INUNDATION MODELLING FOR MAPPING THE HYDRAULIC RESPONSE OF WETLANDS USING HYDRAULIC STRUCTURES FOR MANAGEMENT OF AQUATIC FAUNA: A CASE STUDY FOR SUGAR SHACK COMPLEX

Thesis submitted by

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DECLARATION

I hereby certify that this thesis does not incorporate without acknowledgment any material previously submitted for the completion of a degree or diploma in any university; and that to the best of my belief and knowledge, does not contain any material published previously or written by another person except where due reference is made in this text.

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ABSTRACT

The research was performed to answer the research question *Can the use of upgraded regulators serve to help utilise the wetlands of Sugar Shack System for Common Carp management and Native fish promotion?*

The potential significance of the research was to understand the capabilities of hydraulic models and importance of inundation modelling in understanding the hydraulic response of wetlands when artificially inundated. Common Carp (*Cyprinus cario*) are a pervasive and successful alien pest fish species that has invaded most parts of the Murray Darling Basin in a span of less than 50 years. They are widespread and abundant with biological attributes that allows the population to rapidly expand. Inundation modelling provides an estimation of extent of flow in a given terrain. Carp readily react to change in flow regimes. When used in conjunction with dynamic fish models, inundation modelling can help develop site specific plans for carp management and recruitment of native species with regards to different flow regimes.

The primary data source was a Digital elevation Model (DEM) for the study area and the flow rate data of the Murray River which is the primary source of flow in the study area. The DEM was used to provide the continuous terrain profile of the study area. An estimate of the flow rate for the inlet of the study area was calculated using conservation of mass as no field measured flow rate data was present. A 2D HECRAS model was used to simulate the flow in the study area. The model was calibrated using the measured water depth value upstream of LOCK 1 of the Murray Daring Basin. Simulated hydraulic structures (Gates) were placed at different sites of the study area and the model was simulated under different operational phase of the gates. Water depth map and velocity maps along with shear stress profiles were generated for the entire model.

Inundation extent of Wetland 13 of the sugar shack complex was found to be in direct correlation of the operational phase of the gate placed at its outlet. A literature review based on the relation between fish movement and alteration in flow regimes was conducted and speculations on Wetland 13 as a potential site for carp spawning and recruitment under artificial inundation were made.

CONTENTS

List of Tables

List of Figures

CHAPTER ONE INTRODUCTION

1.1 Overview

River systems and their respective riparian zones play a vital role in the regulation and maintenance of biodiversity in their respective landscape. Rivers are now viewed as important natural corridors that act as communication mediums in multiple dimensions and systems with their own characteristics. Natural rivers and their riparian zone are viewed as the most diverse, complex and dynamic ecological systems (Dynesius and Nilsson, 1994). The rivers systems worldwide also support human activities, as well as biodiversity in the water system. The flow of the river is its governing influence. Humans have altered the river flow through regulation and diversion to meet energy, water and transportation needs. Damming of rivers has been identified as one of the major intentional impacts of humans on the natural environment of the river (Petts, 1984). Such alterations in the natural flow of the river has changed the conditions for aquatic organisms in flowing as well as standing waters (Bain et al., 1988). Expansion of human population has accelerated human activities that has resulted in extensive damming, diversion and regulation of large river systems in the world (Dynesius and Nilsson, 1994). The number of large dams has increased at least seven folds from 1950 to 1986 (Flögl, 2011) .Such flow manipulations can hinder channel development, reduce flood plain productivity and can also cause extensive modification to the aquatic ecosystem (Tockner and Stanford, 2002).

The Murray-Darling basin plays a vital role in the rural economy and as an environmental resource of Australia (Connell, 2007). With the establishment of the irrigation industry, regulation of flow through the use of small weirs was initiated in the late 19th century. The era between 1920 and 1940 brought an intensive increase in the use of regulators along the Murray River which included the Hume dam, 13 low level weirs, a high level weir at Yarrawonga and several barrages across the river mouth. With the addition of more dams in the 1950 an estimated 56% reduction in mean annual discharge of the system was observed. Such river regulation can cause unacceptable effect on the riverine fish community (King et al., 2009). Regulating structures has led to the reduction of diversity of communities (Ward and Stanford, 1979)and have thought to have contributed to creating suitable conditions for non-native species to flourish at the expense of deteriorating the abundance of native species

(Moyle and Light, 1996). In the Murray-Darling system, the trend of reduction in species diversity with the relative increase in abundance of alien species is consistent (Gehrke et al., 1995) and influence of river regulation area associated with the decline in native fish population (Aarts et al. 2004). Regulation of the MDB has caused species of invasive fishes to bloom by creating unsuitable conditions for the native fishes to flourish (Moyle and Light 1996). In the Murray-Darling system, the trend of reduction in species diversity with the relative increase in abundance of alien species is consistent (Gehrke et al., 1995). The lower species diversity index in the regulated catchments of MDB occurs not due to the lower number of total species present, but due to the overwhelming abundance of alien species in particular common carp (Gehrke et al., 1995).

River floodplains and wetlands have been considered to be the most dynamic and productive of all ecosystems present on Earth (Junk et al., 1989, Power et al., 1995) and have proven as valuable grounds for fish reproduction. Off channel water bodies have been a major point sources for common carp as they produce up to 98% recruits there (Stuart and Jones 2001). 70% of wetlands in the lower Murray River in South Australia are permanently inundated and recognised as important sites for Carp spawning and recruitment (Vilizzi 1998). Some species are known to migrate from main river channels to temporary floodplains for spawning and feeding, whereas others may recruit to permanent and semipermanent sites including lakes, anabranches and lagoons (Welcomme et al., 2006). Moreover, the relatively slow rate of fall and rise of the hydrograph could be advantageous for non-native species like Common Carp to use floodplains for recruitment (King et al., 2009). Balcombe et al. 2011 suggested that unregulated river systems in the Murray Darling basin are in a better ecological condition and have better capabilities to recruit native fish population then regulated water systems where reduced flood intensity, duration and frequency have reduced recruitment as a result of no strong flood pulses in successive years. However, the overlap of many native fish species and carp spawning period has posed risk when managing flows to minimise carp and maximize benefits to native species. As Carp are a successful invasive species avoiding potential spawning of Carp is difficult while obtaining multiple objectives so a careful management is necessary to disadvantage carp and benefit native fishes (Koehn et al. 2016) . Koehn et al (2016) suggests that to address this issue the hydrology of each site should be examined with a hydrodynamic model. The model should consider various flow components, the level of inundation and the suitability of inundated area for spawning and recruitment of carp. This will help develop a site specific model of carp recruitment and spawning that may result from managed floodplain inundation at the site through its use in conjunction with carp population dynamic models (Koehn et al., 2016).

This study seeks to simulate flows in the wetlands and open channels along the lower Murray River wetlands using a hydraulic model in order to test inundation extents and hydraulic response of wetlands.

1.2 Aims and Objectives

Insights on the abundance of common carp and its negative impacts on the ecology of the Murray River have been briefly discussed in the previous section. The overall aim of the research for this thesis is to use a conceptual hydraulic model to simulate the environmental watering scenario in Wetland (7,12 and 13) of sugar shack complex through the hydraulic structure (Gates) in order to visualize inundation extent along with water depth , flow velocity and shear stress maps at the given wetland. This research will also look at management options for the control for carp and restoration of the ecology of the wetland based on the use of hydraulic structure to control water flow in a wetland. This will be achieved by building a hydraulic model using the HECRAS 2D and visualized in a GIS environment. This research will help answer the key question

Can the use of upgraded regulators serve to help utilise the wetlands of Sugar Shack System for Common Carp management and Native fish promotion?

The following objectives are proposed to achieve the aim of the research:

a. Highlighting the use of a hydraulic models for simulating surface water flow in the study area.
b. Reviewing the effects of hydraulic structures to the water depth and flow velocity in the study area.
c. Visualizing hydraulic response in a GIS environment

1.3 Potential Significance of the research

The potential significance of this research is observe the capabilities of hydraulic models for simulating surface water flow and how flow manipulation can be a critical part in management of common carp in the given study area. This research may benefit decision makers and stakeholders to find common grounds that will be beneficial to all parties involved regarding management of carp using flow manipulation.

1.4 Organisation of thesis

This thesis consists of 6 chapters. Chapter 1 gives an introduction to the research and states the aims and objectives. Chapter 2 explores the literature related to global flow manipulation and its effects on the river systems. It also incorporates the current scenario of Murray River Basin and Common Carp in Australia and the use of mathematical models in order to simulate surface runoff. Chapter 3 includes the information on the study area and the overall framework of the methods used in order to address the objective carried out for this research. It also gives and insight to the study of methods that was used to simulate flow manipulation in the study area using hydraulic structures. Chapter 4 is a compilation of the all the results obtained throughout the research and Chapter 5 contains the discussion of results and also looks at the way the flow regulation can be used in management for common carp species. Finally, chapter 6 comprises of the conclusion to this research.

CHAPTER TWO LITERATURE REVIEW

2.1 Global flow regulation

Water is one of the most valuable resources for the survival of most living beings on the planet and its flow is the governing influence. The conversion of the nomadic Homo sapiens from hunters and gatherers to sedentary agriculturists was a pivotal point in time in terms of social reform that came as an influence after water dependence (Cech, 2009). Agriculture and domestication of animals required a steady supply of water and distance from the water sources that could fulfil the water demand were established as a location for the first agricultural human communities. With failure of crops in the dry seasons, the diversion of water from nearby riparian systems onto cultivated land evolved. Thus, irrigation was developed as a one of the first modern techniques by humans (Yevjevich, 1992). Most of the primary civilization of the human society first started in or near river valleys. Humans since then have extensively altered river systems through diversions and impoundments to meet their needs of water, energy and transportation.

In a global context, there are more than 45000 dams on operation that care capable of holding more than 6500 km^3 of water or about 15% of the total annual river runoff in the world (Khagram, 2003). Humans have an approximate of almost 60% of accessible global freshwater runoff and estimates indicate this number could hit 70% by the year 2025 (Seckler, 1998).

Such hydrological alteration through dam construction and other associated water diversions have been known to produce adverse effects to the natural state of river systems and have impacted the global environment (Rosenberg et al., 2000). In a global overview, catchment scale impacts of dams on both upstream and downstream ecosystem is generally well known. Inundation of water has resulted in destruction of the terrestrial ecosystem and elimination of lotic biota (Assessment, 2005). Inundation also favours anoxia, sedimentation, greenhouse gas emission and an upsurge in release of nutrients in the new reservoirs. In the past few decades, research on regulated systems has also revealed that streamflow regulations by dams can alter nutrient loading, sediment transport, stream temperature and solute chemistry (Ahearn et al., 2005). Flow manipulations of river systems has been known to hinder channel development, drain floodplain wetlands , reduce floodplain productivity and may also cause the extensive modification of the local aquatic communities (Bunn and Arthington, 2002).

Flow regulation through manmade structures obstruct the dispersal and migration of organisms, and this has been directly linked to the loss of population of freshwater fish (Baxter, 1977). River regulation and water level management often result decreased lotic habitat and increases in lentic habitat which does not facilitate favourable conditions for native species spawning but could benefit in the recruitment of non-native species (Clavero et al., 2004). Large scale hydrological alterations; cause habitat fragmentation; loss of floodplains, adjacent wetlands and riparian zones; deterioration of terrestrial environment under irrigation and associated surface waters. These changes no longer favour facilitate the native species to spawn and the recruitment of non-native species to increase (Lytle and Poff, 2004).

2.2 River Regulation and the Murray darling Basin

The Murray Darling Basin (MDB) has a catchment area of 1.073 x 10^6 km^2 and extends from the south east New South Wales and to 827 km from the sea in South Australia. It has a remarkable length of 5500 km. This is estimated to be 14% of the Australian continent with around 11% of the Australian population living in the MDB. It is considered to be one of the longest river system in the world. However its mean annual discharge has no significance in a global scale. With 90% of the basin area falling under semi-arid or arid land with rainfall and streamflow usually low and erratic, its annual discharge ranges from 1626 to 54168 GL with a mean of 10090 GL and a median of 8489 GL. Despite such low capability in terms of water resource, the MDB supports 50% of the sheep and cropland, 75% of irrigated land and 25% of Australia's cattle and dairy farms (Kirby et al., 2006). Its monetary contribution to the Australian economy is estimated to be around AUD $ 10 billion in annual production with the flows in the MDB allocating water resources to four states of Australia (New South Wales, Queensland (since 1992), Victoria and South Australia) according to the parliament agreement.

With the establishment of the irrigation industry, regulation of flow in MDB through the use of small weirs was initiated in the late 19th century. The era between 1920 and 1940 brought an intensive increase in the use of regulators along the Murray River which included the Hume dam, 13 low level weirs, a high level weir at Yarrawonga and several barrages across the river mouth. With the construction of a regulator at Lake Victoria in 1928, Hume Dam in 1936 , the Murray Mouth barrages in 1940 and a series of 13 low level weirs between Torrumbarray and Blanchetown during 1922-1937, the diversions became significant. With the addition of more dams in the 1950 an estimated 56% reduction in mean annual discharge of the system was observed. The development of the flow regulation structures and its impact on the natural regime of MDB has been discussed in several researches (Maheshwari et al., 1995, Walker and Thoms, 1993, Gehrke et al., 1995, Walker, 1985, Walker et al., 1994). The MDB just like all the other river basins in the world naturally comprises of a set of interconnected biological, physical and chemical elements that are governed by the total flow of water through the system (Norris et al., 2001). Hence the outcomes of any activities or management practices in one part of the basin may result in implications in other parts of the basin. With the interconnectedness, the limited water resources of the MDB and use of regulators to control water flow rates means that flow needs of the ecosystem at any part of the river cannot be met without compromising the demand in another part of the system (Norris et al., 2001).

The flow variability of the MDB on a temporal scale has been reduced by the flow regulation. Under pre regulation conditions, the peak flows for the MDB occurred in spring then rapidly receding in late summer and autumn (Maheshwari et al., 1995). The regulation structures such as high volume locks and dams have altered the natural variation in flow, by holding spring and winter inflows to the downstream of the structure and by holding water in large volumes in the upper reaches of MDB (Maheshwari et al., 1995). Release of water is then regulated in terms of meeting the water demand during peak irrigation in the autumn and summer across the four states. This has led to a reduction in the frequency of mid-range flows or minor to medium floods in the lower MDB and also a reduction in the duration of mid-range floods. This extended modification in the flow of the basin has resulted in the extensive change in the MDB reaches with 69% of the reaches being moderately modified and 29% of the reached being substantially modified (Norris et al., 2001). For regulated reaches where data is available, the hydrological disturbance in the natural regime of the river has been a major contributor to the change in environmental condition of the river (Magilligan and Nislow, 2005). The depletion in the overall environmental index of the river shows the extent of change brought by the human use of the river basin (Norris et al., 2001).

As a result of the impacts of regulation, the in-channel benches of the MDB have been found to be partially eroded by relatively constant regulated high flows. In addition, a steepening of the banks have been reported (Thoms and Walker, 1993). This has resulted in a reduction of micro-complexity and habitat value for the lower MDB system. An increment in the risk of algal blooms due to the combination of low flows and weir pools created stratified conditions was argued by Thoms and Shledon 2000 and Webster et al. 2000. In terms of native species in the MDB , some native species were found to adapt well with the new flow regimes while majority are in decline (Gehrke et al., 1995). Regulation of the Murray, in a biological context of fish diversity, has caused the number of native fish species to be overwhelmed by other exotic invasive species. Moyle and Light 1996 have argued that regulation structures have contributed to creating suitable conditions for non-native species to flourish at the expense of deteriorating the abundance of native species. The Murray and Murrumbidgee catchments of the MDB are particularly dominated by alien species notably common carp (*Cyprinus cario*). Alien species show the tendency to establish in natural systems modified by human activities (Ross, 1991).

2.3 Common carp as an invasive species in MDB

Throughout the Murray-Darling basin, a decline in abundance and distribution of native fish species have been mentioned in numerous literature (Walker and Thoms, 1993, Gehrke et al., 1995, Ross, 1991, Koehn, 2004, Driver et al., 2005, Pinto et al., 2005, Kingsford, 2000). The influence of regulation on fish movement, altered temperature in the river system, reduction in aquatic vegetation, reduced floodplain access and loss of reproductive cues are some of the associated factors for the decline in native fish (Aarts et al., 2004). Gehrke et al 1995 stated that regulation may alter the relative abundance between the population of native fishes and introduced fishes due to the desynchronising reproductive and environmental cycles. Balcombe et al. 2011 suggested that unregulated river systems in the Murray Darling basin are in a better ecological condition and have better capabilities to recruit native fish population then regulated water systems where reduced flood intensity, duration and frequency have reduced recruitment as a result of no strong flood pulses in successive years.

Flow regulation in the Murray Darling Basin has often favoured the recruitment of generalist alien species like common carp (*Cyprinus carpio L.*). Common Carp (*Cyrinus carpio* – Linnaeus, 1758) outside its natural range thrives in regulated rivers in many parts of the world, including the Murray-Darling Basin (MDB) of Australia, where it has competed against the native species, increased the turbidity and also impacted on the aquatic(King et al., 1997, Roberts et al., 1995). They are considered to be one of the world's most widespread invasive fish species(Lowe et al., 2000). Major reasons for the successful invasion of Common Carp includes their tolerance towards poor environmental condition, early sexual maturity and high potential fecundity(Weber and Brown, 2009). They were first introduced in Australia in 1859 and developed as a major pest by the 1960's and compromise of 90% of the total fish biomass of the MDB (CSIRO 2016). The National Carp Control Program has estimated that the common carp infestation in the MDB has resulted up to $500 million to the Australian Government. For the collapse of common carp, a substantial amount of effort has been applied with no long lasting success.

2.4 Carp Control

A proposal was put forward to the affected States to release the cyprinid herpesvirus-3 (CyHV-3), which has proved to significantly reduce Common Carp numbers overseas (CSIRO 2016). However, after the virus was discovered in 1998 in Israel, it was found to have devastated a large number of Carp farms around the world effect on workers present at the farm. A report by the European Commission by the scientific Committee on Animal Health and Animal Welfare has suggested that there is no evidence of any fish virus has been recorded to cause or induce any sort of disease in humans (CSIRO 2016). The proposal to release the virus to Australian is supported by laboratory testing of the virus on non-target species, where it has been shown to have no effect. No pathological or clinical changes have been noted in the laboratory testing taking place at the Australian Animal Health Laboratory (AAHL) in Geelong, Victoria(CSIRO 2016).

Furthermore, there are scientists and professionals in Australia and overseas who have recently spoken out about the release of the virus(ABC news 2017). These scientists are particularly concerned about the release of the virus at such large scale into the Australian waters. Major concerns have been aired that overspread of the virus may lead to the decrease in Dissolved Oxygen level of the water which is favourable conditions for bacterial spores to produce botulinum toxin, increasing the risk of botulism (Getchell and Bowser, 2006). Another concern is the direct environmental impact caused by the blood leaked from the decomposing fish onto the water body which may cause the water quality of the river to be equivalent to that of sewerage. If the timing and location of the virus is not well researched before the release of the virus on the MDB, a 'blackwater' event may occur which leads to a rapid decline the oxygen level of the river(Small et al., 2014). Such rapid death of this sort of population size may cause killing of majority of the fishes and cause the MDB to fall to blackwater in terms of water quality. This could spread up to thousands of kilometres. Another main concern is the estimated physical conditions for the predicted behaviour of the virus in Australian waters may not be achieved in terms of temperature. It is also mentioned that the upstream communities of the MDB will benefit from the release of the virus while the downstream community may suffer the consequences. However, the release of the virus is still under no certainty as research still continues (CSIRO 2016).

Following the overseas experience, another potential downfall of the release of herpes virus onto Australian waters may lead to the decline in the current buyers and consumers of the Carp. A 'pest to plate' program is also suggested by local and national fishing bodies that have shown confidence in fishing out the large population of carp and selling it to the consumer market both nationally and internationally. This may result in an economic boom for the fishing communities (ABC news 2017). In the financial year of 2016 alone, Sydney Fish Market has estimated that a total 83,000 kilograms of carp had been sold and has also expected that these sales number will increase (ABC news 2017). The fact that carp has been one of the most popular table fish in Asian and Europe should also not be underestimated. Also local fishermen add that nothing of the carp goes to waste as it is sold as a consumable table option and its remains being sold as fish bait as well as fertilizer.

2.5 Carp Management and the sugar shack complex

Floodplain wetlands are nutrient rich waters that support primary and secondary production than the adjacent river channel making them highly productive in nature(Brinson et al., 1981). Due to this nature, wetlands can support high aquatic biodiversity. Fish assemblages in wetlands is driven by factor that are governed by the wetting and drying cycle of the wetland (Balcombe et al., 2005). After flooding events, the additional nutrient release to the wetland makes them a potential site for fish food as the large water release can stimulate primary and secondary production (Winemiller and Jepsen, 1998, King et al., 2003). This may result in improved conditions for survival of fish and ultimately an enhanced fish recruitment.

The sugar shack complex is made up of 13 smaller wetlands. Baseline surveys of the complex showed the presence of common carp in all of its permanently inundated wetlands. To control the carp population in the wetlands, sugar shack management plan includes a drying and wetting cycle in a 5 year plan through the use of wetland regulators and include carp screens that prevent the immigration of adult carps back into the wetlands during refilling of the wetlands (NRA , 2015).

However, one of the primary objective of the wetland management program considers the upliftment of native fauna (NRA, 2015). The drying and wetting cycle can have potential risks for native flora and fauna (Koehn et al., 2016) and the carp screen may restrict access to some larger native species as well (Koehn et al., 2016). According to the NRA (2015), drying cycle includes wetland disconnection which may have potential issues with entrained debris and fish as well as may exclude native species from entering the wetlands as well (Koehn etl al. 2016) . Carp risk needs always need to be acknowledged as they have become a conspicuous part of the MDB fish community but not at the expense of reducing benefits to the native biota (Koehn et al. 2016).

2.6 Native Species in the MDB

Native fishes in the MDB have been estimate to suffered serious declines and are estimate at only 10% of their pre European settlements (MDBC 2004). Native fish in the MDB have a range of important conservation, cultural, ecological and recreational values and are therefore, a considerable interest to the public (Koehn et al., 2014, Lintermans, 2007). Aboriginal people have cultural connections to the fishes of MDB (Ginns, 2012) and recreational fishing has a participation rate of 20% nationwide (Henry and Lyle, 2003). Angling provides direct contribution to regional tourism, and an assessment of the economic value of angling is estimated to be around 403M AUD to the national GDP and a contribution of almost 10950 jobs (Ernst and Young, 2011). Among the many threats to MDB native fishes, improving the altered flow regimes, and the management of the invasive native species common carp remain as a key objective of the Native Fish strategy for Murray Darling Basin 2003- 2013 (NFS). Under adequate flow regimes and the control of carp, an estimated potential of 75% of the recovery target for the native fish population has been done. This highlights the importance of carp population control in relation to flows in order to restore native fish species and promote tourism. Increased environmental flows tends to have benefits towards the native fishes (Koehn et al., 2016). Some benefits include:

- increased spawning and recruitment of some species
- increased habitat diversity,
- increased habitat area,
- provision of refuge during low flows,
- Increased egg and larval dispersal.

Compared to native species, carp have recorded to prefer slow flowing waters and inhabit off stream water bodies with slow or zero velocity. Artificial inundation can create large areas of inundations and can allow widespread spawning and movement opportunities for carp with increase in larval productivity and young recruitments often after a prolonged and repeated periods(Koehn et al., 2016). However, there exists a connection between the impacts of channel morphology, flow volume and the hydrodynamics at any given site. Carp spawning may overlap with many native fish species and hence this has posed a potential risk when managing flows to minimise carp and maximise benefits to the native species. As previously mentioned, Koehn et al (2016) suggests that hydrology of the site should be first examined with a hydrodynamic model that considers flow components, level of inundation and suitability of inundation for recruitment and spawning of carp. The model will assist in developing a site specific management plan fir carp recruitment and spawning.

2.7 Modelling

A model is a representation of the real world in a schematic and simplified form using a set of rules (Popescu, 2014). Models have been an important tool in helping engineer, scientists and decision makers in determining what is happening in reality and also a way to predict what may happen in the future (Popescu, 2014). In a model, the system is defined as only part of the real world which is isolated from external factors outside the model itself. It consists of entities which mutually operate in each other's presence and have limited to no interaction with reality outside the system itself. Modelling implies to the construction of a new system or working with an existing one in order simulate (mimic) a real world process within a computational environment (Zeigler et al., 2000).

Computational Hydraulics is a branch of hydraulics that solves a specific problem by using mathematical models with numerical methods in a computational environment, as a process called simulation(Abbott and Minns, 2017). Abbot and Minns (1998) defined computation hydraulics as a reformulation of traditional hydraulics in order to suit the requirements and possibilities of sequential, discrete and recursive processes of digital computation. In recent years the advancement in computer power has increased the attractiveness of the use of hydraulic models for distributed predictions(Novak et al., 2018). Computer models to predict surface runoff are considered to be essential tools to inform management decisions regarding surface water phenomena such as floods. These models can be used for various purposes in simulating hydraulic response under a given number of assumptions within the computational domain. Such models incorporate various mathematical equations to describe and simulate wave propagation and storage and also to account for water balance in given space and time. Major research in this field of environmental flow were done at Harvard university, Stanford university and the U.S army corps of engineering in the 1960s and are considered pioneer efforts in the field of hydrological modelling (Bedient et al., 2008). The HSPF (Hydrologic Simulation Program- FORTRAN) which was the successor for Stanford watershed Model (Crawford and Linsley,1966) was the first major model for simulation of watershed hydrology. The hydraulic model HEC-1 flood Hydrograph Package (Feldman, 1981) was widely used for floodplain analysis. In majority, the traditional hydraulic models used in flow routing represent flow in one dimension. However, recent developments in numerical methods for out of bank flow process which are complex in nature have led to the use of two-dimensional models that allow a more detailed representation of the river channel as well as flow in floodplains (O'Brien et al., 1993, GHANEM et al., 1996, Yoon and Kang, 2004). One-dimensional models have shown limitation in overbank flow where the water flow becomes a two-dimensional phenomenon and the use of a two-dimensional model has become more suitable under such circumstances(Costabile et al., 2015). These models are typically based on the St Venant equation and have shown considerable correspondence to the field data in comparison to the one-dimensional models. Bates et al (1998) demonstrated the potential for the use of 2D schemes by simulating the bulk flow over reaches 10-20km in length and also provided initial evidence on the two-dimensional model's ability to represent data with respect to the model domain. The major problems in the past for the use of two-dimensional model came from inadequate data provision. However, development of modern topographical data capture using airborne remote sensing has allowed a number of model parameterization problems to be addressed and used in various researches (Haile and Rientjes, 2005, Fewtrell et al., 2011, Horritt and Bates, 2002).

The strength of such computer models lies in their flexibility and the fact they can give a dynamic perspective through development assumptions. The major limitation of simulation models is its inability to calibrate and verify applications in cases where input data are lacking (Bedient et al., 2008). The model accuracy is highly dependent on the available input data at the various location in the given study area to be represented in the computational environment. The selection of the model to be used is the most crucial decision in modelling since the overall success of the analysis hinges on the accuracy of the result (Bedient et al., 2008). Current modelling practices assumes that the simplest method that will give a satisfactory result for the given system with the available input data is a major criteria for model selection (Claeskens and Hjort, 2008).

Nowadays, a wide range of numerical models are available from different developers with different capabilities. One of the most popular hydraulic models is the American Model HECRAS developed by the US Army Corps pf Engineers (USACE). It is under constant development and improvement by the USACE. The HEC-2 model was developed by the Hydrologic Engineering Centre in 1982. This program got updated to HECRAS in 1995.HEC-

RAS cam simulate water surface profiles for steady and unsteady flow and also simulate the effects of various obstructions such as culverts, bridges and weirs(Brunner, 1995).

Several applications of 1D HECRAS for hydraulic simulation in terms of floodplain mapping and analysis can be found in different researches (Al-Qudah, 2011, Khattak et al., 2016, Manandhar, 2010, Romali et al., 2018, Sein and Myint, 2016). Horritt and Bates (2002) discussed on the capability of 1D HEC-RAS model when adequately calibrated based on hydrometric data can be used to make adequate predictions of flood extent. Hicks and Peacock (2005) also concluded that even with discontinuity in geometric data and limited historical roughness parameter data available, HEC-RAS model provided forecasts of commensurate accuracy when compared to calibrated hydrologic routing model and to results acquired using other sophisticated hydraulic model.

Moya Quirago et al (2016) used the full HECRAS 2d to analyse the Bolivian Amazonian flood of February 2014 by simulating flood depth, flood duration and flood velocity using a SRTM 90m*90m DEM of the study area. The findings of this study suggested that HECRAS 2d model can simulate flooding models quite accurately. The major limitation of the model, in this study, was the under estimation of the flooding extent by 13% when compared to MODIS satellite imagery which, according to the researchers, was a result of the omitting the smaller tributaries of the river in the model itself and also ponding effect after the saturation of some cells in the model.

HECRAS is free in nature with a simplistic user interface that has been successfully used in various hydraulic studies. HEC-RAS 2D model was selected for the study due to the limited input data available as model calibration in HEC-RAS could be done with limited modelling parameters.

CHAPTER THREE METHODS

This chapter describes and highlights the processes used in order to achieve the desired research objective.

3.1 Study Area

The area of study focuses on the Sugar shack complex in South Australia. The sugar shack complex is a floodplain complex made up of wetlands and anabranch creeks which is located on the lower River Murray immediately upstream of Swan Reach, South Australia. It lies in the Gorge geomorphic zone of River Murray which extends from Mannum to the Overland Corner downstream of River Murray. The sugar shack complex is a discrete floodplain area where the upstream and downstream extent is defined by the main channel of Murray River directly borders the inlet and outlet of the floodplain. The complex is 10.7 km in length on the left bank of the Murray River between 250.5 and 261.2 kilometres upstream from the Murray mouth.

Image removed due to copyright restriction. Available online from page 11 of the Sugar Shack Complex Management Plan December 2015:

https://data.environment.sa.gov.au/Content/Publications/CLLMM_426_Sugar%20Shack%20Complex%20WMP_2015.pdf

Figure 1 Geographical Location of Sugar Shack complex

(Source: NRA 2015)

The climate here is experienced to be hot dry summers and cool winters. The average daily maximum temperature from the weather station closest to the sugar shack complex is 22.9°C ranging from 29.3°C and 16.2°C. The annual rainfall is estimated to be 348.8mm. Local climatic conditions however are not considered to be the main drivers for the inundation of sugar shack complex which is primarily influenced by the flow rates and the waters levels in the River Murray. The study area comprises of two anabranches, five temporary wetlands and 6 permanently inundated wetlands under typical pool level in Lock 1 of the Murray River. The six permanently inundated wetlands are connected to the River Murray by smaller channels and anabranches at normal pool level. Under natural river conditions the wetlands of the sugar shack complex experienced seasonal fluctuations in water flow affecting the water depth in the wetlands of the sugar shack complex. Robinson 2013 states that such seasonal fluctuations would have inundated the riparian zone and the surrounding floodplain. Additionally the wetlands were disconnected from the River Murray in most years as river levels fell below the natural wetland sills.

Image removed due to copyright restriction. Available online from page 18 of the Sugar Shack Complex Management Plan December 2015:

https://data.environment.sa.gov.au/Content/Publications/CLLMM_426_Sugar%20Shack%20Complex%20WMP_2015.pdf

Figure 2 Sugar Shack Complex and its wetlands

(Source: NRA 2015)

The sugar shack complex is considered to be a living body of River Murray and is cared for by the generations of Nganguraku and Ngaiawang as being part of the Ngarrindjeri Nation. It is considered to give life to Ngarrindjeri nation and is cared for is of great cultural heritage for the indigenous people.

The alien species, common carp, has been recorded in all inundated wetlands of Sugar shack complex. The presence of this species in the wetland has impacted the aquatics habitats for other native species through bioturbation, competition and direct impact to submerged flora in the sugar shack complex. And it is believed that reducing the abundance of common carp within the wetlands is likely to have ecological benefits. Carp control in the sugar shack complex can help achieve the following objectives:

- Increased abundance, diversity and extent of littoral zone vegetation and native plant species.
- Increased breeding and abundance of fauna considered to be culturally important for the Ngarrindjeri nation.
- Increased abundance of shorebirds in the sugar shack complex.
- Improve the water turbidity in the sugar shack complex.

3.2 Data

Reliable and detailed data is an important part of modelling in order to produce dependable results.

The data used for this research are:

a. Flow hydrograph. (Source: https://riverdata.mdba.gov.au)
b. Digital Elevation Model of the year 2008.(Source: South Australian Government's Image Baseline Data Project 2007)

3.2.1. Flow Hydrograph:

The flow hydrograph for the River Murray was downloaded from https://riverdata.mdba.gov.au which is an online database that stores and gives access to data to such as the river flowrate, river height, river salinity and water temperature at different locks and locations of the River Murray. The nearest upstream point where flow rate data was measured was 17 km upstream of the study area at Lock 1 located at Blanchetown, South Australia. The flow rate at Lock 1 were estimated using the gauge level measurements at the reservoir site based on latest rating table. These tables are generated by surveying the bathymetric shape of the reservoirs and the cross sectional area of the river channel to calculate the river flow at a given water height (Source: https://riverdata.mdba.gov.au/about-data). Since the change in elevation between Lock 1 and the study site is negligible and no significant river diversions exist between the point of water flow observation and inlet to the study site, the discharge was assumed to be constant.

Due to the operation of locks and barrages as well as artificially lowered sill levels, several wetlands are permanently inundated with constant connection to the river under pool level connections(Robinson et al., 2015).

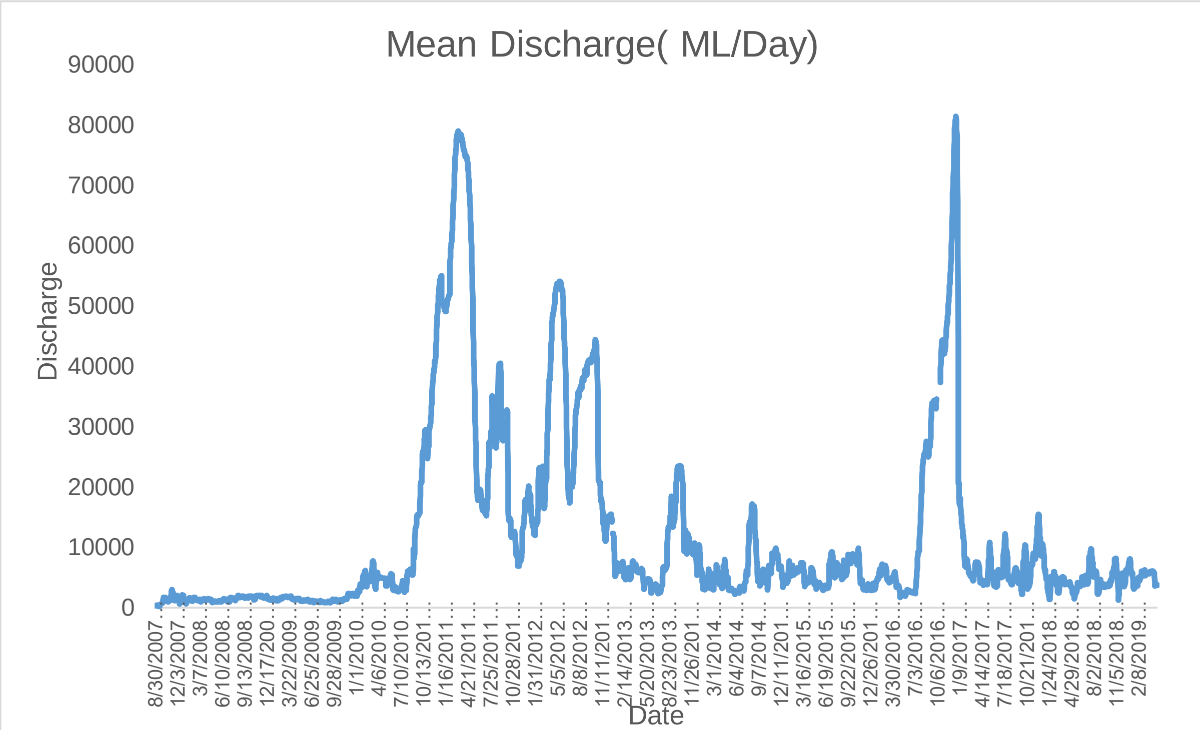

Figure 3 Daily hydrograph at Lock 1 Blanchetown from August 2007 to February 2019

Applying the conservation of mass and momentum equation

$$Q = Q1 + Q2 \quad (1)$$

$$Q = A * V \quad (2)$$

$$Q1 = A1 * V1 \quad (3)$$

$$Q2 = A2 * V2 \quad (4)$$

where *Q, A* and *V* to be the discharge of water, area of channel and velocity of water upstream of sugar shack inlet respectively, Q_1, A_1 *and* V_1 to be the discharge of water, area of channel and velocity of water downstream of sugar shack inlet respectively and Q_2 ,A_2 *and* V_2 to be the discharge of water, area of channel and velocity of water at the inlet of sugar shack complex

Creating a non-linear equation out of the mass and energy conservation relationship;

$$V^2 = (A_1 V_1^2 + A_2 V_2^2)/A \tag{5}$$

The following assumptions were made:

- The flow is unsteady state incompressible flow.
- Zero pressure gradient
- Neglecting losses and external forces

The resulting equation is a non-linear equation and was solved in MATLAB using the following code:

```
t = cputime;
rfr = xlsread('flowrateriver.csv'); %read the excel file
a1 = 365; %river area
a2 = 50; %channel area
idt = size(rfr,1); %size of array
syms x y;
a(:) = 0;
b(:) = 0;
solx(:) = zeros;
soly(:)= zeros;
for i = 1:idt
    eqn = [a1*x+a2*y == rfr(i,2)*0.001157,a1*x*x+a2*y*y == a1*
((rfr(i,2)*0.001157)/a1)^2 ]; %set of equations
    var = [x y];
    [solx, soly] = solve(eqn,var);
    if rfr(i,2) > 0
        a(i) = solx(1);
        b(i) = soly(2);
    else
        a(i) = 0;
        b(i)= 0;
    end
end
e = cputime-t;
```

The resulting data was taken as the water discharge at the inlet of sugar shack complex.

3.2.2. Digital Elevation Model

Terrain patterns are important in determining the nature of different water resources and also in related hydrological modelling. Creating Digital Elevation Models (DEM) offers an effective way of representing the ground surface and allows direct extraction of hydrological features of any given terrain. Such extractions of features from digital representations of terrain has been active approach in research area for the past couple of decades. Such automated extraction of features is faster and less error prone than manual techniques applied to traditional topographic maps.

DEMs are the digital representation of any given natural topographic feature as well as manmade features located at the surface of the earth. DEMs have played a vital role in resource management, urban planning, earth science, transportation planning and other Geographic Information System (GIS) applications.

In recent times, Light Detection and Ranging (LiDAR) systems have become a powerful way of generating DEM. However, the major disadvantage of aerial manned vehicles is their expense, especially for smaller study areas. During the last decade, low cost unmanned vehicles (UAVs) have been used as an alternative due to their advantage in cost, inspection, reconnaissance, surveillance and mapping capabilities. Unmanned aerial vehicles (UAV) is defined as an aircraft designed in order to operate without any human pilot on board (Nex and Remondino, 2014). UAV platforms have revolutionized the way of data acquisition in the recent years(Colomina and de la Tecnologia, 2008). UAV photogrammetry has opened various new approaches in close range aerial data acquisition. Photogrammetry is defined as the art, technology and science of acquiring information about any objects and it's surrounding by recording, analysing and interpreting images and their respective electromagnetic energy. UAVs combined with digital image capturing devices can collect usable data for generation of DEM. A study conducted by Uysal et al. 2015 concluded that UAV based data used for DEM generation using Photogrammetric techniques resulted in a DEM with vertical accuracy of 6.62cm and the resulting 3d model was satisfactory to realize topography with texture.

The DEM with channel bathymetry for the study area was created by stitching the photogrammetry DEM of 2m resolution between Lock 1 and Wellington, South Australia with sonar bathymetry data of 5m resolution. The data was acquired under the South Australian Government's Image Baseline Data Project (IBDP) in 2007.

3.3 Software used

The soft wares that came in use within the time frame of the research along with their respective purposes in generating required results are listed below:

a. Matrix Laboratory (MATLAB):

   MATLAB is a numerical computing environment used in various backgrounds ranging from engineering to economics. For this research, MATLAB was used in order to the solve the non-linear equation of the conservation of mass and momentum relationship in order to generate water velocity for the inlet of the study area from the flow rate data of the River Murray.

b. Earth Resources And Data Analysis System(ERDAS) Imagine 2015:

   The pre-processing of the given DEM in order to remove road and manmade structures was completed in ERDAS Imagine 2015. These structures were viewed as an obstacle as they were present as blockages in the flow path of the wetland. This software provided a platform for the removal of these objects through interpolation with respect to the surrounding pixel values.

c. Hydrological Engineering Center's River Analysis System (HEC-RAS):

   HEC-RAS is a system of software designed for use in a multi-tasking environment by the US Army Corps of Engineering. It is a free to use software in which the 2d unsteady flow simulation, terrain modification and inclusion of hydraulic structures was conducted to fulfil the aim of this research.

d. ArcGIS Version 10.6:

Initially, clipping the DEM of the area of interest from the DEM of River Murray which extends from New South Wales to South Australia was achieved in ArcMap .This software was later used for its ability to create maps and visualize the output from the simulations conducted in HEC-RAS.

3.4 Sub-setting the Raster and Removal of obstructions

Area Of Interest (AOI)is defined as the region within the given image that defines the extent of the user's study. After acquiring the DEM for the River Murray, the study area was selected and extracted from the DEM. The same extent obtained after the sub-setting was used throughout the remainder of the research. Upon further observation of Raster for the study area, some observations in the flow path were observed. Manmade structures and roads crossing the flow path acted as barriers to water flow. The primary intention of using the Interpolate function present in the ERDAS Imagine Raster edit toolbar was to replace the original pixel value with reference to the average pixel values in a given buffer zone around the AOI.

3.5 Overview

The simulation study is based on the use of the HECRAS model to develop a model, which solves the shallow water equation using the finite volume method in order to simulate surface flow over a given terrain. HECRAS allows flow simulation in both 1 dimension as well as 2 dimension. In context to flood plains, the assumption that flow is in 1D dimension in no longer valid. 1 D models cannot predict the flow in floodplains as accurately as 2D models, where the flow is considered to be 2D in nature. The 2D unsteady flow assumes flow in two spatial dimensions and that it varies with time. One of the restricting aspect of 2D River modelling is the lack of river bathymetry data, which has shown to be very important for accurate model results(Cook and Merwade, 2009). But, the availability of continuous bathymetric data has enabled the option for the use of 2D model for this research. Wetland 7, Wetland 12 and Wetland 13 of the sugar shack complex were only simulated as the other two permanently inundated wetlands only had one inlet and outlet channel being regulated by a structure. As the model doesn't account for evapotranspiration, infiltration and other water losses, modelling these wetlands which relied on such phenomenon were avoided.

3.6 Development of 2D mesh

Topographical parameterisation is considered to be an essential component of representing a natural system in a model and remote sensing techniques have been used with success in order to map a topography(Band, 1986). As topography exerts a strong influence on the outcome of a natural system, the representation of the topography in any given numerical model has a profound effect on the model's estimation(Horritt et al., 2006). In order to represent the given topography, the computational domain (time and space) needs to be transformed from a continuum domain into a set of subdomains, whilst conserving the validity of the governing equation throughout the set of subdomains(Popescu, 2014).

The 2D geometry are usually built up by which are made by interconnected cells that may vary in shape and size with a maximum limitation. These grids are generated by the use of algebraic relations that create nodes and cells of a grid(Liseikin, 1999). The grid generation is the dependent on the equation to be solved as type of boundary conditions depending on the nature of governing equation(Ferziger and Peric, 2012). HEC-RAS generates computational mesh using the Delaunay triangulation technique followed by the construction of a Voronoi diagram (Brunner, 1995).

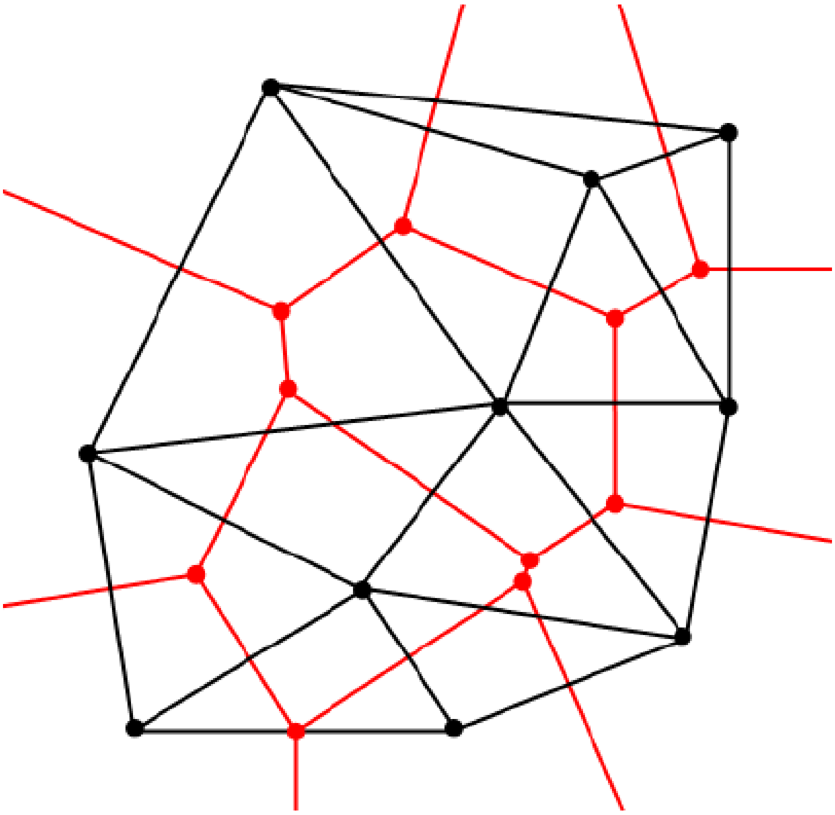

Figure 4 Delaunay triangulation

The computational domain is generated using a grid of triangles, by creating the nodes first connecting them to form a triangular mesh. The Delaunay triangulation method ensure that triangles created during the mesh generation process are not too thin. Figures 4 illustrates an example of mesh created by the use of Delaunay Triangulation. The Voronoi diagram is made up of polygons that are centred on a single point and any given locus of the point is included in the given polygon ensuring that overlapping of two different polygons does not occur does not occur(Chew, 1989).

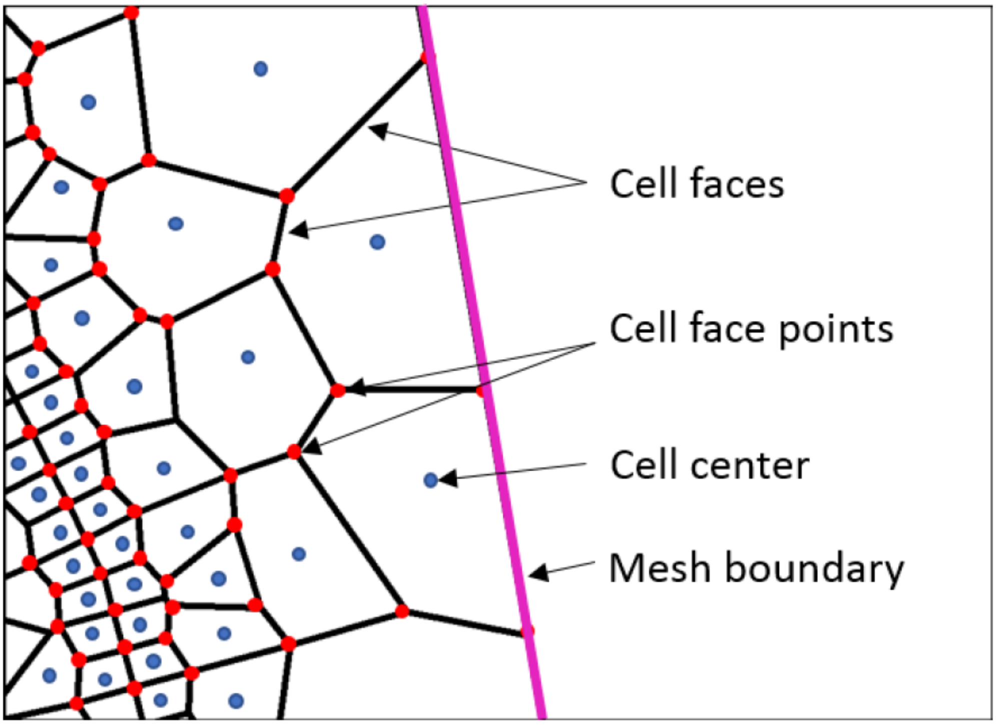

Figure 5 Cell faces and computation faces of grids

The cell faces are similar to cross sectional data used to compute flow between cells except for the outer boundary of the mesh (purple). The cell center is where the water surface elevation for individual cell is computed but it doesn't always correspond to being the cell centroid. The conversion of a continuous domain with infinite number of degrees of freedom into a finite domain is done using this method. This enables the computer used to solve the model to evaluate the continuous unknown variables into each subdomain as its discrete value (Ferziger and Peric, 2012). Hence smaller the discretization, smaller the approximation error. Figure 5 illustrated the different parts of the computational grid created through the use of Delaunay triangulation.

However, creating really small cell sizes may often increase computation time which is one of the major issues regarded by researchers using 2D models for simulating floodplain dynamics. In some cases, the topographic data is too dense to be used directly as a grid for the numerical model. So coarser grids may be required in order to reduce computation time while preserving the underlying terrain features. In order to address this issue, models that represent topographic data on a sub grid level were developed (Yu and Lane, 2006, Casulli, 2009, McMillan and Brasington, 2007) . This enables the important topographical features to be conserved while maintaining a larger computational grid size and eventually improving computation time. As for the resolution of computational grid scale and sub grid scales, Yu and Lane (2011) compared inundation extent for different mesh sizes for a flooding in a rural area concluding that 8m computational cell size with a sub grid of 4m showed improved results compared to a model with 8m grid size with no sub grid. However, corresponding improvements were smaller for larger grid sizes. The development of such sub grid models has improved the scale to which 2D models can be used.

In HECRAS 2d, each cell and face of the computational domain is pre-processed to develop a detailed hydraulic property table of the underlying terrain (Brunner, 1995)(Brunner, 1995)(Brunner, 1995)(Brunner, 1995)(Brunner, 1995). An elevation-volume relationship is derived for each cell by the 2D mesh pre-processor as the computational grid consists information such as hydraulic radius, volume and cross sectional area(Brunner, 2016). These information enables the model to preserve enough information regarding the fine bathymetry through mass conservation while the topographic resolution is compromised as a trade-off for smaller computation time. The conservation of mass equation for the sub-grid bathymetry is given by;

$$\frac{\Omega(H^{n+1}) - \Omega(H^n)}{\Delta t} + \sum_k V_k n_k A_k(H) + Q = 0 \tag{6}$$

Where $\Omega(H)$ is the cell volume and $A_k(H)$ is the face areas that are functions of the water elevation at the cell center given by H. Δt is the difference between two consecutive time steps and V_k and n_k are the average velocity and the unit normal vector at the given face k.

3.7 Hydraulic structures

Hydraulic structures interact with the surface runoff in rural and urban environments that enhance or control the flow in rivers and other water bodies(Novak et al., 2017). These structures help divert, store, manage and control the water inflow and outflow. These are designed pro-actively to control the water flow motion.

However, In HECRAS, techniques for representing the hydraulic structure are based on relationships derived for 1D application. Applying such structures in 2D may not incorporate the energy loss due to expansion and contraction as the formation of eddies around the structures may be much smaller than the reasonable mesh size (Babister and Barton, 2012). The hydraulic structures were designed in a 1D environment and were placed in the model as connectors between two 2D flow areas.

Simulated gates, in particular a sluice gate, were used to manipulate the flow in the given model. Gates are movable barriers that control the passage of surface runoff through a channel. The vertical walls of the sluice gate with movable sections are lifted in order to allow the flow of water underneath the structure. The downstream flow in sluice gate occurs in relation to the ratio of the upstream depth to the height of gate opening. These hydraulic structures were added using the HECRAS model editor. In the HEC-RAS computation environment, flow through the gates occur when they are opened to an elevation that is greater than the upstream water surface elevation.

The equation for free flowing sluice gate is given by:

$$Q = CWb\sqrt{2gH} \tag{7}$$

Where Q is the flow through the gate, C is the coefficient of discharge, H is the upstream energy head ($Z_u - Z_{sp}$) , W is the width of the gate, b is the height of the gate opening and g is the acceleration due to gravity.

Under free flow condition the coefficient of discharge for a sluice gate reaches a saturation value of 0.611. In hydraulic context the gate ceases to exist when the water depth upstream is equal to the opening of the gate. However, under submerged conditions which is defined as the condition when the total energy head downstream is greater than the total energy head upstream, the coefficient of discharge tends to zero (Swamee, 1992). HECRAS, however, automatically accounts for submergence condition when the tail water reaches depth high enough to slow down the flow. As the submergence increases, the program reduces the weir flow coefficient to correct the flow based on the submergence curve(Brunner, 1995). Figure 6 illustrates the submergence curve.

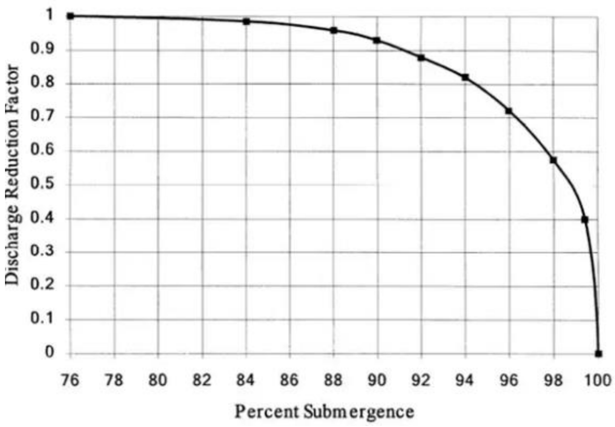

Figure 6 Submergence curve

3.8 Manning's n value

Manning's n value represents the flows in flood plains and channels and the Manning's formula has direct applications variety of fields ranging from flood-insurance studies to flood plain management and also design of hydraulic structures (Chow, 1959). The Manning's formula is given by,

$$V = \frac{1}{n} R^{2/3} S_e^{1/2} \tag{8}$$

Where *v* is the velocity of flow in meter per second, *R* is the hydraulic radius, in meter, S_e is the slope of energy line, in meter per meter, and *n* is the Manning's roughness coefficient. The suggested values for Manning's n can be found in Chow (1959) where it has been tabulated according to factors that affect the roughness. For the selection of n values for an open channel, the most important factors are:

- Type and size of the banks and bed of the channel
- Shape of the channel

3.9 Boundary Conditions

The governing equation for the model is a Partial Differential Equation. The solution of a Partial differential Equation is only integrated numerically. This suggests that the solution to a particular PDE must satisfy three conditions i.e it must be existent, it has to unique and is dependent on the auxiliary condition which is the Boundary condition. The uniqueness of the solution is generally not a problem and if the solution fails to exist then it is due to its failure to fulfil any given auxiliary conditions (Fletcher, 2012). Hence, this suggests that any PDE where the boundary conditions are known can be solved in a given computational domain.

The Boundary conditions used in this research are:

- Upstream Boundary condition: The flow hydrograph derived from the discharge in Murray River from Lock 1.
- Downstream Boundary Condition: The normal depth Boundary C.

3.10 Running the model

The model uses the Shallow water equation using the Finite volume methods as a numerical solution to the PDE for calculating the unsteady flow over the given computational mesh. It is based on the principle of conservation of mass and momentum. This method has several advantages and has been used in numerous researches to solve surface water flow. Shallow water equation demonstrates a perfect numerical balance between the gradient fluxes and source terms. The shallow water equation when solved using the Finite Volume Method can generates results with reasonable accuracy as integrated numerical flux function automatically maintains the numerical balance for the equation (Anastasiou and Chan, 1997).

The robustness of the algorithm used to solve the equation numerically has also shown high flexibility in cells and demonstrates an ability to handle unsteady flow in a given computational domain with high accuracy.

The 2D shallow water equation is based on the following set of assumptions:

- The fluid is incompressible in nature
- Hydrostatic pressure distribution
- Any vertical variation in flow is neglected.
- The average slope of the bed channel is small.
- The flow is described as a continuous function of water surface elevation and the velocity.

The 2 dimensional continuity equation for the model is:

$$\frac{\partial H}{\partial t}+\frac{\partial (hu)}{\partial x}+\frac{\partial (hv)}{\partial y}+q=0 \tag{9}$$

Where *H* is the water surface elevation, *h* is the water depth, *u* and *v* are the average velocities in x and y direction respectively and *q* is the constant representing inflow from any external sources.

The 2 dimensional momentum balance equation in x direction is given by:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-g\frac{\partial h}{\partial x}+v_t\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)-c_f u-fv \tag{10}$$

Here, c_f is the friction coefficient and *f* is the Coriolis parameter and v_t is the viscosity coefficient

Similarly, the 2 dimensional momentum balance equation in y direction is given by:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-g\frac{\partial h}{\partial y}+v_t\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)-c_f u-fu \tag{11}$$

As the water surface elevation and flow velocity both vary in space and time, for each computational step the model determines the values of these variable for the entire computation domain. The 2D engine in HECRAS uses a semi-implicit finite difference scheme where the approximations made for the solving the equation is dependent on the orientation of the mesh in a particular terrain feature (Brunner, 2016).

The solution algorithm for the model is:

1. The geometry and sub grid bathymetry data are pre-computed.
2. Solutions starts with the initial conditions at a time step n=0.
3. Boundary conditions are then set for the next time step.
4. Compute the water elevation at the time step and also the sub grid bathymetry quantities that are dependent on the water surface elevation.
5. Velocities for each computational cell is then calculated.
6. The computed solution is accepted when the residual is smaller than the given tolerance.
7. Increment in time step is then done.

3.11 Model calibration and parameterization

For model calibration and parameterization, a 2D model was used to simulate the flow from Morgan, South Australia to upstream of Lock 1 located at Blanchetown. This area was selected due to the availability of flow rate data at Morgan and the water depth data just upstream of Lock 1. Due to high resolution bathymetric data not being available above Blanchetown, as mentioned in the section above, a bathymetric DEM of comparatively lower resolution of 250mx250m was used to calibrate the model.

The model was calibrated against the water depth measurement through adjustment of different modelling parameters.

Table 1 List of Parameters for HECRAS 2D model

Parameter name	Description	Range
Computation point spacing	Determines the cell size to be used for the development of computation mesh	n/a
Manning's n value	Determines the coefficient of roughness of the terrain enclosed by the 2d flow area. High value determines more friction, lower value determines less friction.	0.01-0.075
Thetha value (θ)	Implicit weighting factor between current and previously computed time line	0.6-1.0
Maximum iterations	Maximum number of iterations used by the solver while attempting to solve the equation.	1-40
Computation interval	Determines the time step for the numerical solver based on courant's number.	1sec- 24 hrs
Water surface tolerance	Tolerance for the given iteration scheme.	<=0.06
Coriolis effect	Option to turn on the effects of earth's rotation on the solution.	Yes/No

The results obtained after the calibration were used as basis for parameterization for the model setup over the Sugar shack complex.

3.12 2D-Model set-up

A 2D computation mesh was created using the 2D flow area tool in HECRAS.A total of 3 2D flow areas were designed enclosing the inlet, outlets and different wetlands of the Sugar shack complex. The first 2D area named 2d_flowarea_1 covered the area from the inlet of the sugar shack complex from the Murray river, Yatco creek and wetland 7. The second 2d flow area names 2d_flowarea_2 was designed from the channel connecting wetland 7 and wetland 12 upto the inlet of wetland 13. The third 2D flow area named 2d_flowarea_3 enclosed wetland 13 starting from its inlet to the outlet. The fourth 2D flow area named 2d_flowarea_4 was designed over the outlet of the wetland 13 on to the Murray River.

A polygon layer was drawn with a computational mesh of 5*5m with a sub grid of 2m were created for each of the flow areas. Manning's n value of 0.035 was assigned to each of the flow areas.

The area enclosed by each of the 2d flow area is listed below with average grid size for each 2D area:

Table 2 Total Area of 2d computation mesh

Flow area	Total area enclosed (km^2)	Average Cell size(m^2)
2d_flowarea_1	683.383	25.57
2d_flowarea_2	372.705	25.54
2d_flowarea_3	1125.019	25.13
2d_flowarea_4	0.87	10.03

3.12.1 Boundary conditions

The boundary conditions for each flow area is listed below:

Table 3 Types of Boundary Condition used

Flow area	Upstream Boundary Condition	Downstream Boundary Condition
2d_flowarea_1	Flow hydrograph	• Gate 1 connecting to 2d_flowarea_2 • Normal depth (DS 1)
2d_flowarea_2	Gate 1 connecting to 2d_flowarea_1	• Gate 2 connecting to 2d_flowarea_3 • Normal depth (DS 2)
2d_flowarea_3	Gate 2 connecting to 2d_flowarea_2	Gate 3 connecting to 2d_flowarea_4
2d_flowarea_4	Gate 3 connecting to 2d_flowarea_3	Normal depth

The normal depth boundary condition is based on the slope of the terrain. A terrain profile was plotted and the slope of the terrain at the boundary conditions were calculated in terrain plot view of HECRAS.

3.12.2 Hydraulic Structures

In this study, hydraulic structures were modelled by creating 1d-connections between two 2d-flow areas. The modelled gates act as both the downstream boundary condition and the upstream condition for flow areas based on the direction of flow of water. The gates were created in the HEC-RAS connection editor tool.

The dimensions of the weirs and gates are as follows:

Table 4 Dimensions Of Gates

Gate	Weir Height (m)	Weir Width (m)	Weir Length (m)	Gate height (m)	Gate width (m)	Weir coefficient
1	1	3.2	44.4	0.5	13	1.67
2	0.85	1.5	12.81	0.35	4.5	1.67
3	1.05	2	16.82	0.8	0.6	1.67

The default sluice coefficient of 0.6 was taken and the submerged orifice flow was also left as default.

Different time intervals for gate opening and closing were taken in order to view the hydraulic response of water and the model under such conditions. No particular rule was followed for selecting this criterion.

The unsteady flow simulation was then performed. The output generated through the use of this conceptual model gave a brief estimate on the hydraulic response of different wetlands were influenced by the structures placed at their inlets and outlets.

The simulation results were then exported onto the ArcGIS platform as raster files. These raster files were used to create velocity, inundation and water depth maps for the study area. ArcGIS was also used to calculate the inundation area for the wetlands at different time frames of the simulation.

CHAPTER FOUR RESULTS

4.1 Model Calibration and model performance

In general, the parameters related to the hydraulic model were unknown for the study area. These parameters were calibrated using the water depth data available at upstream of lock 1. The resulting simulated water depth at the calibration point are shown in. Parameter changes based on the calibration were applied for the rest of the simulation. The simulated water depth and measured water depth were compared (figure 7) and the parameters were changed accordingly.

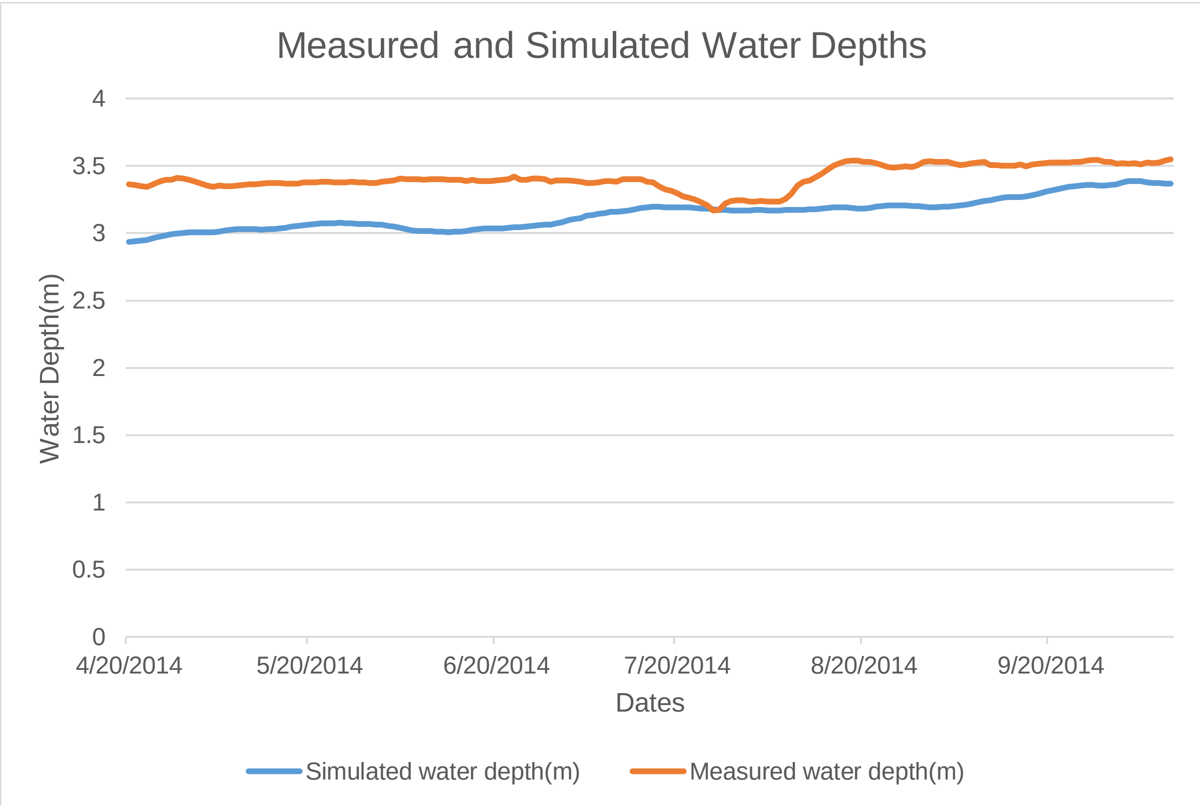

Figure 7 Measured water depth and simulated water depth just upstream of Lock 1

The model setup did not contain large flaws that affects the resulting water depth as the measured water depth and simulated water depth were considerably similar. Not much changes to the initial model setup were to be made for the simulated results to match measured water depth. Initially, a 2d mesh with a 10mx10m grid size was used with a manning’s n value of 0.035.Theta value was set to 0.5 making the scheme semi-implicit/explicit in nature and the limit to the maximum number of iterations was set to 40. The initial computation interval was set to 20 seconds and no Coriolis Effect was applied to the simulation. This model setup resulted in over estimation of the flow with undesirable water depths at the point of validation downstream.

Adjusting the computation interval to 3 seconds resulted in the best fit water depth at the validation point downstream. Lower computation intervals did not affect the results of the model significantly but only increased the computation time taken for the numerical solver to perform the simulation. Hence, a computation interval of 3 seconds as was selected based on the total time taken for the numerical solver to execute the simulation whilst comprising the waiting period for the results to generate.

Obtaining a good correlation between the measured and simulated water depths at the validation point was undemanding with the model even though the model was only hydraulic in nature. Factors such as evapotranspiration, infiltration and sediment transport are not simulated by the given model. Evapotranspiration accounts for the water loss from evaporation from land and water surface as well as transpiration from natural vegetation (Penman, 1948). Radiation from the sun is the primary energy source for driving evapotranspiration. Infiltration is the process of entry of water into the soil made available at the surface of soil (Philip, 1957). Both of these phenomenon, account for water loss. However the model underestimated the water depth at the validation point even though such water loss phenomenon were not considered. The spatial resolution of the bathymetric terrain used for model was comparatively of low resolution i.e 250mx250m. Hardy et. Al (1999) argues that spatial resolution has a direct effect on the inundation extent of the hydraulic model. The spatial resolution of the terrain data also affects the internal results of the model and has a greater effect than calibration parameter such as friction in altering the result of hydraulic simulation. The research suggests that spatial resolution directly affects the bulk flow of the hydraulic model which decreases with lower spatial resolution. This advocates for the under estimation of the water depth at validation point. However, direct identification of systematic trends caused by spatial resolution alone is not feasible due to the complex nature of the entire system but affect due to spatial resolution cannot be neglected either.

The model stability for the HECRAS 2d model depends on the Courant-friedfichs-Lewy condition (Brunner, 2016). The stability and the accuracy of the model is achieved by selecting a time step that satisfies the courant condition. Courant number is a measure of the amount of information that traverses a computational grid at the given time step (Sanz-Serna and Spijker, 1986). Courant number is taken as a measure of accuracy in computational fluid dynamics Under ideal conditions, Courant number, C_r< =1 which signifies that the fluid particles are moving from one cell to another within the given computational time step with reasonable accuracy and C_r >1 suggests that the fluid particle moves through two or more cells at each time step which affects the convergence negatively. Courant number is calculated for each individual grid cell at a given time step. It is dependent on the flow velocity, individual grid size and computational time step taken for the model. For an individual simulation in HECRAS, the grid size and computational time step are constant. A courant number greater than 1 at any given grid may suggests that the fluid particles do not reside within a cell but cross one or more cells over the give time step. This means that there is a loss in accuracy but the solution is still stable.

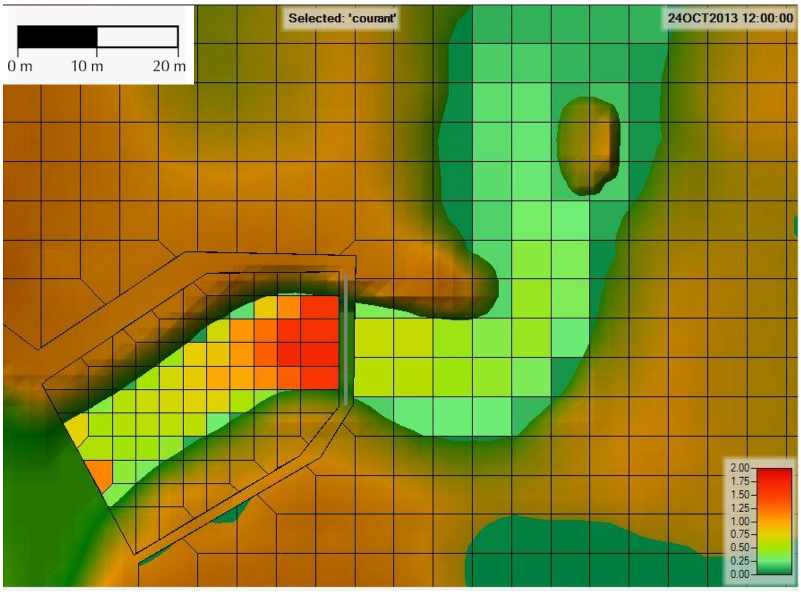

Figure 8 Courant number for individual grids at Gate 3 on 24 october.

Figure 8 illustrates the courant number for Gate 3 during the opening phase of its operation. High values of courant number being calculated downstream of Gate 3 indicates lower accuracy in flow velocity estimation. As the computational time step is constant for the entire simulation and the grid size is static as well, the values of the courant number higher than 1 at the outlet of Gate 3 suggests an overestimation of the flow rate by the numerical solver of the model itself (Brunner, 2016).

4.2 Hydraulic Structures

4.2.1 Flow hydrographs at structures

Hydraulic structures were used in the model to regulate flows at different part of the study site. As, shown in fig 8, Gate 1 was placed in the channel between wetland 7 and wetland 12, Gate 2 was placed at the inlet of wetland 13 and Gate 3 was placed at the outlet of wetland 13. The flow hydrograph for each of the gates are illustrated below.

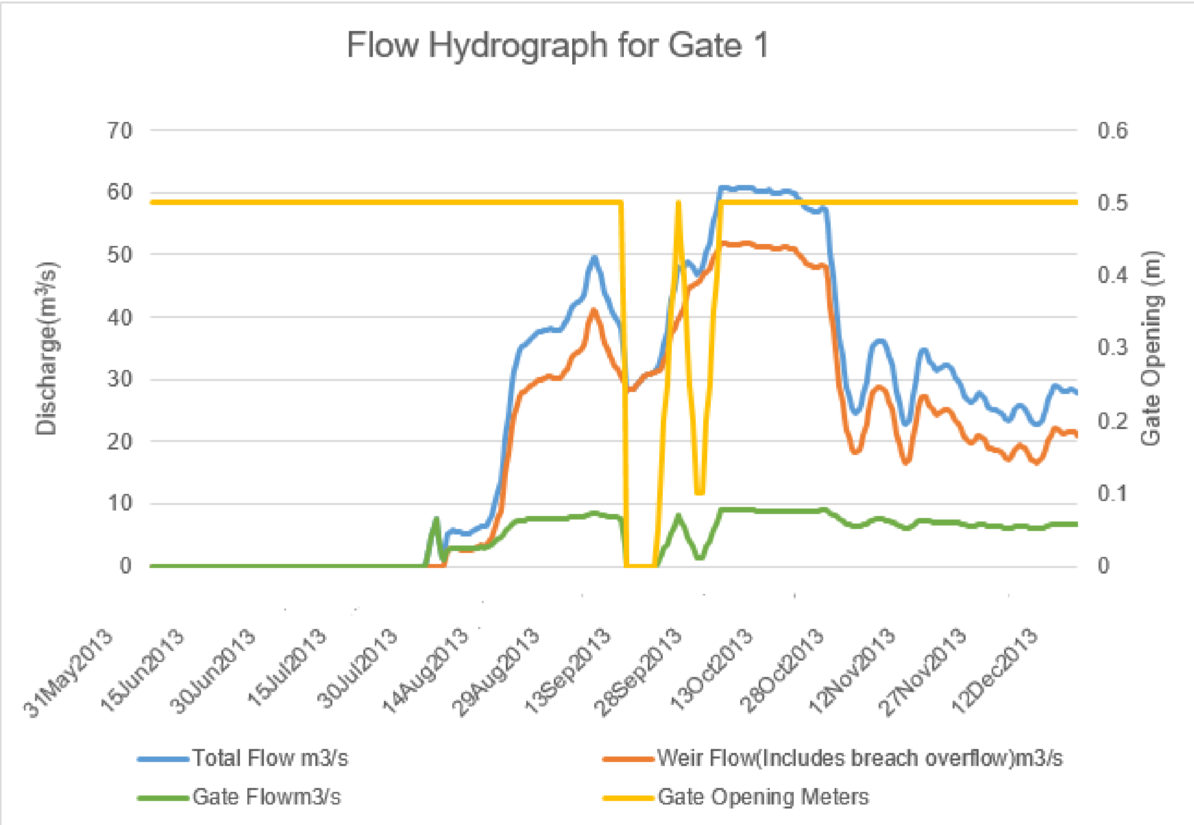

Figure 9 Flow hydrograph for Gate 1

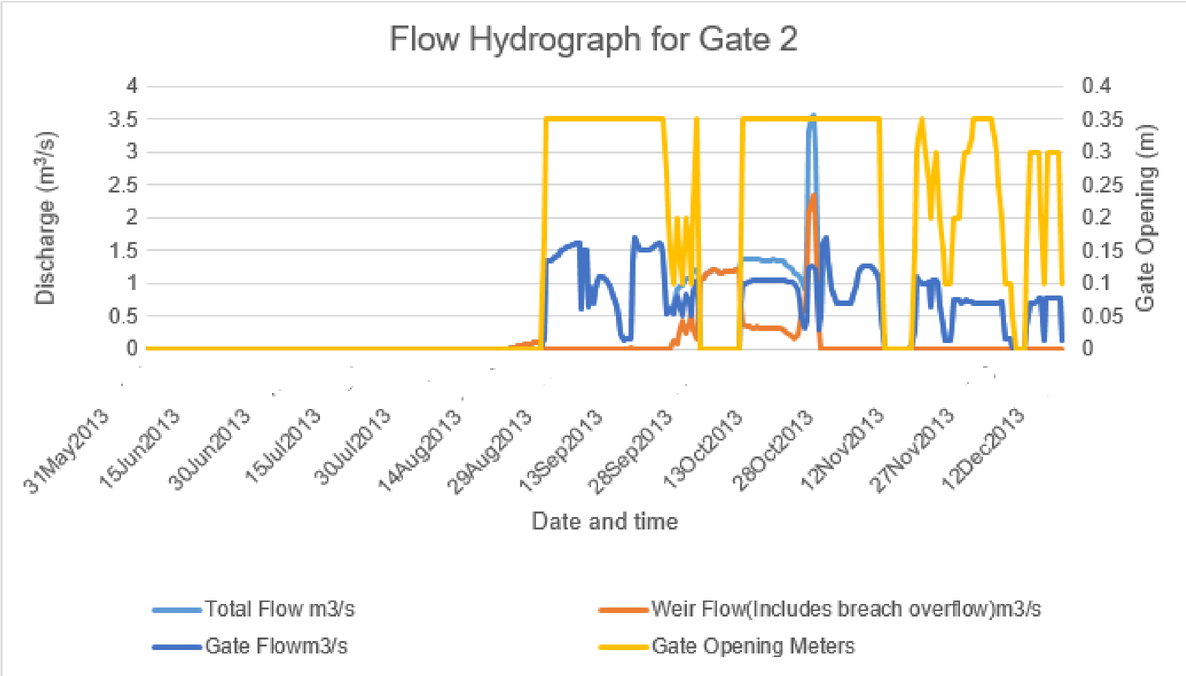

Figure 10 Flow hydrograph for Gate 2

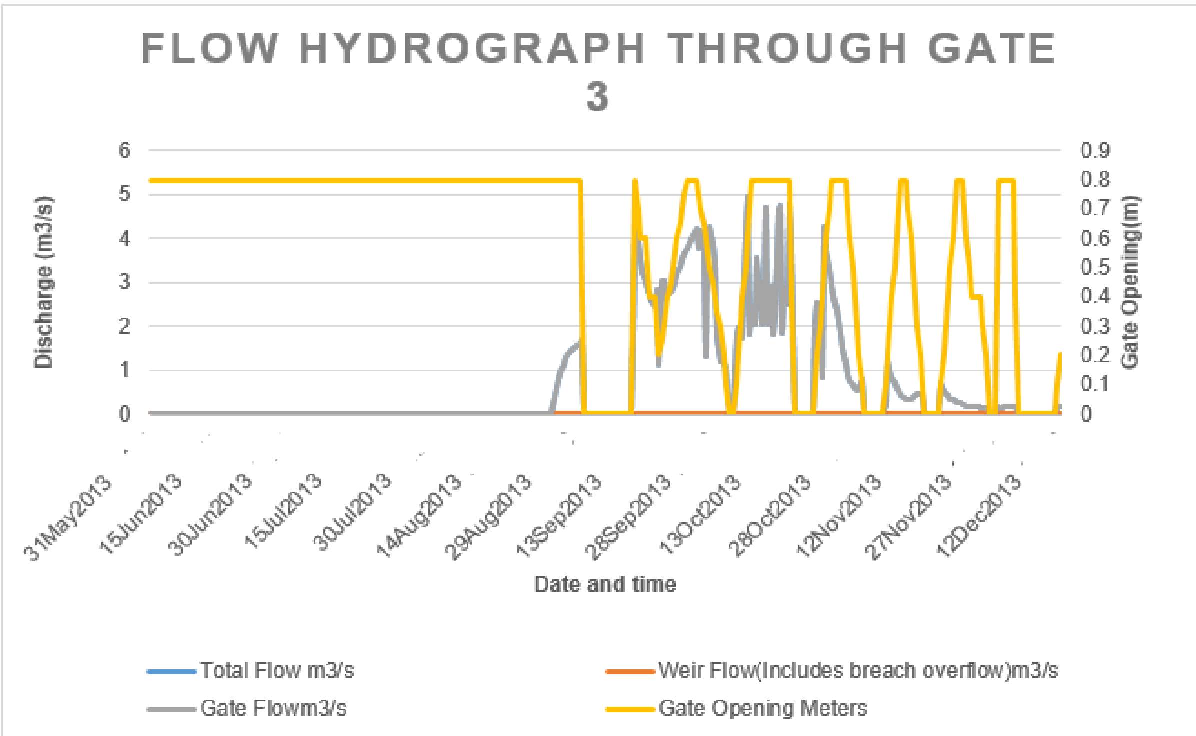

Figure 11 Flow Hydrograph for Gate 3

From the resulting hydrograph (Figure 9) it was observed that for gate 1 the total weir flow (including breach overflow) was high through most of its operational time at its location.

According to the model results, a breach overflow has occurred at gate 1 with water accumulating just upstream of gate 1 and breaching the gate in order to flow downstream. This suggests that a choked flow scenario for water might have occurred at the opening of gate 1. HECRAS relies on the principle of conservation of mass and momentum (Brunner, 1995), the conservation of mass states that the velocity of water increases as it flows through smaller cross sectional areas of the constriction. Choked flow is defined as a limiting condition for a given cross sectional area and mass of fluid so that mass flow rate of the fluid for the given area of passage will not increase with any decrease in pressure downstream (Dixon and Hall, 2013). At Gate 1, even when it is fully opened, a choked flow condition was reached under the given pressure and flow rate of water upstream of gate 1. This indicates that maximum flow rate through gate 1 under the given pressure condition was achieved. But, as the upstream flow rate was higher that the choked flow limit for the gate 1, the model implies that water inundation has occurred just upstream of gate 1 to the point that the water surface elevation upstream of Gate 1 exceeded the weir height causing water to flow by breaching the weir.

However, according to the model results, water surface elevation upstream of gate 1 has reached above 1m with respect to the datum. This indicates that the inundation of water just upstream of Gate 1 exceeds the depth of the terrain with respect to bank of the channel and an overbank flow scenario might have occurred. Overbank flow is defined a diversion in which the water depth surpasses the bankfull stage of a given channel and the excess flows into the nearby banks to a different hydrologic unit (Poff et al., 1997). At gate 1, under normal scenarios and equal bank heights, an overbank flow scenario will cause water flow on the banks of both sides of the channel. However, the DEM from which the terrain for the simulation was created does not contain the elevation data for the north east section with respect to the location of gate1. Hence, no terrain data was available for simulation of overbank flow on one of the banks of the channel where Gate 1 was located. So due to this data restriction the overbank flow would occur at only one side of the channel which would have created a scenario where flood inundation on one side of the channel would be highly over estimated as water is only being diverged onto one bank of the channel. In order to cope with this problem due to data restriction, a closed boundary 2d mesh for the hydraulic model was created only on the channel that connected gate 1 to wetland 7. As HECRAS works on the conservation of mass, the mesh acts as a barrier and does not let water escape from the computational environment (Brunner, 2016). Any volume of water that reaches this closed boundary condition will either be diverted back or inundates within the computational environment. So, upstream of gate 1, overbank flow is being re directed into the channel and being simulated as overreach flow at gate 1. High volume of water that was supposed to escape the channel under normal condition has been conserved within the computational domain. This advocates for the relatively high simulated results of discharge estimated at Gate1 with total flow rate including breach overflow and gate flow reaching a maximum of $60m^3/s$.

Overreach flow was not observed as dominantly as Gate 1 at the locations of Gate 2 and Gate 3 with the total flow estimate being similar to the gate flow estimate in the resulting hydrographs (Figure 10 and Figure 11).

4.2.2 Hydraulic response at the gates

The response of the hydraulic structures to water flow in form of flow velocity as well as shear stress were calculated by the model and visualized in the form of maps across the given terrain at each output interval.

At gate 1 where the model estimated a breach overflow, the velocity profile upstream and downstream of the gate did not show significant change with respect to the opening and closing of the gate.

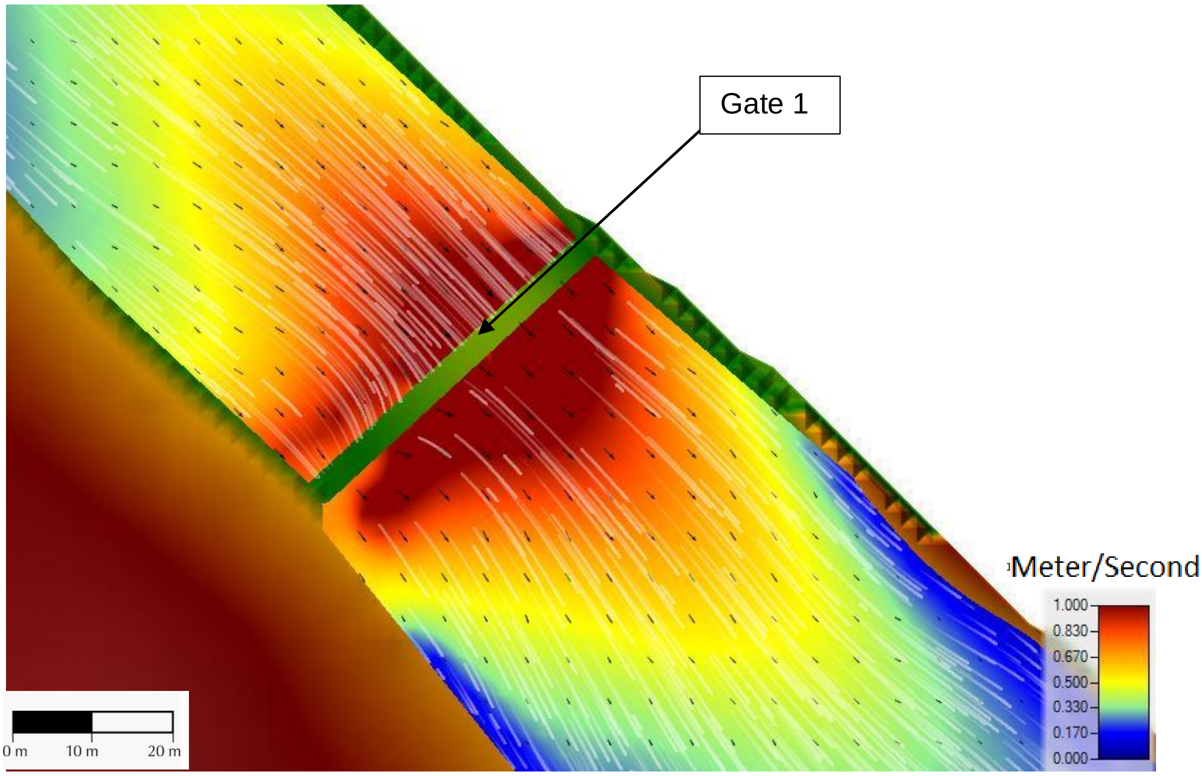

Figure 12 Velocity profile and fluid movement through Gate 1(fully opened) on 05th oct

As seen in the figure 12 and figure 13, the water flow hasn't been abruptly affected by the opening and closing of Gate 1. The illustration of water flow through Gate 1 shows fluid flow and particle movement throughout the weir. While the gate was closed between the time of 8th September and 15th September, the simulation suggests that flow was not affected by the gate opening and breach overflow continued to take place.

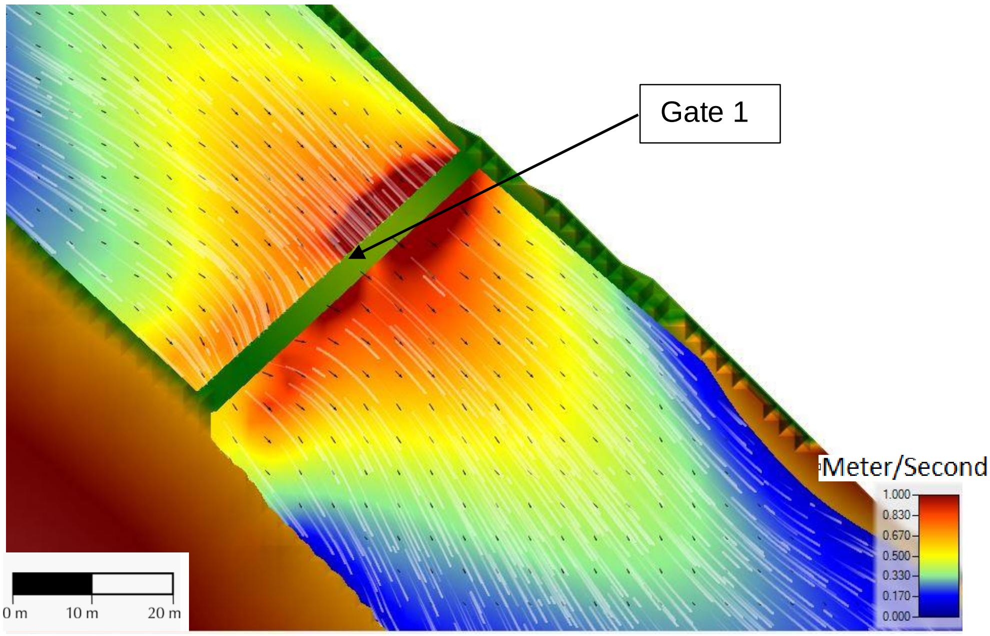

Figure 13 Velocity profile and fluid movement through Gate 1(fully closed) on 08th sept

However, at gate 2 and gate 3 different velocity profiles were with respect to gate opening and closing pattern.

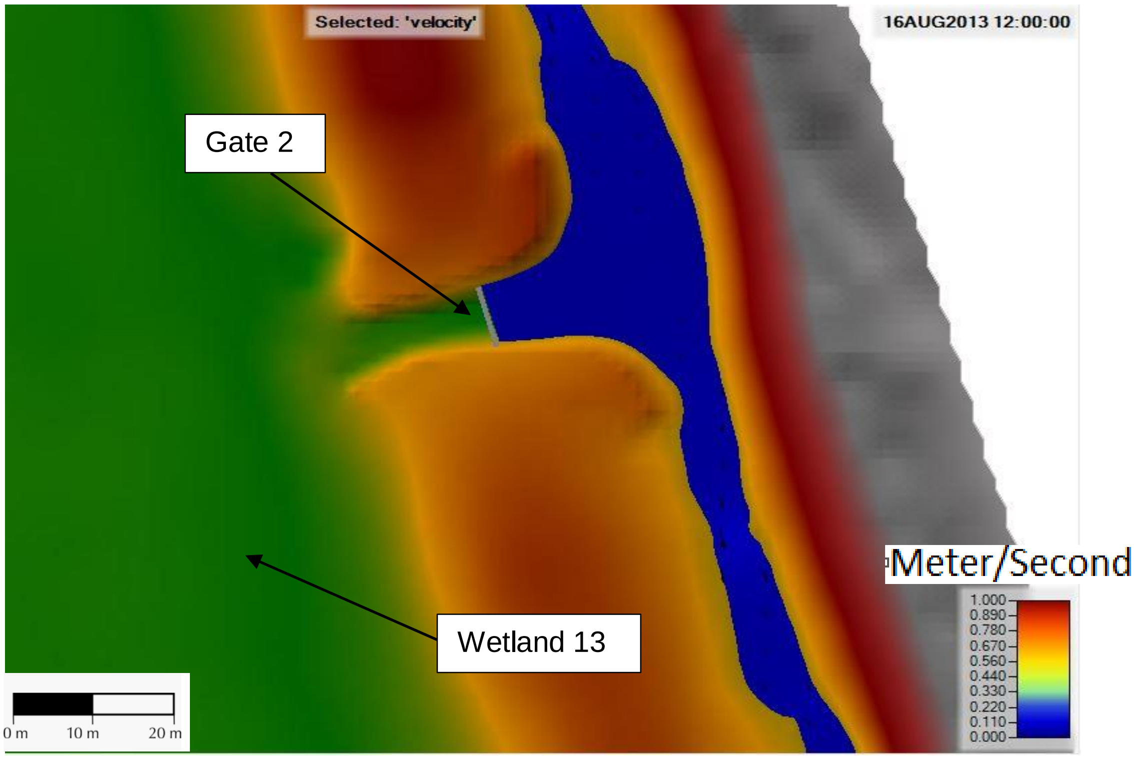

Figure 14 Velocity profile and fluid movement through Gate 2(fully closed) on 16th August

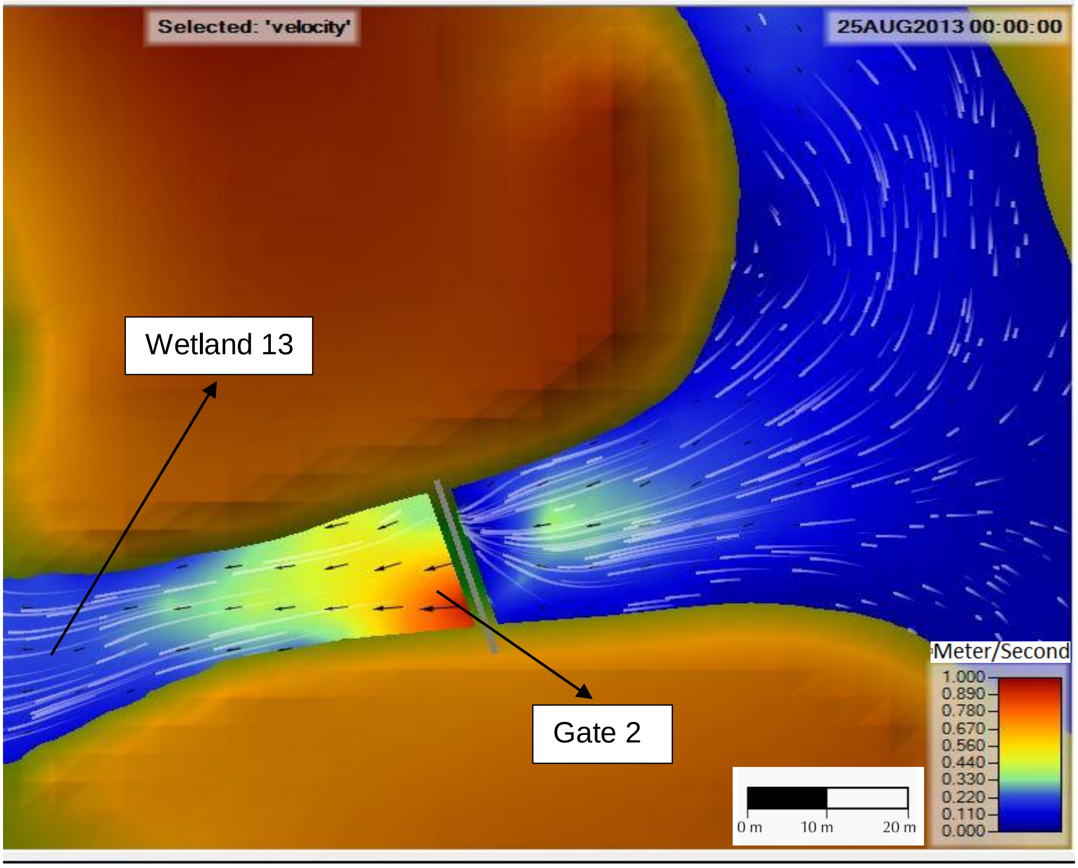

Figure 15 Velocity profile and fluid movement through Gate 2(fully opened) on 25th August

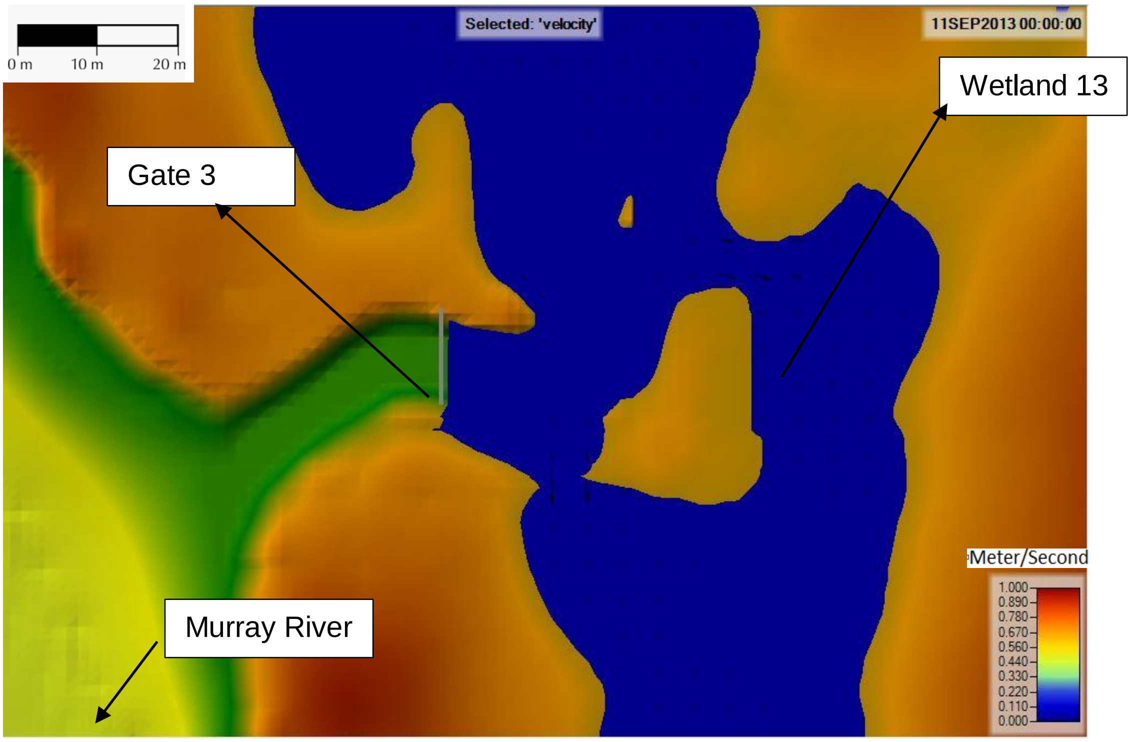

Figure 26 Velocity profile and fluid movement through Gate 3(fully closed) on 11th September

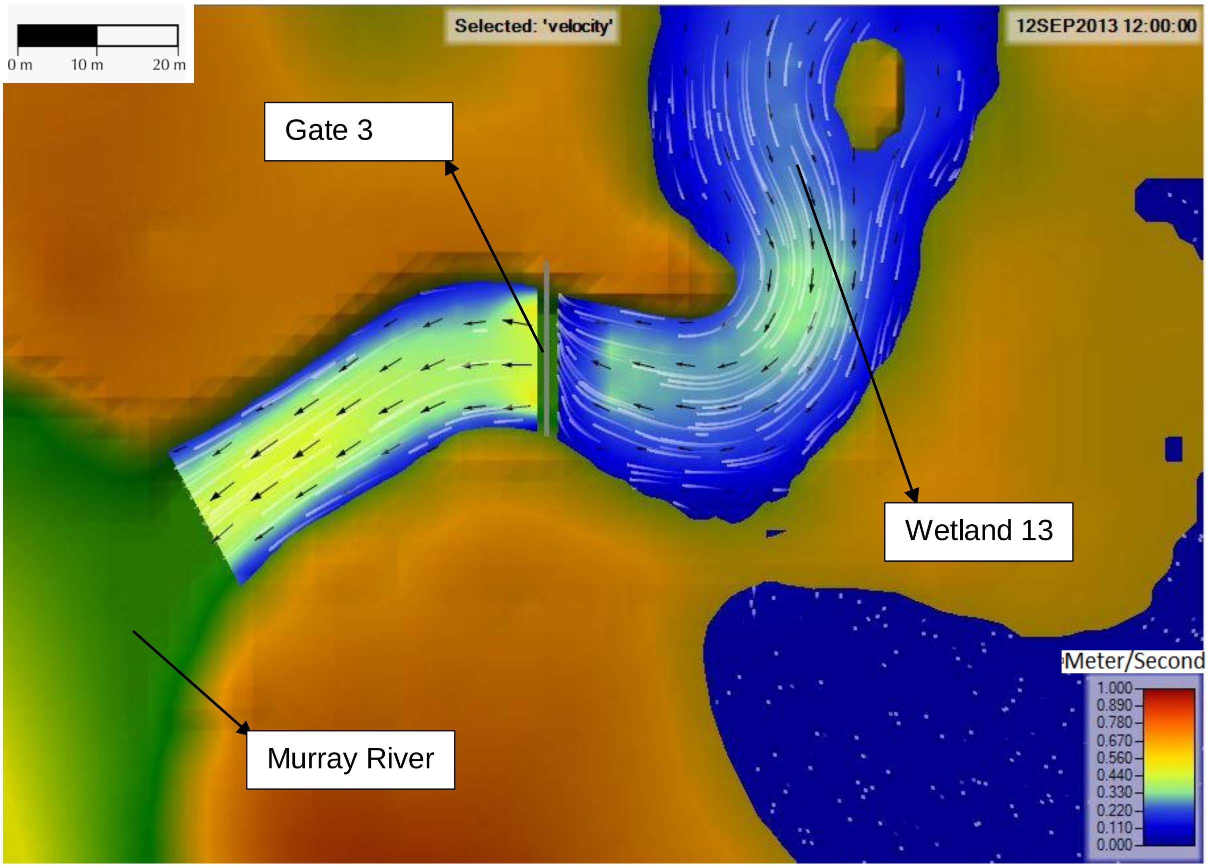

Figure 17 Velocity profile and fluid movement through Gate 1(fully opened) on 12th September

Gate 2 was placed at the inlet of Wetland 13 and was closed till 23th August of the simulation time period. The model estimates that negligible breach overflow occurred through Gate 2 during its time of closure. The dimension and location of the weir and gate was able to divert or store the flow of water upstream of Gate 2 according to the models calculation (Figure 13). Similarly, Gate 3 which was placed at the outlet of wetland 13 also was able to retain water inside the wetland with negligible breach overflow during its time of closure under given flow conditions (Figure 15). Gate 2 was fully opened on 24th August letting water into wetland 13(Figure 14). Gate 3 which remained closed till 11th of September was fully opened on 12Th of September (Figure 16).

As seen in Figure 14 and 16, the fluid flow and particle movement only occurred at the point of gate opening of the weir with all the flow being directed through the gate opening with high velocity downstream of the gate 2 and gate 3 respectively with velocity of water being affected to some extent at upstream of the Gate 3 as well. The velocity profile thus developed by the model is governed by the transitions of fluid flow through contraction and expansion region upstream and downstream of the hydraulic structure.

When the hydraulic structures are constructed their approach embankments act as an obstruction to general water flow through that area. This results in increase in the water surface elevation upstream of the structure at a given discharge in relation to the water surface elevation if the structure is absent. Hence, in upstream of the structure a backwater region formed at which the water depth is higher than unrestricted conditions (Hunt et al., 1999). This region is considered to be the contraction region. Flow velocity and friction loss are considered to decrease as we move from upstream towards the structure within this region. Other additional losses in this region is the result of increased velocities and the turbulent exchange of momentum which coexist with contracting flows through the structure, in this case the gate openings. Just downstream of the structure water surface dips with flow velocity increasing and rapidly varying in within this zone. This zone is referred to as expansion region (Hunt et al., 1999). In this region, energy loss is higher than normal as a result of higher flow velocities and turbulent momentum in correlation to the expansion of flow region. However such losses and change in momentum are local to the structure with no affect in flow beyond the respective regions but the spatial extent of such change in velocity and increased shear stresses indicates of turbulence in water flow entering and exiting the structures (inlet and outlets of wetlands) with respect to the kinetics of the water body beyond the contraction and expansion region.

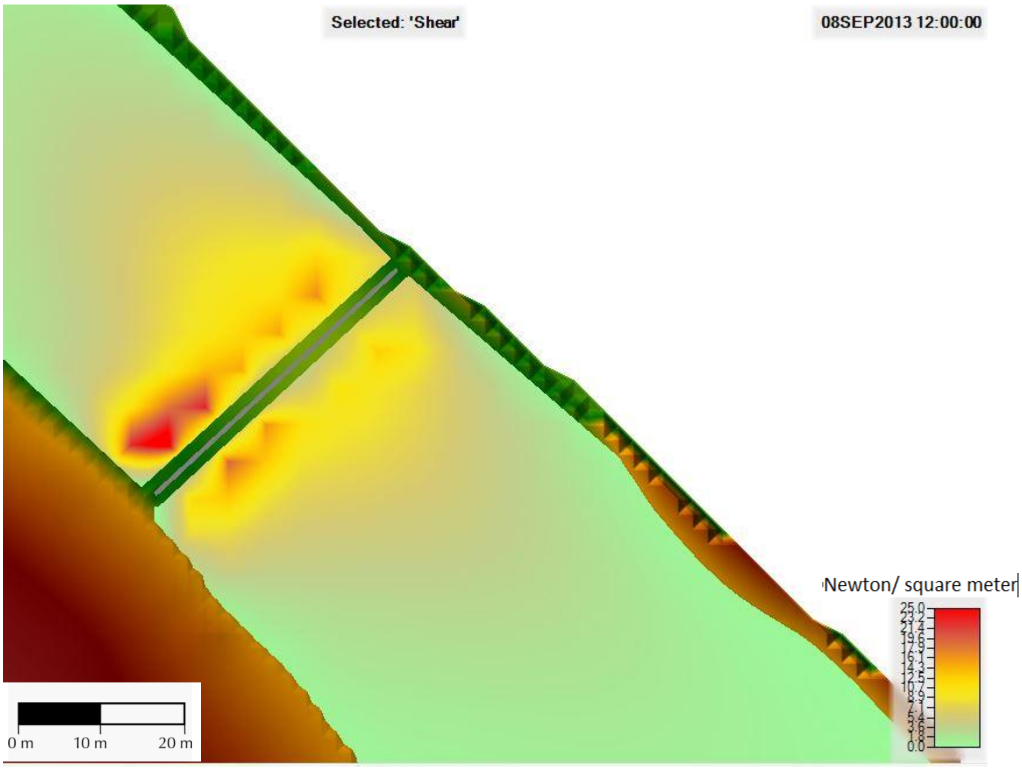

Figure 38 Local shear stress levels at gate 1 (closed)

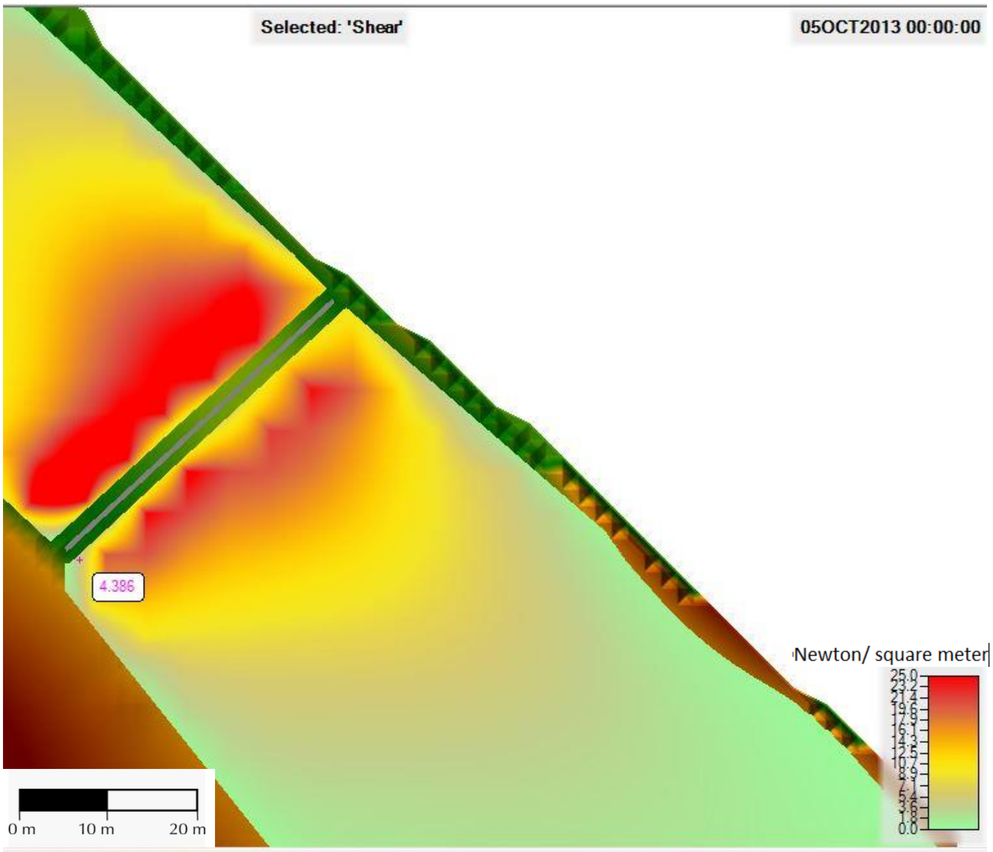

Figure 49 Local shear stress levels at gate 1 (open)

Shear stress is defined as a measure of the frictional force from fluid flow and in case of open channelf low, it is the force of flowing water against the contact surface of the channel(Bedient et al., 2008). The shear forces are created due to vertical changes in water velocity which are parallel to the bed. Shear stress is generated as a result of these shear forces acting on the bed of the channel. The magnitude of shear stress is a function of the channel geometry, flow and slope of water surface. Shear stress is the driving force for the initiation of bedload transport and scour. Scour may occur due to shear stress which is the erosion resulting from shear stress from wave action and flowing liquid(Melville and Coleman, 2000).

At the location of Gate 1 (figure 17 and Figure 18), shear stress through out the simulation period was recorded to be comparatively higher than at the locaitons of Gate 2 and Gate 3. Such constant shear stress level may cause scour if the be channel causing the structure to fail in time due to the erosion of the bed and sediment deposition on the inlet of the structure and sediment erosion at the outlet of the structure. However, as flow velocity of Gate 1 is highly overestimated due to the diversion of water back into the model as stated in the previous seciton, shear stress is also being overestimated at Gate 1 as shear stress is directly proportional to flow velocity (Bedient et al., 2008). At Gate 2, no much shear stress was recorded during it closure and opening phases(Figure 19 and Figure 20). This indicates the channel around Gate 2 and the structure itself it not being subjected to high amount of stress during its operation cycles at the simulated flow rate and water depth upstream of the structure.

At Gate 3, different level of shear stress was observed dependent on the phase of its operation(Figure 21 and Figure 22). During its closure, according to the model, no significant amount of local shear stress was observed around the area where Gate 3 is positioned in the computational environment. During the phase when the Gate 3 was closed, change in inundation extent was observed in wetland 13 with inundation extent as well as water levels increasing within the terrain (computational mesh). This indicates that the terrain supported increase in inunation extent without subjecting high amount of stress on the hydrualic structure itself. During the phase when Gate 3 opened , high shear stress levels on the contraction and expansion region of Gate 3 was obeserved.

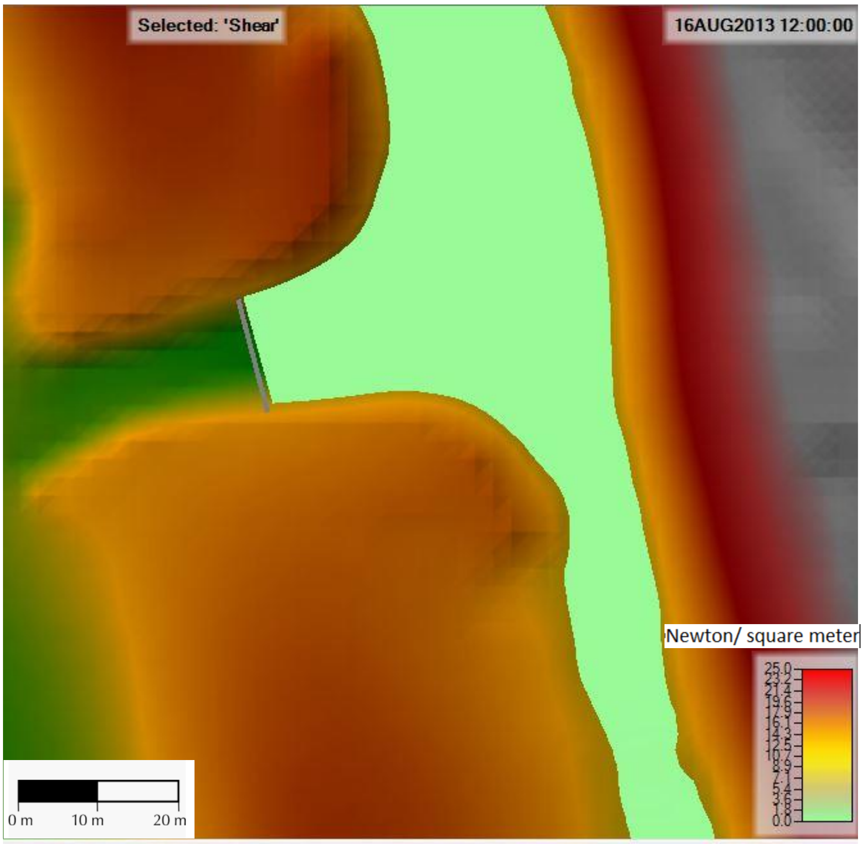

Figure 205 Local shear stress levels at gate 2 (closed)

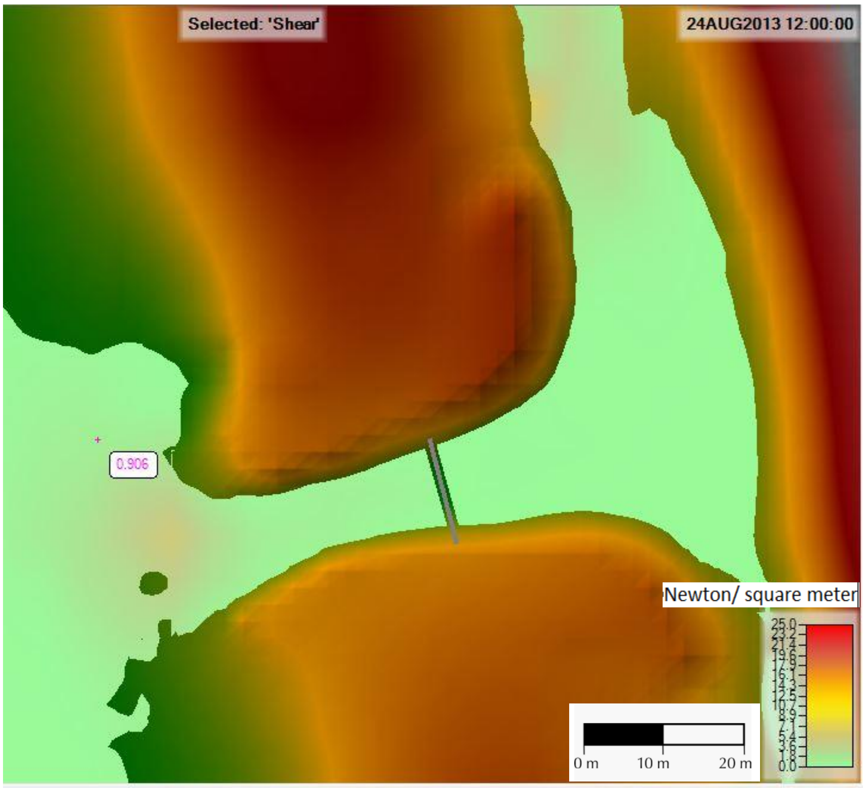

Figure 21 Local shear stress levels at gate 2 (open)

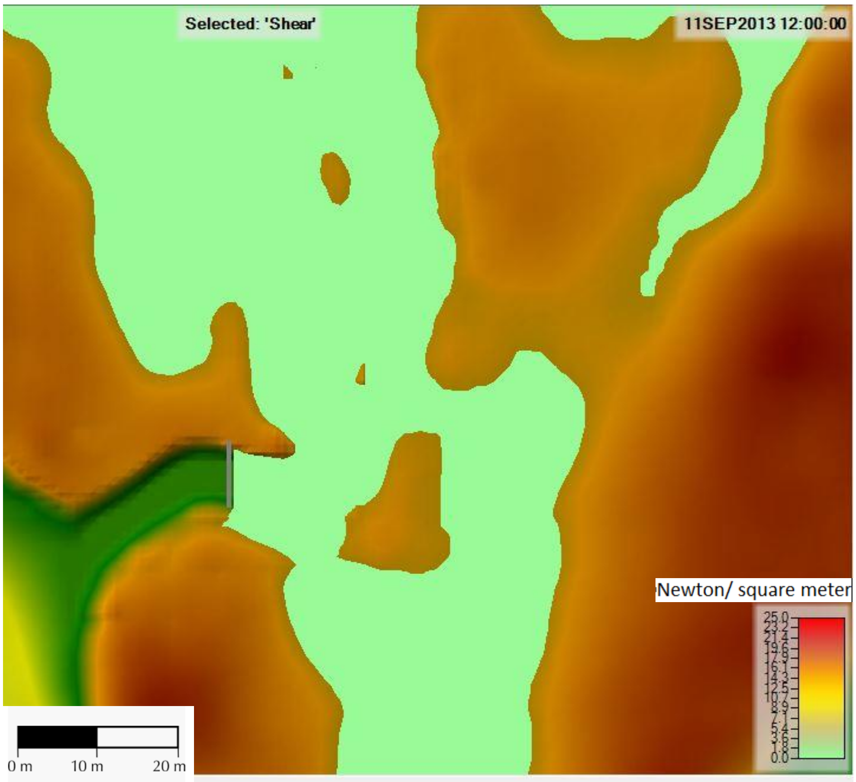

Figure 22 Local shear stress levels at gate 3(closed)

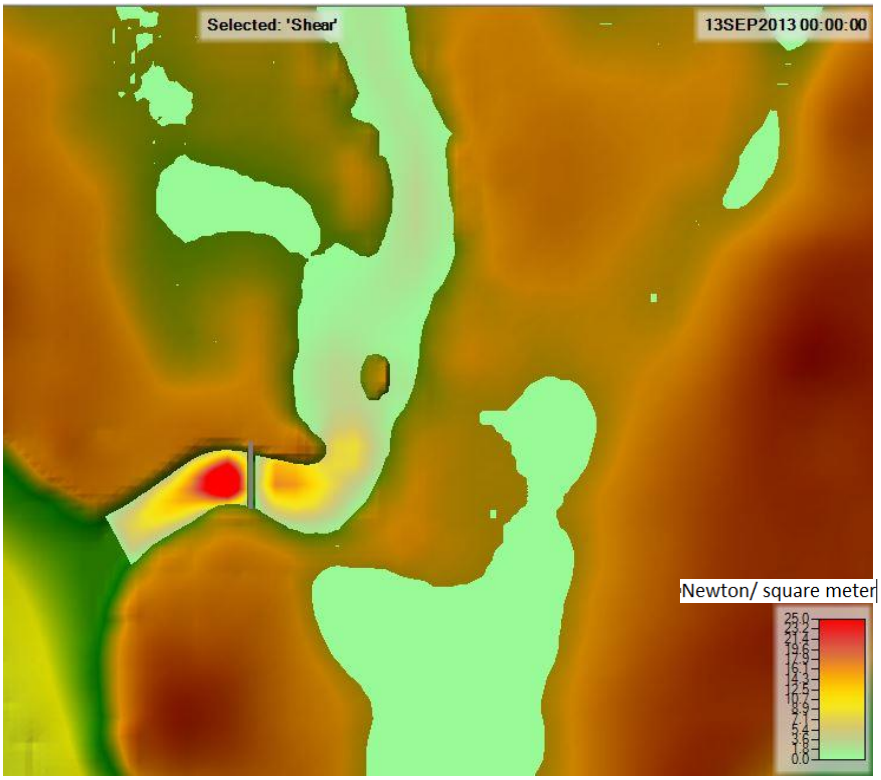

Figure 23 Local shear stress levels at gate 3 (open)

4.3 Change in inundation area

In the model setup, 3 gates were placed within the computational grid. Gate 1 was placed in the channel connecting Wetland 7 and wetland 12, Gate 2 was placed at the channel connecting wetland 12 and wetland 13 and Gate 3 was placed at the outlet of wetland 13. According to the model, Gate 1 was constantly subjected to breach overflow which suggested that the design and location of Gate 1 was not suitable for controlling the water levels in wetland 7 at the given flow rate and time. Gate 2 was not subjected to breach overflow like Gate 1 but during its closure water was redirected to the Creek 14 were it escaped to the Murray River. In both these cases, closure of the gates did not cause significant change in water inundation area and extent in both the wetlands under the given conditions, input parameters and computational extent of the 2d model. However, inundation extent change was significant in wetland 13.

The maximum depth map and velocity map both show the maximum values of depth and flow reached during the entirety of the simulation (Figure 24 and 25). The extent of water inundation shown by these maps also suggests the maximum extent reached or area subjected under water flow during the entirety of the simulation. Evaluating the maximum area of inundation for each of the wetlands, no significant increase of inundation extent were reported for wetland 7 and wetland 12 by the model under the given flow rate and boundary conditions (Figure 26 and 27). However, area around wetland 13 had an increased inundation extent that exceeded the boundary of the wetland and conditions where the water overflowed on the adjoining floodplain were seen. Evaluating the total simulation an increase and decrease in inundation coincided with the operational phase of Gate 3.

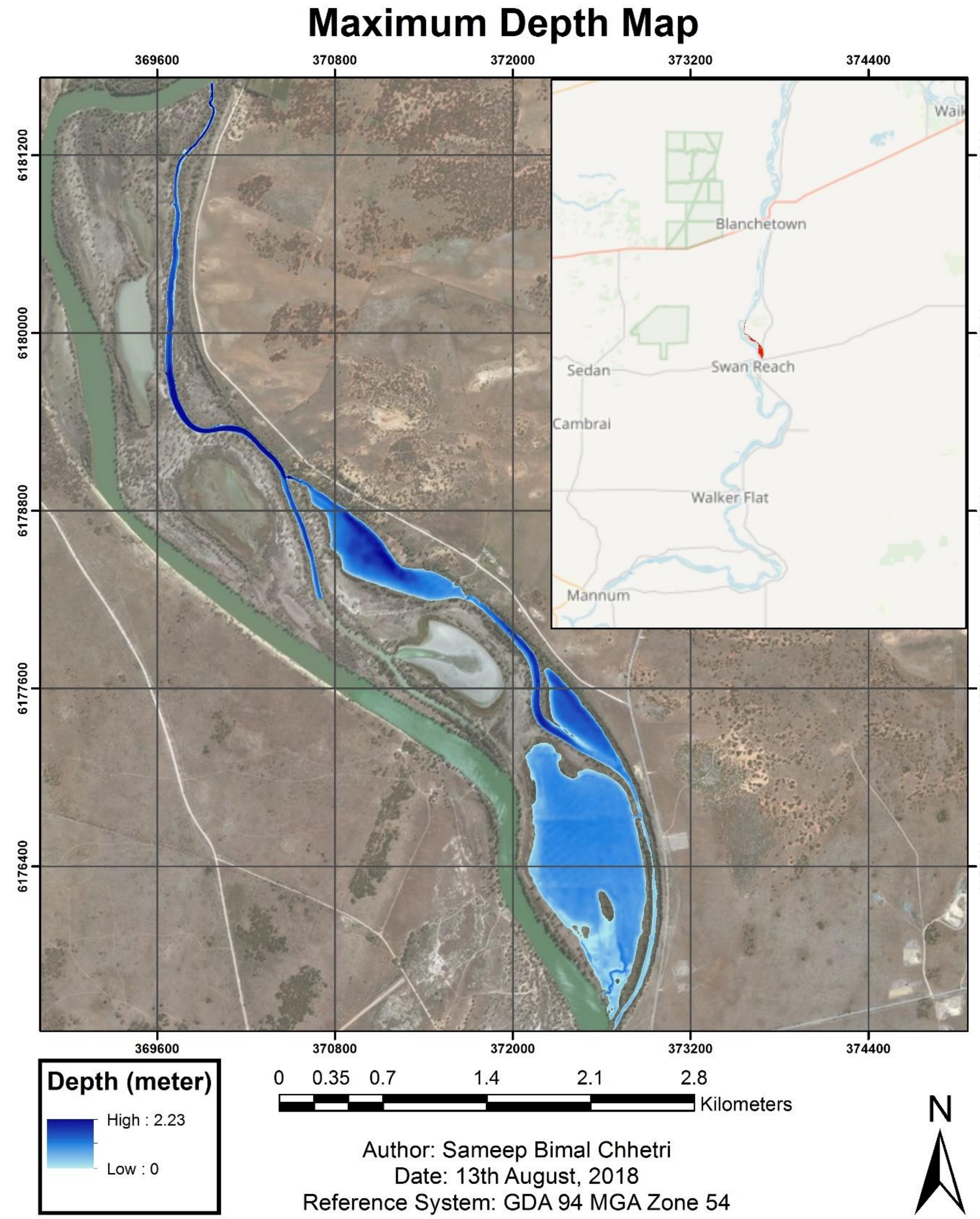

Figure 24 Maximum Depth Map for Wetland 7, 12 and 13 of Sugar Shack Complex

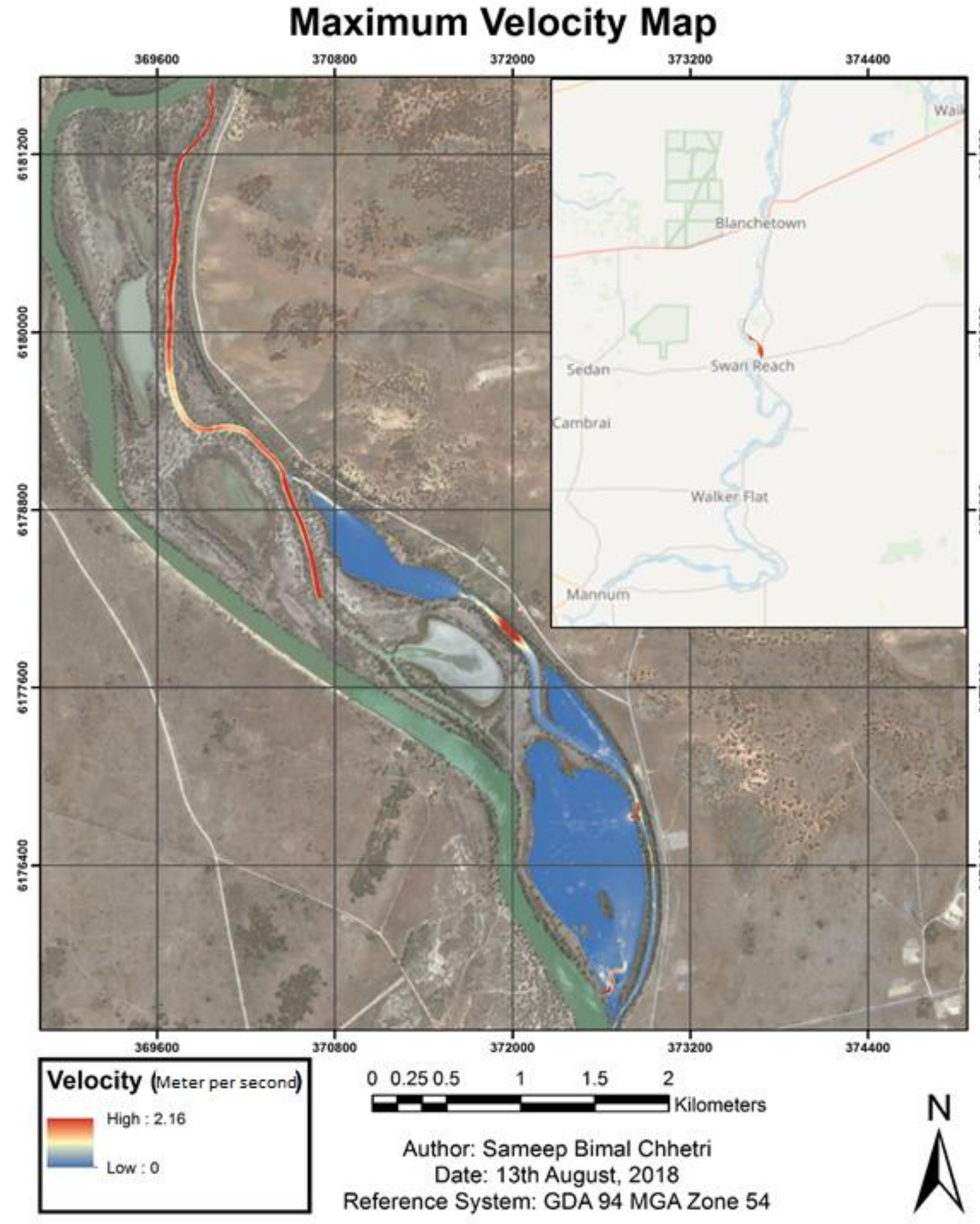

Figure 25 Maximum velocity map for Wetland 7,12 and 13 of sugar shack complex

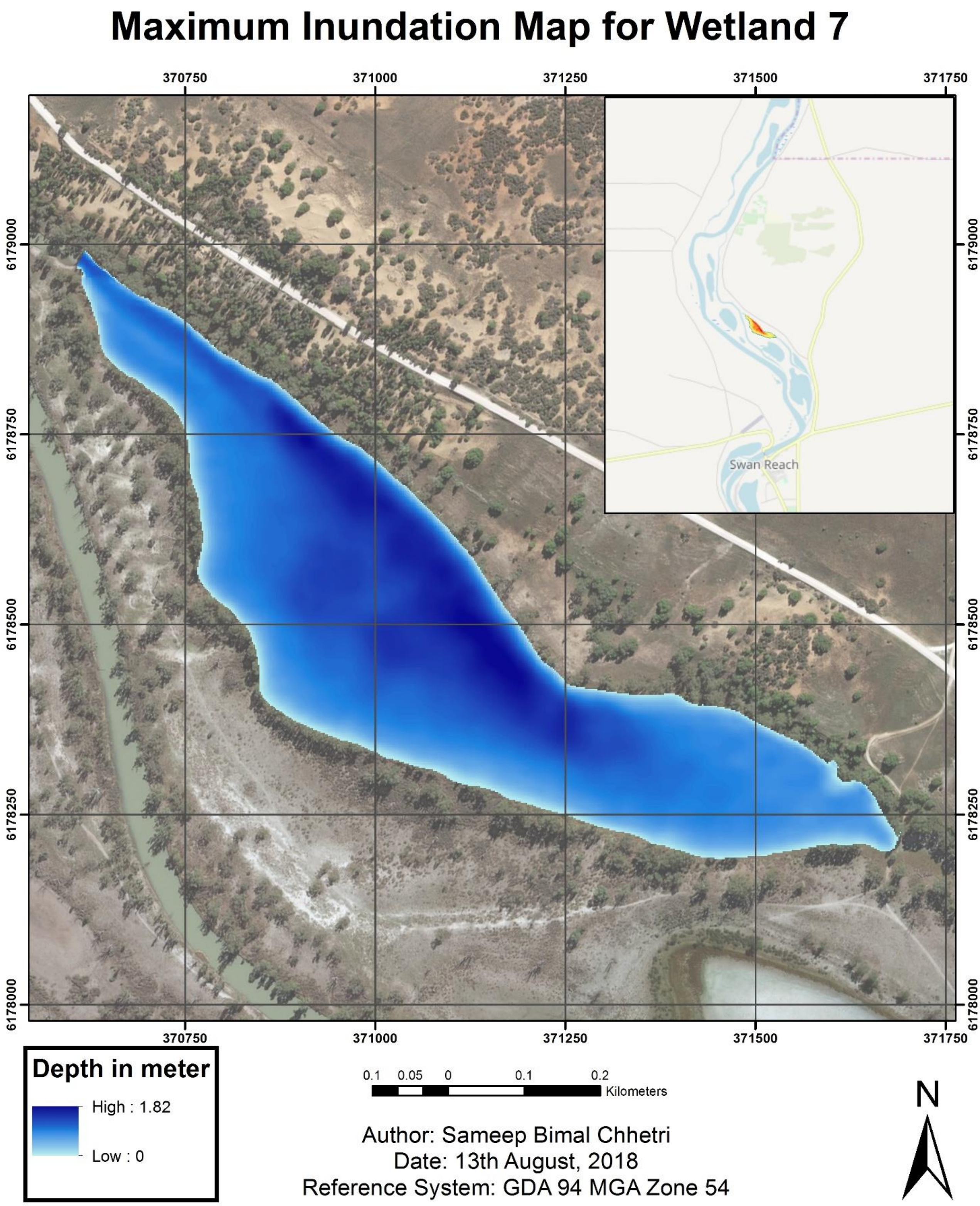

Figure 26 Maximum inundation map for wetland 7

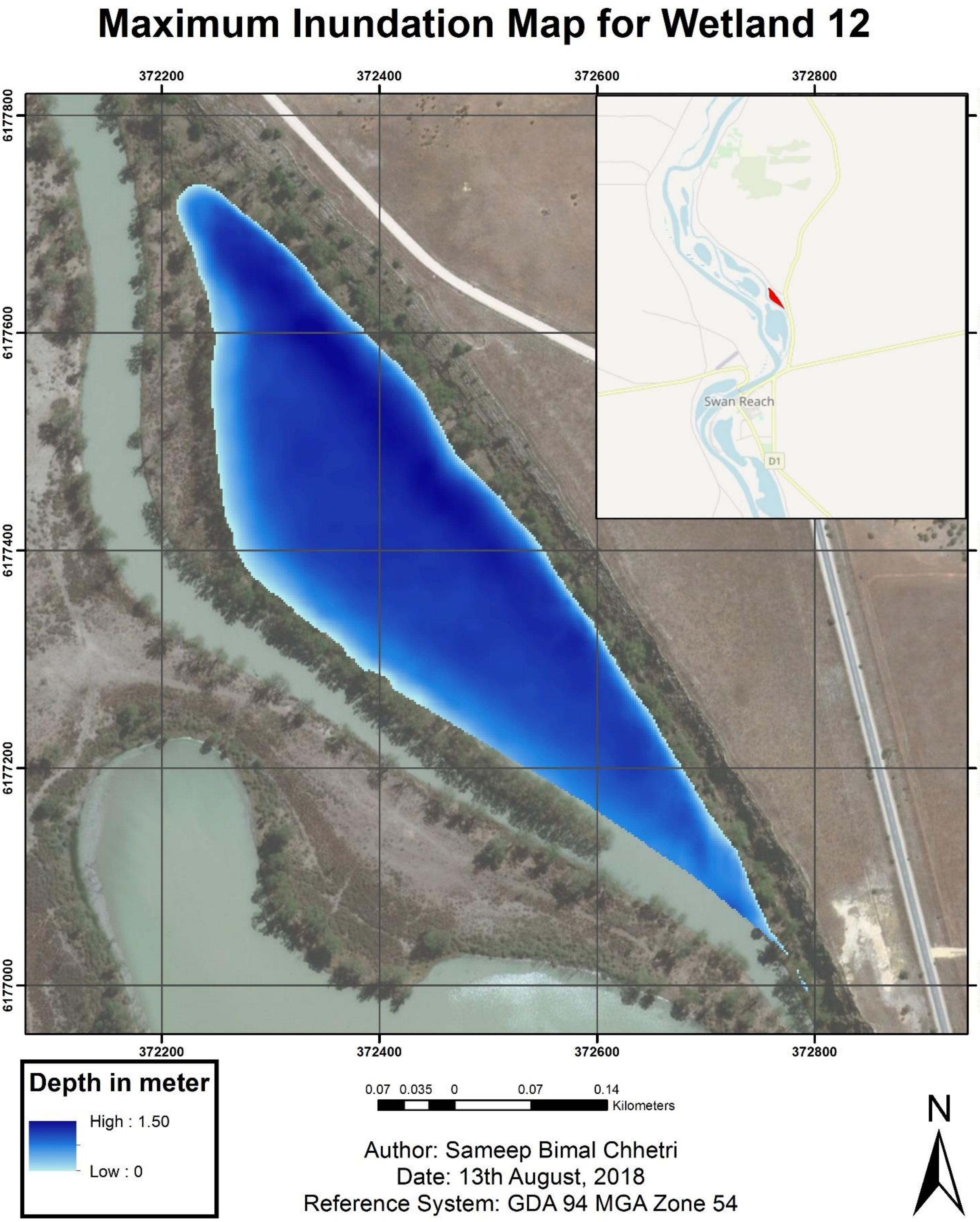

Figure 27 Maximum inundation map for wetland 12

Table 5 Hydraulic response of Wetland 13 to operation of Gate2 and gate 3

Date	Inundation Extent (ha)	Water Surface Elevation (m)	Flow Rate (m^3/s)		Gate opening (m)	
			Gate2	Gate 3	Gate 2	Gate 3
17/10/2013	68.6	0.721	1.11	0	0.35	0
18/10/2013	74.7	0.852	1.04	0	0.35	0
19/10/2013	80.3	0.961	3.32	0	0.35	0
20/10/2013	83.5	1.031	3.54	0	0.35	0
21/10/2013	83.0	1.057	3.03	2.25	0.35	0.10
22/10/2013	78.05	0.874	0.61	2.02	0.35	0.20
23/10/2013	69.3	0.598	1.59	4.27	0.35	0.30
24/20/2013	65.4	0.520	1.36	3.31	0.35	0.40

Table 5, gives an insight on the change in inundation extent and water surface elevation generated by the model for wetland 13. The inundation map for the time period listed in Table 5 can be found in the annex (a – j) of this report. Wetland 13 has a total area of 66.2 ha and during the closing phase of the Gate 3 inundation extent went up to 83.5 ha at the given flow rate. According to the results of the simulation, a decrease in inundation extent as well as water surface elevation was seen when Gate 3 was opened. The results of the model suggest that a controlled environmental watering scenario could be successfully created in wetland 13 and its surrounding terrain as a function of the operational phase of the hydraulic structures, Gate 2 and Gate 3, alone under the given flow conditions.

CHAPTER FIVE DISCUSSION

5.1 Key Findings

According to the simulation, high velocities and shear stress levels were predicted in the main channel in relation to the wetlands of the study area. An environmental watering scenario with significant change in inundation extent could not be achieved for wetland 7 as the model predicted an over bank flow onto adjoining floodplains from the outlet channel when a hydraulic structure was placed in the flow path of the water exiting wetland 7. The lack of data for the adjoining floodplain resulted in uncertainty in predicting whether or not the water flow on the floodplain was under controllable limits through the operation of Gate 1. In case of wetland 12, controlling flow caused the water level to rise with no significant change in inundation area as water escaped the wetland through the artificial channel downstream of creek 14 of the sugar shack complex. Visually accessing the maximum inundation extent for wetland 7 and wetland 12 by overlaying on top of an aerial image indicated that any flooding scenario may cause water to flow outside Sugar Shack complex as they are both located at the Eastern boundary of the study area as shown in Figure 25 and 26.

The water delivered into a wetland can be measured in volumes but it's the water flow and water height and extent that is more meaningful in fish responses (Koehn et al., 2016). Under the given model assumptions, wetland 13 and its surrounding floodplain was the most responsive to the operation and placement of hydraulic structures in terms of rate of increase and decrease of inundation area and extent. The maximum inundation extent of 83.5 ha was simulated by the model at Wetland 13 and its adjoining floodplain. An environmental watering scenario where inundation extent and water level were both controlled using the hydraulic structure was predicted by the model. Both inundation and water level rise increase were observed during the closing of Gate 3 and a decrease was simulated when the gate was opened. The model predicted high velocity and shear stress profile around the structures when Gate 3 was opened after certain time of closure and relatively higher water level at the upstream end of the gate. The spatial extent hydraulic response of the wetland when subjected under such flow regimes can give valuable insight on the precautions required to design such structures.

The channel leading to gate 3 has higher velocity than other inundated areas of the wetland during gate opening (Figure 25). When the gate was opened water level in the wetland decreased, according to the model the channel leading to gate 3 was subjected to high shear stress (Figure 23) as water velocity in the channel was predicted to be higher than rest of the wetland . Hence, the water in the outlet channel of wetland 13 can be said to be more turbulent in nature with varying flow rates while the water in the wetland had relatively lower velocity (Figure 25) and less turbulent nature throughout the simulation of the model.

Common Carp recruitment and spawning is enhanced by flooding of floodplains resulting in an increase of the carp population which has been known to readily response to changes in flow (Stuart and Jones 2006a). All events that cause change in water flow can act as a factor for change in carp population as increased carp spawning as a function of flow has been reported in a wide range of studies in both wetlands and rivers(Bice and Zampatti , 2011; Bice et al. 2014; Crook and Macdonald 2013). Flooding scenarios through both natural and managed inundation expand the extent and area of potential habitat for Carp recruitment and spawning as well potential site for native fish species spawning (King et al., 2003). Carp have been recorded to prefer slow flowing waters and also been observed at water bodies with slow or zero velocity (Bice and Zampatti, 2011). This may suggest that release of water from wetland 13 after certain inundation extent has been met, carp may avoid such channels preferring to reside in areas with lower water velocity even inside the wetland. But, it cannot be neglected that flow velocity in Wetland 7 and wetland 12 were relatively constant and slow in nature. Carp have a tendency to avoid turbulence in water(Qi et al., 2012). This indicates that if carp were to avoid turbulent water flow during to the operation of gate 2 and gate 3 then, wetland 7 and wetland 12 can provide slow and steady water flow which is preferred by carp.

The result suggests that through the use of hydraulic structures, water level and inundation extent can be manipulated significantly at wetland 13 of the sugar shack complex as seen in appendices. Such environmental watering practices will help increase inundation extent of water in the wetland providing benefits towards native fish as well as provide a potential site for carp harvesting (Koehn et al., 2014, Mallen-Cooper et al., 2008). The increase in fish numbers can also help in promoting tourism in sugar shack complex which is also a primary objective under its management plan (NRA, 2015). However, artificial inundation may possess a potential risk in significantly increasing the carp population in wetlands. In case of wetland 13, use of hydraulic structures has expanded the area and extent of inundation significantly under the given water flow conditions and operational cycle of the hydraulic gates as illustrated by Table 5. According to Zampatti et al. 2011, such artificial expansion of inundation extent also increases potential habitat for carp spawning and recruitment. King et al. 2003 discusses on how Common Carp is the only fish species that showed a recruitment benefit from inundation of flood plain on Ovens River. Stuart and Jones 2006a, 2006b also conclude that hydrology has positive effects on recruitment strength of carp population. Crook and MacDonald (2013) stated that absence of any significant flow after spawning events limits dispersal and result in retention closer to the nursery areas. According to these findings and the results of this simulation, it can be assumed that if Wetland 13 were to be artificially inundated, expansion in the area and extent of the floodplain can led to increase in the spawning and recruitment of Common carp in Wetland 13. This will be dependent on the operation of the hydraulic gates.

5.2 Limitations of the study

Even after the best efforts given within the available time and resources, the author faced the following limitations that have made significant impact on the overall outcome of the research. Such limitation should be addressed or minimized in future research work.

1. Flow data:

   The upstream flow data for the model was calculated using various assumptions. A field data collection of flow rate at the inlet would provide a more accurate model output as this has high influence on the overall result of the model. Also the initial condition of the wetlands were unknown hence, an initial ramp up was conducted in order to compensate for this lack of data.

2. Issues with land cover:

   Integrating a land cover map, and allocating the Manning's roughness coefficient for each land cover in the model would provide a more accurate prediction of flow.

3. Lack of terrain data:

   Due to the lack of terrain data, inundation scenario at Wetland 7 and overall performance of the Gate 1 at its given location could not be fully analysed.

4. Software used:

   HECRAS was an easy to use software but a lot of unexpected errors were encountered during the simulation. The software crashed multiple times without warning and also has other flaws in its User Interface that can severely affect the time taken for preparation of the model. The total computation time taken for the numerical solver was also relatively slow. Even when all the cores of the computer were allocated and given utmost priority in processing, the numerical solver only used 10 Mega Bytes of Memory. This led to the simulation taking up to 4 days to complete.

5.3 Future research

As environmental flow is a relatively new field of science, the delivery and management of water is developing at a rapid rate. Our knowledge on Fish-Flow interaction is also increasing, with increase in research regarding the aspects of fish biology in relation to flow rates for a variety of fish species. This can further lead to development of the application of flow with regards to fishes. Wetland 13 of sugar shack complex can provide as an adequate site for study of relation between fish and flow under rapidly increasing and decreasing water levels influenced by artificial inundation using structures.

Such practices in relation to carp and other fish species can prove to be crucial in further understanding the relation between different fish species and flow in the lower Murray Darling Basin. There exist a lack of quantitative data for the carp population throughout the Murray Darling Basin (Koehn et al. 2016). The use of hydraulic structure to artificially inundate wetlands can help mimic components of the wetlands natural flow including frequency, timing, magnitude, rate of change and duration (King et al., 2009). Site specific investigation using the hydraulic model in conjunction to a Carp population model at a local scale can help predict the population response on a local level. As fish population is difficult to manage in the absence of proper field data. A monitoring regime is also suggested to obtain detailed information on the carp population dynamics and their response to interventions such as artificial inundation. Such approach will ensure that carp management is considered in a much balanced and controlled methods in the upcoming future.

CHAPTER SIX CONCLUSION

This chapter concludes by returning back to the research objectives and continues by reviewing other major aspects that were unveiled as the research proceeded. This chapter also discusses recommendations by the author for any future references. The research was conducted under the motive of acquiring a master's degree in the field of Geospatial Information Science.

Research Aims:

This research focused on the answering the following question:

Can the use of upgraded regulators serve to help utilise the wetlands of Sugar Shack System for Common Carp management and Native fish promotion?

The following objectives were answered as the aim of the research:

A. Highlighting the use of a hydraulic models for simulating surface water flow in the study area.
B. Reviewing the effects of hydraulic structures to the water depth and flow velocity in sugar shack complex.
C. Visualizing hydraulic response in a GIS environment.

The overall aim and objectives of the research were only partially met due to insignificant amount of data. The hydraulic model illustrates how change in inundation extent was highly responsive to the operational phase of hydraulic structures in Wetland 13 of Sugar Shack Complex. Chapter 4 also illustrates and discusses the hydraulic response of structures shown during their different operational phase at their respective locations. Chapter 5 further illustrate how the results from the simulation in relation to different literature regarding Carp population dynamics suggests that Wetland 13 can act as a potential site for spawning and recruitment of Common Carp and act as a site for Trapping and Harvesting for the sugar shack complex.

Objective A. was met by using HECRAS 2d model to simulate a conceptual design of artificial inundation practice on three wetlands of the Sugar Shack Complex. The second objective (B) was met through visualizing the change in velocity and shear stress in the contraction and expansion zones of the hydraulic structure. The last objective (C) was met by creating velocity, Inundation and water depth maps for the study area under the given model assumptions.

After the completion of this research, we can conclude that Wetland 13 could provide as a potential site for Common carp harvesting as well as native fish promotion as the surrounding terrain allows expansion and reduction in floodplain significantly as controlled water inundation could be achieved through the use of gate at the wetland's outlet. Although future research work with insights from biologists is advised. This research confirms that hydraulic model can help predict the hydraulic behaviour of wetland or terrain. These hydraulic models when used in conjunction to dynamic fish movement models can provide site specific information on fish behaviour. This can lead to improvement in management practices and also contribute to the new developing science of environmental flow and fish-flow relation.

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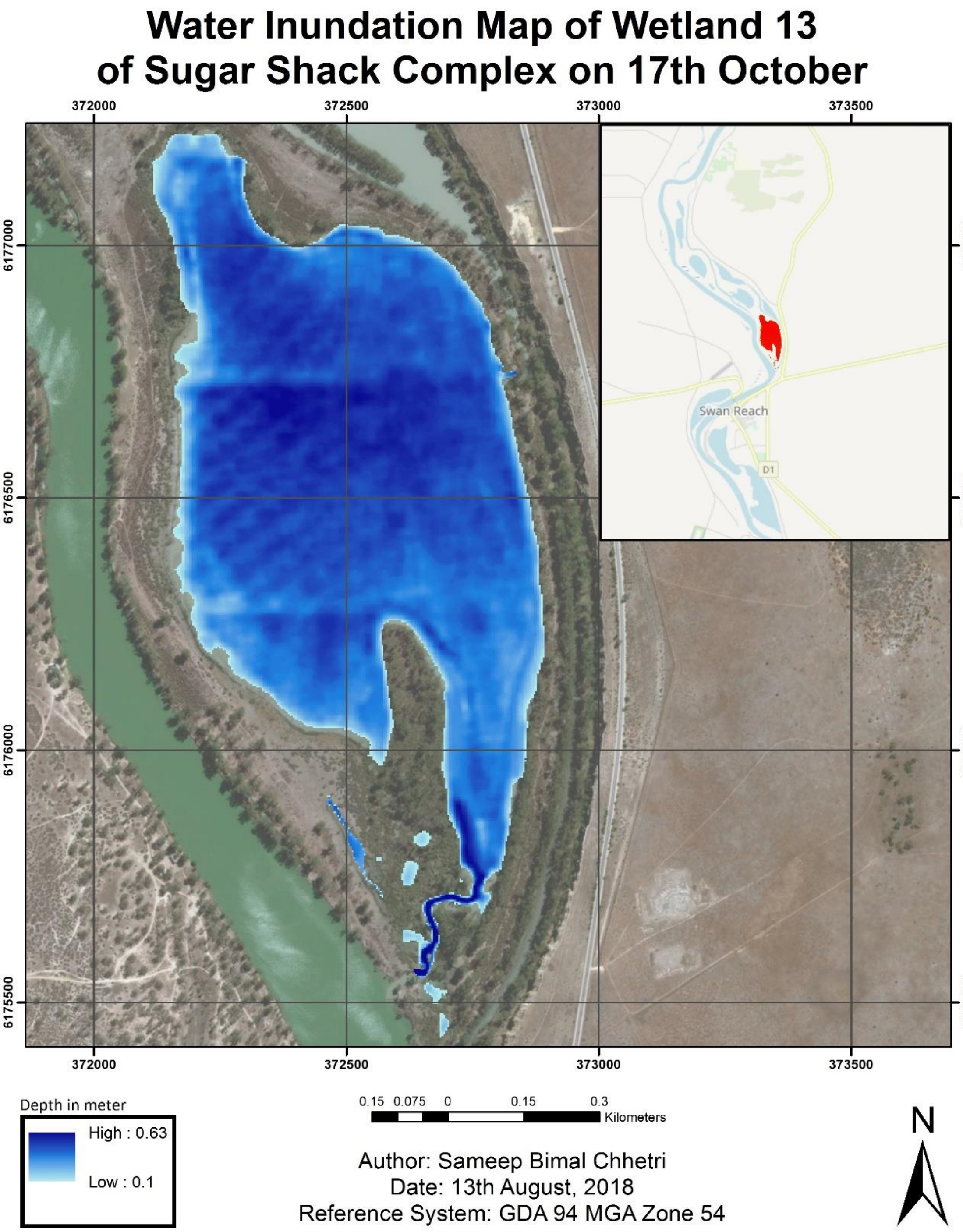
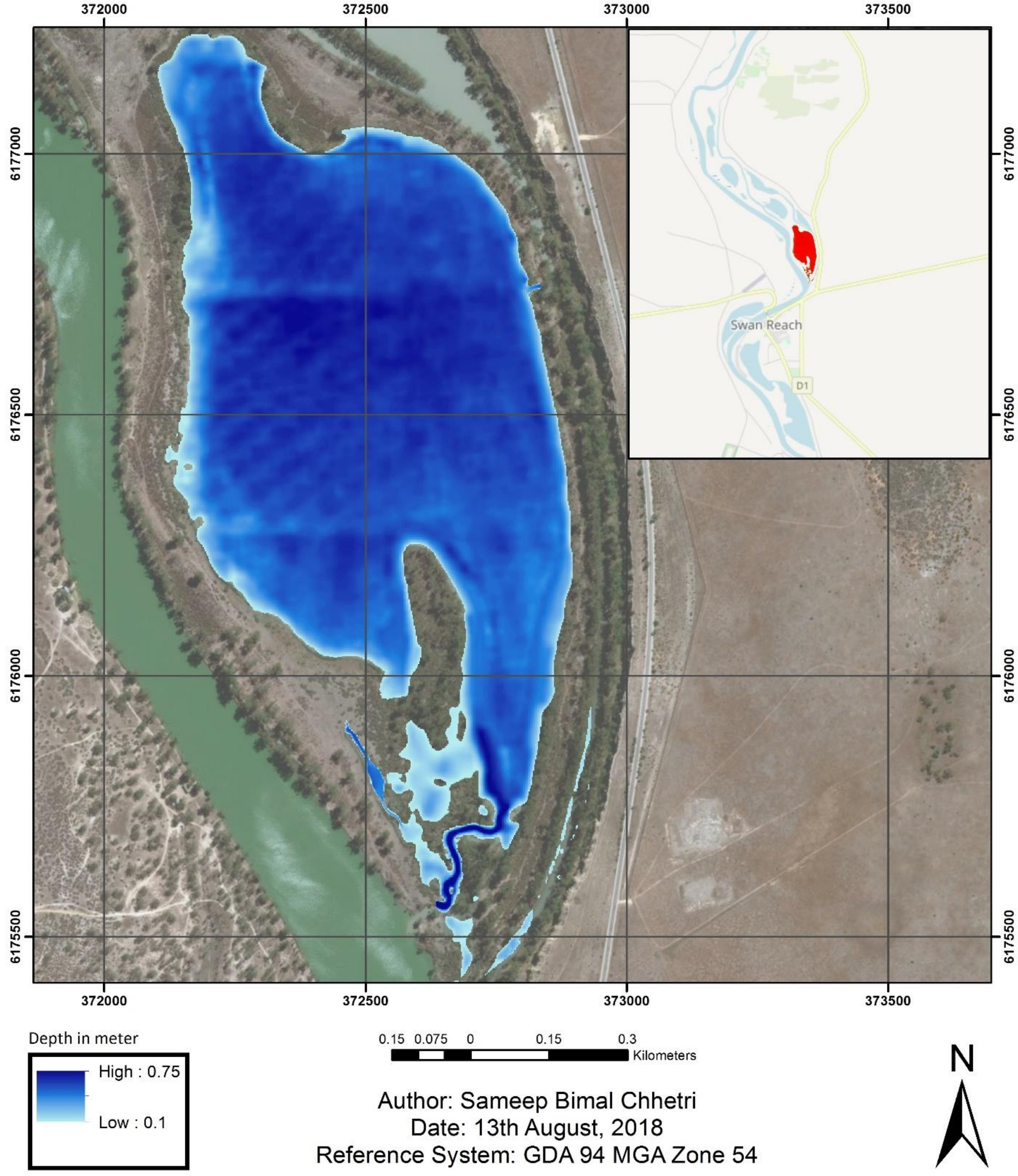
APPENDICES

1. Appendix (a)

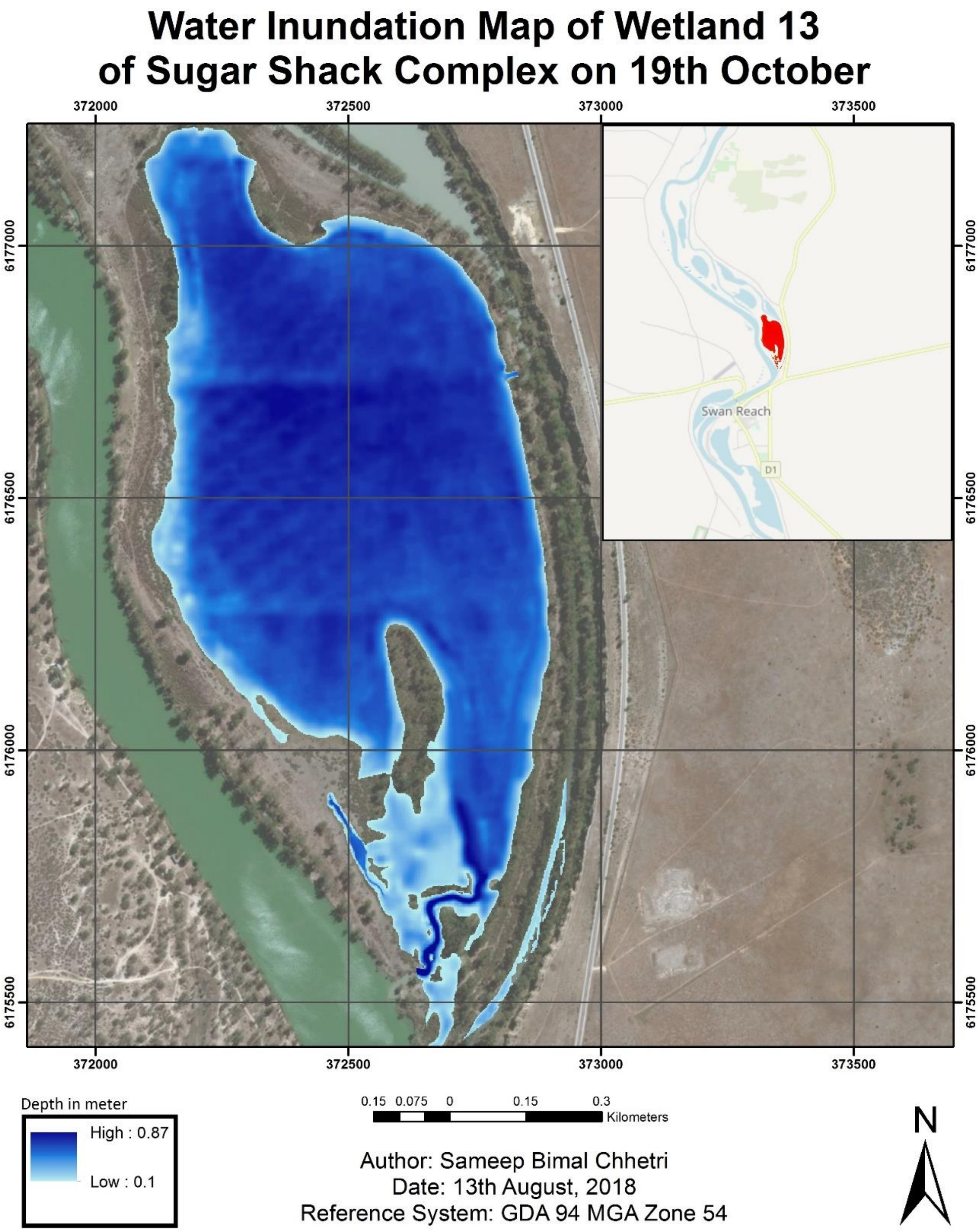


Appendix (b)

Water Inundation Map of Wetland 13 of Sugar Shack Complex on 18th October

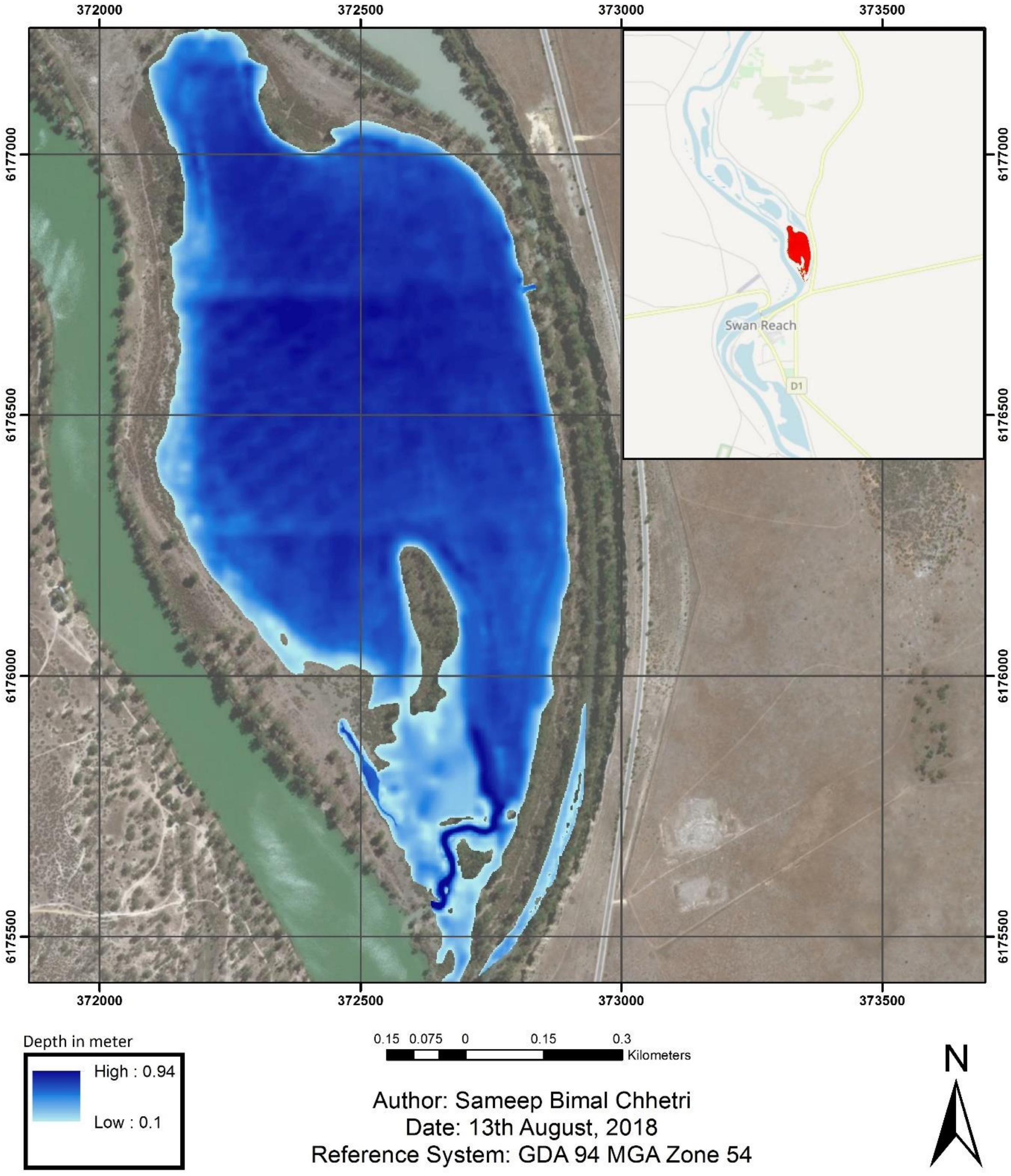


Appendix (c)


Water Inundation Map of Wetland 13
of Sugar Shack Complex on 19th October
372000
372500
373000
373500
6177000
6176500
6176000
6175500
Swan Reach
D1
Depth in meter
High : 0.87
Low : 0.1
0.15 0.075 0 0.15 0.3
Kilometers
Author: Sameep Bimal Chhetri
Date: 13th August, 2018
Reference System: GDA 94 MGA Zone 54
N

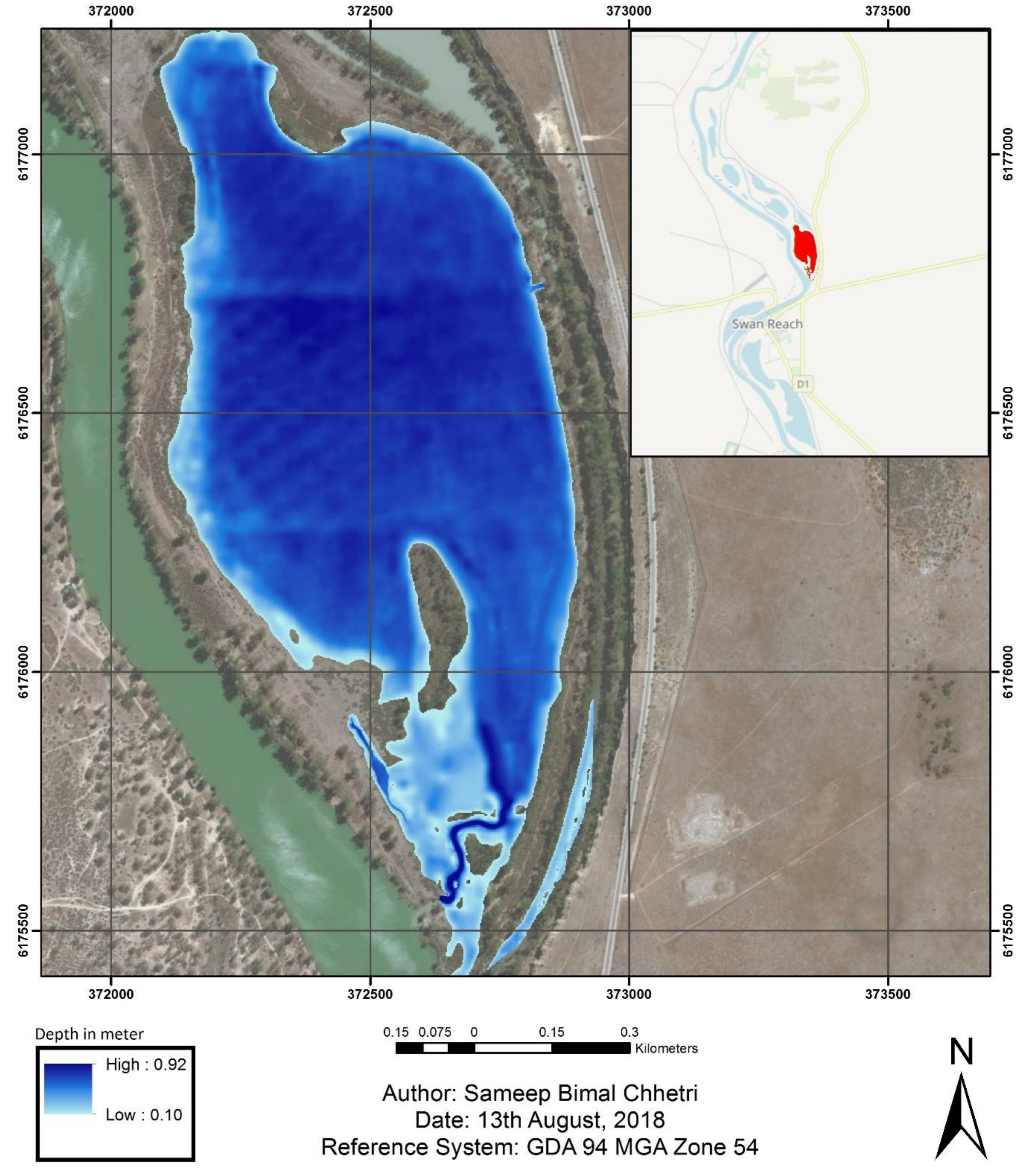
Appendix (d)

Water Inundation Map of Wetland 13 of Sugar Shack Complex on 20th October



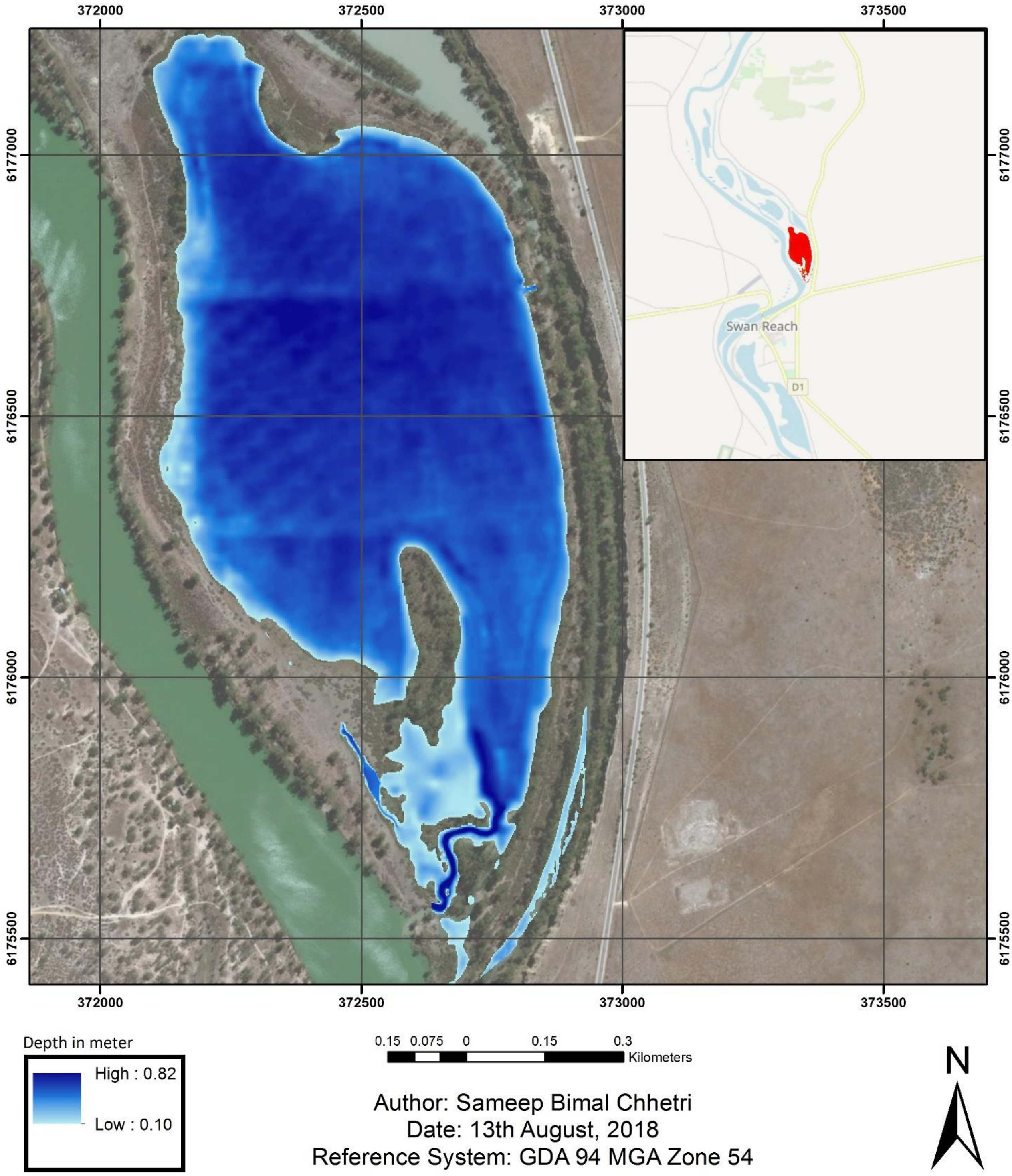
Appendix (e)

Water Inundation Map of Wetland 13 of Sugar Shack Complex on 21st October

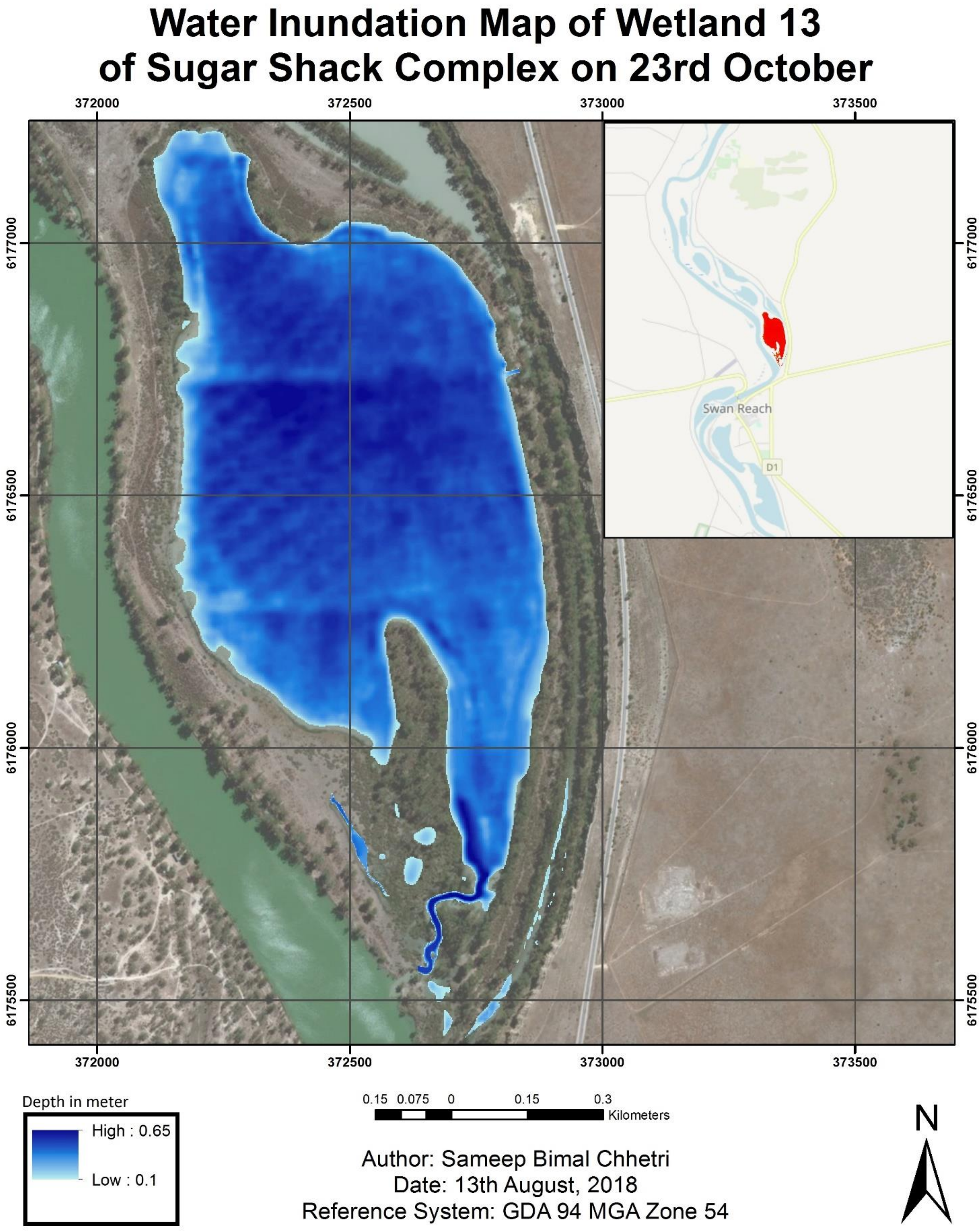


Appendix (f)

Water Inundation Map of Wetland 13 of Sugar Shack Complex on 22nd October



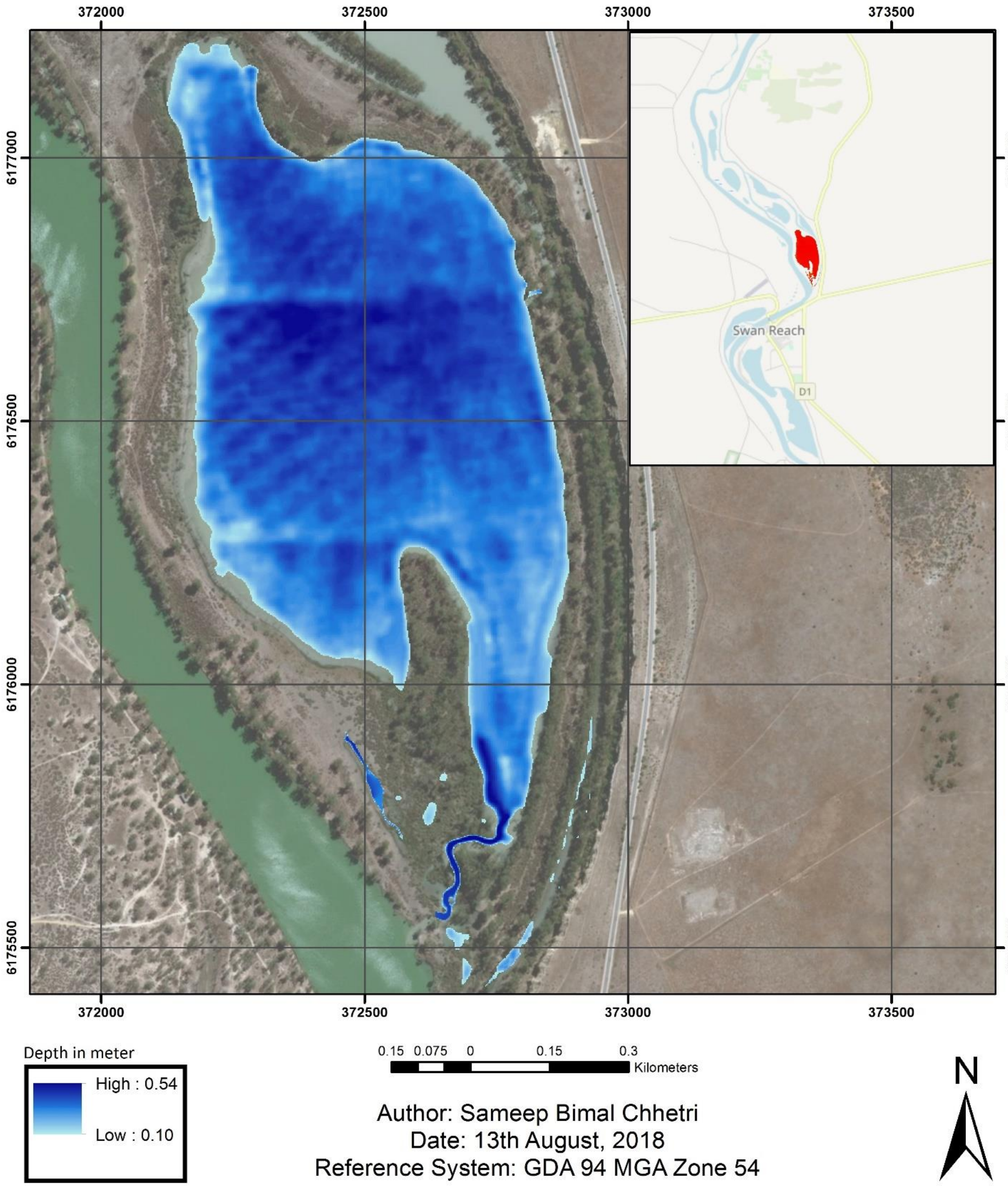
Appendix (g)



Water Inundation Map of Wetland 13
of Sugar Shack Complex on 23rd October
372000
372500
373000
373500
6177000
6176500
6176000
6175500
Swan Reach
D1
Depth in meter
High : 0.65
Low : 0.1
0.15 0.075 0 0.15 0.3
Kilometers
Author: Sameep Bimal Chhetri
Date: 13th August, 2018
Reference System: GDA 94 MGA Zone 54
N

Appendix (h)

Water Inundation Map of Wetland 13 of Sugar Shack Complex on 24th October



Author: Sameep Bimal Chhetri
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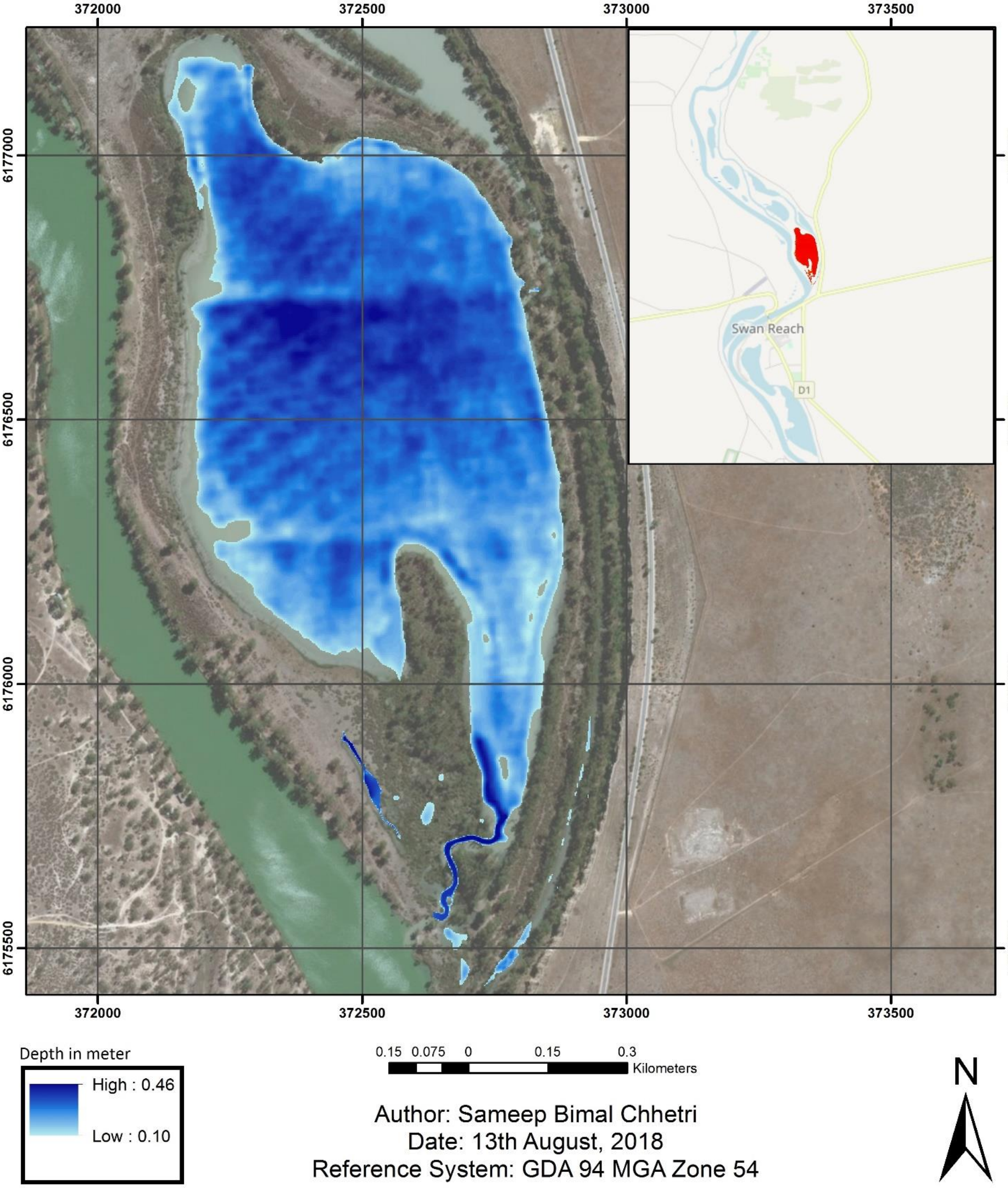
Reference System: GDA 94 MGA Zone 54

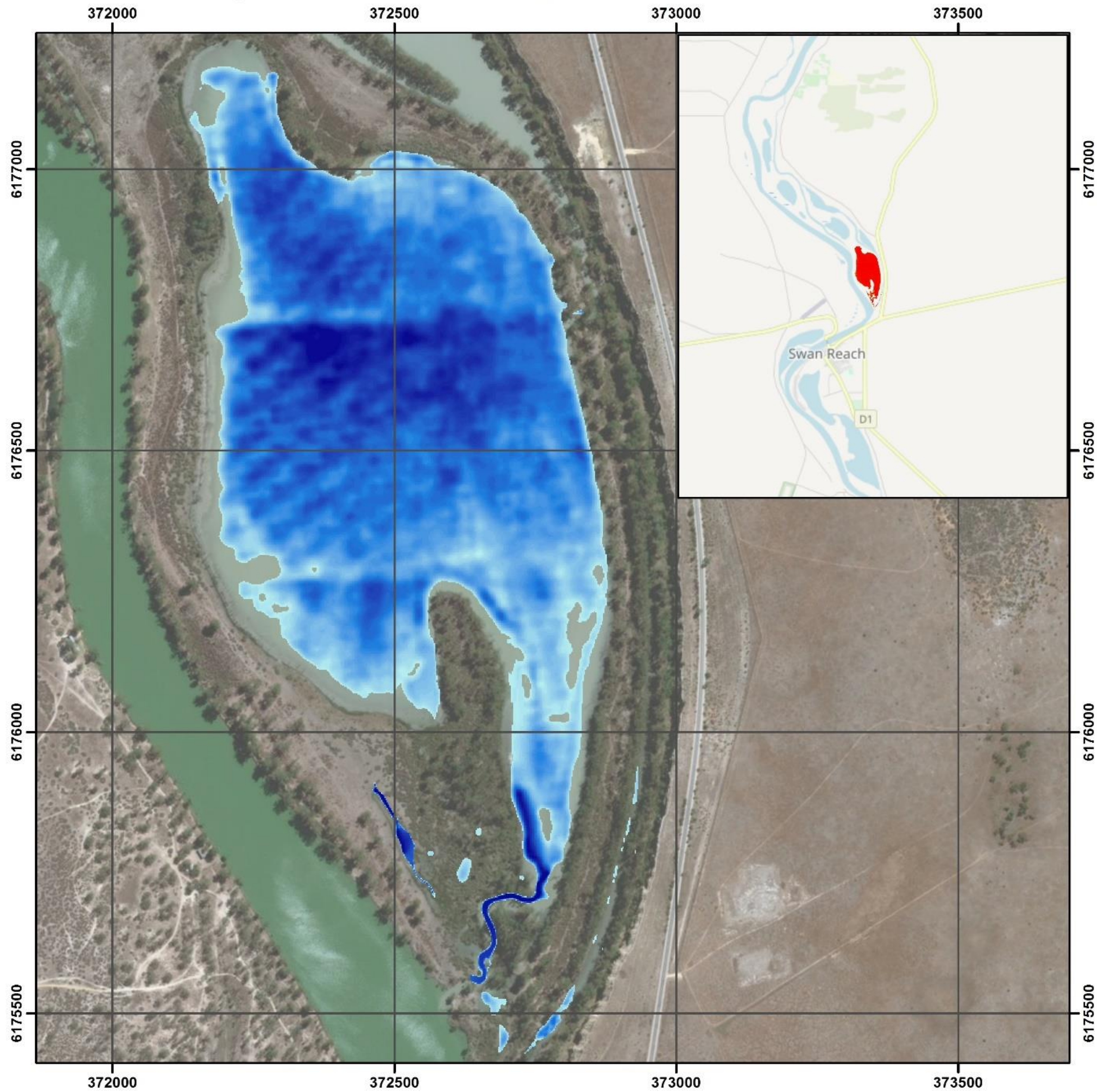
Appendix (i)

Water Inundation Map of Wetland 13 of Sugar Shack Complex on 25th October



Appendix (j)

Water Inundation Map of Wetland 13 of Sugar Shack Complex on 26th October



Depth in meter

High : 0.43

Low : 0.10

0.15 0.075 0 0.15 0.3 Kilometers

N

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