

# **Developing a spatial approach to support local flood-risk-based land use planning**

**Thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy**

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## **DECLARATION**

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I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program; any editorial work, paid or unpaid, carried out by a third party is acknowledged; and, ethics procedures and guidelines have been followed.

SEYEDHOSSEIN POURALI

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## **LIST OF ABBREVIATIONS**

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ABS	Australian Bureau of Statistics
AHD	Australian Height Datum
ANN	Average Nearest Neighbour
ARI	Average Recurrence Interval
ASPRS	American Society for Photogrammetry and Remote Sensing
BCC	Bass Coast Shire Council
BOM	Bureau of Meteorology
CMA	Catchment Management Authority
CRS	Customer Request System
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CVA	Consolidated Vertical Accuracy
DBDLC	Database Development Life Cycle
DEM	Digital Elevation Model
DEMON	Digital Elevation Model Network
DEPI	Department of Environment and Primary Industry
DGNSS	Differential Global Navigation Satellite System
DHS	Department of Human Services
DPCD	Department of Planning and Community Development
DSE	Department of Sustainability and Environment
DTM	Digital Terrain Model
EMA	Emergency Management Australia
EPA-SWMM	USA Environmental Protection Agency – Storm Water Management Model
FAV	Fundamental Vertical Accuracy
FMA	Floodplain Management Authorities
FMF	Floodplain Management Forum

FO	Flood Overlay
GCP	Ground Control Points
GDA	Geocentric Datum of Australia
GIS	Geographical Information System
GPS	Global Positioning System
HEC-RAS	USA Hydrologic Engineering Centers River Analysis System
ICSM	Inter-Governmental Committee on Surveying and Mapping
IDW	Inverse Distance Weight
IT	Information Technology
IWM	Integrated Water Management
KRA	Kinematic Routing Algorithm
LiDAR	Light Detection and Ranging
LSIO	Land Subject to Inundation Overlay
MAV	Municipal Association of Victoria
MFD	Multi Flow Direction
MFM	Mass Flux Model
MGA	Map Grid of Australia
MPiA	Multiple LiDAR Pulse in Air
MTFD	Multi Triangular Flow Direction
MUSIC	Model for Urban Stormwater Improvement Conceptualisation
MW	Melbourne Water
NFMD	Novel Multiple Flow Direction
PM	Permanent Marks
PMF	Probable Maximum Flood
Rho8	Random Eight Nodes
RMSE	Root Mean Square Error

SAGA	System for Automated Geoscientific Analysis
SBO	Special Building Overlay
SCA	Specific Catchment Area
SCARM	Standing Committee on Agriculture and Resource Management
SDI	Spatial Data Infrastructure
SDLC	System and Database Development Life Cycle
SDSS	Spatial Decision Support System
SDSS	Spatial Decision Support System
SES	Victorian State Emergency Service
SFPC	State Flood Policy Committee
SPSS	Spatial Planning Support System
SVA	Supplemental Vertical Accuracy
TIN	Triangular Irregular Network
TOPAZ	Topographic Parameterisation
TWI	Topographic Wetness Index
UCD	User-Centred Database Design
UFZ	Urban Floodway Zone
VCAT	Victorian Civil and Administrative Tribunal
VFWCC	Victorian Flood Warning Consultative Committee
VGI	Volunteer Geographical Information
VPPs	Victorian Planning Provisions
VSDI	Victorian spatial data infrastructure
WGCMA	West Gippsland Catchment management Authority
WSUD	Water Sensitive Urban Design

## **ABSTRACT**

---

Flood-risk-based land use planning is largely a local government responsibility in Australia. In my research I sought to develop a new spatial approach to improve the implementation of flood-risk-based land use planning that can be used by local governments.

Flooding and the damage it causes are likely to increase as a consequence of climate change. Flood management activities can be categorised into three groups: flood prevention, flood recovery and flood response activities. Floodplain management is largely focused on prevention and environmental activities.

In Australia, strategies for floodplain management to reduce and control flooding are best implemented at the land use planning stage. Flood-risk-based land use planning results in sustainable land management activities, including floodplain management. Various strategies, plans, and acts of parliament guide flood-risk-based land use planning in Australia, and multiple stakeholders with varying interests are involved. Flood-risk-based land use planning is largely dependent on flood behaviour across the land development areas, which can be documented in the form of planning zones that warn land use planners about the flood-threatened area. However, these are often out-dated so do not reflect the influence of recent land use changes. This is particularly for peri-urban areas (largely focus on riverine floods) and expensive to update. Developing a new approach based on geospatial science facilitates the implementation of flood-risk-based land use planning process and can provide a better approach for local governments in terms of cost, accuracy and ease of updating.

To develop a new approach, a clear understanding of responsibility for flood-risk-based land use planning, the workflow processes in the authority responsible for such planning, the quality of existing database and how new data sources and the technology (e.g., LiDAR data and crowd source data) that can be used for flood-risk-based land use planning, is essential.

The research involved a case study to document the process of flood-risk-based land use planning processes used by a Victorian council, an assessment of flood-relevant database

completeness and accuracy, determination of missing datasets and information in the council's flood-relevant GIS database, and development of methods based on GIS-embedded hydrological models to generate those datasets.

The Bass Coast Shire Council, located in southern Victoria, Australia, was used as a pilot study area to develop an approach for local governments to use a GIS database and GIS-embedded hydrological models in flood-risk-based land use planning. The pilot study area includes an important part of Victoria's coastline in terms of, for example, RAMSAR conservation areas and tourist attractions. The Bass Coast Shire Council and other responsible agencies follow strategies, plans, and policies to manage coastal water quality. The Bass Coast Shire's status as a Coastal Getaway area means that the council is under pressure to approve land use change in order to cater for its increasing population. The shire also includes major Victorian tourist attractions that encourage people to visit the area.

I began my research by documenting the workflow process for flood-risk-based land use planning in the Bass Coast Shire Council. Then I assessed the information required to establish a comprehensive flood-relevant GIS database to support the process, and identified missing datasets. The quality of fundamental datasets such as surface topography is important for hydrological application. The research also involved development of a method for assessment of the vertical accuracy of a LiDAR dataset, an important precursor to use GIS-embedded hydrological models. Assessment of the LiDAR dataset available for this study showed that such a dataset can be used in applications that do not need vertical accuracy better than 0.5m.

The dataset missing from Bass Coast Shire Council's flood-relevant GIS database were - overland flow paths, catchment boundaries and flash-flood-prone areas. GIS-embedded hydrological models were used to generate them.

Considering the roles and responsibilities for flood-risk-based land use planning, documenting the process for such planning, assessment the accuracy of flood-relevant database to support the flood-risk-based planning, determining missing dataset and developing methods to

generate them established an approach that local government can use to accommodate flood issues within land use planning decisions. The procedure developed in determining missing information for Bass Coast Shire Council enables other local governments to consider the gaps in their existing flood-relevant database required for land use planning.



# 1 Introduction

---

## 1.1 Introduction

Flood-risk-based land use planning (land use planning informed by flood risk) is determined as the strongest tool for reducing flood damage in Australia and is a multi-stakeholder task that needs to be served by corporate responsibility of different agencies. However, the stakeholders' interests are defined based on their organisational strategic view, which will be often different. Land use planning schemes include overlays to counter major flooding issues such as riverine flooding, overland flash flooding, stormwater runoff flooding, tidal flooding and storm surge flooding.

Planning overlays serve to warn decision makers about flooding risks during the land development approval process. However, it is commonly rare to access all abovementioned flooding overlays for a given area. Therefore, decision makers have to use alternative approaches such as existing historical information held by members of community, experts' knowledge, or conceptual models in hydrology to aid flood-risk-based decision-making.

There are two main categories of hydrological models. One category is lumped hydrological models that present catchment hydrological behaviour at a given outlet. The second class of hydrological models include distributed hydrological models which present the hydrological situation for each land unit. The lumped models cannot cover the whole upstream catchment areas but needs less information to run a hydrological simulation. The distributed hydrological models, on the other hand, require detail inputs such as soil hydrological condition, which are often rare. The distributed hydrological model can be conceptual model, which often embedded in geographical information system (GIS) environment such as typical Arc Hydro Tools. The conceptual model follows the natural rule of water movement based on surface topography.

In this study, I sought to develop an spatial approach to support flood-risk-based land use planning using documenting the process, considering the completeness and quality of flood-relevant GIS database in Bass Coast Shire Council as pilot study area by implementing conceptual spatially distributed hydrological models embedded in GIS (hereafter is called GIS-embedded hydrological model in this thesis), high-resolution topography data source, data for manmade features and crowd source information.

The approach for land use planning which I aimed to produce in this study had to be:

- 1-easy to implement
- 2-reliant on few data inputs
- 3-useable without expensive and expert hydrodynamic models
- 4-repeatable by not-flood-expert user

## **1.2 Research objectives and questions**

Local flood-risk-based land use planning responsibilities involves the management of land use change and determination of areas prone to flash flooding in order to make wise decisions for strategic and statutory land use. This research project was designed to develop a spatial approach to support flood-risk-based land use planning at the local level. In particular, I sought to use new forms of information to assist in the decision-making process.

Light Detection and Ranging (LiDAR)-derived surface topography data provide greater detail on flood susceptible areas than previous dataset. The approach I sought to develop in this research was to use LiDAR data to improve on traditional land assessment methods to ascertain the flooding risks for new subdivisions.

The research questions addressed in this thesis are:

1. What are the roles of Australian government agencies in flood and floodplain management at the local and regional levels in Victoria?
2. How is flood risk addressed in land use planning decisions at the local level?

3. What information products are required for flood-risk based land use planning at the local level?
4. What are the gaps in existing local flood relevant databases?
5. To what extent are the LiDAR datasets for the study area vertically accurate?
6. How can a GIS-embedded hydrological model be used in integration datasets to provide missing information products in existing GIS-database?

### **1.3 Research design**

This research involved the implementation of a GIS-embedded hydrological model in order to improve flood-risk-based land use planning practices. I assessed the readiness of a Victorian council's flood-relevant GIS database for on-demand hydrological analysis and flood modelling through investigation of spatial datasets to determine the gaps in spatial data and the required attributes. An analysis of current business workflows and in-house knowledge related to flood management was necessary to understand the required information products (user data needs).

The methodology used in this research was based upon a pilot study approach. It included a literature review focused on flood and floodplain management in the Australian context, user need analysis and conceptual hydrological modelling, and two types of data collection from the staff those involved in flood-risk-based land use planning. The methodology also included comparison of the accuracy of LiDAR ground points with a 'gold standard' dataset. The first pilot study involved the extraction of overland flow paths and catchment boundaries using GIS-embedded hydrological models. The second pilot study focused on determining an overland flash- flood prone area using GIS-embedded hydrological models - the Topographical Wetness Index (TWI).

Through the pilot studies, citizens' information in the form of photographic evidence of flood events was employed as an alternative source of information.

The following stages were followed in order to address the research questions and the overall aim.

1-Document the flood and floodplain management responsibilities of all levels of government in Australia to give insight into each level's tasks and responsibilities

2-Examine the existing databases, policies and decision-making processes of a Victorian responsible agency for flood-risk-based land use planning, particularly the quality of core dataset – the LiDAR datasets for terrain analysis

3-Develop an appropriate spatial data integration models to produce the information products - overland flow path, catchment boundary, flash-flood-prone areas- needed to flood-risk-based land use planning for the pilot study area.

## **1.4 Thesis structure**

The body of this thesis is made up of eight chapters.

Chapter 1, the current chapter, gives some background to the research, present the research aims and questions, and finally outlines the structure of the thesis.

Chapter 2 contains details of the flood and floodplain management responsibilities of the different levels of Australian Government.

Chapter 3 presents the criteria for selecting the pilot study area - the Bass Coast Shire and its hydrological and related characteristics.

Chapter 4 concerns the decision procedures and user data needs in the context of local flood-risk-based land use planning in order to:

1-document Bass Coast Shire's existing local flood-risk-based land use planning procedure

2-analyse user data needs and extract the required spatial and attribute information in the relevant GIS database

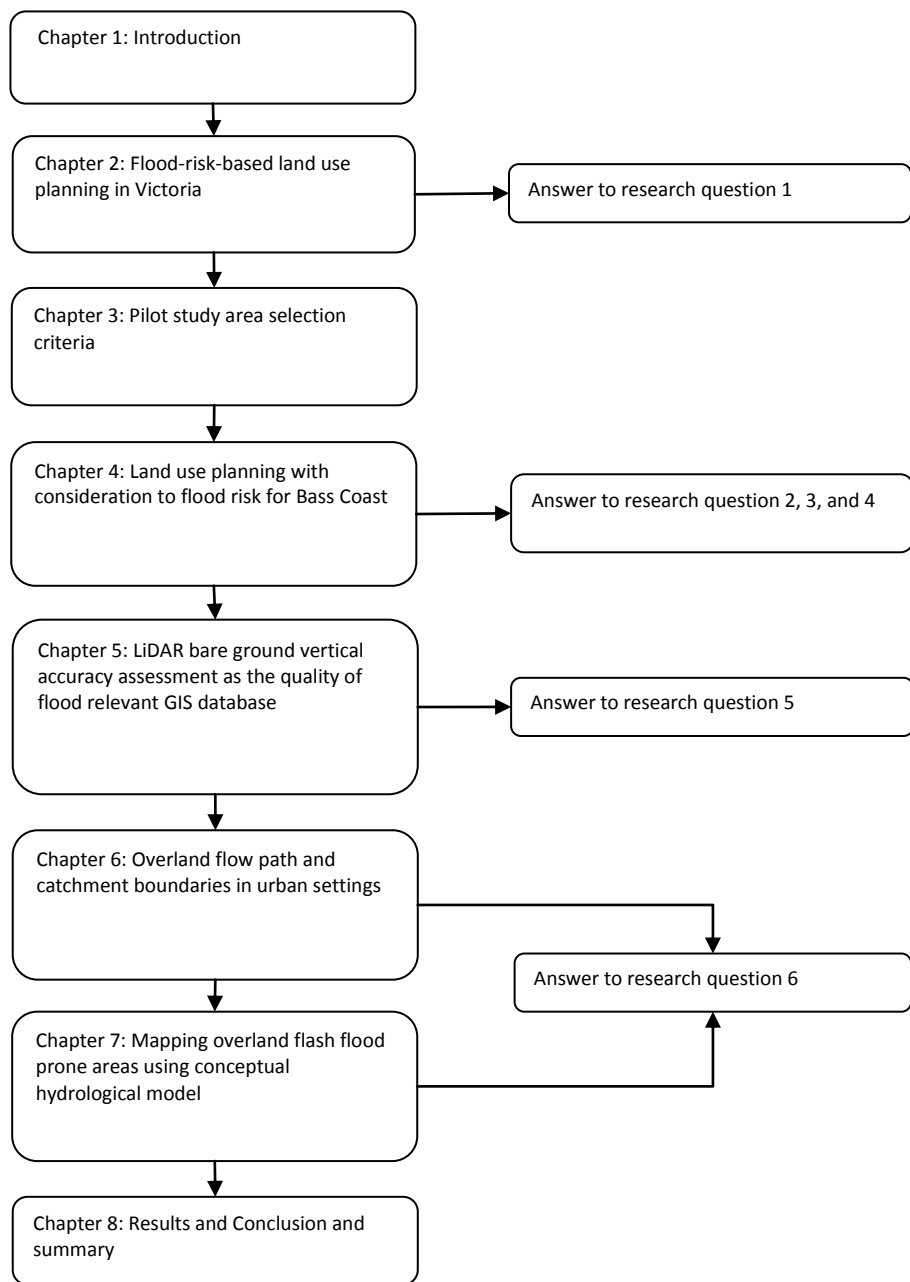
3-identify data gaps

In chapter 4 I answer research questions 2-4 *“how is flood risk addressed in local land use planning decisions?”*, *“what information products are required for local flood-risk based land use planning?”*, and *“What are the gaps in existing local flood relevant databases?”*

In Chapter 5, the accuracy of the LiDAR ground point’s dataset as the base dataset to produce a LiDAR-derived Digital Elevation Model (DEM) is examined. Since the DEM is a major dataset in GIS-embedded hydrological modelling, understanding the accuracy of DEM in this research is the basis of further analysis. Chapter 5 responds to research question 5, which addresses the existing database quality for flood relevant practices at the local level.

Chapters 6 and 7 contain description of the methods and outcome of spatial data integration for extracting overland flow paths and flash-flood-prone areas using GIS-embedded hydrological models. In these two chapters, I also discuss the limitations of widely used spatial tools in urban catchment management and the solutions. Chapter 6 and 7 answer question: *“How can a GIS-embedded hydrological model be used in integration datasets to provide missing information products in existing databases?”*

Chapter 8 presents the overall research findings and conclusions and makes suggestions for future research. Figure 1.1 contains an outline of the thesis structure.



**Figure 1.1. Thesis structure**

## **1.5 Conclusion**

In this chapter I stated that this research was designed to develop an approach to facilitate flood-risk-based land use planning. This chapter outlined the background, research objectives, and research questions to be addressed in order to understand how to utilise a spatial approach to flood-risk-based land use planning.

This research adopted the following stages in order to address each of the research questions the overall aim.

1-Document the floodplain management responsibilities of all levels of governments in Australia

2-Examine the existing databases, policies, decision-making processes of a Victorian responsible agency for flood-risk-based land use planning

3-Develop an appropriate spatial dataset assembly method for generating the required information products

In the next chapter I outline my understanding of the roles and responsibilities of each level of Australian government in flood and floodplain management.

## 2 Flood and floodplain management responsibilities

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### 2.1 Introduction

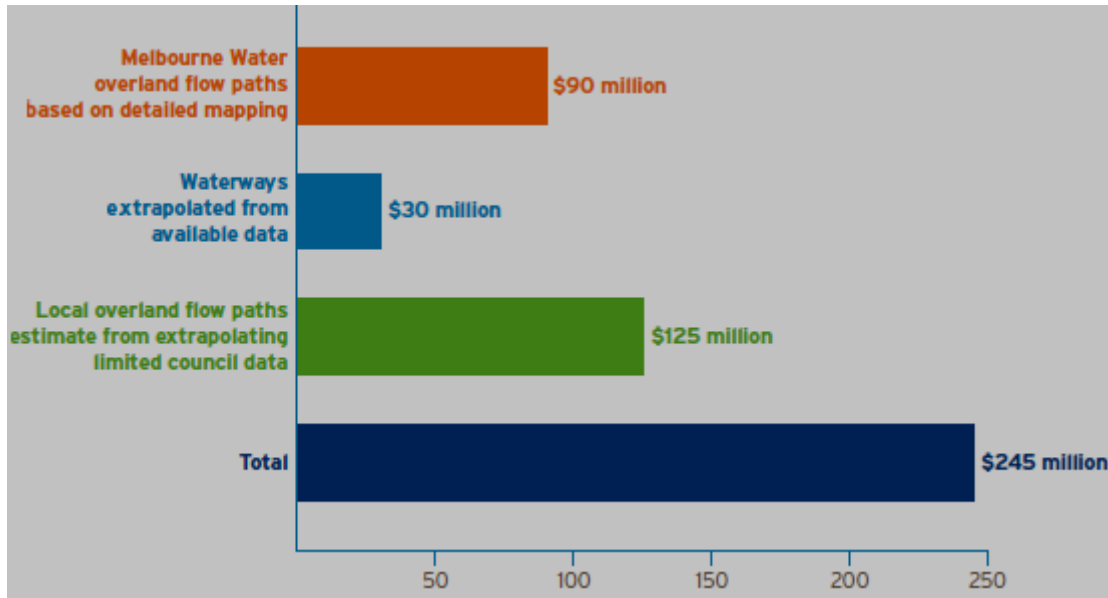
In chapter one, the research problem, objectives, research questions, and methodology were discussed. This chapter focuses on a review of stakeholders' responsibilities in flood-risk-based land use planning through the context of floodplain management in Victoria. The remaining sections of the present chapter give background about: floods in Victoria, rural flooding and urban flash flooding, flood and floodplain management in Victoria, land use planning as an effective measure for flood control in Victoria, and flood-risk-based land use planning at the local government level in Victoria.

### 2.2 Background

Rainfall is the main source of major floods in Australia (Bureau of Meteorology, 2013, Geoscience Australia, 2013). Flooding caused by rainfall is either riverine floods or overland flooding. Floods happen when the channel and drainage capacity is less than the volume of stormwater runoff. Although flood behaviour varies between different geographical locations, approximate geographical extent and time of flooding are relatively predictable using comprehensive rainfall-runoff models. Stormwater flash flooding occurs during storms which yield a runoff volume exceeding the capacity of the subsurface stormwater collection drainage system. Overland flash flooding also occurs when runoff moves above the ground towards the nearest topographic depression area, usually in built-up or rural areas covered by impervious surfaces which accelerate runoff volume. Although flash flooding occurs over a limited extent of area, its cost and damage is often greater than that a riverine flood due to little or no warning time (Melbourne Water, 2006). For example, in 2005 riverine floods threatened around 20,000 properties in the Melbourne metropolitan area, while stormwater flash



flooding in the same region threatened 82,000 properties (Melbourne Water, 2006), resulting in the costs shown in Figure 2.1.



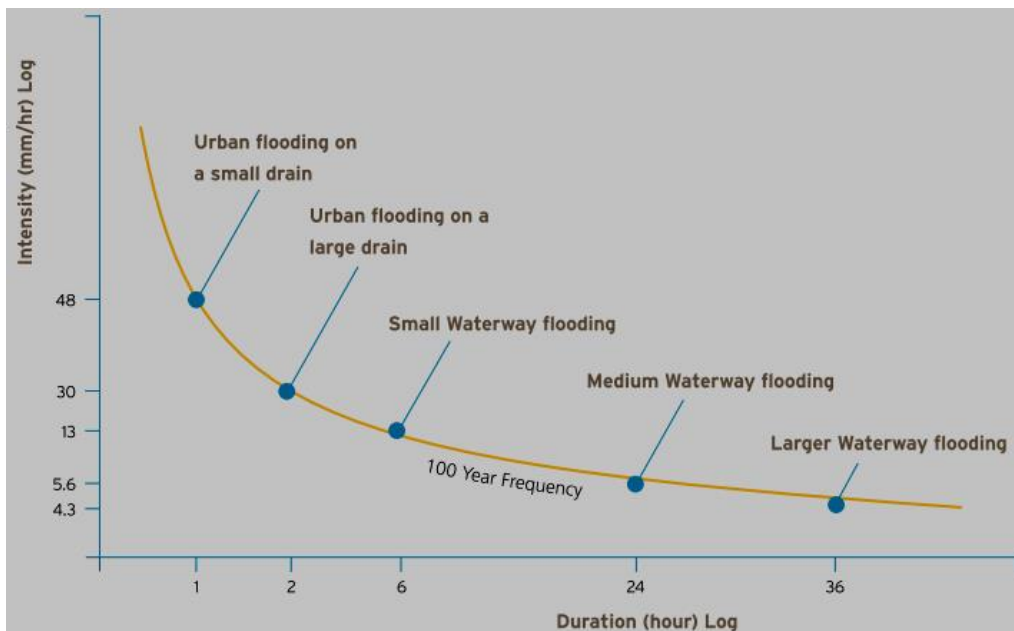
**Figure 2.1: Flood damage for Melbourne metropolitan area(Melbourne Water, 2006)**

In the year 2005, the estimated damage relevant to stormwater flash flooding was around four times greater than that for the riverine floods.

Jones et al. (2005) stated that climate change is likely to increase the frequency of extreme rainfall events, thus increasing flood damage in future and consequent changes in rainfall patterns have more impact on overland flows than riverine flows, and increase stormwater flash flooding because stormwater collection systems are not designed to cope with the greater volume of storm runoff. Jones et al. (2005) also predicted a 5% increase in rainfall intensity for each extra degree of temperature, a 4% increase in flood events by 2020 in Victoria, and up to a 25% increase in flooding by 2100.

Although procedures have been established for flood awareness, information and management, there is little or no available information for flash flooding relating to a specific area in Victoria. A flood event is totally dependent on the hydrological situation of the study

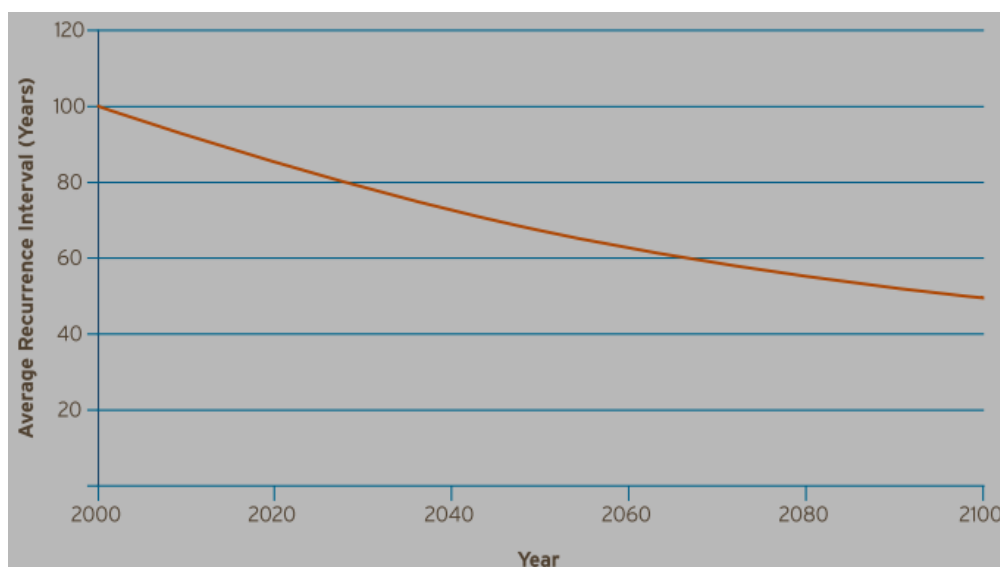
area. Flash flooding happens in small drainage systems in an urban catchment, while longer but less intense rainfall causes flooding in large waterways in rural areas (Figure 2.2).



**Figure 2.2: Catchment size and rainfall event causes a likely flood(Melbourne Water, 2006)**

The warning time for flash flooding is often short, so development of proactive warning information for existing and future urban development areas is necessary.

Climate change is predicted to reduce the recurrence interval for 100-year storms in the Melbourne area as Figure 2.3 shows.



**Figure 2.3: Likely occurrence of a 100 year storm under climate change impact(Melbourne Water, 2006)**

Figure 2.3 shows that the same amount of 100 year average recurrence interval (ARI) rainfall intensity in the year 2000 is expected to occur in the 50 year ARI in the year 2100. Therefore, detailed information for flood prone areas will become even more important.

### **2.3 Floodplain management in Victoria- best practice principles**

As part of working towards a sustainable solution for proactive management of floodplains in Australia, the CSIRO (2000) published “Floodplain management in Australia: best practice, principles and guidelines”. The guidelines were prepared as ‘Report Number 73’ for the Australian Standing Committee on Agriculture and Resource Management (SCARM). The purpose of the SCARM Report 73 is to guide the management process for development for floodplains in Australia, and is applicable to the commonwealth, state and local governments. It also helps the private sector and communities manage the flood risk associated with farming and urban development in flood plains. The floodplain management process suggested by SCARM Report 73 (CSIRO, 2000) includes a planning system, flood management system and flood emergency system. The planning system contains land use planning for townships, environmental planning, and resource management policies.

According to best practice principles, floodplain management needs an integrated approach.

This integration covers:

- 1-policy and legislation
- 2-urban and rural flooding
- 3-flood management measures
- 4-roles and responsibilities
- 5-floodplain management plans
- 6-flood emergency plans
- 7-resource management considerations

The SCARM Report 73 (CSIRO, 2000) presents floodplain management as a systematic process. The process includes:

1-a floodplain management policy

2-a statutory planning system

3-a floodplain management system (including a floodplain management advisory committee, a flood study, a floodplain management study, and a floodplain management plan)

4-establishment of a flood emergency system

5-a study of flood event behaviour

6-a study of land use and hazards

7-a study about new developments in terms of building layout arrangements and building controls

8-suggestions about structural work, such as levee installation

9-social aspects and training

SCARM's floodplain management deals separately with riverine flood and flash flood. Interaction between riverine flooding and flash flooding has also been suggested for consideration in floodplain management plans.

The scope of floodplain management in the SCARM Report 73 (CSIRO, 2000) is the land subject to inundation during the largest designed flood event that can occur in any one place. The guidelines do not cover stormwater flash flooding due to stormwater collection system failure.

As the most Victorian residential settlements are located on floodplains, floodplain management and awareness of flood risk are important. As hydrological behaviour is not consistent in every location, a local floodplain management plan should necessarily include local conditions. Floodplain management should include risks existing, future, and residual floods defined in the SCARM Report 73 (CSIRO, 2000). Existing floods have influenced the buildings currently on the floodplain, while the future floods will affect the buildings and communities which yet to be established. Residual floods are associated with probable

maximum flood (PMF) events. Best practice principles and guidelines cover all of these and are also applicable for urban overland flash flooding management.

The Commonwealth government, state and local governments, water board authorities, and catchment management authorities as regional agencies are stakeholders in floodplain management. All of these agencies are responsible for following principles in the SCARM Report 73 (CSIRO, 2000) for assessing existing, future, and residual flooding problems.

### **2.3.1 The role of the Australian Commonwealth Government**

The main roles of Australian Commonwealth government with respect to flooding are to:

- 1-provide flood forecasting and warning
- 2-support an increase in the state level of emergency management capabilities
- 3-provide natural disaster financial support to state and local government and agencies
- 4-develop insurance policies and legislation
- 5-develop and support national strategies
- 6-help to implement the strategies

Two Commonwealth agencies which play important roles in flood issues are the Bureau of Meteorology (BOM), and Emergency Management Australia (EMA). BOM is responsible for providing information about weather, rainfall, and flood prediction, while EMA provides standards and policies for emergency management countrywide and also assists the states and territories (Victorian Government, 2010c).

### **2.3.2 Victorian Government's roles**

The Victorian Government is responsible for community awareness, emergency management and natural disaster response in the State of Victoria. Flood awareness is promoted in various ways, such as the Flood Victoria website and portal:

[http://www.floodvictoria.vic.gov.au/centric/learn\\_about\\_flooding/flood\\_and\\_floodplain\\_management.jsp?](http://www.floodvictoria.vic.gov.au/centric/learn_about_flooding/flood_and_floodplain_management.jsp?) (Victorian Government, 2010c).

The web portal was developed and is managed by the Goulburn Broken Catchment Management Authority (CMA) on behalf of the State Flood Policy Committee. The major stakeholders who support the website financially are the Department of Environment and Primary Industry (DEPI) – formerly the Department of Sustainability and Environment (DSE), Emergency Management Australia, the Goulburn Broken Catchment Management Authority, and Greater Shepparton City Council. The DEPI, the Office of the Emergency Services Commissioner, the Department of Human Services(DHS), the Catchment Management Authorities (CMAs), Melbourne Water, the Victorian State Emergency Service (SES), the Bureau of Meteorology (BOM) and the Greater Shepparton City Council supervise the information posted on website (Victorian Government, 2010a).

The main responsibilities of the Victorian Government in regards to the flood issue (Victorian Government, 2010e):

- 1-To develop floodplain management strategies
- 2-To take an integrated approach in management using developed standards and strategies
- 3-To support communities technically
- 4-To provide planning advice and planning provisions development
- 5-To provide an emergency recovery support service,
- 6-To determine state wide building regulations

The agencies who are involved in flood management at the state level in Victoria are the DEPI –the office for flood policy coordination, and the repository of the Victorian flood database; the DHS is responsible for community services and providing recovery for all emergency situations; the SES undertakes flood response planning, and is the control agency during a

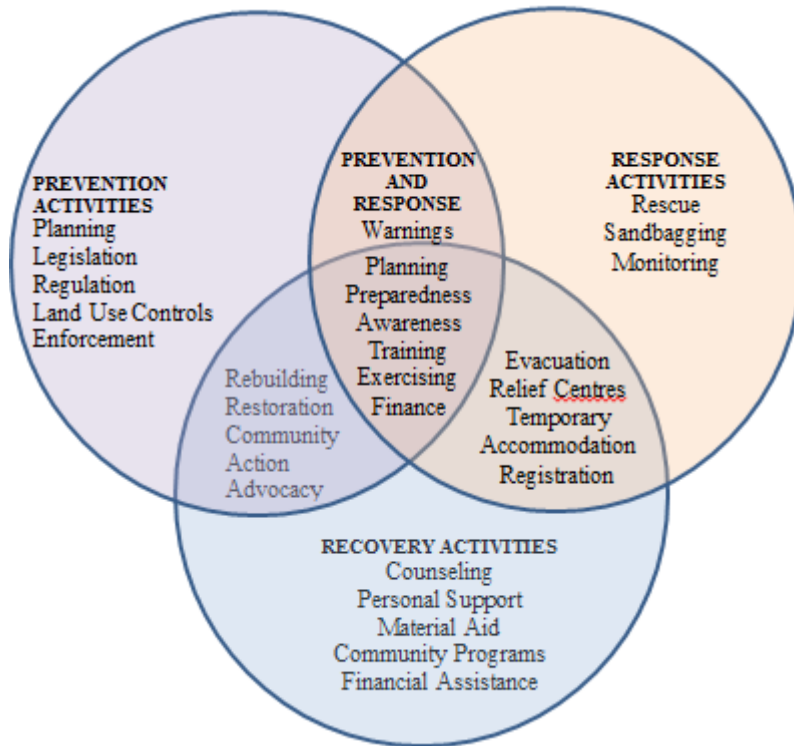
severe flood event; the Department of Justice – the Office of the Emergency Services Commissioner is responsible for emergency management policy, emergency planning and performance in Victoria; and the Victoria Police, who manage disaster control and coordination.

The roles of the Victorian government with respect to floods include:

- 1-provision of and adherence to the state flood policy
- 2-adherence to best practice processes
- 3-the appropriate investment of government resources
- 4-reducing the growth of flood risk and damage by utilising land use planning tools
- 5-facilitating warning systems and emergency management programs
- 6-providing flood information in order to increase community awareness and facilitating decision making
- 7-conserving state environmental values and significant state natural resources

The development of state legislation, policy and standards for flood management and providing input into the national flood management policy are also responsibilities of the Victorian State Government with respect to flood management.

Nine catchment management authorities, as well as Melbourne Water (for the Port Phillip and Westernport Catchment Management Authority's region) are responsible for floodplain management in Victoria. They are known as the Floodplain Management Authorities (FMA). The difference between flood management and floodplain management in the State of Victoria can be understood by comparing Figure 2.4 and Figure 2.5.



**Figure 2.4: Flood management in the broad context of emergency management(Victorian Government, 2010c)**

In addition to flood prevention activities, the FMAs must pursue relevant environmental purposes, such as preservation of flora and fauna habitats, wetlands, flood conveyance, flood storage, stream stability, and water quality.

Prevention activities in Victorian floodplain management need to follow specific guidelines and strategies, notably the Victorian flood management strategies, regional catchment strategies, regional floodplain management strategies, and best practice guidelines.

In brief, each FMA has responsibility for:

- 1-flood mapping
- 2-flood monitoring, including the recording of flood levels, flood velocity and rates
- 3-publishing blueprints of floodplain management plans
- 4-increasing flood awareness
- 5-asset management
- 6-preparing regional guides and strategies



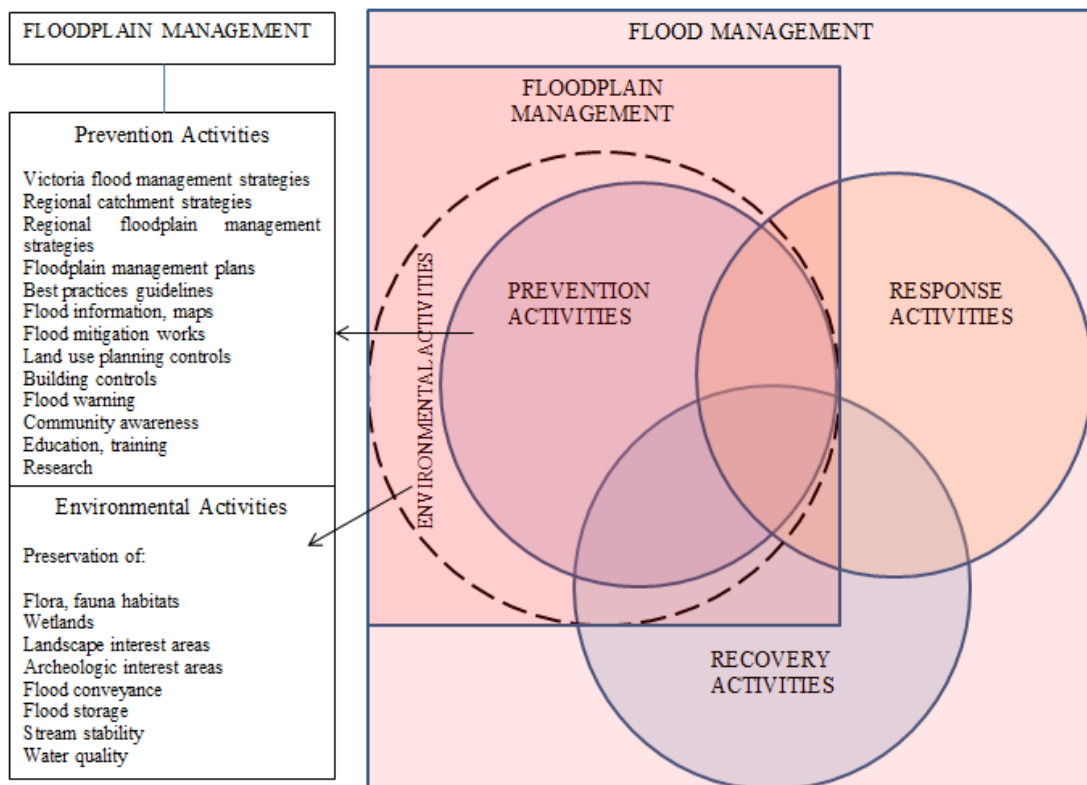
7-assisting in the development of appropriate land use planning schemes at the municipal council level

8-facilitating referral agencies for assessing and responding to land use change and planning scheme amendments based on the *Planning and Environmental Act of 1987* and planning scheme

9-assisting in implementing regional flood warning systems

10-assessing the performance of regional flood management

11-giving advice regarding regional flood management priorities to governments



**Figure 2.5: Floodplain management (Victorian Government, 2010c)**

The key objectives of floodplain management are to reduce the risk of death and damage, to protect and enhance significant environmental features, to improve water quality and stream stability, and preserve the natural roles of floodplains in order to convey and store flood water (DSE, 2011). Although FMAs (Figure 2.6) are responsible for floodplain management, floodplain management plans should be implemented through coordination of the FMAs, local

governments and local communities. Figure 2.6 shows the territory covered by nine FMAs in Victoria.



**Figure 2.6: Schematic floodplain management authorities' territories (Victorian Government, 2010g)**

The statutory powers of the CMA's under the Water Act 1989 give them important responsibilities. Their roles are to (Victorian Government, 2010g):

- 1-develops, oversee, and implement regional floodplain management strategies which play a strategic role in overall catchment management
- 2-integrate local floodplain management issues and priorities
- 3-support local governments regarding referrals for land development
- 4-support regional warning systems and report the progress of regional flood management
- 5-advise local governments about priorities in regional floodplain management plans
- 6-manage waterways and regional rural drainage

However, the responsibilities of the CMA in the Metropolitan Melbourne area (Port Phillip and Westernport CMA), are met in a cooperative approach between Melbourne Water, responsible CMAs and local governments.

Emergency services in Victoria includes support local agencies in emergency planning, flood warning system maintenance and development, needs assessment and impact analysis, and community preparedness. Responsibility for flood response and recovery belong to the Victorian emergency services, while prevention tasks are the responsibilities of regional authorities and CMAs.

### **2.3.3 The role of Victorian local government in floodplain management**

The SCARM report(CSIRO, 2000) highlighted local government's lead role in the development of flood plains. Local government's roles in flood and floodplain management can be classified into different tasks (DSE, 2011):

- 1-supporting emergency response and extensive flood recovery
- 2-local flood warning services
- 3-land development decisions
- 4-stormwater flash flooding management
- 5-overland flow management
- 6-building regulations
- 7-incorporating local flood information, including flood provisions (state and local provisions), into a land use planning scheme known as flood-risk-based land use planning
- 8-implementing all the provisions in the state land use planning scheme in the context of land use planning and environment strategies

Victorian local governments are responsible for conservation of significant natural resources and environmental values, and incorporating flood mapping and controls into local planning schemes, as well as developing and implementing local flood management plans and taking the lead in preventing communities from flash flooding. Local governments are responsible for

floodplain management under to the *Planning and Environment Act 1987*, the *Local Government Act 1989*, the *Building Act 1993* and *Emergency Management Act 1986* (DSE, 2011).

As local governments have the central operational role in land development and land use planning, they need to cooperate and consult with other stakeholders responsible for flood and floodplain management. This structure operates throughout Australia and in other countries with multi-tiered government system. Local governments are often the first point of contact for communities wanting to obtain flood damage compensation, providing information about the level and extent of flood risk in their area, participating in risk assessment and helping to manage flood recovery.

The local community, local agencies and land developers are part of the stakeholders that local government authorities consult in local floodplain management and relevant decision-making.

#### **2.3.4 State wide Flood Committees and roles**

Cooperation between all levels of government is essential for an integrated approach to managing floodplains. However, each state develops its own regulations and standards. Therefore, state wide flood relevant committees are essential authorities in providing coordination between Commonwealth, state and locally responsible bodies. Three Victorian committees work to coordinate various levels of governments for effective flood and floodplain management: the State Flood Policy Committee (SFPC), the Victorian Flood Warning Consultative Committee (VFWCC), and the Floodplain Management Forum (FMF).

The SFPC is a flood advisory body for which meetings are coordinated by the DEPI. The SFPC, as the steering committee for flood policy in Victoria, is comprised of 11 flood representatives from relevant agencies, namely DEPI-the Office of the Emergency Services Commissioner, the Victorian SES, the BOM, Victoria Police, the Municipal Association of Victoria (MAV), the DHS,

the Department of Planning and Community Development (DPCD), Melbourne Water (MW), the Victorian Rural Water Authorities and the (CMA).

The SFPC is responsible for (Victorian Government, 2010f):

1-giving advice to the government through overseeing the development and implementation of flood management strategies

2-reviewing the progress of the state flood management strategy each year

3-providing high level coordination in flood management in Victoria

4-providing an annual report to the Victorian Emergency Management council

5-reporting directly to the Office of the Emergency Service Commissioner

6-grouping experts for the state assessment panel under the Natural Disaster Resilience program

The VFWCC is comprised of representatives from the BOM, the Office of the Emergency Service Commissioner, the Victorian Rural Water Authorities, the Victorian SES, CMAs, local government authorities, the DEPI, and Melbourne Water, and is responsible for setting priorities for (Victorian Government, 2010f):

1-flood warning systems' requirements including upgrading the current system by evolving technologies

2-providing planning and coordination between different relevant organisations in order to implement a scheme

3-monitoring the performance of warning systems and reviewing the systems' performances

The FMF is comprised of representatives from all the above-mentioned committees. The FMF's responsibilities are to (Victorian Government, 2010f):

- 1-coordinate flood management practices across the Victorian state through contributing to policy and program development for floodplain management
- 2-provide knowledge and experience sharing platforms relevant to floodplain management
- 3-find funding opportunities for activities relevant to floodplain management and research

## **2.4 Land use planning in Victoria**

Land use planners must seek permission in line with Victorian planning provisions and local planning schemes in order to achieve the objectives determined in the *Planning and Environment Act 1987*. The main objectives of land use planning are:

- 1-the sustainable use and development of land
- 2-protection of natural and man-made resources to sustain ecological processes naturally
- 3-conservation of significant areas and objects
- 4-making the environment safe and pleasant for Victorian citizens and visitors
- 5-to balance present and future interests

The regulations and guidelines for flood relevant planning controls are available online through the *Our Water, Our Future* website (DSE, 2012).

Flood management in Australia was initiated in the 1970s with a focus on flood control structures, typically levees. However, levees cause flooding elsewhere downstream: therefore, a structural flood control approach is not sustainable. In the 1970s, land use planning was not seen as an important tool for reducing flood damage. This changed after flood damage increased substantially during the 1970s after a series of floods in different states (CSIRO,

2000) which was largely due is to inappropriate development on floodplains. The flood responsible agencies then focused on land use planning as a tool to reduce flood damage.

Flood emergency management and comprehensive floodplain planning, which includes all planning in the target area have become vital activities through a land use control approach. Land use planning has had a significant role in decreasing the consequent damage from flood risk in floodplains (CSIRO, 2000). Decreasing flood damage can be achieved through avoiding the allocation of land use in a natural hazard exposure area (Sutanta et al., 2010).

Major regional flooding happens every five to 10 years in Victoria due to heavy rainfall(Bureau of Meteorology, 2013). Storm surges and high tide floods are the other concerning threats for land use planning in Victorian coastal areas. Local government authorities seek to follow their floodplain management plan including rural and urban catchments. The CMAs, Melbourne Water and local governments are the principal statutory agencies for development in flood-prone areas in Victoria (Victorian Government, 2010d).

Although floods almost always cause inconvenience for human communities, flooding in a rural area is generally not as damaging as flooding in urban areas due to the greater disruption of normal daily activities in the latter. Thus, new developments in an urbanised catchment are subject to flood-risk-based land use planning in accordance with the regional framework for planning of resources.

The SCARM report (CSIRO, 2000) highlighted the importance of land use planning for township growth and its effect on catchment management. Floodplain management initially is a complex issue that needs input from various individual planning bodies about economics, infrastructure, resource management, risk management, flood emergency management, and land use change control. Land use planning tries to create a balance between objectives which are often conflicting due to the high demand for land and the scarcity of suitable land. The success of catchment management efforts rests on the strength of local planning institutions

and of the extent to which adequate land use policies are integrated within catchment management plans (Lara-valencia, 2008).

As Figure 2.5 shows, the three fundamental practices of flood management are prevention, response and recovery. Land use planning is a prevention activity. Besides land use planning, local governments are responsible for overland flow and stormwater flood management, but not for large regional waterways. Consequently, coordination between local government and regional bodies is essential in order to implement effective flood and floodplain management.

The *Planning and Environment Act 1987* empowers local governments to enforce planning schemes in order to control land development in line with the Victorian Planning Provisions (VPPs) and local planning scheme. The VPPs include state policies and frameworks for floodplain management, and are specified for each municipal area through a local planning policy framework.

Four categories of area liable to flooding are identified in planning schemes: the Urban Floodway Zone (UFZ), the Flood Overlay (FO), Land Subject to Inundation Overlay (LSIO), and the Special Building Overlay (SBO). The UFZ is an area in which only recreational and agricultural use are allowed due to high flood risk and consequent possible death and damage. The UFZ applies only to riverine flooding in urban areas. The FO includes urban and rural areas where flood risk is high. Like the UFZ, the FO can convey or store active flood flows. The LSIO includes areas subject to riverine flooding in both rural and urban areas. The SBO focuses on stormwater flooding in urban areas, but only where it is due to its exceeding the capacity of any stormwater collection system. Documents produced by Department of Planning and Community Development (2002) and (2012) contains guidelines for safe land use planning regarding the four above mentioned areas. In addition to the land use planning provisions (controls), local governments are able to enforce building regulations, for example, minimum floor heights.

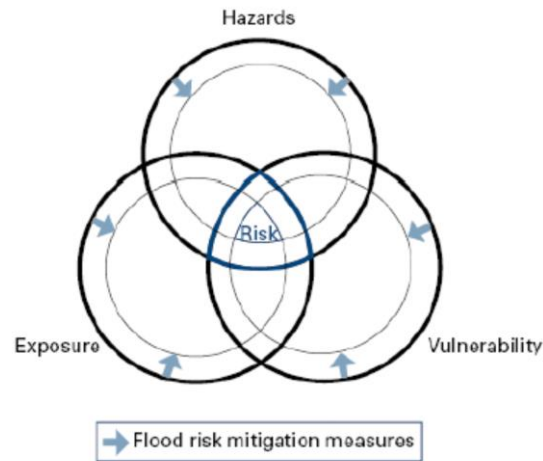


Extensive flood mapping studies outside of the Melbourne metropolitan area have been undertaken since the 1990s. Flood extents for a 1-in-100 year flood and floodway areas have been delineated and can be accessed through the Victorian Water Resources interactive map on the DSE website (DSE, 2002-2008).

The Victorian Flood Database (DPI, 2012) stores information for Victorian floods through a series of GIS layers. This flood dataset contains the most up-to-date flood information for Victorian rural areas. Flood information in metropolitan areas is provided by Melbourne Water upon request.

## **2.5 Flood-risk-based land use planning**

Risk-based regulation has become increasingly prominent over the past three decades due to the push to modernise government and achieve greater efficiency (Peterson, 2012). Therefore, risk-based regulation has become common practice among policy makers, although, a risk-based regulatory system is more complex than a traditional regulatory approach. At the heart of the regulation design and implementation in a modernised government is risk assessment, risk quantification, and risk monitoring (Peterson, 2012). Risk can be determined from a positive viewpoint or in its typical negative (hazard) and dangerous definition. Risk has three important components; hazard, exposure, and vulnerability. A change in one component causes an increase or decrease in the amount of risk. By reducing all three components risk is substantially reduced as can be seen in Figure 2.7.



**Figure 2.7: The three component of risk (World Meteorological Organisation, 2008)**

Exposure refers to people and assets being in the path of flood water. Vulnerability is the ability of something to respond to the effects of a hazard, and can be affected by a combination of different environmental, social, and economic conditions (World Meteorological Organisation, 2008).

Flooding is an ever-present concern for many communities in developed and developing countries; flooding can happen almost anywhere and at any time once the capacity of drainage, either surface or subsurface, is not appropriate to convey the flow volume. A decrease in capacity might occur because natural overland paths have become blocked by the development of an urban catchments or an infrastructure development such as a road. Many floodplains are relatively flat and under extensive use. Any manmade barriers in to a water flow can substantially change the overland flow characteristics in terms of velocity, level, and extent.

Typically, flood management in urban catchments is more complex than flood management in rural area due to the presence of minor and major drainage systems in the former. These systems divert the natural path for overland flow movement and cause changes in flow directions and flow rates.

A minor drainage system includes a pipe network for collecting stormwater runoff which is designed based on the trade-off between cost and frequency of flood events. Therefore, a major flood event creates problems due to the lack of designed capacity. A major drainage system includes access roads, open drains and known floodway (streams and creeks) in an urban area. Retarding basins, sandbags and levees are structural measures used to control flood behaviour in drainage systems. Although the major and minor systems can work properly individually, issues in urban flooding can arise from the interactions between the two systems, for example, the effect of stormwater on the peak of a flood and changing flood behaviour in receiving drainage, or the effect of backflow water in decreasing minor system capacity and causing accelerated flood problems in an urban area. In general, most flooding in urban catchments depends on the lack of capacity of stormwater collection systems.

As upgrading a minor drainage system is very expensive, it is more desirable to design a stormwater collection system with an appropriate capacity, which should be varied in different parts of an urban catchment. In an old urban area, the problem of urban stormwater management is more difficult than for a new estate development area. This is usually because the capacity of a pipe drainage system is based on a standard that is no longer appropriate; therefore, stormwater runoff exceeds the capacity of minor drainage systems.

Flood management by local governments is outlined in local flood management plans. The water authorities, local governments, CMAs, emergency management organisations and other organisations, like VicRoads (the Victorian road authority), are involved in developing local flood management plans.

Local flood management plans' objectives are to (Victorian Government, 2010b)

- 1-complete the knowledge base
- 2-reduce potential long-term pressure on retrofit drainage systems
- 3-manage flood problems in an agreed approach
- 4-improve community education and flood awareness and preparation

5-divide responsibilities between stakeholders

6-improve collaboration between floods responsible agencies

Although a flood management plan can be effective on a local scale, overall problems remain. This is because it is impossible to protect all properties, and this should be noted during land use planning permission process as has been suggested in SCARM report(CSIRO, 2000). The term “Land use planning” is interchangeable with “regional planning”, “Town Planning and Country Planning”, “Urban Planning”, and “Spatial Planning”. Land use planning is an important tool for disaster risk reduction due to its regulatory function for long term use of land (Sutanta et al., 2010). Risk-based land use planning is essential for all levels of government and particularly for local government (Sutanta et al., 2010).

The concepts that underpin the risk-based land use planning philosophical framework (Brenners, 2012) are:

1-A healthy community and economy is dependent on a healthy environment

2-Decision-making processes are best undertaken at the regional and local level aligned with the state wide policy framework

3-Decisions need the best available information

4-Keeping the balance between human use and environmental conditions

Flood-risk-based land use planning includes not affecting floodwater flow capacity by doing structural controlling practices, not reducing the water storage capacity of floodplains, attention to site safety, and attention to safe access to a site during flooding.

Problems in current flood-risk-based land use planning procedure has been discussed by Brenners (2012), who stated that approvals for development during recent drought years have resulted in areas being flooded or that will be flooded in the future because councillors and planners have limited or no knowledge about flooding issues, thus creating the likelihood of designed flood occurrences in the land use planning processes.

Although land use planning is a powerful tool for the control of flooding damage, it is only applicable to new estate land development. In a developed area, for example inside a township, the only flood management solutions are the redesign of the stormwater collection system capacity or the establishment of water sensitive urban design (WSUD) features wherever applicable. However, sometimes it is not possible to find a suitable site in an already developed township area to establish WSUD features like retarding basins (important features in runoff volume control and runoff quality treatment measures). Furthermore, redesigning a stormwater collection system is expensive. Therefore, it is necessary to inform local land use scheme plans about suitable sites before permission is granted for land use change, and to reserve the area for further flood control or WSUD activities if necessary. Such an application is in the spatial domain and relies on a comprehensive and accurate GIS database.

Thus, more input of information, a well-structured database, appropriate tools, highly skilled staff, internal knowledge and extensive experience are required to properly account for flood risk in local land use planning procedures.

## **2.6 Conclusion**

In this chapter I described the floodplain management issue in Victoria. Understanding the responsibilities of relevant agencies is important to determine floodplain management practices. Therefore, in this chapter tasks and responsibilities in floodplain management were considered in order to answer research question “What are the roles of Australian government agencies in flood and floodplain management at the local and regional levels in Victoria?” (Section 1.2)

Land use planning is one of the strongest tools for reducing the cost of flood damage, either tangible or intangible, in floodplain management framework. Tangible damage, which includes direct and indirect costs, can be estimated, while intangible damage, such as damage to society and the environment are difficult to estimate (World Meteorological Organisation, 2008). Direct tangible damage refers to the damage to infrastructure, vehicles and crops, while

indirect tangible damage refers to the costs of emergency responses, and the disruption of normal economic and social activities. Environmental intangible damage also includes erosion and reduced water quality, while social damage focuses on stress, fear, and hardship during flood events.

Flood-risk-based land use planning emphasises on not affecting floodwater flow capacity by doing structural controlling practices, not reducing the water storage capacity of floodplains, attention to site safety, and attention to safe access to a site during flooding. Therefore, including the results of flood studies and consequent flood maps in land use planning is essential.

Regarding the roles and responsibilities of responsible agencies, local governments are responsible for flood-risk-based land use planning. Therefore, considering the procedure for flood-risk-based land use planning in local government enables the present research to develop a spatial approach in order to facilitate the flood-risk-based land use planning.

The next chapter I introduce the selected local government and discuss the reasons as criteria for the selection.

## 3 Pilot study area: Bass Coast Shire

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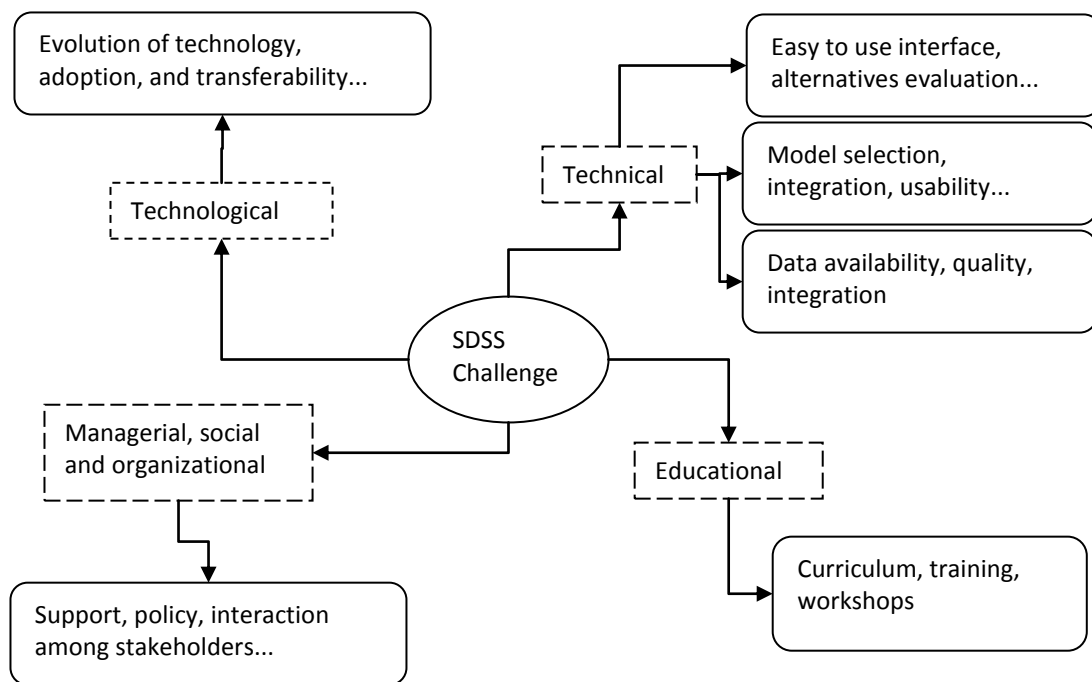
### 3.1 Introduction

Through Chapters 2, it was established that whilst flood management practices are in place at all three levels of governments, integrating local land use planning and flood control provisions into land development practice is the responsibility of local governments. In this thesis, I propose a spatially based approach to the implementation of flood provisions in local government land use planning. In order to represent the benefits of using (GIS)-embedded hydrological models in local flood-risk-based land use planning practices, a pilot study was required. The Bass Coast Shire was selected as the pilot study area for application of GIS-embedded hydrological models in flood-risk-based land use planning. In this chapter I discuss the geographical region and why it was selected as pilot study area, then describe the responsibilities of Bass Coast Shire Council. In the third section of the chapter, I present the criteria on which the Bass Coast Shire Council was chosen as a pilot study area.

### 3.2 Benefits of pilot study in spatial related applications

The problem of incorporation of spatial techniques into routine business tasks is not an issue only for Victorian agencies. Australian federal government documents, notably the “Investigation into the Spatial Capability of Australia”, put forward the argument that the Australian spatial industry has not yet met requirements of business (Commonwealth of Australia, 2012). Mohammadi (2008) noted that user needs are in spatial policies and standards, user needs are not often reflected in spatial policy and standard, particularly in business-oriented datasets. Furthermore, the problem is not limited to Australia, as Sugumaran et al. (2011), Uran et al.(2003), and Vonk et al. (2005) described. Automated computerised system are being used to assist in semi-structured spatial decision-making about dynamic and complex spatially related problems, but such systems are mostly limited to use in

developing prototypes or conceptual frameworks, or are utilised only in academic exercises. Therefore, while GIS-dependent technologies in decision-making is not a new concept, it is not routine (Allan and Peterson, 2002). The reasons for the under-utilisation of spatial technologies could be related to deficiencies in the resolution of the spatial data available to support detailed spatial modelling (Kunapo, 2008); inappropriate temporal resolution as an impediment to adopting real-time geospatial implementation (Zerger and Smith, 2003); lack of spatial skills and the time required to use spatially related technical functions (Vonk et al., 2007), and a lack of suitable data assembly and information integration. The important spatial decision support system (SDSS) or any GIS-relevant project challenges that need to be implemented in routine decision-making activities are shown in Figure 3.1 (Sugumaran and DeGroot, 2011).

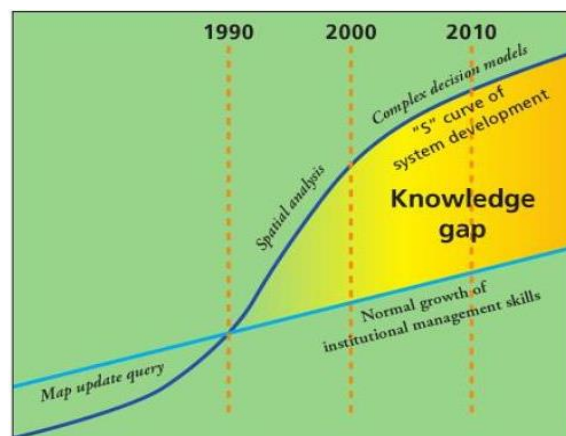


**Figure 3.1: Overall challenges to the implementation of spatial technology**

Understanding of the challenges will help researchers and users to effectively implement GIS related projects. In brief, technical challenges relate to establishing easy-to-use interfaces, adapting systems developed for projects in another area, and data availability, quality and quantity. Technological challenges include the problems which SDSS encounter with advances



in information technology (IT). Managerial issues relate to the utilisation of a customised system in the organisational context. Educational challenges are based on the levels of the training and awareness of different clients from various disciplines. Although technical and managerial problems have been identified as the major limitations of SDSS and other GIS-related project implementations (Sugumaran and DeGroot, 2011), it seems that education is the component most important to the increased utilisation of geospatial science. Training can close the knowledge gap which exists between the development and implementation of spatially enabled technologies. This knowledge gap is described in Figure 3.2 (Tomlinson, 2007).



**Figure 3.2: Knowledge gap in spatial technologies implementation**

The knowledge gap started around 1990 and widened as spatial analysis evolving and spatial decision-making models were developed. The GIS, the advanced innovation at the core of the spatial industry, serves multiple goals in concepts such as spatial-enabled society (Rajabifard, 2010) and decision-making processes (Keenan, 1995). GIS with its in-built capacities for analytical and spatial modelling, spatial and attribute data management, display and reporting capabilities and the ability to communicate with various disciplines and provide a customised environment allows dependent spatial technologies like the spatial planning support system (SPSS), the spatial decision support system (SDSS) and integrated spatial planning and decision support systems (Sharifi and Zucca, 2009) to be adopted by clients during resource allocation

decisions, resource status decisions and policy decisions. However, the assumptions for the incorporation of GIS or dependent systems, like SDSS or SPSS, might not be met in real-world situations due to the challenges described above (see Figure 3.1 and accompanying text). Thus, the promised goals in spatially relevant industries, including spatial data infrastructure (SDI), enterprise GIS and social GIS (Tomlinson, 2007) or community based GIS (Peters, 2008) cannot be attained unless they followed a well-developed spatial data integration, and business-oriented spatial database.

In terms of business-oriented spatial database, for example, the quality of spatial database depends on the quality of topography data source in water resource management. LiDAR-derived topography data can play an effective role in water resource management. A LiDAR dataset is extremely valuable resources that can enable authorities who manage water resources at the local level to achieve their goals in local stormwater and flood management. As soon new emerged spatial data has been available in spatial database, the integration model to utilise new dataset and closing the gap in using the dataset and technology become important.

Solutions are needed to fill the knowledge gap between the development and implementation of spatially enabled technologies in business workflow processes; these can be classified into three groups (McKibben and Pacatte, 2003).The three different classes are:

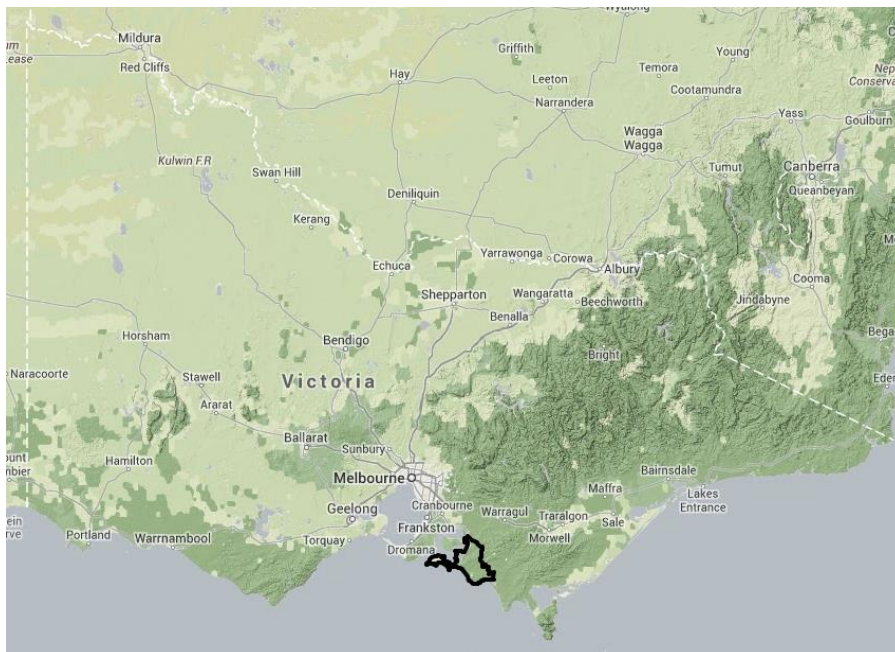
- a) customising tools or systems (like SDSS and PSS) for improving a decision process
- b) refining the target organisation's current business workflows
- c) a combination of group a and b

Solutions in category a are not favoured because they cannot be guaranteed to fill new gaps and prevent additional costs. Class b provides a reasonable long-term solution, but it is not suitable in the short-term to persuade high-level managers of the advantages of using spatial techniques. The most desirable solution is class c, which can be operationalised initially by using spatial techniques in a pilot project study. It can be argued that the knowledge gap can

be filled after pilot project study (Vonk et al., 2007). In summary, not many managers are aware of the value and scope of evolving spatial technologies; a pilot study can offer managers and decision-makers enough information to justify their acceptance of the approach (Vonk et al., 2007).

### 3.3 Bass Coast – the geography

The Bass Coast Shire rural municipality is located in the south eastern part of Melbourne, Victoria, Australia, and covers around 864 square kilometres (Figure 3.3).



**Figure 3.3: The administrative boundary of the Bass Coast Shire, Victoria, Australia (source: <http://profile.id.com.au/bass-coast> retrieved on 27 July 2013)**

The area is located in a coastal-rural municipality which contains numerous tourist attractions, notably Phillip Island. Around 35% of Melbourne’s international visitors visit the shire (DPCD, 2012a). The main cities in the shire are Wonthaggi, Cowes, San Remo, and Inverloch (Figure 3.4)



**Figure 3.4: Bass Coast Shire main cities and administrative boundary (source: Bass Coast Shire Council)**

According to the Australian Bureau of Statistics (ABS), the current estimated population of the Bass Coast Shire is 30,000 people (ABS, 2012). The estimated density of residential population has increased by 17% since 2001 (ABS, 2012). During the peak holiday period, the population increases by up to 60,000 people (DPCD, 2012a). Bass Coast Shire has one of the fastest growth rates in Victoria, and it is estimated that its residential population will increase by 50,000 people by 2031 (DPCD, 2012b).

The Bass Coast Shire boundary stretches northward up to the Great Dividing Range or the Eastern Highlands, which is a mountainous area, and south to Bass Strait. The Bass Coast Shire is bordered by Port Phillip and Westernport Bays on the western side and along the eastern boundary neighboured by the South Gippsland Shire.

Like any other local council, the Bass Coast Shire Council has various responsibilities (Figure 3.5). According to the Bass Coast organisational chart, the Council’s responsibilities are divided among four directorates. Functional practices are initially controlled by third-level managers and then top level managers at the level of directorates and the chief executive officer.

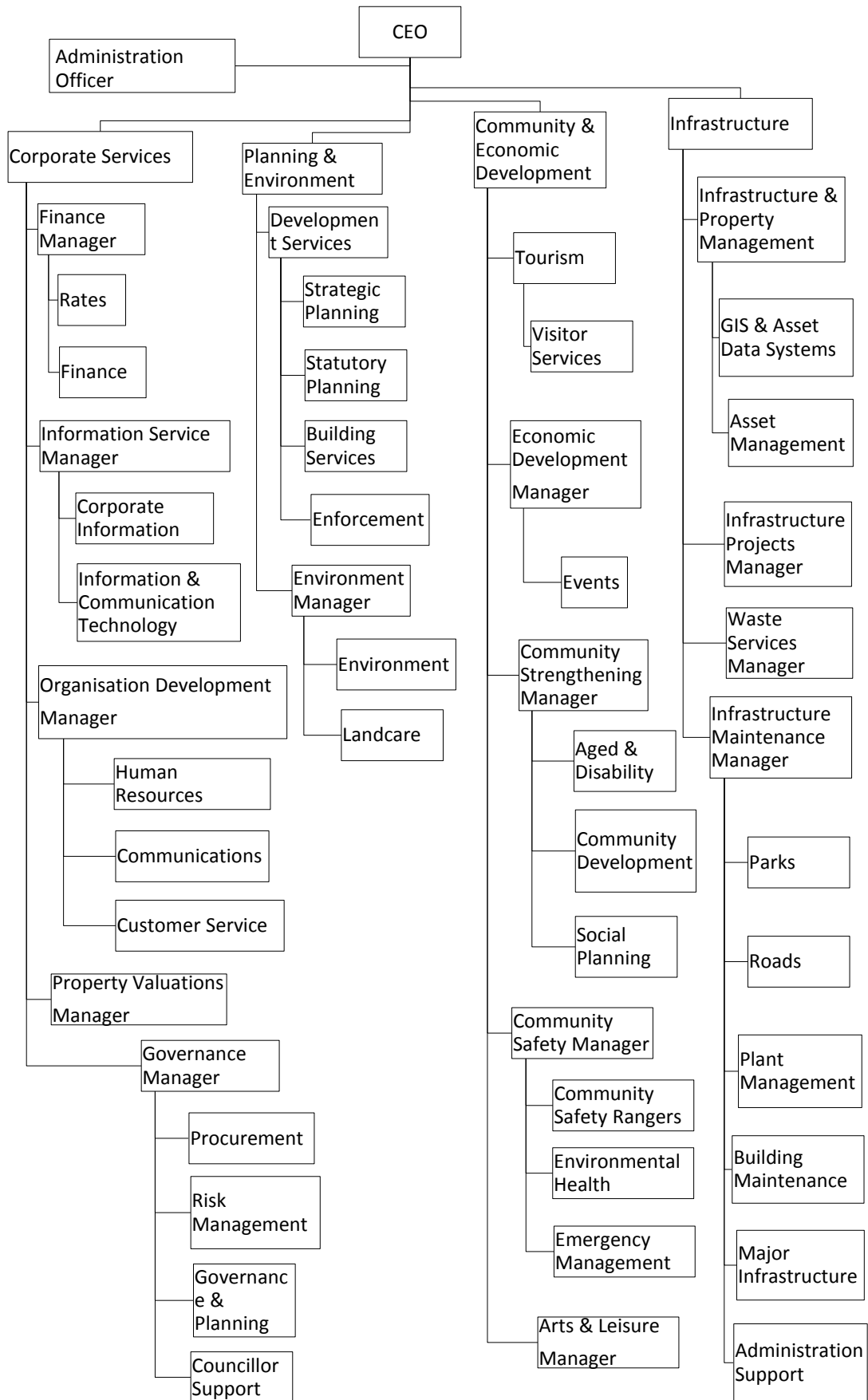


Figure 3.5: The Bass Coast Shire Council – Organisational Chart (Bass Coast Shire Council, 2012)

The structure of the Bass Coast Shire Council, as the organisational chart shows, encompasses many departments, sections, people, relationships, tasks and responsibilities. Nevertheless, the chart cannot show how the organisation operates (Shukla, 2004). From the Bass Coast Shire Council organisational design presented above, I deduced that problems are solved by the decision-makers who encounter the problems in day-to-day work. Therefore, flood-risk-based land use planning, which includes planning and engineering teams, is located between the Planning and the Environment directorate and the Infrastructure directorate. To increase problem-solving performance, the two directorates have to cooperate in terms of technical aspects and relevant policies. The Planning and Environment directorate responsibilities are various, but its major tasks related to the current research are:

- 1-climate change and sustainability
- 2-land and catchment management
- 3-statutory land use planning
- 4-strategic land use planning
- 5-development approvals

The Infrastructure directorate's responsibilities with respect to floods are:

- 1-stormwater collection system design
- 2-infrastructure and asset data management
- 3-GIS and data system administration
- 4-property flood issue considerations and management
- 5-subdivision flood issue consideration (based upon requests from the Planning and the Environment directorate for new estate land development)

The GIS office in the Infrastructure directorate is responsible for administering the data required to support the offices in both the Infrastructure directorate and the directorate of Planning and the Environment.

### **3.4 The criteria for the selection of the study area**

The Bass Coast Shire was easily accessible to me for research purposes and a LiDAR dataset was available for the entire Shire. Other reasons for choosing the study area are listed in the following eight sections.

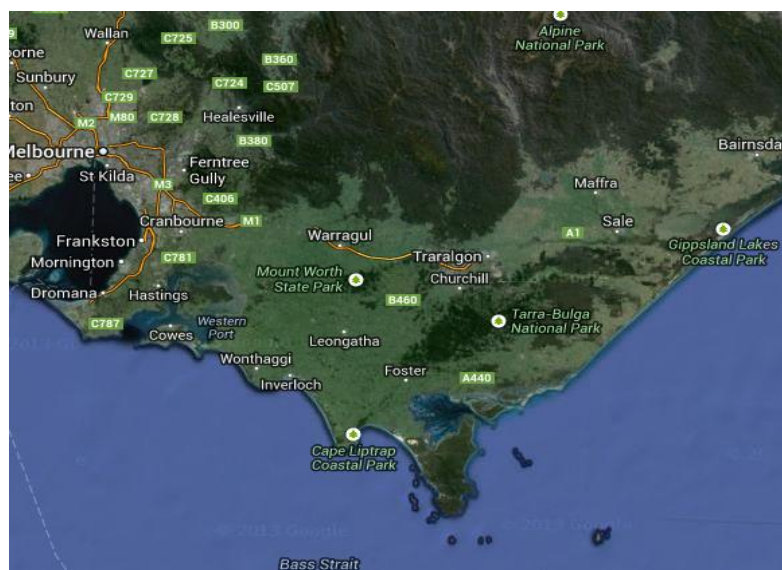
#### **3.4.1 Terrain Characteristics**

The Bass Coast Shire is located in a coastal area to the south of the Great Dividing Range (or Eastern Highlands). The Great Dividing Range are 3,500 kilometres long, and run from Queensland southward to Victoria and then continue westerly through Victoria to the Grampians National Park before fading into Victoria's western plains. The hydrodynamic behaviour of water flow on the two sides of the Great Dividing Range is completely different. The southern part of the Great Dividing Range produces immediate stormwater runoff with a low warning time, while in the north part of this natural separation, stormwater runoff needs more time to become concentrated as an overland water flow in the major regional rivers. Flood behaviour varies markedly across Australia and due to the Greater Dividing Range, as can be seen in Figure 3.6.



**Figure 3.6: The natural separation of hydrodynamic behaviour in Australia. Red box refers to figure 3.7**

The Figure 3.6 shows that areas located on the eastern side of the Great Dividing Range in Queensland and New South Wales contain coastal rivers which are subject to short-duration rapid-onset floods. The same is true for the coastal river areas in Victoria located south of the Range (Figure 3.7).



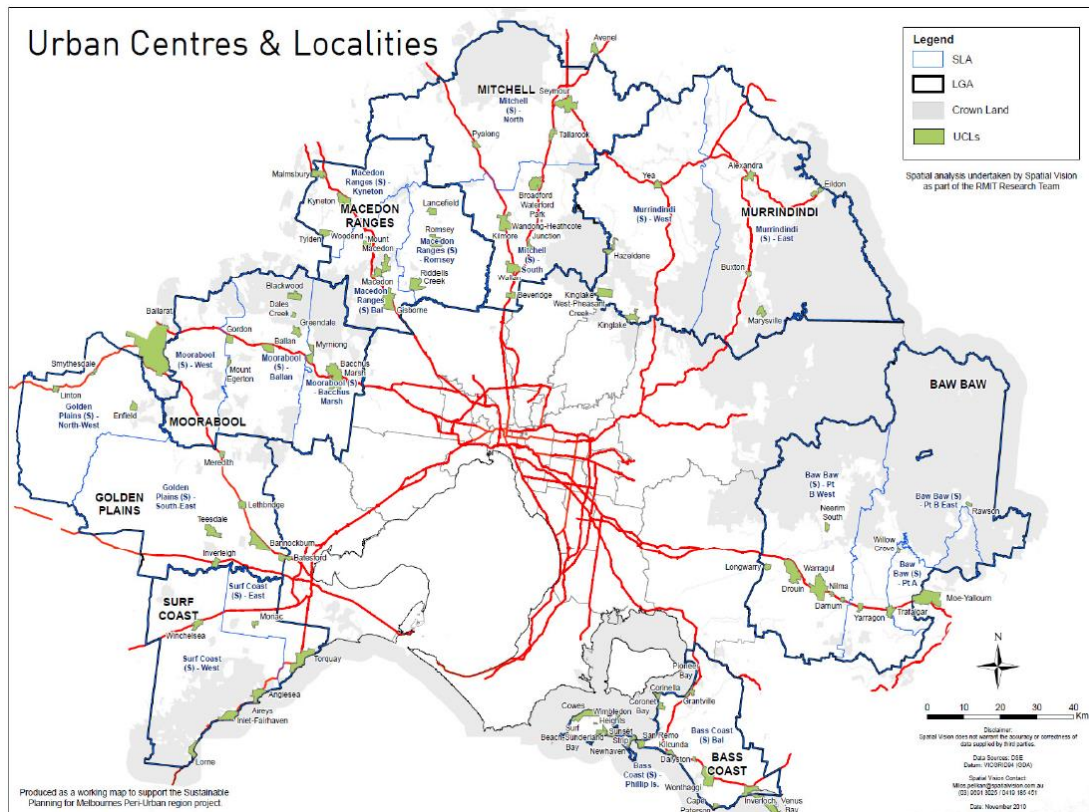
**Figure 3.7: Terrain characteristics in pilot study area (Google map, retrieved 14 February, 2014)**



Two main regional rivers, the Bass River and the Powlett River flow to Bass Strait through the Bass Coast Shire. The outcome of the cooperation between Melbourne Water (MW), the West Gippsland Catchment Management Authority (WGCMA) and the Bass Coast Shire Council (BCC) in flood management planning is the Land Subject to Inundation Overlay (LSIO) for the Bass and Powlett rivers, which is designed to assist the council to improve local flood-risk-based land use planning in the context of floodplain management through the strategic land use planning practices. However, the produced LSIO maps needs to be updated under the climate change scenario.

### **3.4.2 Pressure for green development and refill**

As for any other peri-urban local government in Victoria (Figure 3.8), land use change is a challenging issue for the Bass Coast Shire Council. With the conversion of the pervious agricultural land cover into hard urban surfaces, stormwater runoff increases in terms of frequency, duration, flow rate, overall volume, erosion and transport of pollutants. In addition, demand for coastal living within close proximity to Melbourne is driving demand.



**Figure 3.8: Urban centres and localities in the peri-urban area (Buxton et al., 2008)**

Two of the eight peri-urban areas shown in Figure 3.8 are coastal, the Surf Coast and the Bass Coast. The Bass Coast Shire had the highest development rate of all of Melbourne’s peri-urban local governments between 2001 and 2006 (Buxton et al., 2008). The Bass Coast Shire has one of the highest growth rates of all Victorian shires due to being a “coastal getaway” (Gurran et al., 2005). Coastal getaways are in areas close to major urban centres (for example, Melbourne), with high rates of residents who work from home, and are generally suitable for retirees (Grunbuhel and Coast, 2010).

The Bass Coast Shire can be described as being a coastal rural council in the Melbourne peri-urban region. The shire is subject to flash flooding, rising sea level hazard and coastal riverine flood. Of course, as outlined in detail in chapter 2, the Bass Coast shire Council is the responsible authority for any land use planning involving flood prone areas, including riverine flood land, tidal flood areas, and areas at risk of flash flooding in urban and urban-rural (fringe) areas in the Bass Coast Shire. Therefore, flood-risk-based development is a major concern of

the Bass Coast Shire Council. The council cooperates closely with other stakeholders involved in flood management when making decisions about development.

### **3.4.3 Knowledge-based local government**

Like all Victorian local governments, the Bass Coast Shire Council needs to move from conventional information management to knowledge-based management in order cater for population growth and the consequent increase in service demands. The Municipal Association of Victoria (2012) described that knowledge-management is not solely on storing information. However, Knowledge-management is the lifecycle of information and takes the information and turns it into valuable knowledge which can be embedded into service applications (Municipal Association of Victoria, 2012). In addition, knowledge-management brings benefits for local councils including greater productivity, better decisions, and building a more resilient council.

The Council won the Asia-Pacific Spatial Excellency Award in 2011 and was a finalist for the Victorian Coastal Awards for Excellence in 2012, having shown evidence that it was trying to utilise spatial industry applications to achieve knowledge-management goals. In line with utilising the spatial technology, the Bass Coast GIS team has established an enriched spatial database, provides access to updated information and spatial data, and is utilising spatial technology advancements to improve turning existing data and information into knowledge.

### **3.4.4 Integrated Water Management (IWM)**

As an agency which must manage development land based upon regional provisions, the council takes an integrated approach to water resource management. This approach relies on a holistic plan, including guidelines and frameworks for precise information, the required models and techniques, and the extent of skills that the council needs to meet the defined aims in the different policies and frameworks. The integrated water management (IWM) plan has been recognised and implemented by the council as an appropriate response to the need

for a holistic plan and the rapid growth in the Bass Coast Shire in relation to water resource management. In an IWM approach ecological resources are considered alongside water resources.

The activities which the council has implemented through Clause 56 of the Victorian Planning Provisions (VPPs) to demonstrate best practice stormwater management incorporate WSUD elements like wetlands, bio-retention facilities and rainwater harvesting. Historically, the council has used such features wherever possible in relevant projects without attention to broader catchment considerations (Farrant, 2012).

### **3.4.5 External stakeholders and internal commitment**

The Bass Coast Shire Council is one of the stakeholders in water resources management, including flood management, in the pilot study area. It cooperates with the other stakeholders (such as WGCMA) in delivering optimal environmental outcomes for the shire. The council is committed to good governance, environmental sustainability and cohesive communities as components of its integrated approach to stormwater runoff management (Farrant, 2012). Good governance refers to managing resources effectively in order to create positive outcomes, while a commitment to environmental sustainability means making sure councils' and communities' natural assets are managed in a sustainable manner. The council's commitment to a means it is continually looking for ways to improve lifestyle opportunities in the shire.

### **3.4.6 Driving policies**

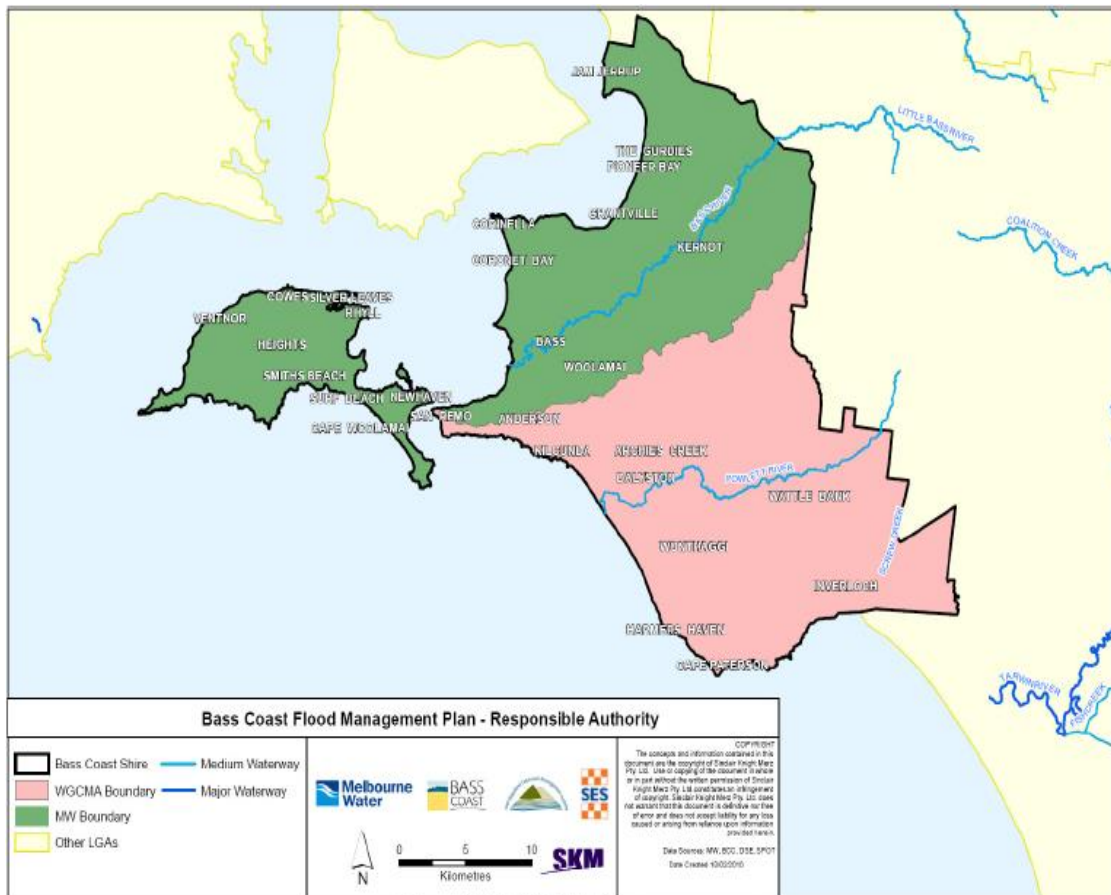
Every council is governed by different policies which are defined under federal or state wide Acts. Due to the complexity of council responsibilities, as can be seen in the Bass Coast Council's organisation chart (Figure 3.5), numerous policies, plans and guidelines are employed to manage the council's efforts. The Bass Coast Shire Council, as discussed in Chapter 2, is one of the key stakeholders in flood management, and specifically in floodplain management for

the West Gippsland Catchment. Floodplain management includes preventative environmental activities which are highly dependent on stormwater quality and quantity management. The key policies related to stormwater runoff management (both water quality and water quantity) for the Bass Coast Shire are the local flood management plan 2010, stormwater management plan 2003 (EarthTech, 2003), the environmental sustainability plan 2008-2013, the infrastructure design manual, the drainage implementation plan and the Bass Coast Shire Council planning policy. The local flood management plan has been prepared to meet the requirements for the Victorian flood management strategies (Victorian Government, 1998).

### **3.4.7 Flood mapping issues in the Bass Coast Shire**

The key flooding issues and the appropriate response of each stakeholder are set out in the Bass Coast flood management plan. One of the high-priority issues covered in the local flood management plan is to determination of overland flow paths. The Bass Coast Shire Council must map overland flow paths for all major townships in the Shire. Flood mapping within the municipality is necessary for informed planning control in the Bass Coast land use planning scheme, to give flood advice to the affected properties and communities, and to consider flood mitigation practices.

Several authorities have responsibility for flood issues within the Bass Coast Shire (Figure 3.9), and different resource limitations and organisational interests create difficulties in achieving the aims of local flood management. For example, while both riverine flood and flood at the property level are important for Council, only riverine flood is the interest of WGCMA and Melbourne Water.



**Figure 3.9: Authority boundaries for flood management for the Bass Coast Shire Council (BCC, 2010)**

Melbourne Water has a plan for mapping a 100-year flood in all the catchments under its control (Melbourne Water, 2006), while the West Gippsland Catchment Management Authority (WGCMA) has mapped the lower part of the Powlett River and does not have any plan for future Shire flood mapping (WGCMA, 2013-2019). Any further flood mapping in the West Gippsland Catchment will depend on the needs of urban or infrastructure development.

### 3.4.8 Important receiving coastal waters

In Australia, apart from designated Commonwealth lands, control over coastal waters rests with state authorities (though power is, in specific instances delegated to local government). Although the state government controls the coastal area up to three nautical miles (5.5 kilometres) seaward (Victorian Government, 2008) in terms of natural resource conservation, local governments' management of the quality and quantity of stormwater runoff has an

effect on coastal water quality. The Bass Coast Shire Council, like any other coastal council, faces stormwater runoff quality and quantity management challenges.

Bass Coast stormwater runoff drains into Bass Strait in the south and south east of the area. The overland flow drains into Port Phillip and Westernport Bay. Coastal areas are important in terms of environmental conservation, particularly the sites which are listed under the Ramsar Convention on Wetlands of International Importance. Stormwater from urban and farmland across the Shire drains into the Ramsar site area located in the western section of the study area, Westernport Bay (EarthTech, 2003). The WGCMA has also determined that the regional catchment contains important landscapes(WGCMA, 2004-2009); the coastal area of the Bass Coast Shire has been identified as a high priority area (Figure 3.10).

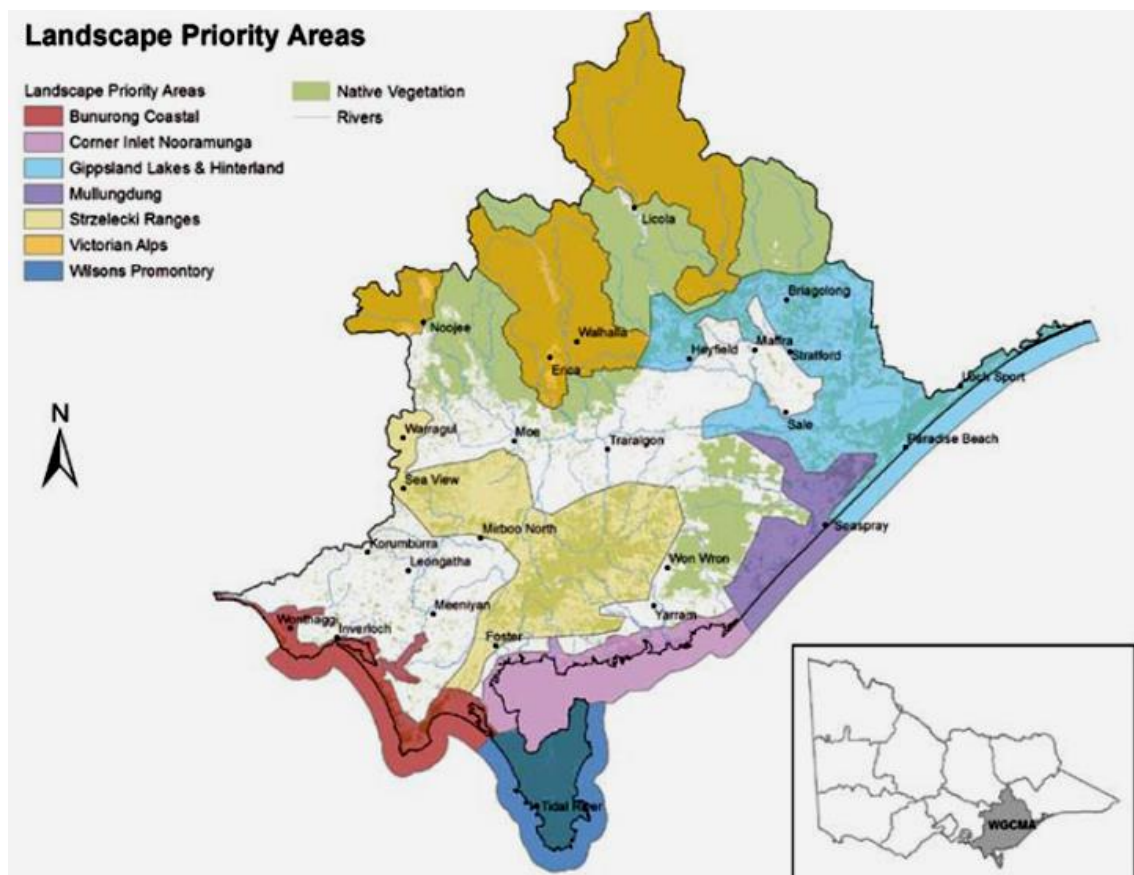


Figure 3.10: High priority landscapes in the West Gippsland Regional Catchment (WGCMA, 2013-2019)

### **3.5 Conclusions**

In this chapter, I introduced the Bass Coast Shire. The reasons why the Bass Coast Shire was selected as the pilot study area was discussed through the chapter. Rapid growth in the area means the Bass Coast Shire Council is under pressure for Greenfield estate developments and refill in built-up areas. Such pressure influences valuable resources in the shire, notably water resources, in regards to reduced stormwater quality and increased stormwater runoff and associated flooding. The pilot study area includes an important part of Victoria's coastline, and the Bass Coast Shire Council and other responsible agencies must follow various driving strategies, plans, and policies to manage coastal water quality. The Bass Coast Shire's status as a Coastal Getaway area means that the council is under pressure to approve land use change in order to cater for its increasing population. The shire also includes major Victorian tourist attractions that encourage people to visit the area, particularly to Phillip Island. Therefore, the Bass Coast Shire Council, as a major stakeholder in the area, needs to manage its flooding issue adequately.

In the next chapter (chapter 4) I focus on flood-risk-based land use planning procedures in the Bass Coast Shire Council and use of the GIS database to support the decision-making in land development. The chapter 4 addresses three research questions:

- 1-How is flood risk addressed in land use planning decisions at the local level?
- 2-What information products are required for flood-risk based land use planning at the local level?
- 3-What are the gaps in existing local flood relevant databases?



## 4 GIS database and land use planning involving the flood risk for the Bass Coast Shire

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### 4.1 Introduction

In chapter 2, I discussed the responsibilities and roles of Australian government agencies and the importance of land use planning in reducing the damage from riverine and overland flash flooding.

In chapter 3, I introduced the pilot study area and the reasons why the location was chosen. The area is the Bass Coast Shire, under the jurisdiction of the Bass Coast Shire Council.

In this chapter, I describe a pilot study of a procedure for flood-risk-based land use planning and consideration of existing GIS database in Bass Coast Shire to support land development decision-making. Business work flow, required information products and survey data in a spatial database are important supports that enable flood-risk-based land use planning policy to be put into practice.

Moreover, to develop a comprehensive flood-risk-based GIS database, a dataset with a proper scale, good quality, sufficient spatial detail, and appropriate attribute information is required, as well as GIS-embedded hydrological models. These matters are discussed in order to answer research questions two, three, and four listed in section 1.2.

In the rest of this chapter I present brief background to the study, then describe study method and findings.

### 4.2 Background

In chapter 2, I outlined how local governments are responsible for floodplain management and particularly for flood prevention practices in Victoria. In addition, I discussed how local governments rely on the flood mapping data produced by CMAs in regional Victoria, and Melbourne Water flood information in the Melbourne metropolitan areas. Local governments

control land use using flood zones and overlays. Depending on location, flood-risk-based land use planning will take account of riverine, overland flash flooding, and rises in sea level and tidal flooding. Flood information varies between authorities in jurisdictions, for example, for the parts of the Bass Coast shire drained by Melbourne Water's drainage system, a stormwater runoff flooding study has been conducted and SBOs have been prepared. Even when an SBO exists, the data relate only to the date of collection, while land use might have been changed since the SBO was developed. Therefore, the SBO flood maps need to be updated to account for new hydrological processes based upon the new conditions of the upstream catchment, in particular where new estate subdivisions have taken place. In order to update flood maps, funding, time, data and expertise are required, along with a well-organised flood-relevant spatial database. Lack of data and well-structured database management make flood-risk-based management difficult for all stakeholders, including Melbourne Water, CMAs and local governments.

The Bass Coast Shire Council, Melbourne Water, and the WGCMA, in cooperation with other stakeholders, developed the Bass Coast local flood management plan, in which the major focus is on flooding in coastal townships. Land use control to reduce riverine flooding and the consequent damage from urban stormwater flash flooding is the responsibility of the Bass Coast Shire Council.

The Council's land use planners rely on the flood information provided by Melbourne Water and WGCMA in major river floodplains, but land use planners also need to consult internally with Subdivision and Project Management offices of Infrastructure directorate, in order to make precise decisions regarding the flood issue at the property level.

If strategic land use plans address an area of BCC for which Melbourne Water or the WGCMA have not provided flood overlays, it is necessary to refer the development plan to one of these stakeholders as the liable referral authority for the land development location. A comprehensive and well-organised updated database including relevant and proper

information is essentially required to enable the Bass Coast Shire Council's engineering office to provide accurate responses to statutory land use planners' requests.

The majority of the information required in flood management is spatial in nature. Collecting data and producing spatial datasets is the responsibilities of the different stakeholders involved. The Bass Coast Shire Council has access to the fundamental spatial datasets produced at state levels and disseminated through the spatial data infrastructure (SDI) initiatives. However, the council creates its own local and specific datasets for routine tasks.

In line with the establishing a well-organised flood-relevant spatial database for a local government, next section will focus on the methodology for database modelling.

### **4.3 Methodology for database modelling**

The database lifecycle and the methodology for establishing an appropriate GIS database needs to be undertaken at the early stage of database development. User-centred database design (UCD) is a widely used methodology in database design and development due to its user-friendly characteristics and its being an effective approach in terms of recognising users' needs and preferences and the constraints relevant to task-oriented business objectives (Yeung and Hall, 2007). The information collected through the UCD method can be implemented for data modelling, which is the first step of database life cycle development.

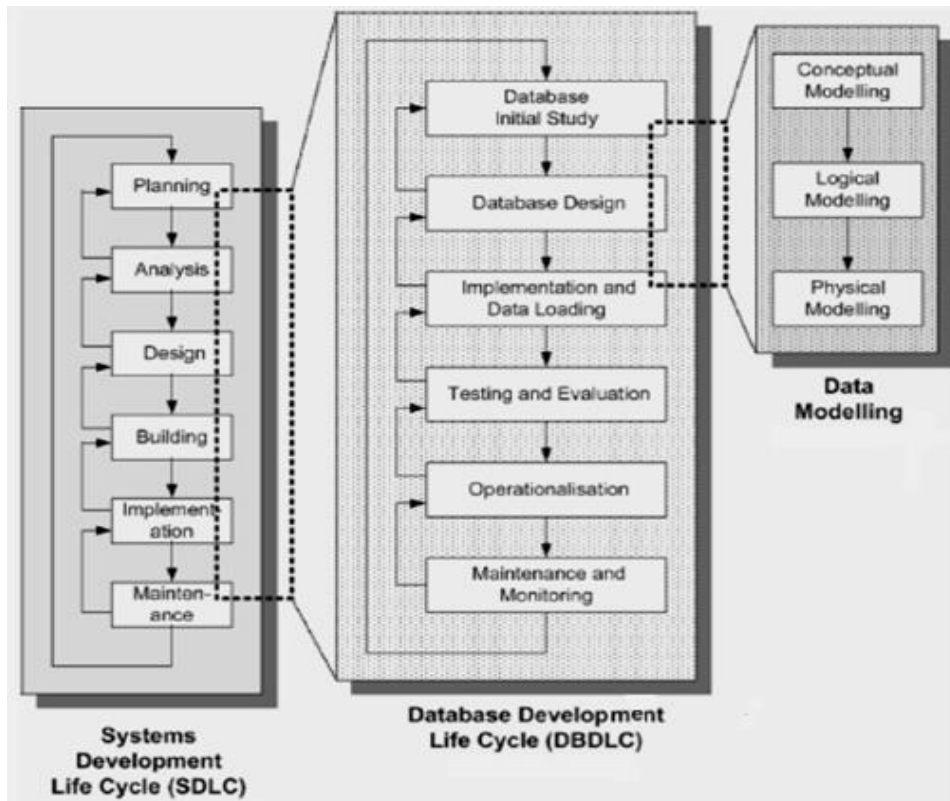
The benefits of UCD in data modelling, as described by Yeung and Hall (2007) are to:

- a) Provide a well-structured framework not only for a System Development Life Cycle (SDLC) design but also for the Database Development Life Cycle (DBDLC) design through identification and definition of the business function of the target agency in specific applications
- b) Accept user participation in the modelling process which allows the development of a database from the users' points of view

- c) Bring about an opportunity to assess user needs and limitations in order to avoid further incurred unnecessary costs to correct the errors which may have occurred during the design stage.

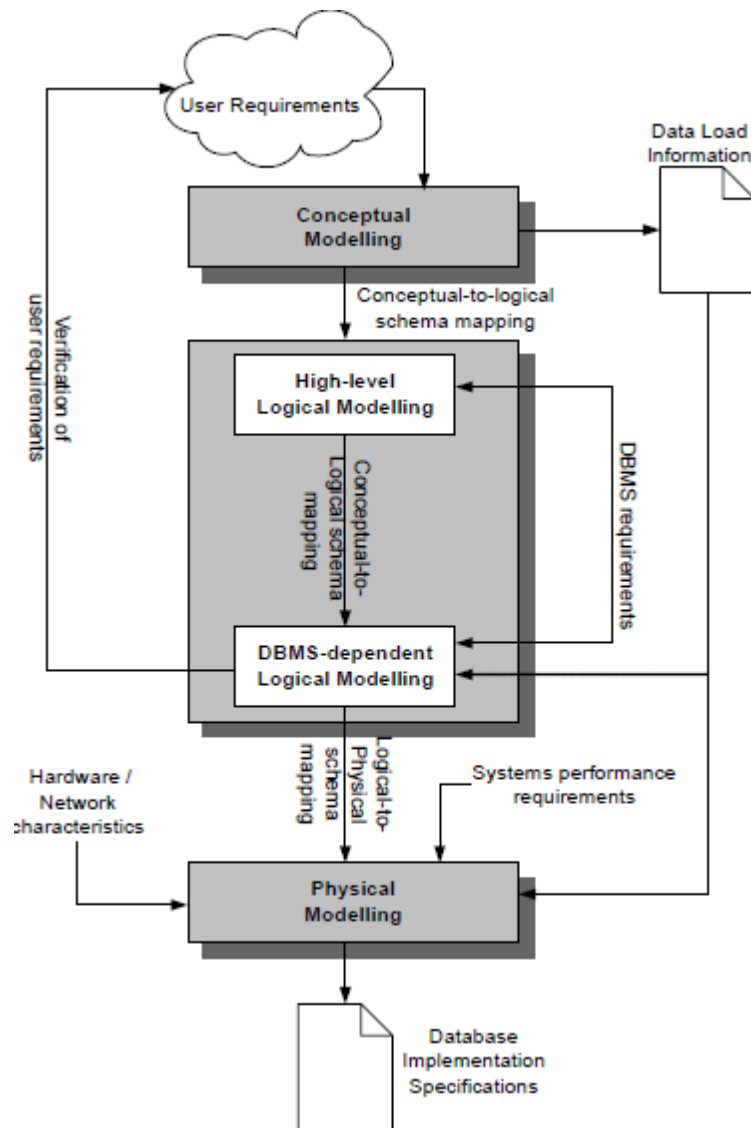
UCD is an iterative approach to data modelling which gives a designer an opportunity to update the previously designed database model based upon recent user inputs and the growing knowledge of the designer (Yeung and Hall, 2007). A UCD iterative approach is a complex process and it is not possible to develop the database system in one phase as can be seen in Figure 4.1. Due to all the merits of using UCD in a DBDLC, UCD is now accepted as the data modelling standard and the cornerstone methodology for development of systems and databases, in both the spatial (GIS) and non-spatial domains. UCD has implications for the whole life cycle of the data modelling including conceptual, logical and physical data modelling.

Conceptual database modelling is a database-independent translation of a real workflow, while a logical data model converts the elements in conceptual database models based upon a specific database management system's requirements. A physical database model is the final stage of database development based upon a specific database management system.



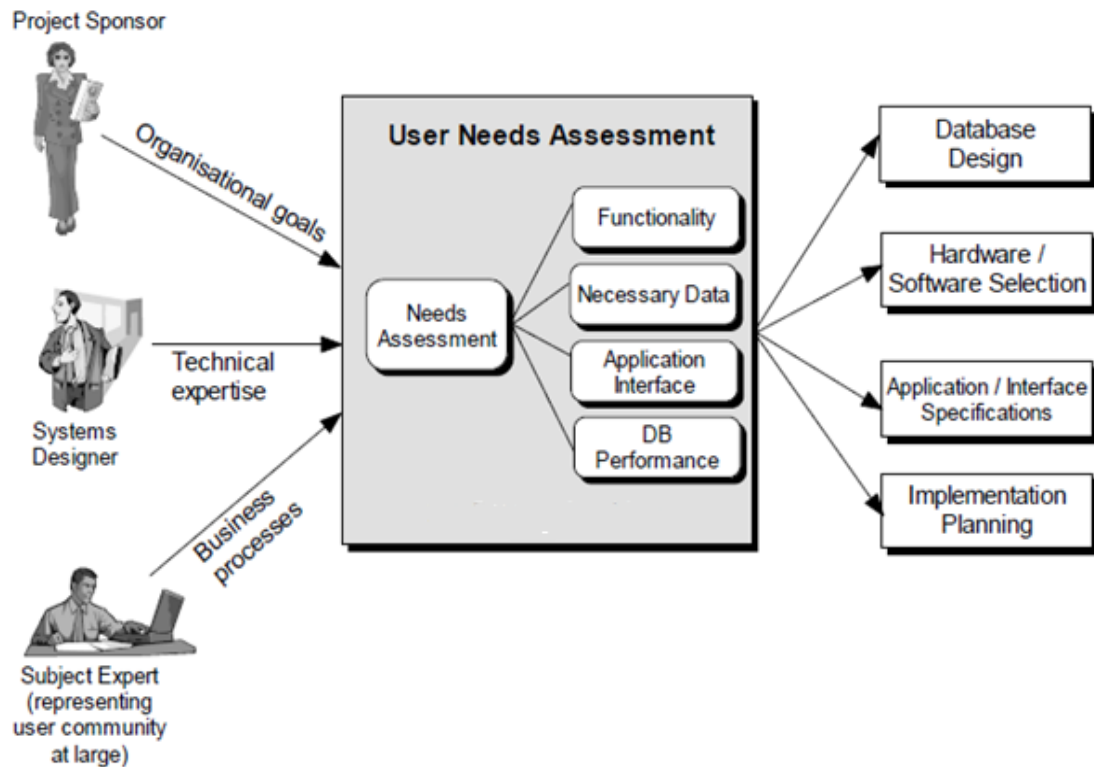
**Figure 4.1: The systems and database development life cycle (SDLC) (Yeung and Hall, 2007)**

The six stages of DBDLC are sequential, interactive and iterative. Data modelling is the most important element of the development of a database system, and is detailed further in the life cycle depicted in Figure 4.2.



**Figure 4.2: Data modelling life cycle in the context of DBDLC (Yeung and Hall, 2007)**

Considering the current flood-risk-based land use planning process as part of a user needs analysis can help the researcher to understand data requirements and data limitations in order to establish a well-organised flood-relevant spatial database. A flood-relevant spatial database is vital to fulfil the requirements of on-demand flood modelling. Using a UCD framework, a user needs assessment, including consideration of the current relevant business workflow process, required datasets, and existing database quality and performance. The user needs assessment is followed by data modelling and spatial database design (Figure 4.3).

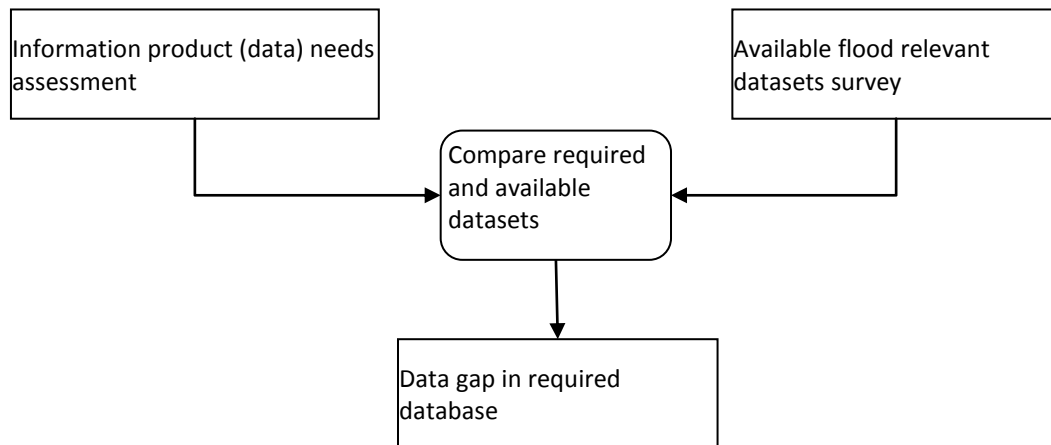


**Figure 4.3: Components of a user needs assessment (Yeung and Hall, 2007)**

A GIS-based application has four major components: data, software, hardware, and users, all of which should be incorporated into a comprehensive needs assessment (Figure 4.3). The major concerns in a user needs assessment are the data (accuracy, lineage and completeness) and the user's tasks and knowledge.

A user needs assessment helps the system developer and database designer to understand the organisation goals and the aims of specific tasks in order to develop business-oriented (Mohammadi, 2008) GIS database.

Figure 4.4 depicts, a proper and usable GIS database is achievable after defining the required dataset through the user data needs assessment stage and evaluation of available datasets.



**Figure 4.4: Data survey and data needs assessment in the context of DBDLC using UCD framework concepts (Becker et al., 1995)**

A user needs assessment is the first step to understanding technical and non-technical requirements before establishing specific aims for a corporate spatial database in a target organisation, and can provide reports about the following matters:

- a) The application to be developed for each department
- b) The spatial functions (query, display, spatial analysis) which need to be included in the final GIS system
- c) The required spatial datasets to be collected and stored in GIS database
- d) Procedures for data creation and updates, including workflow, inter- and intra-departmental responsibility, and user training

The abovementioned matters would be the same regardless of whether the development is for multiple agencies or just one. Furthermore, the database design and planning procedure would be the same for a corporate multi-purpose multi-user integrated GIS application or a single and limited functional-based database system.

The needs assessment procedure focuses on either a whole organisation or a specific goal. However, development of a corporate database for the whole set of responsibilities of the Bass Coast Shire Council was my aim; the focus was only on the flood-risk-based land use



planning data needs in regards to local flood management provisions and the Bass Coast land use planning scheme.

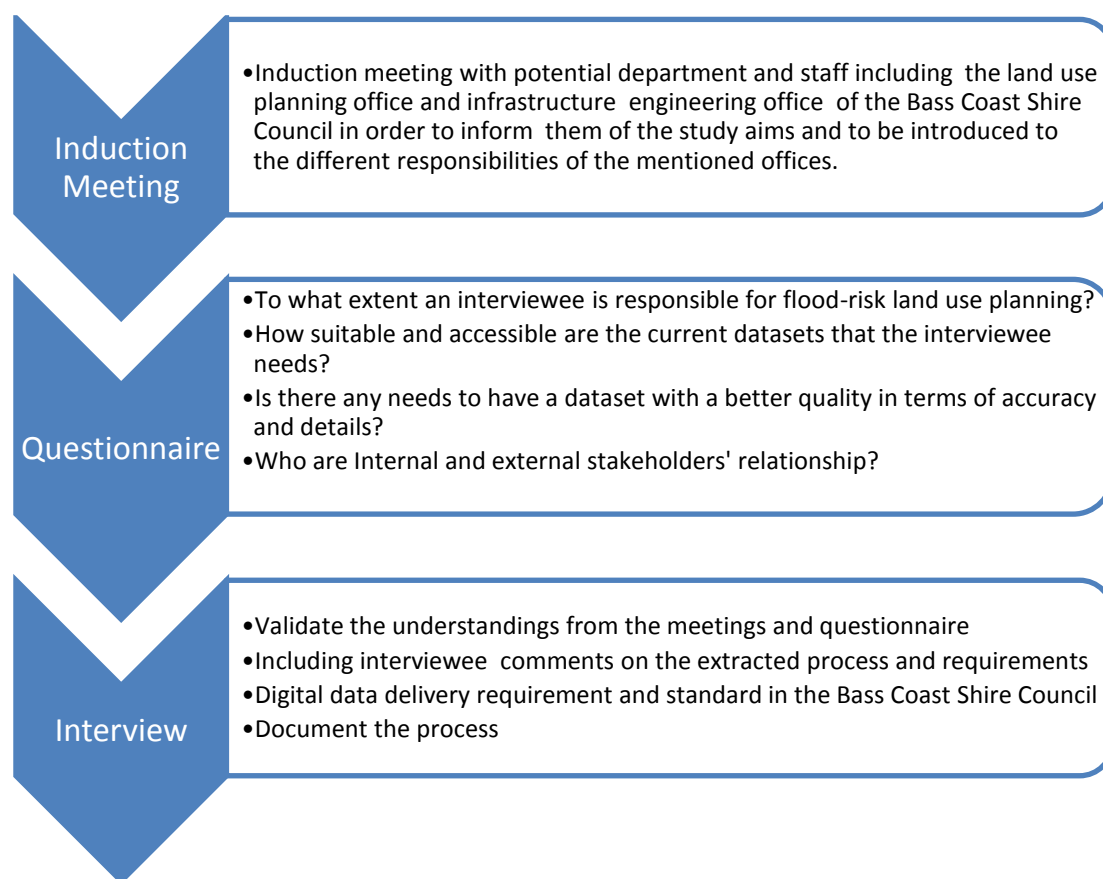
Interviewing potential flood management experts, and land use planning experts at the Bass Coast Shire Council, and considering the land development workflow process regarding flood risk management are the prerequisites for a user data needs assessment in order to find out about any lack in the current flood-risk based database (section 4.9).

#### **4.4 Methods used to conduct the user data needs analysis in the Bass Coast Shire Council**

As noted in section 4.3, a user needs assessment is an integral part of the initial stage of database design and development. It is the most important part of conceptual data modelling. The tools of the “assessment” in a needs assessment include accepted data collection methods (document analysis, task observation, questionnaires and interviews), analytical techniques and a structured approach to understanding business processes, data and applications (Yeung and Hall, 2007). A needs assessment requires a collaborative approach to link subject experts, designer and organisation perspectives (Bédard, 1999).

A needs assessment typically involves different methods at successive stages. The three most common methods for understanding user needs are an induction meeting a questionnaire and interviews (Rigaux et al., 2001).

Considering the Bass Coast Shire Council’s business flowchart to identify the relevant department, these three methods were employed (ethics obtained from RMIT University, BSEHAPP 46-13) as shown in Figure 4.5 to learn about the data needs of users.



**Figure 4.5: User needs analysis, Directorate of Land Use Planning and Directorate of Infrastructure, Bass Coast Shire Council 2012**

Induction meetings were arranged early March 2012 to introduce myself, the research project and the aims of the research, and to gain an understanding of the shire officer's relevant responsibilities. The significance of such meeting is to establish shared vision and language to explain needs and requirements Tomlinson (2007).

Although the induction meeting were useful in that they allowed me to become familiar with the staff responsible for flood management and land use planning, the requirements and procedures they employed to complete their tasks could not be delineated. The induction meetings enabled me to identify the significant staff for the next steps of the study: the questionnaire and interview.

The questionnaire (Appendix A) was designed to understand the following matters:

- a. To what extent the respondent was involved in flood management (Q1)

- b. The suitability and accessibility of the existing datasets used by the interviewee (Q2 and Q3)
- c. The need for a dataset of better quality in terms of accuracy and data details (Q4)
- d. To identify internal and external stakeholders (Q14)
- e. What they already have in terms of model package for on-demand flood modelling (Q6,Q7 and Q8)
- f. The reliability of an alternative source of datasets and information, such as crowd source information (Q5,Q12, and Q13)
- g. Staff awareness about GIS (Q9,Q10, and Q11)

The questionnaire includes 19 questions; 5 questions were optional and asking about the respondent's gender, years of experience, and position to get insight about the participant. The questionnaire (printed) was disseminated among 19 staff through the cooperation of GIS-team coordinator. All participants responded to the questions in questionnaire and sent back to me through GIS coordinator in Bass Coast Shire Council. Considering the answers resulted as below:

*1-To what extent the respondent was involved in flood management*

The result showed that 60% of participants are directly involved in flood management and flood-risk-based land use planning.

*2-The suitability and accessibility of the existing datasets*

In terms of data suitability, accessibility and data sharing, the 50% of participants claimed that the existing GIS database cannot support the process of flood-risk based management including flood-risk-based land use planning.

*3-The need for a dataset of better quality in terms of accuracy and data details*

In the meantime, all participants claimed that better quality datasets are required to be available. The respondents believe that data with better quality helps them to knowledgeable decision-making in different parts of their routine tasks.

#### *4-To identify internal and external stakeholders*

All participants answered using the name of internal and external stakeholders who are involved to provide or consume of datasets in flood relevant GIS database. As it has been described in chapter 2, WGCMA and Melbourne Water are the major external referral authorities while internal relationship is focused between Directorate of Land Use Planning and Directorate of Infrastructure for flood issues.

#### *5-The model packages for on-demand flood modelling*

Bass Coast Shire Council had no specific flood modelling packages that could be used for on-demand flood modelling.

#### *6-The reliability of an alternative source of datasets and information*

Alternative source of datasets and information refer to the information received from sources other than GIS database, such as community (citizen) complaints, and developers' plans. In response to the alternative source of datasets and information, 17 of 19 participants claimed that the developers' plan is not reliable and need to be checked by council's engineer, while 66% of participants claimed that complaints received from community can update existing GIS database and carries spatial detail they needed. However, there is no mechanism to incorporate such information in the existing GIS database.

#### *7-Staff awareness about GIS*

In response to the awareness of respondents to the GIS, all participants were aware of the server-based GIS data visualisation environment (called "Latitude") that enabled them to access maps and information when they required them.

The questionnaire cannot represent the councils flood-risk-based land use planning workflow procedure. The effective method to extract the workflow process and associate data needs is individual interviewing as suggested by Becker et al. (1995).

Interviews sessions were arranged with those staff at the Bass Coast Shire Council who had filled in the questionnaire, were in charge of flood-risk-based land use planning, and were

willing to participate in further investigations. Five participants from Planning Directorate and Infrastructure Directorate were invited to participate in interview sessions. The main purpose of interview was to extract the flood-risk-based land use planning and associate data flow procedure. In the interviewing sessions, the interviewees' attention was drawn to:

- a. The map they produce or use for flood-risk-based decision-making land development
- b. The datasets and procedures they need to produce their required map
- c. Referral procedure

The questionnaire and interviews resulted in valuable outcomes, including documenting the workflow procedure, required information products such as LSIO, a master data list and missing datasets in the Council's GIS database.

Workflow procedure can be documented through an activity flowchart process and a Data Flow Diagram. The Bass Coast Shire Council's activity flowchart process for flood-risk-based land use planning activities in municipality is documented and described throughout the section 4.5 in order to answer research question "How is flood risk addressed in land use planning decisions at the local level?"

#### **4.5 Flood-risk-based land use planning process - activity flow chart**

Delineating the process flow diagram is an important part of the needs assessment, and the activity-type (workflow) process clarifies the relationship between stakeholders in flood-risk-based land use planning. Planning guides and strategies regarding water resources including flood risk in the land use planning process were studied, but the main source for determining and validating the existing workflow process were the interviews with the relevant and key staff in the Bass Coast Shire Council. Figure 4.6 shows the activity flow diagram for the Bass Coast Shire for flood-risk-based land use planning.

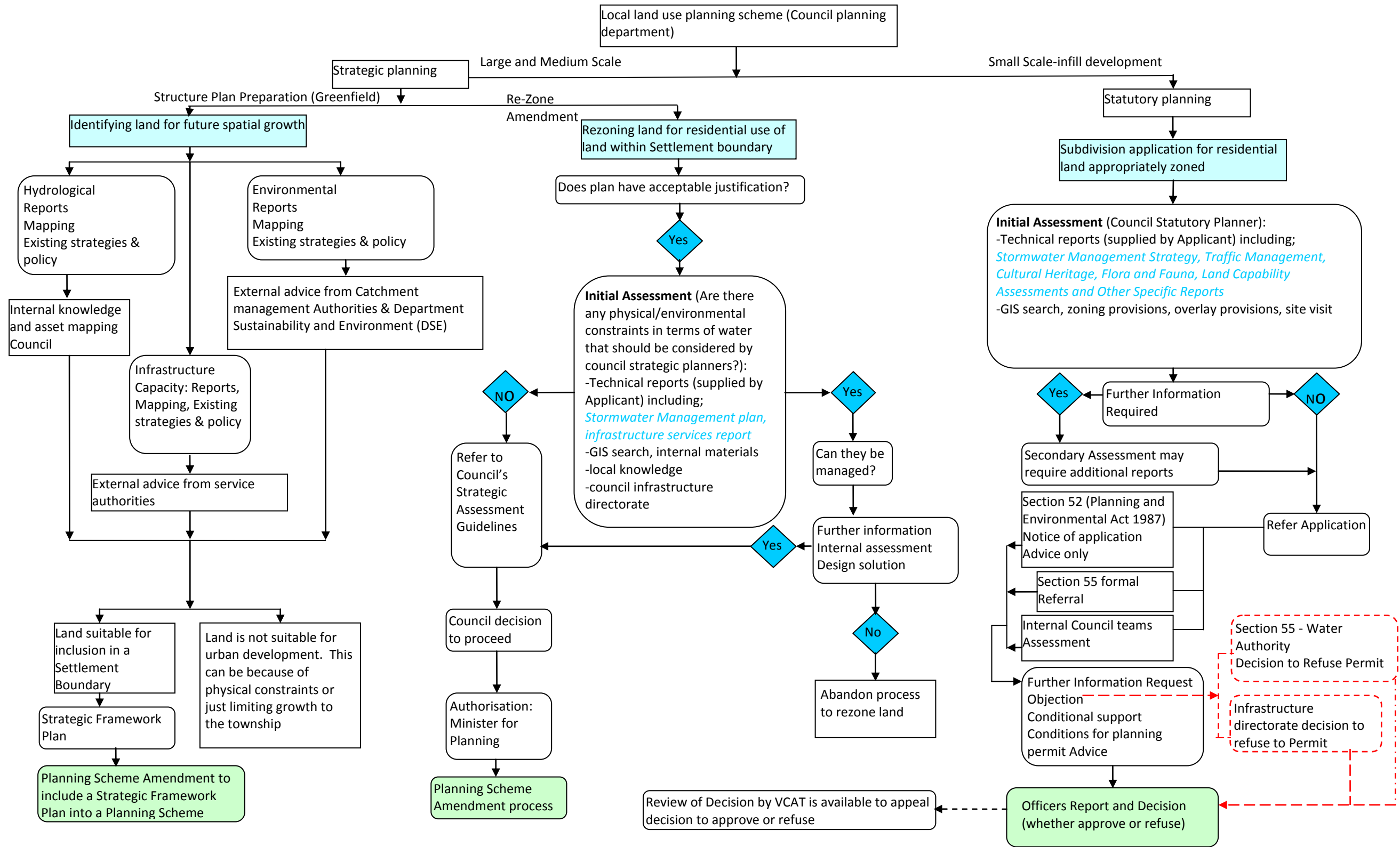


Figure 4.6: Activity workflow in BCC for flood-risk-based land use planning processes

Figure 4.6 shows that there are two major streams in land use planning in local governments: the strategic planning stream and statutory planning. The strategic planning stream includes the Greenfield planning and re-zoning amendments which cover new estate developments. Statutory land use planning also needs to be compliant with the local land use planning strategies of the Council's stormwater management policy. Figure 4.6 shows the decision-making process of flood-risk-based land use planning in Bass Coast Shire Council. The decision for strategic process will be active after authorisation by Minister of Planning in Victoria.

Decision for statutory planning can also be reviewed by Victorian Civil and Administrative Tribunal (VCAT). The process for reviewing of the application in VCAT is accessible on its home page (<https://www.vcat.vic.gov.au/about-vcat>).

Comprehensive database is required in flood-risk-based land use planning process regarding to support right decision-making. The data requirements of a comprehensive database to support flood-risk-based land use planning are considered in remainder sections.

#### **4.6 Information products required for a flood-risk-based land use planning in GIS database**

The information products necessary in flood-risk-based land use planning are shown in Table 4.1.

**Table 4.1: Information products required for flood-risk-based land use planning**

Information product / spatial object	Definition	Attribute
Floodway Overlay (FO) / Polygon	FO is an overlay in the planning scheme to show the area to convey stream floodwater. Floodway usually is a high hazard portion of a flood plain with a deep and high velocity flow. FO is applicable for urban and rural catchments	Reach code, reach name, river name, flood depth, flood velocity, flood level, flood extent, upstream catchment size, upstream catchment name
Urban Floodway Zone (UFZ) / Polygon	UFZ is an urban floodway zone for river flooding inside the township area. The area is highly restricted for residential development	Reach code, reach name, river name, flood depth, flood velocity, flood level, flood extent, upstream catchment size, upstream catchment name
Riverine flood prone land / Polygon	Maximum probable extent of river flood during Probable Maximum Flood event (PMF). For example, 200-years average recurrence interval (ARI)	Reach code, reach name, river name, flood depth, flood velocity, flood level, flood extent, upstream catchment size, upstream catchment name
Land Subject Inundation Overlay (LSIO) / Polygon	LSIO shows the extent with less priority than UFZ and FO but it is applicable for stream flooding in both an urban and rural catchment	Reach code, reach name, river name, flood depth, flood velocity, flood level, flood extent, upstream catchment size, upstream catchment name
Special Building Overlay (SBO) / Polygon	SBO is only applicable for stormwater flooding in an urban catchment	Reach code, reach name, river name, flood depth, flood velocity, flood level, flood extent, upstream catchment size and name
Overland flow path / Line	The natural water flow path shows direction. In rural catchment includes any watercourses, in urban catchment it includes gap flow path.	Catchment code, length, flow direction
Natural overland flash flood prone area / Polygon	The areas where water drains and sits there naturally	Name, code, area, depth, extent, centre XYZ, basin size, connected flow path, upstream catchment
Catchment/Polygon	The area where water drains to similar outlet	Area, time of concentration, slope%, impervious surface%, pervious surface %, maximum and minimum rate of infiltration, bore point location, aquifer name, height of saturated zone in aquifer, dominant land use



The current available flood overlay in the Bass Coast Shire planning scheme is the LSIO for the two major rivers in the Bass Coast Shire jurisdiction. However, the Bass Coast Shire planning scheme is not equipped with an SBO for the urban stormwater flooding and the UFZ for the small creeks. The SBO and UFZ are required to support decisions for flood-risk-based land use planning, particularly for statutory land use planning.

#### **4.7 The master data list**

The datasets needed for producing information products can be classified into those relating to natural and structural entities as below:

1-Natural (topographic) entities

2-Structural entities

Two types of datasets are required in flood-risk- based land use planning which can be categorised into topographical-related and structural-related datasets. Topographic entities include all natural features that influence the hydrological responses of given area, such as surface topography, soil, and land cover. The structural entities include all manmade features that influence the hydraulic behaviour of water flow in catchment. These data includes objects like WSUD features such as retarding basins, stormwater collection systems including pit inlets and pipe drainage network, and flood controlling measures like levees.

Both types of datasets can be provided by any of the stakeholders in the study area, but the majority of topographical based datasets can be acquired from external stakeholders like the DEPI.

Structural datasets are mainly provided by developers for new estate developments or designed and provided by the council. In addition to such datasets, planners and engineers have to extract the required dataset for interpretation of features like the water flow direction or a major overland flow path in development sites. The last approach needs more detail than the dataset external stakeholders can produce. For example, although a catchment boundary might have been provided for a township area, the details in the current dataset could be too

coarse for a designer or subdivision engineers. Therefore, they need to interpret the data based on their own knowledge, which might not be extensive.

For a new subdivision, each developer must submit a report of a stormwater detailed plan of the new development area to the Bass Coast Shire Council. The stormwater plan report is sent to the council subdivision engineers' office for an investigation of the plan's implications for flood control. Subdivision engineers consider developers' plan and these are then matched with the council's stormwater management requirements. As all infrastructure details in the developer's plans, including a stormwater drainage system, will be under council maintenance for a 12- month defect liability period from the time of issue of the Statement of Compliance by service authorities, a well-organised GIS database that can accommodate all the new datasets and allow retrievals upon request is a critical part of the council's asset management system. Due to the different sources and distributed characteristics of new datasets, a data specification document, a data model, metadata, a dataset accuracy check, and a survey of spatial data and attribute information lack in datasets regarding the target application are required. The spatial data and attribute information to produce the required information products can be documented in a list known as the master data list.

The master data list contains valuable information about the datasets required for the target application. It can be compared with the current database through a data survey process. Becker et al. (1995) suggested that the way to document in a master data list is in table format.

The master data list for the present research was compiled through consideration of business workflow procedure (section 4.5), required information products (section 4.6), and typical standards and specifications on drainage datasets such as D-spec, typical model package like EPA-SWMM and HEC-RAS.

#### **4.7.1 Standard specification**

In the interview sessions, which involved semi-structured discussion, the interviewees produced some policies and standard documents. One such document was a drainage specification standard document known as “D-Spec”(Workforce Solution, 2010).

D-spec represents valuable information about the required datasets for urban stormwater collection elements and WUSD features. D-Spec shows the graphical drainage data and associate attribute information that the Bass Coast Shire Council, needs to store in its own GIS database for flood management. D-Spec has been adopted by around 20 Victorian local governments to date(Workforce Solution, 2010). As D-spec was prepared based on local government drainage engineers’ requirements for routine works, D-Spec was a valuable source of information for the master data list for my study.

The D-Spec standard is a part of the A-Spec (All Specification) program for delivering digitally required data for local governments in Australia. Around 50 local governments from Victoria, Western Australia and New South Wales have adopted the A-Spec program in order to deliver the GIS data across councils, consultants and developers (Workforce Solution, 2010). The key aims of the D-Spec initiative program are the receiving, storing, and handling of the required information and datasets in regards to underground infrastructure, particularly drainage data (Workforce Solution, 2010). A-Spec allows organisations to manage GIS database and asset management information systems simultaneously. In addition, it resolves the inconsistent data specification problem which causes barriers to communication between local governments, developers and consultants.

A flood-relevant database needs to be comprehensive and contain many different spatial datasets and attributes, particularly for flood-risk-based land use planning. Flood-risk-based land use planning in local government jurisdictions need detailed local data and information which have not been recorded in the Victorian spatial data infrastructure (VSDI). Local datasets

are those that have been produced by local agencies including local governments (Kunapo, 2008).

Although the D-spec is a drainage specification, it does not include the required attribute information for on-demand flood modelling. Therefore, required attributes information associated with spatial entities should have been determined through the consideration of typical core hydrodynamics model package in an urban catchment.

#### **4.7.2 Typical hydrodynamic model package**

Computerised hydrodynamic models including hydrological and hydraulic models reached their advanced phase and they have been able to provide more reliable result (Zoppou, 2001). The type of model – conceptual or empirical - being used for flood modelling in an agency, helps to establish the datasets and the associated attribute information needed for on-demand flood modelling. However, the complexity of a required dataset completely depends on the type of hydrodynamic model being used to solve the problem at hand.

In a conceptual model, like Arc Hydro Tools (Maidment, 2002), the focus is on the physical laws of water movement while an empirical model, like HEC-HMS (Feldman, 2000), requires field monitoring datasets. Conceptual and empirical models can also be classified into lumped and distributed models. A lumped model does not include spatial variability, while a distributed model includes differences across the study area.

A model can also be classified as an event-based or continuous (Chu and Steinman, 2009). Developed models can be adopted in water resource applications as planning, operational and designing tools.

An operational approach needs models for modelling flood and the controlling structures, while a designing tool models the stormwater runoff in stormwater collection infrastructures. The essential difference in these categories is related to the amount of required data, the information obtained, the sophistication of analysis, and the period of simulation (Zoppou, 2001). The complexity in the integration of different data sources to develop the application

model demanded leads to the collecting and storing of the required entities in the GIS database prior to flood model development and flood simulation.

Nix (1990) stated that the available data archives should be able to meet the requirements of on-demand modelling. It follows that including the data requirements of typical flood modelling packages in a master data list can facilitate the development of on-demand flood modelling in an appropriate model.

The Environmental Protection Agency's (EPA) stormwater management model (EPA-SWMM) is a typical open-source urban stormwater management model. EPA-SWMM is the core of some well-known hydrodynamic models such as XP-SWMM, PC-SWMM, DHI-MIKE SWMM, and 12D.

The HEC-RAS software package is another useful free flood model designed for river system analysis. Access to the HEC-RAS required dataset and information can facilitate the flood modelling and mapping for the little coastal township creeks in the pilot study area.

Urban catchments in Victoria are subjected to implementation of WSUD features in order to improve urban stormwater runoff quality and these features can change the hydraulic behaviour of a water flow. Therefore, the information for these features must be captured and recorded in a flood-relevant GIS database. Although, WSUD features like retarding basins are mentioned in D-Spec document, the implications of these features for flood modelling are not fully considered in the D-Spec standards. The MUSIC (model for urban stormwater improvement conceptualisation) software package allows establishment the required input data and information. The master data list for natural hydrological entities is delineated in Table 4.2, and the list for structural entities in Table 4.3.

**Table 4.2: Master data list for natural entities**

ENTITY (definition)	ATTRIBUTES	SPATIAL OBJECT
Digital Elevation Model (DEM)	Tile number, original source, metadata name, elevation	Raster, TIN
Surface topography contour map and LiDAR point dataset	Tile ID, original source, metadata name, elevation, coordinate system	Contour line for map/ point for LiDAR
Natural water storage (wetland, ponds, lakes)	Name, ID, area, average depth, , upstream catchment ID, flood date (if applicable), historical flood level (if applicable)	Polygon
Open channel hydraulic inspected point	Inspected date, inspected XYZ reach code, reach name, Photo ID (if applicable), inspector, catchment code, Manning's Coefficient, estimated runoff, left bank station's elevation and roughness, centre station's elevation and roughness, right bank station's elevation and roughness	Point
Soil samples	Subdivision code, catchment code, surveyor, date of sampling, laboratory name, Sample points XYZ, type of soil, soil name according Australian soil category, percent of silt, Loam, and Clay, hydraulic group of soil (if applicable)	Point
Land use/ cover	Land use class , land cover type, land use code, Land cover code, percent of pervious area, percent of impervious area,	Polygon

**Table 4.3: Master data list for structural entities**

ENTITY (definition)	ATTRIBUTES	SPATIAL OBJECT
Link: Pipe (stormwater collection pipe network), culvert, kerb, manmade channel, fence and wall, levee, road ditches, conduit, outfall	Type, catchment ID, pipe segment ID, upstream pipe segment ID, downstream pipe segment ID, upstream invert level, downstream invert level, Upstream pit number, downstream pit number, material, pipe diameter, pipe segment length, start XYZ, end XYZ, average height, maximum depth, roughness, inlet offset, outlet offset, initial flow, designed maximum energy loss coefficient, designed exit loss coefficient, designed average loss coefficient, design ARI design rainfall value, property owner, construction date, number of barrels (if applicable), existence of flap gate (if applicable)	Line
Node: Pit (stormwater collection system inlet), bridge, farm dam, WSUD features, manmade storage	node type, node ID, catchment ID, connected pipe ID, depth, material, length, width, wall thickness, design head losses, upstream catchment size, connected overland flow path, hydro ID, upstream pipe ID, downstream pipe ID, storage capacity, discharge, reach code, reach name, designed inflow, treatment(if applicable), connected hydraulic link, connected storage, designed infiltration, elevation-volume curve (if applicable), designed surcharge depth, pond area	Point

One required dataset is information that comes from the community. This information is useful to map flood problem areas and if any photos or description are available for specific flood events, then the developed model can be calibrated and validated based upon the existing information. Due to the scarcity of measuring stations in urban catchments, such information is highly valuable.

At present, community-sourced (crowd sourced) information consists only of a limited amount of data supplied in a tweet or phone call text through a Tweet or phone call. The received information would be more valuable if it was used in order to update and validate the GIS database provided that it is able to produce a gateway for users to enter the target information.

Information received from citizens can be detailed and unique, such as an eyewitness description of a flash flooding problem but is not stored in the official GIS database. It is expected that in the near future the Bass Coast Shire Council will set up a mechanism to accept

such information into its GIS database. Information that comes from the community (crowd-sourced data) needs to be included in the master data list (Table 4.4).

**Table 4.4: Master data list-crowd source data**

ENTITY (definition)	ATTRIBUTES	SPATIAL OBJECT
CRS (Customer Request System) information	date, catchment code, address, complain record number, photo ID (if applicable), flood depth description, flood extent description	Geocoded point

However, including crowd-source data (assumed to be equivalent to volunteer geographical information (VGI)) in an official GIS database is problematic. VGI is described further in the section below.

#### **4.7.3 Volunteer Geographical Information (crowd source dataset)**

Estes and Mooneyhan (1994) claimed that the mapping concept had been in decline for several decades. Goodchild (2007) pointed out that there are various causes for the worldwide decline in the mapping industry. Firstly, governments do not want to spend money on updating existing maps or preparing new maps using traditional mapping approach. Secondly, there is an intention to use satellite imagery instead of using expensive traditional mapping, but remote sensing is not able to show many of the phenomena that are traditionally represented by mapping. Thirdly, although geospatial data is abundant worldwide, the data is still not complete (Qian et al., 2009). Fourthly, official GIS data supports limited detail at one time point, while the real world is infinite and rapidly changing (Qian et al., 2009). Due to the above-mentioned reasons, data providers are often looking for alternative options instead of using expensive and time-consume task of traditional surveying. For example, evolving surveying global positioning system (GPS) has caused less use of traditional total-station surveying.



VGI (Goodchild, 2007) is a method of gathering geospatial information from citizens to use the citizens' information. VGI is a complementary approach for authoritative (conventional) method applied by data provider. VGI fits with the concept of patchworks declared in the United States' National Spatial Data Infrastructure policy. VGI has emerged as a kind of postmodern GIS in which observers are able to contribute opinions about their surroundings and play a role in local decision-making, as opposed to a traditional GIS which is insistent on a single point of view and empower those who can afford its high cost. In essence, such a development is a turnover of the traditional approach to the creation and dissemination of geographic information (Goodchild, 2007). A tremendous amount of geographically relevant information which has been collected through VGI has enhanced environmental knowledge because it provides an esoteric understanding of current local conditions (Flanagin and Metzger, 2008). Table 4.5 shows the differences between a traditional GIS dataset and a VGI dataset.

**Table 4.5: The differences between a traditional GIS dataset and VGI (Qian et al., 2009)**

Catalogue	Traditional GIS Data	VGI data
source	Surveying, mapping, remote sensing, professional	General public, WWW user
Procedure	Centralised production, strictly professional workflow	Volunteered upload, accumulation of data
Advantages	Accuracy, reliable, standardised	Richness, comprehensiveness, promptness
Disadvantages	High cost, limited type	subjective
Evaluation indicator	Precise, accuracy, scale, resolution	Authenticity, up-to-date, data detail
Consumer	GIS software, expert	Mapping website, general public
Application	GIS system, spatial analysis, modelling, scientific data visualisation	Online browser, dissemination and sharing of geospatial information and knowledge

Place names are one of the most successful forms of VGI, and people are clearly willing to spend time providing them to web sites for self-promotion (Goodchild, 2009). VGI allows features to have multiple names and includes names for the smallest, least significant features. Wikimapia, Globe, MapActions, GISCorps, and OpenStreetMap are the known successful VGI systems. However, GIS world is not entirely aligned with Goodchild (2007) postmodern GIS insight about the value of VGI due to focus on specialists rather than information from communities.

Flanagin and Metzger (2008) wrote that VGI is an extension for public participation GIS originated from the National Centre for Geographical information and Analysis (1996). VGI is also known as collaborative GIS, participatory GIS, Community Integrated GIS, and GIS/2. VGI has been designated as being a neo-geography concept (Jackson, 2006; Turner, 2006) in which people use geography without geography knowledge (Flanagin and Metzger, 2008).

#### 4.7.4 Issues in VGI

Goodchild (2008) stated that geospatial technology, surveying and relevant skills, which until recently have belonged to specific professional groups are now available to non-expert users. Crowd-source geographical information cannot be ignored just claiming that such data is less accurate than data gathered through official traditional way. The postmodern GIS world began with the VGI concept, and VGI determines future GIS use and roles. For instance, using GPS, anyone is able to track or map an important feature easily, without any surveying knowledge. Thus, individuals are now spatial data users and also spatial data generators. For instances, , around 200 million people used Google Map during its first year of release (Flanagin and Metzger, 2008). Another example is satellite imagery interpretation to provide land cover map using local community-sourced information conducted by Fritz et al. (2009). Nevertheless, data quality is a crucial factor. Information created via VGI, whether GPS-derived or created online, should be assessed for scale, density, precision, credibility, a data capture method in terms of point versus polygon (Brown and Pullar, 2012), and usefulness for anticipated audiences (Elsley and Cartwright, 2011).

Common errors associated with VGI are:

- 1-duplicate data entry because of multiple data generators
- 2-geometry errors
- 3-missing small geographical features (Accurate large-scale information resources can be created from volunteers when they concern the largest, most prominent, and most important features on the earth's surface)
- 4-Errors in the attribute fields

Errors in the attribute fields are the most important issues in VGI data quality management. For example, a geographical feature may have different names including historical, official, local name and abbreviations, so determination of whether the same geographical features are being identified could be difficult unless users enter more descriptions about entities (Qian

et al., 2009). Metadata is a suggested mechanism for resolving the bad information issue, but crowd- source data sources rarely carry any metadata and it is difficult to encourage people members of public to prepare proper metadata. In addition, as Goodchild (2008) stated, VGI cannot follow the standard metadata in the SDI. Standard metadata focuses on the quality of an individual dataset, while user-generated data - in addition of the quality of an individual dataset, has to focus on the relative quality between pairs of datasets that come from different sources of data into mash-ups in order to be integrated. Thus, in addition to the current standard metadata, VGI needs binary metadata or metadata 2.0.

Geographic information or metadata in the VGI can be attached to the data through Geotagging (Elsley and Cartwright, 2011). Geotagging can be done through either visible textual tags or through the use of geographical positioning (geographical coordinates). GPS is a favourite geotagging method because it removes the ambiguities that users would encounter in determining the geographical location of information.

However, errors can be removed using local volunteers with specialist knowledge to monitor information, nevertheless, an automatic process for the correction of errors to make VGI data applicable information for further analysis in GIS is necessary for abundant non-professional user-generated geospatial data (Elsley and Cartwright, 2011). For the correction of VGI data, characteristics such as frequent updating of the spatial database, the density of data and data distribution, and the consistency of data should be considered. In addition, the credibility of the VGI provider is an important issue to establish when providing a dataset. The data quality confidence rate, confidence in the usefulness of the VGI data of the geographical location are also issues in a VGI dataset (Elsley and Cartwright, 2011). Poor and good data can be separated immediately, while medium-quality data cannot be assessed easily (Elsley and Cartwright, 2011). Furthermore, questions like: "Can VGI integrate with authoritative data?"; "What is the quality of the VGI?"; "What data types are suited for volunteer collection?"; "How can volunteers be motivated and encouraged?"; "What are the costs and benefits of VGI compared

to standard data collection methods?”, and “How sustainable is VGI?” should be considered before using VGI.

#### **4.7.5 VGI and flood-risk-based management**

Flood-risk-based management practices need a comprehensive and updated GIS database. While new technology (e.g. LiDAR) provides highly accurate fine topography datasets, which are the important datasets in water management related practices, they cannot be error free due to errors in data capture, in data pre-processing, processing, and post-processing. All introduced errors cause inaccuracies in the derived products.

Sometimes the differences between the results of an official dataset and reality due to the time lag between data capture and use. For example, data can have been captured two or three years before the user needs access to it, and information can change substantially over such period. Therefore, official data needs to be updated by alternative information. VGI is a useful alternative source of data for a flood-relevant GIS database for the following reasons.

Firstly, information extracted from the community including data extracted from development planning documents, requested services, and complaints about a flood issue are spatial and can be incorporated into an existing GIS database. Secondly, information received from citizens about the location and extent of a flood incident in an urban catchment enables validation of flood modelling and simulation based upon the traditional datasets. Although calibration of a flood model is not possible based on a qualitative description from a non-expert member of public, it is possible to adjust the extent of a flood-prone area based upon the information sent to council by citizens. Such information is particularly valuable in urban catchment due to the lack of measuring station data for a developed model calibration and lack of an event based rainfall–runoff model.

## 4.8 Survey of available datasets relevant to local flood-risk based management

The gaps in required spatial and attribute data can be defined through a comparison between the existing dataset and the master data list. To determine the existing datasets, a data survey needs to be done.

Accessing the Bass Coast Shire Council GIS database, associated metadata documents and reports enabled me to assess the existing flood management relevant spatial datasets and associated metadata. One group of dataset describes natural entities and the other covers structural (manmade) entities such as the stormwater management features. The characteristics of the flood-relevant, natural entity datasets in the Bass Coast Shire GIS database are shown in Table 4.6.

**Table 4.6: Natural entity datasets in Bass Coast Shire Council GIS database**

Group	Contour			DEM	DTM (Digital Terrain Model)	LiDAR raw dataset	Hydrology (lake, river)
Entity	0.5 metre	Contour map	1 metre	1*1 m <sup>2</sup>	20*20m <sup>2</sup>		Manmade and natural hydrography
Name	VicMap Elevation	State wide	Western port	VicMap Elevation		VicMap Elevation	VicMap Hydro
Vertical accuracy	+/- 10 cm		+/-10cm	+/- 10cm	+/- 5 m	+/- 10cm	
Horizontal Accuracy	+/- 35 cm	+/-17.5m	+/-35cm	+/-35 cm		+/-35 cm	+/-17.5m
Vertical Datum	AHD		AHD	AHD		AHD	AHD
Horizontal Datum	GDA94		GDA94	GDA94		GDA94	GDA94
Coverage	Coastal water line up to 10 metre contour		Western port area	Coastal water line up to 10 metre contour		Coastal water line up to 10 metre contour	State wide
Source	LiDAR (2007)	various	LiDAR	LiDAR (2007)		LiDAR (2007)	various
Projection	MGA55		MGA55	MGA55		MGA55	MGA55
Data Tiling	2 Km		2km	2Km		2Km	
Scale		1:25000			various		1:25000
Release date	2009		2007	2009			2007

Regarding Table 4.6, the vertical accuracy values for the LiDAR ground points' dataset and the LiDAR-derived DEM dataset are similar, while the gridding process to convert the LiDAR raw dataset to LiDAR-derived DEM changes the accuracy value due to parameters like cell size and the capability of interpolation technique to estimate the value of unknown points. Therefore, the vertical accuracy of the LiDAR dataset, as the only fine resolution surface topography data source in the study area, needs to be considered as being the most accurate dataset for the flood-risk-based management and modelling.

The Bass Coast Shire GIS database also includes structural datasets like those for the stormwater collection systems including pipe networks, pit inlets, and WSUD features. These characteristics are represented in Table 4.7.

**Table 4.7: Structural datasets in GIS database**

Group	Node			Link		
Entity	Stormwater collection pit inlets	WSUD features	Road structures (bridges)	Stormwater collection pipe network	WSUD features	Road structures (ditches, culverts)
Vertical Accuracy	unknown	unknown	VicMap Hydro	unknown	unknown	VicMap Hydro
Horizontal Accuracy	unknown	unknown	VicMap Hydro	unknown	unknown	VicMap Hydro
Projection	MGA55	MGA55	MGA55	MGA55	MGA55	MGA55
Vertical Datum	AHD	AHD	AHD	AHD	AHD	AHD
Horizontal Datum	GDA94	GDA94	GDA94	GDA94	GDA94	GDA94
Source	Field surveying, design drawing, land developer plans	Field surveying, design drawing, land developer plans	VicRoad	Field surveying, design drawing, land developer plans	Field surveying, design drawing, land developer plans	VicRoad, Bass Coast Shire
Custodian	Bass Coast Shire	Bass Coast Shire	Bass Coast Shire	Bass Coast Shire	Bass Coast Shire	Bass Coast Shire
Attribute	Invert level, pit code, pit type, owner, date of establish	Name, type, date of establish	Name, code (if applicable)	Upstream invert level, downstream invert level, length	Name, type, date of establish	Name, code (if applicable)

The stormwater collection system, including the underground pipe system and pit inlets, comprises the minor artificial drainage system. The road network comprises the major manmade structures in an urban catchment.

Once a natural catchment has been changed by the addition of hard surfaces, its ability to absorb rainfall decreases, thus, the peak of a flood increases and the time of concentration to reach the flood peak decreases. Urban catchments equipped with a stormwater collection system infrastructure decrease the financial costs of urban flooding and reduce the inconvenience of flooding to communities. However, for reasons of cost, the majority of urban drainage systems have been designed with sufficient capacity for a one-off flood event every five or ten years, so cannot cope with extreme rainfall event (Argue, 1986). The main elements in urban catchment flooding are major/minor drainage networks, and runoff retention



measures (Argue, 1986). The stormwater collection system datasets in the Bass Coast Shire Council GIS database are up-to-date, therefore, pit datasets in terms of locations and some common attributes (like the invert level, and the depth to invert) of pit datasets are reliable. In addition, there is a procedure to establish the new subdivision pipe and pit information from the “As-Constructed” drainage plan. Thus, the drainage dataset is being progressively updated in the Bass Coast Shire Council GIS database through routine procedure.

Surface topography plan (cross-section) and profile changes during civil construction in road networks by either the council or any other responsible agencies are not currently updated in the council GIS database, but such changes are important in deviating water movement from natural paths. The road network changes influence flood behaviour in the study area, the two-dimensional spatial representation of the road centreline is accessible through the GIS database for the Bass Coast Shire jurisdiction, however, does not represent the height characteristics of road segments.

Some of the required datasets belong to a state wide database such as the VicMap-Hydro features, which have their own specifications and quality. Road-associated structures like bridges, culverts, and ditches on main roads are controlled by VicRoads. The Bass Coast Shire Council is responsible for the roads and associated structures not maintained by VicRoads in the study area. Therefore, datasets and information about structures like bridges and culverts under the main roads in the study area provided to the council by VicRoads. The accuracy of such data in the Bass Coast Shire Council GIS database relies on the associated metadata provided by custodian agencies.

Council has different flood management projects which contain valuable information about engineering construction practices. However, the procedure to incorporate data from such flood management practices into GIS database covers only drainage data for new subdivision. For the other engineering practices, data cannot be captured by Bass Coast Shire Council’s GIS database due to there being no routine defined capture process and no structured flood-

relevant database model. Although, the existing Bass Coast Shire Council GIS database archives datasets in the Environmental System Research Institute (ESRI) ArcGIS-geodatabase, there are no relations between the feature classes in the feature datasets and also no relation between the different elements for a specific subject (like the water-resource-relevant database). The existing Bass Coast Shire Council existing GIS database is not managed based on standard database model like relational, or object oriented-relational database model. Various datasets are accessible under each departmental name in the Bass Coast Shire Council GIS database, some provided by external stakeholders and some produced internally. Although some datasets- including those describing levee establishments, fence installation, road upgrading, open watercourse channel change, and soil sampling in new estate development areas- are created by the council or a developer, such datasets are not recorded in the GIS database.

Some existing datasets are not directly flood relevant, but they can be used for flood modelling. Archived aerial photographs can be used to assess the current condition of the area in terms of estimating necessary hydrological coefficients like the pervious and impervious areas. The Bass Coast Shire Council GIS database has time-series aerial photos which can be useful for time-series land use change study. These datasets are tagged with relevant metadata which are helpful for quality assessment.

#### **4.9 Missing datasets in the current GIS database**

The Bass Coast Shire Council's GIS database lacks some of the spatial and attributes data, both official and crowd source information needed to provide required information products for flood-risk-based land use planning. Furthermore, the GIS database lacks a well-organised model for accepting datasets and information provided officially or by crowd source information.

Even in the officially provided or collected datasets, the major focus is on collection of location of features rather than the required attributes for flood modelling. Therefore, the

Bass Coast Shire Council's GIS database required to be enriched for flood-relevant attribute data for further flood modelling studies.

Table 4.8 presents the missing information products and master datasets associated with required attributes (refer to previous tables in this chapter) in the Bass Coast Shire Council's current GIS database.

**Table 4.8: Missing data elements in GIS database**

Group	Entity	Attribute
Information product	FO	Refer to Table 4.1
	UFZ	
	SBO	
	Overland flow path	
	Overland flash flood-prone areas	
	Catchment	
Natural entities ( from master data list)	Natural water storage Wetland, ponds, lakes	Refer to Table 4.2
	Open channel hydraulic inspected point	
	Soil samples	
Structural entities (from master data list)	Hydraulic (node)	Refer to Table 4.3
	Hydraulic (link)	
VGI	CRS information	Refer to Table 4.4

Field surveying and access to the responsible agencies' updated datasets are necessary to bridge the gap in the master data list.

Providing some information products such as SBO, UFZ, and FO required datasets, requires dataset, a flood modelling package, experienced staff and a well-organised GIS database. However, the others information products such as catchment boundaries, overland flow paths, and overland flash flood-prone areas can be produced using GIS-embedded hydrological models.

Providing flood-relevant information products using a GIS- embedded hydrological model is within the scope of my research. In the next chapter, I discuss the utilisation of an available spatial analysis model that can produce valuable indicator information to support decisions in

flood-risk based land use planning. The availability of LiDAR datasets enables the filling of gaps in information products by producing details of catchment boundaries, overland flow paths, and flash-flood-prone areas using a conceptual hydrological model and accurate surface topography in the GIS environment. These information products link the project-site-specific view of drainage engineering practices of Bass Coast Shire Council to the catchment view, which is the accepted point of view of state wide and regional stakeholders.

#### **4.10 Conclusion**

In chapter 4, I answered to below research questions in sections 4.5, section 4.6, and section 4.9, respectively. The questions are:

- How is flood risk addressed in land use planning decisions at the local level?
- What information products are required for flood-risk based land use planning at the local level?
- What are the gaps in existing local flood relevant databases?

I considered the current process of flood-risk-based land use planning at Bass Coast Shire Council Figure 4.6 in order to establish the decision-making process.

Flood-risk-based land use planning has to meet different flood and land use provisions in order to permit any land use change, such as a new estate subdivision development. Furthermore, various local policies and strategies, in line with the state wide policies, must be adhered to Practice guidelines to guide the implementation of flood provisions in land use planning. Although land use planning is a powerful tool for controlling flood damage, it is only applicable for new estate land developments. In a developed area, such as a township, the solutions are to increase the existing stormwater collection system capacity or to establish WSUD features for stormwater flood management. However, sometimes it is not possible to find suitable sites in an already developed township areas to establish WSUD features like retarding basins, which are important features in runoff volume control and runoff quality

treatment. Furthermore, redesigning stormwater collection system is expensive. Therefore, it is necessary to inform local governments for a local land use scheme about the potential suitable sites using information products such as overland flow path, overland flash flood-prone areas, and catchment drains to specific outlet before permission is granted for land use change, or alternatively to reserve the area for further flood control or WSUD activities. Such an application is in the spatial domain and relies on a comprehensive and accurate GIS database.

As a GIS database has an important role in wise decision-making for flood-risk-based land use planning, a comprehensive and complete database is necessary. To establish an appropriate GIS database to support flood-risk-based land use planning, it is necessary to consider the decision-making process to identify the processes and data involved.

A proper spatial database can support the adoption of various flood modelling packages. Many flood management tools exist, but their adoption and utilisation can be challenging. As spatial applications like flood-risk management are dependent on a high-quality well-structured spatial database, considering the spatial and attribute gaps in a flood-relevant GIS database and quality of GIS database is a necessary step.

During this study, required flood management datasets were extracted using the flood modelling packages' input requirements, the current flood management activities of the Bass Coast Shire Council, and through considering the available drainage specification guidelines. I compared a comprehensive GIS database (Table 4.1, Table 4.2, Table 4.3, and Table 4.4) and the existing GIS database (Table 4.6 and Table 4.7) to highlight the existing data and the information product gaps (Table 4.8).

An official database can be updated and enriched by incorporating alternative data sources like the information received from citizens' complaints and recorded in customer request system (CRS). Such data and information known as a crowd source datasets or VGI (despite variable scale, quality and reliability) is valuable. Therefore, crowd source datasets as the

closest meaning of VGI was discussed. Although such data contains valuable information, there is no mechanism to incorporate it into an existing GIS database at Bass Coast Shire council due to insufficient financial and human resources to record and use it.

Although manmade structures have an influence on water flow behaviour, the natural surface topography is the major cause of water movement characteristics. Therefore, a highly accurate topography dataset is fundamental to determine the quality of a flood-relevant GIS database. Particular attention to the accuracy of surface topography data source is required to establish high quality flood-relevant GIS database. The most accurate surface topography data source available at Bass Coast Shire Council is a LiDAR dataset. In the next chapter I will assess the vertical accuracy of this LiDAR dataset.

# 5 Vertical accuracy assessment of LiDAR ground points

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## 5.1 Introduction

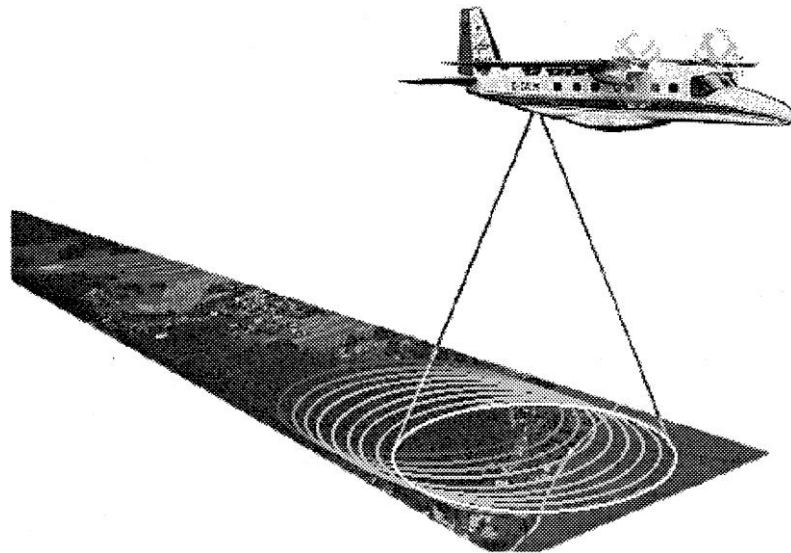
The quality of flood-relevant GIS database is heavily reliant upon the vertical accuracy of surface topography, as rendered in a DEM. The more accurate the DEM results, the more accurate the hydrological simulation. In this chapter I examine the vertical accuracy of LiDAR ground points available for Bass Coast Shire as the data source for DEM development.

The remainder of this chapter is organised as follows. I briefly describe airborne LiDAR technology, and then give a short background about the process of assessment of the vertical accuracy of LiDAR data. The remainder of the section focuses on the sample site. In the final section I describe the datasets I used in my study, the analysis workflow used to compare ground control points and LiDAR ground points, the statistics used to quantitatively assess the vertical accuracy of the LiDAR ground points, and report the vertical accuracy in order to answer research question 5.

## 5.2 Airborne LiDAR 3D point cloud

The basic operation of a LiDAR survey involves the use of equipment mounted on a platform (aircraft or terrestrial vehicle) that sends out a laser pulse and records a distance and (optionally) reflected intensity at each angle. LiDAR technology permits active remote sensing within laser footprints, as depicted in Figure 5.1 (Wehr and Lohr, 1999).





**Figure 5.1: LiDAR footprints (Wehr and Lohr, 1999)**

The footprint characteristics of LiDAR reflected pulses are controlled by beam divergence and flying height (distance from target). The usual commercial beam divergence is between 0.2 and 0.8 miliradians, giving a footprint size between 0.2 metres and 1.10 metres at a one kilometre flying height (Lemmens, 2011). Ground locations for LiDAR are obtained from post- processing of differential global navigation satellite system data or directly in real -time, through the integration of LiDAR and GPS data (Habib et al., 2005). The data collected are latitude, longitude, and ellipsoidal height based on a reference ellipsoid (WGS1984). The captured data are transformed to the formally accepted regional or national horizontal and vertical datum before further use. The vertical or height datum represents the orthometric height value, while the GPS height is an ellipsoidal height value (Liu et al., 2007).

Captured LiDAR reflected pulses can be either discrete or in full waveform. Discrete pulse returns are captured at two or more vertical levels depending upon the ground characteristics. Crowns of trees can return one pulse at one level, whilst the ground will return a pulse at a lower elevation.

Multiple LiDAR Pulse in Air (MPiA) LiDAR has been in use since 2008; it allows a larger ground area to be covered, or the use of lower flying heights, without reducing spatial coverage

(Lemmens, 2011). Flying at lower altitudes results in less air turbulence, therefore MPiA enables LiDAR data to be acquired more efficient than traditionally acquired LiDAR data(Lemmens, 2011, Mallet and Bretar, 2009). The result of these surveys is termed a point cloud. Further processing is needed to turn the raw results into a surface model.

### **5.3 Vertical accuracy assessment-background**

The accuracy, and in particular vertical accuracy, of LiDAR is highly dependent on errors in parameters such as flying height, location(from on-board GPS)and inertial measurement units errors, distance to ground station and LiDAR post-processing (Hodgson and Bresnahan, 2004, Hodgson et al., 2005).

These devices establish the position of the platform, and then the lasers measure distances at different angles. Multiple returns are possible from objects in the landscape, including vegetation, buildings and bare ground. Errors (bias) can be introduced during the LiDAR point cloud segregation that uses a filtering process to separate ground and non-ground points. Most of these effects introduce systematic errors that are non-normally distributed and exhibit kurtosis and skewness in their distribution whilst, according to Aguilar and Mills (2008), the nominal stated accuracy for LiDAR elevations quoted by vendors assumes a normal distribution and is typically derived from limited checks. Therefore, it would seem more prudent to present accuracy with a lower and upper Root-Mean-Square-Error (RMSE) at a specific confidence level.

Evaluation of LiDAR accuracy requires the collection and preparation of observed elevations and ground control points (GCPs), either permanent survey marks or GPS survey points, for comparison. Permanent survey marks with a sufficient number of check points and proper spatial distribution across a given area represent valuable control for LiDAR data accuracy assessment, and their use reduces times and effort. Whether using permanent marks (PMs) or GPS surveying points as GCPs, 30 points are deemed to be the minimum requirement for each prominent land cover across a study area according to the American Society for

Photogrammetry and Remote Sensing (ASPRS) and ICSM (Inter-Governmental Committee on Surveying and Mapping) (ICSM, 2008).

Hodgson et al. (2003) claimed that LiDAR data accuracy varies for different land cover conditions, and that LiDAR data accuracy in flat areas is twice as great as in steeper landscapes with forest coverage. Accordingly, ASPRS (Flood, 2004) and ICSM (ICSM, 2008) guidelines separated LiDAR vertical accuracy assessments into three land categories. Three major terrain categories for accuracy assessment are open terrain, which is suitable to support fundamental vertical accuracy (FAV), areas with various land cover to support supplemental vertical accuracy (SVA), and combined land cover area to support consolidated vertical accuracy (CVA). FAV is assumed to show the highest accuracy in estimating terrain surface height value due to having the fewest barriers for LiDAR pulses.

LiDAR vertical accuracy assessment can be reported at  $1.96 * RMSE$  for FAV at 95 % confidence level or within the 95<sup>th</sup> for SVA and CVA. The ICSM (2008) recommended that the 95<sup>th</sup> value of accuracy should be adhered to for FAV, SVA, and CVA. However, Liu (2011) reported that the value of 95<sup>th</sup> for any types of land cover overestimates vertical accuracy when compared to the  $1.96 * RMSE$  method.

Three main approaches to accuracy assessment exist. Comparisons can be made using an interpolation technique for transforming sample elevation points into a DEM (gridding) and then comparing the cell value to a corresponding ground control point. The gridding procedure imposes error due to the influence of gridding input parameters (cell size, interpolation technique, etc.), therefore interpolating to estimate unknown elevation depends on the interpolation method used, parameters such as neighbourhood distance or the number of neighbours, and anisotropy (directional effect) influences.

The second commonly-used approach is to undertake a one-to-one comparison between the LiDAR ground sample point height and the high values of correspondent points extracted from ground surveying (Hodgson et al., 2003). This approach is suitable to accurately comparing

heights because errors introduced through gridding are eliminated. However, the method is time-consuming and therefore expensive.

The third approach is to use a tool developed by Webster and Dias (2006) based on proximal point algorithm. In this method the user determines a search radius around target GCPs and the tool automatically produces minimum, maximum and other statistical values relating to the GCPs and LiDAR dataset comparison. The values for the heights of the GCPs are compared to the result from interpolation of LiDAR point elevations in a defined buffer around each GCP. Although the proximal approach facilitates the comparison between the LiDAR dataset and the GCPs, there are no rules to limit the search distance.

## **5.4 Datasets and statistical methods for this study**

This section describes the sample site, available LiDAR dataset for the study area, and statistical analysis approach for assessment of the vertical accuracy of the LiDAR dataset available for the sample site.

### **5.4.1 The sample site**

The Bass Coast Shire was described in chapter 3, as were the reasons for choosing it as the pilot study area. In this section I describe the sample site within the pilot study area used to assess the accuracy of the LiDAR ground point dataset, and outline my use of GIS-embedded hydrological tools to fill the gaps in information (i.e., catchment boundary, overland flow path, etc.). Note that my study was limited to a sample site rather than the whole pilot study area due to limited access to datasets and the lengthy processing time required if the whole pilot study area was to be considered.

The nine square kilometre sample site (Figure 5.2) includes Inverloch Township and the surrounding area. Besides reasons for choosing the pilot study area listed in chapter 3, other reasons to choose the sample site for LiDAR accuracy assessment were:

- 1-The three coastal township creeks in the sample site (Figure 5.3)

2-The sample site's high priority in terms of flooding

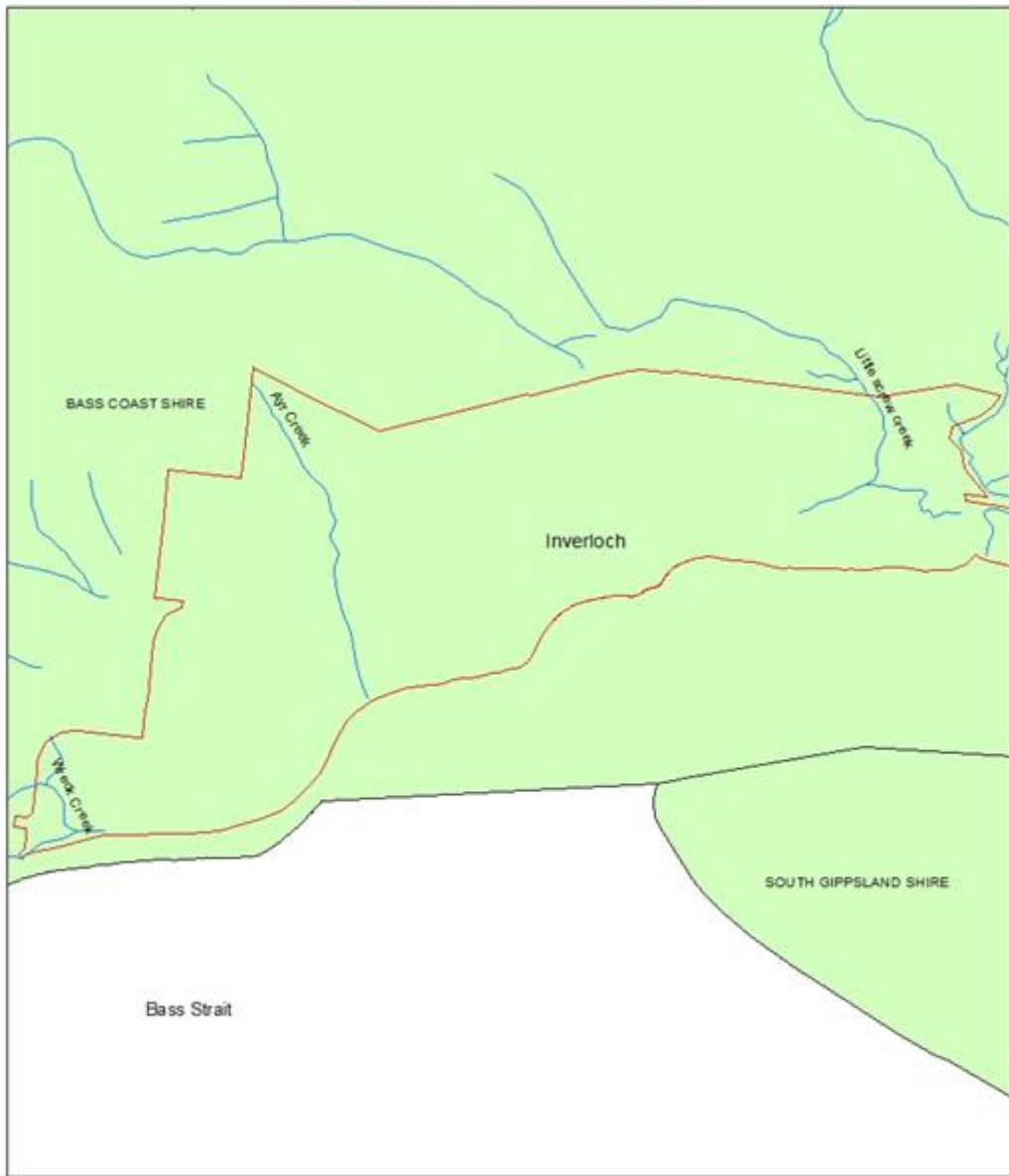
3-The sample site is one of the major cities in the shire of Bass Coast with respect to land use change

4-ongoing pressure for new estate development



Figure 5.2: Inverloch sample site in Bass Coast Shire (Source: Bass Coast Shire Council)

# Inverloch watercourses



## Legend

- watercourse
- Inverloch Boundaries
- LGA-Boundaries

0 0.2 0.4 0.8 1.2 1.6  
Kilometres



Figure 5.3: Coastal township creek in sample site (Source: Bass Coast Shire Council)

Three coastal creeks – Wreck Creek, Ayr Creek, and Little Screw Creek – divide the test study site into four sections: further east (between Little Screw Creek and Screw Creek which drains into Anderson Inlet), central east (between Little Screw Creek and Ayr Creek), central west (between Ayr Creek and Wreck Creek), and further west (the remaining area which drains into Wreck Creek). The area is divided into two distinct sections in terms of surface topography: a low-lying coastal flat area and the area located on a high plain adjacent to low-lying area. The low-lying area located on the plain near the coastline has recently been designated for a new estate development; it has an elevation of around half a metre below sea level. Therefore, it seems a decision has been made by council’s land use planners in the current situation not involving a sea level rise influences.

#### **5.4.2 LiDAR dataset**

The LiDAR technology was described briefly in section 5.2. This section describes the characteristics of the available LiDAR dataset for the sample site.

##### **5.4.2.1 Background**

The Victorian Government embarked upon a program called Future Coast, involving acquiring vertical heights along the Victorian coast using LiDAR (<http://www.climatechange.vic.gov.au/adapting-to-climate-change/future-coasts>)(Victorian Government, 2013).

The intent of this program is to construct detailed DEMs for the littoral zone from the high tide water level inland up to an elevation of ten metres. The inland horizontal extent of this data set varies due to the irregularities in the coastal topography, involving only several metres inland on cliffs and up to several kilometres on low-lying land. The metadata that comes with the dataset claims a vertical accuracy of 0.1m (DSE, 2010).

The vertical accuracy figure of 0.1m DSE claims for its Future Coast DEMs contrasts with the general experience elsewhere. For example, Aguilar et al. (2010) state that the best achievable realistic vertical accuracy in open terrain is around 0.15m; a similar result was reported by

Hodgson and Bresnahan (2004). However, this level of accuracy can rarely be achieved as most airborne LiDAR data capturing accuracy tend to show higher inaccuracies (Aguilar et al., 2010).

Although the LiDAR dataset was acquired for the specific needs of the Future Coast project in Victoria, LiDAR data are in demand for various applications, ranging from research to public resource management (Hodgson et al., 2005). There is a need to convey the limitations of the LiDAR data to end users.

An accurate topographic dataset is important for supporting decisions in water resource management. Local governments, who are responsible for local flood management, can use LiDAR for drainage design in the context of stormwater and overland flood management. The accuracy of the LiDAR dataset is reported by associated metadata, however, the accuracy is measured based on regional assessment and there are concerns about LiDAR vertical accuracy locally.

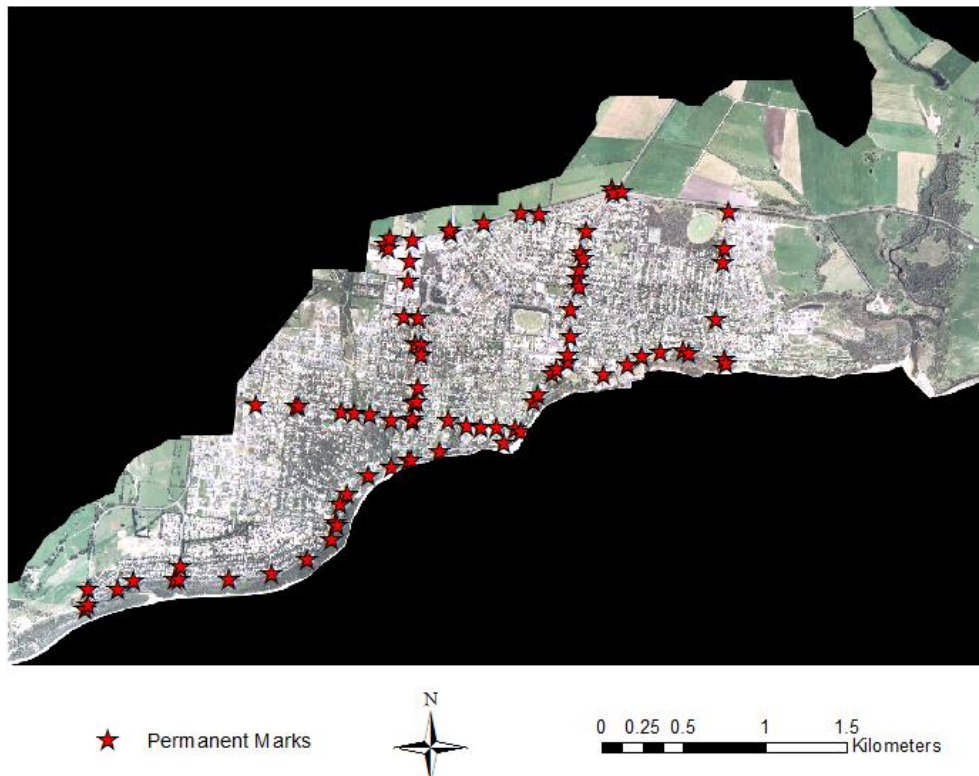
#### **5.4.2.2 Summary of available LiDAR dataset characteristics in sample site**

The test data were selected for the sample site described in section 5.4.1. The test data were sourced under the Future Coast Agreement provided to the Bass Coast Shire Council by the DSE. The data consisted of LiDAR points covering a two kilometre by two kilometre area. The vertical accuracy is stated as +/- 0.10m with 68% confidence, with the positional accuracy being +/- 0.35m (DSE, 2010). Data were projected on the Geocentric Datum of Australia 1994 (GDA94) and elevations defined by the Australian Height Datum (AHD). The data were captured in 2007 and have been accessible to users since 2009 (DSE, 2010).

#### **5.4.2.3 Ground Control Points (GCPs)**

Ground control points such as survey permanent marks (PM), previously established for elevation and position using conventional surveying and levelling techniques were used to assess the accuracy of LiDAR derived points. Figure 5.4 shows the location of 85 PMs that were available throughout the sample site.





**Figure 5.4: Permanent Survey Marks location in Inverloch, Victoria, Australia (Source: Bass Coast Council's GIS database)**

The suitability of permanent survey marks as GCPs was discussed by Liu (2011) who stated that 80% of rural PMs have a vertical accuracy better than  $\pm 0.20\text{m}$  and 90% of urban PMs have an accuracy better than  $\pm 0.03\text{m}$  due to greater accuracy required in urban area. Permanent marks have a density of 0.63 marks per square kilometre in Victoria around ten times the density for other Australian states (Liu, 2011).

#### **5.4.2.4 Statistics for vertical accuracy assessment**

Root Mean Square Error (Equation 5.1) is a frequently used in overall accuracy assessment (Carlisle, 2005). Furthermore, Aguilar and Mills (2008) suggested using the upper (Equation 5.2) and lower (Equation 5.3) RMSE for showing the range of error instead of using it to represent only the average error value. The upper and lower limits show the influence of kurtosis and skewness of error distribution; this gives the end user an appreciation of the range of error each vertical value may have. This means the effect on non-normal distribution of error can be included in accuracy assessment.

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (Z_{model(i)} - Z_{check(i)})^2}{n}}$$

**Equation 5.1: RMSE**

$$RMSE_{upper} = \sqrt{mse + \frac{\frac{\gamma_{2mse} + 2}{\gamma_{1mse}} - \sqrt{\left(\frac{\gamma_{2mse} + 2}{\gamma_{1mse}}\right)^2 + 4 \left( \frac{t_{\alpha} \sqrt{(\gamma_{2mse} + 2)(\gamma_{2mse} + 2 - \gamma_{1mse}^2)} + 1}{|\gamma_{1mse}|} \right)}}{2}} \sigma_{mse} \quad \text{[2]}$$

**Equation 5.2: RMSE Upper**

$$RMSE_{lower} = \sqrt{mse - \frac{\frac{\gamma_{2mse} + 2}{\gamma_{1mse}} - \sqrt{\left(\frac{\gamma_{2mse} + 2}{\gamma_{1mse}}\right)^2 + 4 \left( \frac{t_{\alpha} \sqrt{(\gamma_{2mse} + 2)(\gamma_{2mse} + 2 - \gamma_{1mse}^2)} + 1}{|\gamma_{1mse}|} \right)}}{2}} \sigma_{mse} \quad \text{[2]}$$

**Equation 5.3: RMSE Lower**

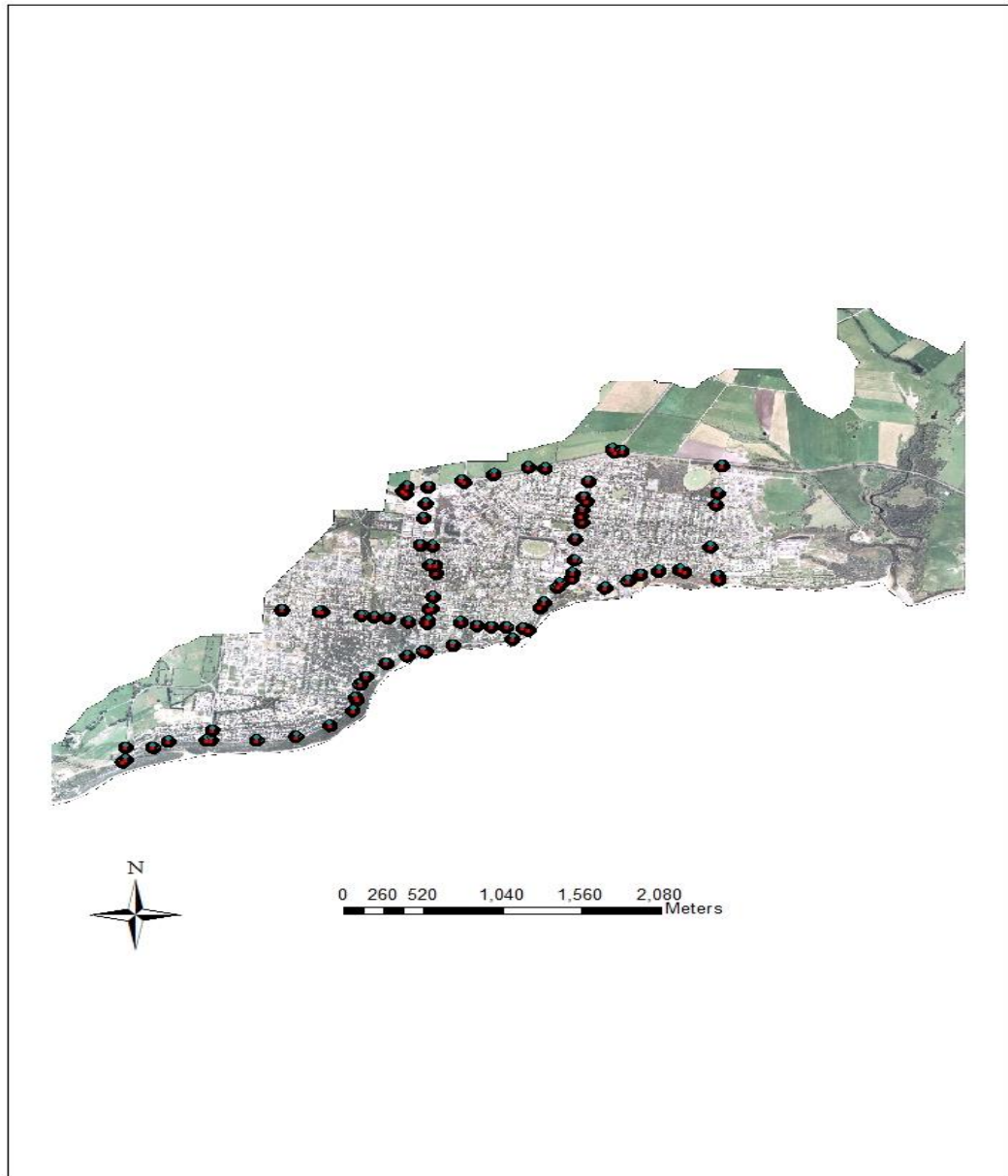
Where  $mse$  is mean square error,  $\sigma_{mse}$  is the  $mse$  standard deviation,  $\gamma_{1mse}$  shows  $mse$  skewness and  $\gamma_{2mse}$  is  $mse$  standardised kurtosis,  $t_{\alpha}$  is the value of a student's t test.

For further information on equation parameters, see Aguilar and Mills (2008); Aguilar (2005); Aguilar and Aguilar (2007).

## 5.5 Analysis methodology

To overcome the search distance problem discussed in section 5.3 and avoid inserting gridding errors into the procedure, the solution is to undertake a one-to-one comparison between the check points or GCPs (for this study, PM) and LiDAR ground points using a sequential minimum distance based on Tobler's first law of geography (Tobler, 1970). This can be used to assess the vertical accuracy of LiDAR ground points. The LiDAR ground points within a spatially auto-correlated distance (closer features are similar) should represent height values similar to those of the PMs.

A buffer zone for each PM was determined to limit the number of LiDAR points in the analysis stage (Figure 5.5). Increasing the buffer distance will increase the number of elevations being compared and therefore relevant analysis time will increase.



**Figure 5.5: The LiDAR dataset in each buffer around PMs**

In each buffer zone, the LiDAR ground point up to around 1m distant from each PM was chosen for comparison with corresponding PM. The 1m distance was chosen due to the typical cell size in the existing LiDAR-derived DEM for the sample site. Within approximately 1m

search distance, those points located at the first minimum distance from PMs selected were compared, then the points located at the second, third and fourth sequential minimum distances up to approximately 1m have been chosen and compared using a separate comparison procedure. The sequential minimum distances for the available LiDAR dataset are located at 0.366m, 0.625m, 0.980m, and 1.252m from the corresponding PMs.

Short-range autocorrelation is the distance over which it is expected that LiDAR points have the lowest difference from check points. In this study, I took the short-range auto-correlated (local auto-correlation) distance into account using average nearest neighbour analysis (ANN).

The influence of interpolation (gridding) methods were compared between the common Inverse Distance Weight (IDW) technique and geostatistic IDW method, the LiDAR ground points for each buffer zone have been used through the IDW technique. The results then were validated by the known value of each PM. Figure 5.6 shows the workflow used in this study.

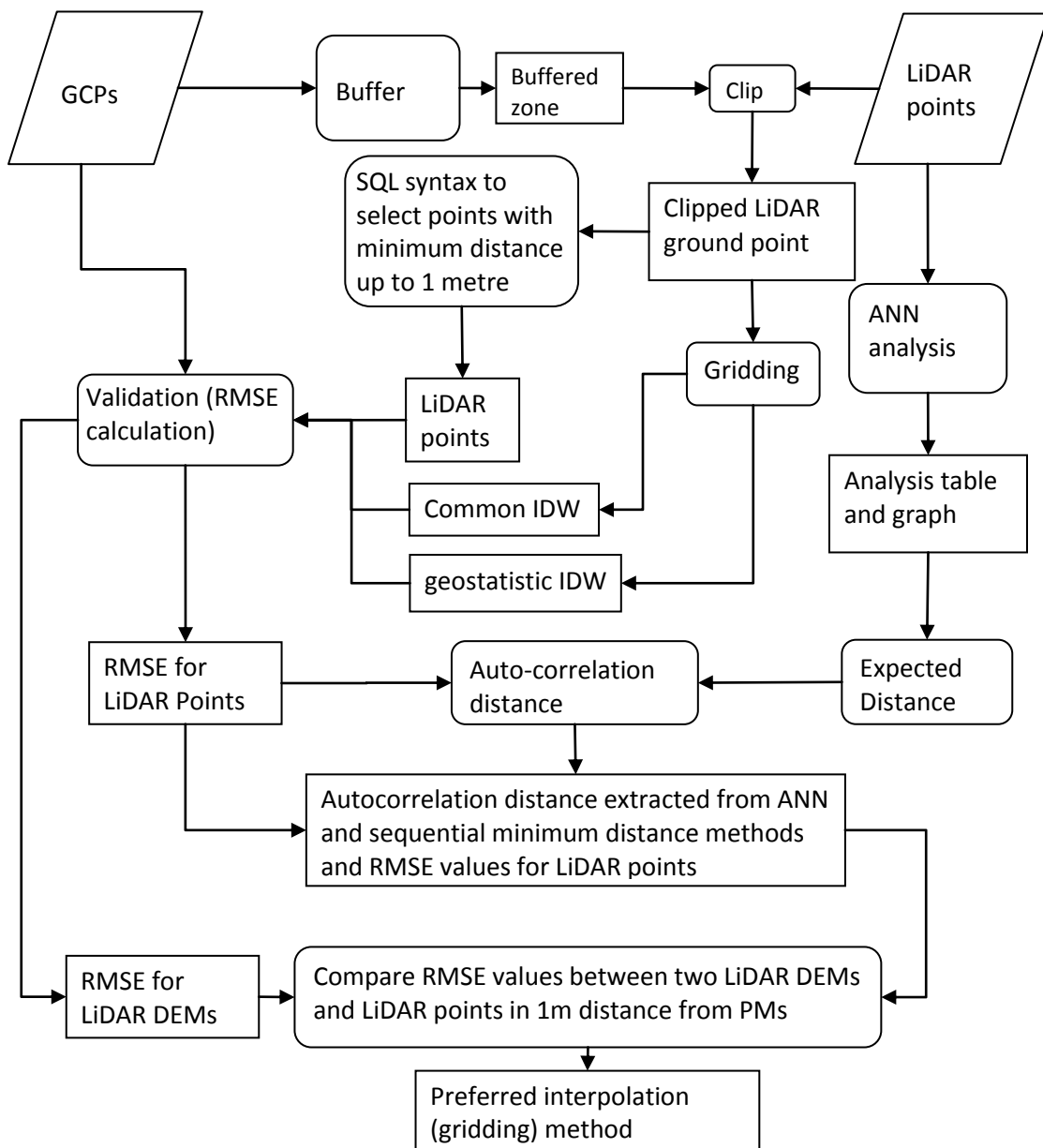


Figure 5.6: LiDAR accuracy assessment workflow

## 5.6 Results and discussion

Using the procedure described in section 5.5, I assessed the accuracy assessment of the correspondence between the sample points and PMs using RMSE.

Table 5.1 shows the results of the analysis: the value for the average distance extracted from the first up to the fourth minimum distance, and the RMSE value and error standard deviation up to around 1m distance around the PMs.

**Table 5.1: Resultant RMSE for the minimum distance at different distances around PMs. N<sup>i</sup> shows i<sup>th</sup> minimum distance**

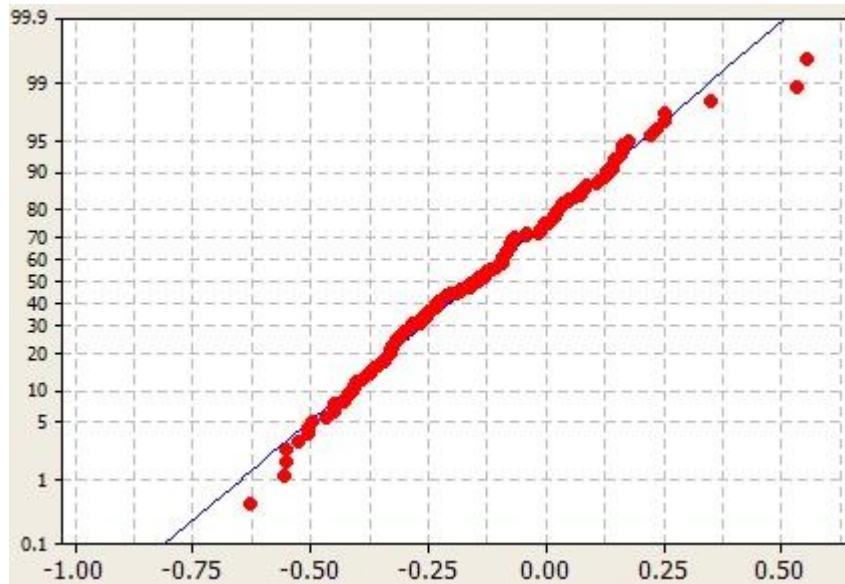
	Average distance (m)	RMSE	RMSE-upper
N <sup>1</sup> _Minimum	0.366	0.241	0.377
N <sup>2</sup> _Minimum	0.625	0.257	0.410
N <sup>3</sup> _Minimum	0.980	0.259	0.413
N <sup>4</sup> _Minimum	1.252	0.270	0.428
Combination of N <sup>1</sup> to N <sup>4</sup>	1	0.260	0.373
Simple common IDW	1	0.228	0.364
geostatistic IDW	1	0.249	0.398

Results in Table 5.1 show that the closest LiDAR ground points to the permanent marks have the lowest value of RMSE. The value of RMSE is 0.241 for the distance up to 0.366m from PMs. RMSE varies from 0.257 up 0.270 between 0.625m and 1.252m from the PMs, respectively. Comparison between combination of all those LiDAR points determined in sequential minimum distance and PMs resulted the RMSE value equal 0.260. The simple common IDW technique produced the lowest RMSE (0.228) while the geostatistic IDW method generated an RMSE equal to 0.249. Thus, while the generated RMSE for the closest LiDAR ground points to PMs is 0.241, common simple IDW-derived DEM shows RMSE equal to 0.228. The result shows that simple common IDW technique tends to show better accuracy than the real accuracy of LiDAR ground point dataset. These results also show that the geostatistic IDW-derived DEM with 1m<sup>2</sup> spatial resolution more accurately approximates the PMs than the simple common IDW. As errors are introduced during the gridding procedure and are inherent in the source LiDAR dataset, it is expected that errors will be propagated and increased in the final DEM.

As the comparison between LiDAR dataset and PMs resulted normal error distribution (Figure 5.7), vertical accuracy is estimated using  $1.96 * RMSE$  at a 95 percent confidence level (Flood,

2004). Assuming a value of 0.260 for RMSE, the vertical accuracy value for LiDAR ground points in the sample site is around 0.5m.

Furthermore, the present study shows that the vertical accuracy in the simple common IDW-derived DEM with 1m<sup>2</sup> spatial resolutions is around a 0.43m.



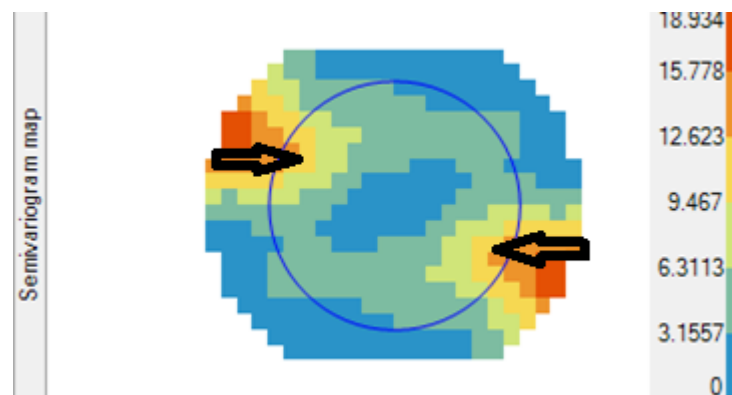
**Figure 5.7: The sample of Q-Q plot to show error normal distribution (X axis shows normal value while Y axis shows target dataset values).**

PMs were used as a control for determining the accuracy of observed LiDAR elevations. Liu (2011) pointed out that determining the elevation value of PMs from LiDAR ground point dataset is critical for accuracy assessment.

It is accepted that elevation is a geographic phenomenon that adheres to Tobler’s first law of geography (Tobler, 1970), that is, “Everything is related to everything else, but near things are more related than distant things.” This is often referred to as autocorrelation. In this study, an autocorrelation distance refers to the distance from PMs that can be used for estimating the accuracy of LiDAR ground point datasets. The autocorrelation distance can be determined using the concept of lag size. Lag size is required to determine long-range autocorrelation based on an empirical semivariogram for a given dataset. However, proper lag size is also needed to be determined to include the short-range autocorrelation.

The ANN analysis results shown in Table 5.2 can be used to determine an appropriate distance to identify short-range autocorrelation distance for LiDAR point from each PM. Table 5.1 shows the expected lowest RMSE value occurs for PMs and LiDAR ground points between zero and 0.531m apart.

Outcomes from the ANN analysis show that the expected short-range autocorrelation for each PM is between zero and 0.531m. Thus, instead of a comparison between LiDAR sample points and PMs in sequential minimum distances, a comparison can occur between any LiDAR ground points and PMs within about 0.531m around each PM in the given sample site to determine the value of RMSE. Although the sample site is influenced by anisotropy in long-range autocorrelation (Figure 5.8), the short-range autocorrelation within 0.531m has been assumed to be isotropic.



**Figure 5.8: Anisotropy (location of pointers) influences on derived empirical semivariogram using 500 random stratified derived sample points in a given LiDAR dataset**

Figure 5.8 shows the northwest-southeast directional effect, calculated from a sample of 500 points drawn as a stratified random sample of the LiDAR dataset. The noted direction (pathway) is caused by the orientation of the coastline and the change from flat areas to more rugged surface in the opposite direction, northwest-southeast.



**Table 5.2: Statistical results of the ANN analysis for given LiDAR dataset**

Ratio	P-value	Expected(m)
1.262	<0.0001	0.531

Table 5.2 shows the result of the ANN analysis. Lag size (expected distance in Table 5.2) is equivalent to short-range autocorrelation. Ratio equals to one or more than 1 shows that the distribution of observation points is not clustered; therefore the nominated distance value (0.531m) is valid for whole sample site.

## **5.7 Conclusion**

In this chapter I presented my examination of the vertical accuracy of LiDAR ground point dataset using survey PMs to assess the quality of existing flood-relevant GIS database using the methodology (section 5.5) developed during this study. The result answered research question 5 (section 1.2) about vertical accuracy of available LiDAR ground points. It showed that the LiDAR ground point dataset can be used for applications that do not need the vertical accuracy to be better than half a metre.

Accuracy was determined using the RMSE, but RMSE is sensitive to outliers and the skewness and the kurtosis effect of non-normal error distribution (Zandbergen, 2008). Therefore, a method to include skewness and kurtosis characteristics in RMSE estimation is preferred where error distribution is not normal (Höhle and Höhle, 2009).

The present study used a statistical method which includes the upper limit of the RMSE value in order to account for the skewness and kurtosis effects on the final accuracy assessment. The worst vertical accuracy reported in terms of RMSE-upper.

In this study I used the sequential LiDAR dataset at different levels of minimum distance around a PM. This approach enabled me to avoid the influence of gridding on the final assessment. To realise the extent to which gridding would influence the final vertical accuracy

assessment, a simple common IDW interpolation technique and geostatistic IDW were used. The difference between the geostatistic IDW, the simple common IDW and PMs showed that geostatistic IDW is better than common simple IDW to develop a DEM.

The autocorrelation distance between a LiDAR ground point and a PM was determined through two approaches – ANN and sequential minimum distance. ANN and minimum distance approaches showed autocorrelation distances 0.531m and 0.366m, respectively. The lowest RMSE occurs for the comparisons in these distances. The difference between the estimated elevation and the elevation as determined by the PMs was around 0.5m at a 95% confidence level.

In the next chapter, I describe how I used the RMSE (0.260) in a Monte Carlo simulation to examine differences between overland flow path extraction methods, and to choose the optimised method to provide overland flow path and catchment boundary information products which are missing from the Bass Coast Shire Council's existing GIS database.

# 6 Mapping urban overland flow paths and catchment boundaries

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## 6.1 Introduction

In section 4.9, I determined which information products were missing from the Bass Coast Shire GIS database; these included Overland flow paths and catchment boundaries. Such information products are essential to the models which integrate hydrological knowledge for real-world hydrological processes. Despite of all complexity for stormwater management in urban catchments (Roy et al., 2008), the overland flow path model and catchment boundaries link site-specific and catchment-scale runoff management. Therefore, overland flow path and catchment boundaries datasets provide the fundamental information products to implement flood-risk-based land use planning provisions through GIS-embedded hydrological models, for which every land unit has its own hydrological situation.

In the remaining sections of this chapter I consider the literature on extracting an overland flow path using GIS-embedded hydrological model, the methods I used to extract the overland flow path and catchment boundaries in the sample site (section 5.4.1) in the presence of stormwater collection system subsurface flow, and the result of developed methodology in sample site as a pilot study. The finishing section of this chapter concludes the study results.

## 6.2 From DEM to an overland flow path

A GIS-embedded hydrological model (known as a spatially distributed hydrological model) can facilitate runoff management in both rural and urban catchments through providing the tools required to determine the overland water flow path and record the resultant information in well-structured GIS (spatial) databases.

Arc Hydro(Maidment, 2002) is one such model that water resource managers have adopted to help them manage rural catchments. Other GIS-embedded hydrological models have been

developed in an open-source GIS environment, like SAGA-GIS, and commercial software like *Vflow*<sup>TM</sup> (Vieux, 2001) also exists. However, Arc Hydro has advantages over these and other GIS-embedded hydrological model because it has been designed to record modelling outcomes in a well-structured geodatabase, which can then facilitate the retrieving of the recorded hydrological information.

The typical GIS-embedded hydrological model is a spatial analysing model in which each pixel has its own elevation, direction and flow accumulation values based on the conceptual rule of water flow movement from an upslope with a higher elevation toward a down slope with a low elevation based on gravity. The procedure includes the DEM preparation, flow direction assignment, a flow accumulation calculation, and finally an overland flow path determination. The procedure is called terrain analysis.

Although the terrain analysis procedure can be used for both rural and urban catchments, the steps for rural areas do not fulfil urban catchment requirements due to the complexity of water flow paths in urban settings.

In this thesis, terrain analysis refers to an analysis of the DEM to extract land surface hydro geomorphologic parameters. Terrain analysis can be done on a raster-based DEM or alternatively by extracting land surface parameters based on the triangular irregular network (TIN). TIN is a model well-known to engineers and gives more flexibility than raster-based DEM for developing the Digital Terrain Model in order to provide the required model for urban runoff management (Djokic and Maidment, 1991). However, TIN needs rigorous computerised processing technique and time (Arge et al., 2003), therefore, processing TIN is more difficult than working with raster-based DEM being relatively time-consuming in both the processing and interpretation of results (Bertolo, 2000). In addition, the raster-based DEMs are more widely available and popular among users. Therefore, the typical GIS-embedded hydrological models use raster DEM for terrain analysis.

Natural overland flow path extraction from the raster DEM generally includes DEM preparation in terms of spurious sink and flat area removal, identification of flow direction for every cell, and a flow accumulation calculation of the accumulated number of upslope cells that drain to a given cell (Djokic, 2008). Stream definition and stream segmentation are two major tasks that must be performed when converting a raster dataset into a hydrological drainage network in a vector data model (Maidment, 2002). The reason for DEM preparation in a terrain analysis is to remove any water movement traps (Reuter et al., 2009).

### **6.2.1 Spurious sinks and flat area removal**

Assuming a high resolution DEM is available, sink and flat area removal are initial steps in a hydrological application of the DEM. Spurious sinks (pits) include artificial depression cells as traps for water movement and artificial flat areas, which are the resultant errors of interpolation step or DEM reconditioning by existing linear water flow collectors like watercourses, or a limited resolution of the DEM which increases the associated errors (O'Callaghan and Mark, 1984, Mark, 1988, Fairfield and Leymarie, 1991, Martz and Garbrecht, 1992, Martz and Garbrecht, 1999). A DEM with spurious sinks cannot be used to extract hydrological parameters like a natural overland flow path (Maune, 2001). Although Tarborton's (1991) study showed that between 0.9 and 4.7 percent of DEM cells can be claimed to be spurious sinks, water flows downstream in a real landscape, even in a subdued relief like a coastal plain area.

Depression-less DEM was developed using a simple smoothing filter technique (Wang and Liu, 2006). Mark (1984) proposed a filter to remove spurious sinks but the method has some drawbacks, particularly in a subdued landscape. For example, loss of information occurs in the DEM smoothing technique (Tribe, 1992, Soille et al., 2003). Also, where a flat area comprises a large portion of the DEM, a smoothing technique will not adequately remove the flat areas (Zhang and Huang, 2009). Therefore, different techniques such as fill sink method have been developed. Flat (subdued) areas in the DEM can be assumed to be real features in the

landscape or spurious sink and needs to be corrected before using the DEM in a hydrological application (Martz and Garbrecht, 1998). Flat areas problem for hydrological application of DEM needs to be evaluated based on their influence on hydrological simulation outcome (Collischonn et al., 2010). Various sink (pit) removing algorithms found in literature are:

1-The fill sink algorithm (Jenson and Domingue, 1988) followed by the outlet breaching algorithm (Martz and Garbrecht, 1999) which is the most widely used function in GIS-embedded hydrological models. The other models in the fill sink category are the algorithms which have been suggested by Planchon and Darboux (2002), and Wang and Liu (2006). Planchon and Darboux (2002) used the concept of the depression storage capacity of soil in a hydrological application. Wang and Liu (2006) used filling techniques to increase the elevation in sink cells based on the spill elevation at the outlet of a depression and not based on the closest outlet to the sink cell. The method proposed by Planchon and Darboux (2002) cannot resolve the flat area problem, while the method proposed by Wang and Liu (2006) uses the shortest path concept to route an overland flow path to the outlet across a flat area. The shortest path concept results an efficient approach to remove the effects of flat areas on hydrological application of DEM.

2-The deepen drainage algorithm using carving or lowering technique (Soille et al., 2003). Unlike the filling method, lowering the cells in order to let continuous water flow towards the outlet does not create additional flat area problem. This method is useful for subdued landscapes where the extracted channel deviates from known networks.

3-The hybrid algorithm which uses the advantages of filling a depression and the carving algorithm to minimise manipulation on the original DEM to develop the pit-less DEM (Soille, 2004).

Each method has its advantages and shortcomings, particularly in terms of processing time for complex spurious sink and flat areas (Wang and Liu, 2006). The filling sinks method and raising the elevation in sink cells and then breaching sink routes from outlet methods creates

new flat areas where there are significant problems in delineating the water's overland flow path. Some methods of sink removal are not initially remove the flat area problem on DEM like Planchaon and Darboux's (2002) method (Wang and Liu, 2006). Therefore, additional techniques for removing a flat area are needed to produce a hydrological DEM (Hydro-DEM). Different methods have been proposed to solve the problem of assigning flow direction in a flat area. Soille et al. (2003) have claimed that the best method to assign a flow network in a flat region is the method suggested by Garbrecht and Martz (1997) based on a geodesic mask and distance. However, the flat area problem can also be solved by user interference to determine the slope threshold between two cells. The user determined threshold causes an increment to the relief to achieve the assigned minimum slope between two adjacent cells in flat areas toward the given outlet.

#### 6.2.1.1 Fill sink method

In the fill sink method (Jenson and Domingue, 1988), spurious sinks can be determined and filled based on the neighbouring cell with minimum elevation. However, this technique produces more flat areas which are an important issue in DEM, particularly in a low-lying flat landscape. In addition, the method is not efficient when the spurious sink is complex due to existing existing frequent spurious sinks and avoiding for creating large artificial flat areas as Wang and Liu Liu (2006) have claimed.

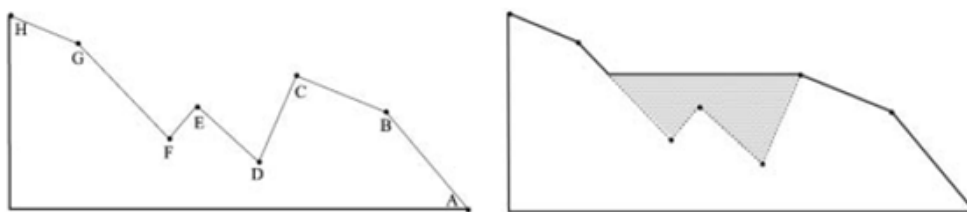


Figure 6.1 shows a schematic depression cell before and after filling.

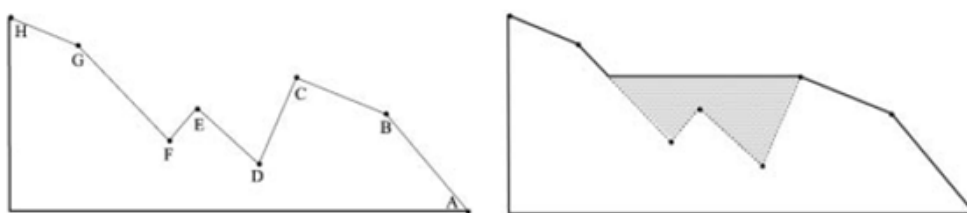


Figure 6.1: Filling algorithm removes the depression but creates a flat area problem (Wang and Liu, 2006)

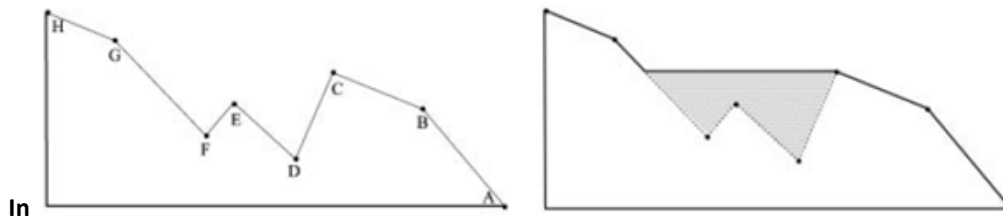


Figure 6.1, the left figure shows a spurious sink (pit or depression) problem before filling, the right figure shows the condition after filling using Jensen and Domingue's (1988) algorithm. Dealing with a complex depression (

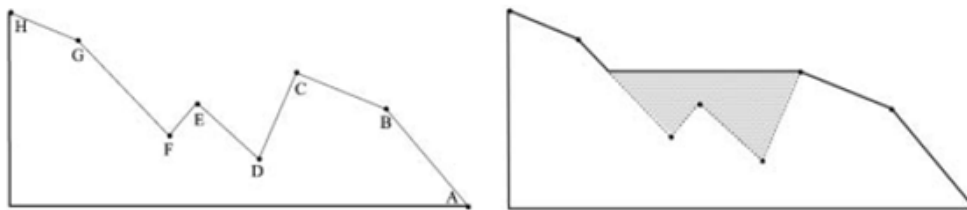
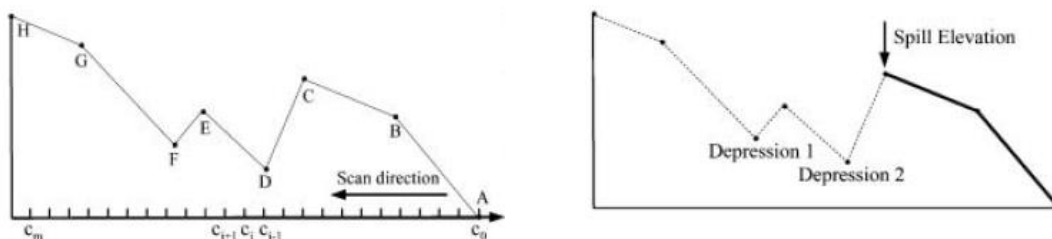


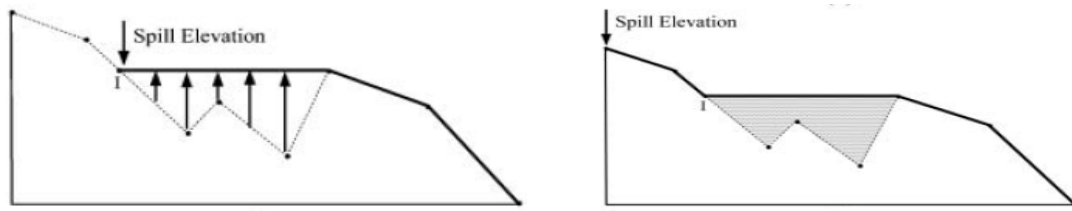
Figure 6.1, left) is not easy and straightforward for a filling algorithm. On the contrary, dealing with sink cells using the shortest path and spill elevation concept as suggested by Wang and Liu (2006) is a relatively straightforward and time-efficient procedure for removing sinks.

### 6.2.1.2 The Spill Elevation and shortest path method (Wang and Liu 2006)

Wang and Liu (2006) suggested a spill elevation concept to deal with different sink cells at the same time, and used the shortest path concept to solve the flat area problem which is created after filling sinks. Figure 6.2 describes the concept suggested by Wang and Liu (2006).







**Figure 6.2: Filling sinks through the spill elevation concept in Wang and Liu (2006) method**

In Figure 6.2, the top left figure shows the sink location (F, D), the top right figure shows the spill elevation determination, the bottom left figure shows how multiple sinks are filled using spill elevation, and the bottom right figure shows the final correction of cell values.

In the shortest path direction from the outlet on the DEM edge, progressive propagation of the spill elevation toward the interior cell can be the threshold for filling the sink cells. Wang and Liu's (2006) method improved the conventional fill sink algorithms regarding deals with a complex depression as the method suggested by Jenson and Domingue (1988). A detailed description of different sink removal techniques has been presented in Wang and Liu (2006).

### **6.2.1.3 Carving method**

Unlike the sink filling method, the carving method developed by Soille et al. (2003) does not create more flat areas. The method works based on flooding simulation procedures in order to remove the spurious sink problem. The same idea can be used in known drainage enforcement on the DEM. The method has improved the continuity of a delineated network in the place of a real drainage channel. The second set of advantages of the carving method over the common drainage enforcement methods are that the resultant delineated channel does not include a parallel flow path and the final result does not need to be considered in terms of the flow direction (Soille et al., 2003). However, Soille (2004) suggested a combination of the two sink removal approaches in order to optimise the associated change in the original values of the DEM. Sink removal algorithms have to be followed by resolving the flow direction assignment over the flat area before taking further steps to establish an automatic extraction drainage network from the DEM.

#### **6.2.1.4 Flat area**

An artificial flat area can be created by any errors in the raw surface topography dataset, interpolation techniques or after filling sinks (Petroselli and Alvarez, 2012). The flat area in a raster DEM can be determined based on positive downward elevation gradients. In the case of zero (flat) and negative (sink or pit or depression) gradients, the target cell cannot be included in further computations and must be treated as a flat or sink area (Pan et al., 2012). Flat areas can be removed using two types of methods. The first group of methods uses techniques to keep the elevation values of Hydro-DEM similar with original DEM. It includes the shortest flow path technique over a flat area towards the outlet (Jenson and Domingue, 1988), the least cost search algorithm in a flat area (Wang and Liu, 2006), and the neighbour-grouping scan technique (Zhu et al., 2006) to assign flow direction over flat areas.

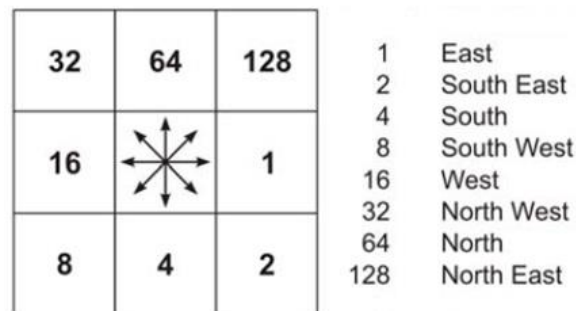
The second types of flat area treatment methods are those methods that alter the original elevation value in the DEM in order to resolve flat area and spurious sink cell problems. These methods incorporate interpolation and optimisation techniques to deal with flat and sink cells in a raster DEM. Examples of this type of method are the iterative finite difference interpolation algorithms developed by Hutchinson (1989); The Topographic Parameterisation (TOPAZ) method developed by Martz and Garbrecht (1998); and methods like those of Pan et al. (2012).

#### **6.2.2 Flow direction assignment**

Flow direction is a specific term in the hydrological interpretation of the DEM and is defined in order to show the water flow route in each raster DEM cell. Every cell in a raster DEM is limited by the surrounding adjacent cells in eight directions, including the cardinal and diagonal. However, water flows over the steepest direction which can be calculated based on elevation differences and the distance between a given cell and its neighbours.

The classical approach for a flow direction assignment on a raster DEM evolved according to the D8 method (O'Callaghan and Mark, 1984) in which each cell centre is linked to the

neighbouring cell centres located along a descending flow pathway. The D8 method (Figure 6.3) resolved the discontinuity problem in hydrological networks that resulted from the geomorphological method proposed by Peucker and Douglas (1975) based upon simple comparison of elevation and curvature coefficients (Bertolo, 2000).



**Figure 6.3: A schematic of classical D8 method (Hutchinson et al., 2008)**

In a classical D8 method, each cell is assigned a code which shows the direction water flows, as shown in Figure 6.3. For example, the cell with the value 1 in flow direction shows that water flows east from the target (centre) cell. Determining flow direction at angle 45 is major limitation of the D8 method.

However, Jenson and Dominique (1988) produced the first automatic catchment delineation tools in ARC/Info. After that, the D8 algorithm has become the most widely used method in GIS-embedded hydrological models.

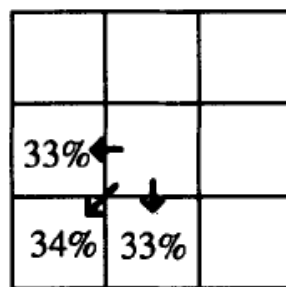
Although the D8 method is implemented in different GIS-embedded hydrological models due to its simple implications, other methods have been developed to improve the accuracy of flow direction assignment with respect to the reality of water flows in landscapes.

### **6.2.2.1 Flow direction assignment methods**

Fairfiels and Leymarie (1991) proposed a new algorithm called the random eight nodes (Rho8) in order to overcome the limitations of the classic D8 algorithm. The Rho8 solves the problem of flow direction limitation to 45 degrees (lateral and diagonal) in the classical D8 method. The Rho8 does not create parallel flow as it is created in classical D8 method using a

stochastic flow routine algorithm which lets flow move freely on the DEM (Cimmery, 2010). A proportioning of a flow between lower neighbours has also been proposed using 1.1 as an appropriate exponent value of slope (Bertolo, 2000). However, the main problem in Rho8 is creating an unrealistic convergent or divergent flow, while the overland flow path is parallel in given study area (Pilesjö, 2008).

In order to overcome the lack of divergent flow in the D8 method, Freeman (1991) suggested a multiple flow direction (MFD8) based on the classical D8 algorithm concept that breaks the flow into different fractions based on the slope-weight between given cells and lower neighbours (Figure 6.4).



**Figure 6.4: A schematic of MFD8 method (Holmgren, 1994)**

The problems associated with the MFD8 model are (Pilesjö, 2008, Pilesjö and Zhou, 1996):

- a) Difficulty in defining the unique proportioning value due to varying hydrological conditions in different places. For example, the value has been determined equal to 1 (Pilesjö and Zhou, 1997) and 1.1(Freeman, 1991) through various circumstances in given study area.
- b) Implementing similar algorithm for different types of landscapes in order to assign a flow network into down slope cells.
- c) Producing an unrealistic representation of a convergent flow in a terrain with well-formed channel.

- d) Creating fuzzy catchment boundary leads to an unclear and unrealistically large catchment.
- e) Neither the classical D8 method nor the MFD8 method includes the trend of a landscape

The form-based algorithm (Pilesjö et al., 1998) was introduced to resolve known issues in the linear D8 methods (Pilesjö and Zhou, 1996) by including the surface topographical trend in the grid DEM analysis. In the new method, the trend of the surface is included to use the appropriate landscape-relevant algorithm to extract the flow direction and drainage network.

Regarding flow direction assignment, the classic D8 algorithm is appropriate for a concave terrain while multiple flow algorithms like MFD8 are suitable for flat and convex terrains (Pilesjö, 2008). A combination of the two types is preferred to model a natural overland flow path (Pilesjö, 2008).

Lea (1992) developed a kinematic routing algorithm (KRA) (Lea, 1992) which produces a uni-dimensional aspect flow routing. Costa-Cabral and Burges (1994) developed an extended KRA method known as digital elevation model network (DEMON) to produce a flow routing based on a bi-dimensional aspect-driven flow movement. However, using DEMON is a complex and time-consuming process. Furthermore, aspect-gradient-based flow tracing algorithms like DEMON are more sensitive to DEM errors than flow routing algorithms like MFD8 which are based on a slope-gradient flow distribution. In addition, unlike other flow algorithms, DEMON does not allow for directional movement from upslope cells to a down-slope neighbour, so it creates a discontinuous surface (Pilesjö, 2008). Furthermore, the DEMON method yields significant error on concave and convex terrain landscapes (Pilesjö, 2008).

In order to overcome the difficulties DEMON, Gruber and Peckham (2009) developed the mass flux model (MFM). The MFM gives an estimation of flow accumulation based on free movement of flow across the given surface.

The methods introduced so far have been based on the raster-based DEM, while the alternative approach can be based on the TIN. TIN is either derived using raw points or extracted from the raster-based DEM.

Tarboton (1997) designed the D-infinity algorithm to solve the limitation associated with the classical D8 flow direction assignment method. It allows flow direction to be found by determination of the steepest angle among eight facets centred at a grid. The D-infinity method represents a bi-flow direction based on triangular facets (Figure 6.5).

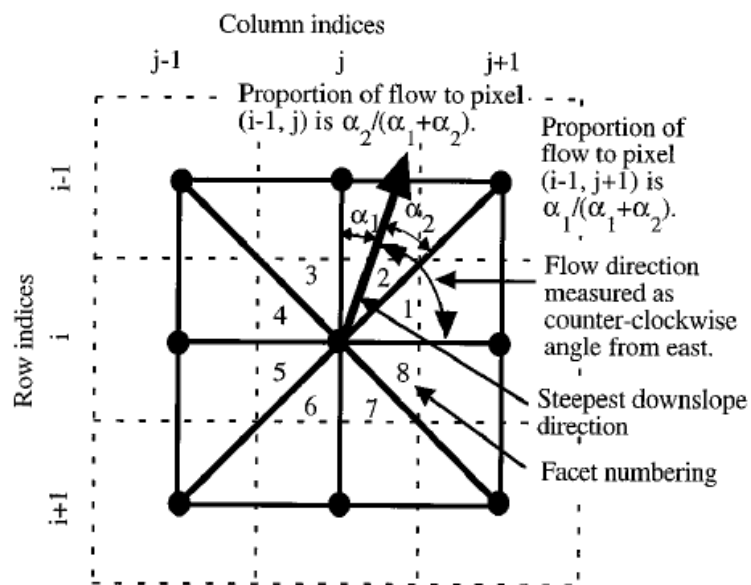


Figure 6.5: A schematic of D-Infinity method (Tarboton, 1997)

Tarboton (1997) pointed out that raster-based flow direction assignment algorithms are simple, and efficient in terms of storage due to the raster data model structure. Such methods minimise the flow dispersions, however, they represent flow direction too coarsely and they are affected by bias due to their orientation and numerical grid.

In comparison to the raster MFD8 method and in order to include TIN-based flow extraction, Seibert and McGlynn (2007) developed the multi triangular flow direction (MTFD) method. The MTFD method represents the multi-flow direction based on triangular facets. However, in both methods, the developed TIN is based on the usual approach in which the edges of the TIN

direction might not be aligned with the local ridge and valley line and in some places the TIN edge intersects with valley lines (Pilesjö, 2008). Taking into account the need to match a TIN edge with the local valley and ridge line, Pilesjö (2008) has introduced a method to form TIN based on the raster DEM in regards to the local relief. In order to include the landscape trend in a TIN- based model, the form-based algorithm (Pilesjö et al., 1998) was integrated with the TIN based algorithm suggested by Pilesjö and Hasan (Pilesjö and Hasan, 2013). In all of the above- mentioned TIN-based methods, each cell in the raster DEM will form resultant triangular facets.

TIN is more flexible than the raster model and represents a relatively accurate terrain model in the presence of dense LiDAR ground points. However, computer processing for vector data like TIN in order to implement an urban feature and extracting an overland flow is a burdensome process. In contrast, most GIS-embedded hydrological models include terrain analysis based on the raster model. Furthermore, flow path determination is based on an aspect gradient analysis using TIN, which is more sensible than the slope-gradient analysis in the raster model in relation to the inherent error in surface topography sample data.

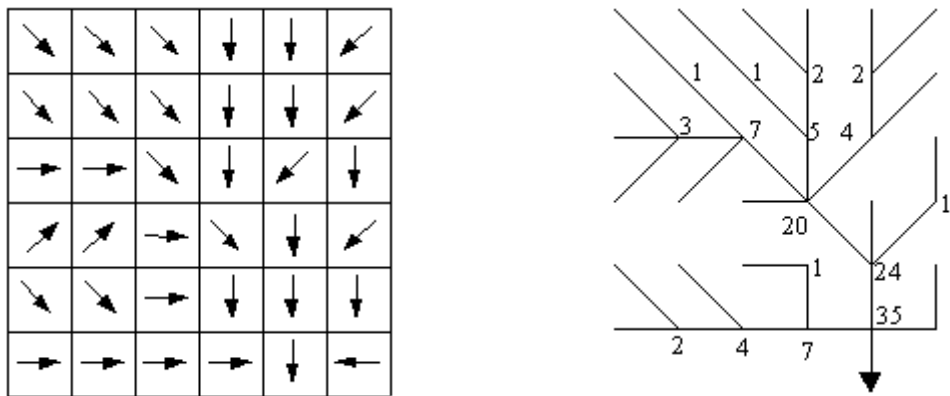
Despite its advantages, terrain analysis based on TIN is still not common approach for overland flow path determination and watershed delineation. It might due to its more time and computer power requirement to edit a LiDAR-derived TIN in order to extract hydrological features. In addition, TIN-based terrain analysis is not available in typical GIS-embedded hydrological models such as Arc Hydro Tools. Furthermore, the raster-based DEM is widely used DEM in GIS environment (Seibert and McGlynn, 2007).

### **6.2.3 Overland flow path extraction**

Hydrological drainage network patterns are a central element of a distributed hydrological model that links the hydrologist's knowledge with the real hydrological processes in a given study area (Kunapo, 2008). Although flow direction (Figure 6.6 left) represents water

movement in each cell in a raster DEM, it cannot show the drainage network pattern and creates an ambiguity due to the enormous amount of information represented.

An issue in automatic overland flow path extraction is how to determine the DEM cell from where channel flow is formed. The cells from which channel flow starts are called channel head (Heine et al., 2004). However, the critical threshold value to separate DEM cells into stream and non-stream cells in typical existing GIS-embedded hydrological models is user-defined. The channel head can be defined using 1% of the maximum value in a flow accumulation model (Maidment, 2002).



**Figure 6.6: A schematic representation of flow direction (left) and delineated overland flow path (right) from a flow accumulation model (Kruger et al., 1993)**

Figure 6.6 shows the water movement direction in each cell, but flow accumulation model is needed to extract drainage network using the flow direction model (left) and its interpretation in the flow network model.

A drainage network pattern can be delineated by the flow accumulation which is dependent on the user-defined threshold in order to take the upstream catchment area into account. Therefore, sometimes a flow accumulation is known as the catchment area. Separation of DEM cells into stream cells and non-stream cells is a controversial issue in spatial hydrology. Different approaches have been developed to determine the threshold in order to initiate a stream channel and to divide DEM cells into stream cells and non-stream cells. Various geographical parameters like climate and soil type influence the threshold (Tarboton et al.,



1991), but the existing hydrological embedded GIS tools use only flow accumulation, which is extracted from DEM. As noted earlier, one percent of flow accumulation is required to form a channel (Maidment, 2002); this rule was determined for rural catchments and does not include urban settings formed by the major and minor system effects.

#### **6.2.4 Summary of the review**

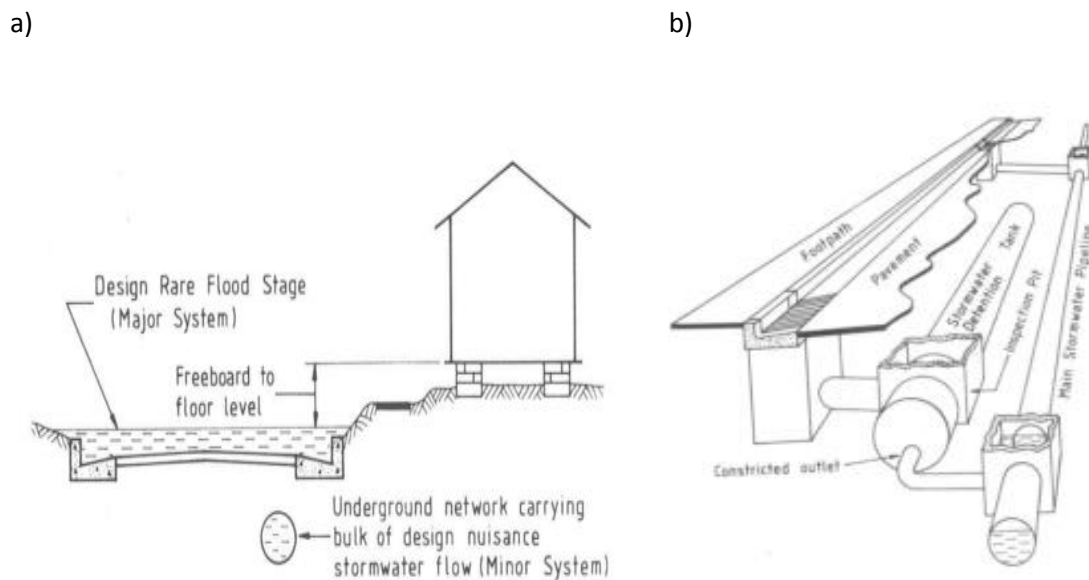
The literature (Jankowsky et al., 2012, Maksimović, 2009, Kunapo, 2007, Kunapo et al., 2009, Fang, 2006) shows that adoption of typical GIS-embedded hydrological tools has some constraints that must be overcome in the adoption of GIS-embedded hydrological tools in an urban catchments setting. The constraints result from various reasons. The first reason is that rural catchments were the target area for developing typical GIS-embedded hydrological models, and are not flexible enough to deal with water flow movement complexity through manmade features like the stormwater collection systems in urban catchments. Secondly, the base data model for analysis for the relevant tools is dependent on the raster data model which is limited to a pixel size, while using a vector data structure is the appropriate data model for engineering practices due to accurate position of features. In addition, before the introduction of the LiDAR-derived DEM, access to coarse resolution topography data was the most important parameter limiting the GIS-embedded hydrological model in urban catchment large scale studies.

The raster-based DEM is the core data source of automatic hydrological (also known as catchment or watershed) models (Kunapo, 2007, Kunapo et al., 2009). The majority of its limitations are related to the capability of the algorithms to determine sink and flat cells (section 6.2.1), and to the assignment of a flow direction for every cell (section 6.2.2). My review of the literature did not result in the choice of a specific method for water flow direction assignment,, therefore it was necessary to test different methods on the sample site.

## 6.3 Overland flow path in sample site

### 6.3.1 Analysis methodology

Comparing a rural area terrain analysis to an urban landscape in order to derive hydrological features, an overland flow path and catchment area, needs spatial details and processing time for the preparation phase on the surface topography due to existing major and minor drainage system structures which divert or collect runoff across a given area away from its natural pathway (Figure 6.7).

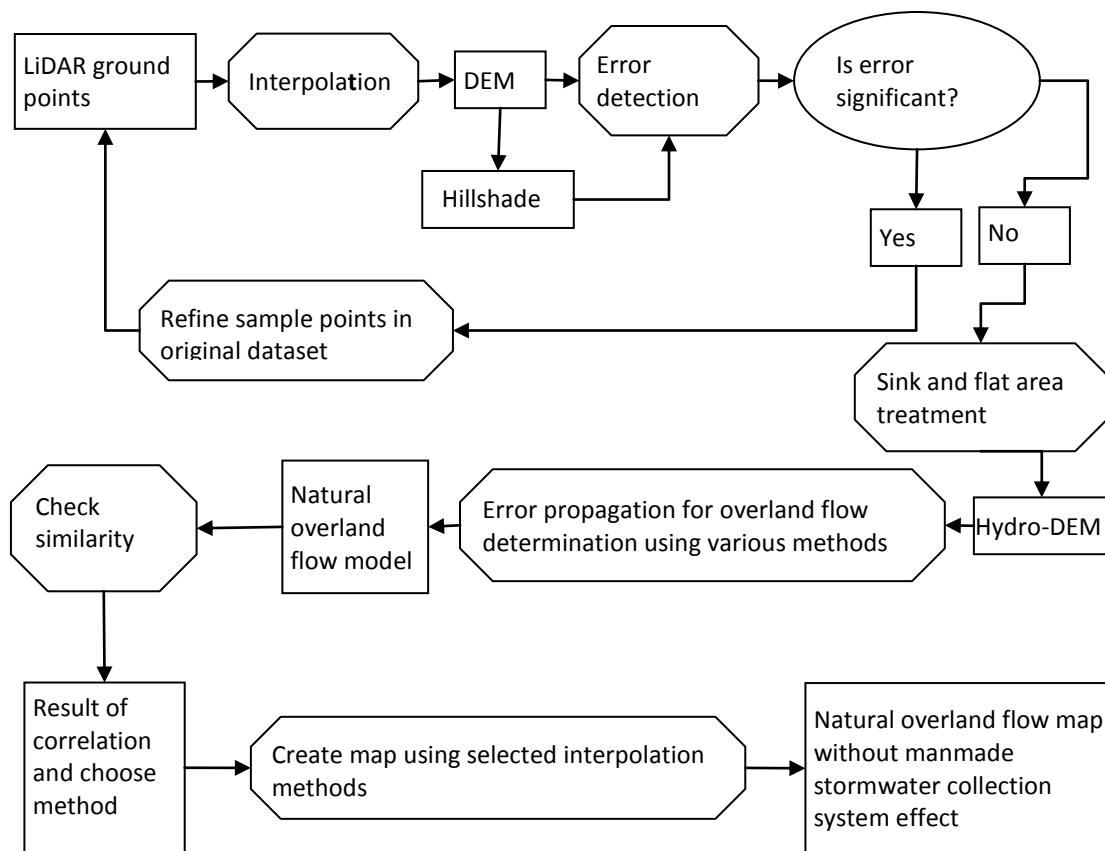


**Figure 6.7: a) Major (left) and b) minor drainage system (right) in an urban landscape (Argue, 1986,page 7 and 16)**

Therefore, a fully automated urban terrain analysis for the purpose of a hydrological model cannot be followed based on the process used for a rural catchment (Djokic and Maidment, 1991) and is often impractical due to a lack of detail in spatial datasets and proper spatial data integration. Nevertheless, Djokic and Maidment (1991) noted that the appropriate approach can be determined based on available data, hardware and software.

In this study, LiDAR ground points were used to develop a 1m<sup>2</sup> spatial resolution DEM for the sample site (Inverloch urban and fringe area) using geostatistic IDW (section 5.5). A pre-

processing step is required to remove spurious sink and flat areas. As described in Section 6.2, sink removal is done using the carving algorithm, which is suitable for the sample site which is a flat coastal urban catchment. Figure 6.8 shows the process for developing a hydro-DEM and extracting natural overland flow path. The resultant hydrological purposed DEM was then used to consider various natural flow direction models' sensitivity in relation to the DEM inherent errors extracted by the vertical accuracy assessment.



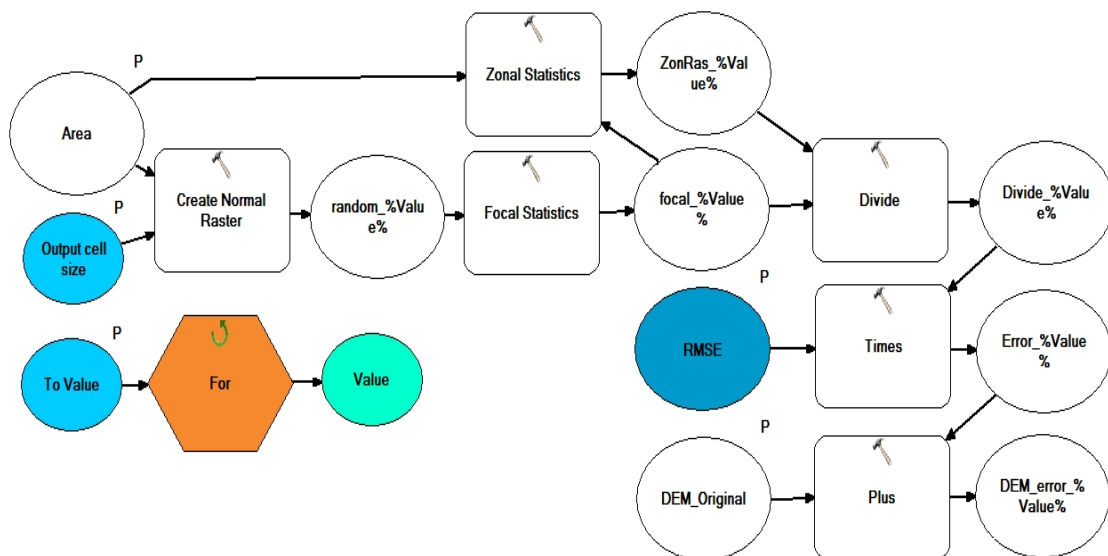
**Figure 6.8: General process applied for the extraction of the natural overland flow path in this study**

The primary DEM was derived using LiDAR sample ground points at 1m x 1m pixel size. The LiDAR dataset was made available for this study as part of research collaboration with the Bass Coast Shire Council.

LiDAR ground points were converted into the DEM using the interpolation technique, geostatistic IDW. The resultant DEM was then inspected using the hillshade model (Kunapo,

2008). If there are any errors, the source LiDAR data needs to be inspected to remove the incorrect sample points causing a problem. The DEM was converted to a hydrological DEM through the pre-processing stage. The hydrological DEM (Hydro-DEM) was then used for overland flow path extraction using selected methods after a sensitivity test.

The sensitivity of flow direction assignment algorithms to the inherited error in the developed DEM was tested using a Monte Carlo simulation as it is the best way for testing model sensitivity numerically (Oksanen and Sarjakoski, 2005). As the Monte Carlo simulation was not embedded in available GIS environment, R (<http://www.r-project.org/>) open-source statistical computing software was used associated with the RSAGA library (SAGA-GIS open-source library that can link SAGA-GIS hydrological models with the R open-source statistical software) (Brenning, 2007) to create a hundred estimations of overland flow path. To run the program, a hundred error-DEM were produced using the model in Figure 6.9.



**Figure 6.9: Autocorrelated random error-DEM generation**

In Figure 6.9, the value for the RMSE was extracted from the vertical accuracy assessment of the LiDAR ground point dataset as described in chapter 5. The nominated RMSE value was determined to be 0.26, or equal to around +/- 0.5m for random errors distributed over the

DEM (chapter 5). The example R-code applicable in the RSAGA library is presented in Figure 6.10.

```
setwd ("F:/DEMs2/fill")
library (RSAGA)

filldem.list<-list.files(getwd(),pattern="fdem_[[:digit:]]*.sgrd")

for (i in 1:length(filldem.list)){

  WF=paste ("F:/DEMs2/Stream/", "DEMON_", i, ".sgrd", sep="")
  rsaga.parallel.processing(in.dem=filldem.list[i], out.carea = WF,
step=1,method=4,linear.threshold=50,convergence=1.1)
  rsaga.geoprocessor("ta_hydrology",2,list(ELEVATION=filldem.list[i],CAREA=
WF,Method=2,STEP=1,MINDQV=0.5,CORRECT=TRUE),show.output.on.console =
FALSE)

}

#in          parallel:[0]D8,[1]Rho8,[2]BraunschweigerReliefmodel,[3]Deterministic
Infinity,[4]Mfd8
#in geoprocessor [0]Rho8,[1]KRA,[2]DEMON

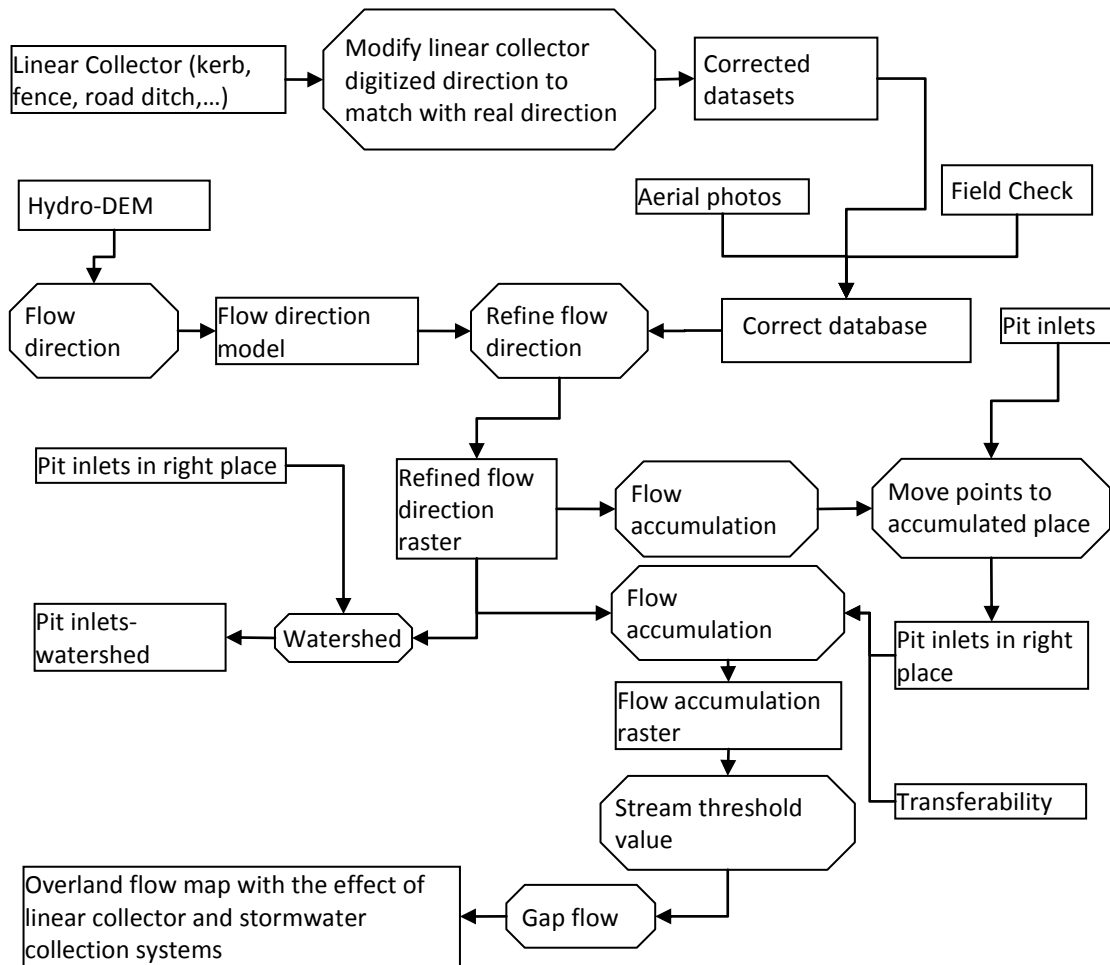
# read all sgrds as g
rids:setwd("F:/DEMs2/Stream/")
careas.list <- list.files(getwd(), pattern="DEMON_[[:digit:]]*.sgrd")
rsaga.sgrd.to.esri(in.sgrds=careas.list,out.grids=set.file.extension(careas.list,".asc"),
out.path=getwd(), prec=0, show.output.on.console=FALSE)
```

**Figure 6.10: Code scripting in R using the RSAGA library**

The program repeats extraction of overland flow paths from DEM in order to map the influence of inherited errors. A hundred repetitions (known as realisation) meets the requirement to achieve a 95 percent statistical confidence level for the output (Zandbergen, 2011). The Monte Carlo simulation results in the extraction of the natural overland flow path from various flow direction assignment methods. The results were then compared using a regression coefficient,  $r^2$ , to measure the similarity between the outcomes of various flow direction assignment methods with the results of the classical D8 method.

The classical D8 method is included in Arc Hydro Tools. I intended to use Arc Hydro tools if the classical D8 flow assignment method did not produce results that differed significantly from the other methods and reality. Arc Hydro tools are comprehensive GIS-embedded hydrological tools and database model (Kumar et al., 2005, Maidment, 2002) solutions for water resource management.

In terms of drainage network extraction, defining a one percent threshold value to separate DEM cells into stream and non-stream cells is not applicable for an urban catchment in which water movement direction follows the surface topographical steepest path and the constructed linear collectors (Djokic and Maidment, 1991). Constructed drainage networks divert the water flow from its steepest pathway where artificial drainage networks lie at an angle with the natural water flow pathway. The intersection between constructed linear features and the natural pathway is important for flood-risk-based land use planning and cost-effective urban drainage design, maintenance and local flood management. Appropriate spatial data integration with enough detail and an accurate spatial database enables identification of the correct overland water movement direction in an urban setting, and subsequently an urban overland flow path and catchment boundaries can be extracted. Therefore, the additional steps depend on appropriate spatial data integration that can represent water movement in an urban catchment with the influence of an overland linear collector and a minor drainage network (Figure 6.11).



**Figure 6.11: General steps for extracting an overland gap flow path in the presence of a linear collector and stormwater collection system effect**

Water movement in urban catchments includes three types of flow:

- Diffused overland flow (sheet flow to the nearest constructed drainage inlet)
- Concentrated overland flow
- Subsurface flow in a man-made network system like stormwater collection pipes

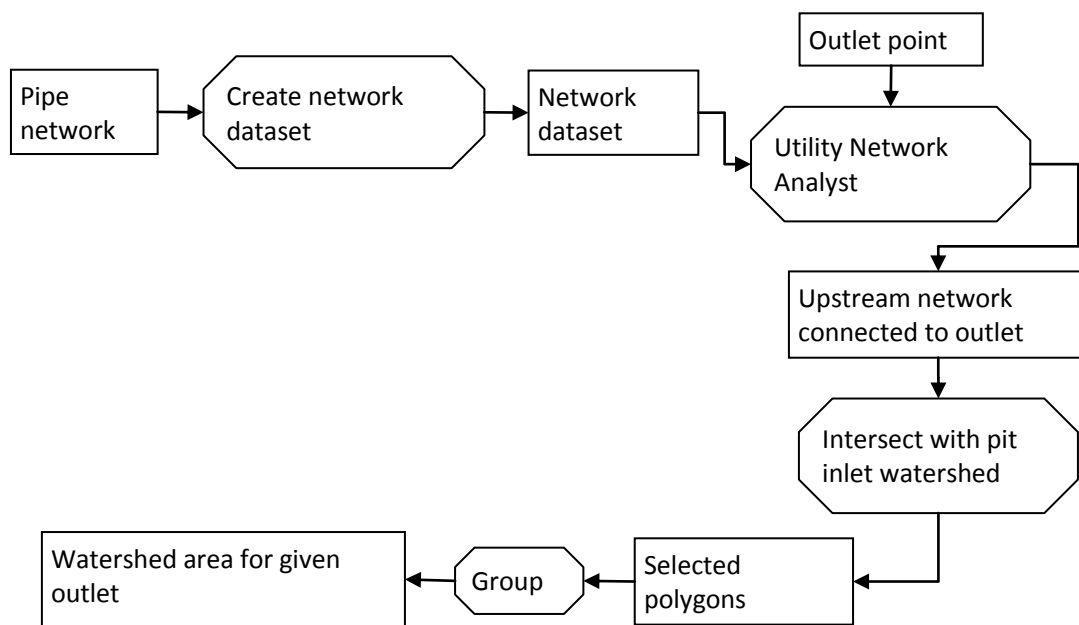
A single terrain model cannot adequately represent all three types of flow and cannot meet the requirements for urban catchment hydrological behaviour (Djokic and Maidment, 1991). If the analysis includes all types of water flow movement, then the resultant overland flow path can be called a coupled surface and a subsurface flow path. Water which does not enter the subsurface flow follows the overland flow path; this flow is called gap flow, and the network comprised by such overland flow path is called the gap flow path (Argue, 1986).

Gap flow includes the flow which cannot be captured by stormwater collection system inlets due to their wrong location, lack of capacity, barriers formed by rubbish or sediment, and the increased runoff amount due to land use changes in the upslope. The influence of a minor drainage system in producing a gap flow also depends on the design ARI for a minor drainage system. The ARI value shows the average interval between selected values of a natural phenomenon like rainfall in a given area. The typical ARI used in the design of drainage infrastructure is five years. Heavy rainfall causes more gap flows and consequently a flood flow on the down slope. A hydraulic analysis is initially required to estimate the gap flow rate, but the required information to estimate the gap flow is rare in the flood-relevant database. Furthermore, a hydraulic analysis is expensive both in time and cost. Alternatively, instead of using a detailed hydraulic analysis, it is possible to assume that the flow which reaches the inlet does not enter the minor drainage system as a whole and so flows over the surface as a gap flow until it reaches other inlets. The amount of gap flow which flows down slope from the location of each entry pit is assumed to be around 50 percent of each inlet capacity in the designing stage (Argue, 1986). The latter can be interpreted as meaning that each cell in the DEM which includes entry inlet pits should contribute to the flow accumulation calculation by 50 percent of water volume transferability.

Figure 6.11 shows the process of flow direction assignment correction and flow accumulation calculation to extract the gap flow. Like calculation of water movement, fully automatic catchment delineation in an urban setting needs a comprehensive process (Jankowsky et al., 2012). Most of the GIS-embedded hydrological models are designed for rural hydrological modelling. Such models need to be coupled with the other GIS-embedded models in order to be useable for urban terrain catchment delineation. In my study, I developed process for extraction of catchment boundary for a given stormwater collection inlet as outlets. Gironás et al. (2010) described the common methods for preparing a DEM in order to implement it in urban hydrological modelling. These methods are dependent on DEM manipulation; however,



the process developed in this study attempts to avoid reconditioning a DEM with a stormwater collection pipe network used in previous studies like the study conducted by Kunapo (2007), due to errors created from DEM reconditioning stage. The developed process in my study is based on the current capabilities in available GIS environments. The concept of network topology with available datasets like pipe network and a natural catchment boundary for each inlet are used to delineate catchment boundaries for given inlets in urban setting.



**Figure 6.12: General steps to extract a watershed boundary for a given outlet in an urban catchment**

Figure 6.12 shows the process used to extract catchment boundary for given outlets in urban catchment. A pipe network creates a utility network dataset that enables identification of all the watershed areas over which water flows into the given outlet.

### 6.3.2 Methods, results and discussion

In the rest of this chapter, I present the methodology I applied to identify the overland flow path network and catchment boundaries in the sample site, and the results. The preparation of the DEM in terms of sink and flat area treatments is described first, followed by the testing of different flow direction assignment methods, and finally the results of the flow analysis and urban catchment determination.

### 6.3.2.1 DEM development and preparation

The boundary of the study area was limited to areas covered by the LiDAR dataset. The DEM for the study area was developed based on the LiDAR ground sample points using geostatistic IDW interpolation in the ArcGIS Geostatistical extension. The developed DEM was pre-processed to remove sink and flat areas using the carving method in the SAGA-GIS open source software.

Figure 6.13 shows a DEM which is suitable for hydrological application for rural areas because it was only treated for sink and depression removal by the current available GIS-embedded hydrological models. The processing of resultant DEM needs to include urban features' influences on flow direction assignment and flow accumulation calculation as resultant Hydro-DEM does not contain urban features.

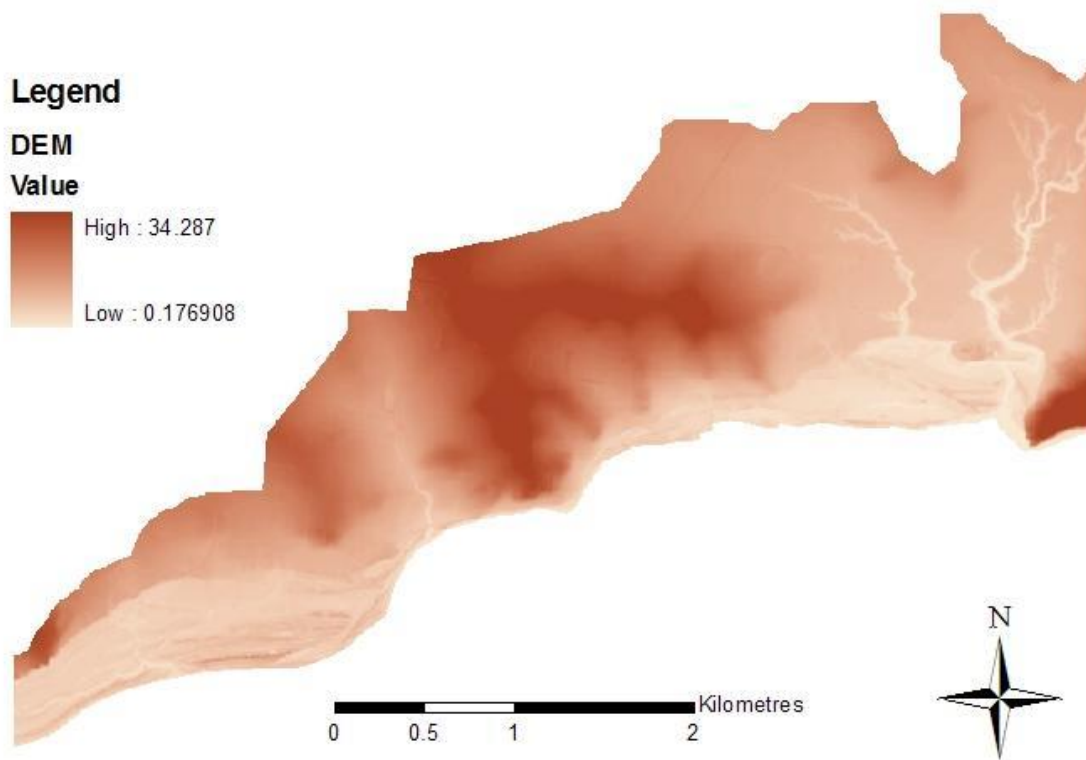
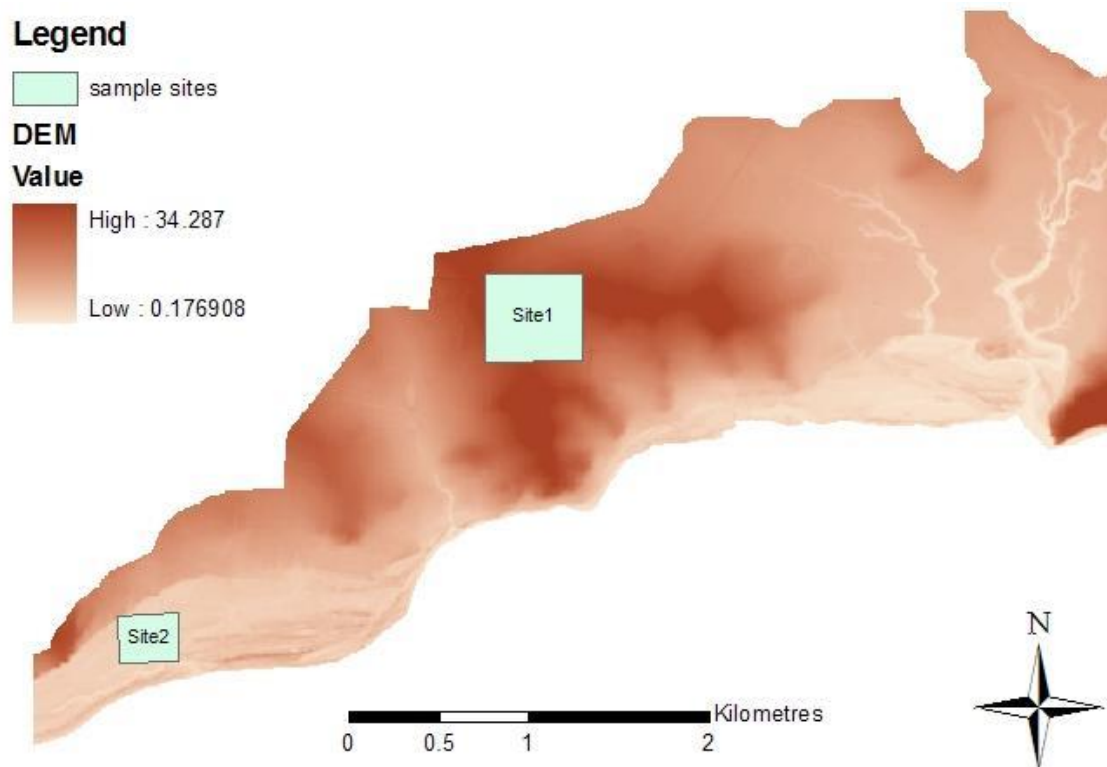


Figure 6.13: Hydrologically DEM (Hydro-DEM) developed from the LiDAR sample points

### 6.3.2.2 Flow direction assignment models comparison

Due to the capture error effects on the results of flow direction assignment methods, a Monte Carlo simulation (Zandbergen, 2011) was used for two subareas in the Inverloch township: including a gentle relief area (Site1 in Figure 6.14) and a relatively flat area (Site2 in Figure 6.14). The selected test sites (Figure 6.14) include both man-made and natural features.



**Figure 6.14: Subareas of the study area for the Monte Carlo simulation in order to compare various flow routing methods**

The results of the Monte Carlo simulation on extracting the natural overland flow path in site1 are shown in Figure 6.15. The threshold value for determining channel head (section 6.2.3) was set to 100. The nominated threshold value is arbitrary and it can be changed, but the value was not an important issue for considering error patterns and behaviour in the final products.

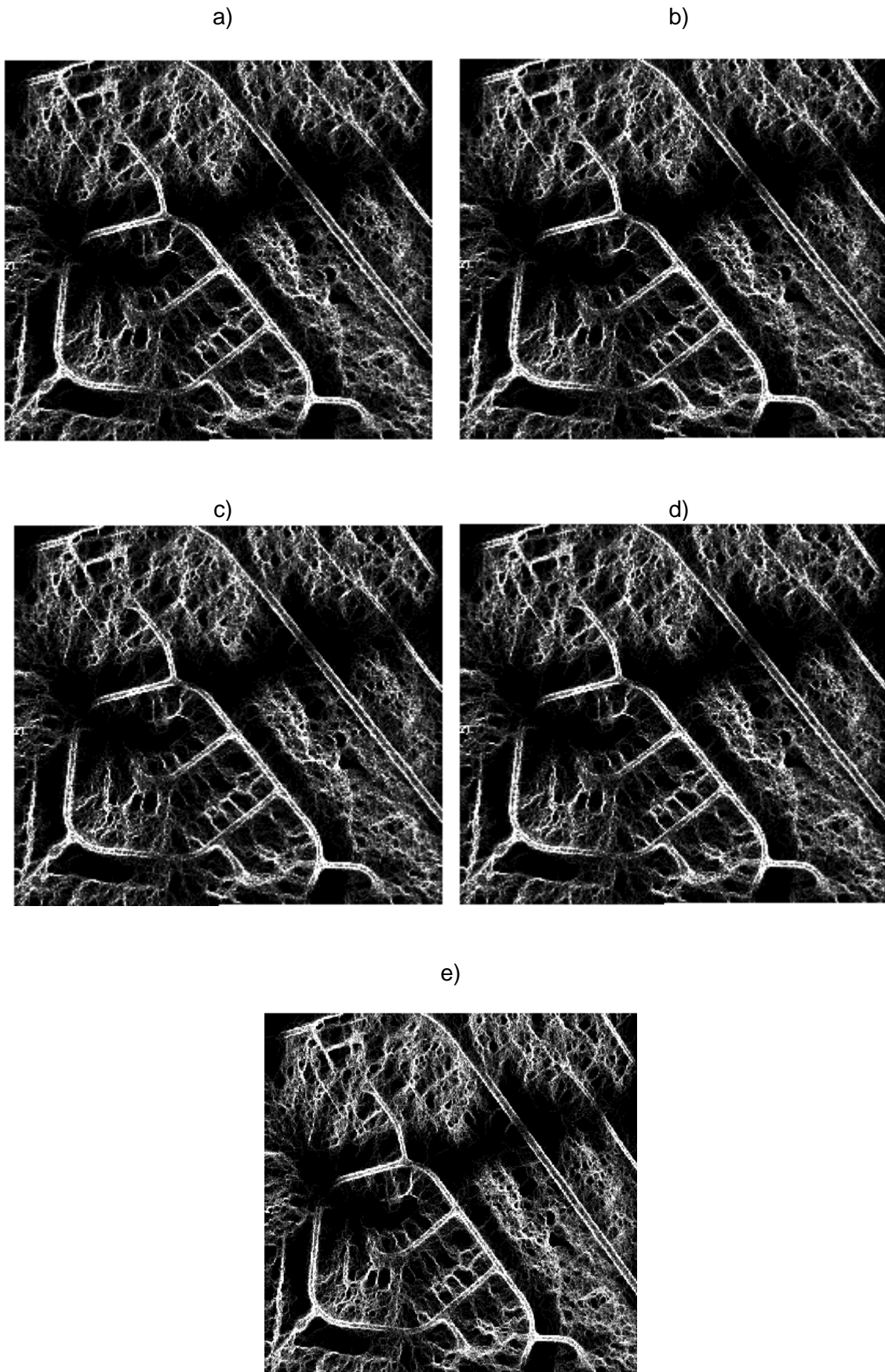
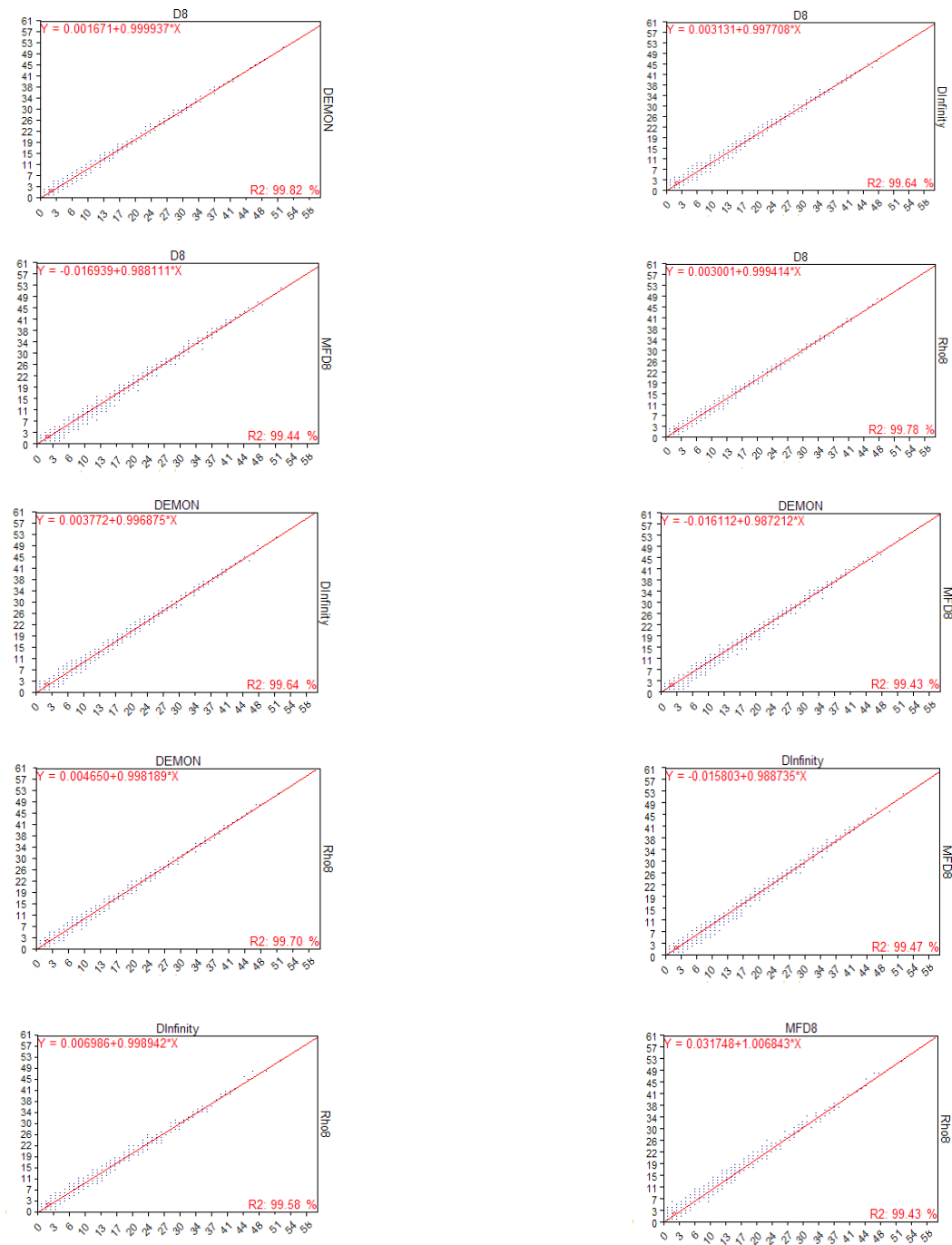


Figure 6.15: Results of the Monte Carlo simulation for extracting the natural overland flow path in Site1 using different techniques: a) D8, b) MFD8, c) D-infinity, d) Rho8, and e) DEMON

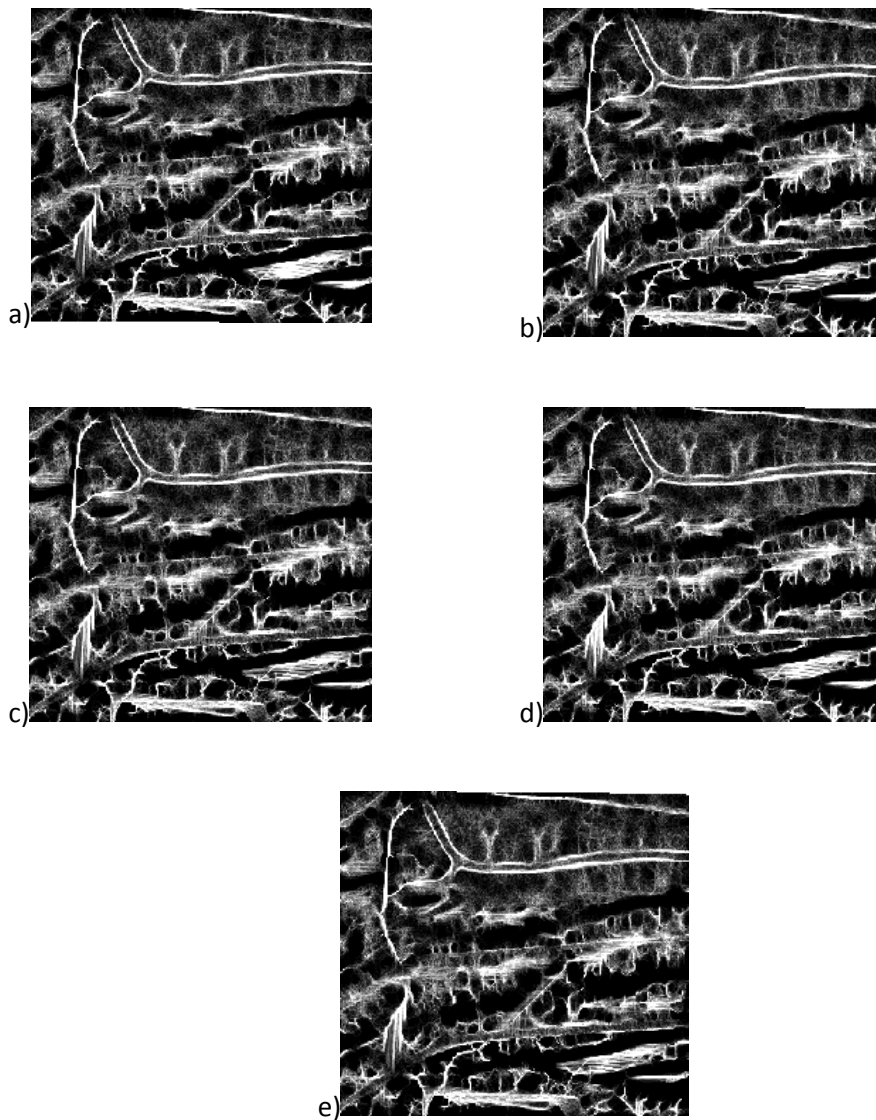
As Figure 6.15 demonstrates, the five tested flow direction assignment methods produced similar results. Statistical analysis confirms that, contrary to the theoretical discussion in section 6.2.2, no significant differences existed between tested methods in determining the overland flow path in Site 1. Figure 6.16 shows  $R^2$  for regression involving the order results of all tested flow direction assignment methods are greater than 0.99.



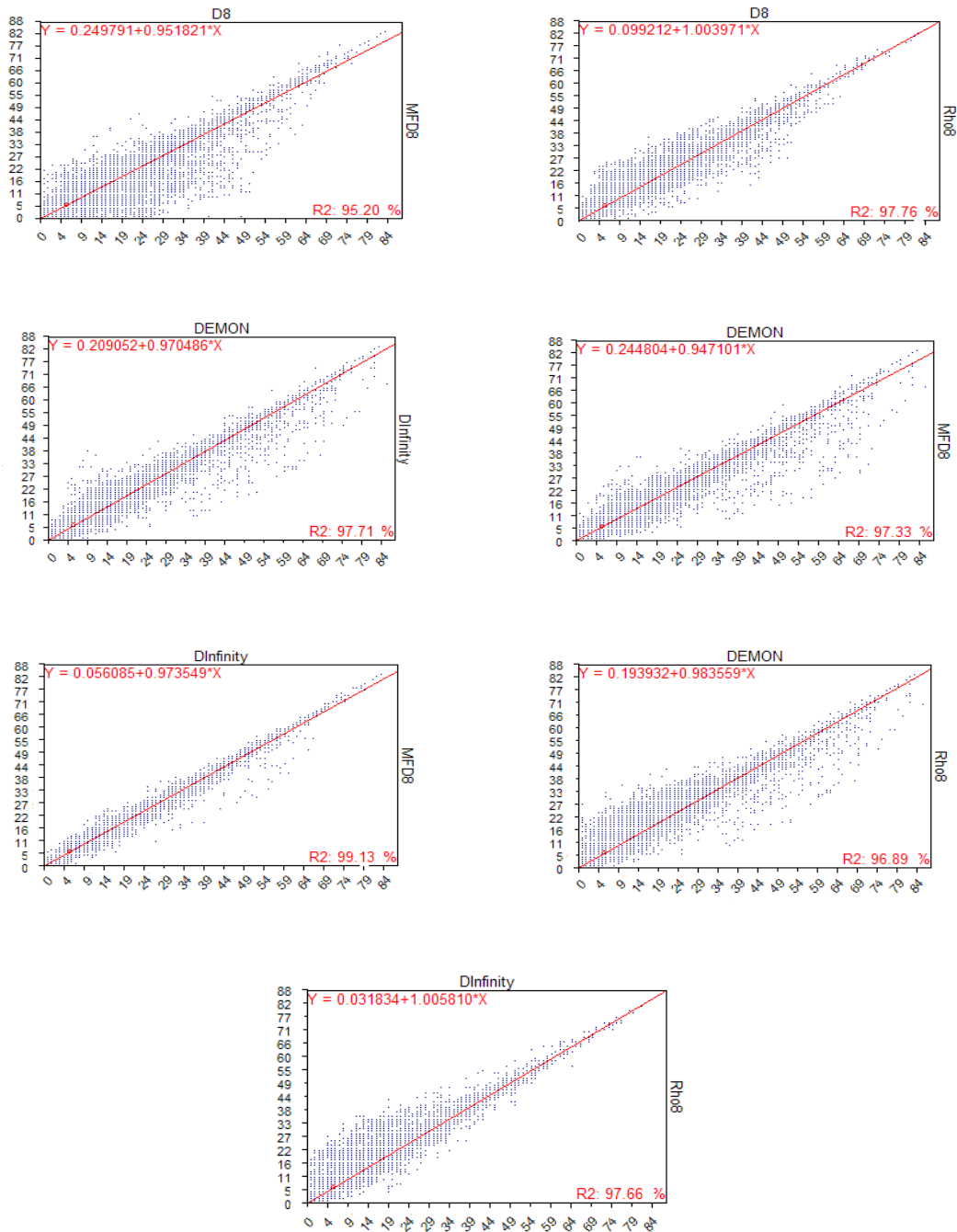
**Figure 6.16: Correlation between the results of different models for Site1 (X and Y axis show the number of repetition out of a 100 times that given cell is assigned to a channel cell)**

The results depicted in Figure 6.16 show that the methods considered had similar responses to the introduced errors on the DEM for Site1.

The same process was repeated for Site2 in the Inverloch Township, where the area is flat and has been recently developed as a new estate (Wreck Creek). Figure 6.17 shows the visual results of five tested flow routing methods. A visual comparison of the results of each model in Figure 6.17, like Figure 6.15 reveals no notable differences. The correlations between the results of the different models are shown in Figure 6.18. Although the values of  $r^2$  for Site2 are lower than for Site1, there is no notable difference between the results for the methods.



**Figure 6.17: Results of the Monte Carlo simulation for extracting the natural overland flow path for Site 2 using different techniques: a) D8, b) MFD8, c) D-infinity, d) Rho8, and e) DEMON**



**Figure 6.18: The correlation between the results of the different models for Site 2 (X and Y axis show the number of repetition out of a 100 times that given cell is a channel cell)**

Figure 6.15, Figure 6.16, Figure 6.17 and Figure 6.18 confirm that no significant differences exist between the flow direction assignment algorithms for the sites. Therefore, the classical D8 method was chosen to map overland flow path, due to following reasons.

- 1-The classical D8 method is a popular and widely used algorithm for flow direction assignment due to its simple implication

2-The Classical D8 method determines flow direction to one of down slope neighbouring cells. This algorithm removes fuzziness, therefore they creates clear overland flow path and catchment boundary. Furthermore, correction of overland flow path based on kerb constructed water linear collector features such as kerb in urban catchment produces is easier. For example, modifying a flow direction model in the location of water linear collector like constructed kerb can be done using the “Flow Direction with Stream” function in the Arc Hydro tools using the classical D8 method, while it is not applicable for the methods which generates fuzziness in the flow direction model. Therefore, due to the requirement for delineating certain flow paths and sharp catchment boundaries in engineering practice. Flow direction assignment models which create fuzzy results are not desirable in practice, particularly when these models do not significantly improve the final map accuracy. Careful consideration in this study show that there is no significant accuracy enhancement in the resultant maps using the methods other than the D8 algorithm

3-The classical D8 method supports typical GIS-embedded hydrological model - Arc Hydro Models- which is a comprehensive database model in water resource management.

### **6.3.2.3 Overland flow path determination**

The resultant flow path does not include the reality of the water movement complexity in urban catchments because the popular GIS-embedded hydrological models focus on rural catchment analysis. Complexity in an urban basin results from the presence of stormwater collection systems including kerbs, gutters, inlets, and pipe networks which create a parallel surface and subsurface flow. Man-made linear collectors can change the shape of a natural catchment in an urban setting. Therefore, appropriate spatial data integration is required to include the effect of an urban stormwater collection system in the terrain analysis process. Figure 6.11 portrays a Data Flow Diagram (DFD) for a proper integration of a spatial dataset in order to map the overland gap flow path in the Inverloch township area.



Although the popular GIS-embedded hydrological models are suitable for rural areas, with a few refinements they can also be used to map an overland water flow path in an urban setting. Refinement of flow direction assignment refers to impose the effect of linear manmade collectors (kerb, fence, road ditches) and small open drains on flow direction model.

Kerbs comprise the majority of artificial linear collectors which can be established for collecting overland flow, and drain stormwater into the nearest installed inlet to the subsurface pipe network. Although water flows downstream in a kerb and pipe network like a stream, kerb cross-section properties are different from river or natural channel cross-sections in rural catchments. Therefore, assuming that linear collectors like a pipe network can play a stream role for draining water in an urban context, as Kunapo (2007) assumed, they can introduce undesired errors in overland flow path mapping. Assuming stormwater pipe network as streams results in wrong hydrological model because water freely interact with pipe network in any location while surface flow and subsurface flow interaction is limited to inlets' location in reality.

In addition, reconditioning of the DEM by the stormwater pipe network, like reconditioning the DEM by a natural stream or channel, can cause substantial errors which must be removed in the preparation phase, which is time-consuming and reduces the accuracy of the final product because removing spurious sinks increases the number of flat areas. Flat areas are important barriers in overland flow path mapping, particularly in an essentially flat land form.

The effect of subsurface flow can be included only in the place of inlets, so stormwater pipe network is not included for flow direction assignment as the effect of subsurface flow is in reducing the stormwater runoff volume. Therefore, the effect of subsurface flow is included in calculation flow accumulation model using inlets' water trap coefficient.

The process developed in this study described in Figure 6.11. It started by modifying the linear collector dataset direction based on surface topography, and then the modified datasets have been used to refine the primary flow direction model. After developing the first flow

accumulation model, stormwater collection inlets locations were modified to be located exactly at the place of concentrated flow as is assumed in stormwater collection system engineering design. Flow accumulation was then calculated again by including the water trap effect of each pit inlet. It was expected that after inclusion of pit inlets a less concentrated flow would be generated due to the collection of runoff by the stormwater collection system. Each pit trap coefficient was assumed as having been based on the pit types (grated pit, side entry pit, and mixed grated-side entry pits) surface elevation at the location of inlets, and surface slopes. The resultant flow accumulation model was then classified into stream (concentrated flow) and non-stream cells based on arbitrarily threshold to determine channel head. The result map shows the overland flow path (gap flow overland path) in the sample site. Figure 6.19 shows the flow path extracted from the threshold flow accumulation (the threshold is set for 5000 upslope cells), before introducing the effect of inlet pits into the flow accumulation calculation. Figure 6.20 shows the same area flow accumulation with the inclusion of pit trap effects. Figure 6.20 shows that the trap's effect of the sequential pit inlets reduced the value of the flow accumulation. Therefore, a part of the concentrated flow is not joined with the other parts in the location of C\_5. This is because the value in the corresponding cell(s) cannot meet the defined threshold value units (as chosen arbitrarily). As can be seen in Figure 6.20, four sequential sample pits with a different transferability value or trap value (1-transferability value) were included in the flow accumulation calculation. Including the pit effects in the calculation reduced the amount of flow accumulation and consequently concentrated overland flow paths (gap flow path). The transferability rate was assumed arbitrarily as being 75%, 50%, 25%, and 0% of the flow accumulation value in the location of pit inlets located in C\_2, C\_3, C\_4, and C\_5, respectively.

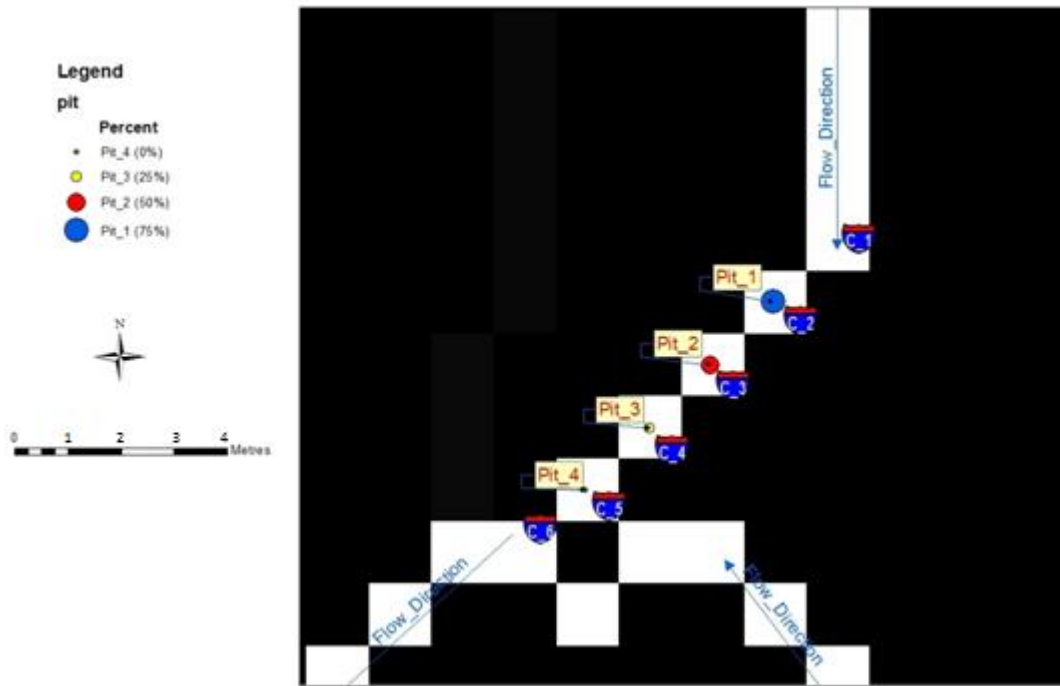


Figure 6.19: Concentrated flow without pit inlets water trap effect

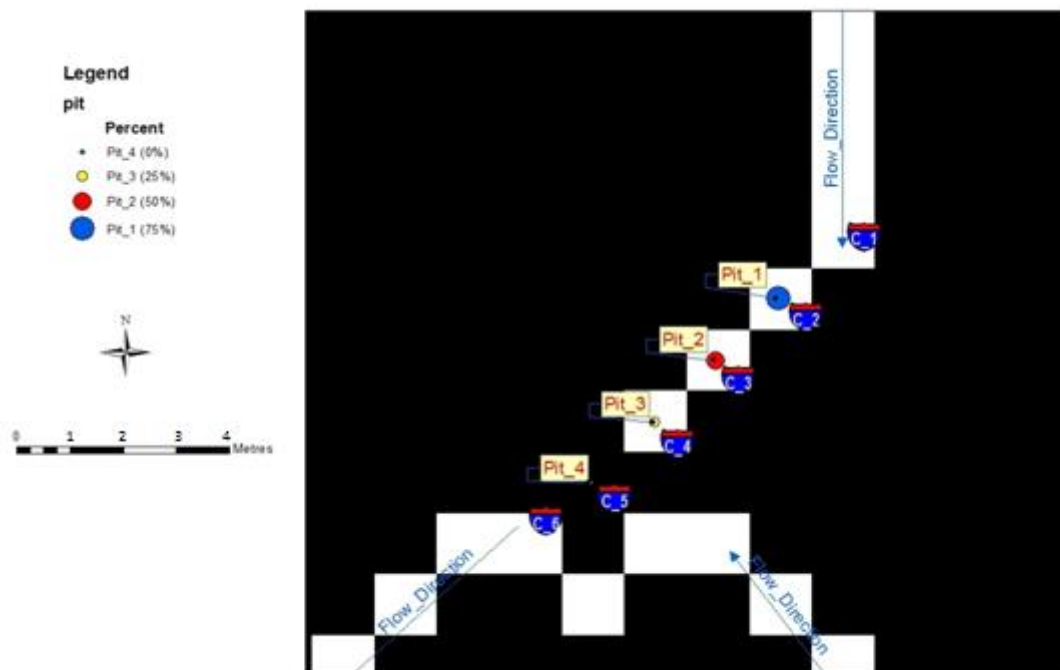


Figure 6.20: Concentrated flow with pit inlets effect  
Circles show pits and are arranged based on 75, 50, 25, and 0 percent of transferability

In the drainage designing stage, the real performance of pit inlets to capture overland flow assumed 50% of the designed capacity. Therefore, transferability (gap flow production) can be assumed to be 50% for all types of inlet capacity.

In the presence of a minor drainage system in an urban catchment can change the effect of the rainfall runoff amount and consequently the gap flow rate. The design storm ARI for a major drainage system is based on a 100-year in Australia (Pilgrim, 2001) . However, the nominated 100-year ARI becomes a shorter ARI with the same rainfall duration for a minor drainage system and stormwater runoff collection system (Argue, 1986). Therefore, gap flow rate can be estimated using the shift in the amount of ARI rainfall and consequently runoff rate.

Table 6.1 shows the modified ARI for a 100-year rainfall event in the southern Australia in an urban catchment with a stormwater collection system network.

**Table 6.1: Modified ARI for runoff in an urban setting equipped with stormwater in the southern Australia (Argue, 1986).**

Minor system under-ground network-design ARI (N-years)	2	3	5	10
Gap flow moving in surface channels only: design ARI with minor system unblocked (M-years)	20	15	10	5
Gap flow moving in surface channels only: design ARI with minor system 50% blocked (M-years)	50	45	40	30

These values can change based on the study area’s climate and physiographic characteristics.

As an example to clarify Table 6.1, if a stormwater collection system has been designed for a

five year ARI, it influences the hydrological process and consequently catchment response so that a hydrologist can use the rainfall amount which is equal to a 10 or 40-year for a further hydrological simulation in unblocked (water traps in inlets based on designed inlet capacity) and blocked (50 percent of inlet capacity) situations, respectively.

As rainfall-runoff modelling is required to estimate gap flow rate, alternatively, the gap flow can be modelled conceptually using the previously mentioned concept of trapping flow in the location of each pit inlets. Using the concept of trapping flow in each inlet means the value from a flow accumulation does not need to be changed into a runoff value and can be estimated straightforwardly at the flow accumulation calculation stage.

In addition to pit inlets, as already noted, a surface linear collector like a kerb has significant influence on the natural overland water movement direction. Although an urban major drainage system's (road and its ditches) role is assumed to be similar to a stream in a rural catchment, their cross-section and longitudinal profile properties are different. Therefore, correction of the flow direction model where natural overland flow paths lie at an angle to a linear collector dataset is a necessary refinement at the flow direction assignment stage in order to develop an accurate flow accumulation model. In summary, in this study manipulating a DEM at the location of a kerb or any other linear collectors influencing a water flow was replaced by a correction of water flow direction due to the following reasons:

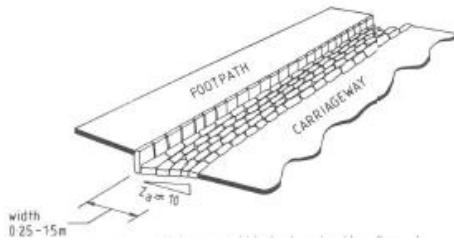
- 1-a kerb cross-section has various patterns and is different from a stream or natural channel cross-section grade (Figure 6.21 a-e)

- 2-the LiDAR dataset has shown surface topography details and the Bass Coast GIS database does not include extra details, therefore, the DEM manipulation stage cannot add more spatial details

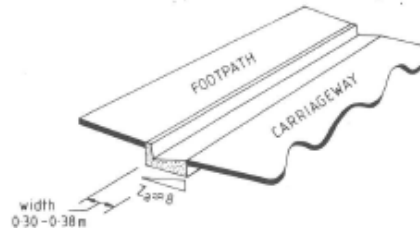
- 3-unlike stream burning no manipulation for neighbouring cells value occurs in this approach (Callow et al., 2007)

4-to preserve the cross-section and longitudinal profile properties of urban feature like carriageways and footpath surfaces topography cross-section and profile properties.

a) Cobble kerb and gutter channel



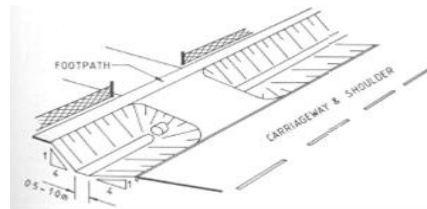
b) Concrete kerb and gutter



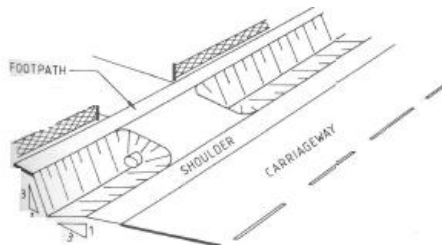
c) Concrete kerb (no gutters)



d) Roadside grassed swale – with crossing



e) Blade-cut earth roadside channel



**Figure 6.21: Different types of linear collectors in an urban catchment (Argue, 1986, page 17)**

Figure 6.19 shows the flow accumulation model before the inclusion of the linear collectors and Figure 6.20 shows the effect of the correction of the first flow direction model after inclusion of the kerb directions using the “Flow Direction with Stream” function in Arc Hydro Tools, which is an alternative way to manipulate the DEM to impose the effect of linear features on a further hydrological calculation.

The influence of a linear collector on water flow direction in an urban setting is presented in Figure 6.22 and Figure 6.23.

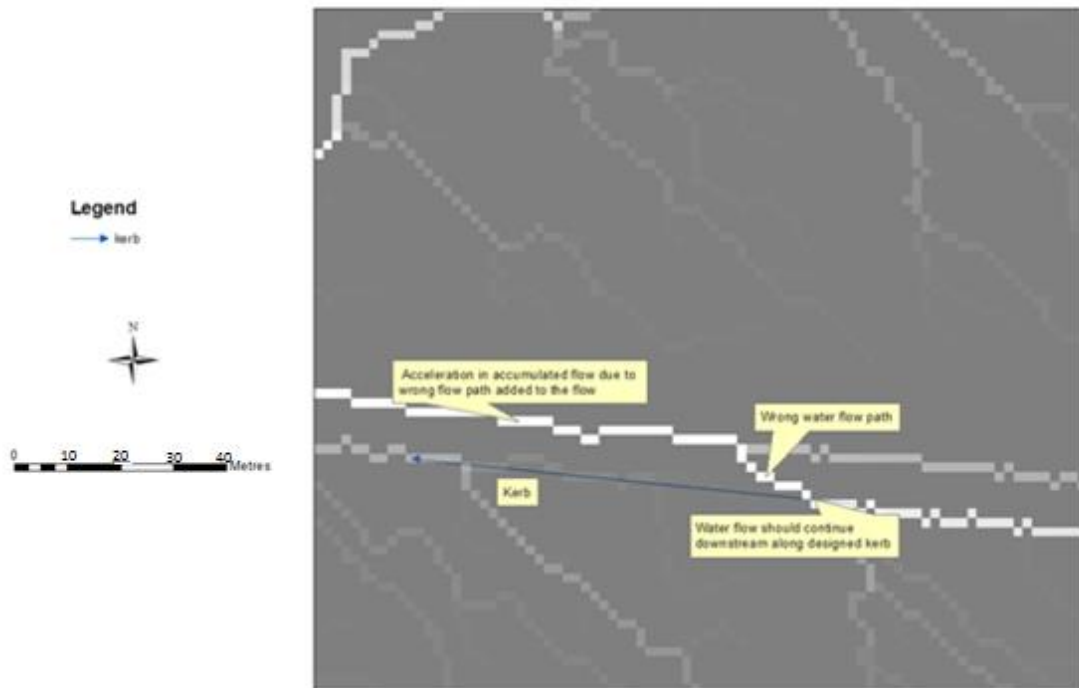


Figure 6.22: Concentrated flow before flow direction correction in the place of a kerb

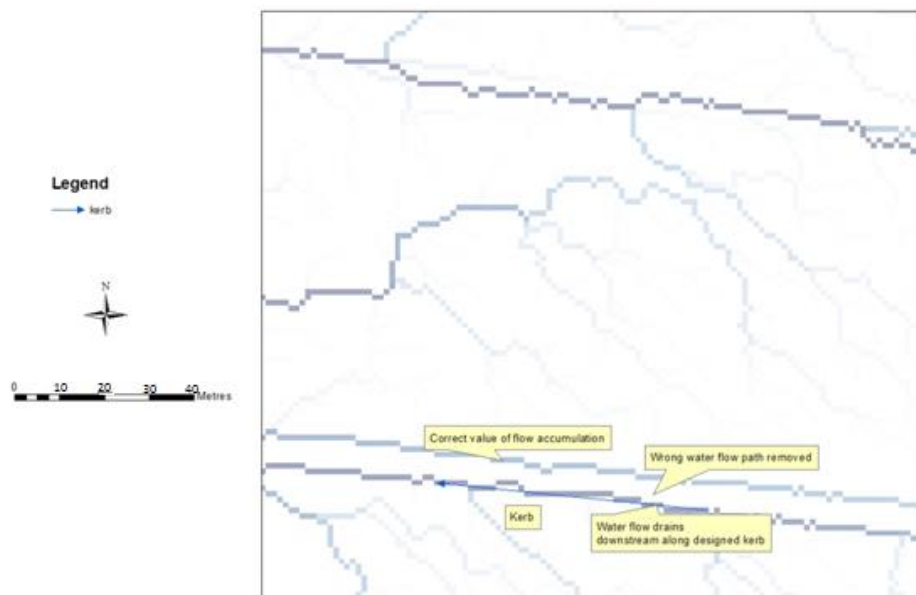


Figure 6.23: Concentrated flow path after flow direction correction

Figure 6.23 shows the effect of a direction correction on the consequent flow accumulation calculation in the location of a linear collector. As can be seen, there are two parallel concentrated flows which move along the constructed kerb.

Water flowing across the road from one side to the other side is possible when the runoff depth and volume are beyond the designed flood ARI (Figure 6.24).

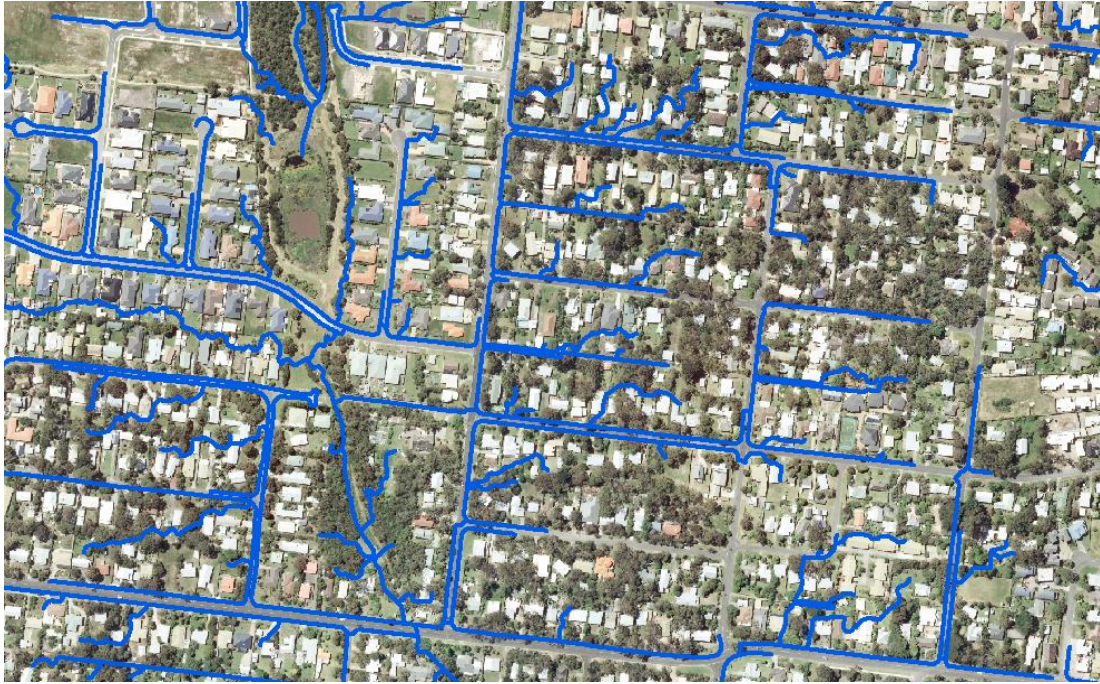


**Figure 6.24: Bass Highway flood 22/6/2012**

Using the “Flow Direction with Stream” function in Arc Hydro Tools, unlike DEM reconditioning, allows correction in the flow direction assignment without changing the original DEM data.

The overland flow path for the study area was delineated after determining the linear collector direction and the influence of the minor drainage system in the location of each pit. Results are shown for part of the sample site in Figure 6.25.

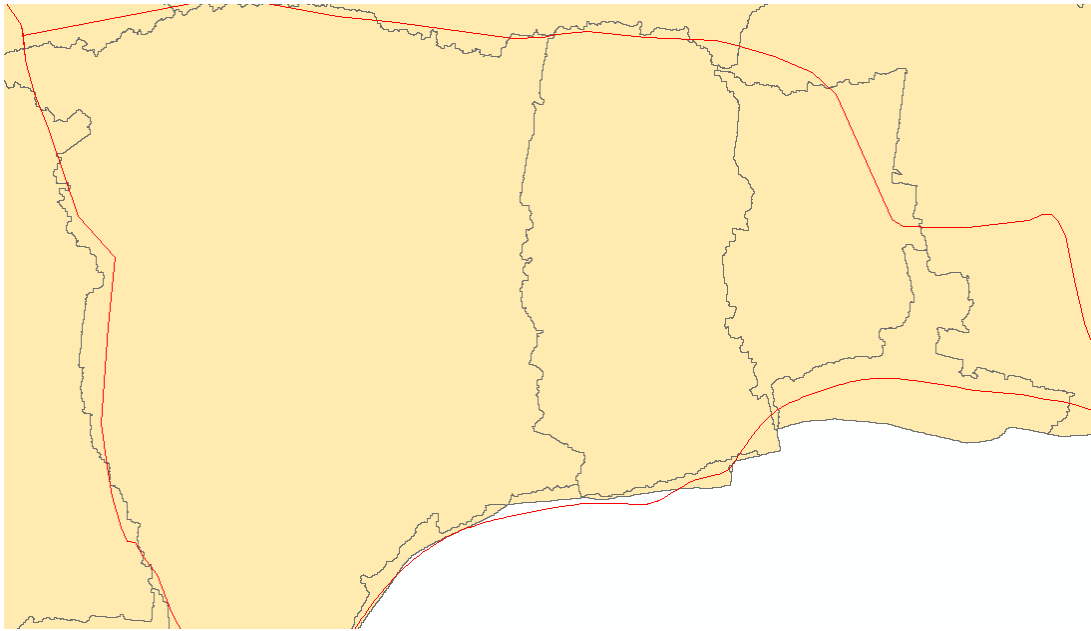




**Figure 6.25: The overland gap flow path in part of the sample site.**

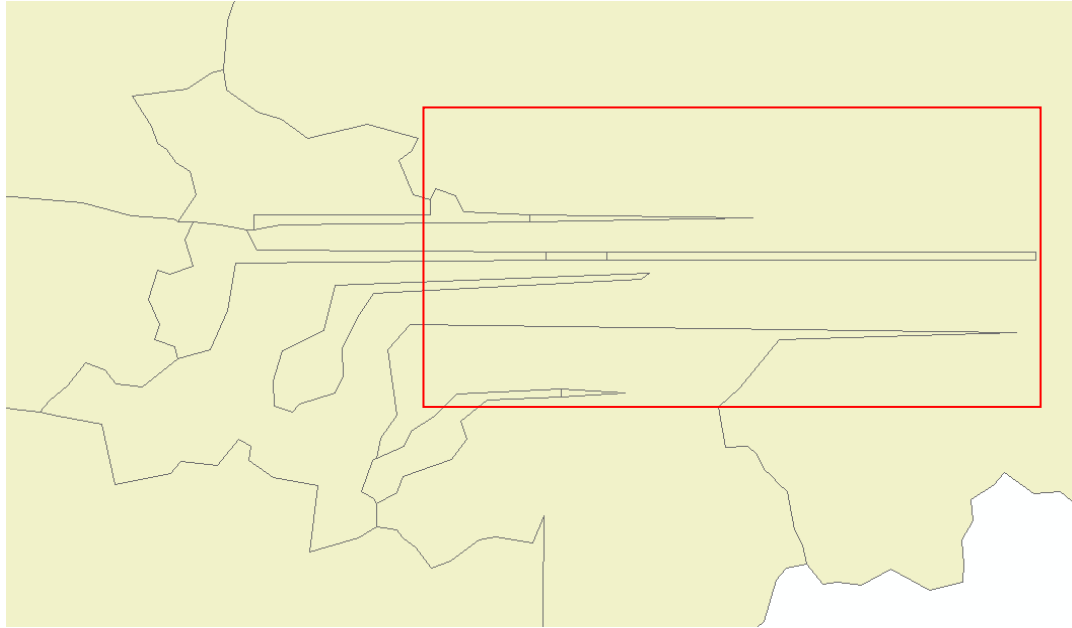
#### **6.3.2.4 Catchment delineation**

In many hydrological models the upslope catchment area is fundamental information for accurate water flow simulation. The catchment area can be calculated after accurate delineation of catchment boundaries. The existing catchment boundary map for the sample study area was general, so that the whole study area comprised one catchment. The catchment was divided into sub-catchments using a terrain analysis based on the LiDAR-derived DEM. Figure 6.26 shows the difference in details.



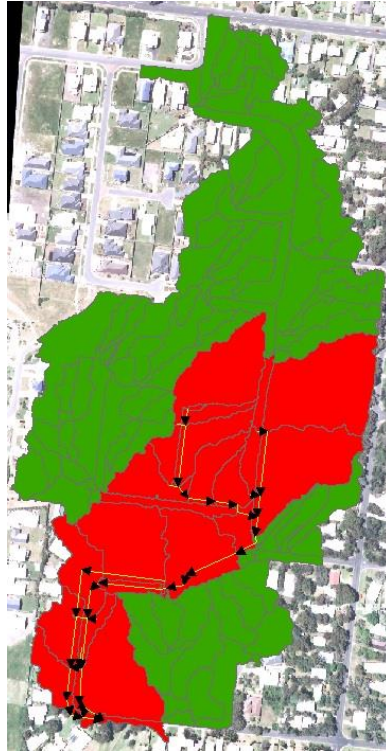
**Figure 6.26: Existing catchment boundary in the sample study area (red line) and LiDAR-derived catchment boundaries (black line) (Source: Bass Coast Shire GIS database)**

As previously noted, typical GIS-embedded hydrological models, such as Arc Hydro Tools, need refinements to delineate urban catchment boundary in the presence of stormwater collection system. The procedure used to extract rural catchment boundaries cannot be used to extract urban catchment boundaries for given outlets due to the subsurface flow influences in an urban setting (Figure 6.27).



**Figure 6.27: Watershed boundary (black line) delineated using a typical process**

The catchment extraction in an urban setting using the standard procedure results in a catchment following the surface topography without including the subsurface diversion as can be seen in Figure 6.28. Developing a proper process to delineate a catchment boundary is essential in urban catchment modelling. Figure 6.12 described an appropriate spatial data integration based on the network analysis concept in order to extract the urban watershed boundary for a given point. The Utility Network Analyst of the ESRI-ARCGIS was used to extract detailed and accurate catchment boundary. The result shows that the natural catchment and the urban watershed are two different sizes.



**Figure 6.28: Green polygons (large area) show the natural watershed while the red ones (small area) show the catchment after including the stormwater pipe network (yellow lines) and pits (black arrow) connected to given points.**

Figure 6.28 shows that the natural watershed for a particular outlet is larger than the watershed influenced by the stormwater collection system due to the effect of the stormwater collection system network in diverting stormwater runoff from its natural path way.

## **6.4 Conclusion**

In this chapter I discussed the utility of GIS-embedded hydrological models and the available high resolution LiDAR-derived DEM to provide the information products required to determine an overland flow path in an urban catchment. The outcome of the research presented in this chapter was new processes of spatial data integration that enabled extraction of overland flow path and detail catchment boundary in an urban catchment.

This chapter began with a review of the relevant literature. Based on that review, I developed the appropriate steps to extract an overland flow path and catchment boundary in a sample urban catchment equipped with a subsurface stormwater collection system.

As a hydrological model depends on the given study area, no specific flow direction assignment model, which is the core step in GIS-embedded hydrological models, is universally applicable. After considering the difference between available developed flow direction assignment methods using Monte Carlo Simulation, the widely-used D8 method was chosen to produce the required information products. The reasons for using D8 method were various, but the most important parameter was that the D8 method has been implemented in Arc Hydro Tools, which present the comprehensive spatial database model for water resource management. The integration model developed in this study enabled the typical GIS-embedded hydrological model, Arc Hydro Tools, to be applicable in flood-risk-based land use planning in urban catchments.

Planning departments use the overland flow path in order to assess development's layout and the land use plan for new estate developments. Drainage engineers can also use the delineated overland flow path in a hydrodynamic simulation. Catchment boundaries are essential information products for flood-risk-based land use planning that enable determination of the downstream area affected by upstream land use change. Changing overland flow from natural paths using an inappropriate road design layout or an unexpected debris blockage of subsurface inlets can result in a significant loss in a storm event. Consideration on the effect of land developments' layouts regarding to natural overland flow path is essential to reduce the cost of flood damage (Weeks et al., 2009).

In this chapter I outlined how I generated overland flow path and catchment boundary information products for an urban catchment in my sample study area in order to answer research question 6 (section 1.2). The next chapter will present the methods used to extract flash-flood-prone areas in order to provide required information products for land use planning.

# 7 Mapping areas subject to overland flash flooding

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## 7.1 Introduction

In chapter 6, I described methods for extracting an overland flow path in urban catchment (in order to answer research question 6 (section 1.2)).

In this chapter, I outline my implementation of a Topographic Wetness Index (TWI) using a high-resolution LiDAR-derived DEM in order to support the flood-relevant decisions which have been made by Bass Coast Shire Council's drainage engineering and land use planners.

In section 4.9, I noted that a map showing the areas prone to overland flash flooding is an important tool for flood-risk-based land use planning. Land use planners are necessarily cautious about granting permission for new estate development based on flood-risk-based land use planning provisions. Similarly, drainage engineers are interested in understanding the effect of an upslope catchment on a specific area and the influence of a newly developed area on retrofit drainage and landscape on the down slope.

Although overland flow path extraction was discussed in the previous chapter, determination of overland flash-flood-prone areas was not mentioned. In the remainder of this chapter, I discuss the original form and advancements in TWI, then the implementation of the model for the sample site (section 5.4.1). My results are compared with the flood event that occurred on 22/06/2012 in the sample site.

## 7.2 TWI: original formula and refinements

Beven and Kirkby (1979) developed the TWI as a part of the runoff model in TOPMODEL(Hjerdt et al., 2004). TWI describes the location and size of a saturation overland flow in a given study area (Wilson and Gallant, 2000). It quantifies the effect of the local topography on runoff generation (Qin et al., 2011) and shows the wet areas in a landscape

(Kopecký and Čížková, 2010). As the spatial hydrological conditions at the first phase can be controlled by topography (Western et al., 1999, Sørensen et al., 2006), TWI is a proper model to determine wet areas. Due to the ease of implementation of the TWI, simple physically-based principles, less dependent on user inputs, and representing a consistent approach to the parameterisation of water movement (Hjerdt et al., 2004), have become widely used in hydrological processes, biological processes, and vegetation patterns (Sørensen et al., 2006). Among developed methods to extract topographical information from a DEM, the TWI has become increasingly popular in different applications (Kopecký and Čížková, 2010). However, various modifications have been made to the base form of the TWI: Hjerdt et al. (2004), Kopecký and Čížková (2010), Qin et al. (2011), and Yong et al. (2012) proposed various improvements in the base form of the TWI calculation discussed later in this section. For example, Sørensen et al. (2006), Grabs et al. (2009), Kopecký and Čížková (2010), Pei et al. (2010), Nguyen and Wilson (2010), Ruhoff et al. (2011), Lewis and Holden (2012) tested different flow path determination algorithms to realise the effect of a chosen method on the resultant TWI model. The base form of the TWI formula is shown in Equation 7.1.

$$w = \ln\left(\frac{\alpha}{\tan\beta}\right)$$

**Equation 7.1: Original form of the TWI formula (Beven and Kirkby, 1979)**

In Equation 7.1,  $w$  is the TWI index,  $\alpha$  is equal to the upslope catchment area divided by the contour length along with the flow pathway, and  $\tan\beta$  shows the steepest down slope direction.

In terms of a specific catchment, TWI describes the effect of gravitational forces on water movement and water accumulating status at a particular location. The base form is known as the steady-state TWI, which has several limitations. Soil transmissibility in the soil profile saturation condition is an influencing parameter, but it is not included in the original form of

the TWI (Equation 7.1); therefore, the equation was changed to Equation 7.2 in order to include the effect of soil profile saturation transmissivity (T) (Wilson and Gallant, 2000):

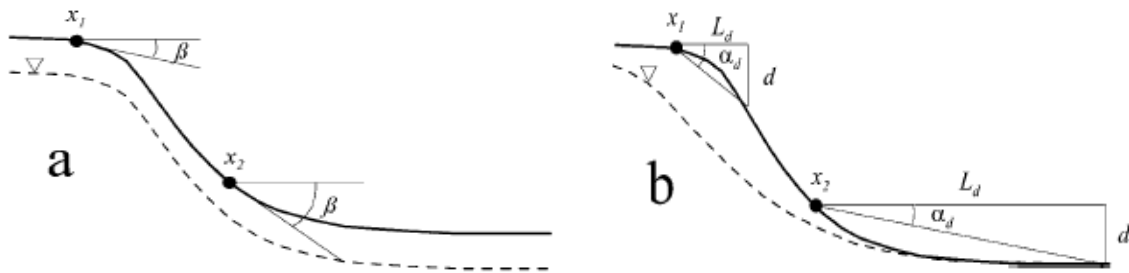
$$w_r = \ln\left(\frac{\alpha}{T \tan\beta}\right)$$

**Equation 7.2: The TWI formula including soil transmissivity**

Modification of the flow routing algorithm influenced the calculation of the TWI (Yong et al., 2012). Recent advances in the flow routing model based on the DEM have not changed the original form of the TWI; modifications are mostly related to the slope calculations, specific catchment area (SCA) calculations, and stream cells determination. However, most proposals of modifying the TWI have been evaluated theoretically while comparison studies with spatially distributed field measurements are relatively few (Sørensen et al., 2006).

Hjerdt et al (2004) claimed that the calculation of slope in the local form of  $\tan\beta$  might not be a good representation of local drainage impedance which controls the hydraulic gradient in some terrains. Therefore, they suggested modifying the TWI to include the distance which influences drainage power degradation due to the loss of potential energy. However, distance impedance is also affected by soil permeability; cell size in DEM, and land relief. The landscape can have a concave or convex slope profile. In the concave slope profile, a gentle gradient and consequently a higher value for the TWI is expected (Hjerdt et al., 2004). The new slope term suggested by Hjerdt et al. (2004) significantly alters the conventional calculated slope for a long distance (Figure 7.1).





**Figure 7.1: a) The local gradient in the base form of the TWI, b) the new slope term suggested by (Hjerdt et al., 2004)**

The dotted lines show the underground water table gradient which is constant in the original TWI (a) but variable in Hjerdt et al.'s modified TWI method (b).

The modified suggested form of TWI is seen in Equation 7.3:

$$w = \ln\left(\frac{\alpha}{\tan_{\alpha_d}}\right)$$

**Equation 7.3: Modified TWI - calculation of slope (Hjerdt et al., 2004)**

Here  $w$  is the topographic wetness index,  $\alpha$  shows the SCA, and  $\tan_{\alpha_d}$  is equal to the down slope gradient, including distance. As Hjerdt et al. (2004) claimed, the new method using the down slope index instead of the local gradient  $\tan\beta$  is less sensitive to DEM resolution and inherent DEM errors than the conventional slope calculation; consequently, the enhanced TWI model can be used for any scale and resolution. Hjerdt et al. (2004) noted that a relatively large value of  $d$  is expected in a high relief area (i.e., the range in the adjacent grid cells' elevation). Calculation of slope in a low relief area needs to be modified in order to calculate the TWI. The slope gradient in a flat area should be 0.5 times the vertical resolution divided by the horizontal resolution (Wolock and McCabe, 1995). To ameliorate the simple rule associated with the Wolock and McCabe's (1995) method which reduced its robustness, Pan et al. (2004) recommended a tracking flow direction algorithm.

Specific catchment area calculation from a DEM is another part of the original TWI which has been modified. An accumulated catchment upslope area (SCA) refers to the area which is

routed to given point(s). Various developed flow direction assignment algorithms and flow routing methods have been developed in order to improve the accuracy of accumulated catchment area estimation. They are the mass flux model (MFM), multi triangular flow direction model (MTFD), multi flow direction (MFD) method, deterministic-infinity ( $D^\infty$ ) method, classical deterministic (D8) method, the DEMON method, and the Rho8 method. These methods were discussed in Section 6.2.2. The MFD method developed by Quinn et al (1991) has been the preferred method for calculation of an accumulated upslope area as part of TWI (Qin 2009; Yong et al 2012). Using the MFD method, the original form of the TWI formula changes to Equation 7.4 as follows:

$$w = \ln\left(\frac{\alpha}{\tan\beta}\right)$$

$$\tan\beta = \frac{\sum_{j=1}^n (\tan\beta_j L_j)}{\sum_{j=1}^n L_j}$$

**Equation 7.4: The TWI equation using the MFD method**

Here  $w$  is the wetness index,  $\alpha$  is the SCA,  $\beta$  is the slope gradient, and  $L$  is the effective contour length between a given cell and the  $j^{th}$  downslope neighbour. The basis of the MFD method is the partitioning of a flow into two or more downstream cells based on a slope-derived weight for each pathway toward the downstream cells. However, the MFD method proposed by Quinn et al. (1991) needs to be refined in order to include the maximum slope in flow partitioning. The original model suggested by Quinn et al. (1991) for calculating the fraction of the flow into downstream neighbours and the new algorithm suggested by Qin(2011) for calculating the fraction of flow which drains downstream based on the maximum downslope value are shown in Equation 7.5 and Equation 7.6, respectively.

$$d_i = \frac{(\tan\beta_i)^p \times L_i}{\sum_{j=1}^8 (\tan\beta_j)^p \times L_j}$$

**Equation 7.5: Original equation for partitioning flows based on a constant (Quinn et al., 1991)**

$$d_i = \frac{(\tan\beta_i)^{f_e} \times L_i}{\sum_{j=1}^8 (\tan\beta_j)^{f_e} \times L_j}$$

**Equation 7.6: The partitioning flow based on the steepest slope as suggested by Qin et al. (2011)**

The difference between Equation 7.5 and Equation 7.6 lies in the way they estimate the water flow fractioning based on the slope between a given cell and the neighbouring downslope cells. In the method proposed by Quinn et al. (1991),  $P$  as a fixed constant power is applied to partition the water flow downstream, while in Equation 7.6,  $f(e)$  is the new equation (Equation 7.7) to estimate a value which equals ' $P$ ', as suggested by Qin et al. (2011).  $B$  is the maximum down slope gradient.

$$f_e = 8.9 \times \min(e, 1) + 1.1$$

**Equation 7.7: The partitioning of a flow based on the method suggested by Qin et al. (2011)**

In Equation 7.6, the original flow partitioning equation in the MFD model (Equation 7.5) has been revised to include the maximum slope gradient using the flexible exponent,  $f_e$ , instead of the calculation of the slope gradient by the fixed exponent,  $P$ . The minimum between  $e$  and 1 is  $\min(e, 1)$ .  $e$  shows the maximum down slope gradient

The TWI value of the downstream neighbour cell influences the TWI estimation for upslope areas, particularly in a flat area. Therefore, Böhner and Selige (2006) suggested a method to modify the SCA calculation for a flat landform which is a function of the slope angle  $\beta$  (arcs) and the neighbouring maximum value. They claimed that values should be yielded by an iterative procedure instead of assuming a homogenous hydrologic condition. Böhner and Selige (2006) developed a new equation in which the maximum value of a SCA is based on a divergent flow routing model determination using the method suggested by Freeman (1991).

Equation 7.8 shows the iterative calculation of a modified SCA, particularly applicable in a flat area.

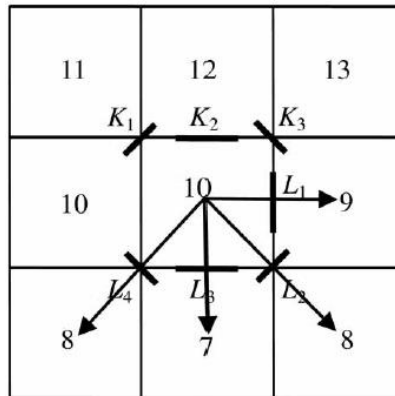
$$SCA_M = SCA_{max} \frac{1}{15} \beta \exp(15\beta) \quad \text{For} \quad SCA < SCA_{max} \frac{1}{15} \beta \exp(15\beta)$$

$$WI_s = \ln\left(\frac{SCA_M}{\tan\beta}\right)$$

**Equation 7.8: The formula for the iterative TWI calculation (Böhner and Selige, 2006)**

$WI_s$  is the SAGA wetness index,  $SCA_M$  is the SCA for a given cell, and  $SCA_{max}$  is the neighbouring maximum value around the given cell.  $\beta$  is the slope angle (arc).

The contour length is required in flow partitioning and also needs to be refined in order to represent an effective contour length, as Yong (2012) has suggested. He modified the base form TWI calculation using his novel multiple flow direction (NMFD) method. Figure 7.2 describes the concept of modification in upstream cell area calculation suggested in the NMFD method.



**Figure 7.2: The direction of in-flow and out-flow in a given cell (Yong et al., 2012)**

Equation 7.9 shows the implementation of the NMFD method refinement in order to include the given cell area for a downslope area.

$$\ln\left(\frac{A}{\sum_{j=1}^n (\tan\beta_j L_j)}\right) + \ln\left(\frac{\sum_{j=1}^n L_j}{\sum_{i=1}^m K_i}\right)$$

**Equation 7.9: The equation of the NFMD method (Yong et al., 2012)**

As discussed in Section 6.2.3, stream cell initiation is a required step to separate a flow accumulation model into two stream and non-stream cells. Stream cell definition was not

included in the original form of TWI; therefore, a threshold parameter can help to classify the flow accumulation into two classes, stream cells and non-stream cells. According to the relation to the whole area, the threshold can be defined by one percent of the upslope catchment area (Djokic and Maidment, 1991, Maidment, 2002). However, this value can be changed based on user local experience and for different landforms.

Despite all the modifications described above, modified TWIs use traditional TWI components: the upslope catchment area and slope, which are sensitive to grid resolution, flow routing algorithm, inherent DEM errors, and variability of soil parameters. In addition to using modified TWI, some studies have taken another approach and added components such as hydrodynamic elements in order to improve TWI estimation. For example, Barling et al. (1994) proposed a quasi-dynamic TWI (QD-TWI) including saturated hydraulic conductivity, effective porosity, and the last precipitation event to overcome the lacks in the static conceptual TWI method proposed by Beven and Kirkby (1979). Furthermore, Nguyen and Wilson (2010) have noted that the base form TWI is not applicable in semi-arid and arid landscapes. The study conducted by Nguyen and Wilson (2010) showed that QD-TWI is still sensitive to elevation errors, like the original TWI.

Grabs et al. (2009) compared the original form of TWI and the catchment model-based TWI which has been called the model-based wetness index (MWI). He concluded that using the model based index can improve the accuracy of consequent results. Grabs et al. (2009) suggested that the dynamic-TWI model (model-based TWI) should be used with the fine resolution digital topography model. TWI models for either a steady or dynamic state remain dependent on the DEM resolution (Sørensen and Seibert, 2007), but TWI results for SCA are more sensitive to changes in DEM resolution (information content) than slope (Sørensen and Seibert, 2007).

Manfreda et al. (2011) developed a modified topographic wetness index which includes hydrodynamic model's components and compare it with the flood extent modelled with a

hydrodynamic simulation. They set  $n$  and its dependent threshold  $\tau$  to divide the TWI values for flooded and non-flooded areas. The modified TWI developed by Manfreda et al. (2011) is shown in Equation 7.10.

$$TWI_m = \log \left[ \frac{a_d^n}{\tan(\beta)} \right]$$

**Equation 7.10: The Modified Topographic Index developed by Manfreda et al. (2011)**

$TWI_m$  is the topographic wetness index. The value of 'n' and consequent threshold ' $\tau$ ' can be estimated using Equation 7.11 and Equation 7.12, respectively. The value of  $\tan(\beta)$  is based on the modification proposed by Hjerdt et al. (2004) described earlier in Figure 7.1b.

$$n = 0.016 \times x^{0.46}$$

**Equation 7.11: The formula to estimate a  $n$  value (Manfreda et al., 2011)**

$x$  is the distance base parameter, therefore,  $n$  is the dependent to the distance. The threshold for dividing a modified TWI into flooded and non-flooded is estimated from the  $n$  value.

$$\tau = 10.89n + 2.282$$

**Equation 7.12: Suggested formula to estimate the value of the threshold (Manfreda et al., 2011)**

Although the method developed by Manfreda et al. (2011) has improved the use of the TWI in flood inundation area delineation, the  $n$  value and consequently  $\tau$  threshold need to be customised based on local conditions in different geographical locations (Manfreda and Sole, 2013). Furthermore, the method was developed based on rural catchments and does not include artificial anthropogenic manipulation like engineering structures which change flood simulation and modelling behaviour.

### 7.3 Overland flash flood prone areas in the sample site

In the remainder of this chapter, I delineate the methodology used to implement the TWI, and compare various TWI with each other and real situations in the sample site.

### **7.3.1 Analysis methodology**

Flash flooding due to a minor drainage system failure or inappropriate planning layout for a major drainage system (roads) is an important issue in a built-up area, particularly for an old area for which the minor drainage system was designed for a shorter return period.

Flash flooding in township areas varies street by street (Gironás et al., 2010). Therefore, land use planners and drainage engineers often encounter an information gap where the flood studies have not been conducted. To overcome this gap, council engineers and planners rely on local knowledge. However, sometimes the matter is far too complicated to be solved by only local knowledge, particularly in built-up areas.

#### **7.3.1.1 TWI for the sample site**

An alternative solution is to use GIS-embedded hydrological model, TWI, which represents valuable information about wet areas. Wet areas are land to which water flows because of gravitational force. Wet areas are threatened by a high risk of overland flash flooding due to a failing drainage system or inappropriate major drainage system layout in urban planning.

A TWI parameter definition and its modifications were described in section 7.2. Some modifications affect slope calculation and others improve the SCA estimation. The SCA is the result of dividing the catchment area by the contour length along the flow pathway.

#### **7.3.1.2 TWI requirements**

Like any other GIS-embedded hydrological model, TWI accuracy is dependent on the accuracy of surface topography. A high-resolution LiDAR-derived DEM enables implementation of a GIS-embedded hydrological model for an urban catchment. Therefore, a DEM suitable for hydrological application, a Hydro-DEM, is needed to develop an appropriate TWI and delineate a flood-prone (wet) area. Section 6.3.2.1 outlined the procedure for developing a Hydro-DEM for this study. The methodology comprises DEM derivatives such as slope and SCA development in order to extract a wetness model.

Different methods for flow direction assignment models were used to estimate the SCA as a part of TWI calculation.  $R^2$  was used to measure the similarity between the resultant TWI models. Resultant TWI models were checked using existing water bodies, including a wetland area, field observation of flood events on 22/06/2012 and citizens' complaints recorded in the Bass Coast Shire Council's customer request service (CRS) database. CRS is important for checking the accuracy of the resultant maps because there are no measuring stations to record water flow parameters in built-up areas. Therefore, using field observations and considering the historical records of citizens' complaints (the crowd source database), including photos, their descriptions, and the flood event date and time allows validation of the accuracy of the conceptual hydrological process and the hydrodynamic modelling results..

#### **7.3.1.3 To classify TWI**

As the TWI model is represented in the continuous raster data model, there is no certain that separates flash-flood-prone areas from other areas. The solution is to use the TWI suggested by Manfreda et al. (2011), but this was not possible for the sample site. The barrier was the need to customise the  $n$  and  $r$  values (section 7.2) based on appropriate length of historical records from a hydrological gauging station, and these records are not available for areas other than major river channels in the sample site.

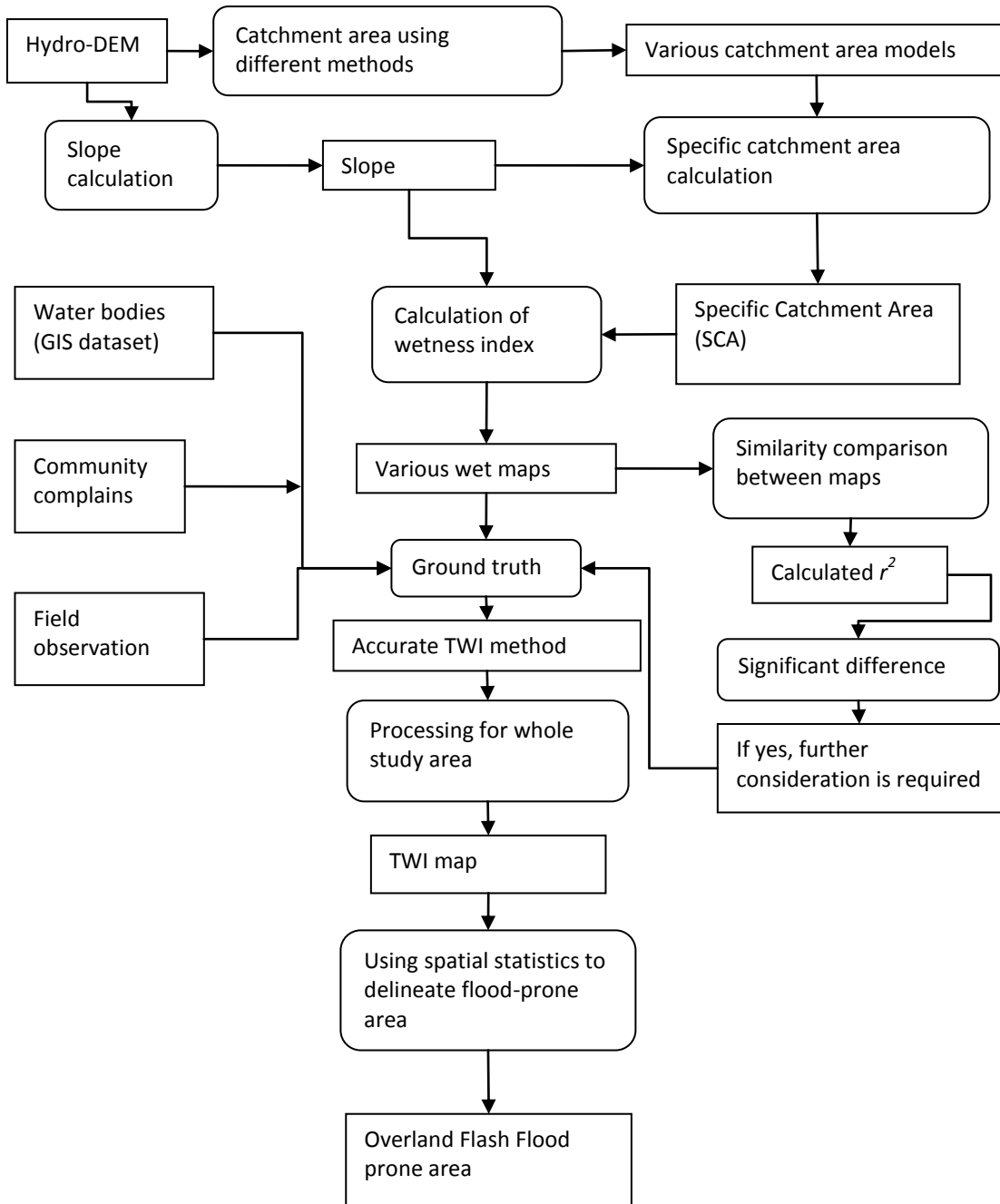
To classify the TWI into flood-prone areas and non-flood-prone areas during an overland flash- flooding event, a cluster and outlier analysis based on Anselin Local Moran's I statistic of spatial association (Mitchell, 2005, Anselin, 1995) was performed. If the association I is positive, it shows that the feature is surrounded by similarly high or low thematic values. A negative value for the association shows that the given feature (a point represents a cell in this study) is surrounded by dissimilar neighbours and is an outlier. Positive associations is represented in the high-high (HH) or low-low (LL) classes.

Features in the HH class indicate the area where water will concentrate during an overland flash-flood event. The HL and LH classes show the outliers, which are not important for this



study. The LL class shows the areas which would not encounter an overland flash-flood problem if the upslope condition does not change. The result is a classified map showing the spatial distribution of flood-prone areas (high value in TWI surrounded by neighbour cells with high value) with a level of statistical confidence.

Figure 7.3 contains the TWI methodology flow chart.



**Figure 7.3: Data Flow Diagram (DFD) used in this study for identifying probable flood-prone areas in the township**

### 7.3.2 Results of analysis and discussion

Various TWI were created for this study using different flow direction assignment methods and can be seen in Figure 7.4 up to Figure 7.9. The map scale is 1:30000 for the maps and the legend shows the unit-less TWI value based on the determined flow direction assignment

algorithm. All maps use the Map Grid of Australia (MGA). The numbers around maps are X and Y coordinates which are based on MGA zone 55(MGA55) for the sample site.

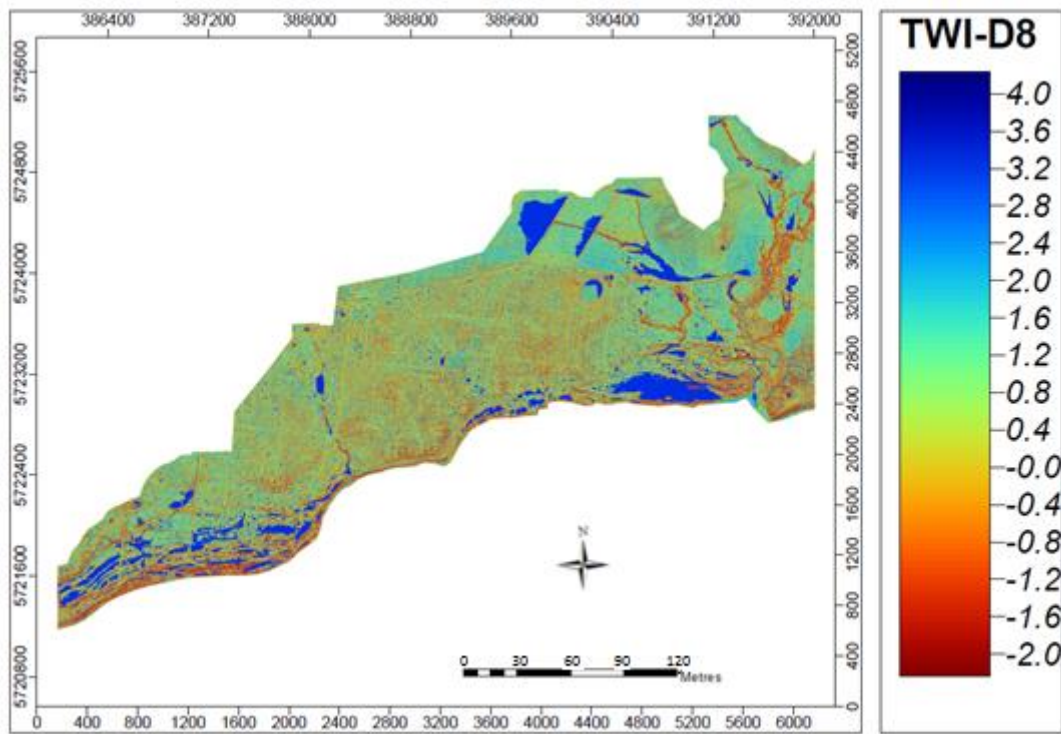


Figure 7.4: The TWI result from a classic D8 flow direction assignment method

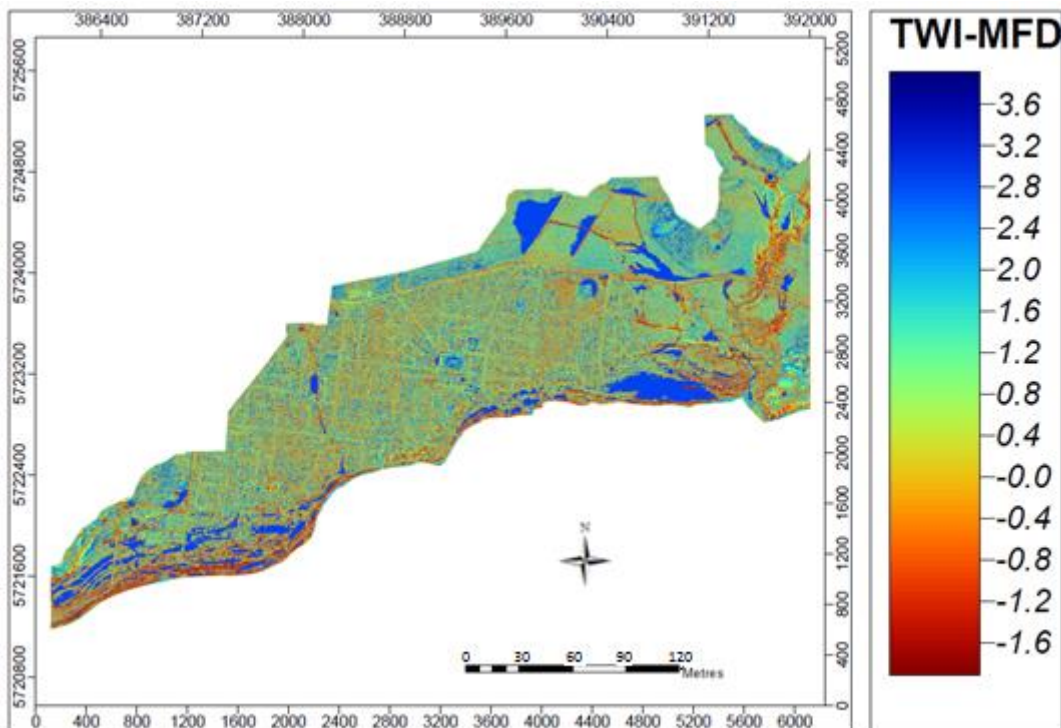


Figure 7.5: The TWI result from MFD flow routing algorithms

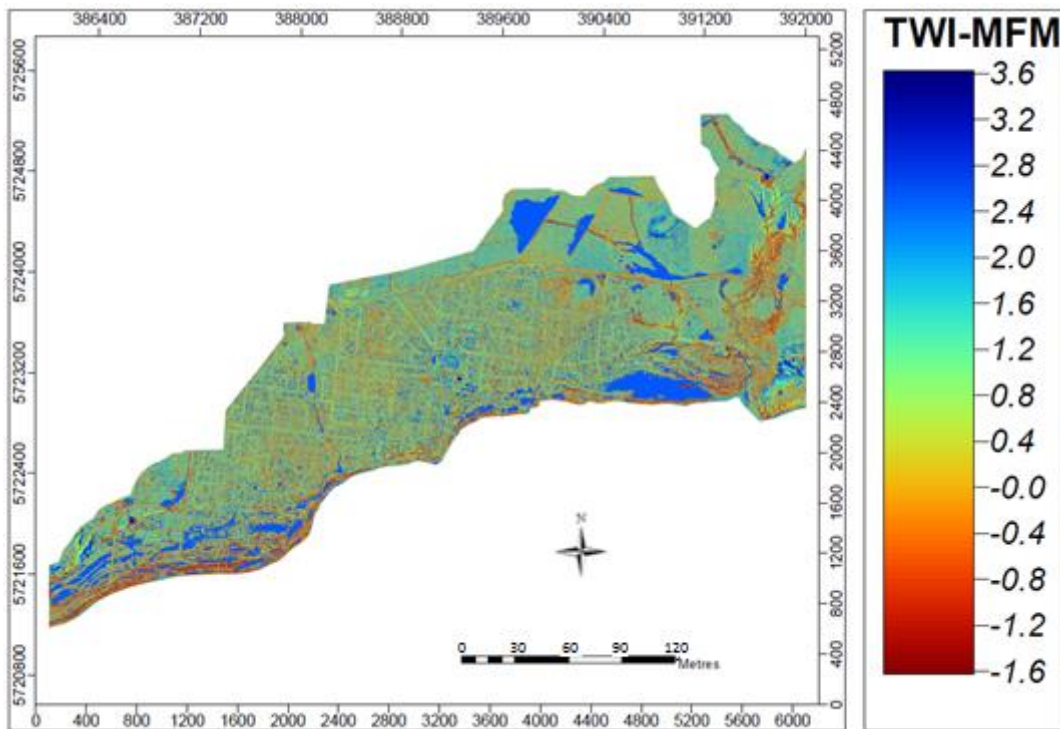


Figure 7.6: The TWI result from MFM flow routing algorithms

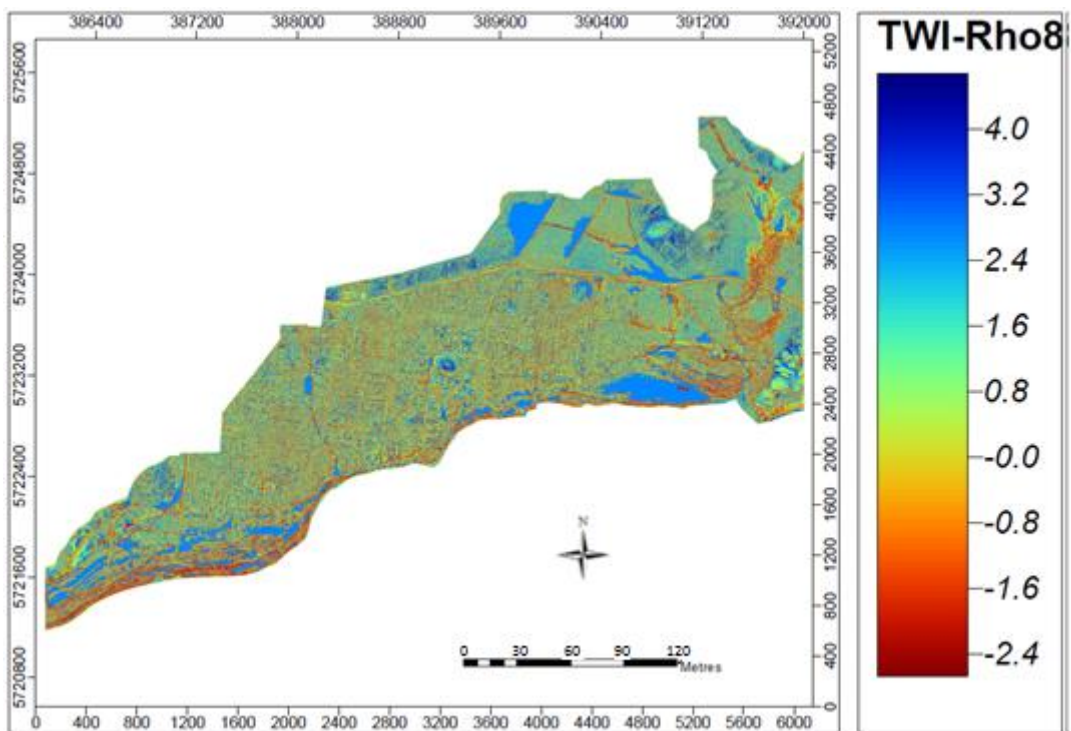


Figure 7.7: The TWI result from Rho8 flow routing algorithms

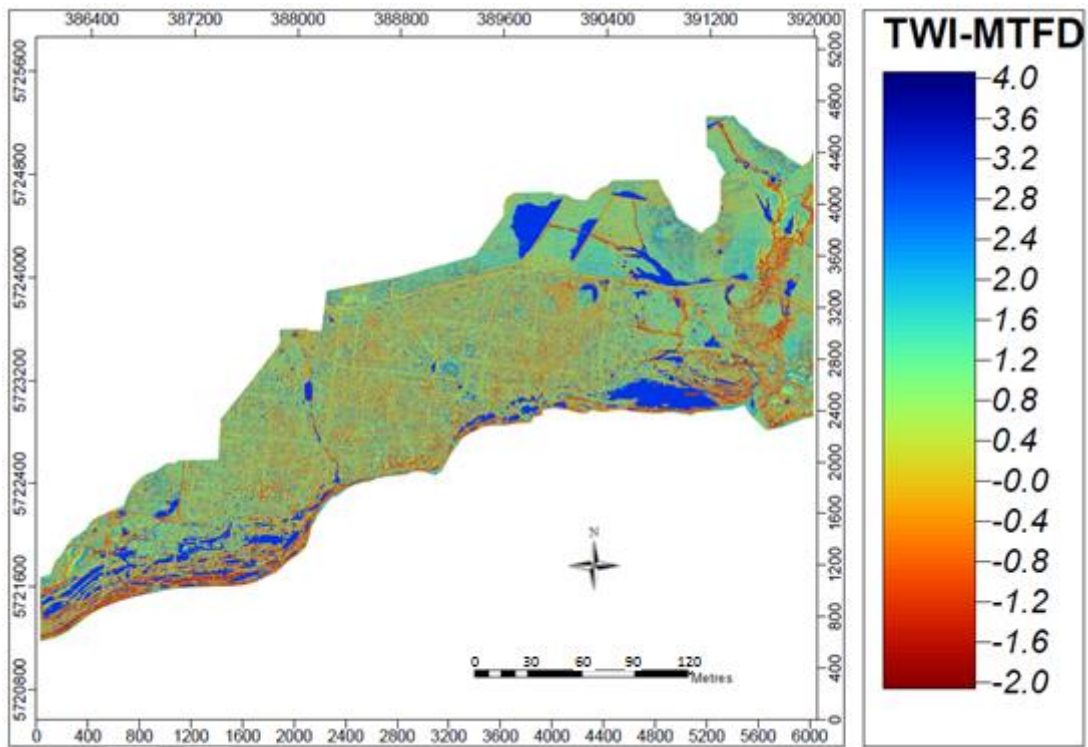


Figure 7.8: The TWI result from MTFD flow routing algorithms

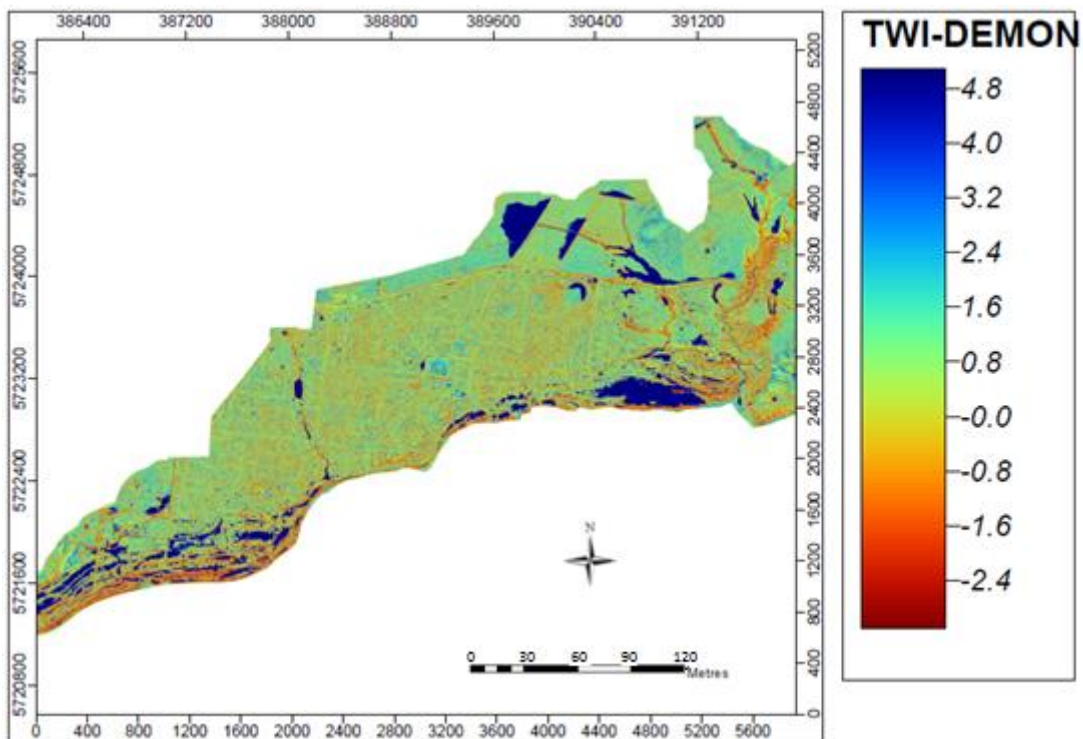
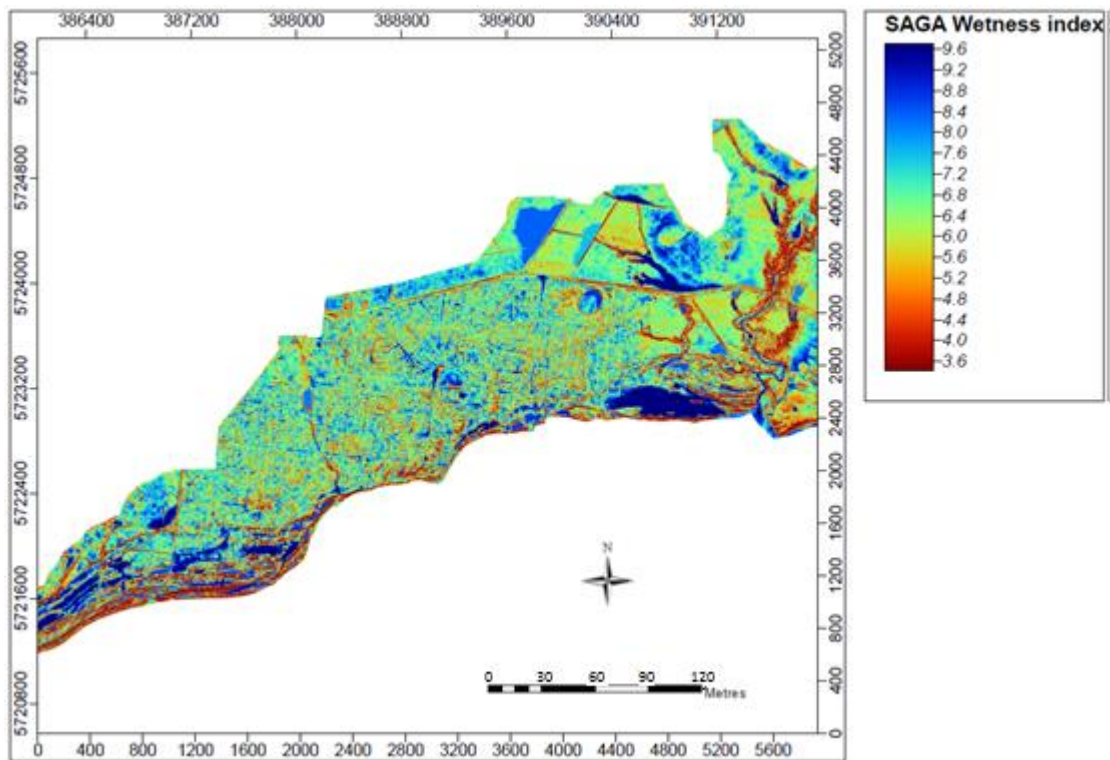


Figure 7.9: The TWI result from DEMON flow routing algorithms



Figure 7.10 shows the iterative wetness index proposed by Böhner and Selige (2006), for which the effect of downstream cells' value has been incorporated to optimise the final result.



**Figure 7.10: The TWI result from an iterative process and optimisation**

As a visual comparison cannot show small differences between different outcomes of various flow routing models,  $r^2$  was used to compare each pair of TWI models. Table 7.1 shows the relationships between resultant TWI from different flow direction assignment methods using  $r^2$  percentages. Flow direction assignment methods were described in section 6.2.2.1.

**Table 7.1: Relationship strength between different TWIs ( $r^2\%$ )**

TWI	_D8	_MFD	_MFM	_MTFD	_DEMON	-Rho8	-ITERATIVE
_D8	100	-	-	-	-	-	-
_MFD	79	100	-	-	-	-	-
_MFM	78	83	100	-	-	-	-
_MTFD	89	91	82	100	-	-	-
_DEMON	72	77	69	77	100	-	-
_Rho8	57	72	62	66	65	100	-
_ITERATIVE	38	44	38	41	49	40	100

As discussed in section 6.3.2.2, different flow direction assignment methods do not show significant differences in resultant overland flow path for the sample site. However, the flow direction assignment methods produce very different TWI results. The major difference occurs between the TWI resulted from non-iterative process (non-iterative TWI) and TWI from the iterative processing (iterative TWI). As Table 7.1 shows, the weak relationships,  $r^2$  less than 50%, are between non-iterative TWI and iterative TWI. It is assumed that the weak relationships due to including the influence of the downstream wetness condition on upstream wetness estimation in iterative TWI estimation.

Table 7.1 shows that the greatest similarity exists between the TWI derived from the MFD and MTFD. TWI extracted from the Rho8 flow direction assignment method is the least similarity to the other non-iterative TWIs. The reason may be because the Rho8 includes aspect to assignment of flow direction, which is more sensitive than the slope based methods to the errors in surface topography dataset described in section 5.6. Although the

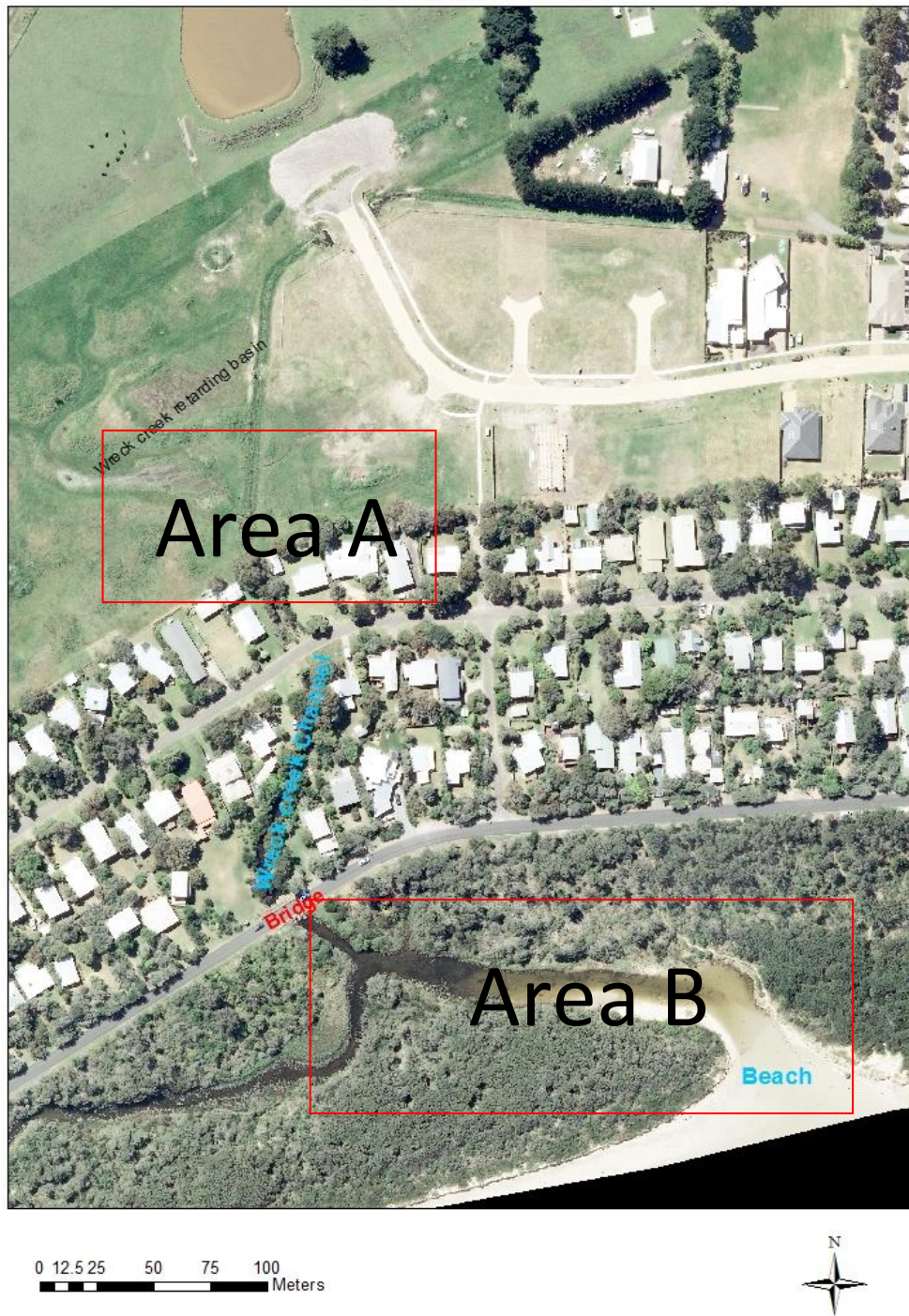
abovementioned comparison shows the similarity of the models, it is not possible to answer the question “Which TWI model represents reality best?” As TWIs are differently derived, the best one can only be chosen after comparison with reality.

### **7.3.3 Choosing the best TWI model for the sample site**

In order to select one TWI model as the most accurate, the area searched to find a highlighted hydrological feature. Site visits and local knowledge showed that the elevation of Wreck Creek’s downstream channel (Area B in Figure 7.11 ) is being equal or higher than the elevation of Wreck Creek retarding basin. The Wreck Creek’s channel adjacent to Wreck Creek retarding basin and the development areas close to the retarding basin (Area A in Figure 7.11) are expected to receive flow from the coast side (Area B in Figure 7.11). Thus, the TWI value in the Wreck Creek channel and development site close to the retarding basin is expected to be higher than the outlet at the coast-line. Thus, the TWI model which includes downstream channel effect into producing the TWI model is the model that can show the reality better than the other TWI models discussed in section 7.3.2.

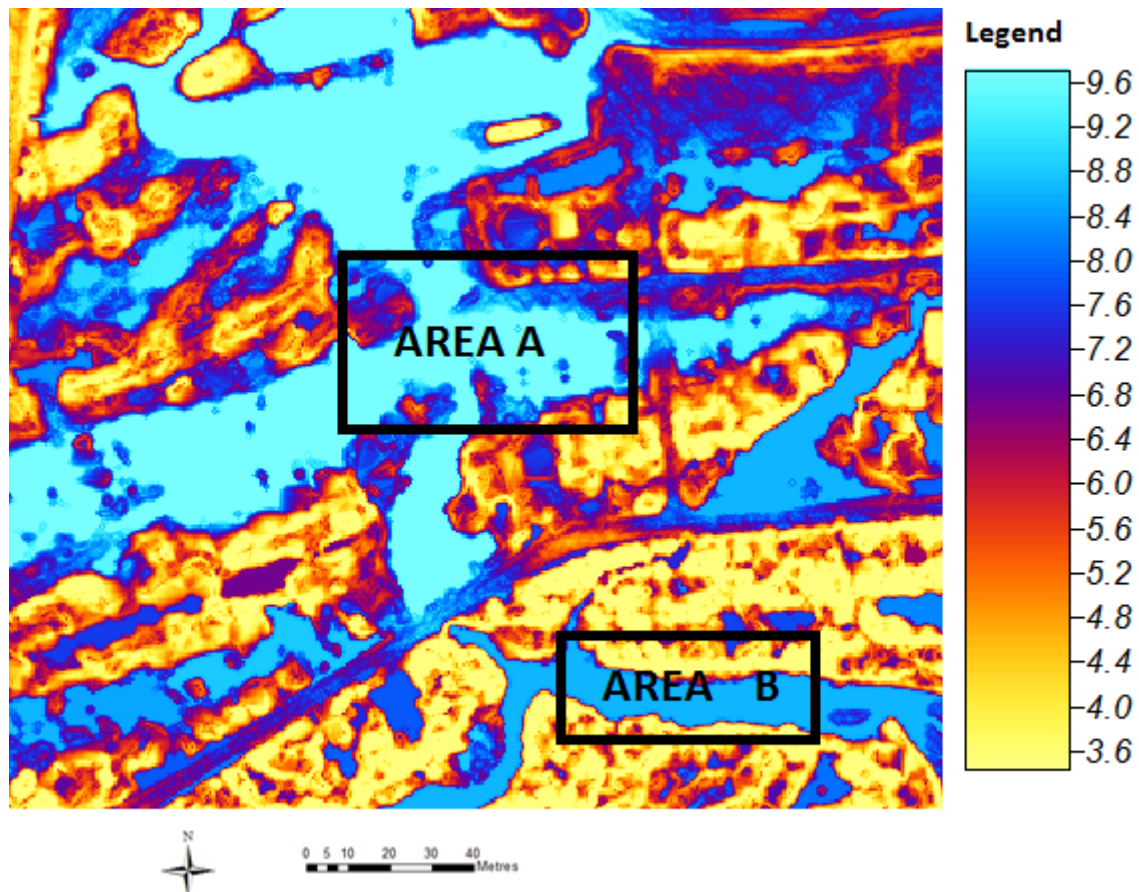


## Wreck creek area



**Figure 7.11: The Wreck Creek area in Inverloch (2009). Area B is equal or slightly higher than Area A**

Considering all extracted TWI models only the iterative TWI model (Figure 7.12) reflects the local reality based on the local wetness condition.



**Figure 7.12: Iterative TWI result matched with the local condition in the Wreck Creek area. Light blue shows the highest value of the wetness**

The other TWI models assigned the same value of the TWI to areas A and B, whereas the natural flow direction is from the coastline into the channel and then into the Wreck Creek retarding basin. Therefore, the iterative TWI proved its advantage over the other methods.

#### **7.3.4 Classification of TWI model**

The iterative TWI model is continuous raster dataset. The question is, how can classify such a continuous model be used to generate a classified map of flash-flood-prone and non-flood-prone areas? In section 7.2 it was mentioned that Manfreda et al. (2011) suggested an equation to determine the value of the threshold to identify flood-prone areas. Although this approach can accurately determine the flood extent, these need to be tested and customised for new test sites (Manfreda and Sole, 2013). Furthermore, arbitrary thresholds produce different results of flood-prone areas. The Manfreda's method needs gauging station records,

which are not available for built-up areas in the sample site, and the arbitrary thresholds create various results.

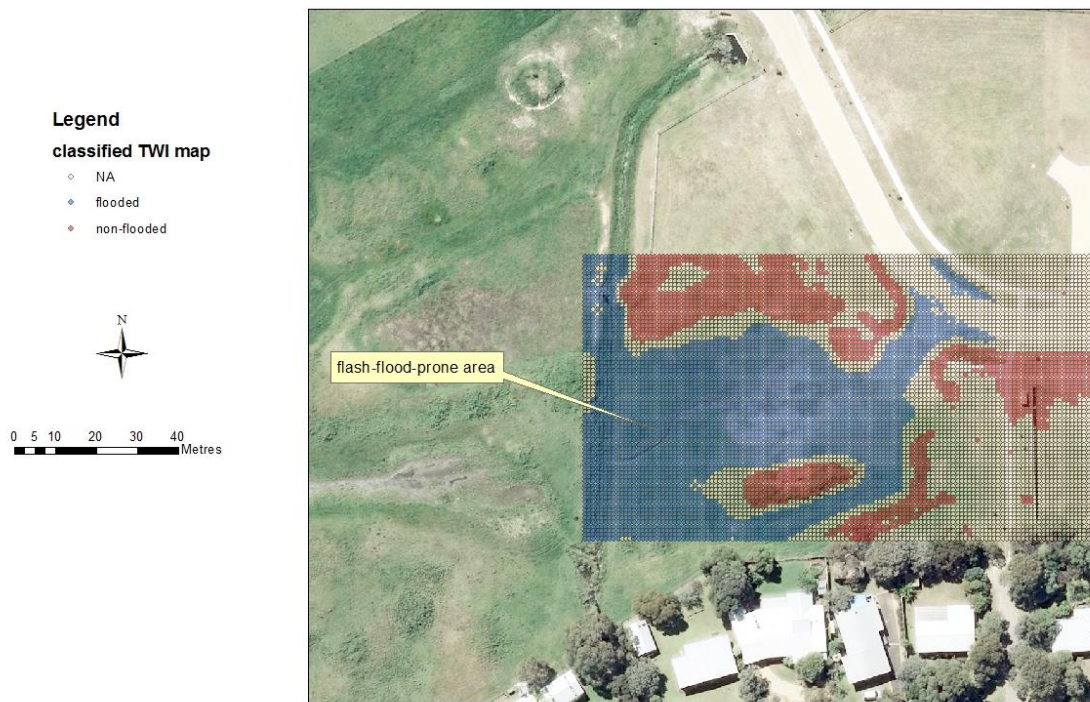
As discussed in the methodology section, in the present study I used a spatial statistic as described by Anselin (1995) to classify TWI model to flash-flood-prone and non-flash-flood-prone areas

The TWI model developed using iterative TWI method, then the raster TWI model was converted to a point dataset. Each point represents a cell in the TWI model. Using the Cluster and Outlier analysis (Mitchell, 2005), each point was analysed and assigned to an HH, HL, LH, or LL class. The class with HH label shows that the point is located in a real depression or wet or overland flash flood prone area; the other classes were not important in this instance. In addition, the model assigns confidence level to each point.

Using this approach, the TWI model was classified into the flood-prone area (the area is formed by points with an HH label) and non-flood-prone areas is shown in Figure 7.13.

The blue point symbol determined as flooded area in the legend of Figure 7.13 and determines flash-flood-prone areas.





**Figure 7.13. Results of spatial statistical “Cluster and Outlier analysis”**

The cluster and outlier analysis used to classify a cell into flood prone area not only focus on the wetness value of given cell but also the analysis procedure in this analysis includes the neighbour cell values.

### **7.3.5 TWI model validation for the sample site**

Field observations were taken over a flash-flooding period in the sample site on 22/06/2012 to evaluate the classified TWI model. In the rest of this chapter, I describe the site validation activities.

#### **7.3.5.1 Flood prone site1: The Wreck Creek fringe area**

Wreck Creek is located in the south-west part of the sample site, Inverloch Township. Permission was recently granted for its development as a new residential estate. The area can still be regarded as an urban fringe area; Figure 7.11 shows its land cover in 2009, and Figure 7.14 shows the same area in 2012.

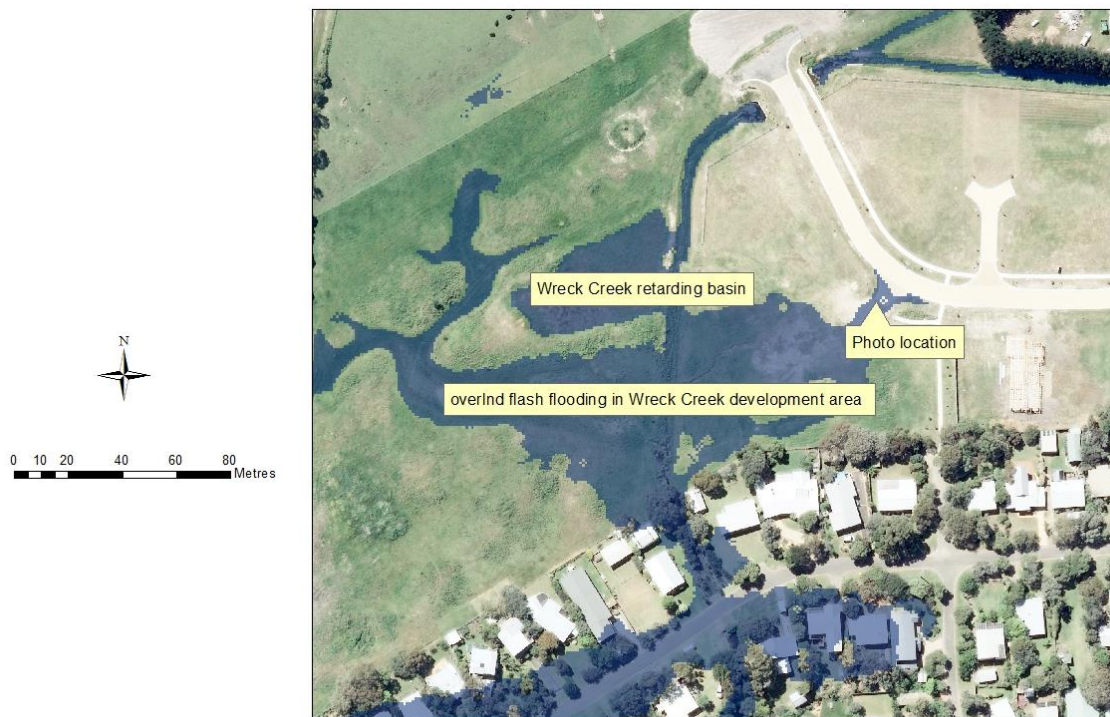


**Figure 7.14: Wreck creek area. Aerial Photo captured 2012 (source: Bass Coast Shire Council). Ellipse shows the area for the newly constructed houses and sealed roads**

As can be seen in Figure 7.14, much of the location has been changed into an impervious area by an increasing number of houses and sealed roads. Although this area is below sea level and



will be exposed to sea level rise and extreme flood events due to climate change, council decision- makers believe that the area is not encountered with flooding issue because the retarding basin can reduce the severity of flood issues. However, TWI model (Figure 7.15) and field observation of the flood event on 22/06/2012 showed that overland flow draining to the channel threatens the area.



**Figure 7.15: The result of TWI model in site1 (Aerial photo captured 2009 was accessible from Bass Coast Shire Council)**

Figure 7.15 shows TWI modelling result. The outcome can be classified using the spatial statistical approach described in section 7.3.4. The blue area shows the flood threatened areas in flood-prone site 1. Photo location label in Figure 7.15 refers to Figure 7.16 and shows a photo of the area was taken on 22/06/2012.



**Figure 7.16: Overland flash flood in the new estate development at Wreck Creek**

Figure 7.16 shows that the TWI model shows precisely the flash flood threatened areas in flood-prone site 1, Wreck Creek area adjacent to Inverloch Township. The area is threatened by overland flash flood even though the retarding basin (Figure 7.17) is working appropriately to capture stormwater runoff.



**Figure 7.17: The Wreck Creek retarding basin**

This site provided good evidence for validation of the TWI outputs ability to delineate the overland flash-flood-prone in fringe area.

#### **7.3.5.2 Flood prone site2: Veronica street flash flooding (citizen's complaint)**

The series flash-flood occurrences of Veronica Street in Inverloch Township resulted in numerous complaints from citizens. The flood in this area resulted from a failure of a minor drainage system to collect storm runoff and some changes in the upstream catchment, notably an increase in the capacity of minor drainage system inlets without any substantial flash-flood modelling. Although the flood event did not occupy a large area, storm runoff flowed onto the property located on the downslope. Residents claimed that the area had not experienced a flood before the installation of the relatively large pit inlets on the upslope (as can be seen in Figure 7.18). The flood issue in this area relates to a failure of a minor drainage system. The council's drainage engineers designed to deviate flood water onto natural overland flow path



at the bottom of Veronica street instead flows down onto the residential property. The solution was designed at site-specific level while water movement analysis at catchment scale is also important. Figure 7.19, which covers the similar area as Figure 7.18, shows clearly that the flooded area is the place where water flows and sits based on gravitational force and the surface topography of the area. Therefore, manipulation upstream, like installing new inlets or upslope land use changes, directly influences the flooded area, as shown in Figure 7.19.



Figure 7.18: Aerial photo (2012) of Veronica Street (source: Bass Coast Shire Council)



**Figure 7.19: The TWI model shows the flood exposed area in site 2**

Figure 7.19 shows that the TWI properly identifies the flash-flood-prone location in this built-up area. For the flash flood issue in Veronica Street, the model matches the information gained from the complaints of the citizens who were affected by the flash flood. They noted that after the increasing of the upslope pit inlets' capacity by the council, the problem had become more severe.

### **7.3.5.3 Flood prone site3: Flash flooding in front of Esplanade Hotel, Inverloch**

The other flooded area which induced citizens' complaints was located at the intersection of A'Beckett Street and Williams Street in the Inverloch built-up area. Flooding often occurs in front of the Esplanade Hotel because of a minor system failure in capturing stormwater runoff due to the manipulation of a drainage system through hide-a-pit inlets. Although council'

drainage engineers believe that the flood problem relates to the failure of a minor drainage system, the TWI model (Figure 7.20) and the history of flash flood problem (Figure 7.21) show that the site is a flash-flood-prone area due to the concentration of surface water flow.

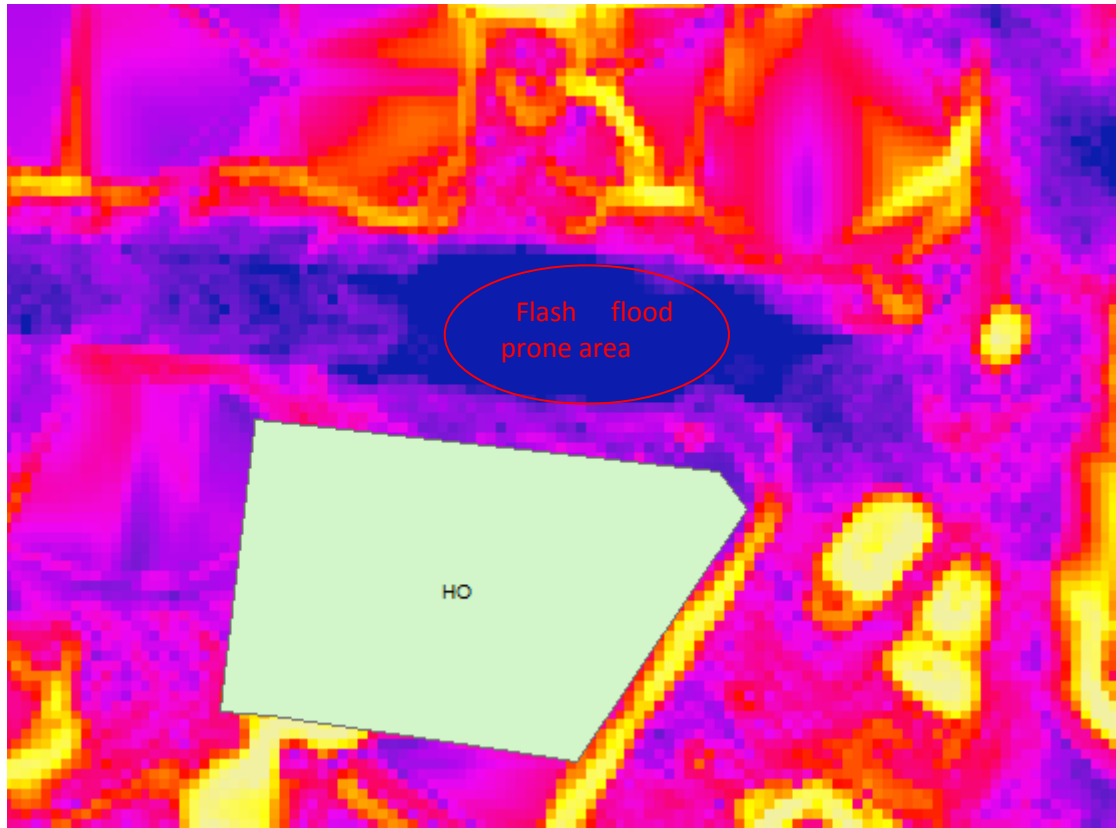


Figure 7.20: The TWI model for flood prone site 3 (HO= hotel)



**Figure 7.21: Photo captured on the 3rd of December 2010, around 7pm (Source: Bass Coast Shire Council)**

Figure 7.20 shows the result of the TWI analysis in highlighting the probable flash flooding area. These areas are flood hot spots and any upslope changes accelerate flash flooding problem in those areas.

### **7.3.6 Conclusion**

The built-up areas of Inverloch which have been developed beyond the determined flood-plain need to be reconsidered in relation to the flooding which might result from the failure of the minor stormwater system due to recent land use changes or minor system extensions in upstream. Planning deliberations often use hydrodynamic models to model flood behaviour in a particular area. Although these models use enhanced hydrological and hydraulic models, the usage of such modelling is limited due to its high cost, unavailability of the required information, limited user skill and experience, and the need for special software and a customised developed hydrological model.

In this chapter, I described an alternative method of delineating flash-flood-prone areas using a TWI model. The TWI model resulted in valuable outcomes, both as an indicator for a further detailed study and use in decision-making for land use planning.

To identify the most appropriate model, the TWI was extracted using different flow routing algorithms. Most of the models were similar, except for the iterative TWI, which included the effect of an adjacent downslope cell wetness condition on upstream cell wetness value.

An iterative TWI developed by Böhner and Selige (2006) was used in order to map the distribution of flash-flood-prone areas in the sample site within the Bass Coast Shire. The extracted map was validated using field observation and local knowledge. The results showed that the TWI model output accurately represents flash-flood-prone areas in the sample site. As TWI model is in continuous raster data structure, classifying the model into flooded and non-flooded areas was done using the concept of a cluster and outlier analysis.

Finally, the study shows that crowd source information (or VGI) through is valuable data for validating of flash-flood prone areas based on TWI, particularly, for ungauged urban catchments.



# 8 Results and Conclusion

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## 8.1 Introduction

The previous chapters dealt with the development of a method of overland flow path extraction, catchment boundary delineation, and overland flash- flood-prone area mapping for the purpose of flood-risk-based land use planning at the local government level. This chapter commences with presentation of the research findings, and then looks at some directions for future research that have been raised through the course of this thesis.

## 8.2 Research findings

Spatially enabled technology is frequently utilised in real-world process modelling, analysis, simulation and visualisation (Sugumaran and DeGroot, 2011). Such technology is relied upon due to its ability to support forecasting, planning and decision support stages (Sharifi and Zucca, 2009). However, spatial analysis and database often need to be enhanced or extended to meet the requirements of business workflow in specific application. Thus, analysis the business workflow for specific application in responsible agency and develop a spatially enabled approach to support business roles is essential. In this context, this research contributed to the knowledge and understanding of:

- 1-The responsibilities and roles of Victorian local governments in floodplain management
- 2-The existing process of decision-making based upon flood-risk-based land use planning in the Bass Coast Shire
- 3-The required information products and data gaps in the existing GIS database for flood-risk-based land use planning in the Bass Coast Shire Council
- 4-How to deploy a minimum distance approach based on spatial autocorrelation to assess the vertical accuracy of an existing LiDAR ground point dataset.

5-Process of incorporating the influence of an urban stormwater collection system in typical GIS-embedded hydrological models, i.e., Arc Hydro Tools, to improve extraction of overland flow path network in an urbanised catchment

6-Deployment of the network analysis capability of GIS in order to extract watershed boundaries in the presence of a stormwater collection system

7-The use of TWI combined with a spatial statistical analysis, to extract precise details of the overland flash-flood-prone areas in urban and peri-urban regions

### **8.2.1 The responsibilities and roles of Victorian local governments**

Victorian local governments are responsible for conservation of significant natural resources and environmental values, and incorporating flood mapping and controls into local planning schemes, as well as developing and implement local flood management plans and taking the lead in preventing communities from flash flooding. Local governments are responsible for floodplain management under to the *Planning and Environment Act 1987*, the *Local Government Act 1989*, the *Building Act 1993* and *Emergency Management Act 1986* (DSE, 2011).

The role of local governments in floodplain management is focused on land use planning. Through land use planning, local governments assure stakeholders that all the necessary flood risk provisions have been incorporated into statutory planning, and that catchment management goals have been included in the process through considering the changes upstream and the effects downstream. In addition to land use planning, which can consider the cumulative impact on an individual development, local governments are responsible for development and building controls.

Flood damage can be significantly decreased if the proper development and building controls are applied by local governments for designing buildings, designing road networks, building floor levels, and flood proofing.

As the central role of local government in floodplain management is local flood-risk-based land use planning, a high-quality local GIS database encompassing surface topographical datasets is a vital tool.

### **8.2.2 The existing decision-making process**

Flood-risk-based land use planning includes different flood and land use provisions for assessing and approving land development in Victoria. Furthermore, various local policies and strategies exist at the local level in line with state wide policies. In this study, the process to make a decision about land use planning in local government was documented in chapter 4.

### **8.2.3 The required information products and data gap**

A comprehensive GIS database is necessary for flood-risk-based land use planning and it is necessary to consider the process of flood-risk-based land use planning and decision-making in order to establish the required database. Understanding the process enables identification of the necessary spatial dataset and attributes information. Comparing a theoretical comprehensive GIS database and the existing GIS database clarifies the information gaps. As flood-risk management is dependent on a high-quality and well-structured spatial database, considering the spatial and attribute gaps in the database and the database quality is a necessary step. In this study, the datasets required for flood management were extracted using the flood modelling package input requirements, by identifying the current flood management activities of the Bass Coast Shire Council, and by considering the available drainage specification guidelines. The gaps in data were delineated (section 4.9) after surveying the existing datasets in the Bass Coast Shire Council's GIS database and comparing these with the required datasets. Some of these data gaps can be overcome by incorporating alternative data like information received from citizens' complaints (a crowd source dataset). Although it contains valuable information, there is no mechanism for incorporating it into the existing GIS database.



Although manmade structures influence water flow behaviour, natural surface topography is the major determinant of water movement characteristics. Therefore, topography data is the fundamental dataset in a flood-relevant GIS database and specific attention to surface topography data source accuracy is required to maintain a high-quality flood-relevant GIS database.

#### **8.2.4 The vertical accuracy of the existing LiDAR ground points dataset**

The present study used a sequential LiDAR ground points at different levels of minimum distance around each PM. The approach taken in this study enables avoidance of gridding influence on the final assessment. To realise the extent to which gridding would influence the final vertical accuracy assessment, a simple common IDW interpolation technique and geostatistic IDW were used. The influence of the geostatistic IDW and simple common IDW in derived DEMs accuracy were explored. Furthermore, the autocorrelation distance between LiDAR ground points and GCPs has been estimated using an Average Nearest Neighbour (ANN) analysis and proposed methods for this study, sequential minimum distance. The estimated distance to capture the autocorrelation (short-range) was around 0.531m. The difference between the LiDAR points' elevation and the elevation as determined by the PMs in estimated distance was around 0.5m at a 95% confidence level. Therefore, the LiDAR ground point dataset can be used for flood mapping that does not need the vertical accuracy to be better than half a metre. The LiDAR ground point dataset does not contain enough vertical accuracy for drainage design, as vertical accuracy of 10cm is required.

#### **8.2.5 The overland flow path in an urban catchment**

The overland flow path is important thematic information for both planners and drainage engineers. Bass Coast Shire Council's planning directorate uses the overland flow path to assess the property layout and the arrangement in the land use plan for new estate development. Drainage engineers can also use the delineated overland flow path and

catchment boundary for rainfall-runoff simulations to estimate designed runoff. Detouring overland flow paths from their natural paths using an inappropriate major system layout (like a road) can cause a significant damage in a storm event or as a result of an unexpected blockage of a drainage system. Although terrain analysis enables overland flow path mapping for a rural area, the common terrain analysis need to be customised relating to an urban setting. In this study, I developed a new conceptual spatial data integration model for extracting and delineating an overland flow path and catchment boundaries in an urban setting.

### **8.2.6 Overland flash flood prone areas**

Despite riverine and tidal flood, new estate development needs to be considered in relation to the overland flash flooding.

Hydrodynamic simulation is often used for comprehensive study of flood behaviour. However, using hydrodynamic simulation is limited to a few cases due to its high cost, information required, user skill and experience, and developed rainfall-runoff model. Alternatively, a conceptual hydrological model can result in valuable outcomes for further detailed study, decision-making for land use planning and drainage design. I used a well-developed concept in conceptual hydrological modelling, the TWI, to map flash-flood-prone areas. Flash-flood-prone area mapping assists land use planners and drainage design engineers in the Bass Coast Shire Council regarding flood-risk-based land use planning.

### **8.3 Did the study answer the research questions?**

This research began with the primary objective of developing a method to enable local government to incorporate new sources of data into a flood-risk-based land use planning process. In order to meet the objective, it was necessary to answer the following research questions.

### **8.3.1 What are the roles of Australian government agencies in flood and floodplain management at the local and regional levels in Victoria?**

In the development of a method to assist local land use planners to bring the local planning schemes into practice, it is necessary to identify the responsible authority for land use planning. The responsibilities of each level of government and agencies in relation to flood issues were discussed in chapter 2. Land use planning to reduce flood damage in floodplain is the responsibility of local governments. Therefore, local government authorities are the closest authority to undertaking the implication of flood provisions. Although local government practices naturally focus on local sites, such practices have a major influence on regional floodplain management practice.

### **8.3.2 How is flood risk addressed in land use planning decisions at the local level?**

In chapter 4, flood-risk-based land use planning was documented through strategic and statutory land use planning streams. It was shown that decision-making on individual land development needs to include various internal and external stakeholders. External stakeholders (referral agencies) commonly focus on region wide activities, while internal referral stakeholders focus on site-specific practices (e.g., property-level or street-level flood-risk-based land use planning).

### **8.3.3 What information products are required for flood-risk based land use planning at the local level?**

Information products in this study are the maps used by land use planners. Such data are commonly included in land use planning schemes as overlays to inform planners about limitations such as flood risk. Flood risk overlays include LSIO, UFZ, SBO, overland flow path, catchment and flash-flood-prone areas. All forms of required information products are described in detail in chapter 4.

#### **8.3.4 What are the gaps in the existing local flood relevant database?**

Information products require access to specific datasets. Such datasets are known as master data and the list of required dataset is called a master data list. Comparing the existing GIS database with the master data list reveals the missing dataset. The gaps in the existing GIS database at the Bass Coast Shire Council were outlined in Chapter 4 (section 4.9).

#### **8.3.5 To what extent are the LiDAR datasets for the study area vertically accurate?**

Any spatial applications in the hydrological world are dependent on the accuracy of topographical surface data. In chapter 5, it was explained that the LiDAR dataset was the only fine-resolution surface topography dataset usable for the proposed hydrological application. Although the metadata associated with the LiDAR dataset specified that the dataset was accurate to 0.1m vertically, this research showed that the LiDAR vertical accuracy was around 0.5m in the sample site.

Absolute vertical accuracy is needed to determine the relative accuracy of the information products produced from the DEM through simulation. The vertical accuracy of the available LiDAR ground point dataset satisfied the requirements for catchment-wide hydrological (demonstrated in chapter 6 and 7). However, the dataset cannot meet the requirements of site-specific drainage designing practices as vertical accuracy of less than 0.1m is needed. Therefore, the available LiDAR ground point dataset cannot be used as a data source for precise GPS surveying as commonly used for designing practice.

In chapter 5, proposed methodology to determine similarity (autocorrelation) distance between LiDAR ground point and PMs was implemented by ANN analysis and sequential minimum distance.

#### **8.3.6 How can a GIS-embedded hydrological model be used in integration datasets to provide missing information products in existing GIS-database?**

The developed spatial data integration overcame the limitations of the typical GIS-embedded hydrological model, Arc Hydro Tools, to extract an overland flow path and catchment

boundary in an urban catchment. Typical GIS-embedded models have been developed for rural catchment and cannot deal with man-made features such as stormwater collection systems in an urban setting. The common procedure considered in the literature was described in section 6.2. The approach focuses on developing a DEM by imposing overland man-made linear collectors. The resultant DEM is known as a conditioned DEM. For example, stormwater pipelines are imposed onto the DEM as a linear collector and it is assumed that the pipeline plays a stream role in the urban catchment. The conditioned DEM cannot be used to extract overland gap flow path due to artificially stopping at the location of the imposed pipeline. Gap flow is defined as the remaining water flow above the surface which cannot be drained to the designated outlet by the installed stormwater collection network and causes a localised flood problem. This research showed that if the effects of manmade features are included into the resultant flow direction and the effect of such structure on water volume has been incorporated into flow accumulation calculation, the resultant information product can show the overland gap flow path in an urban catchment.

The TWI was used to determine the overland flash-flood-prone area shows that it can represent accurate flash-flood-prone areas either at the subdivision scale or at the street scale.

Turning a TWI continuous raster dataset into a vector dataset including flooded and non-flooded areas needs a customised threshold (Manfreda et al., 2011) for a given area, which is rarely available (Manfreda and Sole, 2013), particularly in urban catchment due to lack of flood measuring records. Therefore, it was not possible to set a threshold for classifying the TWI model into flood-prone and non-flood-prone areas. Consequently, this research used a spatial statistical model to delineate the areas where flood water drains. The field check showed that the resultant map accurately delineate the areas under threat from flash flooding.

#### **8.4 Generalisability of the research findings**

Vonk et al. (2007) stated that the barriers to the implement of GIS based application in an organisation can be solved using a pilot study project. This research resulted in several

outcomes related to support local flood-risk-based land use planning. The outcomes of this research as pilot studies are significant in relation to:

- 1-enabling local governments to reduce flood damage
- 2-understanding the information gaps in a Australian council's flood-relevant GIS dataset
- 3-creation of a decision-making platform for multiple stakeholders in flood-risk-based land use planning
- 4-enforcement of flood provisions in local land use planning
- 5-the ability of local governments to utilise newly evolving spatial datasets
- 6-achieve the goals of local flood management plans
- 7-the implementation of water sensitive urban design (WSUD) initiatives
- 8-the facilitation of pre- and post-development flood-risk-based land use planning
- 9-determination of flash-flood-prone areas
- 10-implementation of a GIS-embedded hydrological model in local flood management

Nevertheless, it was accompany with some constraints for its generalisability. Generalisability constraints that accompany the research findings are outlined below.

1-Different agencies are involved in flood and floodplain management in Bass Coast Shire, with different scope, roles and responsibilities, at the time of conducting this research. The roles and responsibilities of such organisations might alter in the future, meaning that findings described in chapter two would no longer be valid.

2-The pilot study area described in chapter 3 has particular terrain characteristics and the organisation with greatest responsibility for flood-risk-based land use planning in the study area, the Bass Coast Shire Council, has its own implementation rate of spatial technology. The uptaking rate of spatial technology by different Australian agencies is likely to vary substantially, and each agency has its own progress. Furthermore, organisational interests in using GIS are broad, from the database management system and mapping system to the spatial analysis platform. Thus, research findings for missing data are for Bass Coast Shire

flood-relevant GIS database. Methods for overland flow path extraction depend to the terrain characteristics; therefore, they need to be examined for new study area.

1-The decision-making procedure for a flood-risk-based land use planning was extracted based upon the practices of experienced planners and engineers working in local governments in Victoria: processes might be different in the other Australian states. Although the information required for flood-risk-based land use planning is similar for local governments, the missing data and information is not necessarily similar to the results of Chapter 4 for every local government within Victoria.

2-Although the vertical accuracy of LiDAR ground points was assessed using the minimum distance approach developed in this study, the vertical accuracy of LiDAR ground points refers only to the sample area and the value may vary based upon different landscape and land cover. Therefore, the result cannot be generalised for the other areas.

3-In extracting flow path and flash-flood-prone areas in an urbanised catchment, high-resolution surface topography data sources are vital; therefore, any further activities are directly dependent on the existence of such a dataset. Overland flow path extraction and flash-flood-prone area determination are limited to urban catchments in Inverloch township area covered by LiDAR dataset in this research.

4-This research was deliberately limited to conceptual GIS-embedded hydrological models (rather than extending to more sophisticated hydrodynamic models). Therefore, the spatial data integrations represented in chapter 6 and 7 inform planners for the overland flow path and flood-prone areas without dealing with water characteristics like velocity and depth.

Despite the abovementioned constraints of this research, the procedures developed to enable the extraction of an overland flow path in an urbanised catchment and the methods to conduct the vertical accuracy assessment and implement the TWI as an index to show flash-flood-prone areas are useable in any other geographical area.

## **8.5 Future research directions**

The focus of this study was on utilisation of spatial technology for floodplain management and flood prevention activities. Future research directions for the use of GIS database and GIS-embedded hydrological models can be divided into three main groups: prevention, response, and recovery.

### **8.5.1 Assessing the usability of GIS-embedded conceptual hydrological models in broader flood and floodplain management**

The present research focused on using and customising currently available GIS-embedded hydrological models in local flood-risk-based land use planning. I developed spatial integrations to include the influence of manmade urban drainage networks on mapping the overland flow path. TWI was also used in order to provide the flash flood prone areas. The outcome of TWI model showed the potential utilisation of spatial technology in local-level-large-scale decision-making related to floor prevention. Future research could develop new spatial data integrations to enable GIS-embedded conceptual models to be usable in floodplain management tasks described in Figure 2.5.

### **8.5.2 Development of a computer interface that includes urban hydraulic features for assigning GIS based flow direction model**

In this thesis (chapter 6 and 7) I outlined the procedures for using typical GIS-embedded hydrological model for extracting overland flow path and boundary delineation in an urban catchment. The procedure could be presented as a user-friendly computer tool which is able to be adopted by the user in an automatic process. Such a tool would simplify customised GIS-embedded hydrological modelling in an urban catchment for those do not have enough time or GIS experience to follow the detailed data integration process.



### **8.5.3 Development of a spatial database model to record the information and datasets received from different resources in flood and floodplain management**

As flood and floodplain management is a multi-stakeholder activity in Australia, future research could focus on the existing data management procedures used by and between stakeholders. The logical extension of this would be to research the establishment of a local flood-relevant GIS database and GIS-based procedures in order to support integrated water resource management within a floodplain management framework.

## **8.6 Contribution and closing comments**

Reducing flood risk is largely relied on proper land use planning in Australia. In this research I consider the roles and responsibilities of flood-relevant agencies. Local governments are the responsible authorities for local flood-risk-based land use planning. The process that local government takes to implement flood risk in land use planning was documented for Bass Coast Shire Council.

In this research, I established an approach to support local flood-risk-based land use planning using GIS-embedded hydrological models by producing the information products required, taking Bass Coast Shire as study area. The developed approach required local governments to consider the flood-relevant GIS database in terms of presence of information products required and to determine the missing data regarding the master data I listed in chapter 4 in order to support the process of flood-risk-based land use planning. I examined the existing GIS database in Bass Coast Shire Council and identified missing data, then assessed the GIS-embedded hydrological models for their ability to provide the information products required for flood-risk-based land use planning. Three information products required in flood-relevant GIS database -overland flow path, flash-flood-prone areas and catchment boundary- were produced using the conceptual hydrological modelling by the spatial data integration methods I developed in chapter 6 and 7. The developed methods enable local governments as

responsible agencies for local land use planning to bring flood-risk-based land use planning provisions into practice.

I used the available LiDAR ground point dataset as surface topography data source for creating abovementioned information products in study area after checking its vertical accuracy against PMs by proposed method I developed for this study. The vertical accuracy of topography data source shows the quality of flood-relevant GIS-database, thus, the method I developed for vertical accuracy assessment enable user to determine the highest accuracy associated with consequent hydrological modelling.

The developed approach enables local governments to assess their flood-relevant GIS database completeness and quality, then using GIS-embedded hydrological models to provide missing information products using developed methods to improve local flood-risk-based land use planning.

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**APPENDIX A: QUESTIONNAIRE**

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Department/office:

Name:

All responses will be treated confidentially.

Please circle your answer to each of the following 19 questions and describe questions 8, 14 and the optional questions. Circle whether you agree (1 for strongly agree) down to disagree (7 for strongly disagree).

1- I am responsible for implementing the Bass coast flood management plan (June 2010):

(Strongly agree) 1    2    3    4    5    6    7 (strongly disagree)

N/A

2- In implementing the flood management plan, I always have the appropriate and adequate flood risk data.

(Strongly agree) 1    2    3    4    5    6    7 (strongly disagree)

N/A

3- The council always has relevant data in a location that is easy to access so that I can make an appropriate decision.

(Strongly agree) 1    2    3    4    5    6    7 (strongly disagree)

N/A

4- In making a decision for flood management, I would like better spatial (geographical) data to give me better solutions to the problems I have.

(Strongly agree) 1    2    3    4    5    6    7 (strongly disagree)

N/A

5- In making a decision for flood management, I rely on the information represented in developers' plans for new estate development.

(strongly agree) 1    2    3    4    5    6    7 (strongly disagree)

N/A

6- I am using relevant and appropriate software and models for preparing (updating) the council flood overlay.

(strongly agree) 1    2    3    4    5    6    7 (strongly disagree)

N/A

7- I am using relevant and appropriate software and models for sorting out flood issues.

(strongly agree) 1    2    3    4    5    6    7 (strongly disagree)

N/A

8- Which software and models do you use? ( flood relevant Software name and version please)



9- I always draw upon the GIS section for making decisions with regard to flood management.

(strongly agree) 1 2 3 4 5 6 7 (strongly disagree)  
N/A

10- I would like to make more use of the GIS in my work and decision making.

(strongly agree) 1 2 3 4 5 6 7 (strongly disagree)  
N/A

11- The decisions, with regard to flood management, I make will always result in a change to the GIS database.

(strongly agree) 1 2 3 4 5 6 7 (strongly disagree)  
N/A

12- I think that the local community has an important role in providing spatial (geographical) information to the council.

(strongly agree) 1 2 3 4 5 6 7 (strongly disagree)  
N/A

13- I think that data provided from the local community is important in our flood management decision making.

(strongly agree) 1 2 3 4 5 6 7 (strongly disagree)  
N/A

14- When you make decisions relevant to flood management in your work, do you ever draw upon data from another organisation or department

- **Within council;**

Which departments?

What data?

How often?

- **Outside the council** (for example: Vic roads, DSE,...);

Which departments?

What data?

How often?

15- Do you have any objections to a follow up interview?

- Yes
- No (please provide your email address and/or contact number)

**Optional:**

16- How old are you?

- 20-34
- 34-50

17- What position do you hold?

18- How long have you been employed at the council?

19- Male / Female?

## **APPENDIX B: LIST OF PEER-REVIEWED PUBLICATIONS**

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**Pourali, S., Arrowsmith, C., Shobhit, C. (2011)**, The utility in spatial data modelling for decision support, Proceeding of Progress in Geospatial Science Research Conference, 12 -14 December 2011, RMIT University, Melbourne, Australia

**Pourali, S., Arrowsmith, C., Peterson, J., Shobhit, C. (2011)**, The utility in spatial data modelling for decision support in water-catchment management: exemplification from Gippsland, Victoria, Australia, Proceeding of Surveying & Spatial Sciences Institute Biennial International Conference, 23-25 November 2011, Wellington, New Zealand (accepted)

**Pourali, S., Arrowsmith, C., Mitchell, D., Lennox, P., Baby, N., (2012)**, An appropriate methodology for using Arc Hydro Tool in urbanised catchment, Proceeding of American Water Resource Association Annual International Conference, 12-15 November 2012, Jacksonville, Florida, USA

**Pourali, S., Arrowsmith, C., Mitchell, D., (2013)**, Assisting local flood management using conceptual spatially based distributed hydrological model, Proceeding of the 5th geo-information technology for natural disaster management (Git4NDM) International Conference, 9-11 October 2013, Ontario, Canada

**Pourali, S., Arrowsmith, C., Chrisman, N., Matkan, AA., (2014)**, Vertical accuracy assessment of LiDAR ground points using minimum distance approach, accepted in Proceeding for Research@Locate'14 International Conference, 7-9 April 2014, Canberra, Australia

**Pourali, S., Arrowsmith, C., Mitchell, D., Matkan, A. (2014)**, Modelling an overland flow path in an urban catchment using GIS, Geoinformatica - An International Journal (GIJ), Vol 4, Issue 1, 2014.

**Pourali, S., Arrowsmith, C., Mitchell, D., Matkan, A. (2014)**, Topography Wetness Index (TWI) application in flood-risk-based land use planning, Applied Spatial Analysis and Policy (accepted)