , details of the detention basin storage characteristics were put in the model.

Stage/discharge curves were calculated for the various outlet structures using excel. The weir and orifice equations were used in the spreadsheet to calculate the discharge condition of the outlets under differing head conditions. Figure 3-4 shows a screen capture of one of the XP-SWMM models.

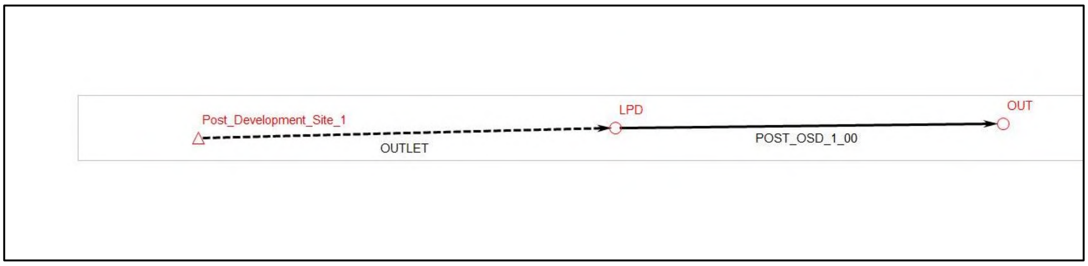

FIGURE 3-4 XP-SWMM MODEL

3.3.2 OUTPUTS

After the basin storage volumes and outlets were detailed in each model, the model files were run and saved for each scenario. The resultant hydrograph for each scenario was then exported as a CSV spreadsheet to the data-base mentioned above, to be utilised in both the XP-RAFTS and TUFLOW models.

3.4 TUFLOW MODELLING

Details of each step involved in developing a TUFLOW model are not included within this report, for further detail on TUFLOW modelling methodology refer to the TUFLOW manual (TUFLOW, 2016).

3.4.1 DIGITAL ELEVATION MODEL

As discussed above TUFLOW modelling is a 2D hydraulic model that routes stormwater runoff across a gridded surface or DEM. For the subject site, DEM was available in the form of LiDAR aerial survey obtained from the Queensland Government through Burchills Engineering Solutions. The LiDAR was sourced through the Queensland Department of Natural Resources and Mines (DNRM) and has a 1m grid spacing with a vertical accuracy of 0.3m at 95% and a horizontal accuracy of 0.8m at 95% (DNRM, 2015).

The LiDAR surface represented a partially developed scenario, that is: it didn't represent either the pre or post developed scenarios, as some of the development sites were partially developed. As a result, modification of the surface for both scenarios was necessary. The surface was modified in TUFLOW using 'Z shapes', which are manual manipulations of the topography using shapes with elevation information. Assumptions and estimations were necessary at this point of the modelling process to ensure the pre and post development surfaces were well represented. Further discussion on the implications and constraints of this methodology is included below in Section 3.5 .

3.4.2 DRM

The Direct Rainfall Method (DRM) TUFLOW model was developed in accordance with the TUFLOW user manual (TUFLOW, 2016).

For the pre-developed and post-developed scenario rainfall depth was applied across the entire catchment incrementally for each model time step.

For the post-development OSD scenario the sub-catchments contributing to the OSD systems were excluded from the rainfall grid. These catchments were replaced with the XP-SWMM resultant hydrographs mentioned above. Figure 3-5 below shows the post-development OSD scenario rainfall grid from the DRM model.

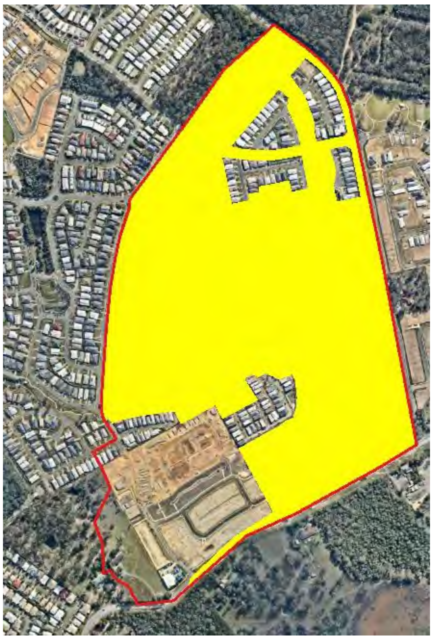

FIGURE 3-5 DRM OSD SCENARIO - RAINFALL GRID

3.4.3 LUMPED HYDROGRAPH METHOD

The typical lumped hydrograph approach was adopted as a modelling comparison for the DRM. Resultant sub-catchment hydrographs from the XP-RAFTS modelling were included in the TUFLOW inflow database and applied to the 2D domain at the lowest point in each sub-catchment.

Figure 3-6 below shows the post-development OSD scenario inflow hydrograph sub-catchments from the Lumped model, with the gaps in the image representing the OSD catchments where resultant XP-SWMM hydrographs were input at the basin outlet locations.

FIGURE 3-6 LUMPED HYDROGRAPH OSD SCENARIO – SUB-CATCHMENTS

3.5 CONSTRAINTS OF MODELLING TECHNIQUE

The above discussed methodology was developed mainly around the budget and time limitations of this study (i.e. there was no budget). Detailed survey of each OSD basin was not available, and as such they were not able to be included in the DEM. Additionally gaining the modelling files and resultant hydrographs of the OSD designs from each engineering consultant was not considered necessary, or possible, and as a result the information gained from PD-Online was considered sufficient.

The modelling methodology presented has many constraints that are a result of the limited catchment details mentioned above. The constraints and limitations of the methodology can be summarised as follows:

- Modelling of individual OSD systems based on reported parameters results in increased risk of misinterpretation of design and other human error;
- 2D modelling using different inflow techniques (i.e. DRM and Lumped in the same model), was highlighted in the literature as a possible cause of errors;

- Manipulation of the DEM (due to limited data) for both the pre and post development scenarios was based on estimation and engineering judgement, this results in an increased risk of error and poor representation of actual surfaces;
- Hydraulic modelling in an un-gauged urban drainage catchment results in un-calibrated runoff models, (this is why the three modelling techniques were adopted for comparison).

It is important for readers to consider these limitations if adopting a similar methodology.

3.6 RESULTS AND MAPPING

Five (5) key points of interrogation throughout the main drainage corridor in the subject catchment were chosen to assess results. Resultant hydrographs were exported at each of these points for the XP-RAFTS model and both TUFLOW models for the pre, post and OSD scenarios.

Once the peak flow results were analysed; mapping of velocities, flood depths and hazards were created in QGIS for the events of interest from the DRM model.

Details of the results of this study are discussed further in Chapter 4 below.

CHAPTER 4 – RESULTS

4.1 PEAK FLOWS

4.1.1 POINTS OF INTEREST

In order to manage the high volume of resultant data from the modelling process, peak flows were assessed at five (5) key points through the catchment. Figure 4-1 shows these points of interrogation.

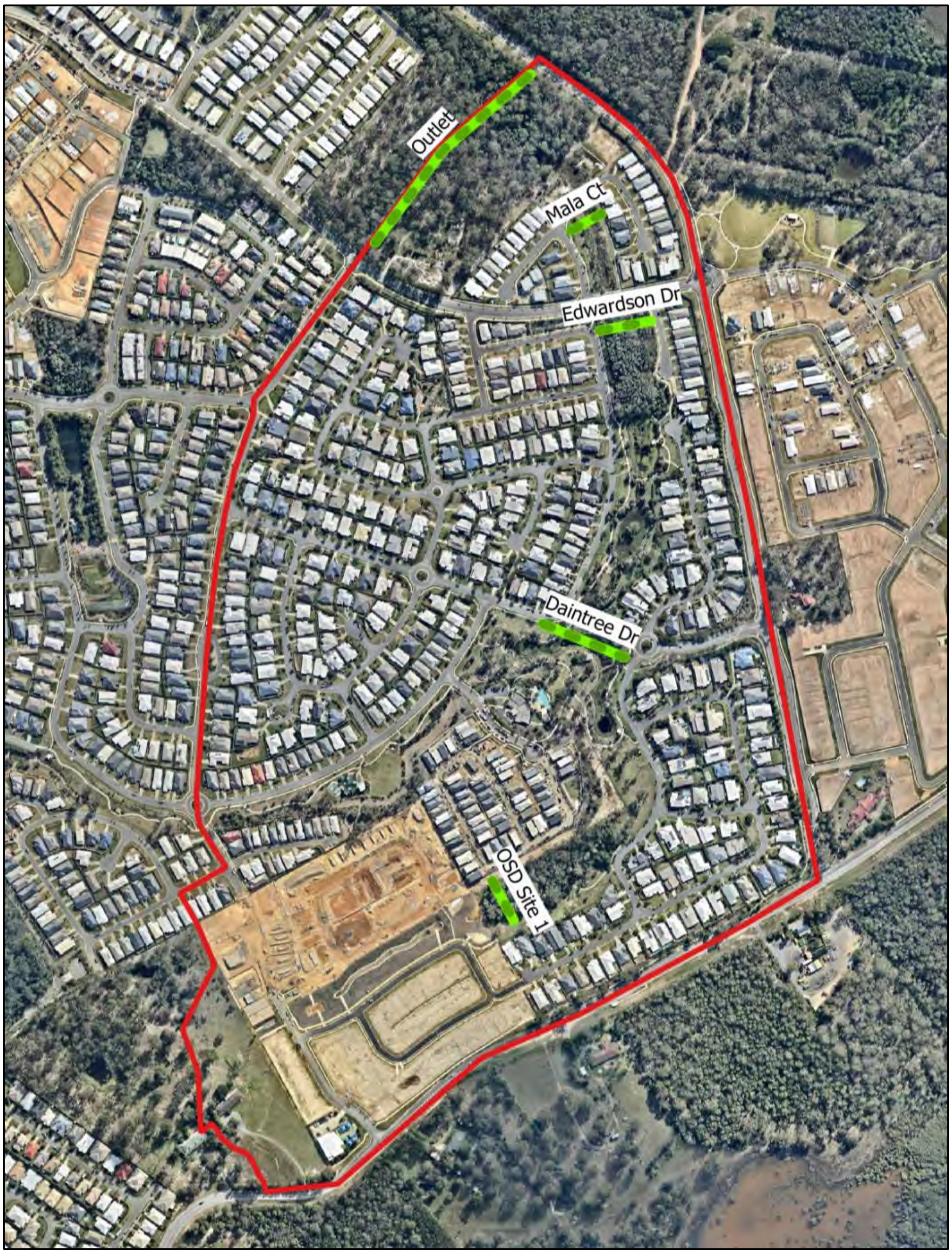

FIGURE 4-1 POINTS OF INTERROGATION

4.1.2 Peak Flow Mitigation

As discussed in Chapter 2 above, OSD systems in this catchment are implemented with the main objective of mitigating peak stormwater discharges from each development. As such peak discharges have been chosen as the basis of the result analysis.

The effectiveness of the OSD systems, in regard to peak flow mitigation, was assessed and the results from the 3 models were recorder for comparison of techniques. This analysis looked at the difference in pre-developed and post development peak flows, and the reduction (or increase) in peak flows as a result of the OSD systems. This data has been tabulated and presented in Appendix G. Please note the peak flows for each scenario at each location are not included with this report due to the amount of data, displaying and reporting on the percentage differences in peak flows was considered a suitable approach to minimise and simplify the results. A summary (averaged) of the DRM result for each ARI is presented below in Table 4-1, the cells highlighted green show a decrease in peak discharges as a result of the OSD systems, and the cells shown in read show an increase.

TABLE 4-1 AVERAGE DECREASE IN PEAK DISCHARGES – DRM MODEL

Scenario (ARI)	INTERROGATION LOCATION	Peak Discharge Mitigation (%)
2yr	OSD SITE 1	+11.94
	Daintree Dr	+14.62
	Edwardson Dr	+14.84
	Mala Ct	+14.84
	Catchment Outlet	+16.62
20yr	OSD SITE 1	-16.97
	Daintree Dr	-4.92
	Edwardson Dr	-0.57
	Mala Ct	+1.09
	Catchment Outlet	+2.12
100yr	OSD SITE 1	-15.93
	Daintree Dr	-5.46
	Edwardson Dr	-2.90
	Mala Ct	-1.44
	Catchment Outlet	-0.90
200yr	OSD SITE 1	-8.50
	Daintree Dr	-4.66
	Edwardson Dr	-1.72
	Mala Ct	-1.08
	Catchment Outlet	-0.42

Table 4.1 shows that the OSD systems did not always mitigate peak flows within the catchment. Appendix G shows that in particular the low duration events were unmitigated, the data shows this is due to low pre-developed peak flows. Further discussion on these results is included in Chapter 5. The lumped TUFLOW model showed different results, these are included in Table 4-2 below, although the 2yr ARI still showed an increase in peak discharges at the catchment outlet due to the implementation of OSD.

TABLE 4-2 AVERAGE DECREASE IN PEAK DISCHARGES – LUMPED MODEL

Scenario (ARI)	INTERROGATION LOCATION	Peak Discharge Mitigation (%)
2yr	OSD SITE 1	-36.88
	Daintree Dr	+0.99
	Edwardson Dr	-10.32
	Mala Ct	+6.43
	Catchment Outlet	+4.57
20yr	OSD SITE 1	-47.87
	Daintree Dr	-8.32
	Edwardson Dr	-20.37
	Mala Ct	-5.42
	Catchment Outlet	-4.32
100yr	OSD SITE 1	-45.92
	Daintree Dr	-8.60
	Edwardson Dr	-20.26
	Mala Ct	-7.31
	Catchment Outlet	-7.49
200yr	OSD SITE 1	-36.59
	Daintree Dr	-3.49
	Edwardson Dr	-14.77
	Mala Ct	-3.08
	Catchment Outlet	-3.53

From the data, the 90min duration was identified as the critical during for most ARI's. Figure 4-2 to Figure 4-9 below shows the peak discharges at Daintree Dr and the Catchment Outlet for the critical events, these results show that the peak discharges are only very slightly mitigated for these events.

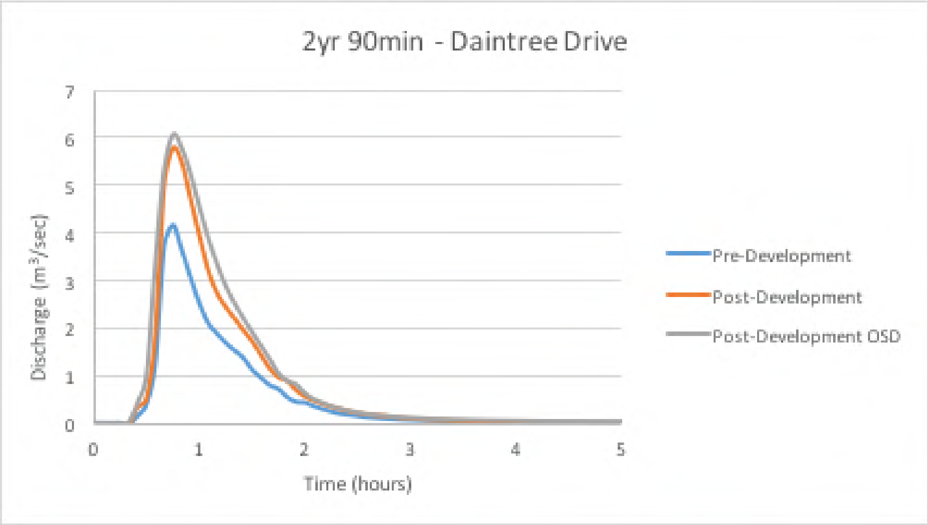

FIGURE 4-2 2YR 90MIN DAINTREE DR

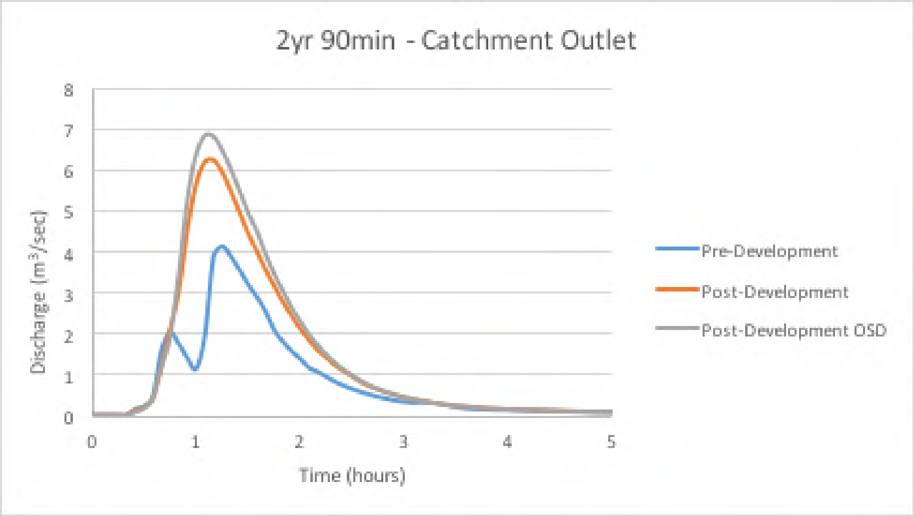

FIGURE 4-3 2YR 90MIN CATCHMENT OUTLET

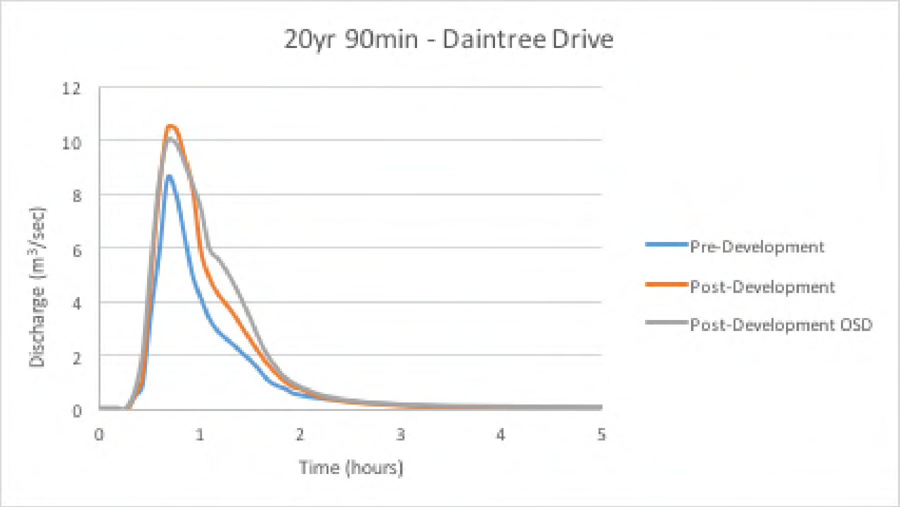

FIGURE 4-4 20YR 90MIN DAINTREE DR

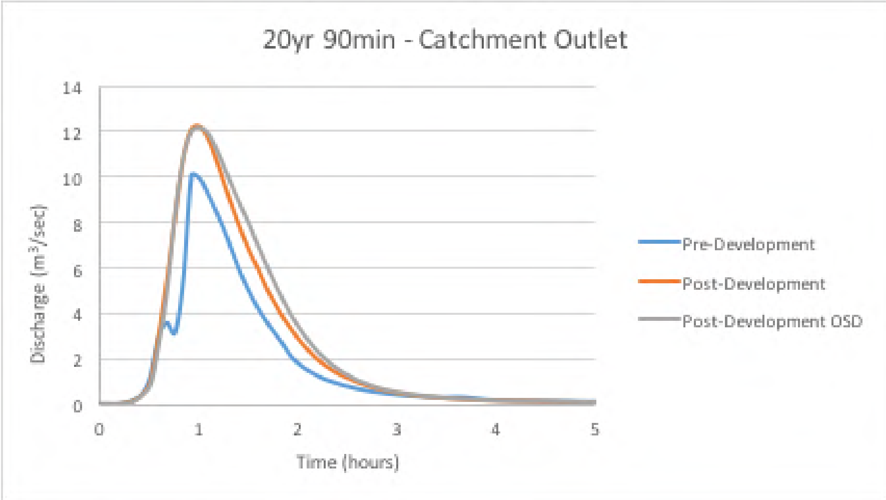

FIGURE 4-5 20YR 90MIN CATCHMENT OUTLET

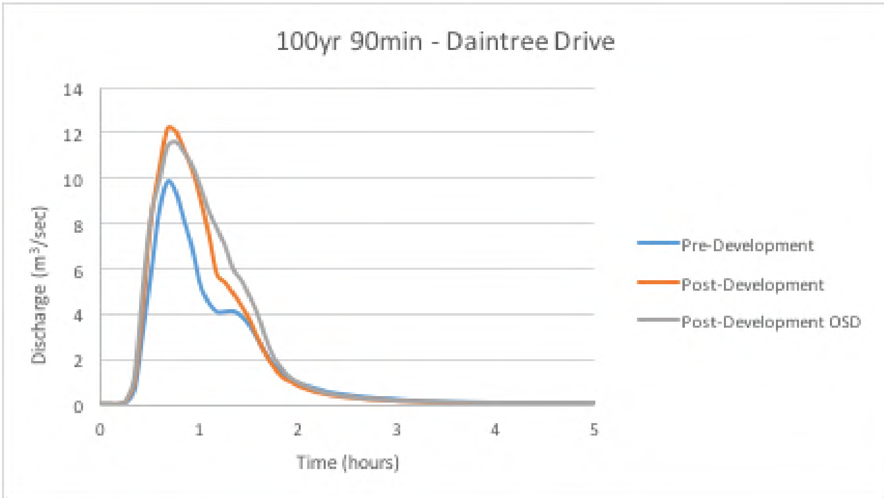

FIGURE 4-6 100YR 90MIN DAINTREE DR

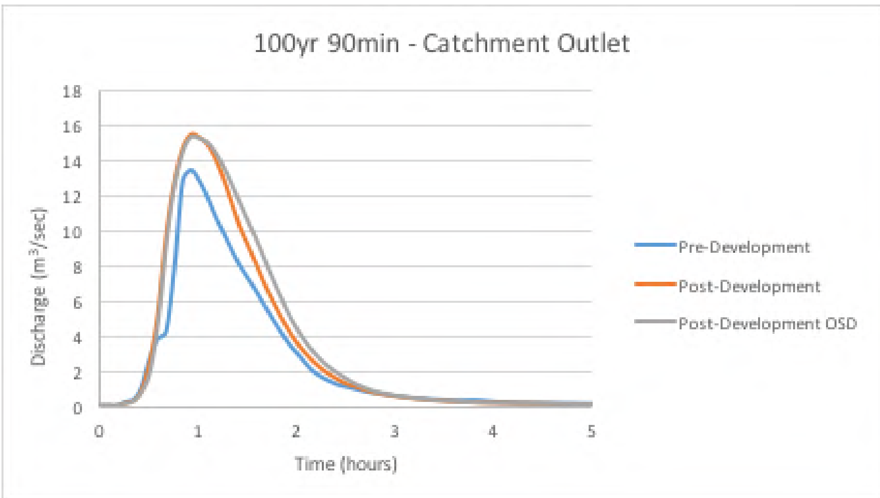

FIGURE 4-7 100YR 90MIN CATCHMENT OUTLET

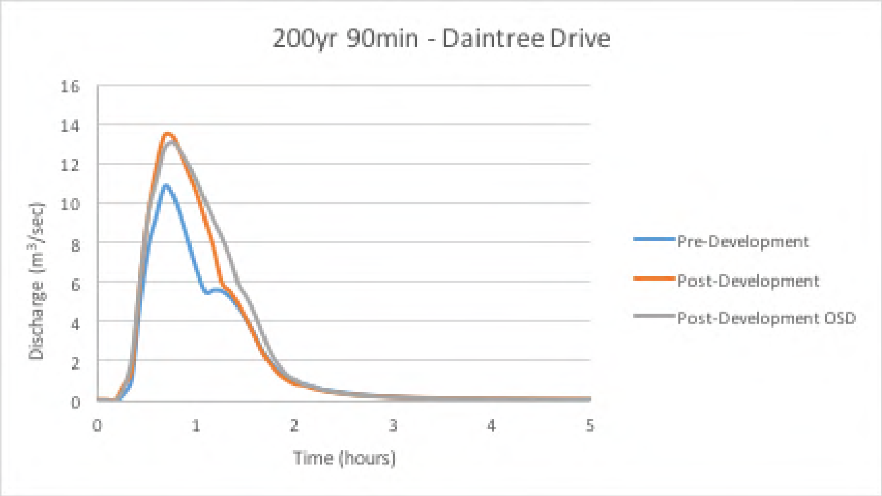

FIGURE 4-8 200YR 90MIN DAINTREE DR

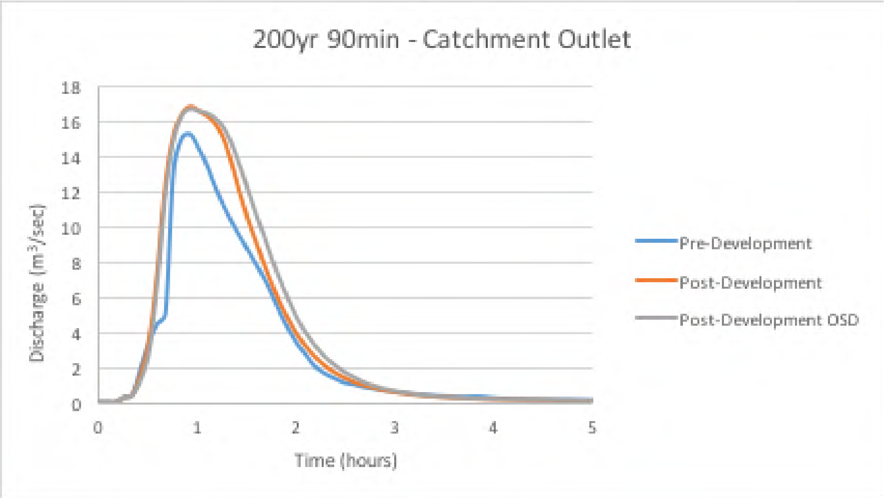

FIGURE 4-9 200YR 90MIN CATCHMENT OUTLET

For durations outside the critical events the OSDs were less effective, achieving less reduction in peak flows. These results are in keeping with the literature outlined in Chapter 2, which state that OSD systems implemented throughout a catchment have the potential to increase flooding impacts in events outside the critical duration (Beecham, et al., 2005).

These events also resulted in lower pre-developed peak discharges and as such the OSD systems were again not successful in reducing post developed peak discharges back to the pre-developed level. Further discussion into the storage effect of the DRM model on attenuation of pre-developed peak discharges, and how this impacted the results is included in Chapter 5.

4.2 Flood Depths

Peak flood depths were assessed for all modelling scenarios, Figure 4-10 shows the flooding depth for the 100 year ARI 90 minute event for the post-developed scenario with the 6 OSD systems implemented throughout the catchment. Gaps exist in the image at the 6 development site locations due to replacing parts of the DRM with direct inflow hydrographs from the 1D detention models.

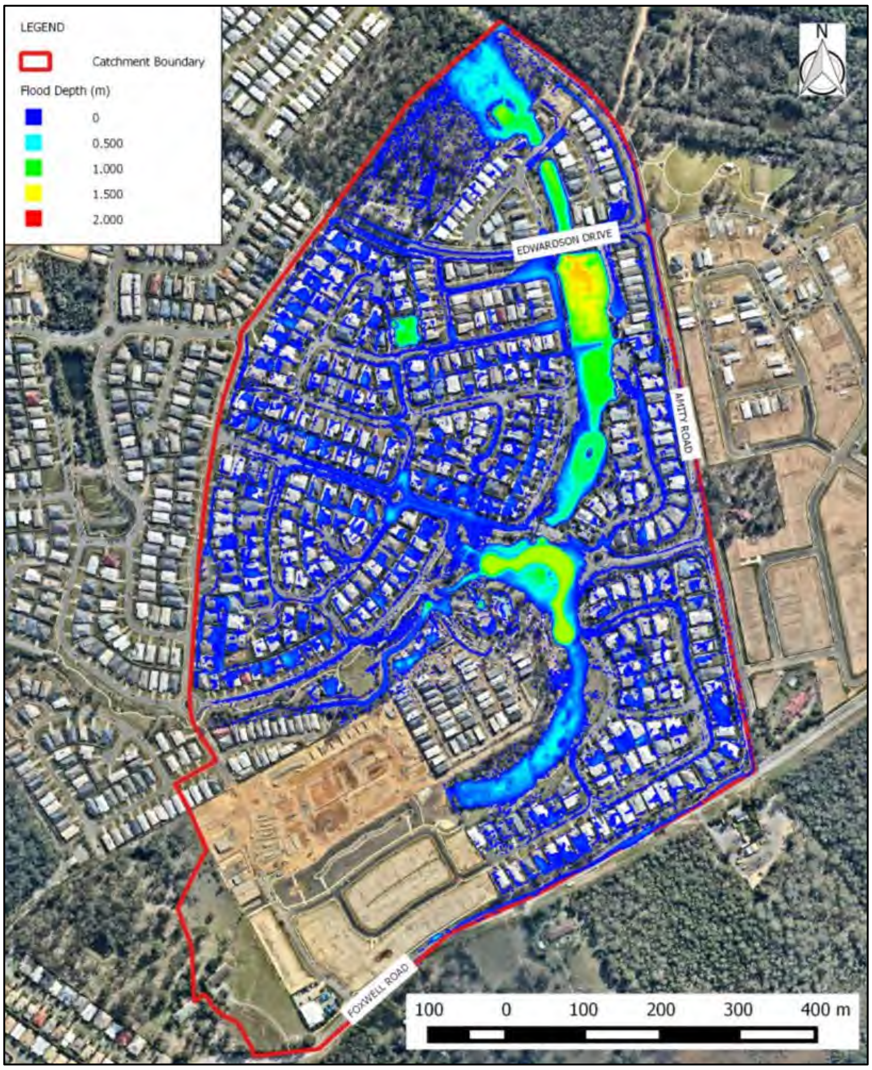

FIGURE 4-10 100YR 90MIN POST-DEVELOPMENT WITH OSD - FLOOD DEPTH

In order to show the impact of the OSD systems on flooding depths, differential plots of the peak flood level were assessed for the critical duration (90 minute). Flooding depths reduced as a result of the implementation of the OSD systems, Figure 4-11 below shows the flood depth differential resulting from the OSD systems during the 100yr 90min event. These differential plots show the reductions and increases of flood levels within the catchment, sections shown as clear in the catchment had negligible flooding differences and are shown as white in the legend. Flood differential maps for the critical duration are included as Appendix C at full scale, and for selected events outside the critical duration, Appendix D. Further discussion on the effectiveness of the OSD systems at flood level control is included below in Chapter 5.

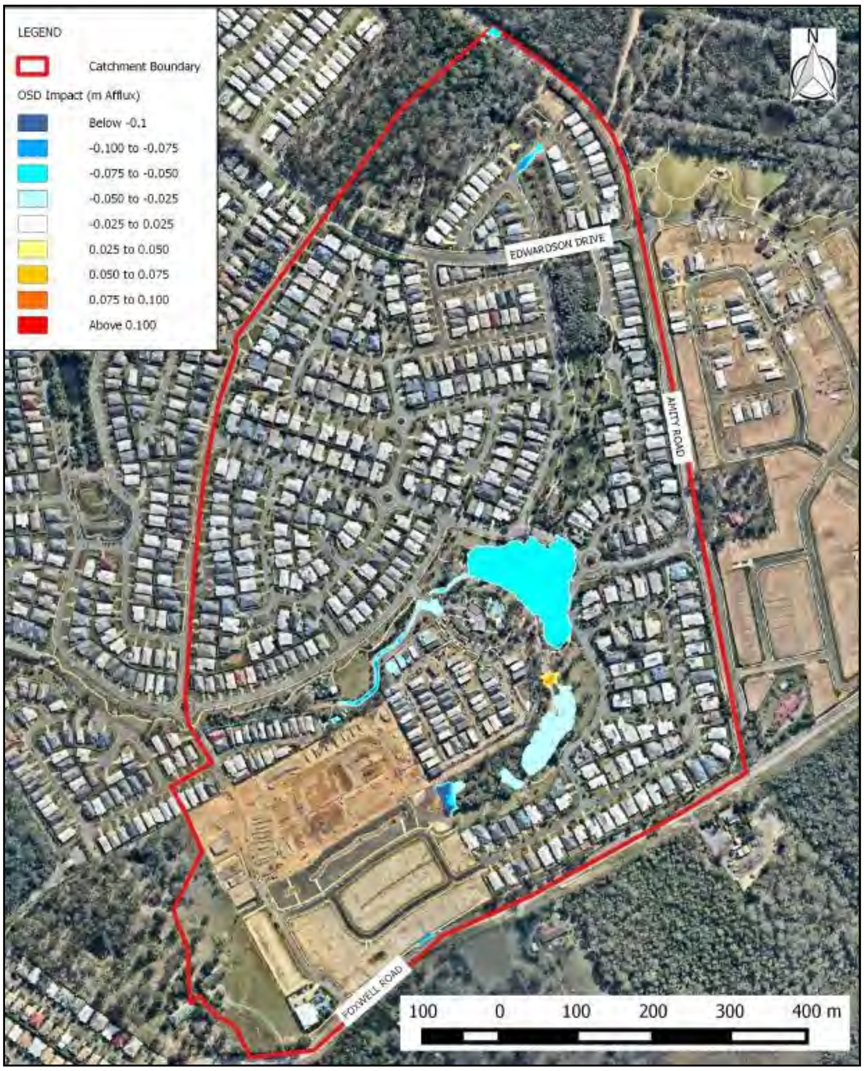

FIGURE 4-11 100YR 90MIN FLOOD DEPTH IMPACT

4.3 VELOCITIES

Peak velocities were assessed for all modelling scenarios, Figure 4-12 shows the flooding velocity for the 100 year ARI 90 minute event for the post-developed scenario with the 6 OSD systems implemented throughout the catchment. Gaps exist in the image at the 6 development site locations due to replacing parts of the DRM with direct inflow hydrographs from the 1D detention models.

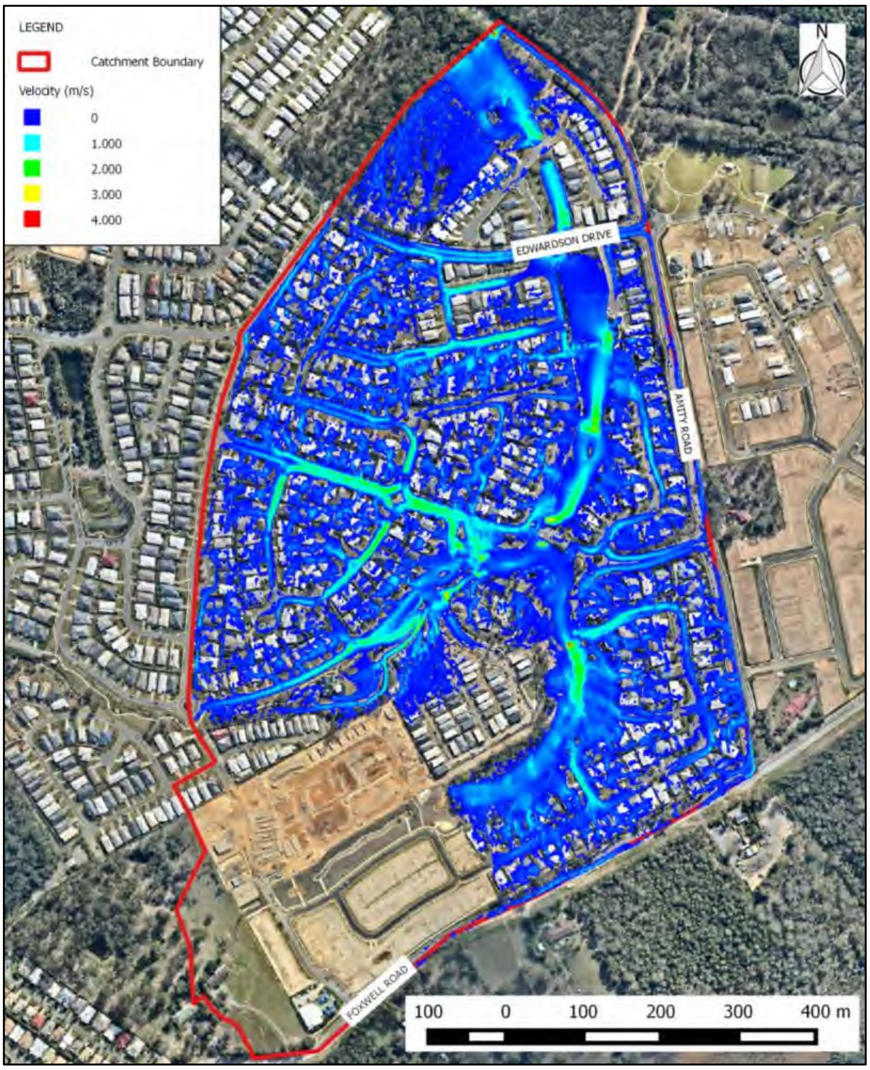

FIGURE 4-12 100YR 90MIN POST-DEVELOPMENT WITH OSD - VELOCITY

In order to show the impact of the OSD systems in regard to velocities, differential plots of the maximum flood velocities were assessed for the critical duration (90 minute). Flooding velocities reduced as a result of the implementation of the OSD systems, although where flows were concentrated at basin outlets velocities were locally increased. Figure 4-13 below shows the velocity differential resulting from the OSD systems during the 100yr 90min event. Velocity differential maps for the critical duration are included as Appendix

E, these differential plots show the reductions and increases of flood velocities within the catchment, sections shown as clear in the catchment had negligible differences and are shown as white in the legend.

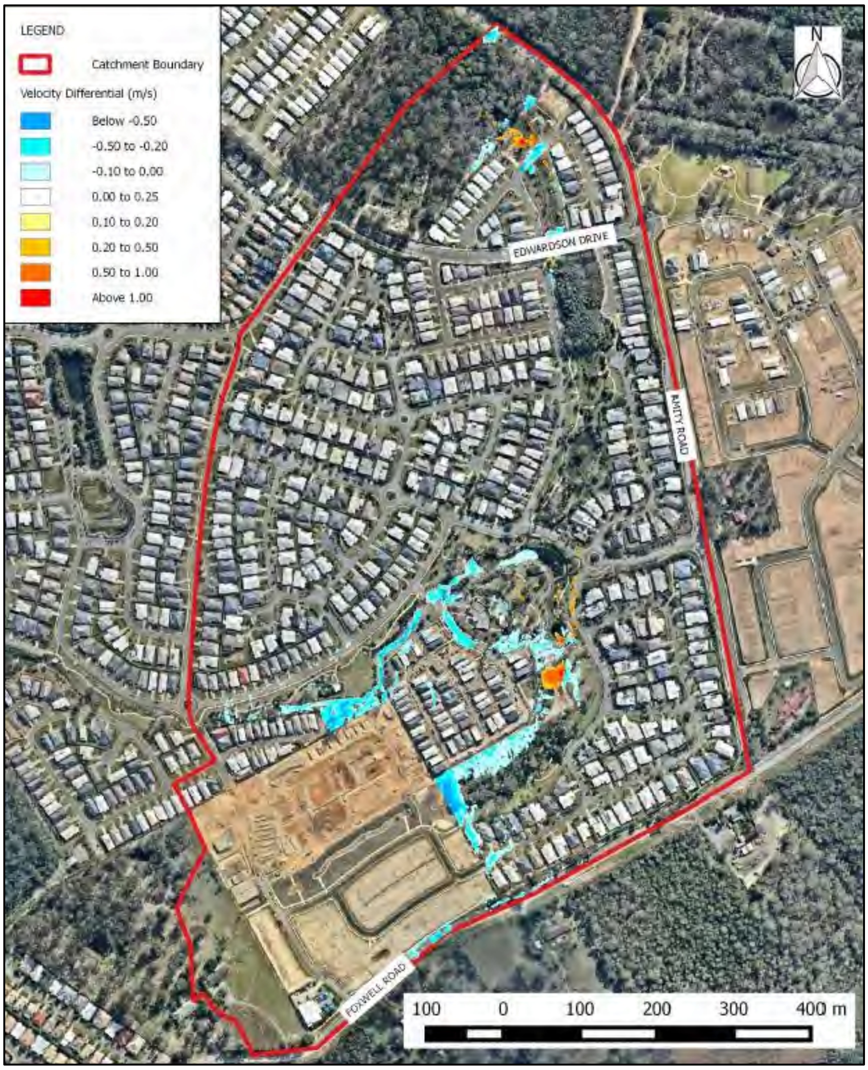

FIGURE 4-13 100YR 90MIN VELOCITY DIFFERENTIAL

4.4 HAZARD

The City of Gold Coast outlines the hazard within the City Plan, and is summarised in Figure 4-14 below (CoGC, 2016). Hazard within the region is based on the depth of flood, velocity and the depth velocity product. This is also in accordance with QUDM stormwater flow hazard (CoGC, 2016) (DNRW, 2008).

Criteria	Degree of flood hazard			
	Low	**Medium**	**High**	**Extreme**
Wading ability	If necessary children and the elderly could wade. (Generally, safe wading velocity depth product is less than 0.25.)	Fit adults can wade. (Generally, safe wading velocity depth product is less than 0.4.)	Fit adults would have difficulty wading. (Generally, where wading velocity depth product is less than 0.6.)	Wading is not an option.
Evacuation distances	<200metres	200-400metres	400-600metres	>600metres
Maximum flood depths	<0.3metres	<0.6metres	<1.2metres	>1.2metres
Maximum flood velocity	<0.4 metres per second	<0.8metres per second	<1.5metres per second	>1.5metres per second
Typical means of egress	Sedan	Sedan early, but 4WD or trucks later	4WD or trucks only in early stages, boats or helicopters	Large trucks. Boats or helicopters
Timing **Note:** **This category cannot be implemented until evacuation times have been established in the Counter Disaster Plan (flooding).**	Ample for flood forecasting. Warning and evacuation routes remain passable for twice as long as evacuation time.	Evacuation routes remain trafficable for 1.5 times as long as the evacuation time.	Evacuation routes remain trafficable for only up to minimum evacuation time.	There is insufficient evacuation time.

FIGURE 4-14 COGC HAZARD CRITERIA (COGC, 2016)

With both flooding depth and velocities being altered as a result of the implementation of the OSD systems, flow hazard was also assessed. Hazard was assessed as depth times velocity and differential plots were developed to assess the hazard impact the OSD systems had (DNRW, 2008). As was the result with velocity, hazard was generally decreased across the catchment, although significantly increased at the basin outlets. Figure 4-15 shows the hazard differential of the 100 year ARI 90 minute event, and other critical events are included at full scale in Appendix F, sections shown as clear in the catchment had negligible differences and are shown as white in the legend.

Discussion on the potential impacts of the increase hazard around the outlets of these basins is included in Chapter 5.

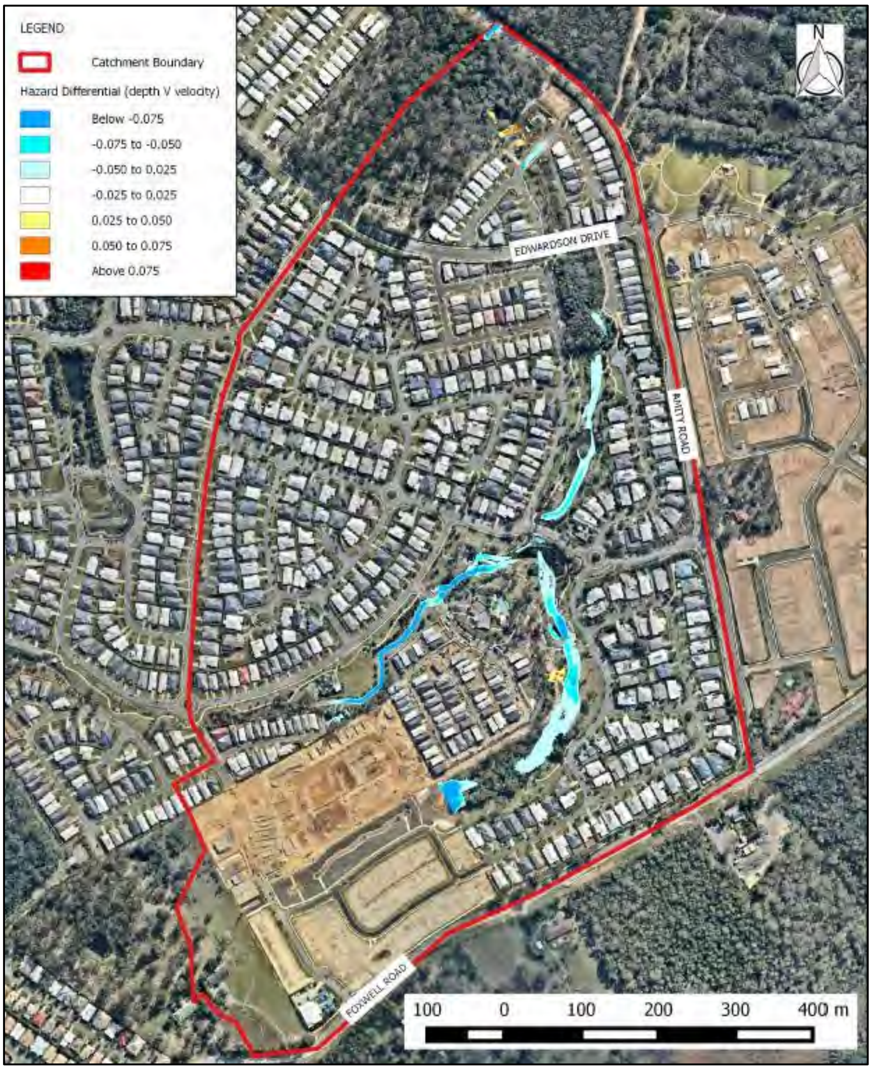

FIGURE 4-15 100YR 90MIN HAZARD DIFFERENTIAL

4.5 Comparison of Models

A comparison of the three modelling techniques was completed in Microsoft Excel, using the resultant peak flows at the catchment outlet, and at Daintree Drive.

Figure 4-16, Figure 4-17 and Figure 4-18 below show the difference between the DRM and lumped TUFLOW models at the catchment outlet, with a positive percentage difference representing higher peak flows in the lumped model when compared to the DRM. These results show that for the post developed scenarios both models had comparable results. In the pre-developed case the models produced varyingly different results, with little correlation or pattern to the difference, although the DRM model produced consistently higher flows.

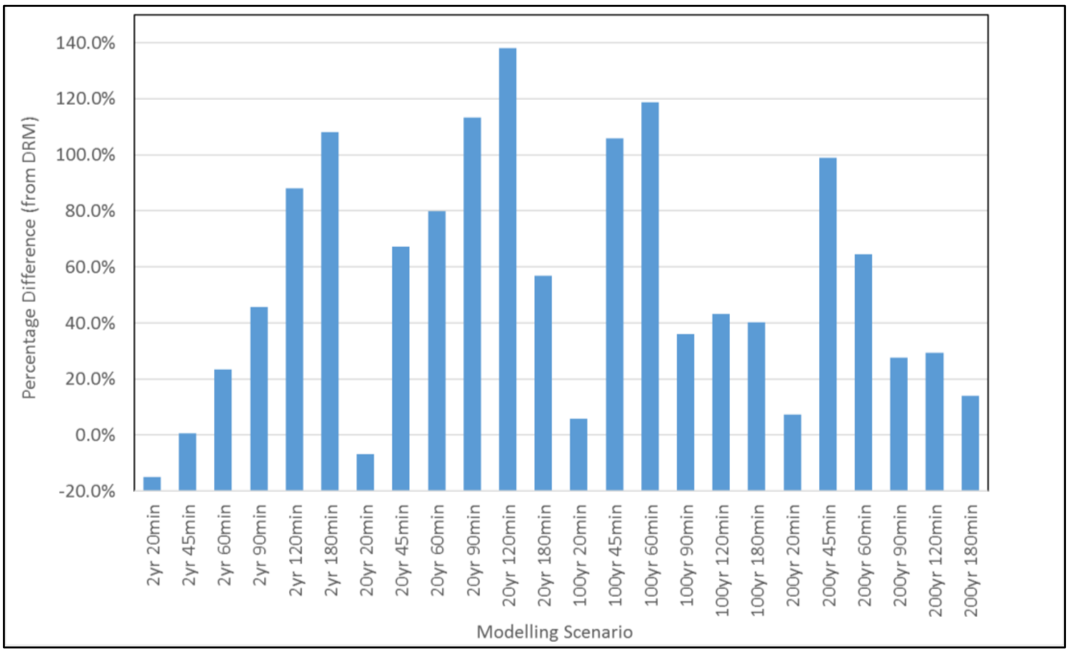

FIGURE 4-16 PRE-DEVELOPMENT MODEL DIFFERENCE DRM & LUMPED TUFLOW

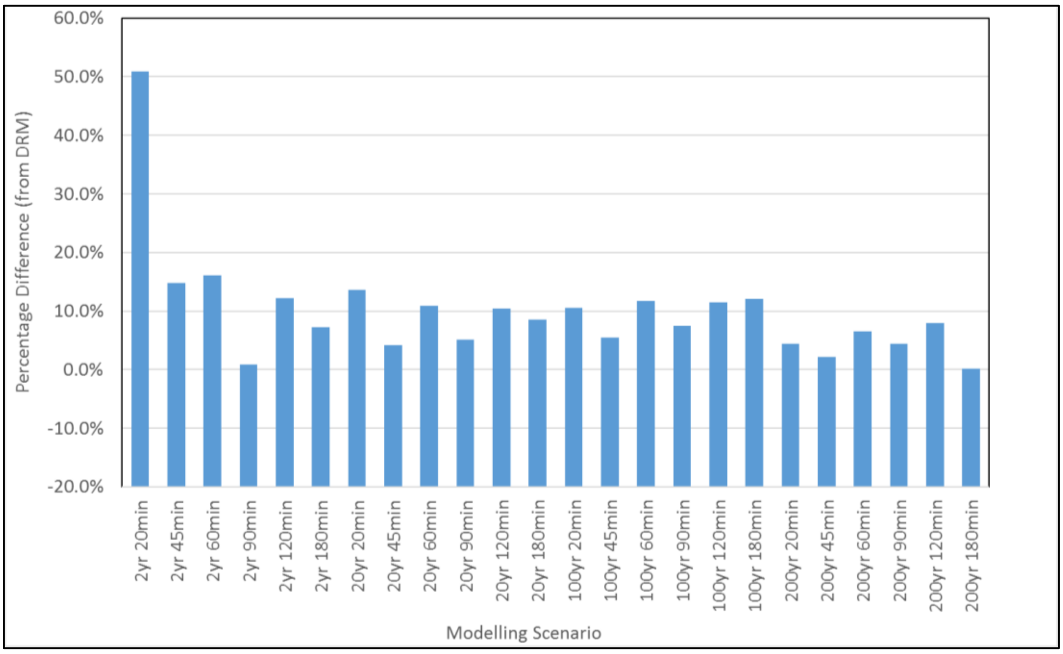

FIGURE 4-17 POST-DEVELOPMENT MODEL DIFFERENCE DRM & LUMPED TUFLOW

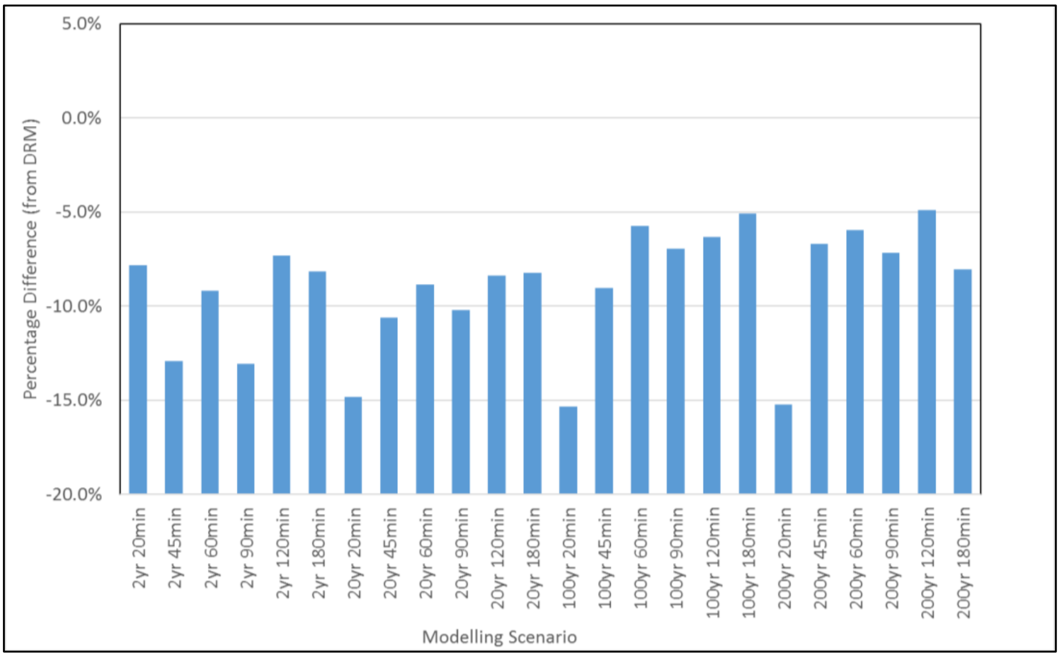

FIGURE 4-18 POST-DEVELOPMENT OSD MODEL DIFFERENCE DRM & LUMPED TUFLOW

A summary of the modelling comparison is included as Figure 4-19 and Figure 4-20, these results show that the TUFLOW models compare well on average, which represents a good calibration (between the two models), although the Lumped TUFLOW model produced lower peak flows than the DRM on average. As expected there is a large variance (standard deviation) and this variance can be seen in the data of the above figures. The XP-RAFTS model produced marginally differing results to both TUFLOW models. Further discussion on the difference in modelling and the calibration of the DRM is included within Chapter 5.

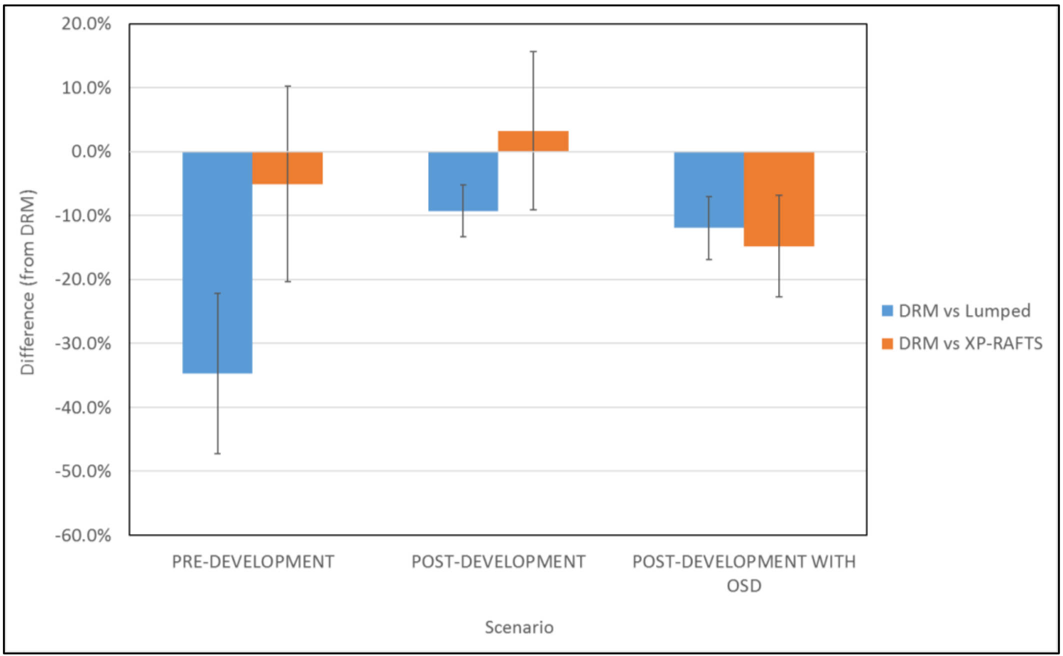

FIGURE 4-19 AVERAGE MODEL DIFFERENCE SUMMARY AT DAINTREE DRIVE

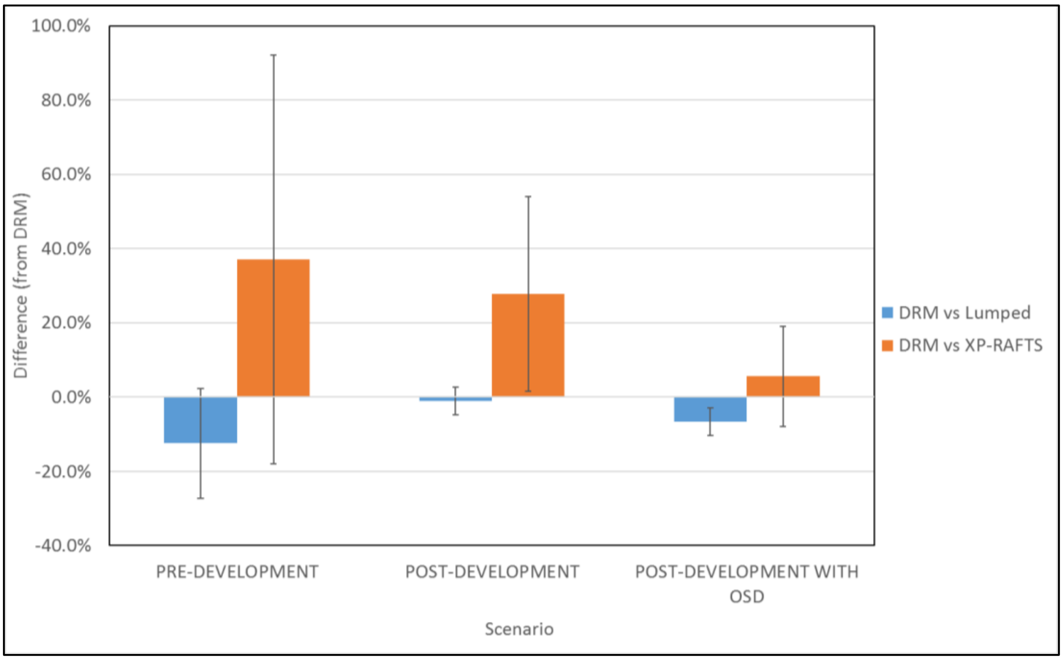

FIGURE 4-20 AVERAGE MODEL DIFFERENCE SUMMARY AT CATCHMENT OUTLET

CHAPTER 5 – DISCUSSION

5.1 OSD EFFECTIVENESS

The main objective of this study was to assess the effectiveness of OSD systems on a catchment wide scale using a DRM 2D flood model. The results of the modelling have shown that the OSD systems implemented throughout this catchment are ineffective at reducing peak stormwater flow rates to within the pre-developed peak stormwater flow rates.

As discussed in Chapter 2 the OSD systems that are the subject of this analysis were designed using 1D hydraulic modelling techniques, and a site based approach. The results of this research have shown that even with a storage multiplication factor applied to the XP-RAFTS 1D model, the peak flows were on average 10% greater than both the TUFLOW models, particularly in the pre-developed scenario. These differences between the 1D modelling technique and the 2D modelling technique highlight the need for more in depth analysis when designing OSD systems. As the designs are based on the concept of non-worsening of pre-developed flow rates, it is critical to ensure the pre-developed scenario is properly represented.

The natural storage within the surface of the catchment (the DEM), is clearly contributing to the attenuation of peak flows in the 2D models, particularly in the pre-developed scenario. As the OSD systems were designed using 1D models it is possible that the storage effects of the catchment were not properly represented in the pre-developed scenarios and as a result the OSD systems are not mitigating peak discharges to within the pre-developed level (when assessed with a 2D model). These results highlight the need for existing catchment storage assessment when designing OSD systems, as it has been shown to have a large impact on modelling results.

Figure 5-1 below shows a timeline of the flood depth results from the 100 year ARI 90 minute pre-developed scenario. This illustrates how the existing farm dam within site 1 attenuates peak discharges in the pre-developed condition. It is possible this storage effect was unnoticed during the 1D analysis of the site, and highlights the need for multiple modelling techniques when developing flood/discharge measures within a drainage catchment.

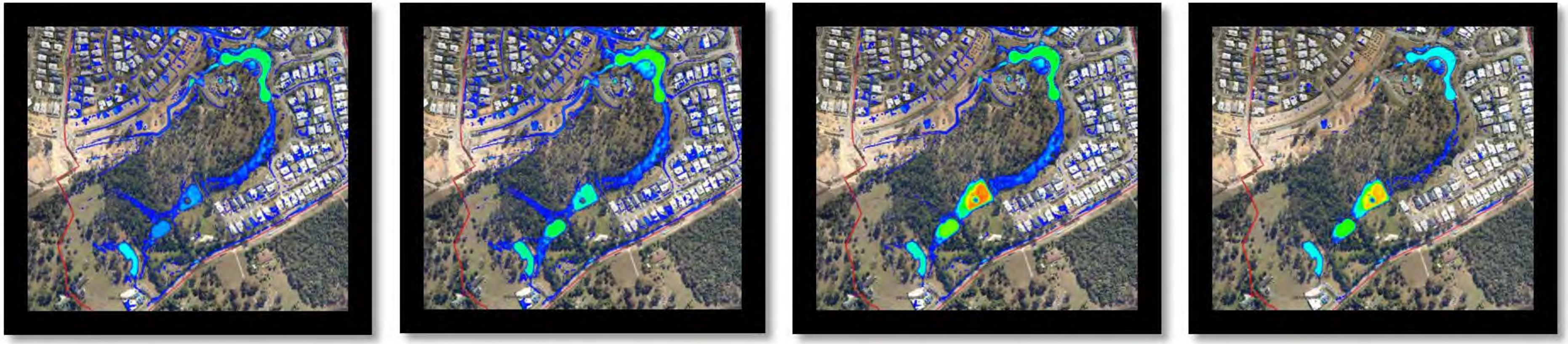

FIGURE 5-1 PRE-DEVELOPMENT EXISTING STORAGE

The reduction of storage within the catchment as a result of the developments within this catchment have contributed to the large increase in flows. It was calculated that the 6 development sites resulted in a loss of catchment storage of approximately 32,000m^3. It should be noted that it is a CoGC requirement to ensure that any development that falls within the extents of a 100yr ARI regional flood event achieves a flood storage balance, i.e. no decrease in flood plain storage. The results of this research show that the loss in storage of a stormwater conveyance network can have a large impact on peak discharges, similar to the flooding impacts of filling in a flood plain.

The OSD systems did slightly mitigate peak discharges, with a peak flow reduction of approximately 1% at the catchment outlet during the critical 100yr ARI event from the implementation of the 6 OSD systems, which is in keeping with the findings of the literature (Beecham, et al., 2005).

The OSD systems caused an increase in peak discharges during the low ARI events (2yr and 20yr), this could be due to delay in discharges from each sub-catchment caused by the OSD outlets. The low level outlets of the OSD systems are typically designed for low ARI events, therefore the falling limb of the resultant hydrograph is more likely to have a negative effect on a catchment scale during these events, this is in keeping with the above literature (Beecham, et al., 2005).

Although peak discharges were not mitigated to within the pre-developed level, and reductions of only 1% were achieved, the OSD systems were effective at reducing peak flood levels and hazard over roads within the catchment, with a reduction of approximately 50mm during the critical 100yr ARI event over some roads.

As a result of implementing OSD systems throughout the catchment stormwater discharges and velocities were locally increased around the outlets, which also resulted in significant increase in hazard. At other locations throughout the catchment, depths, velocity and hazard were reduced. It is important to note that it is common for OSD systems within the CoGC region to be designed using a site based analysis, and they are typically positioned at the lowest point of a site, which is often adjacent a road (unlike the subject catchment). The modelling showed increases of flooding hazard (depth velocity product) of up to 0.05 during the 100 year ARI critical event, and as shown in Figure 4-14 slight increases in depth velocity product has a large impact on the categorisation of hazard. With large increases in hazard around OSD outlets, particularly in large ARI events, it should be considered by local authorities and designers how best to appropriately manage this.

5.2 MODELLING

As discussed above the methodology adopted in this research has many constraints, in particular risk of human error where trying to replicate design modelling from published reports. Any errors in modelling may have contributed to the discrepancies in the above mentioned results. Assumptions in catchment delineation from the 1D modelling and lumped TUFLOW approach clearly impacts on catchment wide analysis, with modelling differences between these methods and the DRM improving as the downstream catchment boundary is approached. This shows a difference between the delineation assumed and the automatic routing of the DRM.

The three modelling techniques produced varying results, although it can be assumed the storage multiplication factor applied to the XP-RAFTS model and the lumped TUFLOW model achieved a reasonable calibration to the DRM. It should be noted that this approach is not ideal, and further research should be completed within a gauged catchment to allow for accurate calibration of models.

5.3 FURTHER RESEARCH

This study has highlighted the need for further research. As discussed above this project was heavily dictated by time and budget constraints, and as such further requirements have been highlighted. Research is required to assess the difference in effectiveness between a regional detention system and OSD systems. It has been made evident through this research that OSD systems are ineffective at mitigating peak discharges to within a pre-developed level on a catchment wide scale, although the effectiveness of a regional system was not explored.

This study has highlighted the need for further research into difference between modelling techniques. A gauged catchment where accurate calibration of modelling techniques would be more appropriate for research on modelling techniques. The storage factor applied in the XP-RAFTS and lumped TUFLOW models of this research was utilised to ensure comparative results between the three techniques, although these models were not calibrated in any other way.

A catchment wide analysis of OSD systems using DRM 2D modelling would be more accurate where the systems are implemented into the DEM and using 1D elements within the 2D domain. This would require a finer grid and a budget that allowed for detailed survey of the constructed OSD systems, so they could be integrated into the 2D surface.

CHAPTER 6 – CONCLUSION

The purpose of this project was to investigate the catchment wide effects of implementing On-Site Detention (OSD) systems on an urban drainage catchment using a Direct Rainfall Method 2D hydraulic model.

The research was completed within a catchment in Coomera, QLD, in the City of Gold Coast region. Within this region OSD systems are typically developed using a site based 1D modelling approach.

This research has highlighted that different modelling approaches (1D and 2D) produce vastly differing results when analysing or designing detention systems. This confirms the need for engineers and practitioners to remain aware of the constraints, strengths and weaknesses of each approach, and additionally confirms the need for further research into the differences between these techniques.

This research has shown that implementing OSD using a site based analysis is not always an effective approach, when an entire catchment is taken into consideration. It has been shown that the catchment wide effects of multiple OSD systems can be unpredictable and hard to calculate, and that a site based approach to stormwater management can cause varying (sometimes negative) impacts throughout an entire catchment. This has further highlighted the need for local government policy reform to allow for more accurate engineering techniques and to move away from these site based approaches.

Engineers and practitioners have multiple tools and techniques at their disposal, to constrain them to a site based approach has been shown to be ineffective, especially when so much data is readily available to accurately and cheaply analyse an entire drainage catchment.

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Appendix A. PROJECT SPECIFICATION

ENG4111/4112 Research Project
Project Specification

For: Jonathan Cuell
Title: Effects of On Site Detention Systems on Urban Drainage Catchments
Major: Civil Engineering
Supervisors: Ian Brodie
Philip Bell, Burchills Engineering Solutions Pty Ltd
Damian Graham, Burchills Engineering Solutions Pty Ltd
Sponsorship: Burchills Engineering Solutions Pty Ltd
Enrolment: ENG4111 – EXT S1, 2016
ENG4112 – EXT S2, 2016

Project Aim: The aim of this project is do an analysis of an urban drainage catchment and the effects of on-site stormwater detention systems that are often implemented and designed without consideration of the greater drainage catchment.

Programme: Issue B, 17th March 2016

1. Research the existing processes for detention basin design and planning;
2. Research on-site detention and peak flow mitigation policies within councils across Australia;
3. Select an appropriate urban drainage catchment, that is suited to medium density development and delineate sub-drainage catchments including sub-drainage catchment slopes and current and future land-use.
4. Build a hydrological model using the XPRAFTS hydrological model software;
    a. During this analysis critical storm durations for each sub-drainage catchment will be determined;
    b. The 50, 5, 1 and 0.5 % Annual Exceedance Probability (AEP) design storm events will be estimated and hydrographs produced to be used in the hydraulic model.
5. Build a 2D fully dynamic hydraulic model, using the TUFLOW modelling software, of the catchment and complete analysis of existing conditions for 50, 5 ,1 and 0.5% AEP;
    a. Within this model any existing hydraulic and drainage infrastructure will be modelled as a fully linked 1D to 2D network;
    b. Define land-use area and Manning's n values
    c. Develop a DEM using a GIS.
    d. Set upstream and downstream boundary conditions.
6. Design detention systems within 30% of the developable area within the drainage catchment;
    a. The development sites will be selected at random and should be spread evenly throughout the drainage catchment;
    b. Detention systems will be designed using standard sizing techniques (XPRAFTS modelling) to meet the local councils and QUDM requirements.

7. Build a TUFLOW model of the post developed scenario implementing the designed OSD systems into the catchment, and complete analysis of the 50, 5, 1 and 0.5 % AEP, and assess the impacts of the OSD systems of this drainage catchment and upstream and downstream.

If time and resources permit:

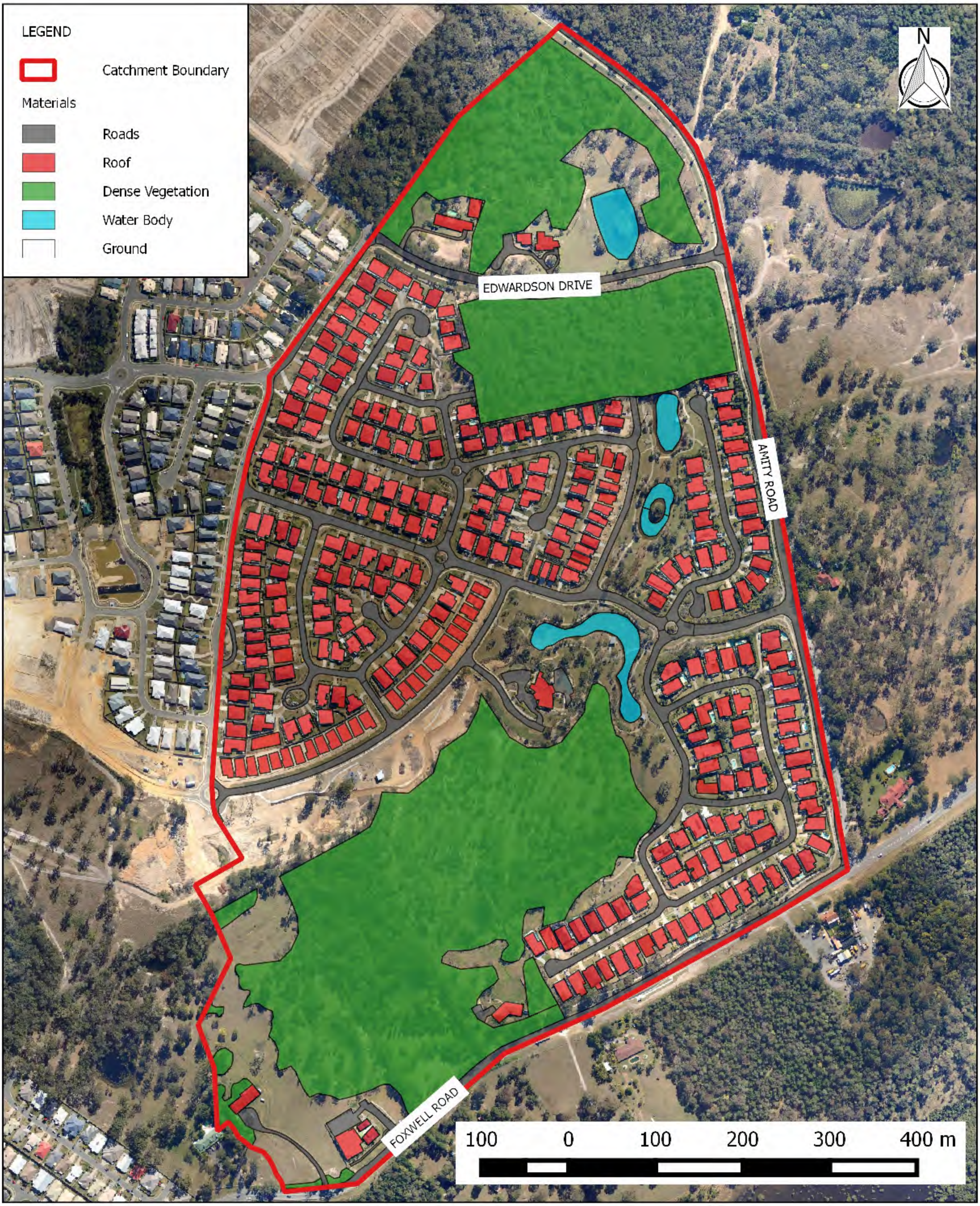
8. Run extra scenarios with more developed area and more OSD systems
9. Run scenario with real rain event obtained from Bureau of Meteorology Data
10. Complete model of another catchment that has differing parameters (i.e. slope, size, shape etc)

Appendix B. CATCHMENT DELINEATION MAPS

ENG4111-ENG4112 - RESEARCH PROJECT
FIGURE B.1
PRE-DEVELOPMENT CATCHMENT PLAN

PROJECTION: GDA94 / MGA ZONE 56
DATE: OCTOBER 2016

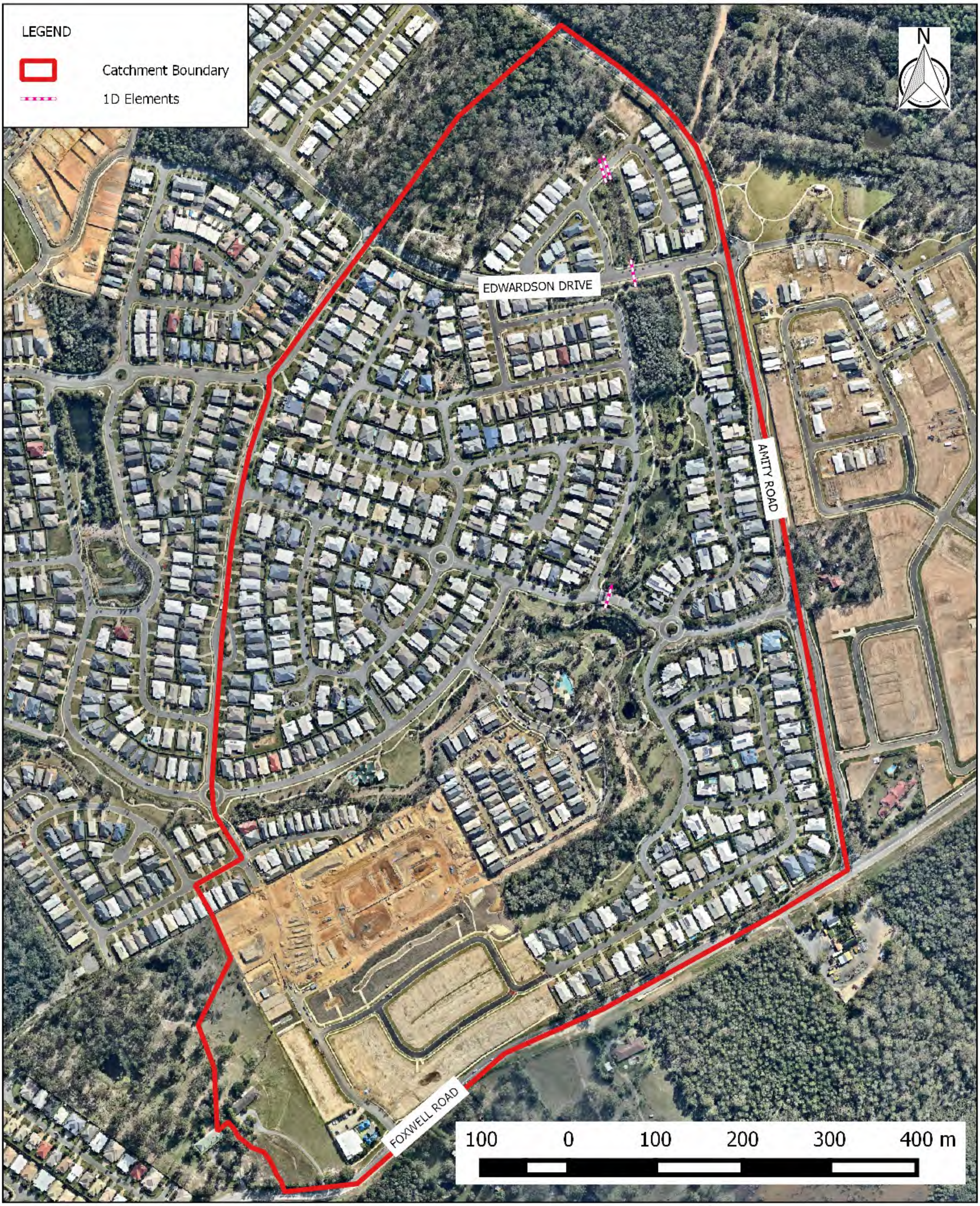
UNIVERSITY OF SOUTHERN QUEENSLAND



ENG4111-ENG4112 - RESEARCH PROJECT
FIGURE B.2
PRE-DEVELOPMENT
CATCHMENT MATERIALS

PROJECTION: GDA94 / MGA ZONE 56
DATE: OCTOBER 2016

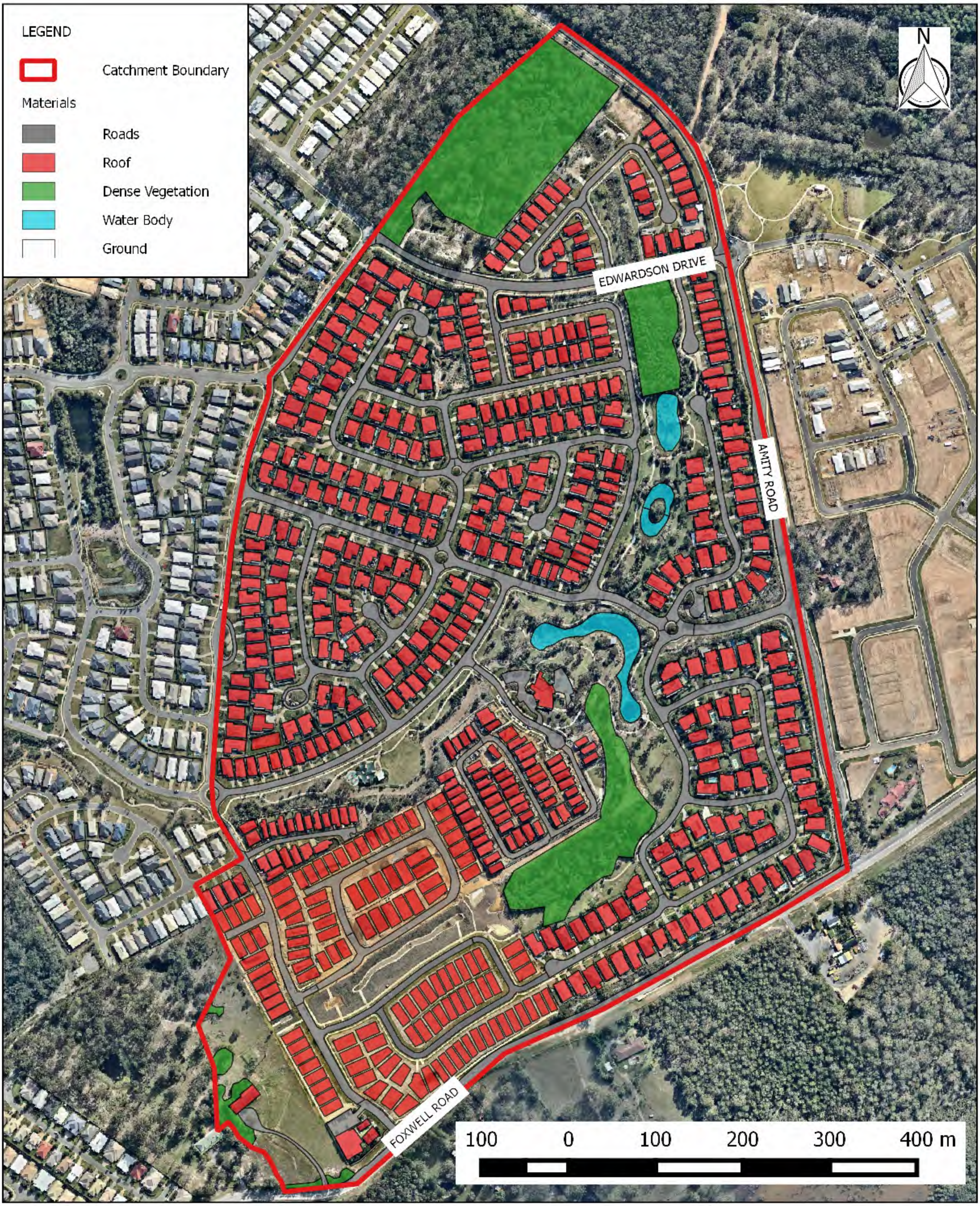
UNIVERSITY OF SOUTHERN QUEENSLAND



ENG4111-ENG4112 - RESEARCH PROJECT
FIGURE B.3
POST-DEVELOPMENT
CATCHMENT PLAN

PROJECTION: GDA94 / MGA ZONE 56
DATE: OCTOBER 2016

UNIVERSITY OF SOUTHERN QUEENSLAND



ENG4111-ENG4112 - RESEARCH PROJECT
FIGURE B.4
POST-DEVELOPMENT CATCHMENT MATERIALS

PROJECTION: GDA94 / MGA ZONE 56
DATE: OCTOBER 2016

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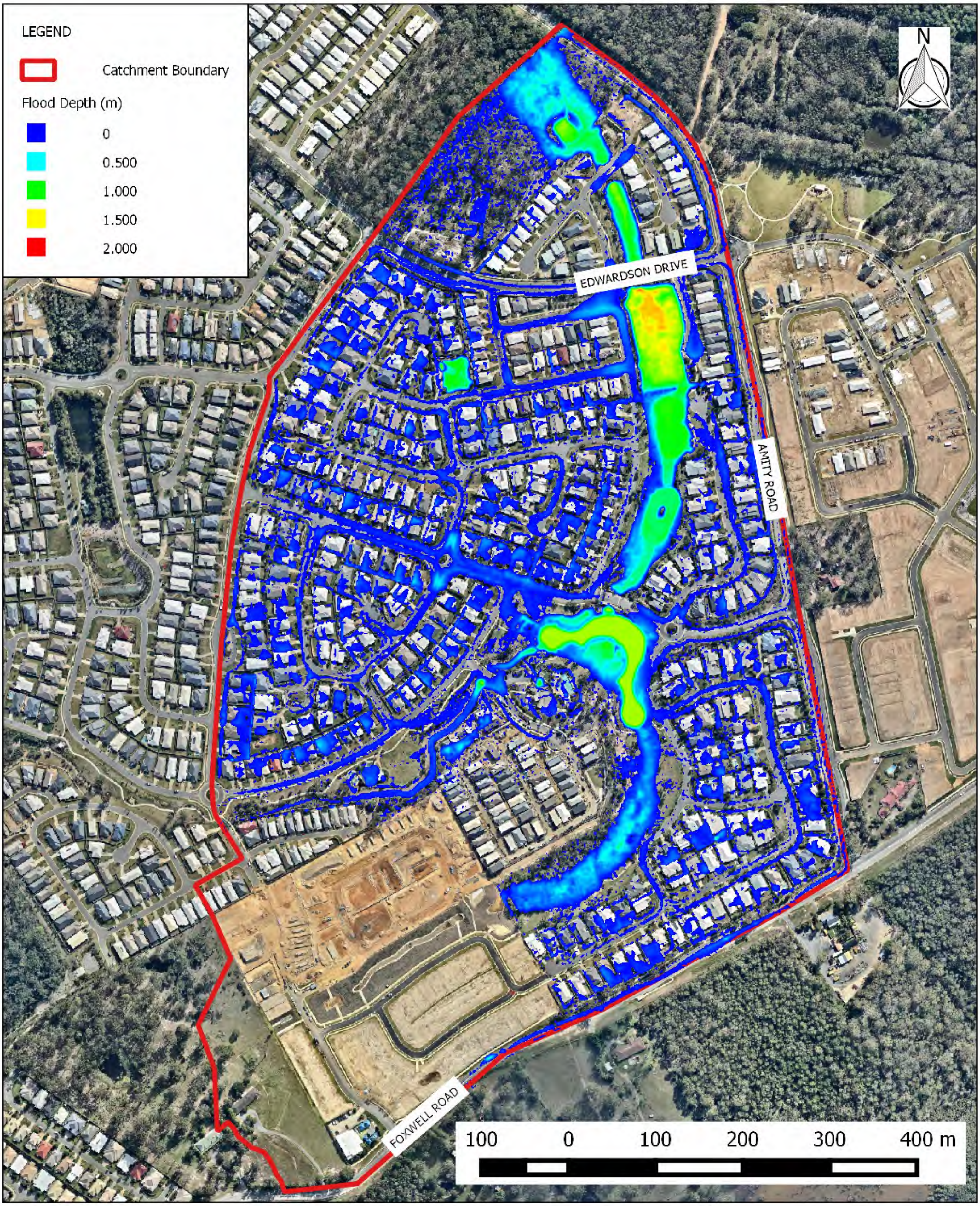
Appendix C. RESULTANT FLOOD DEPTHS - CRITICAL DURATION



ENG4111-ENG4112 - RESEARCH PROJECT
FIGURE C.1
POST-DEVELOPMENT WITH OSD SYSTEMS
FLOOD DEPTH - 100YR ARI 90MIN

PROJECTION: GDA94 / MGA ZONE 56
DATE: OCTOBER 2016

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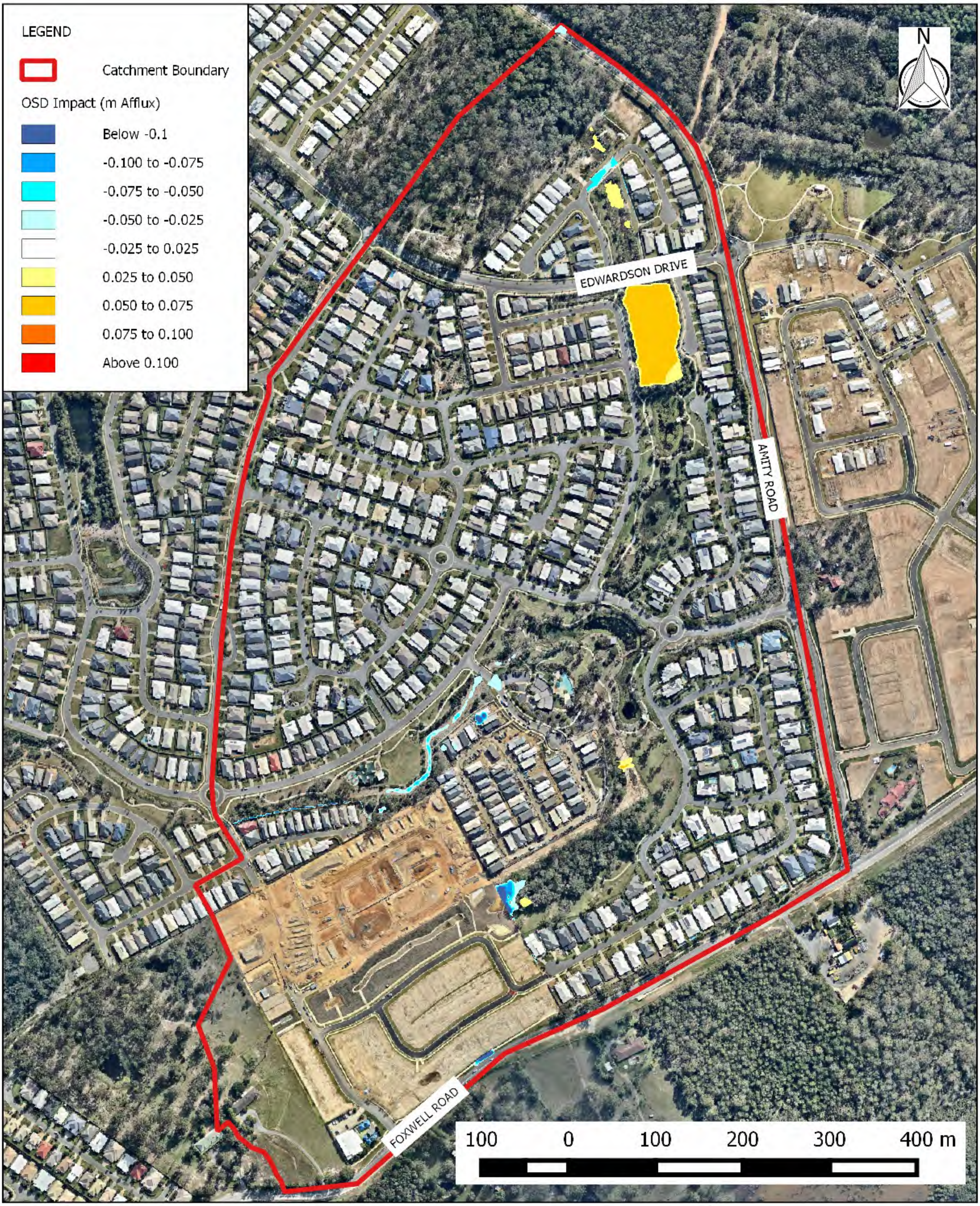
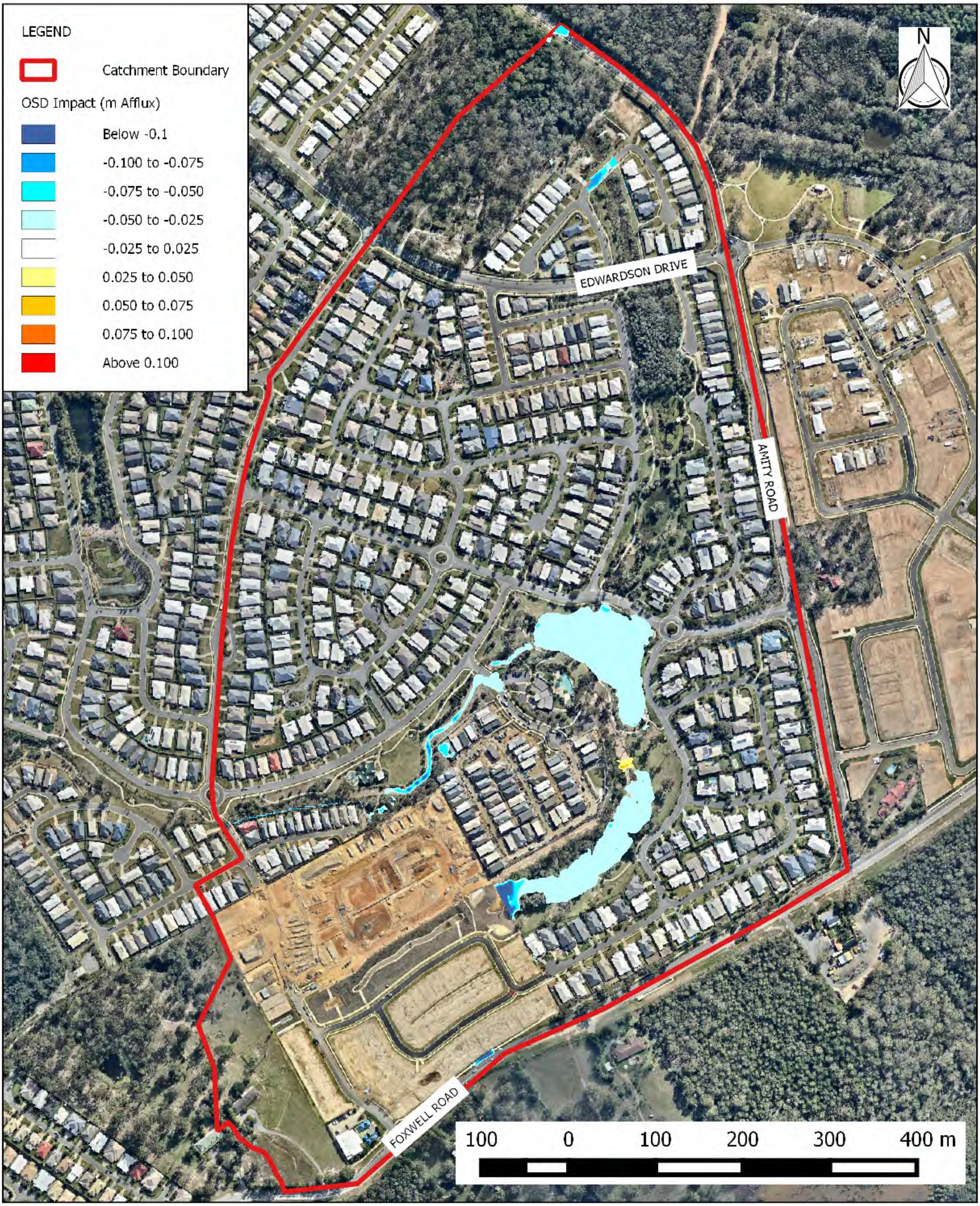


ENG4111-ENG4112 - RESEARCH PROJECT
FIGURE C.2
POST-DEVELOPMENT
OSD FLOOD LEVEL IMPACT - 2YR ARI 90MIN

PROJECTION: GDA94 / MGA ZONE 56
DATE: OCTOBER 2016

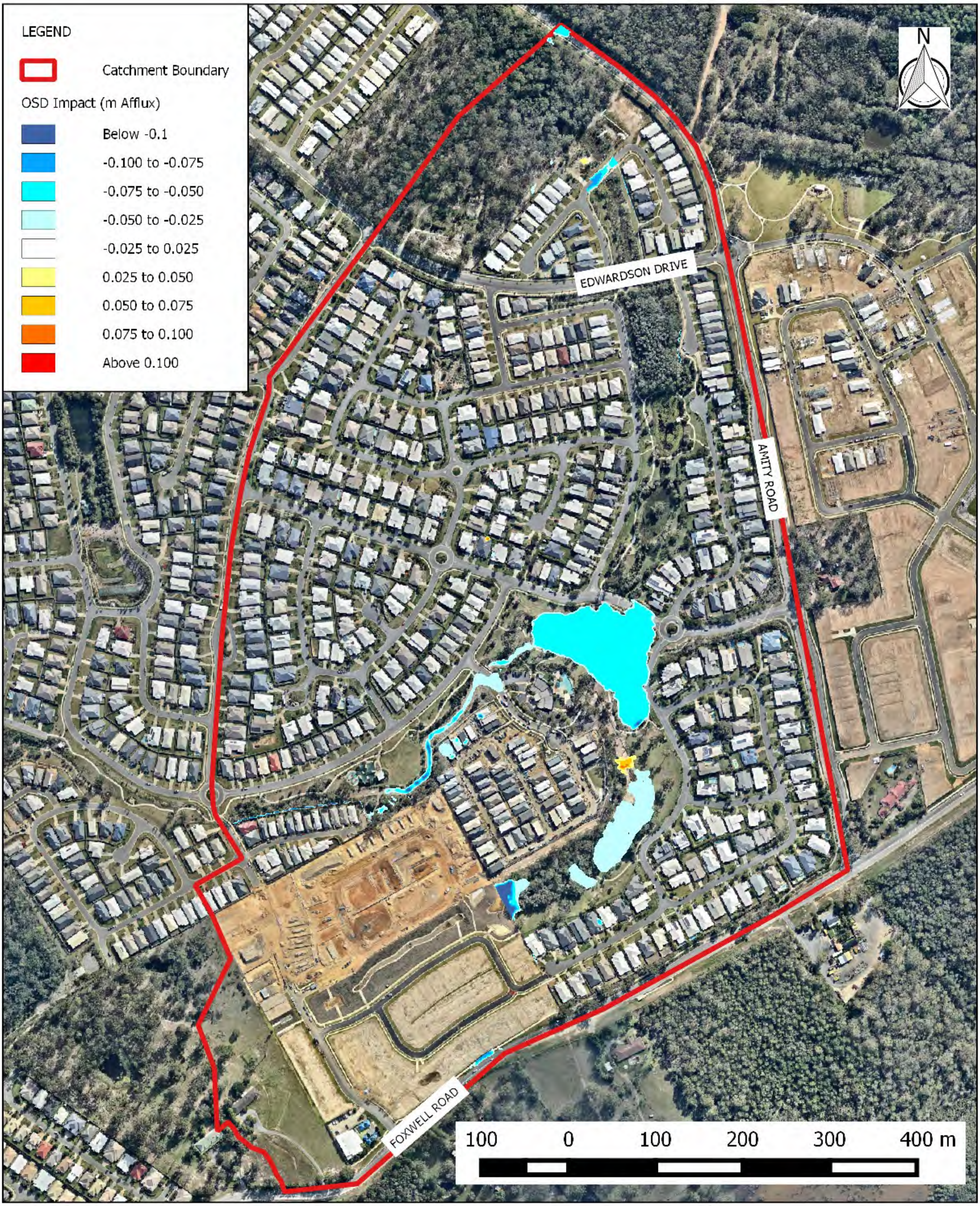
UNIVERSITY OF SOUTHERN QUEENSLAND



ENG4111-ENG4112 - RESEARCH PROJECT
FIGURE C.3
POST-DEVELOPMENT
OSD FLOOD LEVEL IMPACT - 20YR ARI 90MIN

PROJECTION: GDA94 / MGA ZONE 56
DATE: OCTOBER 2016

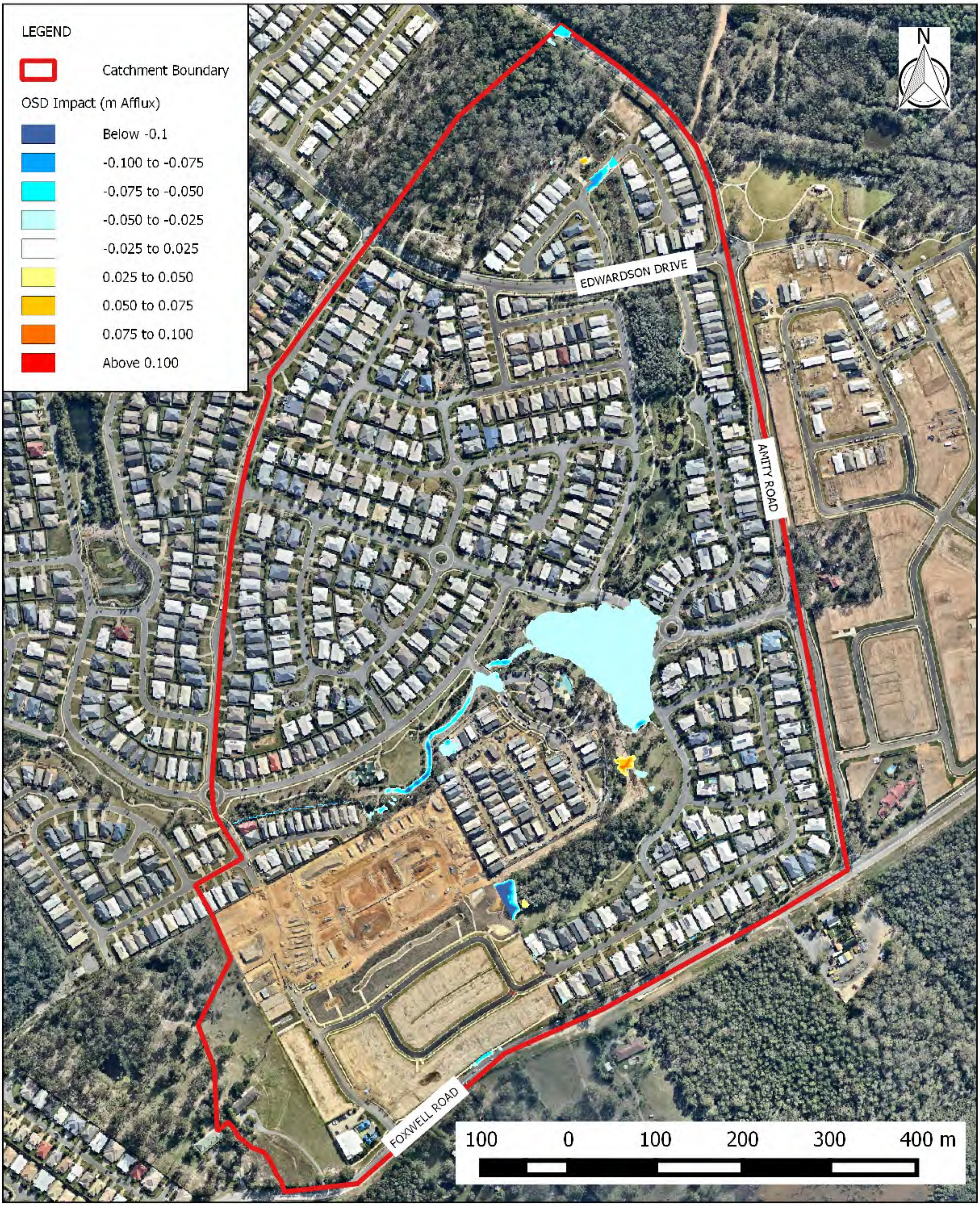
UNIVERSITY OF SOUTHERN QUEENSLAND



ENG4111-ENG4112 - RESEARCH PROJECT
FIGURE C.4
POST-DEVELOPMENT
OSD FLOOD LEVEL IMPACT - 100YR ARI 90MIN

PROJECTION: GDA94 / MGA ZONE 56
DATE: OCTOBER 2016

UNIVERSITY OF SOUTHERN QUEENSLAND



ENG4111-ENG4112 - RESEARCH PROJECT
FIGURE C.5
POST-DEVELOPMENT
OSD FLOOD LEVEL IMPACT - 200YR ARI 90MIN

PROJECTION: GDA94 / MGA ZONE 56
DATE: OCTOBER 2016

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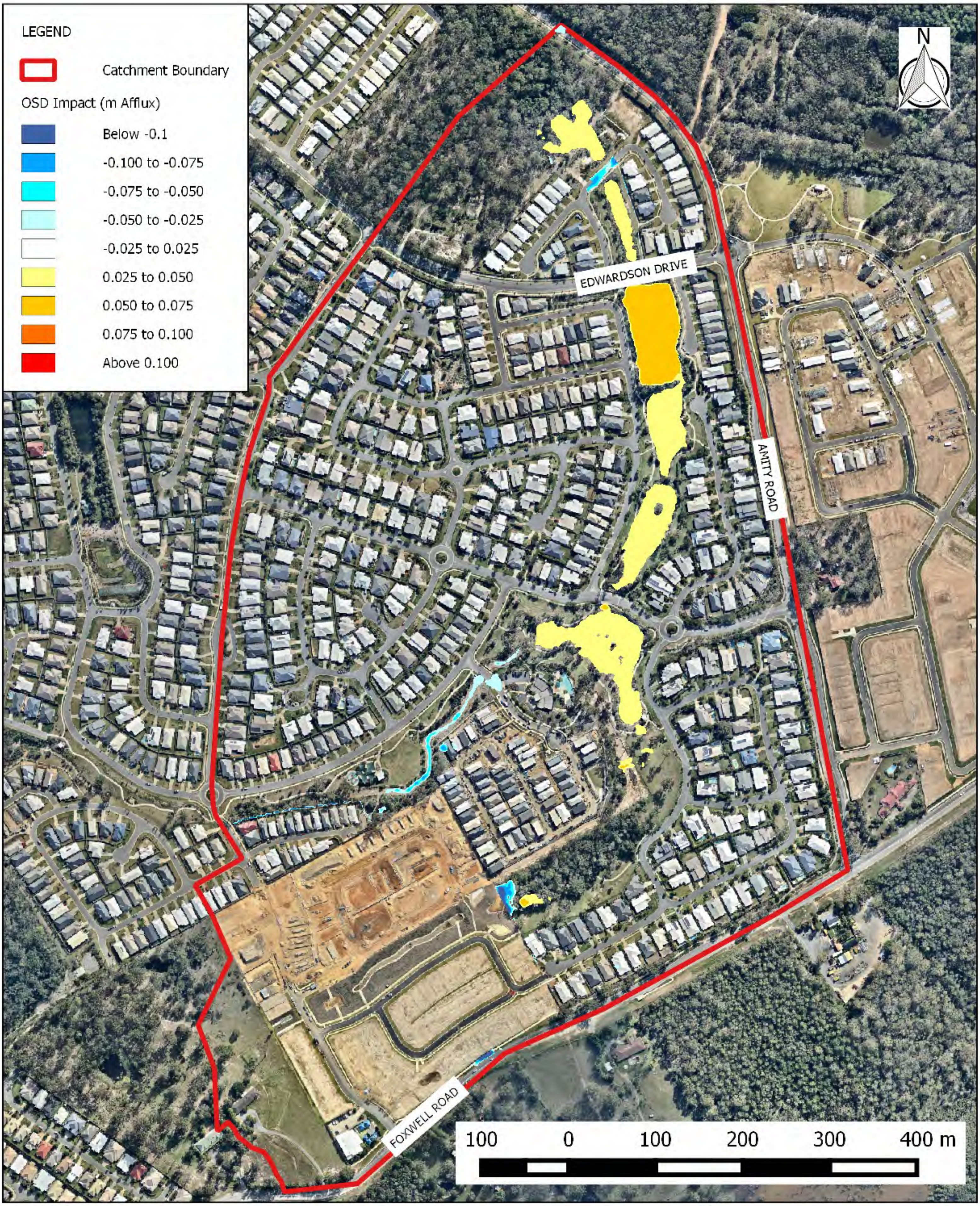
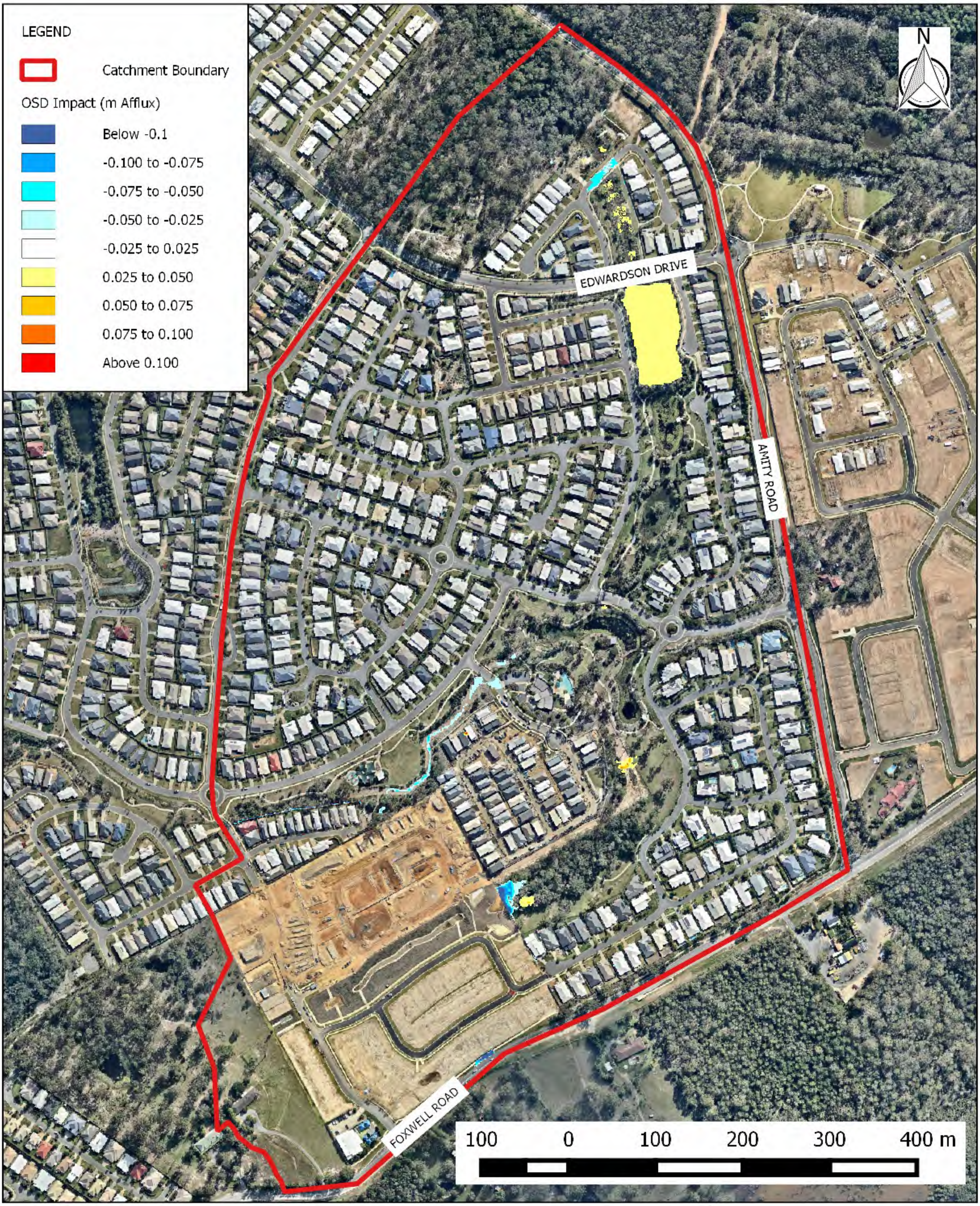
Appendix D. RESULTANT FLOOD DEPTHS – OUTSIDE CRITICAL DURATION



ENG4111-ENG4112 - RESEARCH PROJECT
FIGURE D.1
POST-DEVELOPMENT
OSD FLOOD LEVEL IMPACT - 2YR ARI 45MIN

PROJECTION: GDA94 / MGA ZONE 56
DATE: OCTOBER 2016

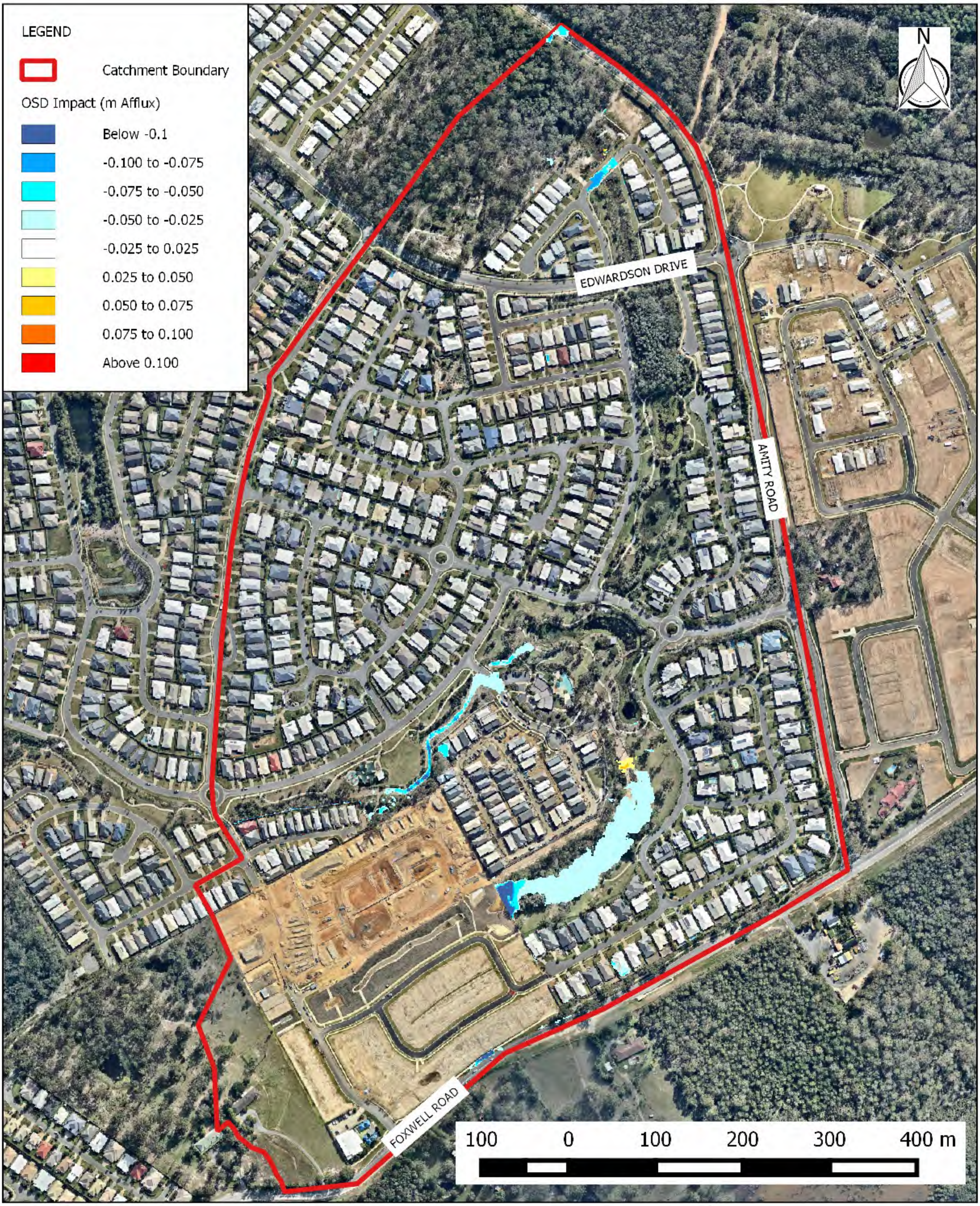
UNIVERSITY OF SOUTHERN QUEENSLAND



ENG4111-ENG4112 - RESEARCH PROJECT
FIGURE D.2
POST-DEVELOPMENT
OSD FLOOD LEVEL IMPACT - 2YR ARI 180MIN

PROJECTION: GDA94 / MGA ZONE 56
DATE: OCTOBER 2016

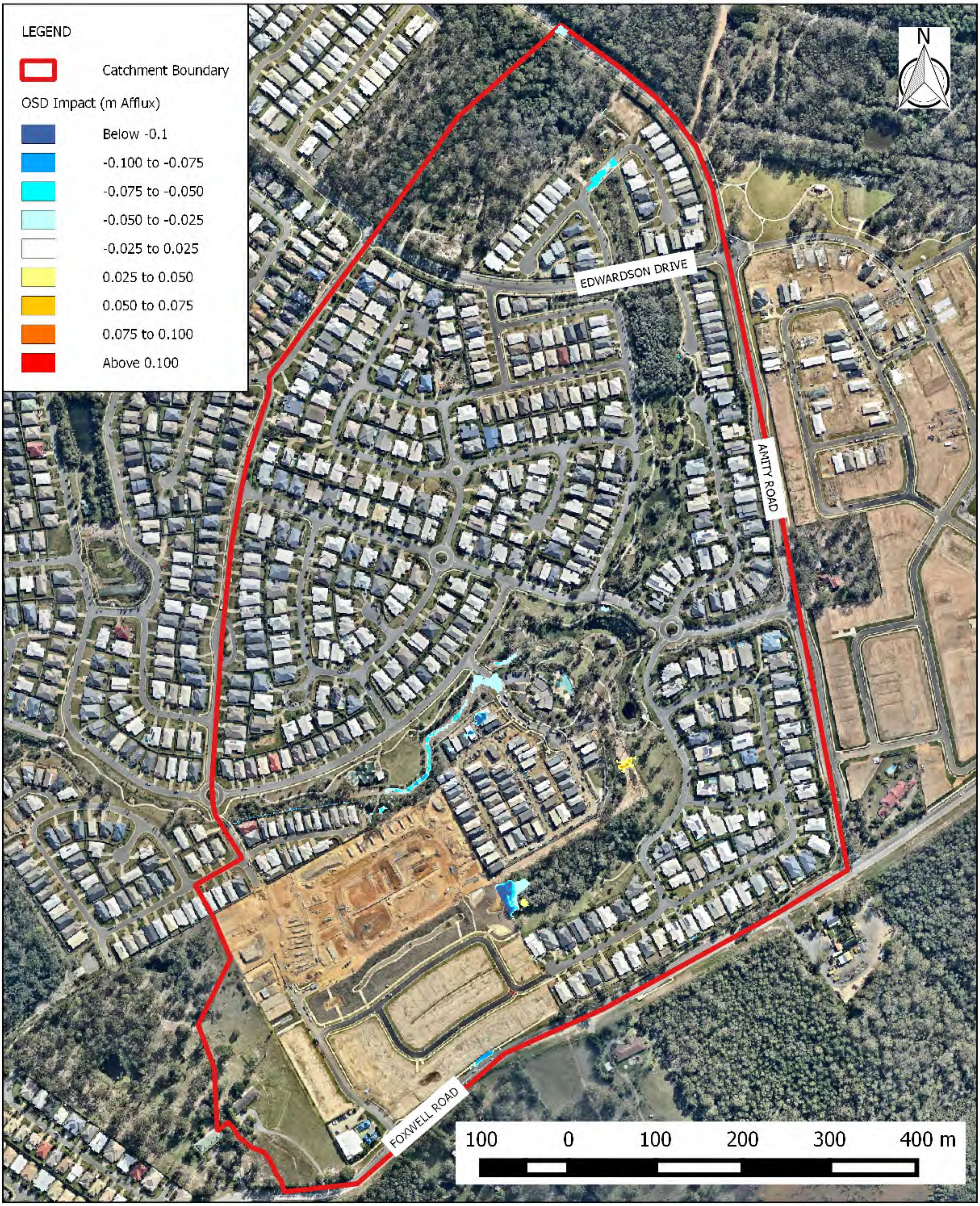
UNIVERSITY OF SOUTHERN QUEENSLAND



ENG4111-ENG4112 - RESEARCH PROJECT
FIGURE D.3
POST-DEVELOPMENT
OSD FLOOD LEVEL IMPACT - 20YR ARI 45MIN

PROJECTION: GDA94 / MGA ZONE 56
DATE: OCTOBER 2016

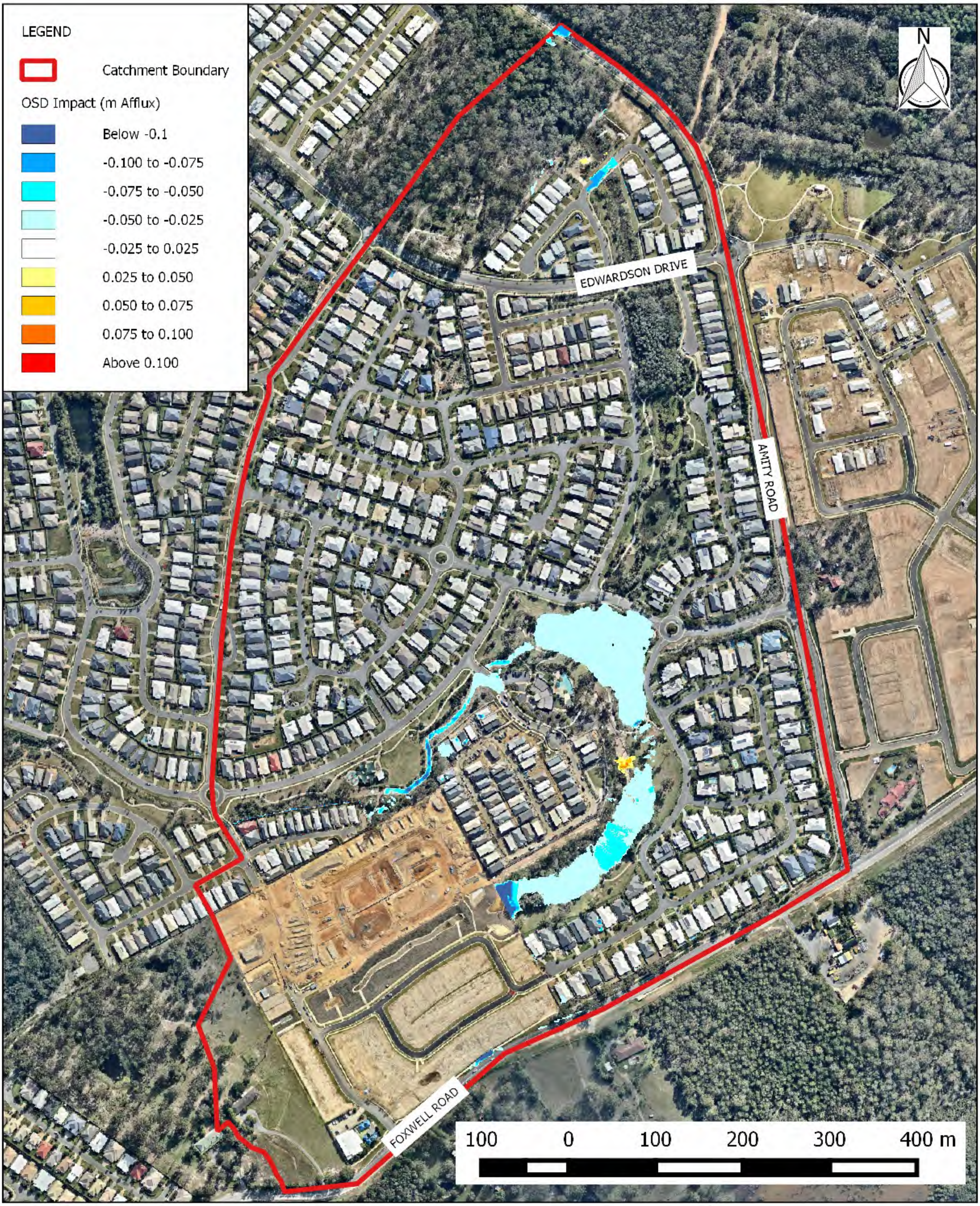
UNIVERSITY OF SOUTHERN QUEENSLAND



ENG4111-ENG4112 - RESEARCH PROJECT
FIGURE D.4
POST-DEVELOPMENT
OSD FLOOD LEVEL IMPACT - 20YR ARI 180MIN

PROJECTION: GDA94 / MGA ZONE 56
DATE: OCTOBER 2016

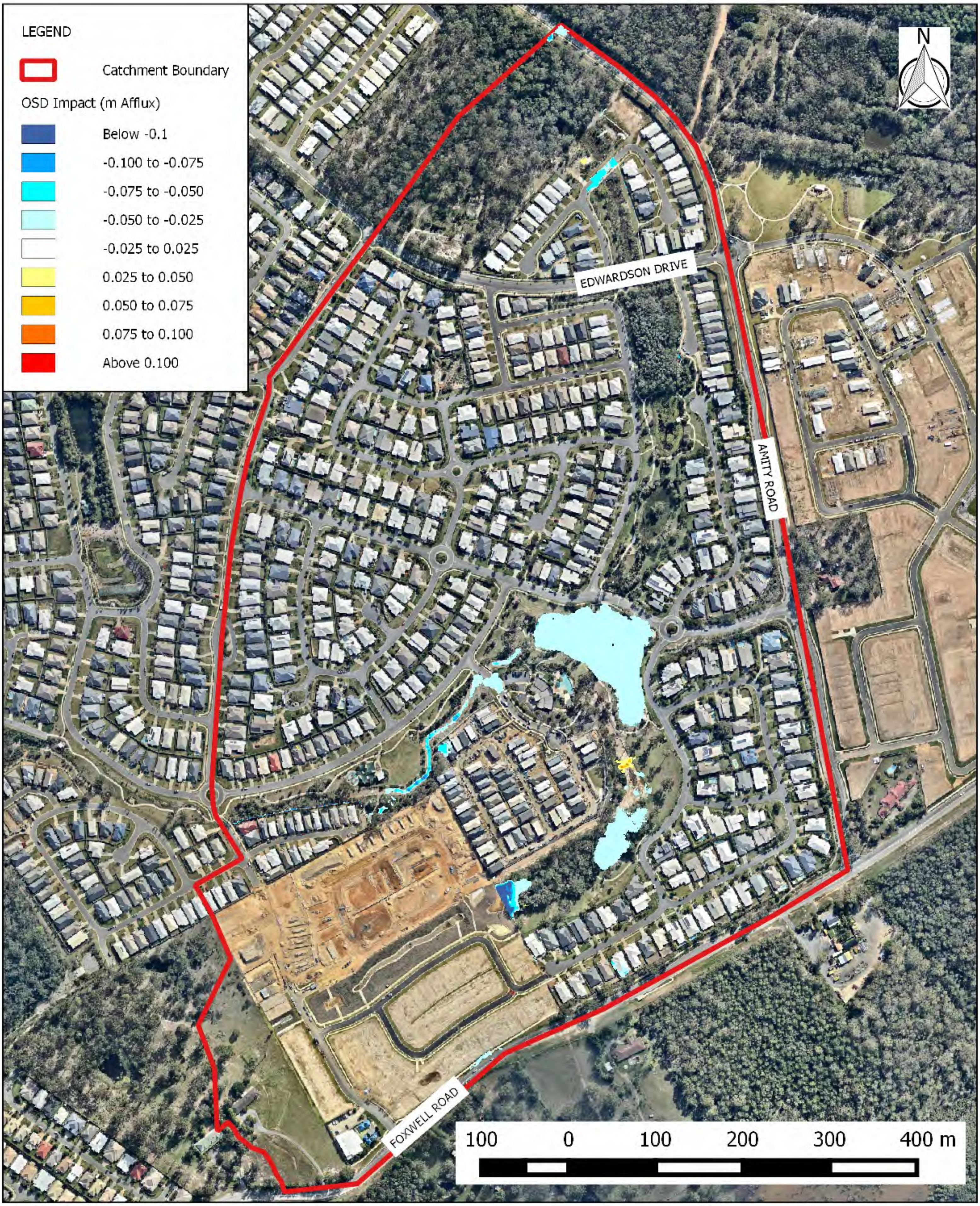
UNIVERSITY OF SOUTHERN QUEENSLAND



ENG4111-ENG4112 - RESEARCH PROJECT
FIGURE D.5
POST-DEVELOPMENT
OSD FLOOD LEVEL IMPACT - 100YR ARI 45MIN

PROJECTION: GDA94 / MGA ZONE 56
DATE: OCTOBER 2016

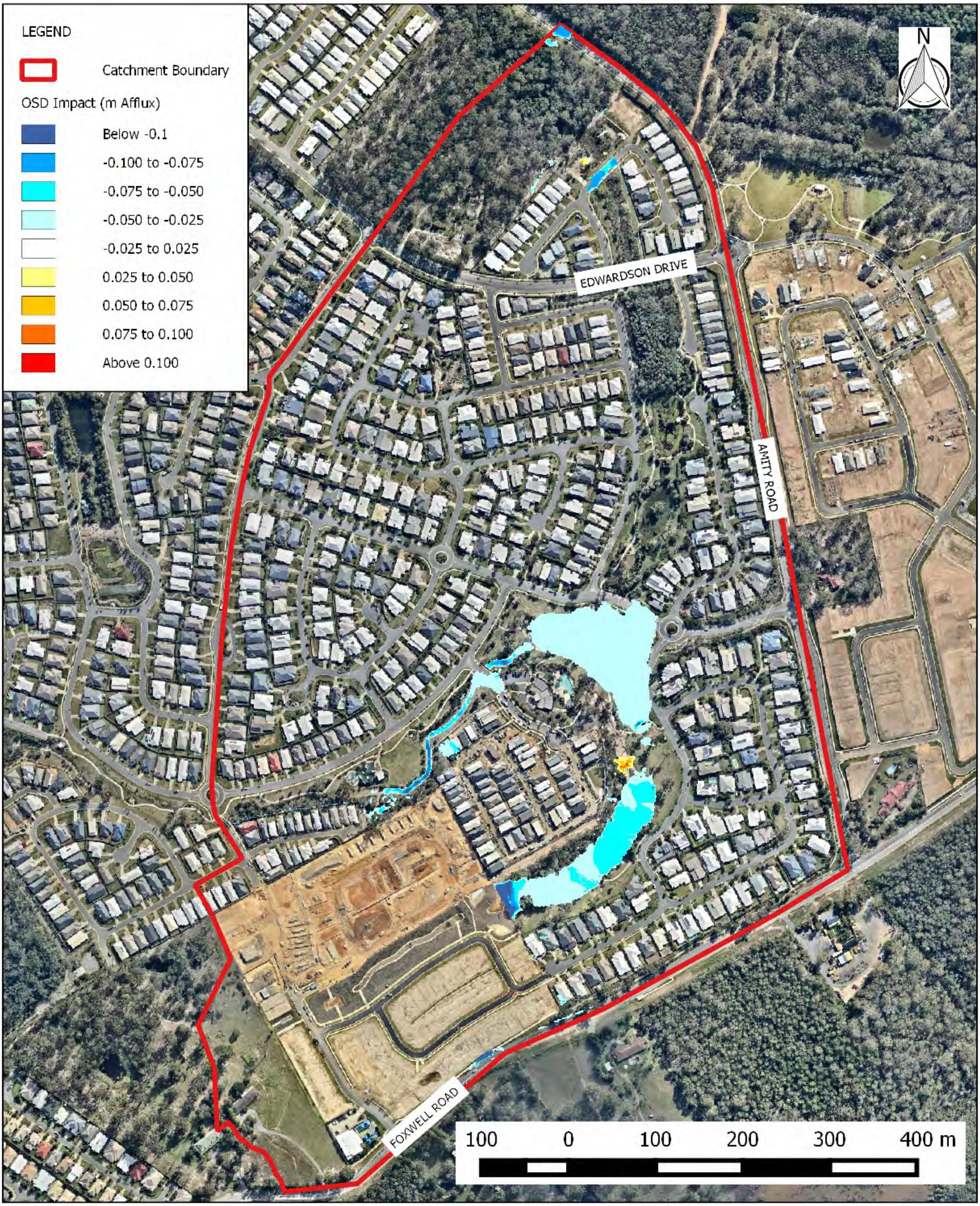
UNIVERSITY OF SOUTHERN QUEENSLAND



ENG4111-ENG4112 - RESEARCH PROJECT
FIGURE D.6
POST-DEVELOPMENT
OSD FLOOD LEVEL IMPACT - 100YR ARI 180MIN

PROJECTION: GDA94 / MGA ZONE 56
DATE: OCTOBER 2016

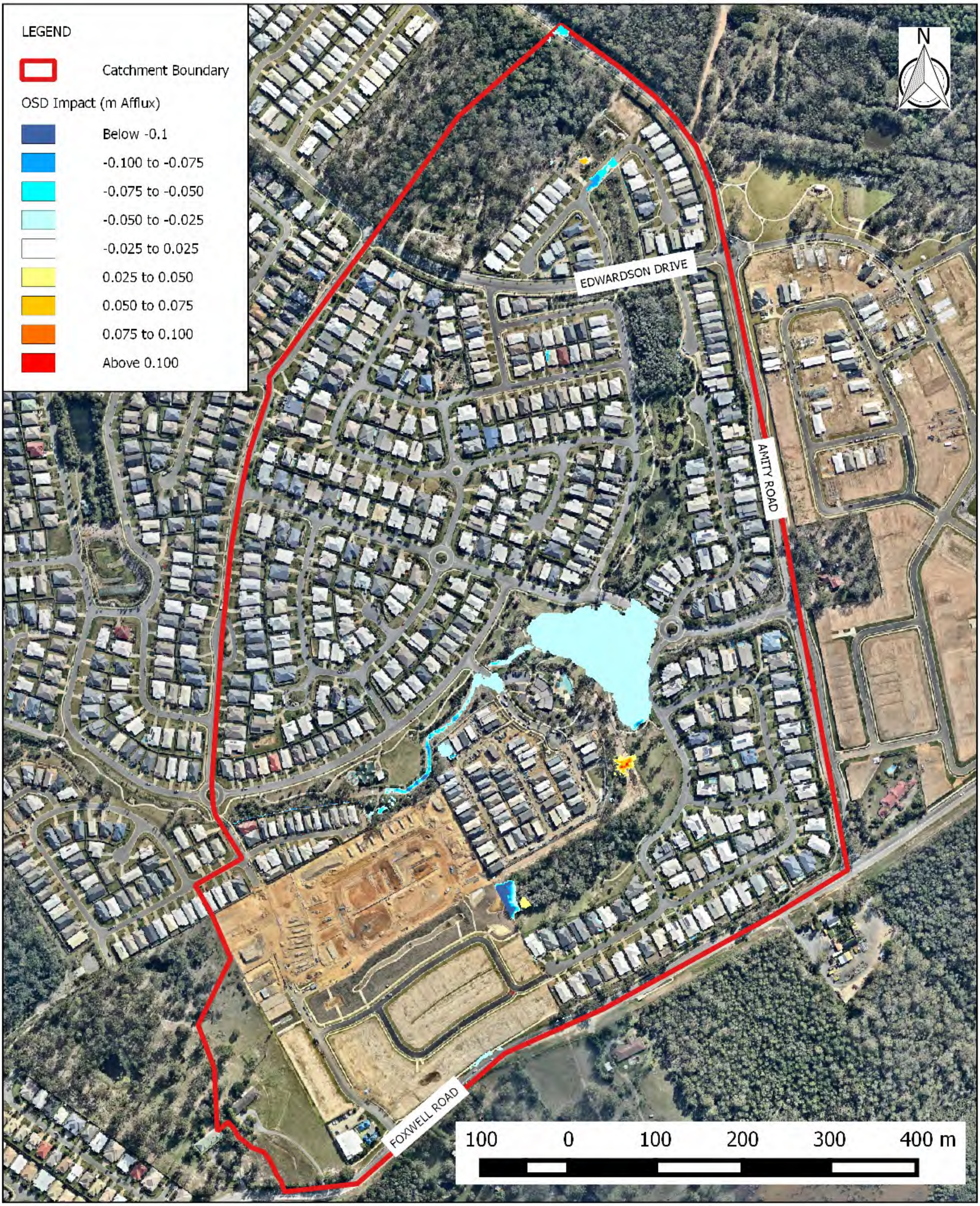
UNIVERSITY OF SOUTHERN QUEENSLAND



ENG4111-ENG4112 - RESEARCH PROJECT
FIGURE D.7
POST-DEVELOPMENT
OSD FLOOD LEVEL IMPACT - 200YR ARI 45MIN

PROJECTION: GDA94 / MGA ZONE 56
DATE: OCTOBER 2016

UNIVERSITY OF SOUTHERN QUEENSLAND

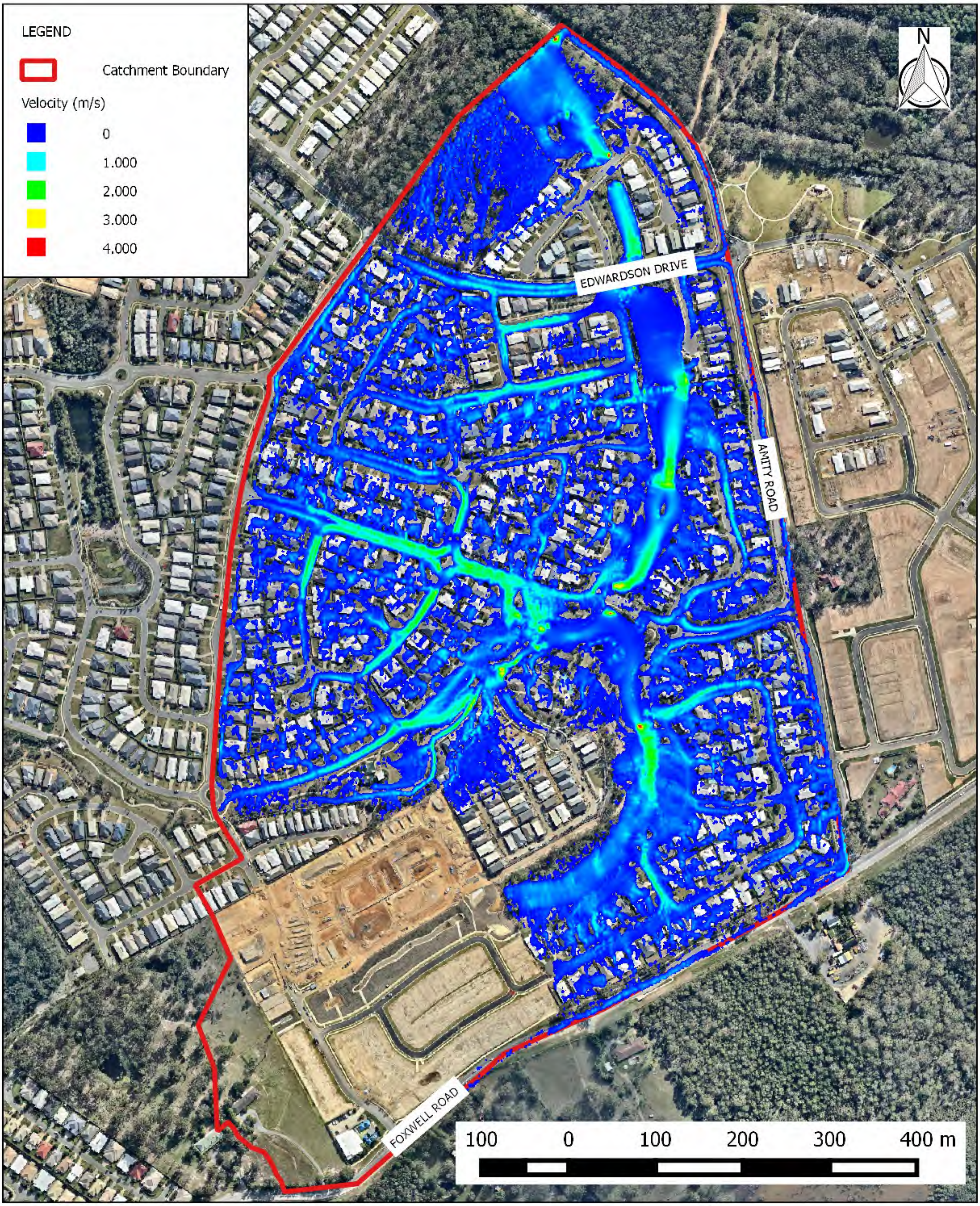


ENG4111-ENG4112 - RESEARCH PROJECT
FIGURE D.8
POST-DEVELOPMENT
OSD FLOOD LEVEL IMPACT - 200YR ARI 180MIN

PROJECTION: GDA94 / MGA ZONE 56
DATE: OCTOBER 2016

UNIVERSITY OF SOUTHERN QUEENSLAND

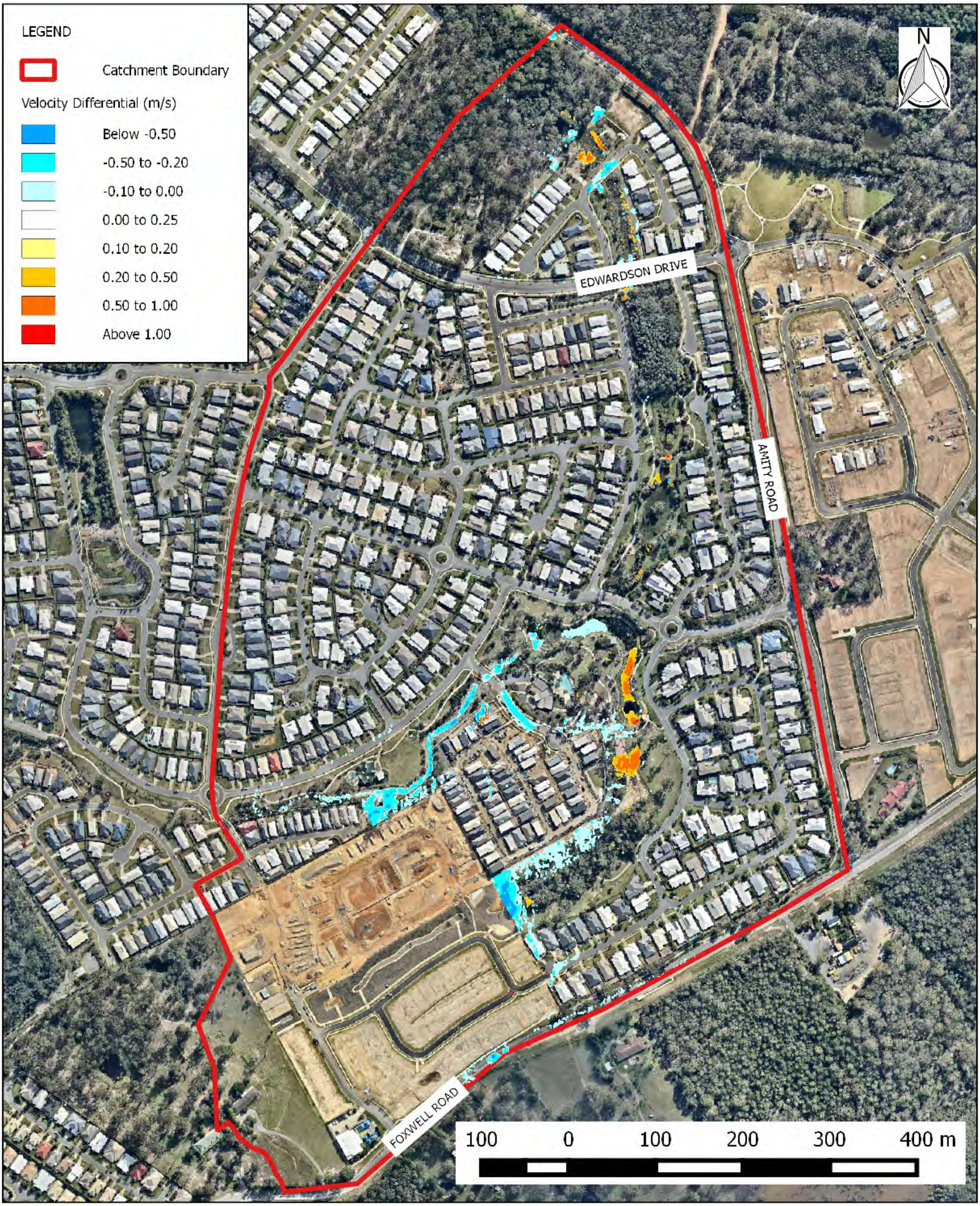
Appendix E. RESULTANT FLOOD VELOCITIES



ENG4111-ENG4112 - RESEARCH PROJECT
FIGURE E.1
POST-DEVELOPMENT WITH OSD SYSTEMS
FLOOD VELOCITY - 100YR ARI 90MIN

PROJECTION: GDA94 / MGA ZONE 56
DATE: OCTOBER 2016

UNIVERSITY OF SOUTHERN QUEENSLAND



ENG4111-ENG4112 - RESEARCH PROJECT
FIGURE E.2
POST-DEVELOPMENT
OSD VELOCITY IMPACT - 2YR ARI 90MIN

PROJECTION: GDA94 / MGA ZONE 56
DATE: OCTOBER 2016

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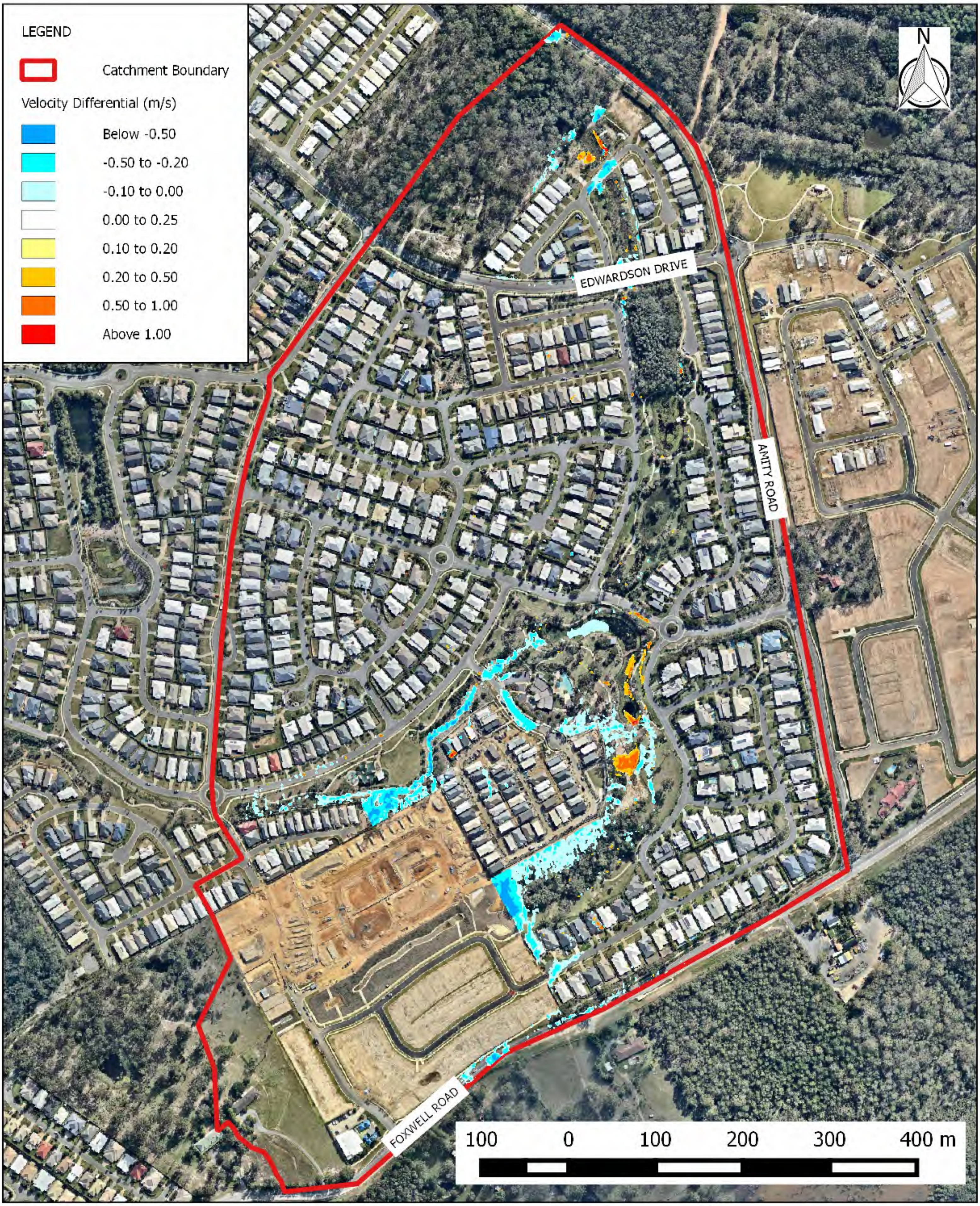
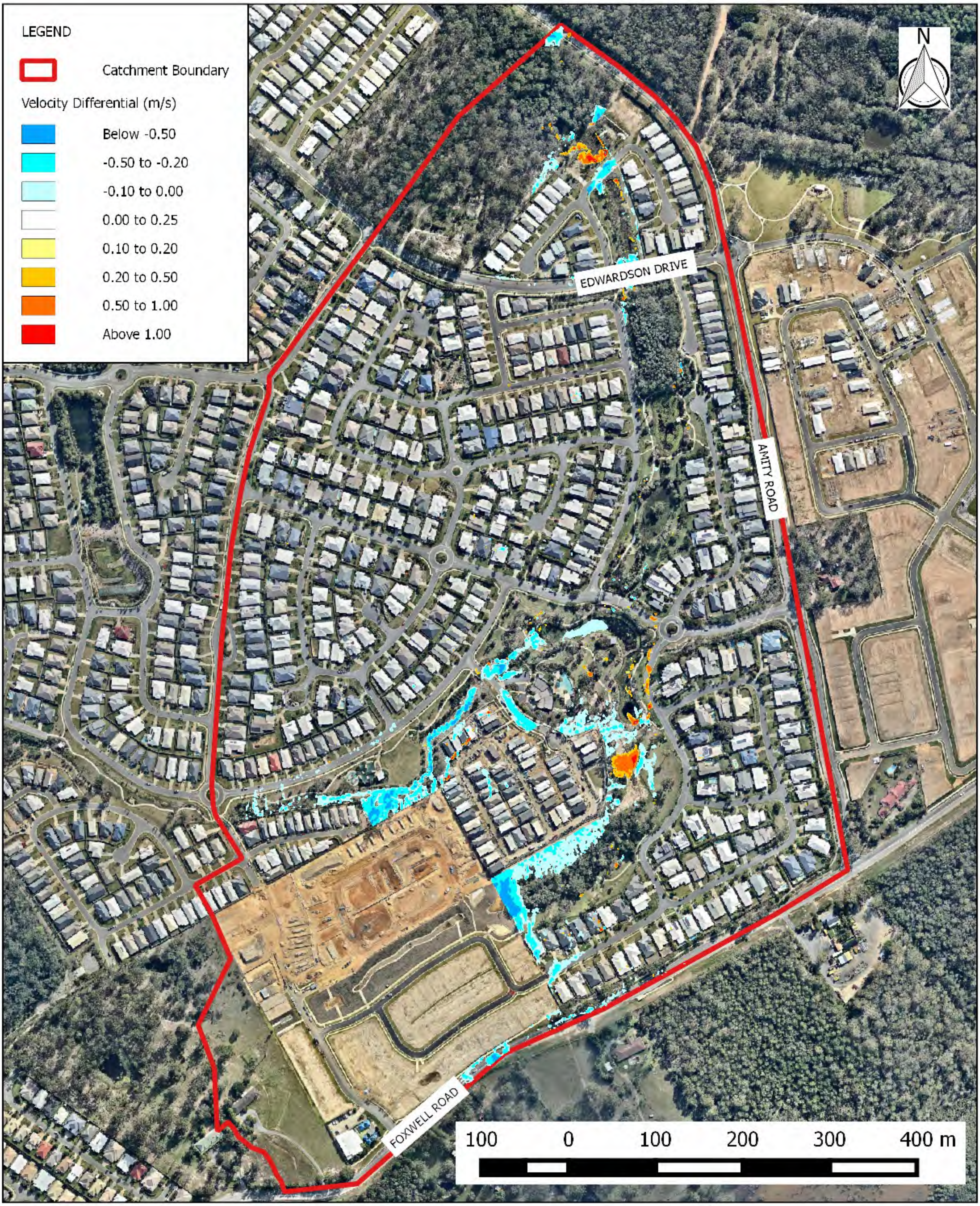


ENG4111-ENG4112 - RESEARCH PROJECT
FIGURE E.3
POST-DEVELOPMENT
OSD VELOCITY IMPACT - 20YR ARI 90MIN

PROJECTION: GDA94 / MGA ZONE 56
DATE: OCTOBER 2016

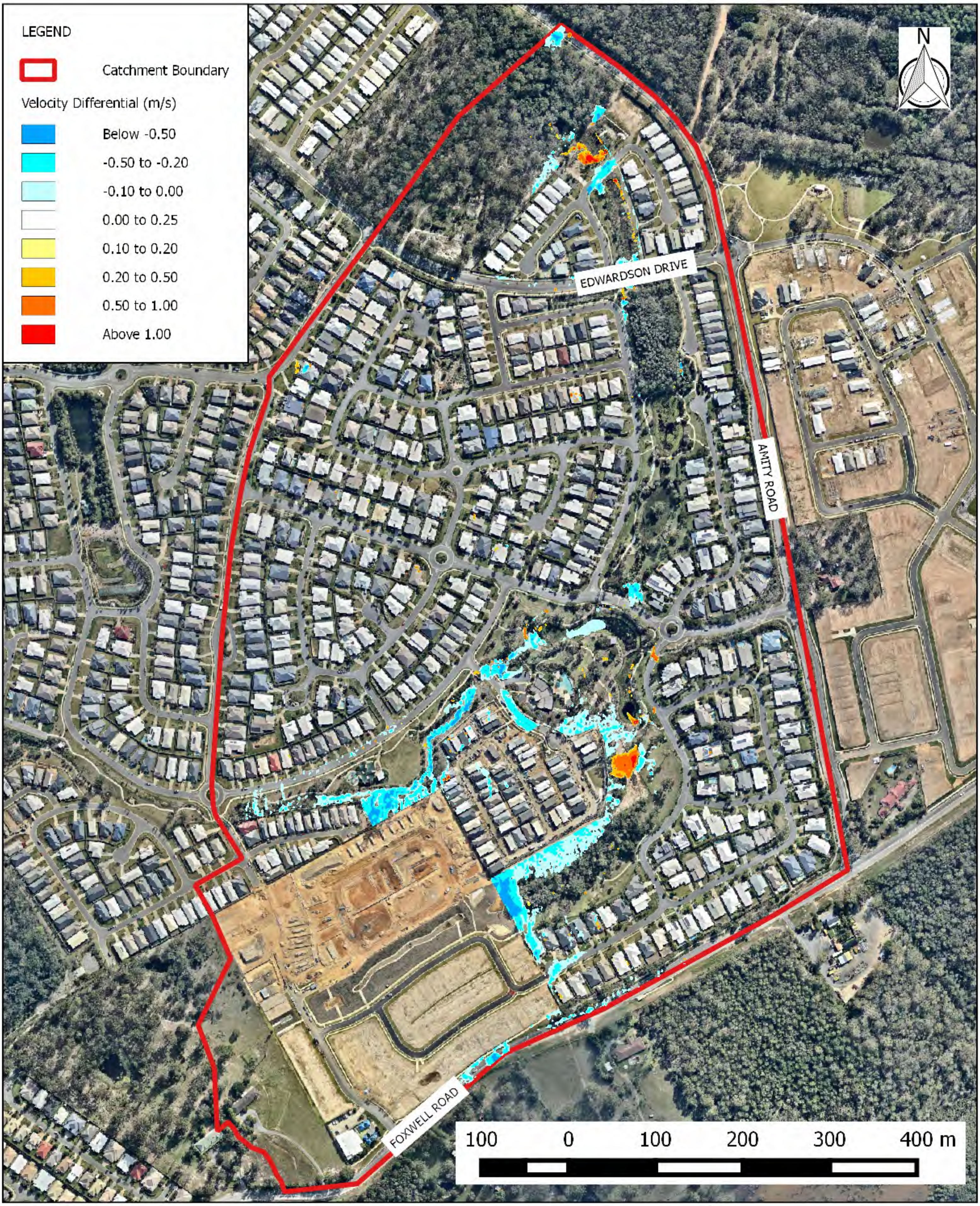
UNIVERSITY OF SOUTHERN QUEENSLAND



ENG4111-ENG4112 - RESEARCH PROJECT
FIGURE E.4
POST-DEVELOPMENT
OSD VELOCITY IMPACT - 100YR ARI 90MIN

PROJECTION: GDA94 / MGA ZONE 56
DATE: OCTOBER 2016

UNIVERSITY OF SOUTHERN QUEENSLAND

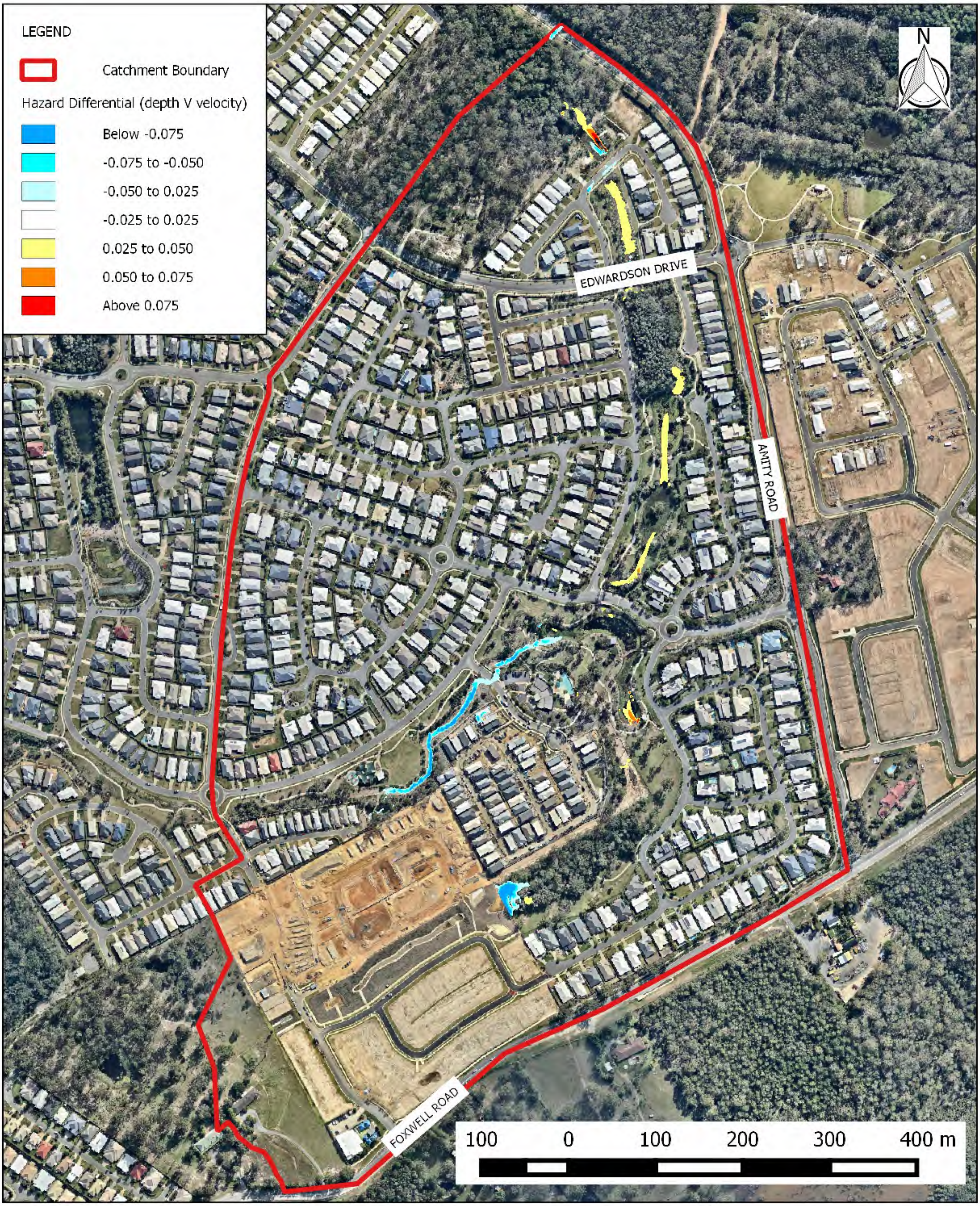


ENG4111-ENG4112 - RESEARCH PROJECT
FIGURE E.5
POST-DEVELOPMENT
OSD VELOCITY IMPACT - 200YR ARI 90MIN

PROJECTION: GDA94 / MGA ZONE 56
DATE: OCTOBER 2016

UNIVERSITY OF SOUTHERN QUEENSLAND

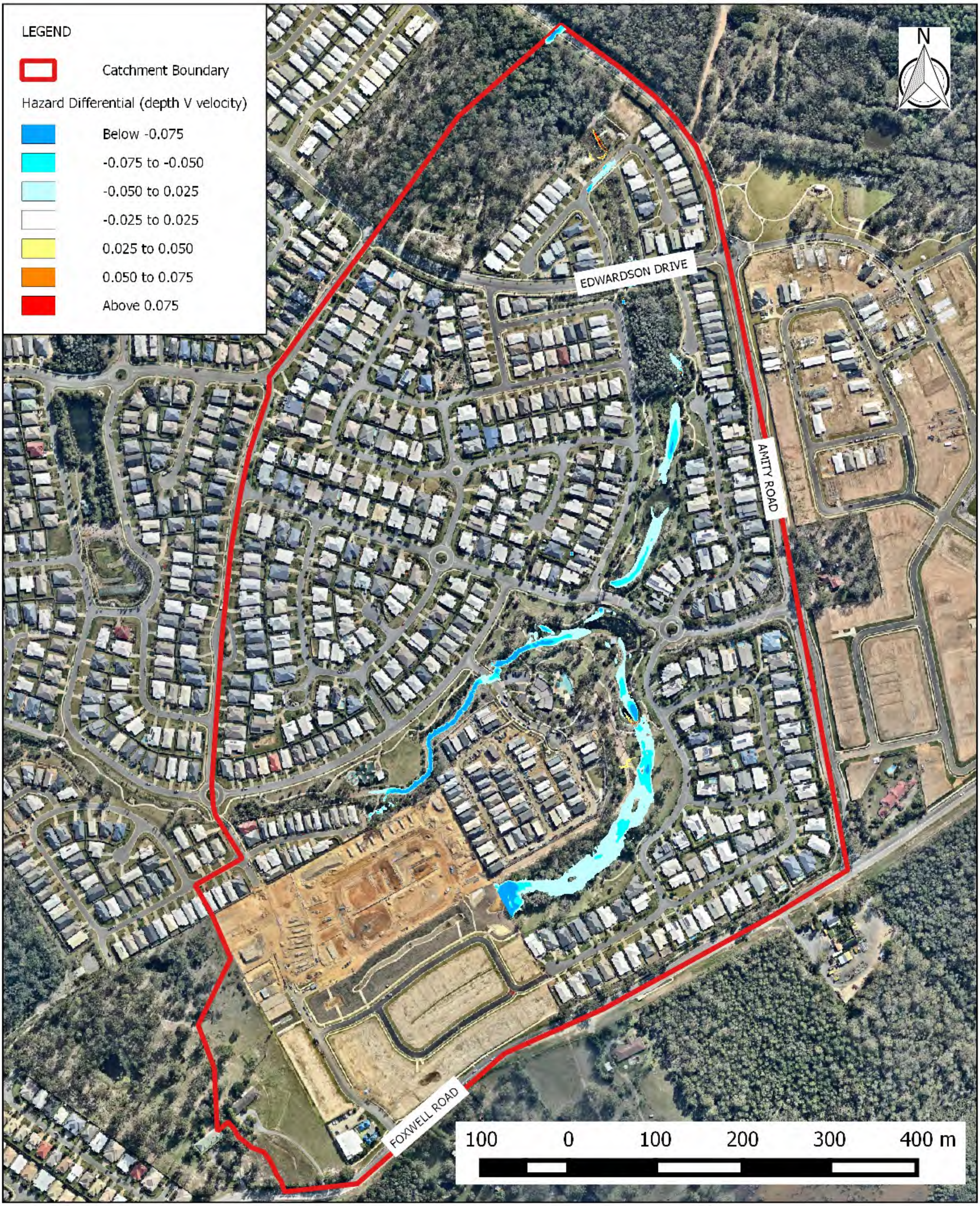
Appendix F. RESULTANT HAZARD



ENG4111-ENG4112 - RESEARCH PROJECT
FIGURE F.1
POST-DEVELOPMENT
OSD HAZARD IMPACT - 2YR ARI 90MIN

PROJECTION: GDA94 / MGA ZONE 56
DATE: OCTOBER 2016

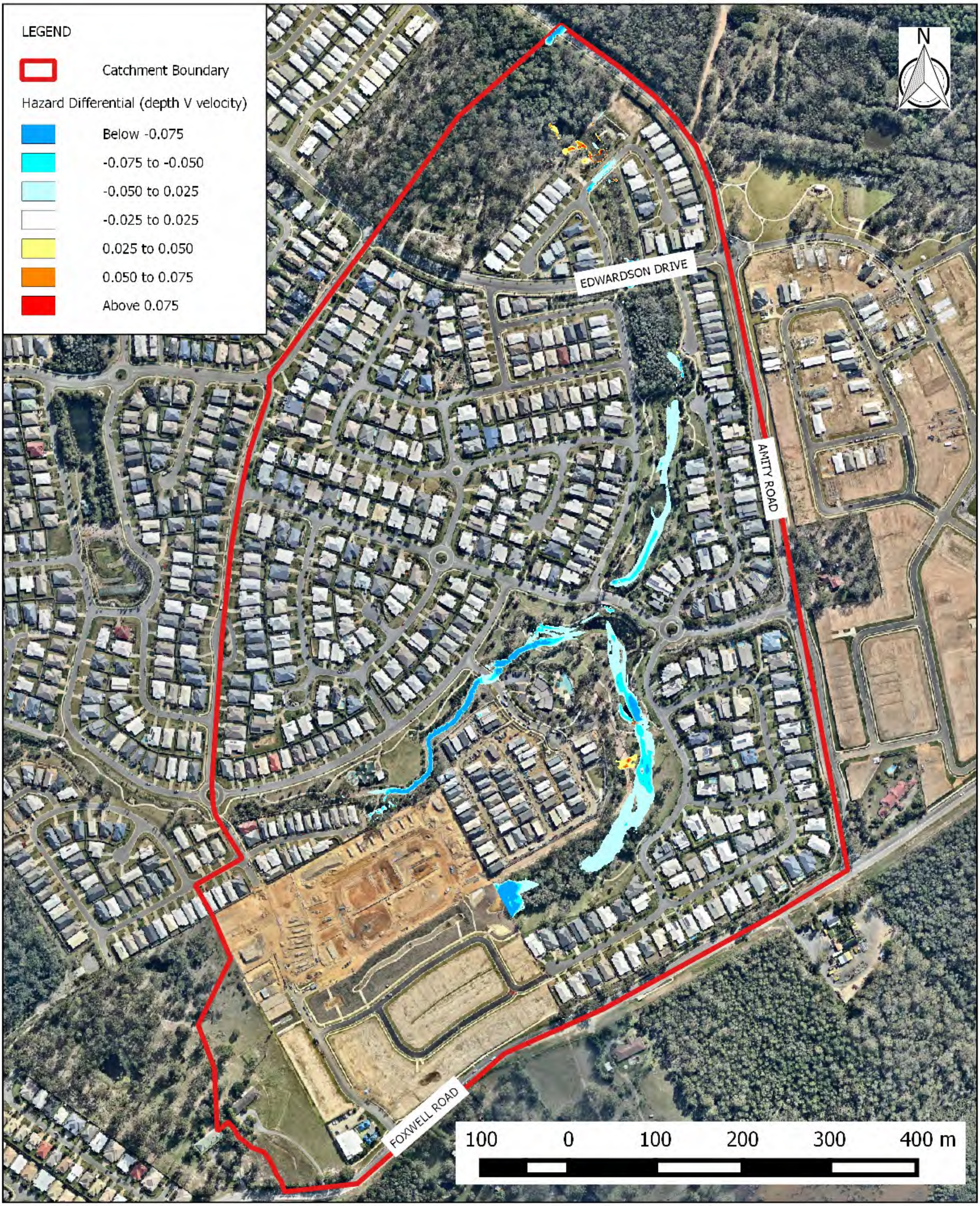
UNIVERSITY OF SOUTHERN QUEENSLAND



ENG4111-ENG4112 - RESEARCH PROJECT
FIGURE F.2
POST-DEVELOPMENT
OSD HAZARD IMPACT - 20YR ARI 90MIN

PROJECTION: GDA94 / MGA ZONE 56
DATE: OCTOBER 2016

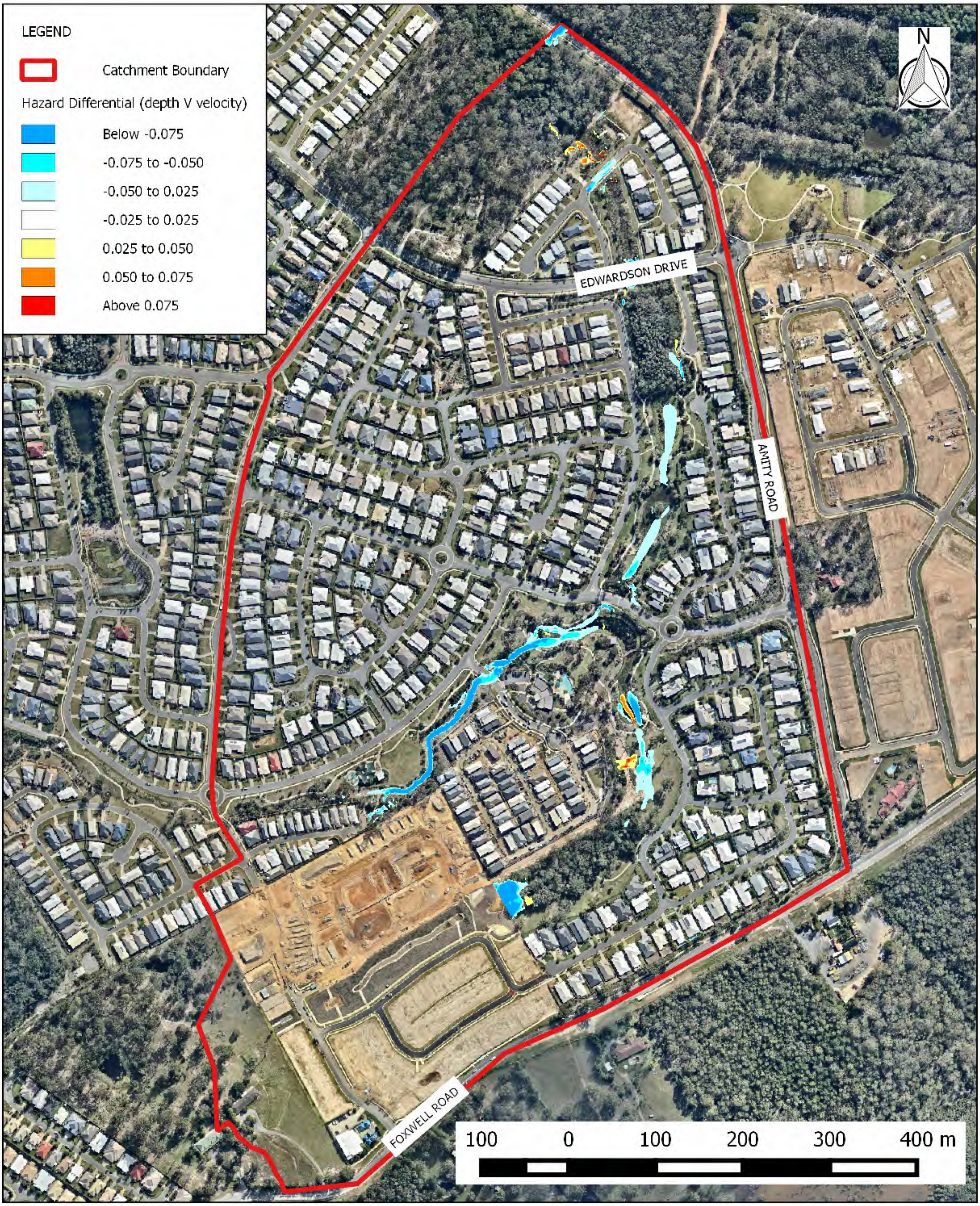
UNIVERSITY OF SOUTHERN QUEENSLAND



ENG4111-ENG4112 - RESEARCH PROJECT
FIGURE F.3
POST-DEVELOPMENT
OSD HAZARD IMPACT - 100YR ARI 90MIN

PROJECTION: GDA94 / MGA ZONE 56
DATE: OCTOBER 2016

UNIVERSITY OF SOUTHERN QUEENSLAND



ENG4111-ENG4112 - RESEARCH PROJECT
FIGURE F.4
POST-DEVELOPMENT
OSD HAZARD IMPACT - 200YR ARI 90MIN

PROJECTION: GDA94 / MGA ZONE 56
DATE: OCTOBER 2016

UNIVERSITY OF SOUTHERN QUEENSLAND

Appendix G. On-Site Detention Effectiveness Results Tables

Scenario	LOCATION	ASSESSMENT	XP-RAFTS	DRM TUFLOW	LUMPED TUFLOW
2yr 20min	OSD SITE 1	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	554.24%	1556.55%	N/A
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	21.89%	31.74%	-48.37%
	Daintree Dr	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	14.91%	131.62%	163.51%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-25.81%	40.08%	-9.62%
	Edwardson Dr	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	13.06%	103.57%	90.29%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-24.63%	34.09%	-6.01%
	Mala Ct	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	13.66%	371.55%	181.66%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-22.77%	33.79%	6.63%
	Catchment Outlet	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	13.66%	214.36%	207.41%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-22.77%	38.49%	3.12%
2yr 45min	OSD SITE 1	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	257.85%	1285.64%	751.02%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	46.32%	19.08%	-39.07%
	Daintree Dr	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	15.77%	57.30%	153.68%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-24.55%	15.27%	10.86%

Scenario	LOCATION	ASSESSMENT	XP-RAFTS	DRM TUFLOW	LUMPED TUFLOW
	Edwardson Dr	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	13.35%	51.12%	65.23%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-19.59%	12.64%	-11.00%
	Mala Ct	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	14.99%	128.22%	90.59%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-16.66%	13.23%	1.63%
	Catchment Outlet	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	14.99%	138.49%	78.63%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-16.66%	16.12%	3.57%
2yr 60min	OSD SITE 1	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	237.07%	1017.85%	331.82%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	35.40%	2.60%	-41.35%
	Daintree Dr	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	12.26%	53.98%	131.39%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-24.24%	11.52%	-3.19%
	Edwardson Dr	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	9.49%	49.64%	59.76%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-20.07%	12.17%	-10.53%
	Mala Ct	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	9.83%	114.94%	82.44%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-17.94%	12.60%	3.60%
	Catchment Outlet	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	9.83%	109.92%	66.79%

Scenario	LOCATION	ASSESSMENT	XP-RAFTS	DRM TUFLOW	LUMPED TUFLOW
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-17.94%	14.08%	3.20%
2yr 90min	OSD SITE 1	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	221.57%	1020.66%	154.44%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	55.59%	2.26%	-32.21%
	Daintree Dr	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	16.17%	43.82%	117.90%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-18.93%	4.10%	1.02%
	Edwardson Dr	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	10.51%	44.24%	58.47%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-17.28%	9.14%	-8.93%
	Mala Ct	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	10.29%	74.19%	87.13%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-15.40%	8.10%	9.40%
	Catchment Outlet	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	10.29%	66.88%	68.60%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-15.40%	10.51%	7.22%
2yr 120min	OSD SITE 1	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	195.03%	1089.52%	94.99%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	45.94%	7.38%	-35.81%
	Daintree Dr	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	20.28%	50.50%	127.88%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-16.28%	10.35%	1.92%

Scenario	LOCATION	ASSESSMENT	XP-RAFTS	DRM TUFLOW	LUMPED TUFLOW
	Edwardson Dr	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	9.15%	48.20%	48.11%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-17.18%	11.19%	-11.89%
	Mala Ct	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	9.20%	83.67%	88.78%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-15.32%	11.36%	12.80%
	Catchment Outlet	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	9.20%	72.57%	65.43%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-15.32%	10.96%	6.97%
2yr 180min	OSD SITE 1	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	185.16%	1169.36%	78.10%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	74.05%	8.55%	-24.49%
	Daintree Dr	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	35.44%	42.07%	119.86%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-3.43%	6.43%	4.98%
	Edwardson Dr	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	24.87%	45.76%	47.75%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-2.88%	9.84%	-13.55%
	Mala Ct	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	23.06%	85.81%	77.33%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-2.29%	9.98%	4.49%
	Catchment Outlet	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	23.06%	72.63%	61.70%

Scenario	LOCATION	ASSESSMENT	XP-RAFTS	DRM TUFLOW	LUMPED TUFLOW
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-2.29%	9.54%	3.36%
20yr 20min	OSD SITE 1	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	299.49%	735.94%	674.14%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	3.98%	-23.26%	-56.06%
	Daintree Dr	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	12.54%	44.52%	57.70%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-25.12%	-7.21%	-21.50%
	Edwardson Dr	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	9.47%	39.84%	56.67%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-23.83%	3.19%	-20.52%
	Mala Ct	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	9.40%	108.71%	79.36%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-22.25%	6.17%	-9.33%
	Catchment Outlet	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	9.40%	128.71%	67.44%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-22.25%	9.46%	-7.83%
20yr 45min	OSD SITE 1	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	397.73%	813.29%	58.10%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	25.96%	-18.34%	-46.43%
	Daintree Dr	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	88.52%	28.00%	131.74%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-23.80%	-2.64%	1.74%

Scenario	LOCATION	ASSESSMENT	XP-RAFTS	DRM TUFLOW	LUMPED TUFLOW
	Edwardson Dr	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	91.31%	28.89%	46.88%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-17.23%	-0.26%	-17.15%
	Mala Ct	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	93.36%	31.91%	68.12%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-15.20%	2.34%	-4.64%
	Catchment Outlet	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	93.36%	31.48%	52.67%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-15.20%	1.82%	-2.13%
20yr 60min	OSD SITE 1	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	126.32%	661.13%	22.40%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	10.39%	-25.13%	-52.44%
	Daintree Dr	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	6.36%	20.58%	80.66%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-24.87%	-5.45%	-13.47%
	Edwardson Dr	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	5.67%	25.73%	39.97%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-19.18%	-1.84%	-22.14%
	Mala Ct	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	5.45%	27.00%	65.11%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-17.18%	-0.43%	-6.57%
	Catchment Outlet	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	5.45%	26.54%	49.26%

Scenario	LOCATION	ASSESSMENT	XP-RAFTS	DRM TUFLOW	LUMPED TUFLOW
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-17.18%	0.45%	-5.88%
20yr 90min	OSD SITE 1	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	663.62%	791.29%	9.14%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	319.78%	-17.23%	-47.13%
	Daintree Dr	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	10.98%	16.54%	90.53%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-18.35%	-6.19%	-6.62%
	Edwardson Dr	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	6.86%	20.38%	37.38%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-15.25%	-2.66%	-21.02%
	Mala Ct	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	6.21%	22.19%	68.63%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-13.58%	-1.94%	-2.38%
	Catchment Outlet	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	6.21%	19.49%	52.45%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-13.58%	-0.80%	-2.40%
20yr 120min	OSD SITE 1	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	114.57%	815.26%	1.41%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	24.56%	-13.05%	-46.41%
	Daintree Dr	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	6.49%	23.77%	71.59%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-22.59%	-4.08%	-7.18%

Scenario	LOCATION	ASSESSMENT	XP-RAFTS	DRM TUFLOW	LUMPED TUFLOW
	Edwardson Dr	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	4.78%	25.42%	29.03%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-17.33%	-1.10%	-19.57%
	Mala Ct	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	4.57%	26.12%	56.42%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-15.52%	-0.07%	-5.64%
	Catchment Outlet	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	4.57%	24.24%	49.26%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-15.52%	0.51%	-4.16%
20yr 180min	OSD SITE 1	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	105.88%	372.03%	-2.72%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	42.40%	-4.81%	-38.72%
	Daintree Dr	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	18.09%	23.35%	76.36%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-7.76%	-3.97%	-2.90%
	Edwardson Dr	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	11.80%	25.09%	20.09%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-6.40%	-0.77%	-21.83%
	Mala Ct	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	10.72%	23.46%	50.13%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-5.50%	0.48%	-3.95%
	Catchment Outlet	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	10.72%	25.21%	43.78%

Scenario	LOCATION	ASSESSMENT	XP-RAFTS	DRM TUFLOW	LUMPED TUFLOW
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-5.50%	1.25%	-3.52%
100yr 20min	OSD SITE 1	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	192.29%	598.92%	168.21%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-2.71%	-35.38%	-58.85%
	Daintree Dr	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	10.34%	14.49%	56.42%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-24.40%	-7.09%	-24.09%
	Edwardson Dr	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	8.46%	24.20%	41.18%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-21.77%	-6.71%	-28.50%
	Mala Ct	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	7.53%	20.53%	59.97%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-20.41%	-1.16%	-16.95%
	Catchment Outlet	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	7.53%	41.16%	46.72%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-20.41%	0.75%	-15.07%
100yr 45min	OSD SITE 1	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	131.69%	804.06%	16.56%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	37.88%	-14.48%	-41.59%
	Daintree Dr	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	10.47%	21.55%	103.02%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-23.10%	-3.03%	-4.00%

Scenario	LOCATION	ASSESSMENT	XP-RAFTS	DRM TUFLOW	LUMPED TUFLOW
	Edwardson Dr	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	8.78%	19.81%	42.33%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-16.80%	-1.90%	-17.43%
	Mala Ct	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	7.32%	19.26%	63.58%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-15.88%	-0.82%	-6.16%
	Catchment Outlet	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	7.32%	15.66%	45.24%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-15.88%	-1.57%	-6.66%
100yr 60min	OSD SITE 1	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	119.61%	743.30%	3.52%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	21.64%	-18.48%	-47.60%
	Daintree Dr	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	2.78%	15.85%	62.86%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-24.88%	-6.48%	-8.24%
	Edwardson Dr	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	2.12%	17.80%	38.05%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-19.12%	-2.23%	-18.50%
	Mala Ct	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	1.57%	17.65%	60.82%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-17.66%	-1.55%	-7.43%
	Catchment Outlet	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	1.57%	16.13%	42.50%

Scenario	LOCATION	ASSESSMENT	XP-RAFTS	DRM TUFLOW	LUMPED TUFLOW
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-17.66%	-1.29%	-7.70%
100yr 90min	OSD SITE 1	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	123.37%	259.94%	-0.46%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	39.70%	-7.67%	-39.80%
	Daintree Dr	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	9.15%	17.63%	28.05%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-15.95%	-5.37%	-6.64%
	Edwardson Dr	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	5.87%	15.78%	23.32%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-13.55%	-1.91%	-14.63%
	Mala Ct	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	4.83%	17.47%	43.30%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-12.47%	-1.65%	-3.30%
	Catchment Outlet	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	4.83%	13.53%	34.76%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-12.47%	-1.44%	-4.47%
100yr 120min	OSD SITE 1	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	96.73%	212.45%	-14.09%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	25.02%	-11.21%	-45.63%
	Daintree Dr	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	5.79%	17.28%	21.32%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-18.74%	-5.89%	-4.70%

Scenario	LOCATION	ASSESSMENT	XP-RAFTS	DRM TUFLOW	LUMPED TUFLOW
	Edwardson Dr	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	5.20%	18.34%	10.27%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-14.53%	-2.45%	-19.27%
	Mala Ct	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	4.06%	18.89%	31.99%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-13.72%	-2.22%	-6.20%
	Catchment Outlet	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	4.06%	16.67%	24.84%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-13.72%	-1.32%	-6.80%
100yr 180min	**OSD SITE 1**	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	79.23%	174.75%	-19.67%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	35.83%	-8.35%	-42.06%
	Daintree Dr	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	11.93%	19.43%	35.92%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-8.31%	-4.92%	-3.93%
	Edwardson Dr	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	7.76%	18.14%	3.10%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-6.45%	-2.20%	-23.23%
	Mala Ct	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	6.63%	21.93%	32.06%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-5.90%	-1.22%	-3.84%
	Catchment Outlet	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	6.63%	17.63%	25.11%

Scenario	LOCATION	ASSESSMENT	XP-RAFTS	DRM TUFLOW	LUMPED TUFLOW
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-5.90%	-0.55%	-4.21%
200yr 20min	OSD SITE 1	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	241.24%	688.32%	165.87%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	21.23%	-24.40%	-49.05%
	Daintree Dr	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	9.85%	11.53%	77.77%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-24.20%	-8.31%	-12.26%
	Edwardson Dr	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	8.57%	20.28%	51.16%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-21.25%	-4.09%	-23.41%
	Mala Ct	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	7.48%	18.10%	66.08%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-20.06%	-1.60%	-15.84%
	Catchment Outlet	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	7.48%	29.67%	50.73%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-20.06%	1.12%	-13.14%
200yr 45min	OSD SITE 1	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	139.42%	752.23%	14.21%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	46.80%	-16.94%	-37.45%
	Daintree Dr	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	9.34%	18.63%	95.44%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-23.20%	-3.22%	1.03%

Scenario	LOCATION	ASSESSMENT	XP-RAFTS	DRM TUFLOW	LUMPED TUFLOW
	Edwardson Dr	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	7.83%	15.55%	49.10%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-17.04%	-1.37%	-13.28%
	Mala Ct	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	6.53%	13.81%	69.91%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-16.02%	-0.24%	-1.59%
	Catchment Outlet	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	6.53%	12.52%	49.04%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-16.02%	-0.71%	-2.81%
200yr 60min	OSD SITE 1	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	140.64%	481.36%	9.74%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	35.28%	-13.45%	-42.05%
	Daintree Dr	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	1.63%	16.96%	40.96%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-24.78%	-4.10%	-2.98%
	Edwardson Dr	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	0.70%	13.99%	32.35%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-19.16%	-1.18%	-13.27%
	Mala Ct	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	0.04%	12.87%	54.07%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-17.91%	-0.98%	-1.75%
	Catchment Outlet	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	0.04%	11.43%	39.56%

Scenario	LOCATION	ASSESSMENT	XP-RAFTS	DRM TUFLOW	LUMPED TUFLOW
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-17.91%	-0.75%	-2.41%
200yr 90min	OSD SITE 1	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	152.33%	242.95%	9.09%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	60.28%	2.98%	-31.23%
	Daintree Dr	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	11.24%	19.72%	32.78%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-13.90%	-4.74%	-4.11%
	Edwardson Dr	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	5.76%	12.10%	11.79%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-12.67%	-0.97%	-11.71%
	Mala Ct	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	4.58%	10.92%	35.07%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-11.77%	-0.73%	0.92%
	Catchment Outlet	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	4.58%	9.82%	25.83%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-11.77%	-0.75%	-0.95%
200yr 120min	OSD SITE 1	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	119.85%	183.21%	-4.61%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	44.05%	-4.93%	-37.89%
	Daintree Dr	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	10.40%	19.92%	26.08%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-13.75%	-4.08%	-2.99%

Scenario	LOCATION	ASSESSMENT	XP-RAFTS	DRM TUFLOW	LUMPED TUFLOW
	Edwardson Dr	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	3.83%	14.60%	9.07%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-14.27%	-1.34%	-13.92%
	Mala Ct	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	2.92%	11.91%	32.46%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-13.48%	-1.50%	-0.32%
	Catchment Outlet	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	2.92%	12.56%	23.83%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-13.48%	-0.98%	-1.63%
200yr 180min	OSD SITE 1	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	136.05%	158.21%	5.82%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	84.55%	5.72%	-21.86%
	Daintree Dr	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	14.76%	20.59%	31.57%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-4.99%	-3.52%	0.39%
	Edwardson Dr	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	10.62%	11.86%	10.28%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-3.25%	-1.38%	-13.02%
	Mala Ct	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	9.40%	12.12%	33.19%
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-2.81%	-1.45%	0.12%
	Catchment Outlet	DIFFERENCE FROM PRE-DEVELOPED PEAK DISCHARGE	9.40%	10.10%	25.47%

Scenario	**LOCATION**	**ASSESSMENT**	**XP-RAFTS**	**DRM TUFLOW**	**LUMPED TUFLOW**
		DIFFERENCE FROM POST DEVELOPMENT (WITHOUT OSD) PEAK DISHCARGE	-2.81%	-0.44%	-0.21%