ANALYSING PEAK FLOW ATTENUATION IN AN URBAN WETLAND

Monica Grace Giermek

Minor dissertation presented in partial fulfilment of the requirements of the Degree of Masters of Science Specialising in Climate Change and Sustainable Development, in the department of Environmental and Geographical Science

University of Cape Town

February 2015

Supervisor: Dr. Kevin Winter
Co-Supervisor: Dr. Piotr Wolski

I know the meaning of plagiarism and declare that all of the work in the dissertation, save for that which is properly acknowledged, is my own.

Signature: Signed by candidate
Signature Removed

Date: 16 February 2015

Acknowledgements

This year of rigorous coursework and challenging research would not have been possible without the support and guidance from many individuals.

I would like to express my gratitude to Dr. Kevin Winter, an absolute star of a supervisor. His continual support, positive attitude and guidance in this research has been pivotal in the completion of this thesis. I appreciate all that I have learned while under his supervision this past year.

Thank you to my co-supervisor,Dr. Piotr Wolski, who spent numerous hours at my desk as I continually hit road blocks while configuring a hydrodynamic model for the very first time. His knowledge of hydrology, climate and modelling was immensely beneficial throughout this research.

Mr. Mark Randall of Computational Hydraulics International and Mr. Onno Fortuin of Onno Fortuin Consulting have both played important and helpful roles in the model configuration for this study. I am grateful for having both on board throughout this research. Mr. Nicholas Lindenberg and Mr. Thomas Slingsby of UCT's GIS lab were incredibly helpful in providing geoinformatic data for the model configuration as well as impromptu GIS lessons.

Dr. Bradley Rink went above and beyond what any postgraduate student hopes for in a course convener. From shaping the ACDI masters coursework component to expose us to a wonderful variety of climate change discussions, to always having an open door for conversations on research, career advice and overall well-being. I am thankful for all of his contributions to this masters program.

My fellow ACDI classmates have been a sound source of support through this past year. I have thoroughly enjoyed getting to know each class member and for their company at the office on peanut butter toast and Red Bull fuelled nights. I cannot wait to see what 2015 has in store for each of us as we re-enter the career world as climate scientists.

My parents and sisters, though halfway around the globe, have been such fantastic sources of encouragement, cheering me on through this academically rigorous year. I am thankful for every call and message of encouragement that has been sent my way.

Lastly, this research would not have been possible without the financial assistance of the African Climate and Development Initiative, Dr. Kevin Winter, and my parents, Peggy Giermek and Bernard Giermek. I express my great gratitude for this support.

Abstract

Keywords: urban hydrology, flooding, wetlands, attenuation, climate change

Worldwide urbanization and climate change are influential in changing precipitation patterns and hydrological flow resulting in event driven urban flooding. The approach to flood protection has recently shifted from engineered and technical solutions to more sustainable and integrated solutions, by considering social, ecological and physical implications and exploring sustainable urban drainage options. Attenuation of peak stormwater flow using natural wetlands is one of many sustainable urban drainage methods used to reduce flooding and is an approach of interest for this research. The study site is located within the small, urbanized river system of the Liesbeek River in Cape Town, South Africa, which is prone to localized flooding during annual winter rainfall events. The study measures the attenuation capacity of a small-scale wetland adjacent to an urban river using a 2D PCSWMM hydrodynamic model. Research is focused on illustrating the attenuation capacity of this wetland. The model ran historic flow data to determine the attenuation capacity and to measure peak flow reduction. While the reduction is not sufficient to reduce damaging floods, the findings provide new knowledge and understanding of the attenuation capacity of this wetland and motivation for expanding sustainable urban drainage within the catchment. The study aims to build a baseline dataset for the research site with the data available at present. Peak flow of the Liesbeek River was reduced in scenarios with the Valkenberg Wetland present to accept on a portion of this flow. Attenuation was most effective for rainfall events with sudden spikes in peak flow, where a 42 per cent reduction of peak flow was observed. For a scenario with lower flow rates yet a prolonged peak flow rate, the wetland was less effective, with a 20 per cent reduction observed. This wetland was found to have the potential to provide valuable ecosystem services to the area by attenuating peak flow and thus reducing the occurrence of property damaging flooding downstream.

Acronyms and Abbreviations

2D	Two dimensional
CHI	Computational Hydraulics International
DEM	Digital elevation model
IPCC	Intergovernmental Panel on Climate Change
km	Kilometre
km^2	Kilometre squared
m	Metre
m^2	Metre squared
m^3/s	Meters cubed per second
mm	Millimetre
PCSWMM	Personal Computer Storm Water Management Model
SUDS	Sustainable urban drainage systems
SWMM	Storm Water Management Model
US EPA	United States Environmental Protection Agency

Contents

1. Introduction

1.1 Introduction to Research

Human pressures are prompting anthropogenic changes in the Earth System which are driving scientists to suggest that humanity has entered a new geological epoch (Rockström et al. 2014). In the human-dominated Anthropocene (Crutzen 2002), urbanization and thus urban flooding is now more than ever a global issue, with climate change adding further stressors (Huong & Pathirana 2013). In the mid-20th century urbanization and the management as well as establishment of infrastructure to deal with for flood risk was assigned to civil engineers who created drainage systems capable of routing stormwater runoff to receiving waters (Burns et al. 2012). Thus, during most storm events, runoff was discharged directly into receiving waters with minimal or no attenuation or treatment (Burns et al. 2012), often causing negative impacts downstream even though flooding impacts downstream were addressed. New thinking and practice in sustainable urban drainage are now being aligned with efforts to build resilience to future uncertainties caused by factors including population growth, urbanization and climate change (Wong & Brown 2008).

The urban syndrome describes the observed ecological degradation of streams which drain urban land (Walsh et al. 2005). Symptoms include a flashier hydrograph (the graph has sharp vertical jumps and equally steep vertical lines, which likely means water falling within the watershed quickly makes its way to rivers with little to no infiltration); elevated concentrations of contaminants and nutrients; altered channel morphology; and reduced biotic richness with an increase in the dominance of tolerant species (Walsh et al. 2005). Recently in many global cities, approaches to flood protection have shifted from purely engineered and technical solutions to more natural and sustainable solutions, including the social, physical, and ecological implications. It is no longer thought that purely technological solutions are solely appropriate for dealing with stormwater and the need for a shift in focus on hydrological systems (Montanari et al. 2013). Within urban areas, sustainable options can be limited due to space and other constraints; however there are multiple possibilities, such as opportunities in utilizing small depressions and wetlands in flood management (Javaheri & Babbar-Sebens 2014; Acreman & Holden 2013).

Attenuation of peak stormwater flow using natural wetlands is one of many sustainable urban drainage methods used to reduce flooding and is an approach of interest for this research. This study utilizes 2D modelling to understand the performance of a particular seasonal wetland in attenuating peak flow of an adjacent urban river, while exploring a shift in the way attenuation is perceived. Until recently, it was assumed that precipitation was fairly predictable and stable (Rockström et al. 2014). This assumption of a 'stable supply side' no longer exists in the Anthropocene (Rockström et al. 2014). The shifting climate and increasingly variable storm events globally are a driving factor for the selection of this research topic. While the scope of this study does not focus specifically on water quality, pollution remains a major global challenge within water resources and many studies have explored how wetlands can aid in improving water quality (Mander & Mitsch 2009; Mitsch et al. 2012; Imfeld et al. 2013; Keller et al. 2014;). Human activities more or less affect all river and groundwater systems, proving that water resource management has itself entered the Anthropocene epoch (Meybeck 2003). The emerging Anthropocene water agenda challenges previous steady state thinking and incremental change, and require strategies which are capable of handling complexity, uncertainty and surprise (Scheffer et al. 2009). Climate change brings the possible effect of an increased focus on management and governance responses to fluctuations in water dynamics and related impacts including flooding, drought and changes in precipitation patterns (Kabat and van Schaik 2003).

This study investigates the catchment of the Liesbeek River, in which nearly half of the 2600 hectare catchment area is urbanized with most of the remaining portion comprising of Table Mountain National Park and Kirstenbosch National Botanical Gardens. The urban river system is located in Cape Town and is prone to localized flooding during the winter season. The research focuses primarily on understanding the attenuation capacity of a small-scale wetland. Modelling is used to determine the value of utilizing this wetland to reduce the severity of flooding by attenuating peak flow.

1.2 Research Design

The focus of this study is to determine how a small-scale wetland performs in attenuating the peak flow of an urban river. It investigates surface water flow from rainfall events which, due to topographic features, most frequently occur in the upstream part of the catchment. Particular interest lies within how wetlands within the catchment could be used to attenuate a portion of this flow in order to reduce flood risk downstream. The primary research methods use historic hydrological data from the Liesbeek catchment along with a 2D hydrologic modelling of the Valkenberg Wetland.

The study examines literature on urban hydrology and flooding (Willems et al. 2012a; Chocat et al. 2007; Fletcher et al. 2014; Anguelovski et al. 2014); the 'urban stream syndrome' (Walsh et al. 2005); the use of wetlands to attenuate peak flow (Nascimento et al. 2000; Walsh et al. 2005; Zhou et al. 2013; Zhou 2014; Willems et al. 2012a); hydrologic modelling (Willems et al. 2012a; Egger & Maurer 2015); and future climate scenarios (Huong & Pathirana 2013; Semadeni-Davies et al. 2008; Zhou 2014; Schulze 2011; Ziervogel et al. 2014). The discussion of the literature focuses primarily on streamflow attenuation following large precipitation events in urban areas, as this is the area of interest for the study site.

While urban flooding is often thought of from a purely engineering perspective, this study connects the issue with the concurrent theme of the "urban stream syndrome" (Walsh et al. 2005), which explores the historic degradation of urban waterways. The study addresses the urban river system as a whole rather than merely treating the symptomatic flooding. Rockström et al. (2014) state that to transform to the sustainable management and use of water and ecosystem services, passivity in both governance and management structures and systems must be addressed. Transformation involves experimentation with resilience-based approaches to integrated water resource management and ultimately a significant shift in thought towards a new social-ecological water paradigm, where protection of water resources is in support of human prosperity and within the safe operating space of a stable planet (Rockström et al. 2014).

The primary rational for this study lies in the routine occurrence of property damaging flood events downstream of the research site. When an urban area is a 'resilient' urban system, major system 'disturbances' (such as floods, droughts and waterway health degradation) provide the potential for opportunities for innovation and development (Wong & Brown 2008). In 'vulnerable' systems however, even small disturbances (such as extended storm events), have a high likelihood of causing dramatic social consequences (Adger 2006). Seasonal flooding during rain events is a reoccurring issue within this particular study location. Flooding is caused by factors such as development within the river floodplain and the use of conventional stormwater drainage design which swiftly carries stormwater away from residential and commercial properties with little to no opportunity for flow to be slowed and adsorbed into the ground. Folke (2006) explains that resilience is not just being persistent or robust to a disturbance, it is also a reflection of how a system creates opportunities from the disturbance for renewal and the pursuit of new trajectories. The urban system our study focuses on is seemingly not 'resilient' at present, as damaging floods are harming local business property and appear to be increasing in occurrence in recent years. In an email on with local business owner, Nick Ferguson of The

River Club (Ferguson 2015), it was stated that the area of Valkenberg Wetland along the Liesbeek River experiences property damaging floods roughly every six and a half years (1999, 2004, 2012), however in the past three years alone, there have been three damaging flood events (two events in 2012 and one in 2013)(Ferguson 2015). The pressures climate change add to this urban system in regards to flooding, along with potential for increased urbanisation in this area, are both driving factors for the motivation of this research.

1.3 Aim

This research aims to determine the attenuation capacity of a small-scale wetland to capture the peak flow of an adjacent urban river during storm events and to contribute to a baseline understanding of the research area. Specifically, the study will evaluate how a portion of peak flow from the Liesbeek River can be attenuated within the Valkenberg Wetland, located in the Observatory neighbourhood within the City of Cape Town.

The majority of existing research which examines the impacts of urban areas focuses attention on correlations between in stream ecological metrics and percentage of catchment imperviousness (Walsh et al. 2005). More recent studies are revealing that a portion of the variance in these correlations can be explained by the distance between the reach of the stream and the area of urban land, or by the efficiency of hydraulic stormwater drainage (Walsh et al. 2005). The Liesbeek catchment has an efficient hydraulic stormwater drainage which is observed in above-average rainfall events cause peak flow rates within the Liesbeek River to cause damaging floods (Raubenheimer 2013). Walsh et al. (2005) stress that these patterns need further experimentation at the catchment scale to understand the mechanisms behind them and to identify best management approaches for the conservation and restoration of urban streams.

This study seeks to develop an approach and methodology to evaluate how a small-scale wetland performs in attenuating peak flow of an urban river. It will be determined if and to what extent the Valkenberg Wetland is capable of attenuating peak flow of the Liesbeek River and discuss future climate influences. While reference data in relation to attenuation is not available, 2D modelling tools are used to evaluate the attenuation capacity of the small-scale wetland. With this single example thoroughly understood, it will be possible to determine the benefits of utilizing existing wetlands or constructing additional wetlands, along with other forms of sustainable urban drainage methods, throughout the 2600 hectare Liesbeek River catchment.

1.4 Study Site

The Valkenberg wetland is an urban wetland with a surface area of 1.54 km^2 and is adjacent to the Liesbeek River, separated from the river by an elevated bank. Being an urban area, the impermeability levels of the catchment when compared to a rural area lead to exaggerated peak flow rates in the Liesbeek River following storm events, as much of the stormwater runoff is swiftly directed away from urban areas and directly into the river. During summer months, the wetland is dry and quickly becomes filled with invasive reed species.

Figure 1 Western facing view with the Valkenberg Wetland on the right, taken 29 August 2014. Photo credit: Monica Giermek

Multiple factors were considered in the selection of the site. Historic flow data is available and there is also social interest in the area by various community organizations such as Friends of the Liesbeek and those involved with Two Rivers Urban Park. (green space between the Liesbeek and Black rivers). Additionally, there has been recent discussion of large-scale development (R15 billion) within this area (WDC 2014). These conversations have led to questions around the value of the Valkenberg Wetland and its attenuation capacity during peak flow events.

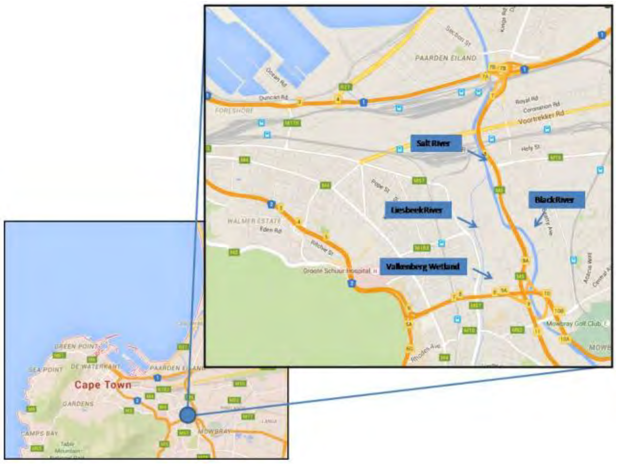


Figure 2 Study site location Map

2. Literature Review

2.1 Introduction to Literature

The twenty-first century has been labelled the century of cities and urbanization (Wong & Brown 2008). New features of a swiftly emerging water agenda in the Anthropocene challenge, historic steady state thinking and incremental change, calling for a shift to strategies which can handle complexity, uncertainty and surprise (Scheffer et al. 2009). Urban populations are increasingly looking to establish cities that are resilient to future uncertainties, specifically in urban water supplies (Wong & Brown 2008). Such resilience must be created in the face of uncertainty regarding the future magnitude and frequency of extreme weather events (Ziervogel & Parnell 2014), an area of interest in this study as we examine urban flooding. While cities are beginning to develop policies and plans to adapt to climate change impacts (Ziervogel & Parnell 2014), change is slow, with many urban areas facing ongoing investment in conventional approaches (Wong & Brown 2008), due to traditional planning and trends.

While South Africa produces ample water resource literature, the use of wetlands as a means of peak flow attenuation appears to be a theme not yet published within a South African context and most heavily published in North America and Western Europe (such as Javaheri & Babbar-Sebens 2014; Acreman & Holden 2013). This gap of local research underlines the relevance of this specific study, and as no local examples have been published, literature from several overseas examples will be discussed.

2.2 Urban Hydrology

Over the last century, cities worldwide have used combined sewer systems (transporting both urban runoff and sewage in the same combined piped drainage system) and separate systems (parallel sewers for storm and waste water), to reduce urban vulnerability to health risks. However these systems have the potential to increase the vulnerability of cities to extreme events, in part due to a lack of consideration to what occurs when precipitation exceeds design criteria (Willems et al. 2012a). As a consequence, cities which have increased impervious areas must now cope with shorter response time in urban catchments. These shorter response times enhance stormwater runoff volumes and velocities beyond the capacity of existing drainage systems can lead to flooding and property damage. High-intensity, short-duration precipitation events are the primary driver of urban flooding, as well as sewer overflows (Willems et al. 2012a). Cities are becoming increasingly vulnerable to flooding due to rapid urbanization, the construction of complex infrastructure, and changes in the precipitation patterns caused by anthropogenic climate change (Willems et al. 2012a). Costs associated with flooding in urban areas are much larger than in rural areas due to the high concentration of values within cities, translating to small floods potentially resulting in large damage (Freni et al. 2010), further underlying the necessity of exploring sustainable urban drainage techniques within the urban catchment area of this study.

Conventional drainage systems primarily have a single-objective orientated design, with the focus being on controlling water quantity and thus also reducing exposure to health risks. The densely populated catchment of the Liesbeek River is no exception; it too has been designed to swiftly move storm water away from residential areas and directly into the river, quickly leading to spikes in peak flow rates. More recent drainage designs around the globe are now incorporating other aspects in urban water management, from runoff quality, visual amenity, recreational value, ecological protection and multiple use water (Chocat et al. 2007; Echols 2007). Fortunately, there is now widespread acknowledgement of the degrading impact urban stormwater runoff has on stream ecosystems, as well as the need to mitigate these impacts using stormwater control measures (Fletcher et al. 2014).

Many urban water systems are particularly vulnerable to population growth and climate change (Semadeni-Davies et al. 2008; Zhou et al. 2012), and it is expected that these trends will continue over the coming decades (Willems et al. 2012a). Simultaneously, much of the developed regions of the world are realizing the urgent need to incorporate sustainable approaches into their urban design and planning processes (Willems et al. 2012a). In addition, the life span of urban drainage infrastructure are is long, in the order of 50-100 years or more, making it sensible to include climate predictions whenever assessing such infrastructure. With runoff and peak flows expected to rise due to climate change altering the frequency and intensity of precipitation, drainage systems at present will likely not satisfy the necessary service level in the future (Mailhot & Duchesne 2010), emphasizing the need for a swift increase in diversified means of urban drainage methods.

Urban drainage systems are crucial for collecting and moving stormwater and wastewater away from urban areas (Chocat et al. 2007). Conventional urban drainage and stormwater have been designed to move rainfall runoff as quickly as possible, resulting in 'end of pipe' solutions which often have the provision of large interceptor and sewers, large storage tanks located downstream, and centralised wastewater treatment facilities (Abbott & Comino-Mateos 2001). Local governments are increasingly recognising that the impacts of climate change on various urban sectors have been increasing in recent years. The City of Cape Town recently (2014) appointed a Director of Climate Change, thereby publically acknowledging the importance of becoming a climate resilient city. This trend has many local governments pursuing provisions for climate adaptation, with the aim of attaining preparedness through reducing vulnerability and also enhancing the resilience of citizens, assets and municipal operations (Anguelovski et al. 2014).

The Intergovernmental Panel on Climate Change (IPCC) reports that for the late 20th century, a worldwide increase in the frequency of extreme rainfall events is most likely as a result of climate change. The IPCC defines extremes as events which are relevant from a disaster risk management perspective, for example, urban flooding disasters. Furthermore, the Panel has concluded that it is very likely that this trend will continue throughout the 21st century (IPCC 2007). Climate change is expected to affect the water cycle particularly due to the influence on precipitation patterns (Zhou et al. 2012; Anguelovski et al. 2014) and anticipated changes of precipitation patterns must therefore be integrated into the design of urban drainage in response to the increased risk levels of urban flooding due to climate change (Zhou et al. 2012). Planning for climate change adaptation is one of the most multifaceted and complex challenges which cities are facing at the moment and municipalities play a central role in both the planning of and implementation (Anguelovski et al. 2014).

It is likely that there will be an increase of river runoff due to climate change; an increase of urban runoff driven by impervious areas; and extreme rainfall due to urban growth-driven microclimatic change (urban heat islands) (Huong & Pathirana 2013). The anticipation of climate change needs to be incorporated into designs of urban drainage and in response to the increased level of risk in urban areas (Zhou et al. 2012). Fortunately, developments in South Africa such as the Water Services Act (Republic of South Africa 1997) and the National Water Act (Republic of South Africa 1998) have created major paradigm shifts in the management of national water resources (Schulze 2003). Such shifts are assisting to pave the way for positive changes within water resources in South Africa. Stuart-Hill and Schulze (2010) recommend that information and increasing knowledge regarding climate changes multifaceted consequences on water resources must be integrated into decision-making processes. They state that a ‘business as usual’ approach to the management of water resources in the long term will not only be costly, but also far from sustainable. This study aims to change the ‘business as usual’ approach within the Liesbeek catchment, as sustainable urban drainage is explored.

2.3 The Use of Wetlands for Water Attenuation

Wetlands provide a range of goods and services, and possess an assortment of attributes which are of value to society (Barbier 1993). In southern Africa, many wetlands have disappeared or become degraded as a result of increasing demands for both land and water (Lannas & Turpie 2009). Lannas and Turpie (2009) argue that it is crucial that there is an understanding of the socioeconomic value of wetlands when deciding between conservation and development priorities related to land use, as well as the allocation of scarce water resources. Ecosystem services is a well-defined and active field of scholarship that has gained a dedicated journal on the subject (Costanza & Kubiszewski 2012). In this study, attenuation is a component of ecosystem services as the reduction of peak flow of the Liesbeek River benefits local residents and businesses by decreasing the occurrence of property damaging floods. With one of the most recent definitions of ecosystem services being that they are the direct and indirect contributions of ecosystems to human well-being (TEEB 2010), attenuation which reduces damaging floods is the primary ecosystem service which the Valkenberg wetland provides. This study will use the TEEB 2010 definition when discussion ecosystem services. As there are many definitions of ecosystem services, the definition is still discussed from various viewpoints and arguments from ecology to economics (TEEB 2010). Lannas and Turpie (2009) recommend more studies be done within southern African on wetlands which focus on developing tools designed to enable a rapid assessment of the value of wetlands using key indicators and characteristics. The current study does not attempt to put a monetary value on the Valkenberg Wetland as ecosystem services are not the primary theme, though the study does recognize the need for an increase of wetland studies and aims to contribute towards southern African wetland research.

Sustainable drainage systems are widely endorsed as an alternative to or a means to complement, a traditional approach to address long-term sustainable designs (Larsen & Gujer 1997; United Nations 1992). Presently, there is an increasing trend towards more sustainable water management by triggering natural behaviours and processes in the urban environment (Fryd et. al 2012). While the frequency of hydrological impact studies of climate change has steadily increased in recent years, this work often focuses on river discharge extremes and low flow risks (Willems et. al 2012b), frequently overlooking many aspects of urban drainage such as the social and aesthetic implications. The occurrence of climate change studies focusing on urban drainage impacts is still fairly limited (Willems et. al 2012b) particularly in the realm of attenuation methods. This absence of literature and lack of previous case studies on the matter is one of the reasons why this study uses a modelling approach to improve the understanding of wetland attenuation.

There is no single definition of a wetland, partly because of the diversity of environments which are permanently or seasonally influenced by water, but also because of the specific requirements of the diverse groups of people involved with the study and management of these habitats (Scholz 2006). The Ramsar Convention helped draw global attention to wetlands in the early 1970s, and compiled the widely recognized and cited definition of “wetlands are areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water, the depth of which at low tide does not exceed six meters” (Anon 1971). An additional, more concise and complementary version of the Ramsar definition emerged a decade later, “Wetlands are a half-way world between terrestrial and aquatic ecosystems and exhibit some of the characteristics of each” (Smith 1980). Both definitions place an emphasis on the ecological importance of wetlands, but there is still no single accepted ecological based definition of wetlands (Scholz 2006).

Nascimento et al. (2000), drawing on studies of urban stormwater detention basins from France and the United Kingdom concluded that there may need to be a change in the basic design principles, operation and management of such systems in a Brazilian context. This point is an important note as many sustainable drainage designs in South Africa draw on international examples. The authors point out that from the 1970s and onwards, the concept of complimentary or alternative solutions for urban drainage began gaining traction in Europe and North America. Such solutions were aimed to compensate for the effects of progressive urbanization on hydrological processes, without creating constraints on the urbanization process (Nascimento et al. 2000). One of the first solutions implemented was flood storage basins which permit a temporal redistribution and attenuation of peak flow up to a specified storm design limit (Nascimento et al. 2000), a point which this study is specifically interested in exploring at the chosen study site.

Municipal drainage systems have begun to shift towards sustainability and such techniques have also gained interest from the public in recent years thanks largely to positive effects on water quality and hydraulics, as well as a perceived increase of recreational amenities in urban landscapes (Zhou 2014). The relatively recent coined concept of ‘artful rainwater design’ is a concept that is based on the premise of stormwater management techniques focusing on non-point source pollution, water balance, and small-storm hydrology that can be used to create designs which hold greater user satisfaction and perceived value than conventional means (Echols 2007). There is a noticeable trend in stormwater management designs that expand beyond the traditional approach of merely controlling flow rates (Echols 2007). Globally, sustainable drainage methods (often referred to by different terms in various countries) have gained momentum and are becoming increasingly more discussed among municipalities and the public sector. Shifts in public attitude and the use of a neighbourhood and its waterways are likely to create tangible economic benefits such as real estate value increases, which if combined with education will increase public awareness regarding the social and ecological advantages. These kinds of initiatives are likely to increase and reinforce acceptance of sustainable urban drainage systems (SUDS) by management authorities (Walsh et al. 2005).

SUDS have similar goals but vary slightly in specific objectives. In Western Europe, sustainable urban drainage systems are primarily used with an emphasis on preserving public health, guarding valuable water resources from pollution and conserving biological diversity and natural resources for future needs (Butler & Parkinson 1997). In Australia these ideas are extended to designs that are implemented at a catchment scale (Zhou 2014). Australians have primarily referred to sustainable urban drainage as a planning and engineering approach to integrate urban water management in a sustainable manner into urban landscapes, to reduce environmental harm and create harmony between water resources and the urban environment (Roy et al. 2008). The United States and Canada take an approach to promote the interaction of natural processes with the urban environment to maintain and recreate ecosystems for water management (Coffman et. al 1998).

Case studies using infiltration trenches and detention ponds to mitigate flood risk under climate change impacts have highlighted the enormous potential of detention basins in attenuating water runoff in extreme events, as well as providing additional recreational amenities in the urban landscape (Zhou et al. 2013). In spite of these positive findings, there are concerns about the actual operation and maintenance of the detention ponds, including issues such as urban erosion, water pollution and a lack of regulation measures. In addition, many studies have discussed the limitations of sustainable urban drainage methods in response to the increasing hydrological and hydraulic loading under climate change impacts (Holman-Dodds et al. 2003; Nascimento et al. 2000). Such techniques were found to impact water flows, however water volume reduction has been quite limited in certain extreme events and also sensitive to local conditions (size and duration of precipitation event, soil material and texture).

Even with advancing techniques and tools within urban water management, the implementation of sustainable drainage remains a large hurdle in reality. Zhou (2014) states that while the models that are available for these systems have progressed over the years, such programs generally remain limited in their mimicking of the natural responses of the devices from both quantity and quality perspectives. Often practical applications of such methods underestimate their complexity and thus the performance of the system is not satisfactory due to, for example, a lack of experience of sustainable urban drainage operations and maintenance, ignorance of interaction with other bodies of water, and institutional barriers towards these practices (Zhou 2014). A failure of there not being a management plan designed or implemented has already been observed at a constructed small-scale wetland within the Liesbeek catchment (Winter 2014), further underlying the intricacy and needs of these systems.

Sustainable urban drainage design incorporates multiple disciplines and multidimensional criteria (Fryd et al. 2012), however it is common for specialists and professionals to focus and prioritize their own fields in decision making processes (Brown & Farrelly 2009). Such oversights can result in subject-specific techniques and solutions often being applied, which do not account for important impacts from other disciplines (Zhou 2014). A challenge faced specifically by stream ecologists in furthering their understanding of urban streams is to not only a failure to understand interactions between catchment and stream processes, but to fail to integrate such work with social, economic and political drivers within the urban system (Walsh et al. 2005).

Higher temperatures and longer dry spells associated with climate change may also affect landscape based stormwater management systems (Willems et. al 2012b). Vegetated sustainable urban drainage systems are engineered structures which are designed to capture and retain proportions of precipitation in urban areas. Often such structures also have the benefits of enhancing social amenity through greening of cities, reducing urban heat island effects as well as enhancing urban biodiversity (Willems et. al 2012b). The Valkenberg Wetland is no exception, and a well-managed area may encourage public use of the public open space.

2.4 Hydrological Modelling and Future Climates

This study is built on two initiatives. Firstly, historical data are unavailable for the Valkenberg Wetland, and a model can simulate scenarios and assist in further understanding the hydrology of the site. Secondly, as a widely acknowledged global issue, climate change is anticipated to impact urban water systems in terms of changes in water runoff and urban flooding (Willems et. al 2012b). In situations where urban drainage design relies only on observed precipitation data series, the uncertainties associated with current and future climate variability are neglected (Egger & Maurer 2015). When modelling hydrologic systems, limited data and uncertain future climates can be overcome, to an extent, through the opportunity of modelling multiple scenarios. Modelling is being used to understand the performance of the Valkenberg Wetland in attenuating peak flow.

South Africa is situated in one of the regions of the world that is most vulnerable to climate variability and change (IPCC 2007) and impacts on the South African water sector are therefore likely to be significant (Schulze 2011). While the number of hydrological impact studies of climate change has steadily increased in recent years, this work generally focuses on river discharge extremes and low flow risks (Willems et. al 2012b). Climate change studies focusing on urban drainage impacts are still quite limited, likely due in part to the need to focus on small urban catchment scales (generally a sale of 1-10 km^2) and short duration precipitation extremes (generally less than one hour). These small characteristic time scales of hydrological processes involved within urban areas are not supported by the majority of future climate modelling work that focuses on global and regional scales. As a result, there is a lack of sufficient literature (Willems et al. 2012b).

In South Africa, mean annual temperatures have increased by at least 1.5 times the observed global average rate of 0.65°C in the last half century and extreme precipitation events have increased in frequency (Ziervogel et al. 2014). Studies on the impact of climate change on the water resources sector have begun to look beyond merely changes in stream flow to changes in the timing of flows and the partitioning of stream flow into base flows and stream flows, reservoir yields, and extreme hydrological events (Stuart-Hill & Schulze 2012). Complexities of climate change within the hydrological cycle, impacts of land use and management, as well as the connections to society, health, and the economy show far higher levels of complexity within the water resources sector than other sectors (Ziervogel et al. 2014). Impacts due to climate change and urbanization have been widely recognized, which may create a considerable rise in the frequency and intensity of urban flooding in many regions of the world (Huong & Pathirana 2013; Semadeni-Davies et al. 2008; Zhou et al. 2012). In addition to environmental concerns, Krebs and Larsen (1997) have noted increasing criticism on the limited abilities and flexibility of traditional sewer systems to adapt to future climate variability as well as increased urbanization. Pahl-Wostl (2007) mentions that current water management systems have not been designed to be flexible. Specific to South Africa, the diversity and inequalities of the nation’s society make for a wide range of potential vulnerabilities to projected climate change impacts with regard to water resources (Stuart-Hill & Schulze 2010). With inherent uncertainties of climate models along with societal changes, water resource management now requires continuous updating of scientific and other information on impact assessment, as well as socio-economic developments in order to prioritize adaptation actions accordingly and avoid potential practices which can have negative impacts on other sectors or neighbouring regions (Stuart-Hill & Schulze 2010). The water regulatory framework of South Africa offers a uniquely flexible set-up to proactively adapt to climate change, with five-year review cycles offering routine opportunities to reassess adaptation actions as well as general management approaches and implementation (Stuart-Hill & Schulze 2010).

Researchers have shown that the expected increase in design intensities due to climate change can reach 20 to 80 per cent, depending on the region (Willems et al. 2012a). Urban drainage systems therefore are under severe capacity constraints in coping with the increasing amount of water due to climate change impacts (Zhou 2014) in addition to growing populations and aging infrastructure. The design of future drainage systems need to take the increased frequency and intensity of precipitation events into consideration to decrease frequency of system overloading (Mailhot & Duchesne 2010; Burrel et al. 2007). Urbanization exemplifies a critical influential factor to the quantity and quality of urban water (Zhou 2014).

Conventional practice of urban drainage design involves long-term planning and design based on historical meteorological observations and the assumption that such observations adequately represent future meteorological conditions, but it is clear now that such an approach is no longer viable (Willems et. al 2012b). Potential changes in climate and the associated consequences must be considered, as well as additional drivers in society which threaten business as usual in the urban drainage community (Willems et. al 2012b). It is anticipated that climate change will have significant impacts on precipitation patterns (Zhou et al. 2012), something which adds an element of uncertainty within the location of this study. It is anticipated that there will be an increase of river runoff due to climate change; increase of urban runoff driven by imperviousness; and an enhancement of extreme rainfall due to urban growth-driven microclimatic change (Huong & Pathirana 2013). The Fourth Assessment Report (AR4) of the IPCC reports a global increase in the frequency of extreme precipitation events as a result of global warming for the late 20th century. Based on climate model simulations with various future greenhouse gas emission scenarios, the IPCC concluded that it is very likely (defined by more than 90% certainty) that this trend will carry into the 21st century (IPCC 2007). It must also be noted that projected impacts of climate change on urban drainage systems are uncertain not only due to the uncertainties of climate projections, but also due to the uncertainties in the impact models (Willems et. al 2012b).

Downscaled climate model predictions for extreme rainfall and the impact on urban drainage systems show that climate change may create an increase of surcharging and flooding issues (Willems et. al 2012b). Impact indicators include runoff peak discharges and volumes, number of nodes surcharged or flooded, number of properties flooded, duration of flood, economic loss due to flood damage, inflow to wastewater treatment plants, and (in instances of combined systems) combined sewer overflow volumes and frequencies, and their quantitative and qualitative impacts on receiving surface waters (Willems et. al 2012b). In addition to scenarios of future precipitation extremes, impact analysis must also factor scenarios of additional key variables of change over time such as intensity of urban development, degree of imperviousness, and local management practices in order to improve urban stormwater management (Willems et. al 2012b).

The performance of urban drainage systems is extremely sensitive to fluctuations in the water cycle, especially precipitation extremes (Willems et al. 2012a). Downscaling of climate scenarios must be transmitted through urban drainage models. This is generally accomplished by using the rainfall time series derived from the climate model outputs as drainage model inputs. Upon simulating both the series derived from the climate model control simulations (present climate) and the scenarios simulations (future climate), changes within urban drainage systems can be examined (Willems et al. 2012a). Despite inherent uncertainties, future climate scenarios cannot be overlooked within present urban hydrology studies. The literature reviewed for this study underlines the uncertainties of future climates and the potential issues they may bring to urban areas, further underlining the need for enhanced resilience within urban catchments.

3 Context and Methodology

3.1 Introduction to Methodology

While evaluating how this small-scale wetland performs in attenuating peak flow of the Liesbeek River, a combination of quantitative and qualitative approach was taken. Several flood events were selected from a hydrometric gauging station data of Liesbeek River to be used in this study. These flood events represent various types and magnitudes of flood discharge hydrographs. The selected events are modelled using a 2D hydrodynamic model of the reach of Liesbeek River that includes the Valkenberg Wetland. For each of the events the hydrodynamic model is used to simulate three scenarios. These three scenarios represent an initially dry wetland; a wetland with initial water storage; and a circumstance where the river is not connected to the wetland. Comparison of outflow hydrographs under these scenarios allowed for assessment of the flood peak attenuating role of the wetland. Deficiencies in data available to configure, calibrate and validate the hydrodynamic model have limited the results as they cannot be analysed in a strictly quantitative sense, and are thus interpreted qualitatively.

The ten largest by volume peak flows were examined from a single year (September 2012 through August 2013) of historic hydrograph data. Three events were chosen for the modelling exercise. Firstly, an event on 17 April 2013 when the flow of the Liesbeek River peaked at 37.74 m3/s was selected based in its sheer volume and sharp peak, the highest on record for this one year data set. A second event occurred on 28 August 2013 and this was chosen as it represented a prolonged event, with peak flow around 15 m^3/sand continuing for nearly eight hours. Lastly, an event on 15 September 2008 was chosen to represent a comparatively smaller event. This event was the eighth highest peak flow from the data set (13.79 m^3/s) and was a short event, lasting less than two hours. This data are as input for a 2D hydrodynamic to highlight the potential attenuation capacity of the Valkenberg Wetland.

3.2 Data for the Study

3.2.1 Rainfall, Hydrograph and Groundwater Data

Secondary data was obtained for river flow and rainfall records. Ten year historic rainfall data from the catchment was obtained from a University of Cape Town PhD candidate, Lloyd Fisher-Jeffes (Fisher-Jeffes 2015). Flow data available for this study was generated from two gauging stations located on the

Liesbeek River as well as historic rainfall data collected by the City of Cape Town. One of the stations, located in the suburb of Claremont, is dysfunctional to the rate of the data being deemed unusable. The second station, located in Mowbray and the closest to the wetland of interest, has provided useful data. This data was collected and corrected to an extent by a current PhD candidate who is evaluating rainwater harvesting potential within the Liesbeek catchment (Fisher-Jeffes 2015). As this data had already been collected and corrected, it provided an ideal opportunity for an additional study within the catchment. Limitations for this site include a lack of groundwater data and of any downstream data. In addition, the gauging station used for the study has provided data that has been corrected by eliminating outlying data likely due to mechanical error, however the accuracy of these corrections are uncertain.

Precipitation could not be modelled in this study for two main reasons. Firstly, rainfall is ideally modelled at the catchment scale (or at least sub-catchment level) and modelling this scale was not appropriate because of the study is focused on a small scale wetland in the lower reaches of the Liesbeek River. Delineation of the model was determined by the location of the hydrometric gauging station where the flow data was obtained.

Reliable rainfall data for the catchment was also limited. There are two rainfall gauges with available data within the catchment (Observatory and Kirstenbosch). These two gauges indicate a strong spatial heterogeneity of rainfall, likely caused by proximity to Table Mountain. The Observatory rain gauge (located closest to the wetland) receives roughly 600 mm/year, while the Kirstenbosch gauge, located on the slopes of Table Mountain receives roughly 2000 mm/year (Fisher-Jeffes 2015). Had there been both increased project scope as well as resources to create a model better equipped to run precipitation data, this aspect would have been considered.

The three peak flow events which were modelled were some of the largest for 2013, but as seen in Figure 3, all three were not out of the range of a one in one year precipitation event for this site. In the case of the Observatory rain gauge, which is the closest to the study site, a one in ten year event is just over 70 mm/day and a one in a hundred year is defined by just over 100 mm/day. The three dates modelled were amongst the top six highest rainfall events for 2013. The largest rainfall event of the year occurred in early November 2013 (CIP 2015) however this did not fall within the September 2012 to September 2013 dataset used in this study (Figure 4).

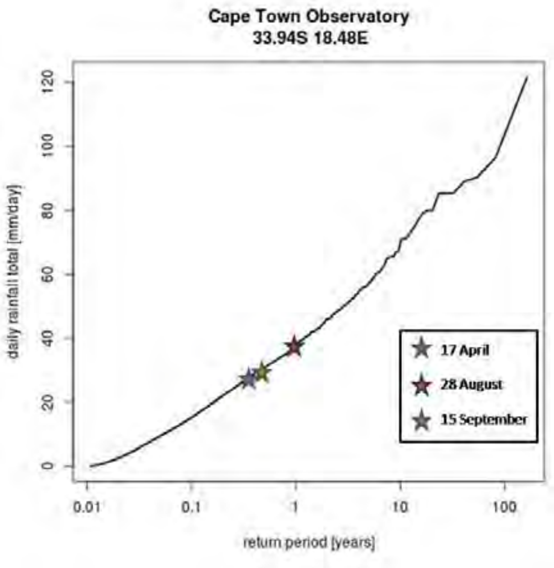


Figure 3 Rainfall intensity curve for Observatory

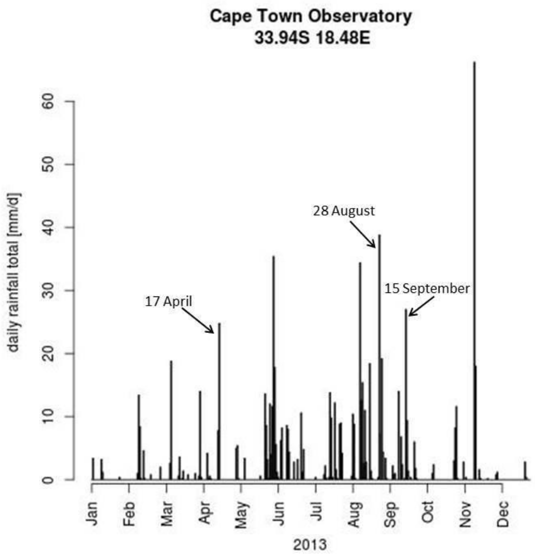


Figure 4 Total rainfall for Observatory in 2013

One year historic hydrological data from a station 0.75 km upstream from the Valkenberg Wetland was also collected from the City of Cape Town and then corrected by Fisher-Jeffes (Fisher-Jeffes 2015). The city's hydrograph curve for this station only modelled for flows of 5 m^3/s or more and was thought to be outdated and not fully accurate. Fisher-Jeffes followed a process similar to which the city follows to correct the data and made updated adjustments (assumed to be corrections) to the data by examining outliers in the data, which were presumed to be inaccurate readings. These corrections are assumed to provide increased accuracy for extreme peaks and low flows (Fisher-Jeffes 2015).

Groundwater data would have been helpful to this study to examine interactions with both the Liesbeek and the Black River and thus the availability of any existing data was thoroughly explored. Unfortunately after regular conversations with members of the Stormwater and Sustainability branch of the Transport for Cape Town division which are responsible for capturing this type of data, it was determined that groundwater data within or near the site location was not available. The primary contacts for inquiries were Mr. Rod Arnold, Head of Stormwater Planning and Business development, and Mr. Justin Smit, Professional Officer of Stormwater and Sustainability. In the absence of data from the municipality, the researcher explored the potential to collect data from residents who had access to private boreholes. Local businesses and homeowners in the vicinity of the Valkenberg Wetland were contacted via email. Local residents were eager to help in response to this request, but again no data was found. While groundwater would have been of interest for this study, as the surface and groundwater interactions would tell much of the attenuation story this study aimed to tell. Due to the scope of this research, installing a groundwater monitoring well to collect primary data was not feasible. In addition, it is clear that when groundwater reaches the level of the base of the wetland, it essentially acts a seal and therefore groundwater levels are no longer required, as the wetland is at capacity. After exploring many options to identify groundwater data, this element of hydrology was not included in the model and it was decided to move forward with the data available.

3.2.2 Digital Elevation Models

Digital elevation models (DEM) and aerial photographs were sourced from the University of Cape Town's (UCT) Geographical Information System (GIS) Laboratory. Aerial photographs were extracted on November 28, 2013 from the database. The dates of the DEM layer were unknown, though the GIS Laboratory researchers believe they were created between 2005 and 2010 based on having earlier versions prior to 2005 and knowing that it was not created within the past four years. The DEM was likely created from multiple sources and it was not possible to identify an exact year for this data source. The aerial photographs were useful when configuring the model and the DEM layer for creating the 2D mesh layer for the creation of the 2D model.

3.3 Model Configuration

Modelling was the chosen tool for measuring the attenuation of the Valkenberg Wetland, based on interest in calculating possible reduction of peak flow in the adjacent Liesbeek River. A 2D model was chosen to explore various scenarios within the study site.

3.3.1 2D Modelling

Initially, the study utilized the Danish Hydrologic Institute's (DHI) Mike Urban program for modelling. After finding a lack of local workshops or technical support for the software, modelling methods were re-evaluated. It was found that Computational Hydraulics International (CHI) offered a course on their PCSWMM modelling program and after completion of a two day workshop; methods were adjusted to utilize this program. PCSWMM has been a user-friendly and effective modelling program for this study, with very helpful support staff for any technical questions.

To analyse alternative attenuation abilities of the wetland, three scenarios were explored for each of the three peak flow events examined within this study (17 April 2013; 28 August 2013; 15 September 2013).

Scenario A: Examining the flow of the river and its interactions with the wetland under dry season (summer) conditions

Scenario B: Examining the flow of the river and its interactions with the wetland under saturated, rainy season (winter) conditions

Scenario C: Examining the inflow and outflow (at a point in the river immediately downstream from the wetland) levels of the river with no connection to the wetland, simulating these rates as if the area was developed and there was no longer open green space to take on peak flow floods)

The rate at which the wetland can accept peak flow greatly varies between the dry summer and the wet winter seasons. When a rainfall event occurs at the onset of the rainy season, there is no standing water in the Valkenberg Wetland and the ground is not yet saturated. In this instance, scenario A, the water table is low and the wetland has the greatest attenuation capacity. When the rainy season begins, the ground becomes saturated, the water table rises, and water begins to pool in the area of depression within the wetland. This saturated state was reflected within scenario B. Lastly, the study was interested in exploring how the peak events would look when run through the model with no connection to the Valkenberg Wetland. This scenario (scenario C) simulates how the Liesbeek River would handle peak flow events with the Valkenberg Wetland being developed and thus not able to absorb a portion of peak flow during large precipitation events. To overcome seasonal variance, 'hot start' files within PCSWMM were created, which establishes pre-existing conditions. Hot start files are generally used to undertake seasonal modelling, as models for different seasons use different parameters to represent seasonal conditions (CHI Water 2015).

The three scenarios (A, B and C) for each of the three events (17 April 2013, 28 August 2013, 15 September 2013) were explored through the use of CHI's PCSWMM program, which has hydrologic, hydraulic, and water quality capabilities, with this study utilizing the hydrological component (CHI Water

2015). The 2D modelling option of the program was selected, as evaluating the overland flow with obstructions and relief maps is explored. 2D surface flows can be from overbank flooding from rivers and/or distributed rainfall. The 2D component of PCSWMM extends the dynamic 1D approach in PCSWMM/EPA SWMM5 to 2D free surface flow. Overland flows can be problematic for a 1D model alone, as there can be many flow pathways both around and through obstructions, and overland flow paths can be ill-defined and variable between flood events. PCSWMM is capable of providing accurate 2D modelling of flood depths, flows and velocities for urban areas, which this study utilizes for the Valkenberg Wetland area.

3.3.2 Model Boundary Delineation

The 2-D hydrodynamic model was configured with the primary aim of understanding the attenuation capabilities of the Valkenberg Wetland for the flood events generated within the Liesbeek catchment upstream from the wetland. In that respect, fluvial (from upstream river discharge) flooding was of much more interest than pluvial (i.e. combined local rainfall and upstream river discharge) flooding. The model domain was therefore not delineated based on the extent of catchment or subcatchment contributing to the inundation of the wetland, but rather on location of the upstream hydrometric station and local knowledge of areal flooding during peak flow events. When approaching model delineation for this study, it was decided that due to the close proximity of the Black River (0.5 km) to the east of the Valkenberg Wetland, the model could be delineated between the Liesbeek River and the Black River. The Stormwater and Sustainability branch of the Transport for Cape Town was contacted to explore available data and it was discovered that there was no flow data for the Black River.

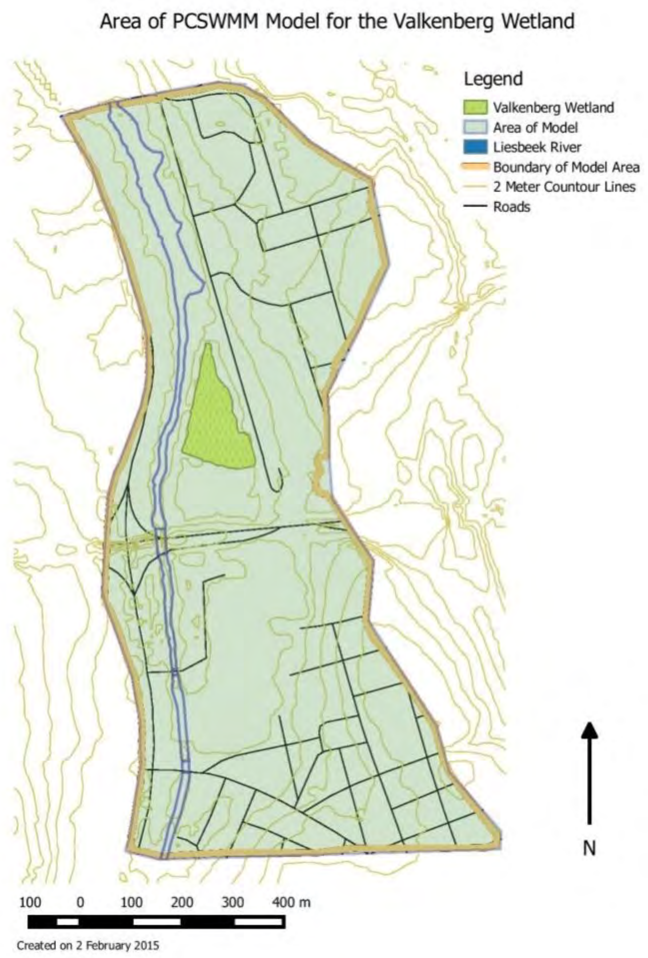


Figure 5 Area of Model as shown with contour lines

With no flow data for the Black River, combined with a lack of groundwater data, it was decided that the Black River could not in fact be used as a boundary. The eastern boundary of the model domain was then determined from contour lines and set at the water divide between the two rivers (Figure 4).

The southern boundary was delineated based on the location of the Klipfontein Road gauging station on the Liesbeek River, which was the source of flow data for this study. As there are no further hydrodynamic stations downstream, the northern boundary was delineated by the Station Road Bridge, which is one of the last geographical references before the Liesbeek and Black River confluence. To the west, the western boundary was then delineated based on the elevation of the roadway and the line was drawn along the curvature of this road, running parallel to the river.

3.3.3 DEM and 2D Mesh

Aerial photographs were added into the 2D model, followed by a digital elevation model (DEM) to display topographical features of the land at play. A bounding layer was then drawn to delineate the study area, which defined the extent of the 2D model. The bounding layer for this study was drawn using topographical and physical features of the site, as described in section 3.3.2.

Once bounding layers were drawn and the DEM is in place, a point grid was created for generating 2D nodes. The invert elevations of each node are assigned the average bottom elevation within each cell. Every node was connected to adjacent nodes with rectangular open channels or 2D conduits.2D nodes were provided with a small surface area (typically 0.1 m^2) and the surface area in each cell is assigned to the 2D conduits connected to the node to preserve continuity.

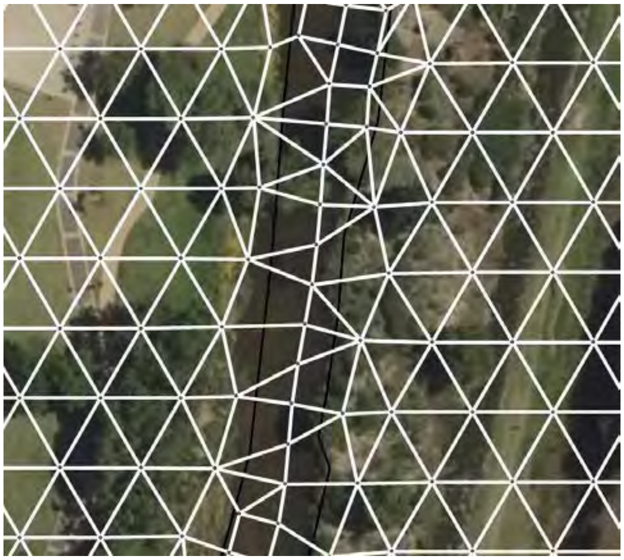


Figure 6 Visual of the 5 m hexagonal (land area) and 3 m directional (Liesbeek River area) mesh created for the 2D model

Lengths and widths of conduits are adjusted by PCSWMM according to a specific ratio dependent on the number of links connected to the node, and which was determined in a large number of tests to give expected wave speeds under a wide range of scenarios. The program calculates depth averaged water velocity for each 2D cell by considering the vector sum of the velocities of links that have flow leaving the cell. For the mesh resolution, PCSWMM recommends that a 2D mesh should only be as fine as necessary to reduce model run time. For the river bounding layer, a higher resolution of a 3 metre directional mesh is created to simulate flow and an edge definition was utilized which signals abrupt elevation changes, further defining the river. A 2D hexagonal mesh was generated at a 5 metre resolution for the land area. With the river being relatively narrow (three to five metres wide at narrow sections), the higher resolution was chosen for the river section, while leaving the resolution lower throughout the land area.

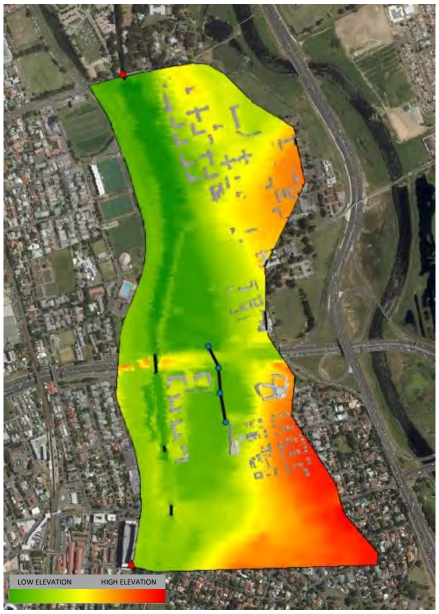


Figure 7 2D cells rendered to show elevation of model area

For post-run analysis, PCSWMM can thematically render the 2D velocity (Figure 6). Animated 2D simulation results, complete with velocity vectors, were also available and were helpful in interpreting simulation runs for this study.

3.3.4 Roughness Coefficient and Infiltration Equation

The empirical Manning's formula (Manning 1891) was used for estimating the average velocity of water flowing in a conduit with does not completely enclose the fluid, such as an open channel.

Manning's formula (Manning 1891):

$$Q = VA = \left(\frac{1.00}{n}\right) AR^{\frac{2}{3}} \sqrt{S}$$

Where:

Q = Flow Rate, (m^3/s)
v = Velocity, (m/s)
A = Flow Area, (m^2)
n = Manning's Roughness Coefficient
R = Hydraulic Radius, (m)
S = Channel Slope, (m/m)

Manning's coefficient (u) ranges from 0.013 for an asphalt lined channel, to 0.100 for an irregular natural channel with pools. For this model, Manning's *n* value of 0.120 was used for the concrete lined portion of the Liesbeek River, and 0.060 for the natural stretch of the river. For the overland area of the model, an n value of 0.24 was used, which is a typical value for grassy areas (Manning 1891).

The infiltration rate of any site is the rate at which soil is able to absorb water and is measured in millimetres per hour. This rate decreases as the soil becomes saturated and at the point of fully saturated soil, runoff will occur, or in the instance of a topographical depression such as the Valkenberg Wetland, ponding will begin. The 2D model for this study utilized Horton's equation (Horton 1933). The parameters used were: maximum infiltration rate of 3 (rate for loam soil); a minimum infiltration rate of 0.5 (equivalent to the saturated hydraulic conductivity); decay constant of 4; drying time of 7 (number of days for fully saturated soil to dry completely); and maximum infiltration rate of 0.

Horton's Equation (Horton 1933):

$$f_t = f_c + (f_0 - f_c)e^{-kt}$$

Where

f_t = Infiltration rate at time *t*
f_0 = Initial infiltration rate or maximum infiltration rate

f_c = Constant or equilibrium infiltration rate after the soil has been saturated or minimum infiltration rate
k = Decay constant specific to the soil

3.3.5 Selection of Modelled Events

This study evaluated the peak flow rates of the Liesbeek River from September 2012 through September 2013 (data set dates selected based on the availability of flow data for this period), as measured at the Klipfontein Road hydrodynamic gauging station and then corrected by PhD student, Lloyd Fisher-Jeffes (2015). The top ten peak flow rates were identified from the available 13 month data set and then evaluated for key interests points, such as highest peak flow rate and longest duration of peak flow. The three events which were of particular interest after having graphed the flow rate (m^3/s) versus time (24 hour day) were the 17 April 2013, 28 August 2013, and 15 September 2013events. The peak flow rate of 37.78 m^3/s on 17 April was the largest flow volume for a single 24 hour day during the one year data set (Figure 8). The duration of a high flow rate was found to be the longest on 28 August, with a peak flow that illustrated a sudden increase of flow rate which then plateaued and remained for nearly 8 hours until decreasing to a pre-storm event level (Figure 9).Lastly, the eighth largest peak flow event for this data set was on 15 September 2013 and was chosen based on its comparatively lower, yet pronounced peak flow curve, which illustrated a rapid increase of flow to the Liesbeek River which quickly decreased (Figure 10).

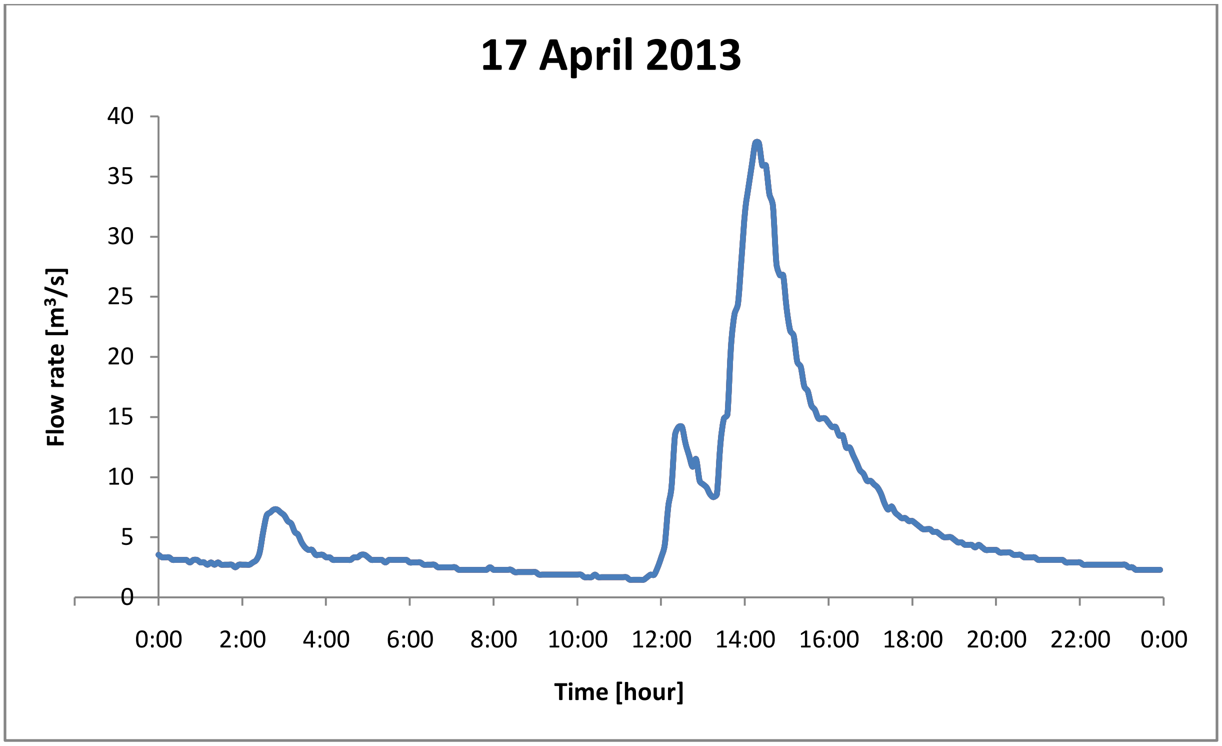


Figure 8Hydrometric gauging station data for 17 April 2013

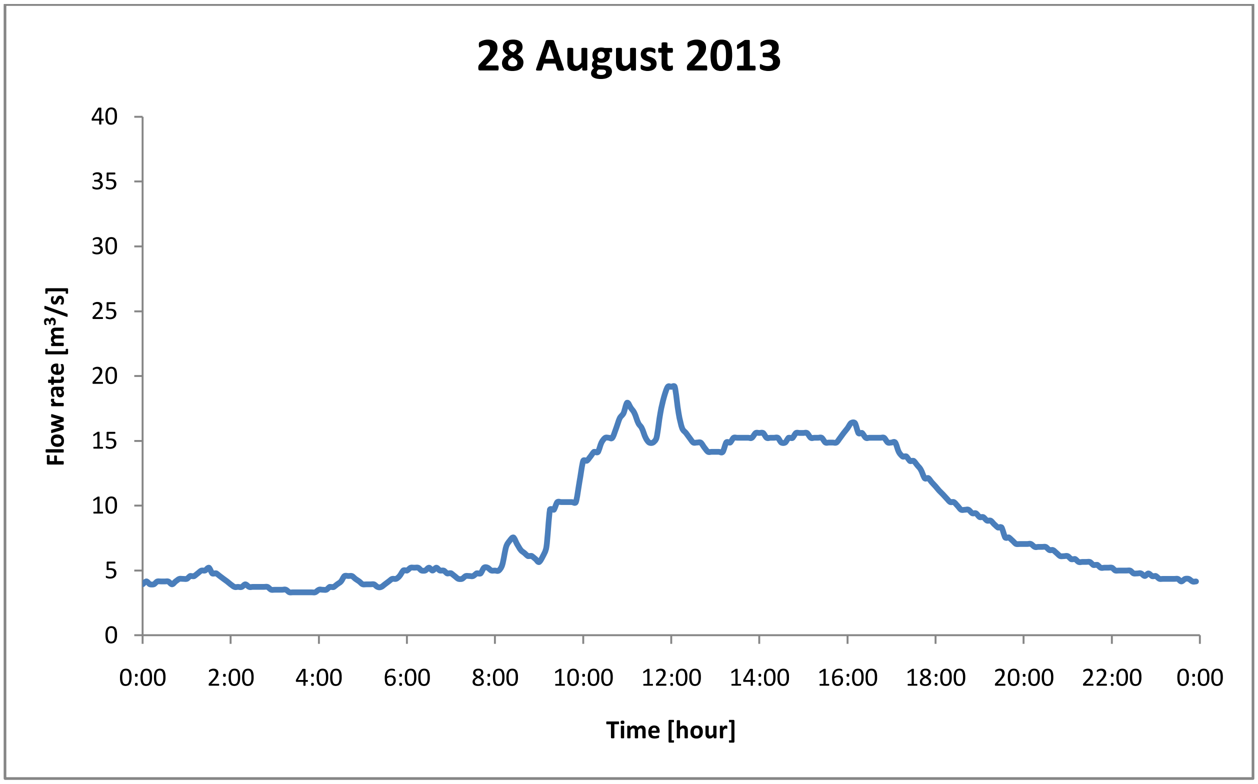


Figure 9 Hydrometric gauging station data for 28 August 2013

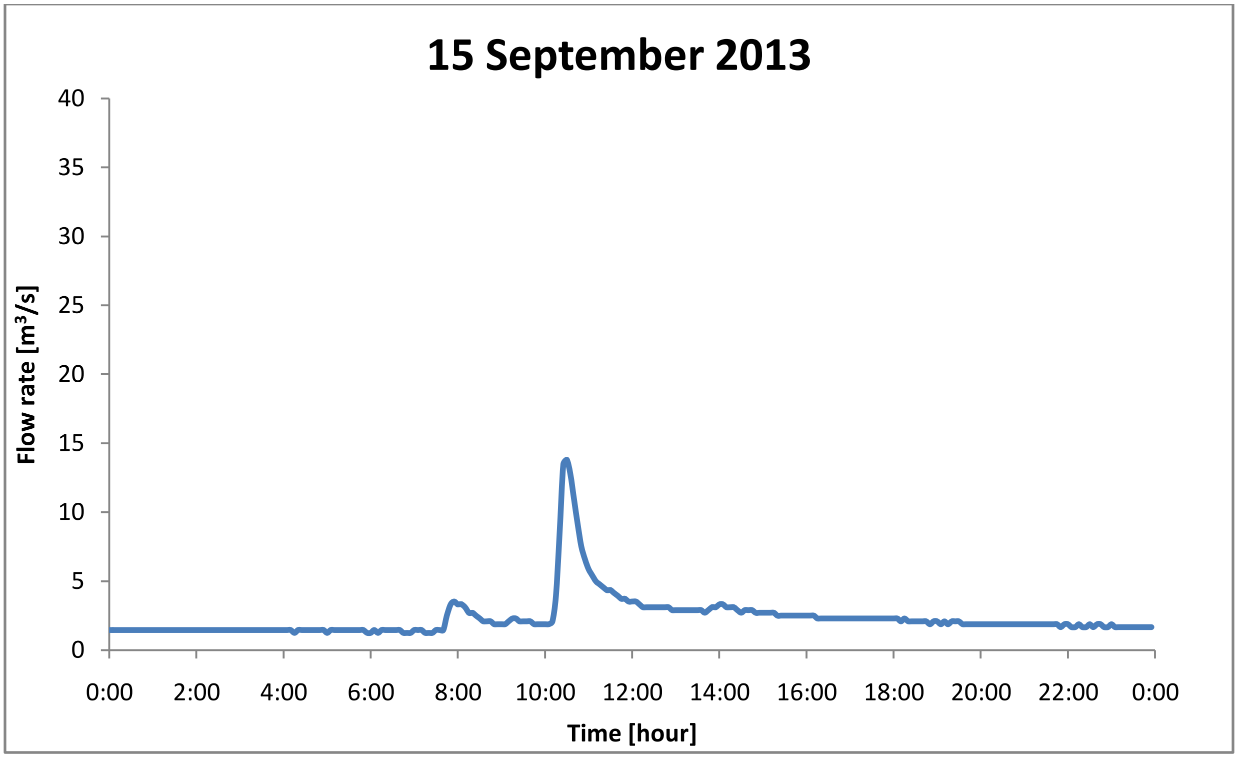


Figure 10 Hydrometric gauging station data for 15 September 2013

3.3.6 Model Calibration and Validation

When modelling a hydrological system, the performance of the model is generally evaluated by comparing the model results against data which has been independently derived from either experiments or observations of the system. To validate the model configured for this study, observations such as a downstream hydrodynamic gauging station or water level monitoring within the wetland would be necessary, which unfortunately were not available at this time. To calibrate the model, the study would require a known input and known output. As there is no available data for downstream of the wetland, a strict quantitative calibration was also not possible. This study produced a model which has been configured with the best available data, but cannot be used in quantitative assessment due to data limitations. Establishing monitoring within the wetland and enhancement of monitoring within the catchment would be beneficial for future work. Additionally, an approach either including or focusing on historic flooding photographs could be taken, however this approach was not chosen for this study as it was decided to remain strictly to numerical data. As the limitations of model validation are recognized, this study limits conclusions to general understandings of the wetland to qualitatively illustrate the potential of the wetland, or rather wetlands of similar type, in reducing peak flow of flooding events.

3.4 Limitations

Models are an approximation of reality and are not capable of accurately representing exact natural systems. Modelling of the Valkenberg Wetland system was configured as best as possible with the data available, and by doing so, the study was able to evaluate the performance of the wetland in attenuating peak flow and assist in the creation of a baseline study.

Understanding the hydraulics of the river is not as clear as other rivers which are better monitored. There are only two hydrometric gauging stations upstream from the study location; one of which does not function properly and the other is also not ideally placed to pick up low flows, and there are no gauging stations downstream. This limited data has however been collected from the City of Cape Town and then corrected by a PhD student at UCT, Lloyd Fisher-Jeffes (2015), adding to its usefulness.

There were three major areas of interest where data are either absent or limited. Firstly, there were intentions to use groundwater data to examine interactions between the Liesbeek River, the Valkenberg Wetland, and the nearby Black River with the groundwater table. After consulting with the City of Cape Town, a local business in the area (The Wild Fig Restaurant), it became clear there was no groundwater data for the area. Secondly, this study required flow data from the nearby Black River. The Black River flows parallel to the Liesbeek River at the point of the Valkenberg Wetland, only 700 m to the east. The City of Cape Town's Stormwater and Sustainability Branch were contacted and it was confirmed that the Black River did not have any gauging stations. Thirdly, it would have been ideal to have a downstream gauging station in order to further understand downstream flood events as well as assist with model validation and calibration.

Regarding rainfall, after evaluating multiple factors, it was determined that rainfall data would not be modelled within this study. This decision was made for two main reasons. Firstly, rainfall is ideally modelled at the catchment scale (or at least subcatchment level) and modelling at such a scale was not within the scope of the project. Delineation of this model was decided by the location of the hydrodynamic gauging station where the flow data was sourced, and then the parameters were chosen by observed areas which flood during peak flow events, as described in greater detail in section 3.3.2

which discusses model delineation. In addition to model scope, reliable rainfall data for the catchment was lacking.

While some aspects of historical data was lacking, this study aims to build a baseline dataset of the attenuation capacity for the site and provide insight on urban drainage in a South African context which future studies can build from and expand on.

4 Results and Discussion

This study found that the Valkenberg Wetland could potentially delay peak flow rates of the Liesbeek River. The attenuation capacity of the wetland and the ability for it to reduce peak flow of the Liesbeek River varied depending on the characteristics of the rain event, as well as the seasonal conditions (less attenuation possible during saturated winter months, more so in the early spring when the ground is not yet saturated) modelled as seen in the rainfall events and scenarios outlined in the following sub sections. The reduction of flow can be seen as 'peak flow clipping.' For flashy floods where the flow rate increases and then decreases over a short period of time, the wetland performed most effectively in reducing peak flows. This was observed most prominently for the 17 April 2013 and 15 September 2013 events. With prolonged periods of steady rain, such as the 28 August 2013 events, the wetland contributed to peak flow reduction at a lesser extent.

Further exploration within the entire catchment could lead to other features (bridges, weirs, etc.) which could influence peak flow rates. Due to the scope of this project, catchment scale evaluation was not further examined.

4.1.1 17 April 2013 Peak Flow Event

The rainfall event of 17 April 2013 (24.8 mm) (CIP 2015) led to the largest peak flow rate recorded (37.78 m^3/s) within the September 2012 through September 2013 data set this study used. There were reports of flooding around the City of Cape Town as a cold front arrived, bringing heavy rains across the entire peninsula (Loggenberg 2013).

For scenario A (Appendix A) (dry, summer conditions) where the wetland was fully connected to the river, the wetland assisted in reducing the peak flow from 37.78 m^3/s to 22.24 m^3/s and delayed the outflow peak by approximately one hour. This 42% reduction of flow would be beneficial to downstream properties which historically experience damage during high peak flow events. The outflow hydrograph is, however, extended in time, with higher flows observed at the end of the simulation. This reflects drainage of water from the wetland storage back to the river.

In scenario B (Appendix B) (wet, winter conditions) where the wetland was fully connected to the river, but partially filled prior to the flood event, peak flow was reduced by 21.77 m^3/s. This 42% reduction of flow generates only slightly different response in terms of outflow hydrograph than that of scenario A. The water level fluctuations in the wetland, however, behave differently than in scenario A. In this scenario B, they indicate that during the time prior to the flood, the wetland was still draining to the river and that the peak water level in the wetland was approximately 8 cm higher than that under scenario A.

Scenario C (Appendix C), where the wetland is not connected to the river, generates outflow peak that is slightly delayed (approximately one hour) and lower by 3.47 m^3/s with respect to inflow peak. The lack of response of water levels in the wetland confirms that there was no flow between the river and the wetland in this scenario. This shows that for this event, water did not reach a flow rate high enough to leave the river banks and enter the wetland. Reduction in this scenario is likely caused to small spillage during low bank areas of the river as well as absorption in pervious portions of the river. For a rain event such as this, scenario C highlights what potential development would do to downstream flooding and underlines the ecosystem services the Valkenberg Wetland provides for the area, as observed in scenario A and scenario B.

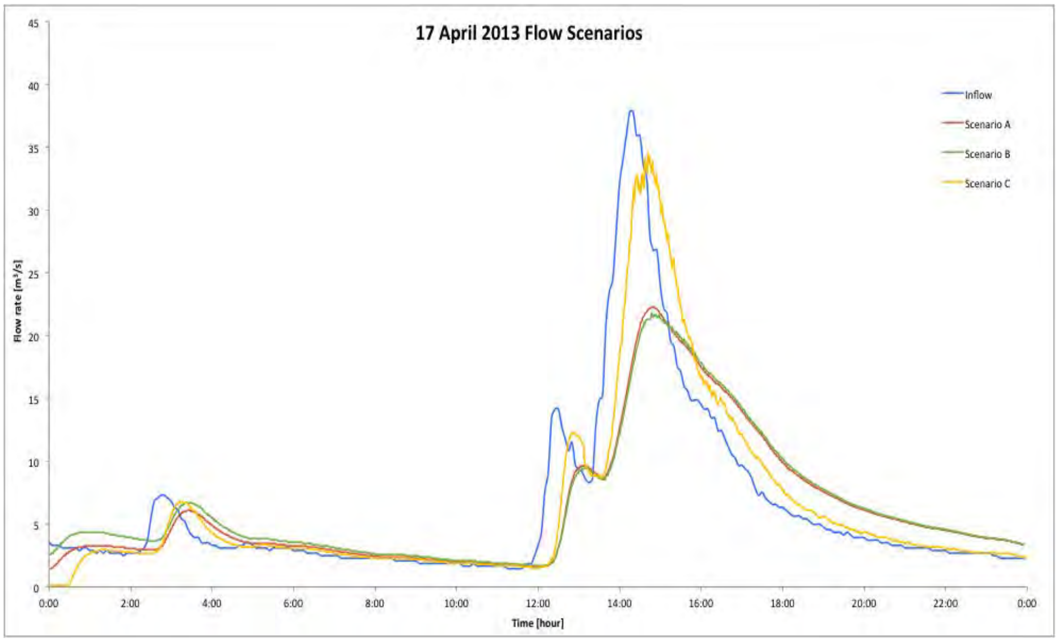
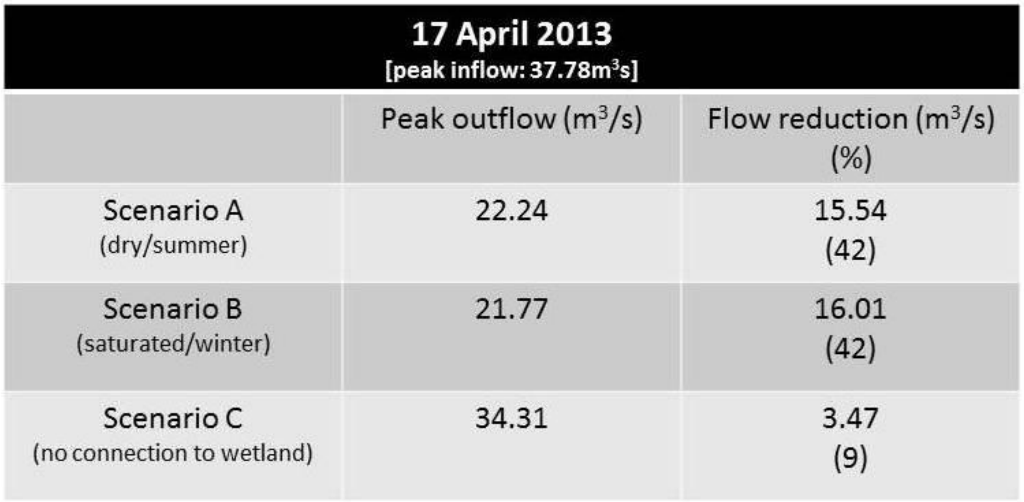


Figure 11 Flow scenarios for 17 April 2013

Table 1 Scenario comparison for 17 April 2013



17 April 2013 [peak inflow: 37.78m^3s]		
	Peak outflow (m^3/s)	Flow reduction (m^3/s) (%)
Scenario A (dry/summer)	22.24	15.54 (42)
Scenario B (saturated/winter)	21.77	16.01 (42)
Scenario C (no connection to wetland)	34.31	3.47 (9)

Depth within the wetland varied by scenario, but did not reach capacity (completely fill with water) in any of the scenarios, based on the peaking observed in scenario A and scenario B. Had the wetland reached capacity, flow depths would have reached a constant and a maximum value (Figure 12). Scenario B highlighted how the wetland performs when there are consecutive large rainfall events one day after the other. With the flow data from 17 April 2013, the wetland begins to drain before the next peak flow event arrives 24 hours later. Had groundwater data been available to include within the model, this simulation may have produced different results by reflecting ground saturation more explicitly. For example, if the ground had been saturated, scenarios would have taken on less water within the wetland. Scenario C has no depth observed, as this scenario was run with no connection to the wetland.

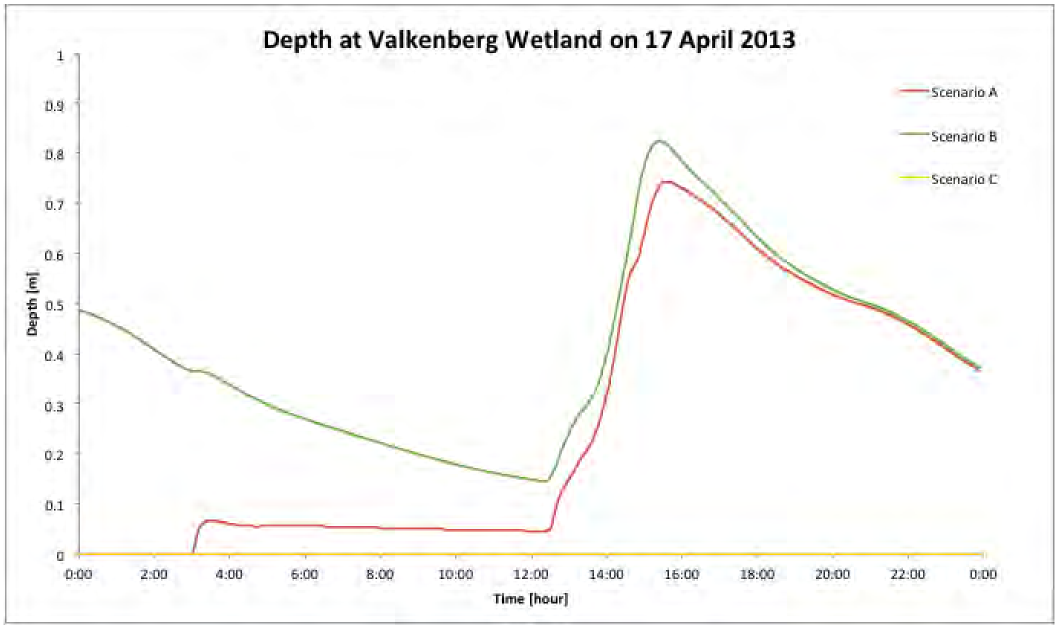


Figure 12 Depth of water attenuated by the Valkenberg Wetland on 17 April 2013

4.1.2 28 August 2013 Peak Flow Event

On 28 August 2013, 38.3 mm/day of rainfall fell at the Observatory rainfall station within a 24 hour period(CIP 2015). It is likely that the rainfall was significantly more intense upstream within the catchment, as that is characteristic of this catchment. This was the third highest peak flow event from the September 2012 through September 2013 data set this study used and of particular interest due to the longevity of the peak flow. This event consisted of approximately eight hours of constant flow rate which began just after 9:00 and continued until nearly 18:00. In this instance, unlike that of the 17 April 2013 event, the Valkenberg Wetland did not make a significant impact on the magnitude of peak flow. Attenuation by the wetland did appear to remove the initial peaks from the event, and cause a delay in the flow by about thirty minutes; however the overall effect was much less pronounced than in the other analysed events.

The dry, summer conditions of scenario A (Appendix D) showed that the wetland reduced peak flow from 19.16 m^3/s to 15.42 m^3/s, a 20% decrease. Scenario B (Appendix E) (wet, winter conditions) saw nearly identical results as scenario A, with the peak flow being reduced to 15.41 m^3/s as the wetland attenuated 20% of the flow. A 4% reduction of peak flow was shown in scenario C (Appendix F), with that portion being lost only within the channel of the Liesbeek River, as this scenario is not connected to the wetland.

Once again, as observed in the 17 April 2013 scenarios, both scenario A and B are nearly identical. An understanding of the ground water-surface water interactions would have been beneficial when simulating these two scenarios, as it may have revealed further information on the attenuation capacity when the soil is at full saturation.

Regarding depth within the 28 August 2013 scenarios, both scenario A and B are nearly identical, with A being less than 0.1 m lower than B (Figure 14). The depths of the wetland decrease quite quickly after therain event, as seen in scenario B where the pre-existing conditions were saturated. No depth level was observed with scenario C, as this scenario was run with no connection to the wetland.

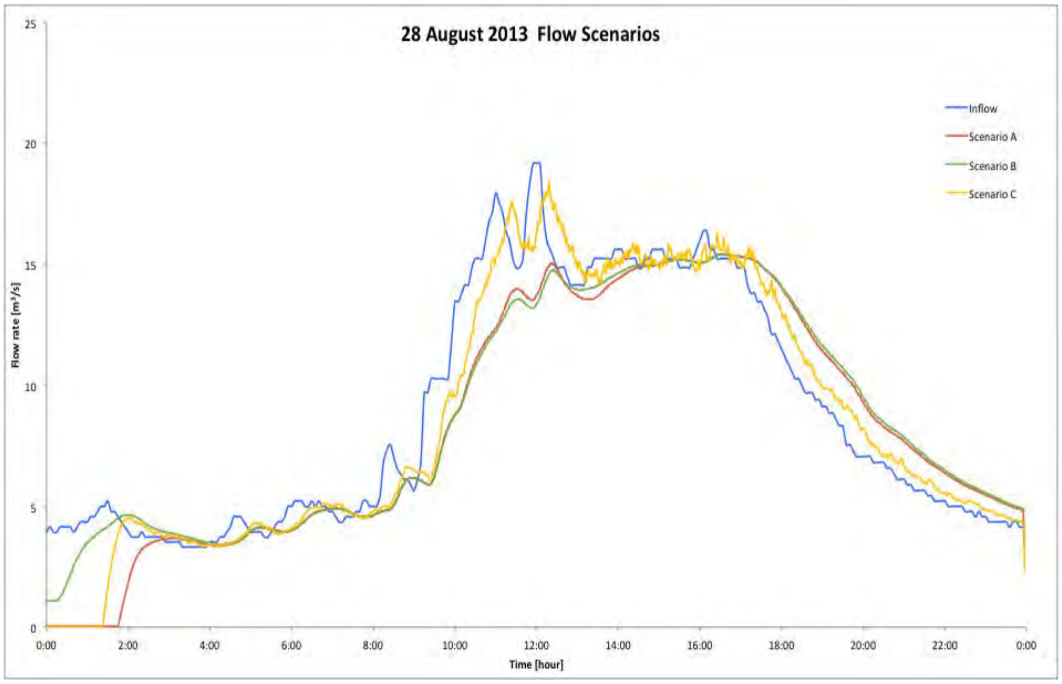


Figure 13 Flow scenarios for 28 August 2013

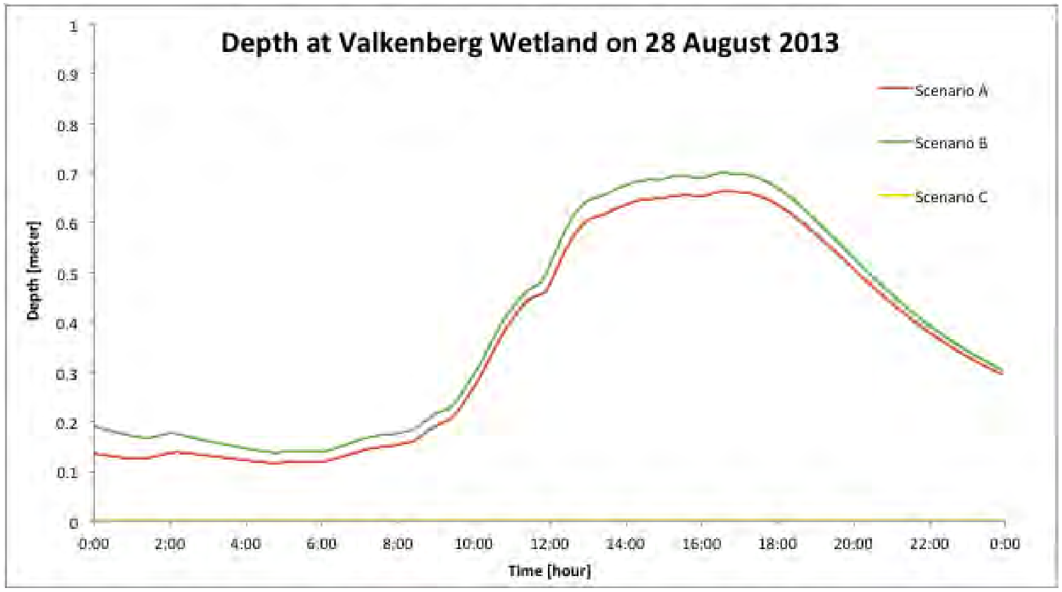


Figure 14 Water depth within the Valkenberg Wetland on 28 August 2013

Table 2 Scenario comparison for 28 August 2013

28 August 2013 [peak inflow: 19.16m³s]		
	Peak outflow (m³/s)	Flow reduction (m³/s) (%)
Scenario A (dry/summer)	15.42	3.74 (20)
Scenario B (saturated/winter)	15.41	3.75 (20)
Scenario C (no connection to wetland)	18.44	0.72 (4)

4.1.3 15 September 2013 Peak Flow Event

The rainfall event on 15 September 2013 brought 6.8 mm/day (CIP 2015) to the Valkenberg Wetland area, though again this is likely to have varied throughout the catchment and have been more intense upstream. A peak flow of the Liesbeek River was recorded at 13.79 m^3/s at just before 11:00. The event was the eighth highest peak flow event within the September 2012 through September 2013 data set used. This event was chosen to represent a short event of smaller magnitude.

Scenario A (Appendix G) displayed a flow reduction of 42 per cent with the dry, summer conditions. As seen in the 17 April 2013 and 28 August 2013 events, again the saturated winter conditions of scenario B (Appendix H) were similar, with B reducing the flow rate by 41 per cent, just 1 per cent less than that of the dry conditions of scenario A. Scenario C (Appendix I) reduced the peak flow by 22%, the largest percentage of the three dates modelled, due to the relatively lower peak flow rate for this 15 September 2013 event and therefore a larger percentage, though not a larger volume, was able to be adsorbed within the banks of the channel. Scenario A and scenario B demonstrated the ability to reduce localised flooding, as peak flow was reduced by 42 and 41 per cent, respectively.

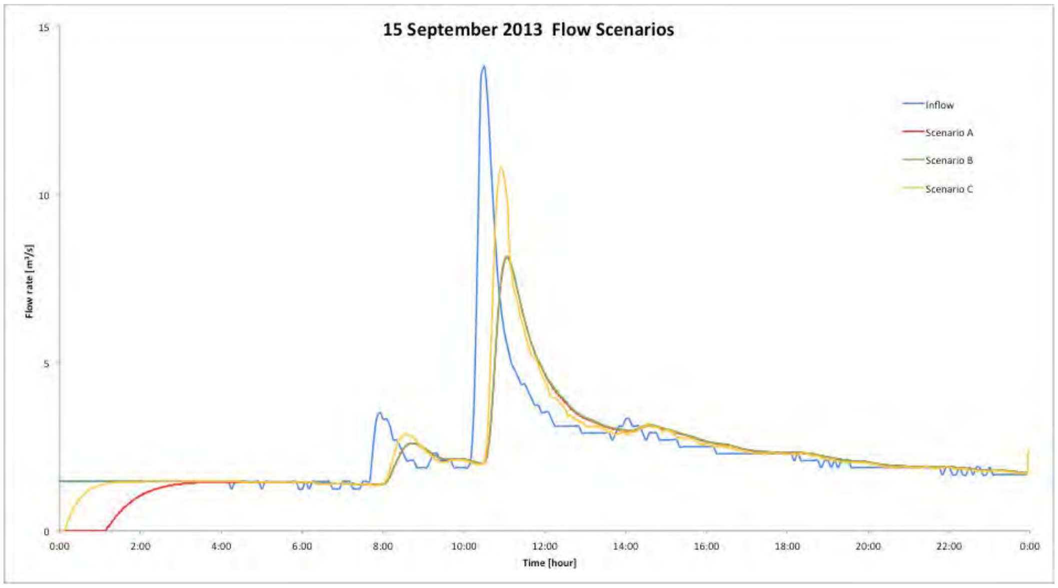
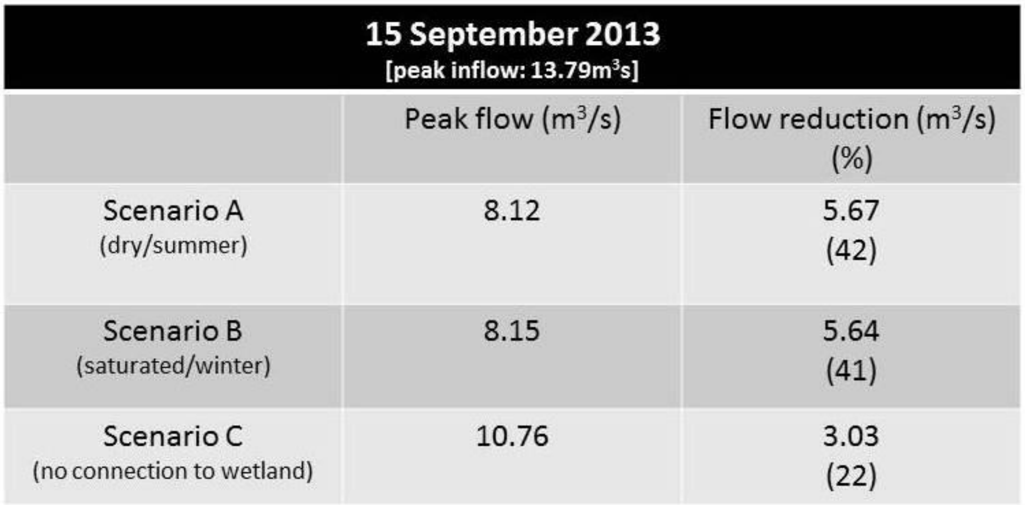


Figure 15 Flow scenarios for 15 September 2013

Table 3 Scenario comparison for 15 September 2013



15 September 2013 [peak inflow: 13.79m³s]		
	Peak flow (m³/s)	Flow reduction (m³/s) (%)
Scenario A (dry/summer)	8.12	5.67 (42)
Scenario B (saturated/winter)	8.15	5.64 (41)
Scenario C (no connection to wetland)	10.76	3.03 (22)

Depth for scenario A was at zero up until nearly 11:00, when the peak flow event arrived, at which point the depth increased from 0.0 to 0.1 m (Figure 16). Scenario B remained ponded initially and then also increased as the peak flow arrived just before 11:00. The depth for both A and B begin decreasing within an hour of the peak flow event, where the wetland begins emptying.

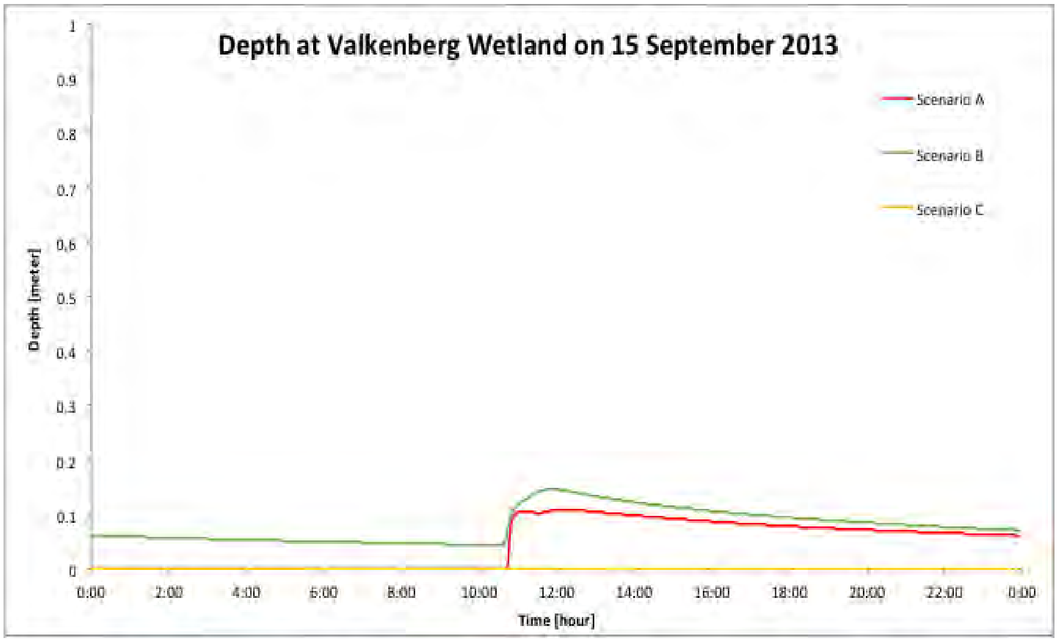


Figure 16Depth of water attenuated by the Valkenberg Wetland on 15 September 2013

5 Conclusion and Recommendations

5.1 Conclusion of Study

This research explored urban flooding in the Liesbeek catchment, specifically in the area of the Valkenberg Wetland, where the ability to reduce peak flow by attenuation has been observed.

The results of all three simulated events indicate that the Valkenberg Wetland plays a significant role in reducing flood events of short duration, and various magnitudes, but is less effective for reducing events that are of longer duration. This is likely an effect resulting from the relatively small storage capacity of the wetland. Once this storage is full, the influence of the wetland on downstream flow is limited. This conclusion is relatively robust with regards to quality of the available data, as it largely depends on the relationship between the volume of the wetland's depression, and the typical flow volumes of the Liesbeek flow, which are elements this model appears to capture well.

The influence of the residual storage on the flood attenuating capacity of the wetland is limited. It seems that the natural dynamics of water flow between the wetland and the river is enough to maintain the flood attenuation capacity considering the diurnal cyclicity and time scale of events observed in the Liesbeek river (i.e. events lasting between 2 and 5 hours, occurring at approximately 24 hour intervals. This suggests that no special management of the wetland water levels, such as draining after peak flow events, is required. This finding is however strongly conditional on the configuration of the model, particularly topography of the wetland and elevation of river banks, which, as we describe in the limitations section, was not well captured by the available DEM. It is therefore recommended that this conclusion is verified with further research.

Open spaces such as the Valkenberg Wetland are beneficial in many ways, including providing ecosystem services by taking on peak flow that would otherwise have the potential to cause property damage (by naturally attenuating peak flow rates, the wetland can potentially reduce damage to properties). If the area were to be developed, the loss of the open space of the wetland has the potential cause downstream residents and businesses property damage. While this study does not focus on the biological aspects of the study site, there are inherent benefits for flora and fauna by preserving the natural space. The found benefits of using the wetland to attenuate peak flow and thus reduce downstream flooding underlines the benefit of the ecosystem services the wetland provides.

Based on the results of the modelling carried out in this study, peak flow of the Liesbeek River was reduced in scenarios with the Valkenberg Wetland present to accept on a portion of this flow. While this reduction is not significant enough to eliminate flooding as a whole, likely due to the small volume of the wetland compared to the flow volumes in the typical events, the ability of the wetland to accept part of stream flow appears to be able to reduce the severity of flood events downstream from the wetland. Through modelling, the study provided an example of wetland functionality that could potentially be replicated throughout the studied catchment (and also in other similar catchments), creating potential for the entire combined system to significantly reduce peak flow of storm events and thus reduce risk of and property damaging flooding.

In addition, this study highlighted that the depth of the wetland increases with peak flow as overland flooding occurs. The modelled draining of the wetland following peak flow occurred within 12 hours for all three peak flow events, leaving the wetland to return to a pre-peak flow event level. It is noted that this may differ with an improved model which includes ground water data, which would highlight the ground water-surface water interactions. It is also likely to differ for higher intensity rainfall events, which the 13 month data set did not include.

By discussing the urbanization of rivers in Cape Town and addressing urban flooding aspects with hydrological modelling, this study addressed a gap previously found in the literature. Attenuation within this urban wetland appears to have positive downstream implications by reducing peak flow of the Liesbeek River and thus decreasing the severity of property damaging flooding.

5.2 Recommendations for Further Studies

As a shortage of available data kept the study from calibrating and validating the model, the conclusions of this study are highlighted as a general understanding of the wetland to illustrate the potential role the Valkenberg Wetland plays in reducing peak flow flooding events. A fully comprehensive model would have included groundwater inputs and hydrograph readings from downstream of the wetland, as well as flow data from the nearby Black River. Due to data limitations which imposed restrictions on modelling, the study designed a model that could best represent the area of interest with the data available at present to establish a baseline study for the Valkenberg Wetland area.

Future research would be beneficial in terms of determining Black River flow rates and groundwater – surface water interactions within the Valkenberg Wetland. This data would assist in further understanding the attenuation of the wetland and could contribute towards a more inclusive model of the wetland and river interactions. In addition to expanding hydrologic data, the mapping of existing wetlands and potential areas for constructed sustainable urban drainage techniques would be beneficial for evaluating the extent to which a larger system of attenuation methods could reduce peak flow resulting from intense rainfall.

6 References

Abbott, C.L. & Comino-Mateos, L., 2001. In Situ Performance Monitoring of an Infiltration Drainage System and Field Testing of Current sign Procedures.

Acreman, M. & Holden, J., 2013. How wetlands affect floods. *Wetlands*, 33, pp.773–786.

Adger, W.N., 2006. Vulnerability. *Global Environmental Change*, 16(3), pp.268–281. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0959378006000422 [Accessed July 9, 2014].

Anguelovski, I., Chu, E. & Carmin, J., 2014. Variations in approaches to urban climate adaptation: Experiences and experimentation from the global South. *Global Environmental Change*, 27, pp.156–167.

Anon, 1971. Convention on Wetlands International Importance Especially as Waterfowl Habitat. In Iran: Ramsar.

Barbier, E.B., 1993. Sustainable Use of Wetlands - Valuing Tropical Wetland Benefits - Economic Methodologies and Applications. *Geographical Journal*, 159(1), pp.22–32.

Brown, R.R. & Farrelly, M., 2009. Delivering sustainable urban water management: a review of the hurdles we face. *Water science and technology�: a journal of the International Association on Water Pollution Research*, 59(5), pp.839–46. Available at: http://www.ncbi.nlm.nih.gov/pubmed/19273882 [Accessed July 19, 2014].

Burns, M.J., Fetcher, T.D., Walsh, C.J., Ladson, A.R., Hatt, B.E., 2012. Hydrologic shortcomings of conventional urban stormwater management and opportunities for reform. *Landscape and Urban Planning*, 105(3), pp.230–240. Available at: http://linkinghub.elsevier.com/retrieve/pii/S016920461100363X [Accessed November 24, 2014].

Burrel, B.C., Davar, K. & Hughes, R., 2007. A Review of Flood Management Considering the Impacts of Climate Change. *Water International*, 32(3), pp.342–359. Available at: http://www.tandfonline.com/doi/abs/10.1080/02508060708692215 [Accessed July 15, 2014].

Butler, D., Parkinson, J., 1997. Towards sustainable urban drainage. *Water Science and Technology*, 35(9), pp.53–62.

CHI Water, 2015. SWMM Modeling with PCSWMM. Available at: http://www.chiwater.com/Software/PCSWMM/ [Accessed January 2, 2015].

Chocat, B., Ashley, R., Marsalek, J., Matos, M.R., Rauch, W., Schilling, W., Urbonas, B., 2007. Toward the Sustainable Management of Urban Storm-Water. *Indoor and Built Environment*, 16(3), pp.273–285. Available at: http://ibe.sagepub.com/cgi/doi/10.1177/1420326X07078854 [Accessed July 15, 2014].

Christopher J. Walsh, Allison H. Roy, Jack W. Feminella, Peter D. Cottingham, Peter M. Groffman, and R.P.M.I., 2005. The urban stream syndrome: current knowledge and the search for a cure. , 24(3), pp.706–723.

CIP - Climate Information Portal, 2015. 2013 Cape Town Observatory (33.94S 18.48E) Daily Rainfall Total. *CIP Rainfall Data*. Available at: http://cip.csag.uct.ac.za/ [Accessed February 2, 2015].

Costanza, R. & Kubiszewski, I., 2012. The authorship structure of "ecosystem services" as a transdisciplinary field of scholarship. *Ecosystem Services*, 1(1), pp.16–25. Available at: http://dx.doi.org/10.1016/j.ecoser.2012.06.002.

Crutzen, P.J., 2002. Geology of mankind. *Nature*, 415(23), p.2002.

Echols, S., 2007. Artful rainwater design in the urban landscape. *Journal of Green Building*, 2(4), pp.156–167.

Egger, C. & Maurer, M., 2015. Importance Of Anthropogenic Climate Impact, Sampling Error And Urban Development In Sewer System Design. *Water Research*. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0043135415000044 [Accessed January 18, 2015].

Fisher-Jeffes, L., 2015. *The viability of stormwater harvesting in South Africa (working title)*. University of Cape Town.

Fletcher, T.D., Vietz, G. & Walsh, C.J., 2014. Protection of stream ecosystems from urban stormwater runoff: The multiple benefits of an ecohydrological approach. *Progress in Physical Geography*, 38(5), pp.543–555. Available at: http://ppg.sagepub.com/cgi/doi/10.1177/0309133314537671 [Accessed November 20, 2014].

Folke, C., 2006. Resilience: The emergence of a perspective for social–ecological systems analyses. *Global Environmental Change*, 16(3), pp.253–267. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0959378006000379 [Accessed July 9, 2014].

Fryd, O., Dam, T., Bergen Jensen, M., 2012. A planning framework for sustainable urban drainage systems. *Water Policy*, 14, pp.865–886.

G. Freni, G.L.L. and V.N., 2010. Uncertainty in urban flood damage assessment due to urban drainage modelling and depth-damage curve estimation. *Water Science & Technology*, 61(12), pp.2979–2993.

Holman-Dodds, J.K., Bradley, A.A. & Potter, K.W., 2003. Evaluation of hydrologic benefits of infiltration based urban storm water management 1. , 53706, pp.205–215.

Huong, H.T.L. & Pathirana, A., 2013. Urbanization and climate change impacts on future urban flooding in Can Tho city, Vietnam. *Hydrology and Earth System Sciences*, 17(1), pp.379–394. Available at: http://www.hydrol-earth-syst-sci.net/17/379/2013/ [Accessed August 6, 2014].

Imfeld, G., Lefrancq, M., Maillard, E., Payraudeau, S., 2013. Transport and attenuation of dissolved glyphosate and AMPA in a stormwater wetland. *Chemosphere*, 90, pp.1333–1339. IPCC, 2007. *Summary for Policymakers. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* H. L. M. Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor, ed., Cambridge, United Kingdom and New York, NY, USA.

Javaheri, A. & Babbar-Sebens, M., 2014. On comparison of peak flow reductions, flood inundation maps, and velocity maps in evaluating effects of restored wetlands on channel flooding. *Ecological Engineering*, 73, pp.132–145. Available at: http://dx.doi.org/10.1016/j.ecoleng.2014.09.021.

Kabat, P. & van Schaik, H., 2003. *Climate changes the water rules – how water managers can cope with today's climate variability and tomorrow's climate change*, Delft: The Dialogue on Water and Climate.

Keller, A.A., Chen, X., Fox, J., Fulda, M., Dorsey, R., Seapy, B., Glenday, J., Bray, E., 2014. Attenuation Coefficients for Water Quality Trading. *Environmental Science & Technology*, 48, pp.6788–6794. Krebs, P. & Larsen, T.A., 1997. Guiding the development of urban drainage systems by sustainability criteris. *Water Science and Technology*, 35(9), pp.89–98.

Lannas, K.S.M. & Turpie, J.K., 2009. Valuing the provisioning services of wetlands: Contrasting a rural wetland in lesotho with a peri-urban wetland in south africa. *Ecology and Society*, 14(2).

Larsen, T.A. & Gujer, W., 1997. The concept of sustainable urban water management. *Water Science and Technology*, 35, pp.3–10.

Loggenberg, C., 2013. Road Flooding in Cape Town. *EWN Eyewitness News*. Available at: http://ewn.co.za/2013/04/17/Flooding-around-CT.

Mail & Guardian, 2012. Cape Town ramps up flood relief efforts. *Mail & Guardian*. Available at: http://mg.co.za/article/2012-07-09-cape-town-ramps-up-flood-relief-efforts.

Mailhot, A. & Duchesne, S., 2010. Design Criteria of Urban Drainage Infrastructures under Climate Change. *Journal of Water Resoruces Planning and Management*, 136(April), pp.201–208.

Mander, Ü. & Mitsch, W.J., 2009. Pollution control by wetlands. *Ecological Engineering*, 35(2), pp.153–158.

Meybeck, M., 2003. Global analysis of river systems: from Earth system controls to Anthropocene syndromes. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, 358(1440), pp.1935–55. Available at: http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=1693284&tool=pmcentrez&rendertype=abstract [Accessed October 26, 2014].

Mitsch, W.J., Zhang, L., Stefanik, K.C., Nahlik, A.M., Anderson, C.J., Bernal, B., Hernendez, M., Song, K., 2012. Creating Wetlands: Primary Succession, Water Quality Changes, and Self-Design over 15 Years. *BioScience*, 62(3), pp.237–250. Montanari, A. et al., 2013. "Panta Rhei—Everything Flows":

Change in hydrology and society—The IAHS Scientific Decade 2013–2022. *Hydrological Sciences Journal*, 58(6), pp.1256–1275. Available at: http://www.tandfonline.com/doi/abs/10.1080/02626667.2013.809088 [Accessed November 5, 2014].

Montanari, A., Young, G., Savenije, H.H.G., Hughs, D., Wagener, T., Ren, L.L., Koutsoyiannis, D., Cudennec, C. Toth, E., Grimaldi, S., Blöschl, G., Sivapalan, M., Beven, K., Gupta, H., Hipsey, M., Schaefli, B., Arheimer, B., Boegh, E., Schymanski, S.J., Di Baldassarre, G., Yu, B., Hubert, P., Huang, Y., Schumann, A., Post, D.A., Srinivasan, V., Harman, C., Thompson, S., Rogger, M., Viglione, A., McMillan, H., Characklis, G., Pang, Z., Belyaev, V., 2013. ―Panta Rhei—Everything Flows‖: Change in hydrology and society—The IAHS Scientific Decade 2013–2022. *Hydrological Sciences Journal*, 58(6), pp.1256–1275. Available at: http://www.tandfonline.com/doi/abs/10.1080/02626667.2013.809088 [Accessed November 5, 2014].

Nascimento, N.O., Ellis, J.B., Baptista, M.B., Deutsch, J., 2000. Using detention basins: operational experience and lessons. *Urban Water*, 1(2000), pp.113–124.

Pahl-Wostl, C., 2007. Transitions towards adaptive management of water facing climate and global change. *Water Resources Management*, 21(1), pp.49–62. Available at: http://link.springer.com/10.1007/s11269-006-9040-4 [Accessed July 9, 2014].

Raubenheimer, G., 2013. Western Cape Hit By Flash Floods. *EWN Eyewitness News*. Available at: http://ewn.co.za/2013/11/16/CT-mops-up-after-major-flooding.

Republic of South Africa, 1998. *National Water Act No 36 of 1998*,

Republic of South Africa, 1997. *Water Services Act no 108 of 1997*,

Rockström J, Falkenmark M, Folke C, Lannerstad M, Barron J, Enfors E, Gordon L, Heinke J, Hoff H, P.-W.C., 2014. *Water Resilience for Human Prosperity*, Cambridge: Cambridge University Press.

Rockström, J., Falkenmark, M., Allan, T., Folke, C., Gordon, L., Jägerskog, A., Kummu, M., Lannerstad, M., Meybeck, M., Molden, D., Postel, S., Savenije, H., Svedin, U., Turton, A, Varia, O., 2014. The unfolding water drama in the Anthropocene: towards a resilience based perspective on water for global sustainability. *Ecohydrology*, 1261, p.n/a–n/a. Available at: http://doi.wiley.com/10.1002/eco.1562 [Accessed October 24, 2014].

Roy, A.H., Wenger, S.J., Fletcher, T.D., Walsh, C.J., Ladson, A.R., Shuster, W.D>, Thurston, H.W., Brown, R.R., 2008. Impediments and solutions to sustainable, watershed-scale urban stormwater management: lessons from Australia and the United States. *Environmental Management*, 42(2), pp.344–59. Available at: http://www.ncbi.nlm.nih.gov/pubmed/18446406 [Accessed July 15, 2014].

Scheffer, M., Bascompte, J., Brock, W.A., Brovkin, V., Carpenter, S.R., Daksos, V., Held, H., van Nes, E.H., Rietkerk, M., Sugihara, M., 2009. Early-warning signals for critical transitions. *Nature*, 461(7260), pp.53–9. Available at: http://www.ncbi.nlm.nih.gov/pubmed/19727193 [Accessed July 9, 2014].

Scholz, M., 2006. *Wetland Systems to Control Urban Runoff* First edit., Amsterdam: Elsevier.

Schulze, R.E., 2011. Approaches towards practical adaptive management options for selected water-related sectors in South Africa in a context of climate change. *Water SA*, 37(5), pp.621–646.

Schulze, R.E., 2003. On Models and Modelling for Integrated Water Resources Management: Some Thoguhts, Background Concepts, Basic Premises and Model Requirements. In R. E. Schulze, ed. *Modelling as a Tool in Integrated Water Resources Management: Conceptual Issues and Case Study Applications*. Pretoria, South Africa, pp. 20–46.

Semadeni-Davies, A., Hernebring, C., Svensson, G., Gustafsson, L.-G.,, 2008. The impacts of climate change and urbanisation on drainage in Helsingborg, Sweden: Suburban stormwater. *Journal of Hydrology*, 350(1-2), pp.114–125. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0022169407006749 [Accessed July 15, 2014].

Smith, R.L., 1980. *Ecology and Field Biology* 3rd ed., New York: Harper & Row.

Stuart-Hill, S.I. & Schulze, R.E., 2010. Does South Africa's water law and policy allow for climate change adaptation? *Climate and Development*, 2(2), pp.128–144. Available at: http://www.tandfonline.com/doi/abs/10.3763/cdev.2010.0035 [Accessed January 4, 2015].

Stuart-Hill, S.I., Schulze, R.E., 2012. *An Evaluation of the Sensitivity of Socio-Economic Activities to Climate Change in Climatically Divergent South African Catchments*,

TEEB, 2010. *TEEB: The Economics of Ecysystems and Biodiversity: Ecological and Economic Foundations* 1st ed. P. Kumar, ed., London, UK: Earthscan.

United Nations, 1992. *Agenda 21: Programme of Action for Sustainable Development*, New York, NY: United Nations Conference on Environment & Development. Available at: http://www.un.org/esa/sustdev/documents/agenda21/english/Agenda21.pdf.

WDC - World Design Capital, 2014. Two Rivers Urban Park #WDC235. Available at: http://www.wdccapetown2014.com/projects/project/213 [Accessed February 1, 2015].

Willems, P., Arnbjerg-Nielsen, K., Olsson, J., Nguyen, V.T.V., 2012a. Climate change impact assessment on urban rainfall extremes and urban drainage: Methods and shortcomings. *Atmospheric Research*, 103, pp.106–118. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0169809511000950 [Accessed July 11, 2014].

Willems, P., Olsson, J., Arnbjerg-Nielsen, K., Beecham, S., Pathirana, A., Gregersen, I.B., Madsen, H., Nguyen, V.T.V., 2012b. *Impacts of Climate Change on Rainfall Extremes and Urban Drainage Systems* 1st ed., London, UK: IWA Publishing.

Winter, K., 2014. Constructed wetlands need attention or else they fail. *Friends of the Liesbeek*. Available at: http://fol.org.za/wordpress/wp-content/uploads/Constructed-wetlands-need-attention.pdf [Accessed January 2, 2015].

Wong, T. & Brown, R., 2008. Transitioning to Water Sensitive Cities: Ensuring Resilience through a new Hydro-Social Contract. In *11th International Conference of Urban Drainage*. Edinburgh, Scotland, pp. 1–10.

Zhou, Q., 2014. A Review of Sustainable Urban Drainage Systems Considering the Climate Change and Urbanization Impacts. *Water*, 6(4), pp.976–992.

Zhou, Q., Panduro, T.E., Thorsen, B.J., Arnbjerg-Nielsen, K., 2013. Adaption to extreme rainfall with open urban drainage system: an integrated hydrological cost-benefit analysis. *Environmental management*, 51(3), pp.586–601. Available at: http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3579472&tool=pmcentrez&rendertype=abstract [Accessed July 15, 2014].

Zhou, Q., Panduro, T.E., Thorsen, B.J., Arnbjerg-Nielsen, K., 2012. Framework for economic pluvial flood risk assessment considering climate change effects and adaptation benefits. *Journal of Hydrology*, 414-415, pp.539–549. Available at: http://linkinghub.elsevier.com/retrieve/pii/S002216941100816X [Accessed July 15, 2014].

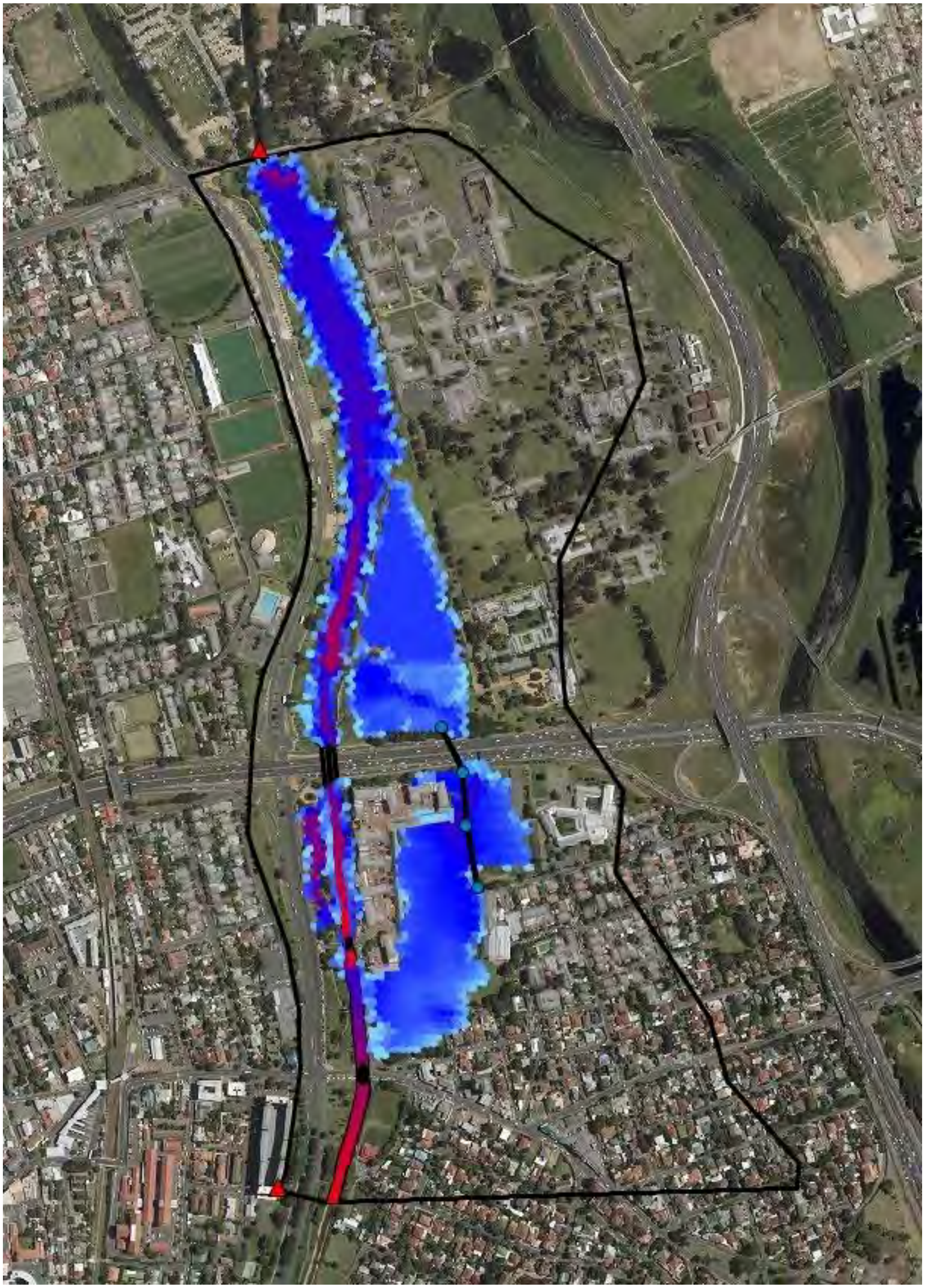
Ziervogel, G., New, M., Garderen, E.A.V., Midgley, G., Taylor, A., Hamann, R., Stuart-Hill, S., 2014. Climate change impacts and adaptation in South Africa. *WIREs Climate Change*.

Ziervogel, G., Parnell, S., 2014. Tackling Barriers to Climate Change Adaptation in South African Coastal Cities. In G. P. Glavovic, B.C., Smith, ed. *Adapting to Climate Change: Lessons from Natural Hazards Planning*. Springer Netherlands, pp. 57–73.

Appendix

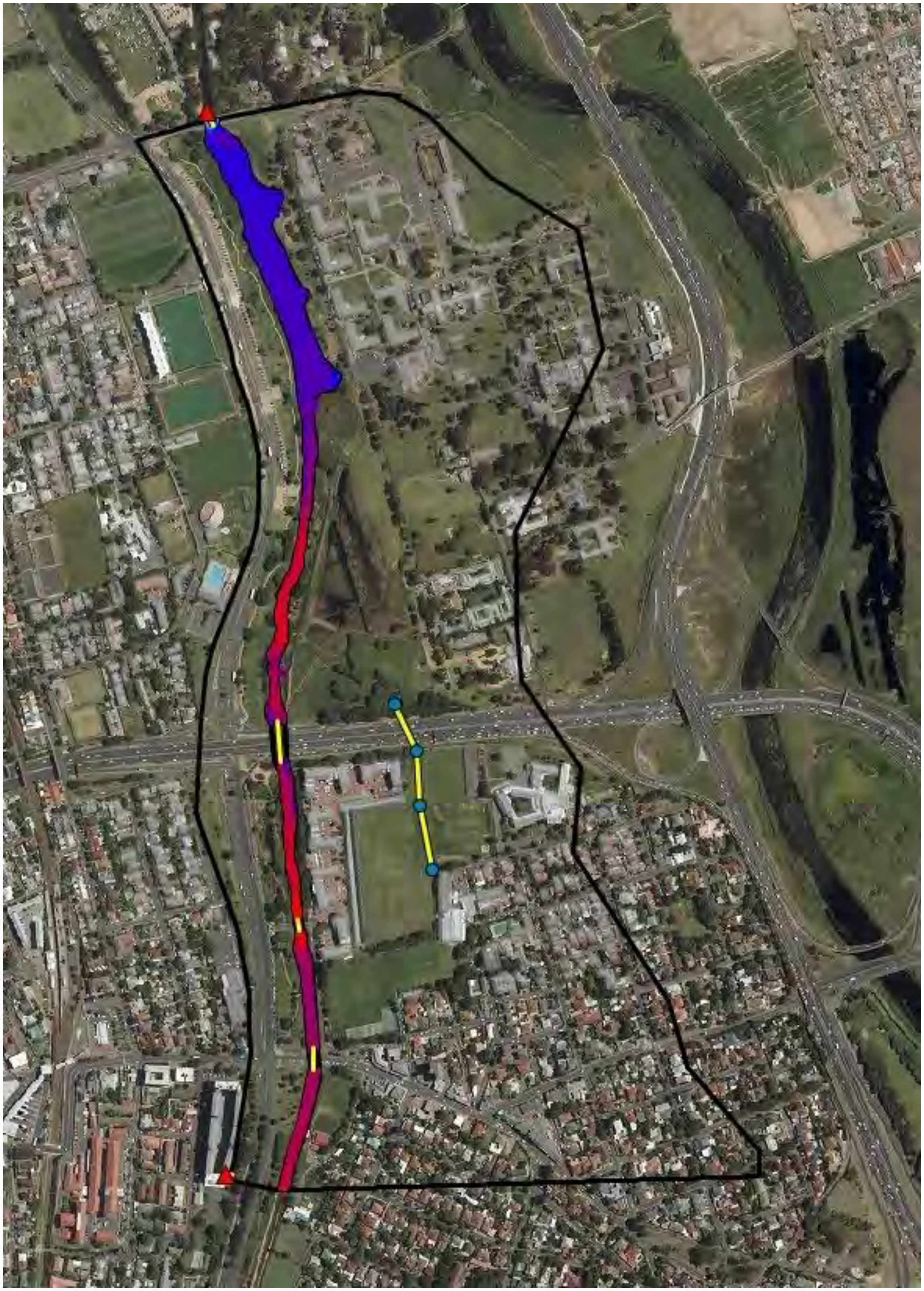
The following illustrations show the three scenarios (A, B, and C) for the three peak flow rate events which were modelled.

Appendix A 17 April 2013 maximum depths, scenario A

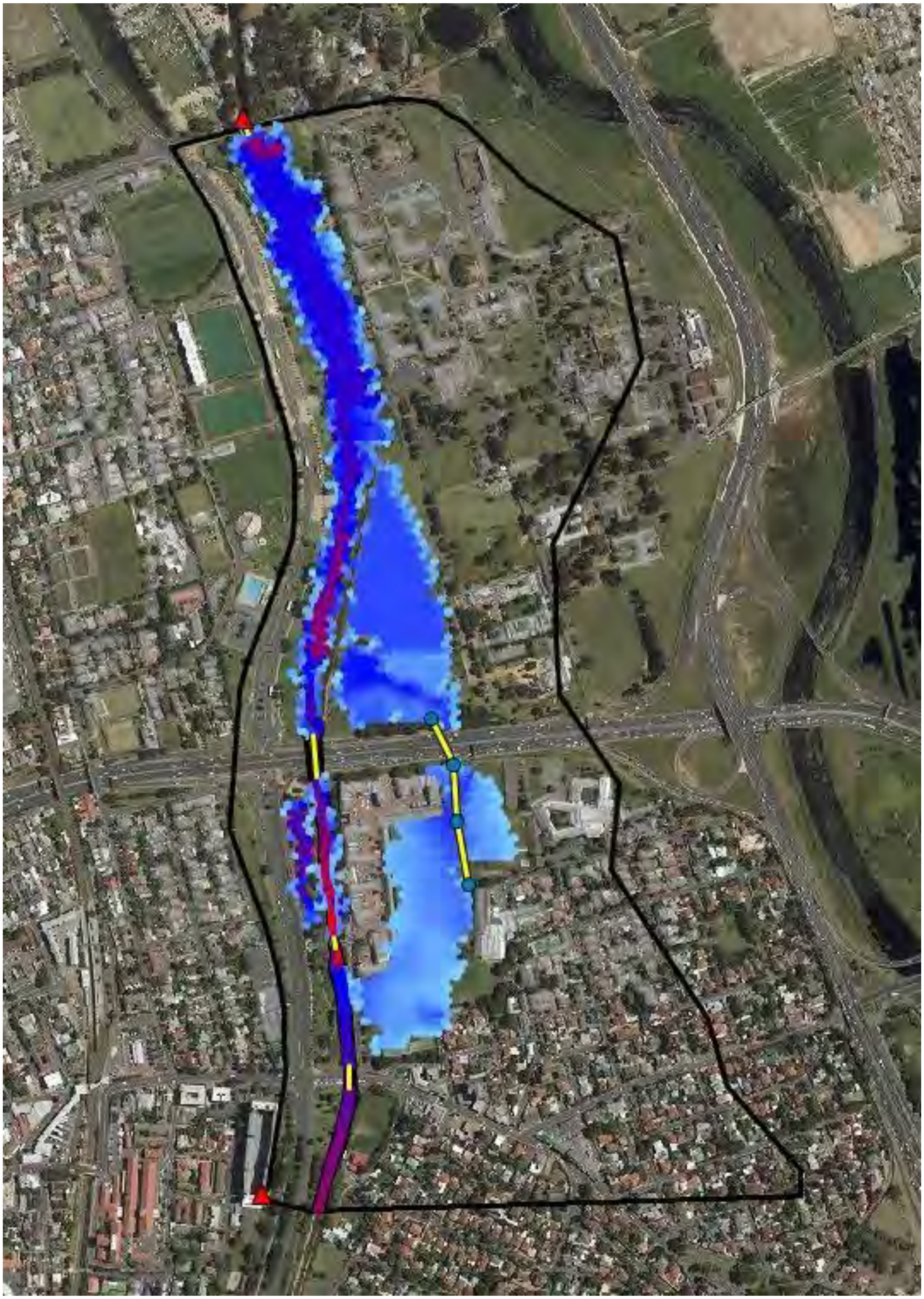


Appendix B 17 April 2013 maximum depths for scenario B

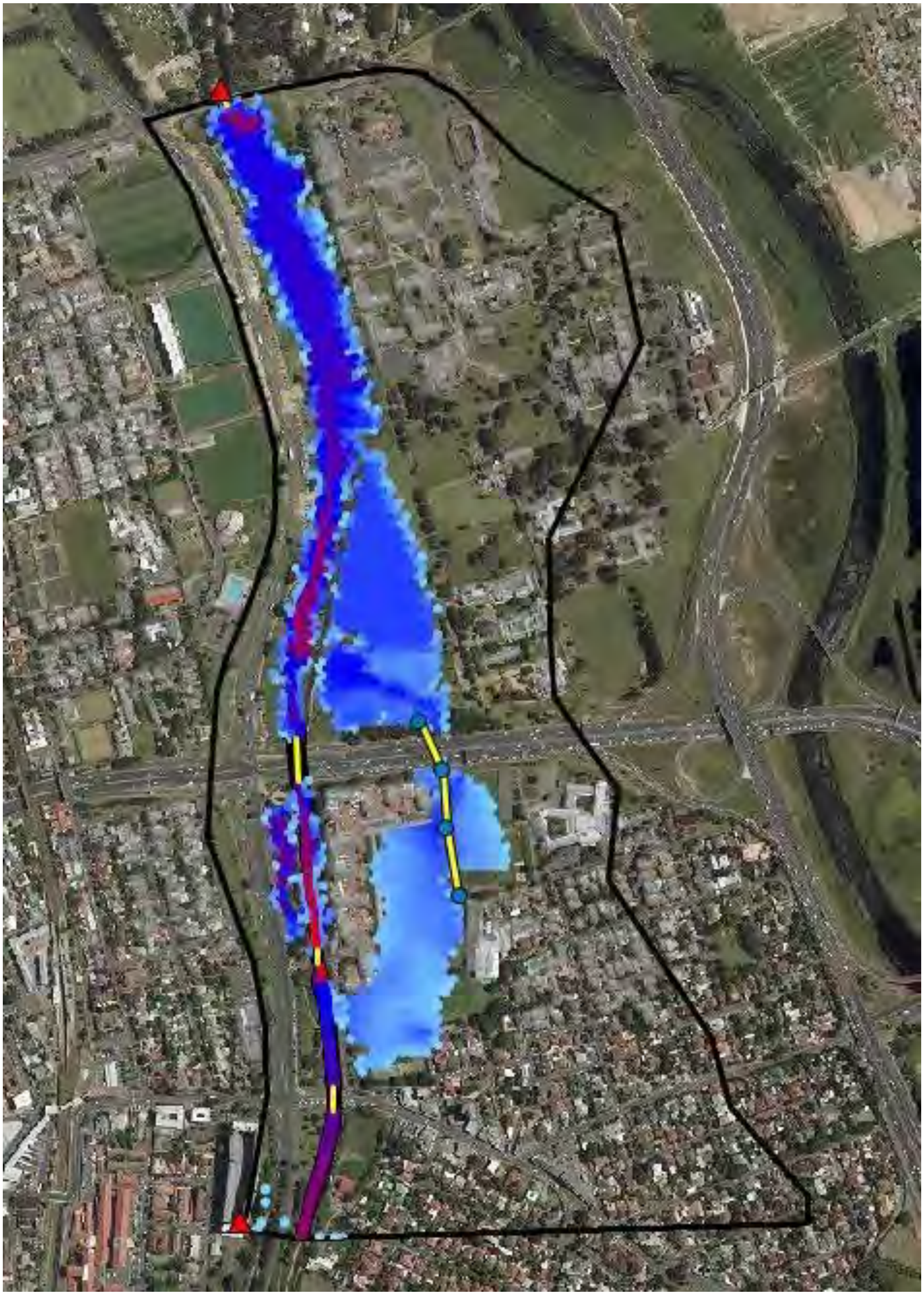
Appendix C 17 April 2013 maximum depths for scenario C



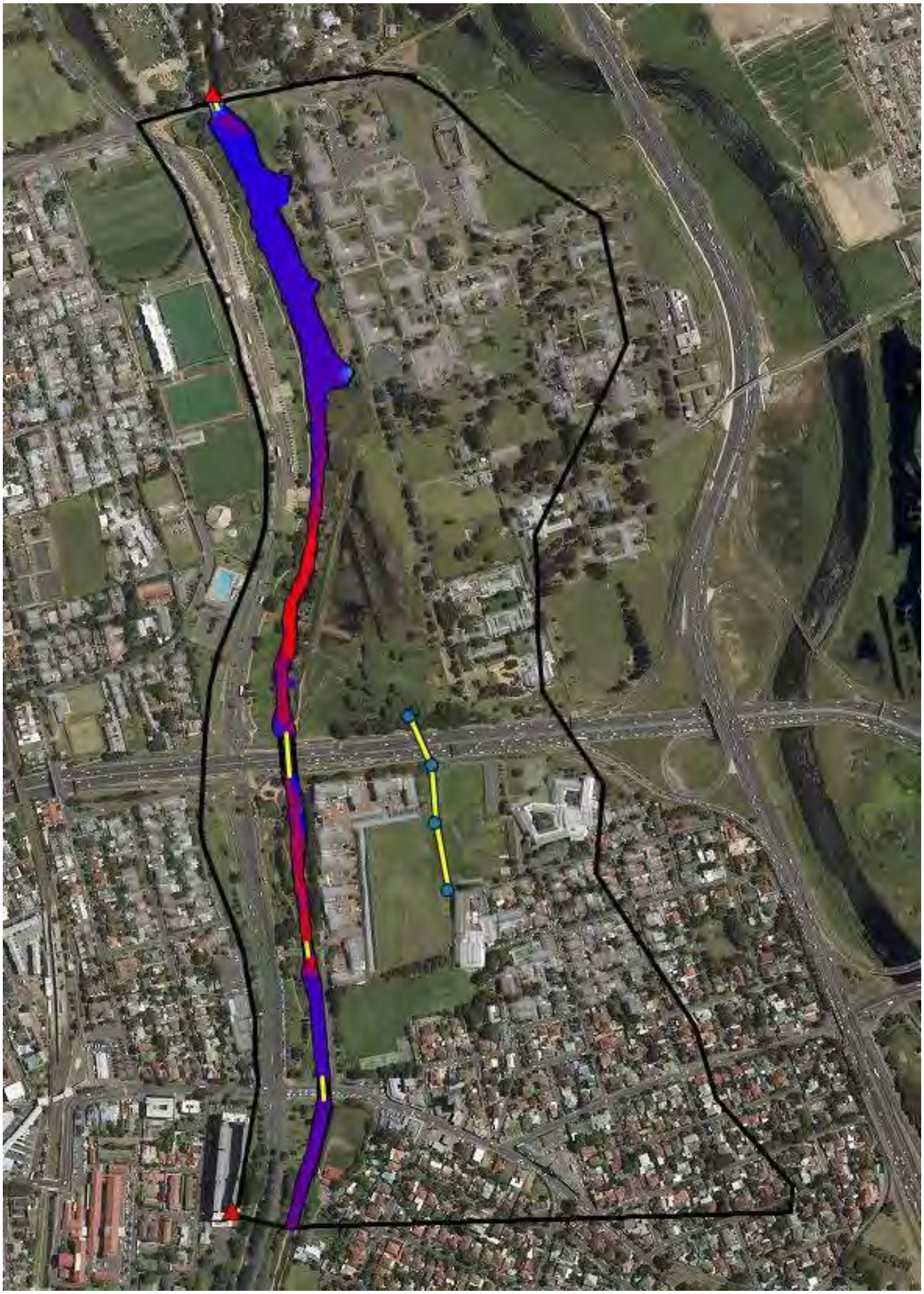
Appendix D 28 August 2013 maximum depths, scenario A



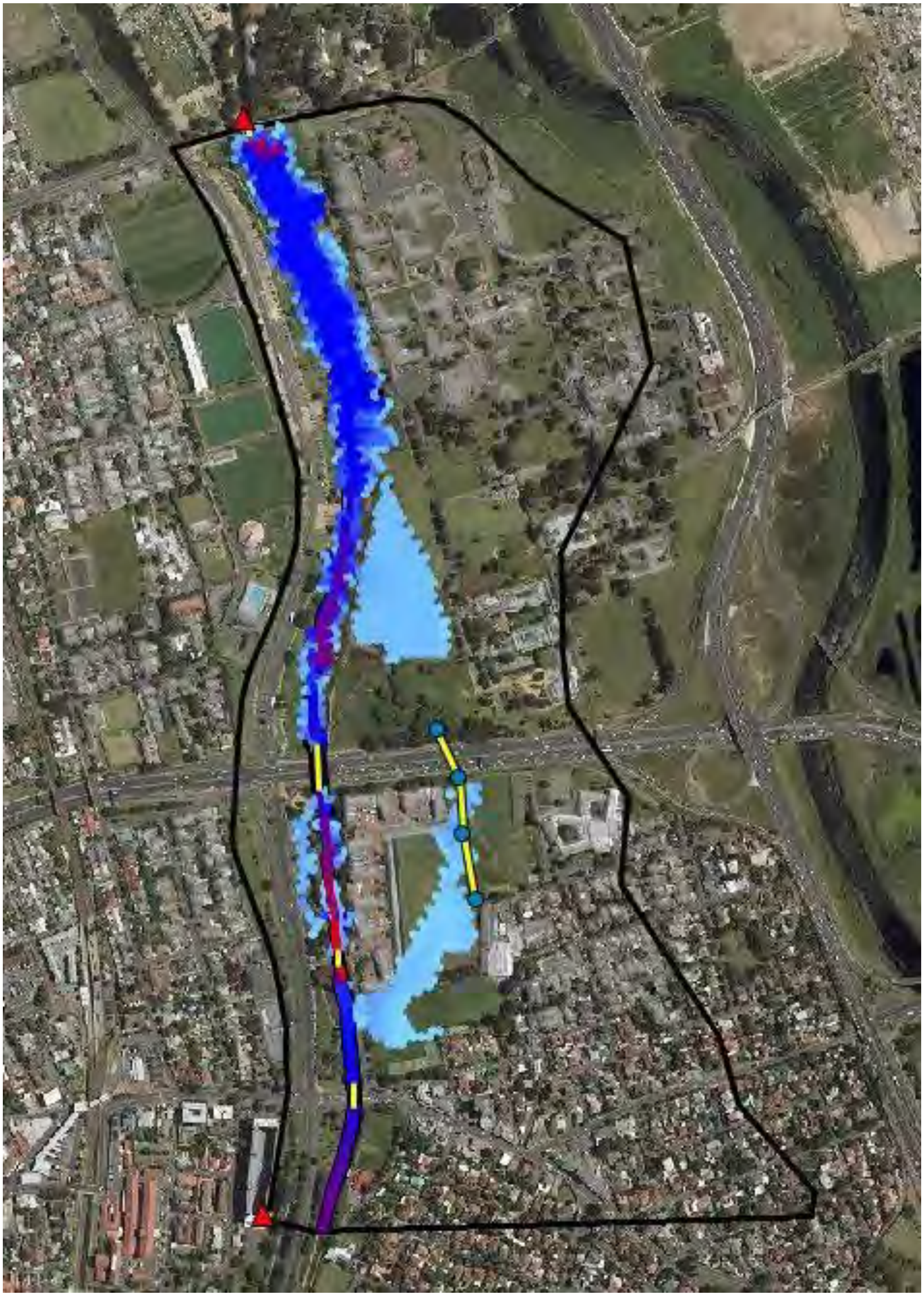
Appendix E28 August 2013 maximum depths, scenario B



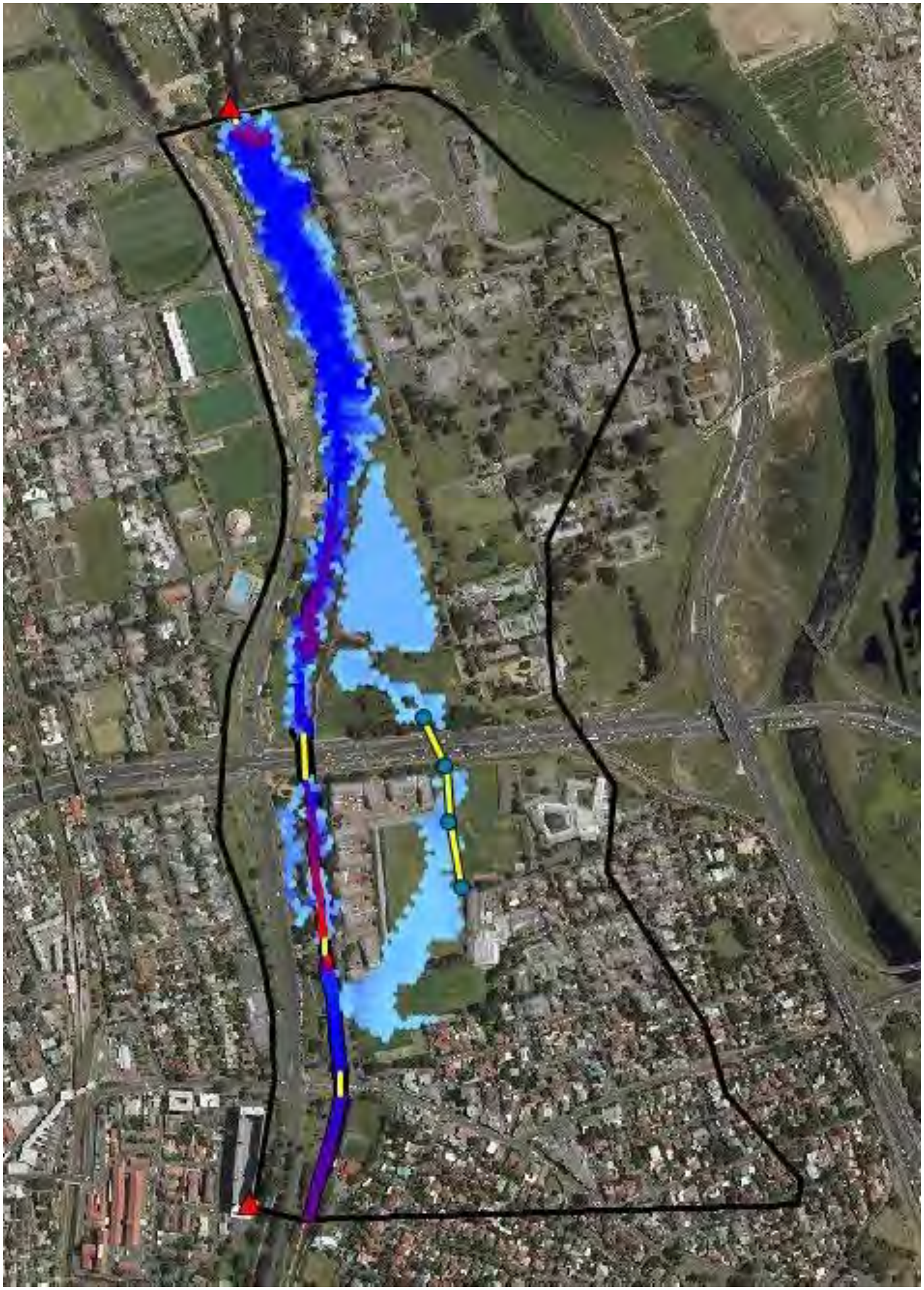
Appendix F28 August 2013 maximum depths, scenario C



Appendix GAppendix G 15 September 2013 maximum depths, scenario A



Appendix HFigure 23 15 September 2013 maximum depths, scenario B



Appendix IFigure 24 15 September 2013 maximum depths, scenario C