Water Research Laboratory

Big Swamp Rehabilitation Project Hydrological Study

WRL Technical Report 2012/23
February 2014

by
W C Glamore, J E Ruprecht, D S Rayner and B Smith

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Water Research Laboratory
University of New South Wales
School of Civil and Environmental Engineering

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Water Research Laboratory
110 King Street, Manly Vale, NSW, 2093, Australia
Tel: +61 (2) 8071 9800 Fax: +61 (2) 9949 4188
ABN: 57 195 873 179
www.wrl.unsw.edu.au
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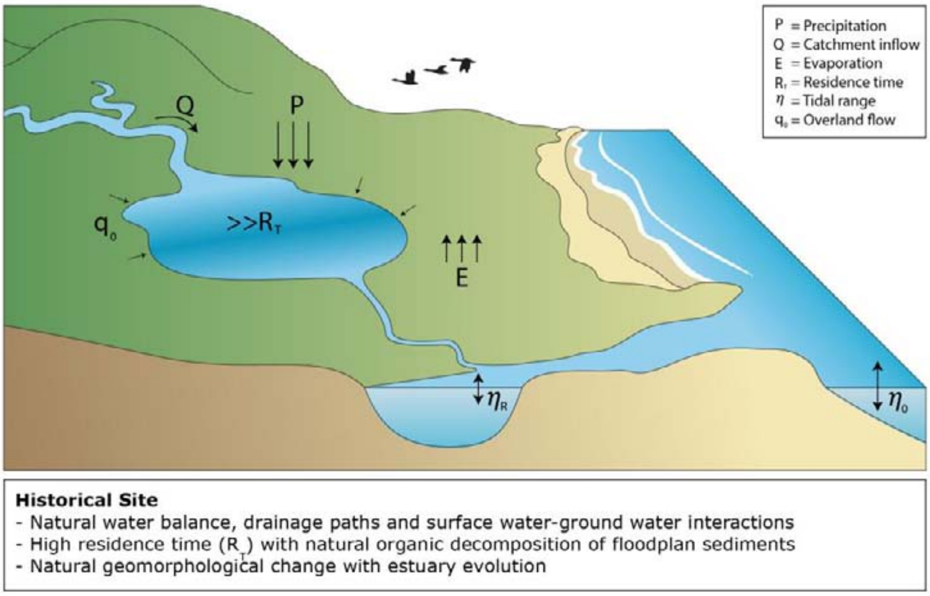
Executive Summary

The Water Research Laboratory (WRL) of the School of Civil and Environmental Engineering at The University of New South Wales was commissioned by the Greater Taree City Council (GTCC) to undertake a hydrologic study of Pipeclay Canal and the adjoining Big Swamp floodplain. Pipeclay Canal flows into Cattai Creek, a north bank tributary of the Manning River, and is located 15 km upstream of the northern entrance of the Manning River, NSW. Draining into Pipeclay Canal, the Big Swamp floodplain is located immediately north of Cattai Wetlands and includes approximately 2,000 hectares below 2 m Australian Height Datum (AHD). The Pipeclay Canal-Big Swamp floodplain system has been nominated for remediation due to ongoing poor water quality from the drainage of acid sulfate soils.

The primary aim of this hydrologic study was to provide a comprehensive scientific analysis of any proposed on-ground remediation activities aimed at reducing the potential for release of acidic water from the floodplain. Additional outcomes from the study include a detailed literature review, the development of conceptual and computer models, an evidence-based assessment of the remediation works, prioritised actions for on-ground works and future recommendations. The outcomes from the study will also support the development of an Acid-Sulfate Soils Management Plan for the Big Swamp floodplain.

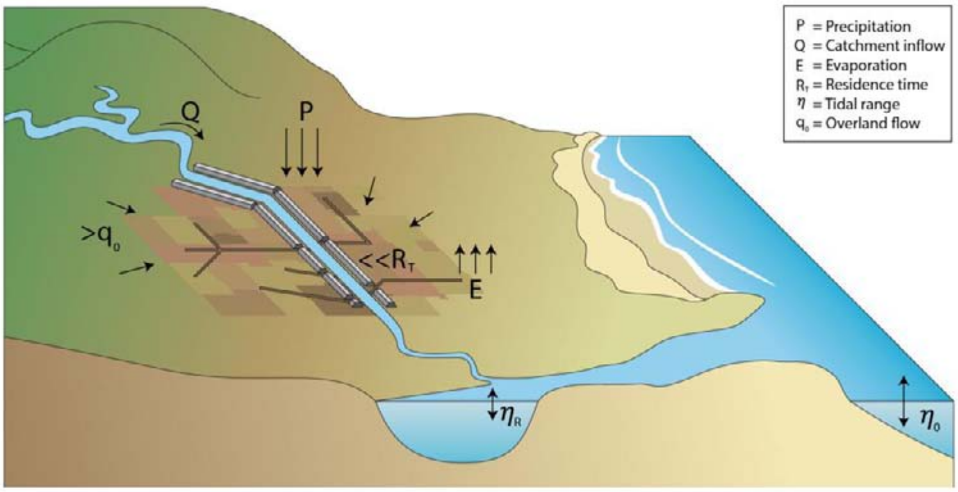
Information was initially gathered to conceptually model the Big Swamp-Pipeclay system during dry and wet periods. The catchment above Pipeclay Canal comprises 1.3% of the total Manning River catchment. The floodplain experiences minor local catchment floods as well as major backwater flooding from the Manning River. Over the past 150 years, the system has undergone major hydrologic modifications, primarily due to agricultural and transport infrastructure development. Historically, the Big Swamp floodplain was a shallow freshwater swamp, draining from Pipeclay Creek in the north to Cattai Creek in the south. Information sourced from available literature suggests the freshwater Pipeclay Creek and the tidal/brackish Cattai Creek were hydrologically connected and periodically formed a continuous channel through the floodplain (as per schematic in Figure ES.1). These backswamp conditions provided an ideal setting for the accumulation of sulfidic sediments (termed potential acid sulfate soils).



Historical Site
- Natural water balance, drainage paths and surface water-ground water interactions
- High residence time (R_T) with natural organic decomposition of floodplan sediments
- Natural geomorphological change with estuary evolution

Figure ES.1 - Conceptual (Hydrology) Model of the Historical Big Swamp-Pipeclay System Pre-1820

European settlement of this region commenced in the 1820s. Since the 1840s, large areas of native vegetation were cleared and minor drainage lines constructed. The Big Swamp Drainage Scheme was completed in 1905 and was designed to pass upland inflows from the catchment directly downstream to Cattai Creek. The scheme included the construction of a large canal (approximately 6.5 km long, 15 m wide and 1.2 m deep) through the Big Swamp floodplain, dividing the floodplain into eastern and western sides. Large continuous levees flank the canal on both sides with sub-drains and tidal floodgates draining the floodplain (Figure ES.2). Additional floodgates and drainage lines were installed during later years to expand agricultural grazing.



Post 1905 (Pipeclay)
- Rapid removal of surface flood waters altered natural groundwater budget and site hydrology
- Drainage increased oxidation of pyritic material with rapid export from backswamp to estuary
- Flow control structures restrict tidal acid neutralisation and allow a concentrated discharge of acid water during ebb tide

Figure ES.2 - Conceptual (Hydrology) Model of the Big Swamp-Pipeclay System Post 1905 Including the Big Swamp Drainage Scheme

The drainage works have had a detrimental impact on surface water and groundwater quality. The canal, drains and floodgates lowered the groundwater table and oxidised the sulfidic sediments (termed active acid sulfate soils) creating acidic water with high concentrations of heavy metals. The site is now recognised as a major acid hotspot with approximately 2500 hectares mapped as high-risk acid sulphate soils.

Despite the water quality problems on the Big Swamp floodplain, limited field data was available to characterise the basic hydrology of the site. To overcome this knowledge gap, targeted field campaigns were undertaken to measure surface water, groundwater, topography, bathymetry, hydro-geologic and meteorologic variables. Additional field campaigns were undertaken to understand the surface and groundwater regimes, including acid dynamics during prolonged dry conditions and following a minor flood events.

The field investigations showed that the entire floodplain is impacted by acid sulphate soil discharges with extreme acidity measurements recorded during dry and wet conditions. During prolonged dry periods, evaporation lowers the groundwater table and acid concentrations increase across the floodplain. During these dry periods, catchment inflows are limited and tidal waters penetrate the length of Pipeclay Canal. This results in increased acid neutralisation and dilution, although the floodplain and surface waters remain acidic. Subsurface investigations indicated that acidic groundwater is quickly transported to adjacent drains during wet events.

A detailed field campaign was undertaken in January 2013 following widespread rainfall in the Pipeclay Canal and Big Swamp catchments. Surface water measurements from this event highlighted the mechanisms for acid transport across the site as floodwaters recede. Over a 16-day period, surface water pH decreased from slightly acidic (pH ~5) to extremely acidic (pH ~3) with high total acidity and discharges recorded. The most acidic measurements were obtained in the south-eastern and south-western regions of the Big Swamp floodplain, but acidic discharges were measured in surface waters as far as 7 kilometres downstream of Pipeclay Canal at the junction of Tappin Creek and the Manning River.

Despite the on-going poor water quality and other acid sulfate soil problems, it was determined through stakeholder consultation that, while desirable, the remediation of the entire Big Swamp was not feasible within the scope of this study. As such, an evidence based assessment method was developed to determine which sub-catchments of the floodplain should be prioritised for immediate remediation. The assessment method included various factors such as groundwater acidity, surface water transport, sub-catchment size and potential restoration methods. Sub-catchment zones in the south-western and south-eastern areas of the Big Swamp floodplain were rated the highest priority areas for remediation actions. During this study, private properties located within these zones were acquired or are in the process of being acquired by Council (Figure ES.3).

A series of on-ground remediation works were recommended for the nominated properties. These works are focused on reducing acid production, limiting acid transport, neutralising and diluting acidic waters and removing hydraulic structures, where feasible. As only a portion of the site will be remediated, the on-ground works were also designed to not impact local or regional drainage, during or immediately after flooding (Figure ES.4).

A computer model of the Big Swamp floodplain, Pipeclay Canal and Cattai Creek system was developed and calibrated for this study. The model was primarily designed to test specific proposed remediation strategies and determine on-ground impacts. The modelling results indicated that removing all tidal floodgates along Pipeclay Canal would have implications on a limited area of the Big Swamp floodplain and tidal inundation would be largely focused in the south-western paddocks. As this is a prioritised zone, further scenario modelling was undertaken to test alternative on-ground works and to ensure that the paddocks to the north remain arable. Scenario testing of remedial strategies was also undertaken for the prioritised south-eastern areas.

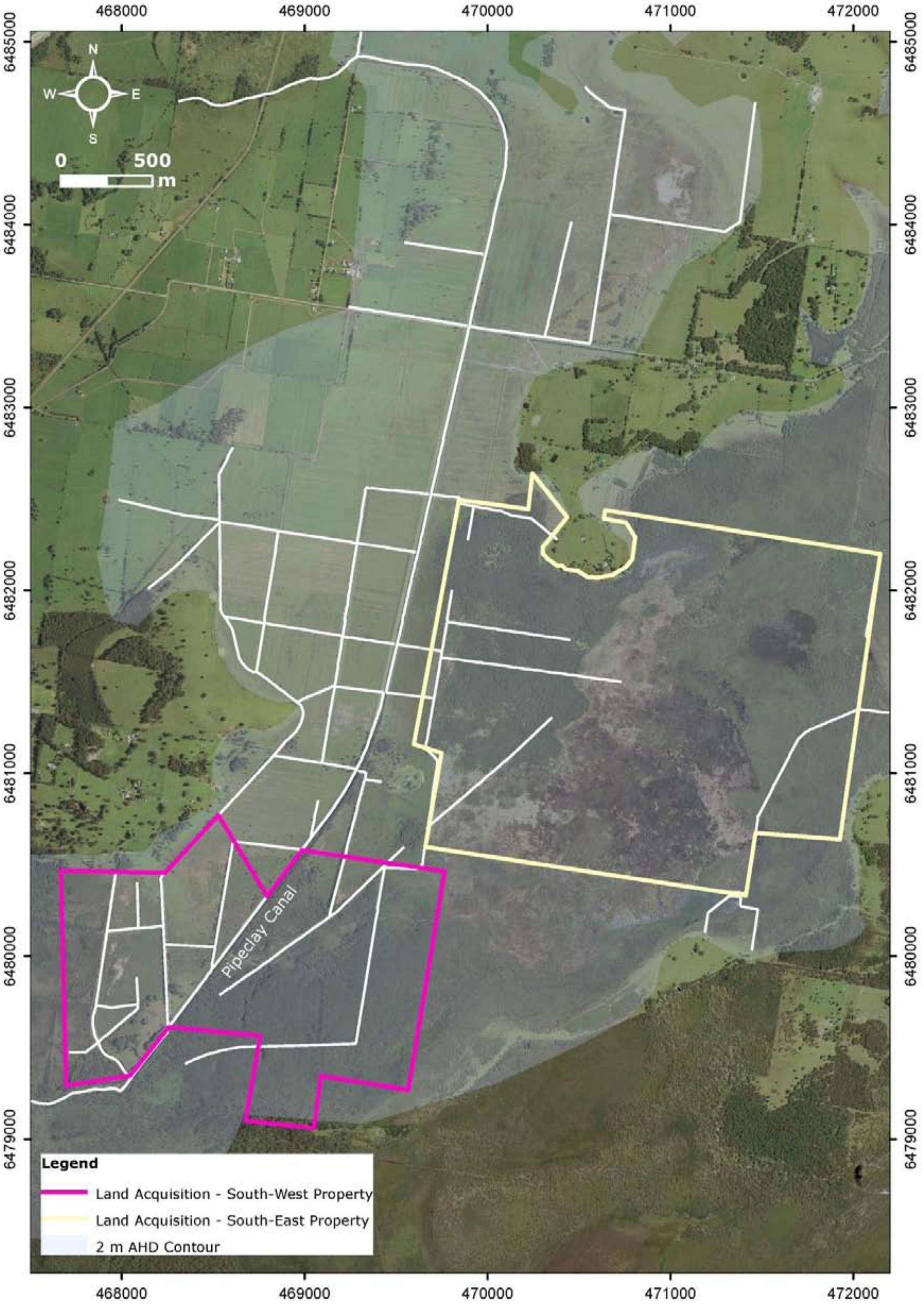
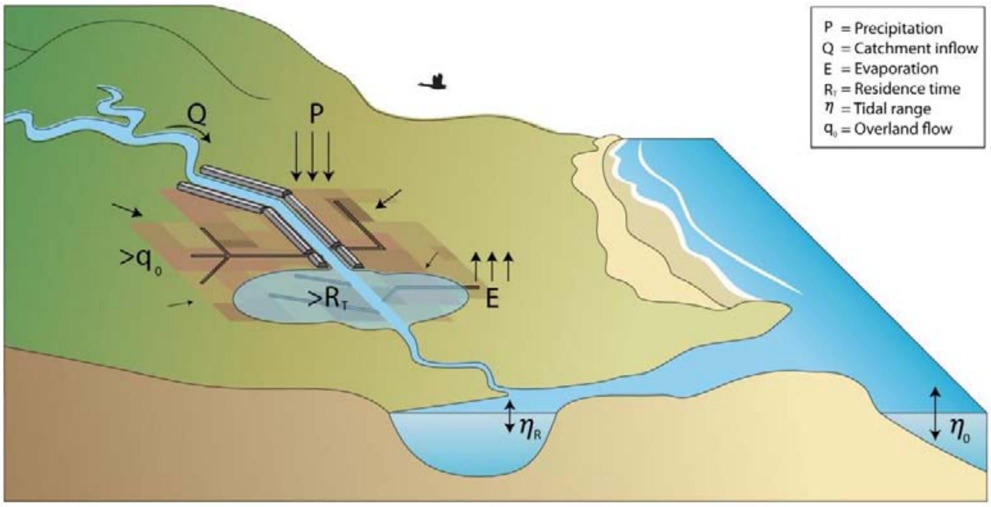


Figure ES.3 - Proposed Acquisition Areas for the Pipeclay-Big Swamp Floodplain

The computer modelling results have direct implications for future land management. The modelling indicates that the proposed on-ground works should achieve the stated aims by reducing acid generation and transport in the south-western properties. This would be achieved through a combination of tidal inundation, retaining shallow surface waters onsite, encouraging organic matter decomposition, removing/altering existing drains and floodgates, and hydrologically isolating the restored areas from the arable land to the north. Conversely, limited on-ground works are proposed for the south-eastern properties, as several landholders remain upstream of the acquired properties and require the drainage network for flood mitigation (Figure ES.5). In this area, the primary recommendation is to remove internal levee bunds along the tidal drains to encourage rewetting and limit overland drainage of acquired properties.



Proposed Restoration (upper un-remediated site unchanged)

- Restoring hydrologic properties and ecological values to remediated areas
- Encouraging a natural balance of freshwater and saline wetlands through natural hydrogeological processes
- Removal of flow control structures, reduced drainage density by filling old drainage lines to encourage shallow overland flushing

Figure ES.4 - Conceptual (Hydrology) Model of the Big Swamp-Pipeclay System with Proposed On-Ground Remedial Works

Based on the outcomes of the study, various recommendations are provided. Important recommendations include the need for further detailed design of on-ground works, onsite monitoring, a staged works program and recognising a high priority for future land purchases as part of a long-term management plan to remediate the entire Big Swamp floodplain. The field investigations for this study highlight the need for continuous monitoring to ensure that future acid discharge events are measured. As only a portion of the floodplain will be remediated in the immediate future, the full restoration of the Big Swamp floodplain is strongly recommended.

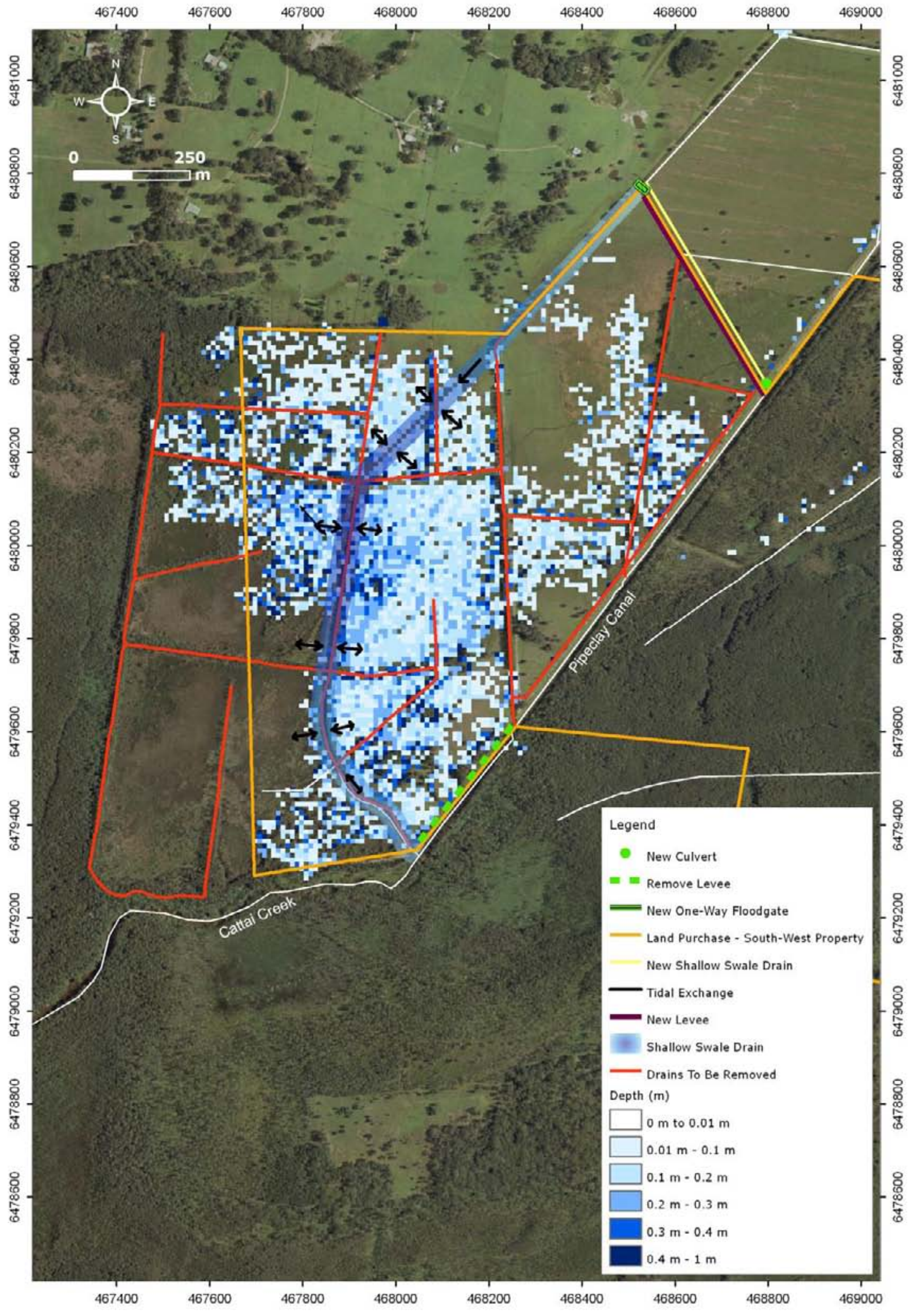


Figure ES.5 - Proposed Remedial Works for the South-Western Property Including a Representative Modelling Prediction of Inundation Coverage as a Result of the Works

Glossary of Terms

acid	A substance that has a pH of less than 7, which is neutral. Specifically, an acid has more free hydrogen ions (H+) than hydroxyl ions (OH).
acid export	The mass of acid products discharged from a given system (e.g. a drain or floodplain). Acid can be exported via two common mechanisms, by either a hydraulic gradient (pressure head) or concentration gradient.
acid sulfate soil	Estuarine sediments in which metal sulfides (mainly pyrite) accumulate, and the subsequent dehydration of these sediments by evapotranspiration and/or disturbance which enables the oxidation of pyrite/sulfides to produce sulfuric acid.
alkaline	Sometimes water or soils contain an amount of alkali (strongly basic) substances sufficient to raise the pH value above 7.0 and be harmful to the growth of crops.
alkalinity	The capacity of water for neutralizing an acid solution.
alluvium (also *alluvial*)	Deposits of clay, silt, sand, gravel, or other particulate material that have been deposited by a stream or other body of running water in a streambed, on a flood plain, on a delta, or at the base of a mountain.
anaerobic conditions	The absence of atmospheric oxygen required for certain biological processes.
antecedent conditions	An index of moisture stored within a drainage basin prior to a rainfall event.
aquifer	A geologic formation(s) that is water bearing. A geological formation or structure that stores and/or transmits water, such as to wells and springs.
Australian Height Datum (AHD)	A common national plane of level corresponding approximately to mean sea level.
backwater	Water backed up or retarded in its course as compared with its normal or natural condition of flow.
bankfull stage	Water height at which a stream first overflows its natural banks.
base flow	Sustained flow of a stream in the absence of direct runoff.
basic hydrologic data	Includes inventories of land and water features that vary only from place to place (topographic and geologic maps are examples), and records of processes that vary with both place and time (records of precipitation, streamflow, groundwater). Basic hydrologic information is a broader term that includes surveys of the water resources of particular areas and a study of their physical and related economic processes, interrelations and mechanisms.
bathymetry	The measurement of depths of water taken to the bed of the channel.
capillary action	The process of liquid moving through the porous spaces in a solid, such as soil and plant roots due to the forces of adhesion, cohesion and surface tension.
catchment	See *drainage basin*.
channel storage	The volume of water at a given time in the channel or over the flood plain of the streams in a drainage basin or river reach.
delta	The flat alluvial area at the mouth ofsome rivers where the mainstream splits up into several distributaries.
discharge	The volume of water that passes a given location within a given period. Usually expressed in cubic feet per second.
dissolved oxygen	Atmospheric oxygen that dissolves in water. The solubility of oxygen depends upon temperature and salinity.
drainage basin	Land or catchment area where precipitation runs off into streams, rivers, lakes, and reservoirs. It is a land feature that can be identified by tracing a line along the highest elevations between two areas on a map, often a ridge. Also called a "watershed."
drains	A primary drain (Pipeclay Canal), a secondary drain (floodgated or not floodgated), a tertiary drain (laterals from secondaries) and field drains (shallow surface drains).

drought	A period of deficient precipitation or runoff extending over an indefinite number of days, but with no set standard by which to determine the amount of deficiency needed to constitute a drought.
estuarine processes	Those processes that affect the physical, chemical and biological behaviour of an estuary, e.g. water movement, water quality etc.
estuary	A place where fresh and salt water mix, such as a bay, salt marsh, or where a river enters an ocean.
evaporation	The process of liquid water becoming water vapour, including vaporization from water surfaces, land surfaces, and snow fields, but not from leaf surfaces.
flood	An overflow of water onto lands that are used or usable by man and not normally covered by water. Floods have two essential characteristics: The inundation of land is temporary; and the land is adjacent to and inundated by overflow from a river, stream, lake, or ocean.
floodplain	A strip of relatively flat and normally dry land alongside a stream, river, or lake that is covered by water during a flood.
freshwater	Water that contains less than 1,000 milligrams per litre (mg/L) of dissolved solids; generally, more than 500 mg/L of dissolved solids is undesirable for drinking and many industrial uses.
gaging station	A site on a stream, lake, reservoir or other body of water where observations and hydrologic data are obtained.
ground water	(1) Water that flows or seeps downward and saturates soil or rock, supplying springs and wells. The upper surface of the saturate zone is called the water table. (2) Water stored underground in rock crevices and in the pores of geologic materials that make up the Earth's crust.
hydraulic gradient	A pressure difference that drives potential energy from a high pressure to a low pressure state.
hydrograph	A graph showing stage, flow, velocity, or other property of water with respect to time.
hydrologic cycle	The cyclic transfer of water vapour from the Earth's surface via evapotranspiration into the atmosphere, from the atmosphere via precipitation back to earth, and through runoff into streams, rivers, and lakes, and ultimately into the oceans.
intermittent	Open and closed at various points in time.
impermeable layer	A layer of solid material, such as rock or clay, which does not allow water to pass through.
hydrologic pathway	A water movement pathway above ground (evapotranspiration), on-ground (runoff/overland flow) and below the ground surface (groundwater/infiltration).
hydrogeological assessment	In a broad sense refers to the study of water both on and beneath the Earth's surface.
infiltration	Flow of water from the land surface into the subsurface.
leaching	The process by which soluble materials in the soil, such as salts, nutrients, pesticide chemicals or contaminants, are washed into a lower layer of soil or are dissolved and carried away by water.
levee	A natural or manmade earthen barrier along the edge of a stream, lake, or river. Land alongside rivers can be protected from flooding by levees.
mol	A standard scientific unit for measuring large quantities of very small entities such as atoms, molecules or other specified particles.
organic matter	Plant and animal residues, or substances made by living organisms. All are based upon carbon compounds.
pH	A measure of the relative acidity or alkalinity of water. Water with a pH of 7 is neutral; lower pH levels indicate increasing acidity, while pH levels higher than 7 indicate increasingly basic solutions.
peak flow	The maximum instantaneous discharge of a stream or river at a given location. It usually occurs at or near the time of maximum stage.

permeability	The ability of a material to allow the passage of a liquid, such as water through rocks. Permeable materials, such as gravel and sand, allow water to move quickly through them, whereas impermeable materials, such as clay, do not allow water to flow freely.
porosity	A measure of the water.
precipitation	Rain, snow, hail, sleet, dew, and frost.
river	A natural stream of water of considerable volume, larger than a brook or creek.
runoff	The component of the precipitation, snow melt, or irrigation water that appears in uncontrolled surface streams, rivers, drains or sewers. Runoff may be classified according to speed of appearance after rainfall or melting snow as direct runoff or base runoff, and according to source as surface runoff, storm interflow, or groundwater.
salinity	The total mass of dissolved salts per unit mass of water. Seawater has a salinity of about 35 g/kg or 35 parts per thousand.
sediment	Usually applied to material in suspension in water or deposited from suspension.
seepage	(*groundwater*) The slow movement of water through small cracks or pores of a material into or out of a body of surface or subsurface water.
shoal	A sandbank or sand bar in the bed of a body of water, especiallyone that is exposed above the surface of the water at low tide.
soil profile	Soil is a natural body consisting of layers (soil horizons) that are primarily composed of minerals, mixed with at least some organic matter, which differ from their parent materials in their texture, structure, consistency, colour, chemical, biological and other characteristics.
solute	A substance that is dissolved in another substance, thus forming a solution.
solvent	A substance that dissolves other substances, thus forming a solution. Water dissolves more substances than any other, and is known as the "universal solvent".
streamflow	The water discharge that occurs in a natural channel. A more general term than runoff, streamflow may be applied to discharge whether or not it is affected by diversion or regulation.
surface water	Water that is on the Earth's surface, such as in a stream, river, lake, or reservoir.
tidal exchange	The proportion of the tidal prism that is flushed away and replaced with fresh coastal water each tidal cycle.
tidal planes	HHWSS - High high water spring solstice MHWS - Mean high water springs MHW - Mean high water MHWN - Mean high water neaps MSL - Mean sea level MLWN - Mean low water neaps MLW - Mean low water MLWS - Mean low water springs ISLW - Indian spring low water
tributary	A smaller river or stream that flows into a larger river or stream. Usually, a number of smaller tributaries merge to form a river.
water table	The top of the water surface in the saturated part of an aquifer.

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- Local oyster farmers for their assistance and local knowledge;
- Harrington Community Action Group for their assistance and support; and
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1. Introduction

The Water Research Laboratory (WRL) of the School of Civil and Environmental Engineering at the University of New South Wales was commissioned by the Greater Taree City Council (GTCC) to undertake a hydrologic study of Pipeclay Canal, a north bank tributary of the Manning River, and the adjoining Big Swamp floodplain (Figure 1.1). The site is located 15 km upstream of the northern entrance of the Manning River at Harrington and includes approximately 2,000 hectares of land below 2 m Australian Height Datum (AHD) (Figure 1.2). The site (Figure 1.3) has been nominated for rehabilitation by GTCC due to the ongoing discharge of acidic by-products caused by acid sulphate soils (ASS) and the previously successful remediation of Cattai Wetlands, immediately downstream.

The primary aim of this hydrologic study is to provide a comprehensive scientific analysis of the impacts of any proposed on-ground remediation activities. Additional outcomes from the study include a detailed literature review, important information on floodplain management including the development of conceptual and numerical models, an assessment of the remediation works on catchment flooding, prioritised action lists for on-ground works and recommendations for future works. The outcomes from the study will support the development of an Acid Sulfate Soil Management Plan.

The study has been divided into stages to achieve the project objectives. Each stage builds on knowledge acquired from stakeholders, available literature, acquired field data or investigations and, where relevant, computer modelling outcomes. A brief outline of the project is provided in Figure 1.4 and described below:

- A comprehensive literature review was undertaken that focused on the hydrology of Big Swamp, Pipeclay Canal, Cattai Creek and adjoining areas;
- An initial field investigation was undertaken to obtain basic hydrologic and hydraulic information;
- Targeted field investigations were then undertaken to assess the water, soil and groundwater quality during dry and wet conditions;
- The collated data and available literature were subsequently used to develop a conceptual model of the site's historic and current hydrology;
- On-ground actions were then prioritised based on an objective assessment method;
- A computer model was developed and calibrated to simulate the existing conditions and to test a range of potential on-ground actions; and
- Outcomes from the computer model tests, discussions with stakeholders, field results and the prioritised actions were used to develop prioritised recommendations for remediating the site (or parts-thereof).

During the study, several stakeholder meetings were convened including the project's steering committee, GTCC members, local landholders and local interest groups. The outcomes from these meetings have directly contributed into every stage of the project. Preliminary outcomes from these meetings highlighted that there were insufficient funds to attempt rehabilitation of the entire site. As such, this study assessed the key areas within the Big Swamp floodplain that should be immediately addressed and associated on-ground remedial works. Further, key remediation options have been recommended to initiate on-going land purchases as part of the long-term management plan to remediate the entire Big Swamp floodplain. Acquisition of these properties should remain a high priority for GTCC to reduce the impact of acid discharge from the Pipeclay-Big Swamp system on the Manning River estuary.

1.1 About this Report

Throughout this report the terms hydrology, hydraulics and hydrodynamics are regularly used. As per the project brief, 'hydrology' is used in the broader sense relating to the interaction of surface water, groundwater and the contributing climate, topographic, soil, geology and vegetation characteristics which drive the water cycle. 'Hydrologic modelling' is used to quantify the volume and timing of water that flows from the upland catchment. 'Hydraulics' is used to define the flow of water through and around structures such as culverts and weirs. Finally, 'hydrodynamics' is used to define water movement in terms of flow depths, levels, velocities and flow distributions through the landscape. Hydrodynamic modelling is used to quantify water movement through the floodplain both before and after remedial on-ground works.

Following this introduction, the report has six main sections:

- **Section 2** provides a summary of relevant available literature and an analysis of the acquired field data to develop a hydrologic conceptual understanding of the site;
- **Section 3** discusses the assessment method developed and applied to generate prioritised on-ground actions;
- **Section 4** provides a rationale for the remediation works;
- **Section 5** summarises the numerical model testing including model assessment of restoration scenarios;
- **Section 6** provides a discussion of the modelling outcomes and the proposed remediation options for the site; and
- **Section 7** outlines recommendations from the study.

All report **figures** are located at the end of the report after **Section 9: References**.

A large volume of information was obtained during the study that has not been included in the main body of the report but is relevant background information. This information has been included in the report appendices:

Appendix A provides a summary of available literature including a description of the relevance of each reference to the study.
Appendix B provides an outline of site specific data available for model construction and calibration.
Appendix C details the development and testing of the numerical model.

2. Conceptual Understanding of Site Hydrologic Conditions

This section describes the development of a conceptual hydrologic model of the Big Swamp floodplain and its interaction with the Manning River estuary based on available literature and field investigations. The conceptual model is categorised into three stages, with each stage representative of specific environmental conditions. The conceptual model evolved from a review of the key broad-acre hydrological and bio-geochemical processes operating in the lower Manning River estuary system, and was used to examine management options to reduce acidic outflows from the site.

Targeted field campaigns completed during dry/wet/acid periods provided understanding of surface water and groundwater regimes, including understanding of acidic outflow dynamics. The field campaigns collected coordinated datasets from various locations across the site. The field investigations focused on measurements of topography, bathymetry, surface water, groundwater, hydrogeologic and meteorologic variables. Review of historical information and the linkages to present surface water – groundwater behaviour was an important component of understanding the current impact of disturbed acid sulfate soils (ASS) to the surrounding environment.

Note that the ecological history and vegetation mapping of the site was outside the scope of works for this hydrologic study.

2.1 Background to Acid Sulfate Soils

In Australia, coastal floodplains have the longest record of agricultural use of any geographical region due to their favourable temperature and soil-water regimes (King, 1984). Their plentiful soil-water profile comes from rainfall in excess of evapotranspiration and high water tables, both of which have historically been artificially manipulated by land drainage and clearing of native vegetation. Many coastal floodplains in eastern Australia, including the Manning River floodplain, have been drained with adverse impacts on estuarine ecosystems from loss of wetlands (Sammut et at., 1995; White, 1997).

The development of acid-sulfate soils in NSW coastal floodplains is intrinsically linked to historical ocean level fluctuations. Sea levels around Australia rose at a rate of about 6-10 mm y^{-1} between 10,000 and 6,500 years ago, after which they fell approximately 1 m between 6,500 and 4,500 years ago. Over the last 4,500 years, sea levels have remained stable and the Australian land surface has been tectonically stable. During and following this time, brackish water containing sulfate from the ocean inundated areas, such as backswamps, with highly decomposed organic matter. This, combined with iron from the sediments under anaerobic (limited oxygen) conditions, produces iron sulfides the most common being iron pyrite (DERM, 2009; White et al., 1997). Because of the low energy environments in which sulfides are formed, soluble bicarbonate is flushed from the accumulated sediments, leaving sulfides to accumulate as a potential store of acid in the soil (White et al., 1997). Deposits of these soils are predominantly located on coastal floodplains within 5 m of mean sea level (0 m AHD).

Soils containing iron pyrite that remain anaerobic are termed Potential Acid Sulfate Soils (PASS). When oxidised, these soils are called Actual Acid Sulfate Soils (AASS). Oxidation occurs when these soils are drained and exposed to atmospheric oxygen, ultimately to form sulfuric acid (H_2SO_4). Completely dry pyrite exposed to atmospheric oxygen does not appear to oxidise (White et al., 1997). However, in moist sediments, once pH drops below 4 (i.e. acidic) oxidation proceeds rapidly due to the presence of bacteria (White et al., 1997). The oxidation reaction involves the conversion of solid pyrite to dissolved iron and sulfates (White et al., 1997; Glamore, 2003) and is summarised by the following equation:

$$\underbrace{FeS_2}_{\text{Solid pyrite}} + \underbrace{{}^{7}\!/_{2}\, O_2}_{\text{atmospheric oxygen}} + H_2O \rightarrow \underbrace{Fe^{2+}}_{\text{dissolved iron}} + 2SO_4^{2-} + \underbrace{2H^+}_{\text{acid}} \tag{1.1}$$

The dissolved iron produced in Equation 1.1 is soluble at pH<4.5 and can be transported into streams for considerable distances away from the pyrite source (White et al., 1997; Glamore, 2003). Downstream, further oxidation of dissolved iron can produce characteristic red-brown flocs and 'acid at a distance' from the source (Equation 1.2).

$$\underbrace{Fe^{2+}}_{\text{dissolved iron}} + {}^{1}\!/_{4}\, O_2 + {}^{3}\!/_{2}\, H_2O \rightarrow \underbrace{FeOOH}_{\text{Red-brown floc}} + \underbrace{H^+}_{\text{acid}} \tag{1.2}$$

In areas affected by ASS, one-way floodgates increase pyrite oxidation (Figure 2.1) (Glamore, 2003). Floodgate invert levels are generally set to maintain floodplain water levels at the low tide mark. Since the pyritic layer is normally at the mid to high tide level, by maintaining drain water elevations lower than the pyritic layer, the one-way floodgates increase the hydraulic gradient between the drain water and the groundwater (Figure 2.2) (Glamore, 2003). This promotes the transport of oxygen into the sulfidic subsoil and the leaching of acid products into the drain (Glamore, 2003). This process is particularly evident following large rainfall events when floodgates quickly establish low drain water levels while the groundwater table remains elevated (Glamore et al., 2001).

Detrimental impacts of pyrite oxidation include lowered dissolved oxygen contents in streams (White et al., 1997), decreased plant growth (Dent, 1986), corrosion of engineering infrastructure (White et al., 1996), massive fish kills and fish diseases (Callinan et al., 1993; Sammut et al., 1994), as well as threatening oyster production (Dove, 2003). Furthermore, acid leached from an oxidised soil profile can react with clay minerals in the sediments to release metal ions, principally aluminium, iron, potassium, sodium and magnesium. It is important to note that as long as sulfides remain in reduced conditions below the water table, they remain inert. It is only when they are exposed to oxygen, such as in periods of prolonged drought, or after draining, dredging or excavation that these problems occur.

The rate of oxidation is a critical question in the management of sulfidic sediments. This rate depends on the prevailing hydrology, how the soil is drained, the climatic conditions, the permeability of the soil, and the soil temperature (Johnston et al., 2004). Typically, in finer textured sediments, which are not freely draining, the principal supply path for oxygen is through preferential flow paths such as old root channels (White et al., 1997). Water quality data, together with water balance estimates, can be used to estimate the rates of acid production and export from drained coastal floodplains.

A range of management and remediation techniques are advocated to decrease acid production and the net discharge of acid products from ASS affected landscapes. Dilution, containment, tidal buffering (neutralisation) and reduction of acid have all been recognised as key strategies for remediation of recognised ASS hot spots (Glamore, 2003; Johnston, 2007). A brief description of these mechanisms is provided below for reference.

'Dilution' relates to the process of reducing the concentration of a volume of acid (low pH) by adding a larger volume of fresh/saline (neutral pH) water. It is based on the concept that the pH of water increases by one pH unit for every ninefold increase in the volume of freshwater, as pH is measured on a logarithmic scale (i.e. pH = -log [H^+]), whereby a pH of 5 has a concentration of hydrogen (H^+) ions 10 times greater than a pH of 6. An example of this strategy includes re-instating wetting and drying patterns to wet soils and preventing the build-up of acidic sediments through dilution with freshwater flows. However, despite reflooding, pyrite oxidation can proceed even though dissolved oxygen is absent of acidic soils via bacterial oxidation. For these reasons, simply reflooding oxidised ASS landscapes to rehabilitate wetlands may not solve the acid discharge problem (White et al., 1997).

Acknowledging that dilution has had limited success as a stand-alone remediation technique, strategies associated with 'containment' of acid discharge from ASS affected landscapes have been trialled. Blunden (2000) investigated the effectiveness of manipulating groundwater levels using weirs in flood mitigation drains to improve the groundwater and drain water quality. Implementation of this strategy was shown to be beneficial in reducing the atmospheric oxidation of pyrite by saturating the sulfidic soil with water, as well as facilitating the slow release of acid products into waterways (Blunden, 2000). However, the management of groundwater elevation alone was shown to not be the governing factor for improving groundwater quality, as various bacterial processes can influence the pyrite oxidation rate under different pH conditions (Blunden, 2000). Once acidified, the impact of bacteria on pyrite oxidation is orders of magnitude greater than the atmospheric oxidation process (Evangelou, 1995).

Neutralisation of acid by bicarbonate (HCO_3^-), herein referred to as 'tidal buffering', is based on the concept that seawater has an available concentration of bicarbonate/carbonate and incoming tides transport these acid buffering agents throughout an estuary (Stumm and Morgan, 1996). Previous studies (Glamore, 2003; Rayner, 2010) have related salinity to available bicarbonate in seawater. The key factor in tidal buffering is the consumption of H^+ ions. When this reaction occurs, one mole of H^+ ions reacts with one mole of available bicarbonate to form an aqueous carbonate, which in turn forms water and carbon dioxide (Equation 1.3). This strategy has been encouraged in cases where sufficient bicarbonate concentrations are available. Generally, this involves the modification of floodgates to encourage shallow tidal inundation on acid hot spots. Glamore (2003) showed that after floodgate modification, tidal buffering improved drain water quality and was most effective during prolonged dry periods when the incoming tide is super-saturated with bicarbonate.

$$H^+_{(aq)} + HCO^-_{3\,(aq)} \leftrightarrow H_2CO_{3(aq)} \leftrightarrow H_2O_{(l)} + CO_{2(g)} \qquad (1.3)$$

Tidal buffering can only be effective when the estuarine waters contain sufficient buffering agents and where the topography of ASS hot spots permits inundation, which is generally the lower reaches of an estuary. However, recognised ASS hot spots do not always satisfy these conditions and therefore other strategies may be required. In such situations, Dent (1986) suggests that remediation of ASS may be possible where sufficient organic matter is available to establish anaerobic conditions using containment or dilution techniques. To establish conditions suitable for the reduction of sulfate and dissolved iron, a considerable quantity of organic matter/bacterial content is required (Dent, 1986). Therefore, this strategy is typically encouraged over longer timeframes after on-ground remediation works have taken place to reinstate drainage patterns.

2.2 Manning River Floodplain History

2.2.1 Geology

The Manning River catchment is part of the New England sedimentary basin that formed during the Palaeozoic period between 250 to 600 million years ago and spans the East Coast of Australia between Port Stephens and the Queensland border. The catchment, with an estimated area of 8,420 km^2, is the sixth largest catchment on the NSW coast (SPCC, 1986; GTCC, 1997) and is comprised of high country, coastal ranges and associated valleys, and the coastal floodplain (Dove, 2003). The Manning River catchment is depicted in Figure 2.3.

The Manning River is classified as a mature, infilled barrier estuary that is channelised and has a strong tidal range (Roy, 1984). It has an extensive deltaic floodplain composed of recent (less than 6,500 years old) alluvial deposits (Roy, 1984; Dove, 2003). A barrier dune system consisting of marine deposits exists within the Wallabi Point – Crowdy Head embayment and extends up to 400 m inland on Mitchells Island (Dove, 2003). Behind the dune system, swamps and marshes drain into the Manning River.

2.2.2 Estuarine Processes and Hydrology

The Manning River estuary is one of the few double delta river systems in Australia, another being the Shoalhaven River. The Manning system is made up of a complex system of tributary creeks, branch channels and two natural ocean entrances approximately 10 km apart (Ruprecht and Peirson, 2011). The two entrances separate the coastal towns of Old Bar and Harrington, which are located adjacent to the southern and northern inlets, respectively, on the mid-north coast of NSW. The estuary has an approximate surface area of 30 km^2 and has a mean spring tidal range that attenuates up to the tidal limit approximately 54 km upstream from the northern entrance (GTCC, 1997) (Table 2-1). The tidal response of the estuary is highly dependent on the degree of sand shoaling in the entrances (GTCC, 1997). On large spring ebb tides, peak velocities through the entrance channels can exceed 3 m/s (GTCC, 1997).

Table 2-1: Tidal Attenuation Across the Manning River Estuary Using Mean Annual Spring Tidal Amplitude (Ruprecht and Peirson, 2011)

Site ID	Mean Annual Spring Tidal Range (m)
Ocean	1.3
Harrington	0.94
Croki	0.5

Prior to any training works at Harrington, the ocean entrance had a highly variable position and was heavily shoaled at times of low freshwater flows. Without sufficient dredging, only floods maintained a navigable inlet (Coode, 1989). Consequently, a training wall on the northern bank of the Harrington Inlet was completed in 1899 and terminated with a breakwater approximately 100 m offshore. Following these training works, the mouth at Harrington exhibits many features of a single-trained entrance including an asymmetrical entrance bar with a meandering channel and large shifting shoals on the unprotected southern side.

The southern entrance to the Manning River at Old Bar, commonly known as the *Farquhar Inlet*, comprises a series of shoal-filled channels that meander across a wide, beach ridge plain. With no training works undertaken to date, the inlet is prone to intermittent closures. In the past, Farquhar Inlet has been reported closed or severely restricted for approximately 20% of the time. However, historical records highlight that very few observations have been made over the last 200 years. Studies also indicate that the closure time would be much higher if the entrance had not been mechanically opened under flood conditions on a number of occasions (Miller and Tarrade, 2010; Ruprecht and Peirson, 2011).

Estuarine hydrology is characterised by fluctuations in salinity due to inflows of freshwater from upstream catchments and saltwater from the ocean, climatic variations and by mixing currents (Roy et al., 2001). For the Manning River estuary, saline and freshwater flow interactions are greatly dependent on cycles of drought, flood, and ocean entrance conditions. During periods of low freshwater inflow the tidal extent can reach significantly further upstream in the estuary (Miller and Tarrade, 2010). Recent observations by WRL have indicated that the salinity in the upper sections of Pipeclay Canal is approximately 50% seawater during dry periods. During low to medium freshwater flows, salinity in the middle reaches of the Manning and Lansdowne Rivers, including Cattai Creek and Pipeclay Canal, become highly variable and often show stratification (GTCC, 1997; Tulau, 1999; Dove, 2003). During high freshwater flow periods, there is unlikely to be stratification throughout the estuary (GTCC, 1997).

At Big Swamp, the climate is dominated by coastal synoptic systems. Average annual rainfall in upland catchment areas is 1,650 mm (Sonter, 1999), while average annual rainfall at Moorland is 1,436 mm (BOM, 2013). The Manning Valley has a dominant summer rainfall pattern, with most precipitation falling between January and June, and a pronounced and reliable dry season running from July through December (GTCC, 1997). During extended droughts, which have occurred several times over the last century, evapotranspiration of groundwater caused groundwater levels to fall up to 2 m below the ground surface across the Big Swamp floodplain (GTCC, 1997; Sonter, 1999).

Local evapotranspiration data is unavailable for Big Swamp, however, estimates of rates can be obtained from records at Taree Airport (BOM Station ID 060141), located approximate 10 km south-west of Coralville. Evaporation is generally higher during the summer months and lower during the winter months. Average evaporation rates during August are estimated at 3.2 mm/day. A summary of evaporation data is presented in Appendix B (Table B-2).

2.2.3 Land Drainage

The Big Swamp catchment has a total catchment area of approximately 11,300 hectares (113 km^2) and is characterised by high surrounding hills draining to large areas of low elevation backswamp (mostly near or below 0 m AHD) on the Manning River floodplain (Figure 1.2). Big Swamp experiences flooding from local catchment inflows as well as backwater flooding from the Manning River. The site drains via Cattai Creek into the north arm of the Manning River channel.

Historically, the Big Swamp area was reported as a shallow freshwater swamp, draining from Pipeclay Creek in the north, to Cattai Creek in the south (PWD, 1911). Available literature suggests the freshwater Pipeclay Creek and the tidal/brackish Cattai Creek were hydrologically connected and periodically formed a continuous channel through the floodplain (PWD, 1911). The wetlands were vibrant with extensive birdlife and aquatic fauna, providing a rich food source for local Aboriginal people (GTCC, 2010). This area was part of the territory of the Ngamba tribe of Aboriginals belonging to the Biripi language-speaking nation (GTCC, 2010). European settlement of this region commenced in the 1820s.

Since the 1840s, large areas of native vegetation found on the Manning River floodplain have changed drastically, primarily through land clearing and drainage. The losses in vegetation and organic matter have had a significant ongoing impact on lowering the groundwater table (Sonter, 1999). The drainage carried out has largely been of a small scale with one exception being the Big Swamp Drainage Scheme. The Drainage Scheme, which was the first of its kind undertaken by the NSW Department of Public Works (PWD) and therefore experimental, was completed in 1905.

Extensive flooding occurred on the north coast of NSW in the latter half of the nineteenth century, resulting in large agricultural losses and fuelling a climate of community expectation for the draining of private freehold land on coastal floodplains (Tulau, 2001). The government obliged and the colonial *Drainage Promotion Act 1865* and later, the *Drainage Promotion Act 1901*, were enacted to provide for the "better drainage of lands" and the establishment of drainage unions (Tulau, 2001). The PWD also facilitated drainage by undertaking extensive investigation surveys and designed swamp drainage schemes from the early 1900s under the provisions of the *Water and Drainage Act 1902* (PWD, 1904; PWD, 1911). Although frequently justified on flood mitigation grounds, an additional and often primary motive was the reclamation of dry arable land, typically by the drainage of backswamps and exclusion of tidal waters (Tulau, 2001; PWD, 1904).

In 1899, the Big Swamp Drainage Scheme was approved, declaring intent to construct Pipeclay Canal and drain the swamp to 'open up' the area to dry land agricultural production (PWD, 1911) (Figure 2.4). The Drainage Scheme was designed to pass upland catchment inflows from Pipeclay Creek (and local catchment inflows draining from the floodplain) directly to Cattai Creek. This relied on the construction of a canal (approximately 6.5 km long, 15 m wide and 1.2 m deep) through the Big Swamp floodplain, separating the catchment into two halves. The canal was flanked by large continuous levees on both sides (Fig 3. in Figure 2.5) and interconnected with sub-main drains on the floodplain through 14 one-way flood-gated culverts of 0.9 m diameter. Aside from the sub-main drains running parallel to the main canal, the remainder of the floodplain had limited efficient drainage.

In 1911, the PWD reported that the Drainage Scheme was inefficient and a proven failure. The efficiency of the Drainage Scheme as a whole was sacrificed to ensure the passage of upland inflows from Pipeclay Creek to Cattai Creek were strictly isolated from the surrounding floodplain. This meant that the land remained wet for extended periods and was starved of natural silts deposited from floods. Further inefficiencies were attributed to (i) limited ongoing maintenance resulting in drain infilling and reduced conveyance through sedimentation; (ii) bank subsidence and weed growth; (iii) faulty floodgates; and (iv) through the lack of lateral tributary drains and effective land gradients across the site. The Sydney Morning Herald (28th February 1912) reported the failure:

"…the drains are about as good as useless, as far as getting rid of the water is concerned. If the water was any good some use might be made of it, but nothing will live in it, and the stock won't touch it – though it is clear and sparkling, and would have one believe it is absolutely pure. However, the taste of it is most objectionable…even eels and frogs die quickly if put into it."

Irrespective of these early indicators of ASS, a number of efforts were made after the 1911 PWD report to extend and augment the early drainage network with an efficient one, for the purpose of draining more of the Big Swamp landscape. In 1911, the PWD approved further construction works and maintenance of the existing design. The works included:

1. Periodically cleaning out the main drain for improved conveyance capacity;
2. Modifying the existing levees for improved floodplain drainage (Fig 3. in Figure 2.5);
3. New sub-main drains of average flow area of approximately 2 m^2 and tributary drains of average flow area of approximately 1 m^2, for improved floodplain drainage;
4. Design and construction of the Two Mile Creek Drainage Scheme in the south-west corner of the site, to prevent Two Mile Creek water competing with Pipeclay Canal water at its confluence with Cattai Creek; and
5. Inclusion of 3 additional one-way flood-gated culverts (a total of 17 culverts across the site).

Limited literature is available about onsite engineering works between 1911 to 1960. However, following the floods of the 1950s, the response of successive Local and State governments facilitated the construction of extensive drainage systems by drainage unions and private landholders. Although scientists had understood the dangers of draining ASS by the 1960s (uncited in Walker 1960, 1961, 1963), this decade was the most active period for the construction of drainage and flood mitigation works in NSW (Tulau, 2001). Laurie, Montgomery and Pettit (1980) expressed "substantial ecological and economic reservations" about further works in the Big Swamp area and recommended soil type surveys and water quality monitoring be carried out. Nevertheless, existing drains, including the main canal, were periodically cleaned out, with the last approved excavation works of Pipeclay Canal were undertaken in 1997 (GTCC, 2010). From a hydrogeological perspective, the 1997 works to deepen Pipeclay Canal has lowered floodplain water levels, subsequently increasing groundwater drawdown and exacerbating the ASS problem in the Big Swamp floodplain. Recently, private landholders were observed undertaking maintenance excavation works during the wet events in January/February 2013.

The site today consists of an extensive floodplain drainage network system discharging to Pipeclay Canal. An initial 5-day field campaign was undertaken for this study on the 25 – 29th June 2012 to collect basic site data and information, including channel cross-sections, that showed:

- Levee heights across the site vary. Floodplain drains have a levee height of approximately 1.0 m, while the average elevation of the levees along the main canal is approximately 1.8 m AHD. These elevations are consistent with ground-truthed observations of LiDAR data supplied by GTCC (Figure 1.2) and provided in Appendix B;
- Drain bottom elevations (inverts) were observed between -0.5 to 1.0 m AHD, with the main canal surveyed as low as -2.5 m AHD. This is consistent with most drained NSW backswamp areas (Tulau, 2001). Representative cross-sections from the field survey are shown in Figure 2.6. A complete summary of all the cross-sections surveyed is provided in Appendix B; and
- The site has in excess of 30 concrete culverts, having diameters ranging between 0.9 m and 1.5 m, with less than half flood-gated. This count is more than double the original number of culverts in the drainage system design of 1899.

The Big Swamp floodplain has been reported as being one of the most intensely drained sites observed in NSW (Johnston, 2007). The combination of extensive drainage and pyritic soils has resulted in the site being listed as one of the three worst ASS hotspots in NSW (GTCC, 2010). According to the ASS risk maps described by Naylor et al. (1995), approximately 2,500 ha of land in the Big Swamp floodplain has a high risk of ASS occurrence.

2.3 Conceptual Model

A conceptual model of the site is hypothesised and presented in Figures 2.7 to 2.10. These schematics shows the drainage history of Big Swamp and its' conceptual progression from past to present hydrologic conditions. In summary:

The *Historical Site* (Pre-1900) (as shown in Figure 2.7) was governed by natural drainage paths and geomorphological processes, surface water-ground water interactions and evaporation (E). The site hydrology was likely characterised by fluctuations in salinity due to inflows (Q) of freshwater from the upland catchment, a variable tidal prism from ocean tidal boundary water levels (η_O) and climatic variations (i.e. drought/flood conditions). Following a rainfall event (P), catchment runoff (Q) would have resulted in overland flows (q_0) to low-lying areas of the landscape. This would have created a shallow freshwater swamp, with a high residence time (R_T), draining to Cattai Creek as river levels (η_R) return to normal. High residence times following rainfall events would have provided an ideal environment for natural organic decomposition of floodplain sediments.

Post-1905 (Figure 2.7) the site was heavily engineered for flood mitigation to reclaim dry land for agricultural production. This was achieved through clearing, extensive drainage networks and exclusion of tidal waters by one-way flood-gated culverts. The Big Swamp Drainage Scheme was originally designed to completely bypass catchment inflows (Q) through the system. This implies that the Big Swamp paddocks would remain wet until downstream river levels recede. Therefore, direct rainfall (P) and run-off (q_0) on the Pipeclay/Big Swamp catchments are the main mechanisms causing inundation of pastoral land at the site (provided the water level is below the height of the levee). However, in comparison to the *Historical Site*, a high drainage density resulted in the rapid removal of surface water run-off (q_0), altering the natural groundwater budget (i.e. decreasing the groundwater table during dry conditions) and site hydrology (i.e. changed flow paths and reduced residence times (R_T)). Low surface water elevations, artificially created by one-way floodgates, (i) encourage oxidation of floodplain sediments (i.e. pyritic material); (ii) maintain a strong hydraulic groundwater gradient towards the drain; and (iii) result in rapid export of poor quality acidic surface waters from the landscape to Cattai Creek.

The *site today* operates differently under dry and wet conditions. During dry conditions, saline water diffuses from the tidal ocean boundary creating a gradient of salinity throughout the estuary. Under these conditions, acidic discharges from an ASS drain is neutralised via the high buffering capacity (i.e. high bicarbonate concentration) of the saline water in the estuary and consequently, environmental impacts are localised. Individual acid plumes are usually isolated, unable to merge with adjacent acidic plumes from nearby channels/drains. These dry periods are characterised by high acid buffering and limited groundwater gradients (Figure 2.8).

Conversely, rainfall events flush the estuary of bicarbonate-rich seawater, reducing the buffering capacity of the water body and flushing contaminates from the floodplain drainage system. These wet periods are characterised by high dilution and lesser environmental impact (Figure 2.9).

However, the tail end of a flood hydrograph is a period of low dilution and high pollutant load, with virtually zero buffering capacity in the receiving water (Figure 2.10). Johnston et al. (2003) identified that 90% of the total pollutant load is discharged over the last 10% of the flood hydrograph. During this period, the surface water on the floodplain has subsided due to the presence of floodgates and large drains, creating a strong gradient between high groundwater levels and low drain water levels. This, in turn, drives the flow of acidic groundwater into the floodplain drainage network and subsequently, the receiving estuary. Large acidic plumes may have long residence times in the estuary and multiple plumes can join to form what is termed a 'super-plume' (Rayner, 2010).

On-ground field investigations were undertaken for dry and wet periods to test the hypothesised conceptual models. The results of these investigations are detailed in Section 2.4 and Section 2.5.

2.4 Hydrogeological Assessment – Dry Period Response

Following a detailed literature review, it was determined that there was limited information available to develop a conceptual understanding of how Big Swamp currently functions under various hydrologic conditions. In particular, no channel surveys, tidal discharge volumes or water level information was available and little was known about the tidal extent and salinity/tidal dynamics in Pipeclay Canal. A 5-day field study, including a 'dry snapshot', was undertaken on 27 – 31 August 2012, to provide information on Pipeclay Canal during typical dry weather conditions and to obtain coordinated data sets measuring water levels, flow and water quality from various locations concurrently. The information collected from this field campaign included:

- RTK-GPS survey levels of key structures that control flow (i.e. bridges, culverts and floodgates);
- Cross-sections of important drains;
- Water levels at 3 sites including Cattai Creek, as well as the downstream and upstream extents of Pipeclay Canal;
- Upstream and downstream flow measurements in to and out of Pipeclay Canal;
- Coordinated flow and water quality measurements from the various field drains; and
- Groundwater level measurements.

Based on the collected data, an assessment of the site's hydrologic and water quality response during dry weather conditions was undertaken. This period was representative of typical dry weather conditions as negligible total rainfall (less than 2 mm) was recorded at Moorland up to 48 days prior to the field investigations being undertaken (Figure 2.11). A description of the findings from this field investigation and subsequent data analysis is provided below.

Note that when paddock areas in the Big Swamp floodplain are referred to in this report, the reference is relative to Pipeclay Canal, for example, the 'western paddocks' are west of Pipeclay Canal. Furthermore, during the field investigations the site was divided into 4 sections: north and south of Coralville Road and, east and west of Pipeclay Canal, with measurements taken across all sections.

2.4.1 Site Hydrology (Dry Conditions)

The water balance during dry periods for the ground/surface water system is dominated by evapotranspiration, with limited tidal flushing influencing water levels across floodplain drains. Pipeclay Canal, through its connection with Cattai Creek, remains tidally influenced, however, natural and man-made barriers along the canal attenuate tidal water levels (Table 2-2). To quantify the water balance, several data loggers were installed at the study site measuring pressure, which can be converted to an equivalent water level. Further information on these monitoring stations is provided in Appendix B.

Table 2-2: Maximum Recorded Tidal Variation during the Dry Period Snapshot

Site ID	Water Level Variation (m)
Upper Cattai Creek	± 0.90
Lower Pipeclay Canal	± 0.70
Upper Pipeclay Canal	± 0.55

During typical dry conditions, baseflows to the Big Swamp catchment are relatively small at less than 5% of the typical spring tidal prism in Pipeclay Canal of 80,000 m^3. Based on field discharge estimates taken daily at the top of the Pipeclay Canal, WRL estimated typical inflows under dry conditions of 0.1 m^3/s. These field measurements were estimated using a hand-held current meter and detailed cross-section surveys. In addition to these field estimates, an AWBM catchment model was developed to calculate runoff from rainfall. This model has been extensively tested on Australian catchments (Boughton and Chiew, 2007) and successfully applied in nearby catchments (Miller and Tarrade, 2010). Ninety-nine (99) years of daily rainfall data was used from the Moorland rainfall station (BOM Station 060024) and combined with monthly average evaporation data from Taree Airport. Based on estimated daily averaged inflows, the 50th percentile discharge value, representative of catchment baseflow, was estimated at 0.1 m^3/s from the model. Predicted discharges are provided in Figure 2.12.

During dry periods, surface water movement across the site is limited by (i) a flat gradient (north to south); (ii) disconnected depressions in the ground surface; and (iii) a surface roughness typical of uniform channels with an earth bottom. The paddocks across the Big Swamp floodplain are also separated by road and levee embankments and only connect during wet periods. Floodgates, high site drainage and deep drains through the western paddocks provide more efficient drainage of surface waters and potentially lower groundwater levels than the eastern paddocks.

Field observations of the eastern paddocks indicated that the ground surface on properties east of Pipeclay Canal and south of Prairie Grass Island (Figure 1.3) were boggy underfoot (Figure 2.13), despite the long-term dry conditions. There were also consistent flows discharging from the drains along the eastern side of Pipeclay Canal. Based on these observations, it was surmised that the hilly dune system and sandy soil east of Pipeclay Canal provide some baseflow to the eastern paddocks. Historical evidence from surveys undertaken in 1899 (PWD, 1911) suggests that there are several natural flow paths through the eastern side of the site including Freshwater Creek, Duck Holes Creek and Native Dog Creek (Figure 2.4) that also contribute to this baseflow. Conversely, no similar systems exist on the western and northern paddocks.

2.4.2 Field Groundwater Investigations

Extensive spot field measurements of pH across the Big Swamp landscape were carried out during the dry period field investigations (Figure 2.14). The results indicated that highly acidic groundwater is located throughout the soil surface profile. Shallow floodplain drains were observed to have extensive ferric iron staining on the ground surface, indicative of the evapotranspiration process resulting in a seasonal accumulation of acid products. The field data measurements taken of pH and flow indicate (Figures 2.15 and 2.16) that the eastern side of Pipeclay Canal has a greater acidic flux than the western side of Pipeclay Canal, despite low pH measurements across the entire site.

In addition to the field measurements of pH, a series of saturated hydraulic conductivity (K_{sat}) measurements were undertaken based on the methods outlined by Johnston and Slavich (2003). This method comprises the excavation of a shallow pit, extraction of standing groundwater and measurement of the rate of infilling. This technique provides a rapid, semi-quantitative assessment of the insitu bulk hydraulic conductivity and estimation of the transport rates of acid from the soil profile to the adjacent surface waters.

Results (and locations) of the onsite investigations conducted in August 2012 were compared to previous work undertaken by the NSW Department of Primary Industries in May 2007 (Figures 2.17 and 2.18). Local groundwater levels were on average 0.2 m lower in August 2012 than May 2007, as less than 2 mm of rainfall had fallen up to 48 days prior to the fieldwork. Generally, the soil profile was consistent between both site investigations. The soils comprised of dark organic loams (0 – 0.27 m), overlaying a pale grey to greyish brown silty clay sulfuric horizon (AASS), with extensive iron (Fe) mottling throughout and pale jarosite mottling at depth of approximately 0.7 m below ground level (Figure 2.19). This broadly aligns with other soil survey data reported for the site (see Tulau, 1999). Many small, 1 – 2 mm in diameter, macropores (old root channels) were observed during the pit excavations, with few larger than 5 mm diameter. The dominant orientation of the macropores appeared to be vertical, as seen during the May 2007 investigations.

During the May 2007 study, hydraulic conductivity varied by an order of magnitude across the site. Values ranged from 2.1 m day^{-1} at site P1 to 29.0 m day^{-1} at site P4 (Table 2-3). These results are lower than those observed by WRL during the August 2012 investigations (Table 2-4). However, all data suggests that the hydraulic conductivity is high to extreme based on the categories outlined by Johnston and Slavich (2003). Representative K_{sat} results for test pit 1 are provided in Figure 2.20. Results for the other test pits are provided in Appendix B.

Based on these field results, lateral groundwater movements are likely to be a significant pathway for acid export across Big Swamp. As a result, the release of acidic groundwater from the soil profile into adjacent surface waters is related to the hydraulic gradient between the groundwater table and the drain water level (Glamore, 2003). In low-lying floodplains, such as those found at the study site, the hydraulic gradient is mainly controlled by boundary conditions (i.e. deep drains and floodgates) as well as environmental conditions (i.e. rainfall and evapotranspiration).

Table 2-3: Previous Soil Acidity Assessment by Dr Scott Johnston (May 2007)

ID	Property	Date	Easting (m)	Northing (m)	Indicative K_{sat}	Approximate K_{sat} (m/day)	pH
P1	Buttsworth	16/06/2007	468214.791	6479921.239	Low-Moderate	2.1	3.14
P2	Buttsworth	16/06/2007	468116.366	6479912.772	Moderate	6.9	3.15
P3	Buttsworth	16/06/2007	468078.266	6479770.955	High-Extreme	18	3.46
P4	Nolan	16/06/2007	469474.210	6480871.624	High-Extreme	29	-

Table 2-4: Soil Acidity Assessment by WRL (August 2012)

ID	Property	Date	Easting (m)	Northing (m)	Indicative K_{sat}	Approximate K_{sat} (m/day)	pH
1	Buttsworth	15/08/2012	469062	6480970	High-Extreme	60	-
2	Buttsworth	15/08/2012	469243	6481231	High-Extreme	20	-
3	Buttsworth	15/08/2012	469435	6482521	High	15	-
4	Buttsworth	28/08/2012	467979	6479503	High-Extreme	35	4.00
5	Buttsworth	28/08/2012	469668	6484688	Extreme	100	4.75
6	Buttsworth	28/08/2012	469797	6483516	High-Extreme	60	3.40
7	Buttsworth	28/08/2012	470084	6483083	High-Extreme	30	3.39
8	Buttsworth	29/08/2012	469483	6481467	High-Extreme	90	3.84
9	Buttsworth	29/08/2012	468888	6480137	High-Extreme	70	4.35
10	Buttsworth	30/08/2012	469172	6480564	High	15	4.28
11	Buttsworth	30/08/2012	470570	6483794	Moderate	8	3.68

2.4.3 Surface Water Quality

Surface water quality is often used as an indicator of estuary health. As highlighted above, acidification affects both soil and water and it is now widely accepted that ASS oxidation has negative impacts on estuarine water quality. Consequently, a range of parameters are required to properly assess acid flows being exported into estuarine receiving waters.

To date, there have been several studies into the water quality of the Manning River estuary and the drainage system of the Big Swamp catchment. A summary of these investigations is shown in Table 2-5. Full details on all reviewed information for this study can be found in Appendix A.

Table 2-5: Water Quality Investigations Associated with ASS Problems in the Manning River Estuary

Source	Project Summary
SPCC (1986)	Water Quality in the Manning River
Lawrie (1996)	Short-term spot testing of drains in the Pipeclay Creek Canal and Lansdowne River areas that noted very acidic drains.
GTCC (1997)	Estuary Processes Study by Webb, Mckeown & Associates. Short-term spot testing of drains and tidal waters in the Cattai Creek, Lansdowne River and Ghinni Ghinni Creek (in August 1995 and August 1996) that identified acidic drains and tidal waters.
Silcock (1998)	Soil study that included spot testing of drains on North Oxley Island, measured drains with pH < 4.5.
Sonter (1999)	Water quality study (March to June 1999) in Pipeclay Creek Canal and Cattai Creek that measured acidic drain and tidal waters. Spatial and temporal variability.
Tulau (1999b)	Identification of Cattai-Pipeclay, lower Lansdowne-Moto-Ghinni Ghinni Creek as ASS priority management areas.
Smith & Dove (2001)	Water quality study (February 1999 to August 2001) of drains on North Oxley Island, which measured persistent acidic conditions.
Dove (2003)	Identification, measurement and investigation of sources of acidification and its' spatial and temporal characteristics in the Manning and Hastings Rivers.
Johnston (2007)	Preliminary ASS Assessment
NSW DPI (2007)	Initial Monitoring of Drains on Buttsworth Property.
GTCC (2010 – 2011)	Short-Term Monitoring of Pipeclay Canal and Cattai Creek Following Acid Plume Event in May 2010.

Although the studies listed in Table 2-5 provide a preliminary assessment of water quality in the Pipeclay Canal-Cattai Creek system, they lack long-term concurrent data sets relating site hydrology and water quality across the Big Swamp floodplain. The establishment of several long-term data collection stations, in conjunction with intensive short-term spot measurements, ensured the provision of good quality data with greater spatial coverage across the floodplain. In addition to continuous time-series measurements of conductivity and temperature at three stations along Cattai Creek – Pipeclay Canal (recorded every 15-minutes), WRL obtained spot measurements of in situ drain water dissolved oxygen, pH, electrical conductivity (EC) and temperature. These measurements recorded the time and location of collected samples using calibrated field Hach and Aquaread water quality meters (Figure 2.21). A summary of the range of pH values can found in Table 2-6 (Figure 2.15).

Table 2-6: Summary of Paddock-by-Paddock Surface Water pH Measurements during the Dry Snapshot on 29th August 20112

Location	pH Range (pH units)
NE Paddocks	2.6 – 3.7
NW Paddocks	3.2 – 5.3
SE Paddocks	3.2 – 4.1
SW Paddocks	2.7 – 4.3

For the dry snapshot, EC measurements varied from approximately 5.9 mS/cm (seawater is approximately 56 mS/cm) at the confluence of Cattai Creek – Pipeclay Canal to near 0.0 mS/cm at the top of the canal. Floodplain drain EC values were recorded below 1.0 mS/cm across the floodplain study domain. Throughout the entire measured period, a maximum value of 25 mS/cm was reached at the top of the canal around 20th December 2012 and a maximum value of 25.7 mS/cm was reached at the downstream logger station in Pipeclay Canal on 13th November 2012. The maximum reported EC value at the top of the canal was based upon measurements recorded since the automatic logger was installed during the August 2012 field investigation. The logger in the downstream section of the canal was installed during the June 2012 field investigation, however, this unit was vandalised on the 13th November 2012. A second data logger was also vandalised on the same day near Coralville Bridge. These loggers are yet to be recovered and as such, no data from this secondary station has been presented in this report. A summary of all measurements taken during the August field investigation is provided in Appendix B (Table B-10).

2.4.4 Summary of Dry Period Response

In summary, the dry period measurements showed that following relatively long-term dry conditions:

- Groundwater levels are dominated by evapotranspiration with limited tidal flushing influencing groundwater recharge across floodplain drains;
- The tide is attenuated along Pipeclay Canal with salinity reduced in upstream areas;
- Upland inflows are comparably small to the tidal prism;
- Surface water movement across the floodplain is limited by several factors including flat topography gradients, ground surface depressions and roughness;
- The eastern paddocks remained wetter for longer and had some baseflow compared to the dry western paddocks;
- The soil has high to extreme saturated hydraulic conductivity; and
- All of the Big Swamp landscape is acidic with low pH soil and surface water recorded on every paddock.

While the collected field data and observations presented in this report have provided an assessment of the site's hydrologic and water quality response during dry conditions, it has also highlighted a gap in understanding of the transitioning phase from dry to wet periods. This critical information provides an understanding of how Big Swamp functions immediately after floods and during subsequent acidic plume events. Details of the wet period response of the Big Swamp floodplain are provided in Section 2.5.

2.5 Hydrogeological Assessment – Wet Period Response

During mid-late January 2013, an East Coast Low event (ex-tropical cyclone Oswald) caused heavy rainfall and flooding across much of the Queensland and New South Wales coastline. Over 5 days from the 24th January to 28th January, the Big Swamp catchment received in excess of 280 mm of rainfall, flooding Pipeclay Canal to a bankfull state and inundating the surrounding landscape (Figure 2.22). Following the rainfall event, a strategic and targeted 16-day field investigation from 30th January to 15th February 2013 was undertaken to obtain intensive water quality and flow measurements across the Big Swamp landscape. This data provides:

- An understanding of how Big Swamp functions during floods and wet/acid periods;
- Quantification of the acid plume dynamics and severity in Cattai Creek;
- An understanding of the acid/buffering kinetics in an estuarine environment;
- Determination of hotspot acid flux zones within the various sub-catchments of Big Swamp;
- Prioritisation of locations for on-ground actions for remediation of the landscape; and
- Details of the flushing dynamics of the Big Swamp floodplain.

This section highlights the hydrologic response of the Big Swamp site during and immediately after wet weather conditions. A discussion of site hydrology and water quality during the event will form the basis for the hydrogeological assessment. The event that occurred is representative of a typical catchment based rainfall event at the site. This wet event is of particular relevance to this study because:

1. It highlights acid plume dynamics originating from the Big Swamp floodplain;
2. It was predominately a coastal storm event based in the Pipeclay/Big Swamp catchment (not a broader Manning River catchment flood);
3. It was an appropriate sized flood for this study;
4. The site was accessible following the rainfall event;
5. The antecedent conditions of the site were dry; and
6. The site was largely dry for a period of 13 days after the rainfall event.

Analysis of the data collected during the wet event is ongoing and only data relevant to onsite remediation is provided in this report. A summary of the findings of the field investigations is provided in Section 2.5.1 to Section 2.5.4.

2.5.1 Site Hydrology (During Wet Events)

During medium to large floods, Pipeclay Canal and the Big Swamp catchment act as a flood storage area for the lower Manning River estuary. The four ways the Big Swamp catchment can be flooded (Figure 2.23) are:

1. Flooding from the upland catchment through Pipeclay Canal;
2. Backflows from the Manning River through Cattai Creek during large floods (i.e. greater than a 10% AEP event) and ocean storm-surge;
3. Backflows from a combination of extreme high tides and storm-surge; and
4. By direct rainfall on the Big Swamp catchment.

With this understanding, upland (i.e. Coralville/Moorland) or downstream (i.e. Harrington) landholders could only be affected by any proposed on-ground works at Big Swamp if one of the following scenarios were to occur:

1. Any changes made to the Big Swamp landscape impact the larger Manning floodplain;
2. Water storage capacity is reduced in the system;
3. Water is added to the system; or
4. Overland flow paths are changed.

None of these options are proposed as options for the Big Swamp floodplain and furthermore, landholders will not be affected because:

1. The Big Swamp catchment is a very small part of the Manning River Basin (65 km^2 vs. 8,420 km^2, or less than 1% (Figure 2.3)), therefore any on-ground works will have a negligible impact on larger Manning River catchment floods.
2. Any proposed on-ground works will be designed specifically so as to not reduce the existing water storage capacity in the system. The remediation would be achieved by modifying how water accesses the floodplain from Pipeclay Canal-Cattai Creek. This would involve removing appropriate floodgates and using the tide to inundate the land through shallow overland tidal flushing. The levee bank would be retained where necessary.
3. Any on-ground works will not add water to the system or alter the flood storage function of the remaining farmlands in the Big Swamp catchment floodplain. As the levee bank will be largely unaffected by the on-ground works and the tidal range is small, only floods below the height of the existing levee banks are able to inundate overbank areas (i.e. moderate to large floods that overtop the levee will be unchanged).
4. Any changes to the flow paths between Pipeclay Canal and the floodplain will benefit upstream and downstream landholders, as the proposed works will:
    a. Provide additional flood detention;
    b. Be hydrologically separate from adjacent landholdings; and
    c. Not alter flow paths between adjacent townships including Harrington or Moorland.

Note that in preparation of this report, WRL has not recreated the Manning River flood study (PWD, 1991) as this is outside the scope of works and not necessary for this study. Any proposed on-ground works will ensure that the existing hydrologic capacity of Big Swamp is maintained and reinstate a more natural hydrology to the remediation areas to promote the regeneration of a dynamic seasonal saltwater/freshwater wetland vegetation complex to remediate acid stored in the soil.

An assessment of floodplain inundation for a range of flood levels is an important step in understanding the wet period response of the site. A key step in assessing the flooding response is to develop a stage-volume relationship from the site topography. The stage-volume relationship indicates the volume of water below a certain elevation applied globally across the Digital Elevation Model (DEM). This volume data was extracted for the site using the DEM at a range of flood heights (Table 2-7 and Figure 2.24).

Key hydrological features as floodwater elevations increase (Figure 2.25) are:

- Below 0.5 m AHD (approximately HHWSS (MHL, 1999)) − minor inundation of the Big Swamp floodplain occurs primarily in the south-west paddocks;
- Above 0.75 m AHD − minor inundation of the eastern paddocks occurs;
- Above approximately 1.0 m AHD − the western paddocks north and south of Long Point hydrologically connect, while on the eastern side inundation is contained mainly in the south-east paddocks;
- Between 1.5 m AHD and 1.8 m AHD − a substantial increase in inundated area occurs, with a 90% increase in storage-volume; and

- Above approximately 1.8 m AHD − the levee flanking Pipeclay Canal is fully inundated and the entire floodplain area is connected to Cattai Creek. Water elevations in excess of 1.8 m AHD are predominately due to backwater flooding from Manning River. Evidence of historic flood levels was observed across the site during recent field investigations with flood debris found in trees and fences across the lower-lying areas and along the levee banks flanking Pipeclay Canal. This elevation equates approximately to a 10% AEP flood event for the Manning River catchment.

Table 2-7: Big Swamp Stage-Volume Relationship

Elevation (m AHD)	Approximate Volume Below (m^3)
0	45,000
0.25	97,000
0.5	324,000
0.75	1,125,000
1.0	3,145,000
1.25	6,598,000
1.5	11,122,000
1.75	16,357,000
2.0	22,082,000
2.25	28,231,000
2.5	34,766,000

2.5.1.1 Local Catchment Flooding

Desktop analysis was undertaken to assess the approximate magnitude of a rainfall event that would be required to flood Big Swamp up to a given elevation. Design rainfall estimates for Moorland were utilised to assess the filling of the Big Swamp catchment from an elevation of 0.0 m AHD to 1.0 m AHD, a volume of approximately 3,145,000 m^3 (Table 2-7). The design rainfall for Moorland (Table 2-8) was combined with a catchment area of approximately 65 km^2 (which includes the Big Swamp and Pipeclay Creek catchments, Figure 2.26) to characterise the rainfall/runoff events (Table 2-9). It was assumed losses would be 2.5 mm/hour (PWD, 1991).

Table 2-8: Design Rainfall Intensity-Frequency-Duration Data for Moorland (mm/hour)

DURATION	1 Year	2 years	5 years	10 years	20 years	50 years	100 years
5Mins		125	158	177	202	235	260
6Mins		117	148	166	190	221	245
10Mins		96.2	122	137	157	183	203
20Mins		70.1	89.6	101	116	136	151
30Mins		57.1	73.2	82.7	95.2	112	124
1Hr		39.1	50.4	57	65.8	77.4	86.2
2Hrs		26.2	33.8	38.2	44.1	51.8	57.7
3Hrs		20.7	26.6	30	34.6	40.6	45.2
6Hrs	10.7	13.8	17.6	19.8	22.8	26.7	29.7
12Hrs	7.14	9.17	11.7	13.2	15.1	17.7	19.7
24Hrs	4.73	6.09	7.8	8.81	10.1	11.9	13.2
48Hrs	3.05	3.94	5.1	5.78	6.68	7.86	8.78
72Hrs		2.97	3.87	4.39	5.08	6	6.69

Table 2-9: Design Event as a Percentage of Required Volume to Fill the Floodplain from Dry to 1.0 m AHD (Note: Greater than 100% indicates events that can fill the floodplain to 1.0 m AHD)

DURATION	1 Year	2 years	5 years	10 years	20 years	50 years	100 years
5Mins		21%	27%	30%	34%	40%	44%
6Mins		24%	30%	34%	39%	45%	50%
10Mins		32%	41%	46%	53%	62%	69%
20Mins		47%	60%	68%	78%	92%	102%
30Mins		56%	73%	83%	96%	113%	126%
1Hr	57%	76%	99%	113%	131%	155%	173%
2Hrs	74%	98%	129%	148%	172%	204%	228%
3Hrs	84%	113%	149%	171%	199%	236%	265%
6Hrs	102%	140%	187%	215%	252%	300%	337%
12Hrs	115%	165%	228%	265%	313%	377%	427%
24Hrs	111%	178%	263%	313%	377%	466%	531%
48Hrs	55%	143%	258%	325%	415%	532%	623%
72Hrs		70%	204%	281%	384%	521%	624%

Based on the historical context of the site, the Big Swamp Drainage Scheme was originally designed to completely bypass catchment runoff through the system. This suggests that the Big Swamp floodplain would remain wet until in-channel water levels recede. Therefore, direct rainfall and run-off on the Pipeclay/Big Swamp catchments are the main mechanisms causing inundation of pastoral land at the site (provided the channel water level is below the height of the levee). Table 2-9 shows that the smallest event able to inundate the paddocks from a dry state to approximately 1.0 m AHD, is a 1 in 1 year occurrence, 6-hour duration rainfall event. As an aside, this analysis shows that a 1% AEP, 48 hour duration rainfall event (results not presented here) in the upland catchment is required to flood the Big Swamp over the height of the existing levee banks flanking Pipeclay Canal (approximately 1.8 m AHD).

2.5.1.2 Backwater Flooding from the Manning River

Despite localised flooding, the wider Manning River catchment is the predominant source of floodwaters in major catchment floods. When the Manning River experiences elevated water levels greater than approximately 1.0 m AHD, backwater effects from the main river channel are observed through increased water levels in Pipeclay Canal and increased inundation in the lower sections of Big Swamp. A representative water level record for Croki was sourced from Manly Hydraulics Laboratory (MHL) to assess the impact of this flooding. This record provides approximately 15 years of data on an hourly time-step from August 1997 to February 2013 (Figure 2.27). The 5%, 2% and 1% AEP flood levels were sourced from the Manning River Flood Study (PWD, 1991) and are listed in Table 2-10.

Table 2-10: Design Flood Heights at Croki (PWD, 1991)

Annual Exceedance Probability (AEP)	Level at Croki (m AHD)
5%	2.5
2%	2.9
1%	3.1

Since 1997, the Manning River has experienced frequent flood events in excess of 1.0 m AHD, resulting in regular inundation to parts of Big Swamp. The Bureau of Meteorology (BOM, 2013) lists 1.8 m AHD as a minor flood level at both Taree and Harrington. Analysis of the past 15 years of water level data at Croki (Figure 2.27) shows that this level was exceeded approximately every 3 years. Applying global water level elevations to the DEM (Figure 2.28) shows, the extent of inundation from floodwaters at Big Swamp and Harrington for a minor (1.8 m AHD) and major (3.10 m AHD) flood level at Croki. The Big Swamp topography demonstrates that the lowest levels in the ridge between the Great Swamp (to the south of Big Swamp) and Wards Creek are approximately 2.3 m AHD (WBM, 1998). This is a separate system to the Big Swamp and there is no direct drainage path evident that connects the Big Swamp wetland to Harrington (below an elevation of 2.3 m AHD).

As mentioned previously, the Manning River is the main mechanism causing flooding in the lower estuary. The Manning River Flood Study, undertaken by Public Works Department (PWD, 1991), showed that peak flood levels of 2.3 m AHD inundated the Big Swamp area during a 5% AEP rainfall event. PWD (1991) indicated that the volume of water discharging from the Big Swamp catchment to Cattai Creek was equivalent to approximately 1% of the flood volume flowing down the Manning River. Furthermore, during the March 1978 flood event (1.3% AEP), the calculated runoff flood volumes for Pipeclay Canal were insignificant at less than 1% in comparison to the total runoff volume for the Manning River calculated at Killawarra. There is a general trend between the volume of runoff proportionally to the size of the contributing catchment (Boughton, 2004). In this respect, the Big Swamp catchment area compared to the total Manning River catchment area is less than 1%. These numerous analyses support the conclusion that on-ground works at Big Swamp will not measurably affect flood levels or flow distributions outside of the immediate remediated area.

2.5.2 Field Groundwater Investigations

Lateral groundwater movement into drains is the most significant pathway for acid discharge from ASS landscapes (Tulau, 2007). Field observations indicate that this is also the primary pathway for acid export across the Big Swamp floodplain. The manipulation of groundwater is therefore often a key objective of any ASS remediation project, requiring the monitoring of groundwater dynamics. The objectives of groundwater monitoring for this study were to provide an understanding of the relationship between groundwater table/gradients and to relate these to drain water levels and chemistry following a rainfall event.

Three monitoring sites were selected across the Big Swamp floodplain. Each site included two measurement locations, these being 2 m and 10 m from the drain (Figure 2.29). The magnitude and spatial variation of groundwater levels between the measurement locations across the site were consistent (Table 2-11). Generally, it was observed that between 1st to 8th February 2013 the groundwater level dropped further nearer to the drains, with a maximum variation in groundwater elevation of 0.34 m, just north of Coralville Road. A summary of the variation in groundwater elevation measurements over this period is shown in Figure 2.30.

These field investigations highlighted the importance of the water balance between rainfall and evapotranspiration on groundwater levels. Furthermore, the results indicate groundwater table dynamics, due to drought-flood variations, has a direct impact on acid export dynamics (i.e. gradients/production/export windows). As such, successful management of ASS requires a thorough understanding of the impact of the rainfall/evaporation rates on groundwater dynamics.

Table 2-11: Short-term Groundwater Measurement Location and Level Variation

Location	Distance from Drain (m)	Easting (m)	Northing (m)	Groundwater Level Variation (m)
BH1	2	469189	6481057	0.27
BH2	10	469190	6481064	0.17
BH3	2	468260	6479734	0.24
BH4	10	468269	6479744	0.14
BH5	2	469814	6483472	0.34
BH6	10	469817	6483486	0.19

2.5.3 Water Quality

The field program involved installation of various short-term deployable flow and water quality measurement devices, including:

- Two Gamet auto-samplers to collect water quality samples at 6-hour intervals. The samplers were positioned just upstream of Coralville Bridge and downstream of the Cattai Creek – Pipeclay Canal confluence;
- A Sontek Argonaut-IQ real-time acoustic doppler flow logger installed to measure discharge at 15-minute intervals from the site; and
- Installation of a Sontek 6600 V2 Multi-Parameter Water Quality Sonde, capable of measuring pH, temperature, conductivity (EC), turbidity and dissolved oxygen (DO) and monitoring at 15-minute intervals.

Water quality spot samples at key locations were also recorded by boat during the wet/acid event monitoring. The primary aim of the coordinated sampling between the Big Swamp floodplain and boat sampling on Cattai Creek was to observe the site transitioning from a saline-dominated/low acidity system to a high acidity system following a local catchment-sized wet event. At the same time, total acid fluxes at varying locations and in the acid plume were quantified.

The Argonaut-IQ and Multi-Parameter Water Quality Sonde were installed downstream of Cattai Creek – Pipeclay Canal confluence, at the same location as the auto-sampler, to capture the flow and water quality conditions of the site over the monitoring period (Figure 2.31). These instruments were installed in addition to the three pre-existing conductivity-temperature-depth monitoring stations across Cattai Creek – Pipeclay Canal. Recorded water level and EC data from these stations is presented in Figures 2.32 to 2.34. Note that a filter was applied to the recorded EC for Cattai Creek where a value less than 40% of the previous record was excluded to remove outliers. In addition to the continuous monitoring equipment, daily snapshots of site hydrology and water quality characteristics were obtained across the study domain at specified locations. Drain discharge readings were obtained using calibrated hand-held current meters, a Sontek FlowTracker and drifter drogues. Site water quality (pH, EC, DO and temperature) parameters were measured using calibrated field Hach water quality meters and grab samples analysed at the UNSW Analytical Laboratory.

Figures 2.35 to 2.42 provide selected 'snapshots' of the site evolving to an acidic state over the 16-day wet period. Water quality sampling in Cattai Creek was undertaken on Day 8 and Day 9, as well as Day 15 and Day 16, of the field investigation (Figures 2.43 to 2.46). Once an acidic plume (pH < 4.5) was detected in Pipeclay Canal, a boat was deployed to track the plume during daylight hours, moving through Cattai Creek (Figure 2.47). Detailed water quality measurements of the plume under ebb and flood tides were undertaken on these days. The sampling area included the confluence of Cattai Creek with Pipeclay Canal to the oyster leases opposite Mangrove Island on the north-arm of the Manning River (Figures 2.43 to 2.46).

Across the four-day boat sampling period, over 170 samples were collected in Cattai Creek. Measurements were taken at several depths in the water column including the surface, 1 m below the surface and 2 m below the surface, where creek depths allowed. Field water quality parameters were analysed on-site with calibrated water quality probes. Parameters measured from the boat included pH, DO and EC. The field parameters were measured within a flow cell using a peristaltic pump until they reached equilibrium. A filtered (0.4 µm filter paper) and unfiltered sample were collected at each location and then acidified with 2% nitric acid (HNO_3). The UNSW Analytical Centre carried out further analysis of the filtered/unfiltered samples. A summary of the laboratory analysis is provided in Appendix B. Laboratory measured parameters included:

- ICPOES: Ca, Fe, K, Mg, Mn, Na, Si, Sr, S; and
- ICPMS: B, Al, Cd, Cr, Ni, Cu, Zn, Pb, Ba, As.

In summary, the results of the 16-day field investigation showed that:

- On Day 1 (Figure 2.35), two days after the rainfall event, the site was effectively *pH neutral* (pH > 5.50) due to rainfall-runoff;
- By Day 5 (Figure 2.36), water levels across the site were decreasing and starting to become acidic (pH ~ 4.50 – 5.50);

- On Day 8 (Figure 2.38), the site was drying out, tertiary and field drains were becoming more acidic and the lower south-east and south-west paddocks were exporting acidic water into Cattai Creek (Figure 2.43);
- By Day 15 (Figure 2.41), the entire site was strongly acidic, secondary drains had discharged surface water and were ponding acidic water, while primary drains from the eastern and western paddocks were discharging acidic water into Cattai Creek (Figure 2.46). A distinct acid plume was captured in Cattai Creek with pH readings as low as 2.70 at the surface (Figure 2.47);
- Values of EC measured across the site indicated freshwater dominance, while measurements taken within Cattai Creek showed distinct stratification on the flood tide. Values ranged across the site from 0 – 44.7 mS/cm (seawater is 56 mS/cm). Lower values were measured nearer to the surface and at the top of Cattai Creek, while higher readings were found at depths and in the Manning River.

Based on these observations, it is surmised that the hydrologic evolution of the Big Swamp landscape in the weeks following the January rainfall event, agrees with the conceptual understanding of the transition between the dry/wet/acid phases presented in Figures 2.8 to 2.10. For the weeks preceding the rainfall event, the Big Swamp landscape represented a relatively long-term dry period, with high acid buffering and limited groundwater gradients (Figure 2.8), analogous to the hydrogeological assessment provided in Section 2.3. The days immediately following the rainfall event represented a short-lived wet period characterised by dominant freshwater flows, high acid dilution combined with a limited tidal prism (Figure 2.9), as shown in Figures 2.35 (Day 1) to 2.36 (Day 5).

The landscape started to become acidic from Day 5 (Figure 2.36) to Day 13 (Figure 2.40). Over this period, secondary drains had discharged surface water and were ponding moderate concentrations of acidic water. Field observations indicated that the south-east corner of the study area had become acidic first, followed by the south-west corner, as a result of the potentially high stores of acidity in soil profile. Following Day 13, the entire site had evolved to a highly concentrated acidic environment with limited dilution and buffering, resulting in strong acid flux being exported from the system (Figure 2.10). The south-east corner of the site was shown to discharge on average an estimated 23,000 mol day^{-1} of acid, 23 times greater than the south-west corner.

Boat sampling indicated that acidic by-products were being transported within Cattai Creek from the Big Swamp, moving further downstream at higher concentrations by Day 15 (Figure 2.45) and Day 16 (Figure 2.46). Aerial photographs highlight the spatial extent of the acid plume throughout Cattai Creek and the high pollutant loads being discharged into the north arm of the Manning River estuary.

Towards the completion of the study, acid flux from the Big Swamp landscape was reduced, while acid water reservoir concentrations remained high. In turn, it is hypothesised that without subsequent rainfall events occurring in the Manning River catchment in mid-late February, the site would have transitioned back towards the hydrogeological dynamics observed during the dry conditions (Figure 2.8). Note that the environmental impact occurring downstream from this acid plume event was not quantified during this study (Figure 2.48).

2.5.4 *Summary Wet Period Response*

In summary, the wet period response of the site showed that, following a local Big Swamp-Pipeclay catchment rainfall event:

- Big Swamp experiences frequent inundation from local catchment, tidal, and backwater influences from the Manning River. Despite localised flooding, the larger Manning River catchment is the source of floodwaters in major catchment floods;
- The whole site becomes connected following a large flood event and remains fresh for several weeks until the tidal influence returns and upland inflows are reduced;
- Lateral groundwater seepage was identified as a significant hydrologic pathway for acid export across Big Swamp. Strong hydraulic gradients between groundwater and drain water levels are created following rainfall events as a result of existing one-way floodgates in the drainage network; and
- From 5 to 14 days following the wet period, drainage of the site resulted in the discharge of acidic water into Cattai Creek when river levels returned to normal and low pH concentrations were found on every paddock.

3. Site Priority Assessment

The conceptual model developed in Section 2 highlights the need to restore the hydrologic values of the former historical Big Swamp landscape. Analysis of past and present evidence suggests that the site is currently in a poor ecological condition due to the impacts of disturbed ASS and is likely to deteriorate further without remediation. The ideal solution would involve restoring the entire site through various remediation options to minimise acid production and transport. However, within the constraints of property ownership and limited funding, a strategic approach to remediating the site is required. Therefore, the best use of resources in the short term is to target areas that meet a range of acidity, discharge and catchment priorities. In the future, there remains a high priority for GTCC to acquire further properties across the Big Swamp floodplain, as additional resources become available.

This section uses data collected during the dry and wet field investigations, in addition to a range of GIS techniques, to prioritise on-ground actions. It introduces a desktop analytical priority assessment methodology (PAM) that divides the site into hydrologic management units and prioritises each unit for future on-ground works. The outcomes of PAM will:

- Improve understanding of the conceptual hydrogeological model of the site;
- Assist in prioritising on-ground works;
- Assist in developing on-ground recommendations; and
- Guide strategic management scenarios to be tested using numerical modelling techniques.

3.1 Methodology

The extent and magnitude of acid drainage is relative to the water balance of the floodplain and the characteristics of the drainage system. Using data collected during the dry and wet field investigations, the Big Swamp floodplain was divided into areas that contribute to acid discharge/flux. In addition to the outcomes of the PAM, other issues that were accounted for within the framework of the methodology include:

- Connectivity issues after modifying secondary, tertiary and field drains (shallower and reduced drainage density);
- Reinstating a more natural hydrology to the remediation area to promote the regeneration of a dynamic seasonal saltwater/freshwater wetland vegetation complex to immobilise acid stored in the soil;
- Minimising deep ponds of stagnant water in the remediated areas;
- Ensuring remediation does not worsen flooding in other areas of the site;
- Minimising fire risk due to uncontrolled growth of grasses and phragmites; and
- Minimising risk of feral animals across the site.

The PAM provides an objective-based methodology to guide on-ground works at Big Swamp. Further discussion of these issues and the recommended remediation strategies is provided in Section 4.

For this study, a generalised desktop analytical assessment methodology was developed. The methodology recognises that areas of higher acid transport are dependent on a relationship between a combination of parameters, including:

1. A normalisation factor, which allows a relative paddock-by-paddock priority rating assessment. The reference zone is the zone having a normalisation factor of 1;

2. A drained area factor, which is the ratio of the drained catchment area and the total catchment area. These areas were identified and calculated using topography supplied by GTCC and a drainage network map of the study area provided by NSW Department of Lands, within a GIS software package;
3. An estimated total drain length, which is calculated as the total length of all drains in a given floodplain area using GIS techniques;
4. A drainage density, which defines the ability of the floodplain area to transport acid and is given as a function of the drained catchment area and drainage length. The larger the drained catchment and the greater drainage length the more potential for acid mobilisation and transport; and
5. A groundwater factor (GWF), which is a function of hydraulic conductivity (K_{sat}) and pH. This combines the physical properties of the ground hydrogeology (K_{sat}) to the groundwater quality (pH). The GWF is calculated using Equation 3.1 and is derived so that a high K_{sat} and low pH will result in a larger GWF and subsequently, a higher score.

$$GWF = K_{sat} \times (14 - pH) \tag{3.1}$$

Based on these parameters a *priority score* (or area rating) can be calculated to determine priority actions and remediation strategies. The priority score is determined by a function of several parameters to give a score out of 100. The higher the score, the more critical the zone and hence, the higher priority given to remediating that floodplain area. The score is calculated as follows in Equation 3.2:

$$Priority\ Score = NF \times DAF \times DD \times GWF \tag{3.2}$$

Where:
NF = Normalisation Factor
DAF = Drained Area Factor
DD = Drainage Density
GWF = Groundwater Factor

While this method does not directly quantify a total flux estimate of acidity from specific floodplain drains, it calculates an acidity contribution from identified zones, through the incorporation of a groundwater factor. Once prioritised, individual remediation actions can be determined for key drains responsible for transporting acidity.

The zones in Figure 3.1 were derived using the catchment topography and drainage lines. Based on an assessment of the spatial variation in hydraulic conductivity, it was surmised that there is negligible variation in hydraulic conductivity between Zone 6 and Zone 0 in the western paddocks, and Zone 7 and Zone 1 in the eastern paddocks. No field investigations for hydraulic conductivity were undertaken in Zone 6 and Zone 7 due to poor site access. Therefore, the derived GWF for Zone 0 was applied to Zone 6 and the same factor calculated for Zone 1 was used for Zone 7.

3.2 Results and Discussion

The PAM provides an effective method for prioritising areas of the landscape for immediate remediation. The results of the assessment are provided in Table 3-1. The results show Zone 0, Zone 1 and Zone 6 are the critical zones for acid transport within the Big Swamp floodplain. While Zone 0 and Zone 6 (located on the south-eastern side of Pipeclay Canal) have a relatively low drainage density across a proportionately large total sub-floodplain area (compared to the Big Swamp floodplain area), the zones scored a higher combined rating than Zone 6 due to influence of the high K_{sat} and low pH values observed in the field. Conversely, the high drainage density and low pH values observed in the field for Zone 6 identified this property as a high contributor of acidity.

Table 3-1: ASS Prioritisation Methodology and Area Rating Results

Zone ID	Normalisation Factor	Total Catchment Area (km^2)	Drained Catchment Area (km^2)	Drained Area Factor	Total Drain Length (km)	Drainage Density	K_{sat}	pH	GW Factor	Score	Priority Area Rating
0	1.00	7.9	2.6	0.33	6,120	0.00233	80	3.84	813	63%	1
1	0.45	3.5	2.2	0.63	12,021	0.00542	38	3.70	395	60%	2
2	0.86	6.8	4.1	0.60	14,730	0.00362	15	4.00	150	28%	4
3	5.16	40.8	1.4	0.03	1,542	0.00114	80	4.10	792	15%	6
4	0.56	4.5	0.3	0.08	1,800	0.00538	35	4.75	324	7%	7
5	0.70	5.5	3.0	0.55	9,213	0.00303	15	3.39	159	19%	5
6	0.97	7.6	3.7	0.48	5,200	0.00141	80	3.84	813	53%	3
7	2.58	20.4	0.5	0.02	1,210	0.00243	38	3.70	391	6%	8

On the 6th February 2013, a meeting was held between WRL, GTCC, WetlandCare Australia (WCA) and key stakeholder groups to discuss prioritisation actions for the site. WRL presented the PAM and provided advice to GTCC on which key areas would provide the most immediate and effective remediation in the short term. As a result, GTCC began the acquisition process through negotiation with several landholders on the Big Swamp floodplain to determine the landscape that could be reclaimed through land purchase. Currently, a total minimum area of 220 hectares of the property in the south-east and south-west corners of the site (Figure 3.2), and a total area of approximately 410 hectares of property in the south-east section of the site (Figure 3.2), is under negotiation to be acquired.

As noted, the PAM was applied based on the hydrology and characteristics of the sub-catchment zones. The areas currently undergoing acquisition, albeit a relatively small percentage of the total site containing high-risk ASS soils (Sonter, 1999 uncited in Flewin, 1997), aligns with the PAM (Table 3-1 and Figure 3.1). However, since the PAM zones and property boundary lines do not exactly correspond with each other, the final on-ground actions are slightly different to the selected PAM zones. The next section (Section 4) tests the hydrologic implications of remediating these properties.

4. Rationale for Remediation Works

Drainage of wetlands and backswamps on the NSW coastal floodplain, such as Big Swamp located within Manning River estuary, dates back to the latter half of the nineteenth century. Acid discharges to the Manning estuary as a result of these hydrologic changes have had a significant widespread impact on water quality and continue to degrade the natural environment. Analysis of past and present evidence suggests that the Big Swamp site currently is the source of large volumes of acidic surface water and requires immediate and ongoing future remediation when resources become available.

The key restoration objectives, as agreed upon in conjunction with the GTCC and the outcomes Big Swamp Feasibility Study (GTCC Feasibility Study, 2010) for Big Swamp, include:

1. Preserving existing wetlands;
2. Converting key paddocks into tidal wetlands (preferably salt marsh with limited fire risk and low-lying shrubs);
3. Elevating groundwater levels above the acidic layer to reduce acid plume discharge to the Manning River (i.e. improve downstream estuarine water quality); and
4. Restoring ecological values of the former wetland to the site.

This section aims to address the key questions associated with the remediation works. The answers provided below detail the rationale for the on-ground works to proceed.

1. What remediation strategies are proposed?

Section 2 identified four key remediation strategies of varying merit and applicability. Of these, three key remediation strategies are proposed for the immediate on-ground works to be undertaken at the site. These remediation strategies will focus on achieving the restoration objectives in the short term (1 – 3 years). They include:

1. Neutralisation: This remediation strategy involves removing appropriate floodgates and encouraging shallow tidal/brackish inundation across acid hot spots at the site. The most effective results for this strategy will be achieved during dry periods when the incoming tides are super-saturated with bicarbonate used in neutralising acidic by-products. This strategy is directed towards remediation of the south-west corner of the Big Swamp floodplain;
2. Dilution: During wet periods, this strategy will take advantage of the increase in the volume of freshwater across the floodplain to encourage anaerobic conditions to form (via increasing organic content on-site). This strategy will be encouraged across all remediation areas of the Big Swamp floodplain; and
3. Reduction: This is achieved by encouraging anaerobic conditions to enforce sulfidic formation in freshwater environments.

A containment strategy is not proposed for the immediate on-ground works to be undertaken at the site. This strategy is mainly applicable for the south-east acquisition zone due to its elevation limiting the application of tidal buffering. However, the large existing primary ring drain is not floodgated and by introducing a sill/weir to hold back acidic flows would reduce the drainage capacity of the system and impact upland landholders via flooding. Impoundment of freshwater also minimises the many exchanges required to neutralise acid stored in partially oxidised soils. However, this is recommended as a future remediation strategy to raise the invert level of the ring drain as funding becomes available to purchase additional properties adjacent to the south-east acquisition zone.

2. What are the potential/disadvantages benefits of neutralisation/dilution by floodgate removal?

The merits of removing floodgates include:

1. Improved downstream water quality (i.e. pH and DO);
2. Reduced acid ponding and associated weed infestations by introducing tidal water into drains and drained partially oxidised landscapes;
3. There is a twice daily exchange of tidal re-flooding, enhancing acid neutralisation. In addition, this estuarine water contains algae. Algal biomass is amongst the most labile of organic matters (Stumm and Morgan, 1996);
4. Tidal ingress across the floodplain is likely to be limited in the long-term due to revegetation of the re-flooded areas with a dense mat of reeds and rushes as a result of drain infilling, floodgate removal and cessation of grazing;
5. Improved long-term ecology through increased fish passage in Cattai Creek, creation of salt marsh areas across the south-west areas of the floodplain and increased wading birds populations; and
6. Decreased hydraulic gradients to reduce groundwater drainage by deep drain infilling and subsequent increased drain invert levels above the PASS layer.

The potential disadvantages of re-flooding may include:

1. Freshwater has only a small neutralisation capacity and many exchanges would be necessary to neutralise the vast quantities of acid stored in partially oxidised soils;
2. Where organic matter is not present, soil acidity is not reversed by freshwater inundation in the short-term. Sufficient organic carbon must remain in the soil to reverse the acid products caused by oxidation; and
3. In lengthy dry periods, evapotranspiration may dry out shallow freshwater ponds and potentially promote the re-oxidation of iron pyrite or hyper-saline landscapes.

3. How will the restored areas of the site operate under dry/wet conditions?

On-ground remedial works aim to minimise impact on existing landholders adjacent to the proposed acquisition areas. This goal will be achieved through buffer zones including levees and floodgates, where necessary, along the boundaries of the reclaimed paddocks. To guide the on-ground remediation process, a range of key objectives were established. These objectives were divided into dry and wet periods, so that:

For dry periods:

1. Encourage acid neutralisation through tidal buffering at the acid discharge source via removal of floodgates and appropriate sections of levee;
2. Prevent further acid production via ensuring the invert of targeted drains are raised above the AASS;
3. Reduce acidic flows via drain infilling and reduced groundwater gradients;
4. Minimise stagnant water via drain connectivity and landforms; and
5. Encourage anaerobic conditions to form via increasing available bacterial content.

For wet periods:

1. Encourage acid dilution through freshwater inundation via removal of floodgates and appropriate sections of levee;
2. Encourage anaerobic conditions to form via increasing organic loads;
3. Ensure on-ground modifications do not impact drainage elsewhere via buffer zones;
4. Minimise stagnant water to avoid mosquito breeding via drain connectivity; and
5. Allow for off-channel flood detention via drain infilling.

4. Will the remediation works impact flooding in the lower Manning River?

The remediation works will not measurably affect flooding in the lower Manning River estuary. Based on the flooding mechanisms outlined in Section 2, upland (i.e. Coralville/Moorland) or downstream (i.e. Harrington) landholders could only be affected by the proposed restoration works at Big Swamp if one of the following scenarios were to occur:

1. Any changes made to the Big Swamp landscape impact the larger Manning catchment;
2. Water storage capacity is reduced in the system;
3. Water is added to the system; or
4. Overland flow paths are changed.

None of these options are proposed and landholders will not be affected because:

1. The Big Swamp catchment is a very small part of the Manning River Basin (65 km^2 vs. 8,420 km^2, or less than 1% (Figure 3.1)), therefore any on-ground works will not impact larger Manning River catchment floods;
2. Any proposed on-ground works will not reduce the existing water storage capacity in the system. The restoration would be achieved by only modifying how water accesses the floodplain from Pipeclay Canal-Cattai Creek. This would involve removing tidal floodgates and using the tide to inundate the land daily through shallow overland tidal flushing. The levee bank would be retained in all areas, where necessary;
3. Any on-ground works will not add water to the system or alter how the remaining farmlands in the Big Swamp catchment flood. As the levee bank will be largely unaffected by the on-ground works and the tidal range is small, only floods below the height of the existing levee banks are relevant (i.e. moderate to large floods that overtop the levee will be unchanged); and
4. Any changes to the flow paths between Pipeclay Canal and the floodplain will benefit upstream and downstream landholders, as the proposed works will:
    a. Provide additional flood detention;
    b. Be hydrologically separate from adjacent landholdings; and
    c. Not alter flow paths between adjacent townships (including Harrington or Moorland).

Proposed on-ground works will ensure that the existing hydrologic capacity of Big Swamp is maintained and the remediated areas will naturally evolve towards a dynamic freshwater/saltwater wetland to reduce acid production and export. Results of this study prove that any proposed on-ground works are negligible when assessing risk associated with a large Manning River catchment-storm events.

5. What are the potential implications of any proposed remediation works?

The potential implications associated with the remediation strategies (by floodgate/levee removal) adopted for this study, may include:

1. While floodgate removal can result in improved water quality, specifically pH and DO during dry periods, the export of deoxygenated water and metals are not eliminated for all periods (Tulau, 2007);
2. Limited neutralising capacity in receiving waters during wet/acid periods (i.e. Cattai Creek);
3. Removing floodgates and sections of levee may result in a progressively increasing tidal prism in Pipeclay Canal. Ongoing monitoring to determine if channels across the Big Swamp floodplain are unstable and scouring is recommended;
4. Reduced access in remediated areas due to more regular inundation;
5. Vegetation changes in the remediated areas will prevent future agricultural practices; and
6. Anaerobic conditions can emit hydrogen sulfide (i.e. strong 'egg-like' odours).

5. Model Scenarios of Management Options

The issue of poor water quality as a result of ASS across the Big Swamp floodplain is well established. As such, remediating prioritised areas of the floodplain, as discussed in Section 3, would reduce the current problem of acid export from the site. A detailed numerical floodplain inundation model was developed to quantify/test remediation options and confirm that the proposed changes will not negatively impact surrounding areas. The model was constructed using field observations and current understanding of the site.

This section first describes the conceptual development of the numerical model. It then briefly details the modelling process and model validation. Following this, the modelling scenarios are provided to compare the existing site to a range of on-site modifications. These results are then used in conjunction with the conceptual model and field data to develop recommended on-ground actions.

5.1 Computer Model Setup

5.1.1 General Concept

The following description should be read in conjunction with Figure 5.1, which highlights the conceptual process of developing a computer model. In a broad sense, the modelling process starts with a "bucket of water" (Figure 5.1(i)). Site features are then incorporated into the model domain including site topography, channel network systems and backswamp areas. Field measurement and monitoring techniques (Figure 5.1(ii)) are used to provide information on how the site functions including hydrodynamic processes and to validate the model.

Irrespective of its size and complexity, a model is simply a tool that incorporates site characteristics and field data into a mathematical approximation of reality. This is achieved by dividing the study area into discrete pieces (or grid cells) and applying mathematical equations within each grid cell to simulate the real system. Once a model has been developed and validated it can be used as a predictive tool to test "what if" scenarios.

5.1.2 MIKE FLOOD Modelling Suite

MIKE FLOOD is a commercially available software package that has been specifically developed to simulate problems of wetting and drying on a floodplain or a wetland. For this study, LiDAR data of the Big Swamp floodplain was adopted as the topography for the numerical model. The resolution of the model was governed by balancing an appropriate grid resolution to represent physical wetland processes against a reasonable simulation time within the time constraints of the project. The choice of grid resolution is a key step in the model development process because if the grid size is overly refined, then the model will take an excessively long time to converge. If the grid size is overly coarse, the accuracy of the answer is likely to be compromised as the finer details and connectivity of the channel network across the floodplain may not be adequately represented in the model grid. For this study, an appropriate refinement was selected to ensure the capacity of the Big Swamp primary drainage network (1-D network) was sufficiently represented. A hybrid modelling approach was used where the primary channel network was simulated by a series of detailed 1-D network branches (Figure 5.2) and cross-sections measured using high resolution survey techniques with a 2-D model used to simulate the wider floodplain topography and the spreading of floodwaters across the floodplain. The 1-D channel network includes important flow control structures and floodgates.

5.1.3 Model Calibration/Validation

Throughout the development of the model, a calibration and validation process was undertaken to ensure that the model was "fit for purpose" and capable of testing the proposed on-ground remediation activities. The model was initially tested to ensure conservation of mass. The model was then calibrated against measured water levels and flow data for sensitivity to several key parameters including channel roughness, off-channel storage and catchment inflows (Figures 5.3 to 5.6). Further details on the development and calibration of the model used for this study are provided in Appendix C.

While the model is considered fit for the purposes of this study, improved confidence in model predictions could be achieved through further field trials against the scenarios, additional data collection, adaptive management and accurate measurement of the restoration areas following site modifications.

5.2 Tidal Inundation Scenarios and Results

Once calibrated, a range of tidal inundation options were tested using the hydrodynamic model. The two aims of the modelling scenarios were to:

1. Understand how the system functions during dry and minor floods conditions (i.e. below the levee crest level); and
2. Test various remediation strategies to assess how the site hydrology would change with on-ground works under tidal conditions.

The initial model runs involved simulating the existing conditions onsite including levee heights, operational one-way floodgated culverts and inundation extents. Subsequent model runs focused on testing remediation outcomes for the site. This was achieved by removing all tidal floodgates on the entire extent of the site (i.e. full remediation). These two model setups were tested under representative dry and wet conditions, producing a total of four model runs (Table 5-1). The existing model was then systematically modified with the outcomes of the conceptual model, action prioritisation and full remediation scenario, to ensure that the site can be inundated in a controlled manner, yet still achieves the remediation objectives. The implications of these remediation options are discussed in Section 6. Further details of the modelling scenarios are provided in Section 5.2.1 to Section 5.2.4.

A summary of the scenarios tested is provided in Table 5-1, with a brief rationale for each setup. Table 5-2 provides a summary of the modelling duration and time steps.

Table 5-1: Summary of Modelling Runs

Model Run #	Conditions	Description	Rationale
1A	Dry	Existing Site	To determine the base level of inundation for comparison with the remediated sites.
1B	Wet		
2A	Dry	Full Remediation	To determine the effect, if any, of flooding extents as a result of opening all floodgates across the site.
2B	Wet		
3A	Dry	Partial Remediation Option 1	To determine the effect, if any, on flooding extents resulting from drain modifications on the south-east and south-west areas.
3B	Dry	Partial Remediation Option 2	As per model run #3A, with a modified channel entrance connecting Cattai Creek to the south-west area.

Table 5-2: Summary of Modelling Scenarios Conditions

Model Run #	Conditions	Model Time Step (sec)	Model Simulation Period
1A	Dry	4	22/08/2012 4:45 AM to 22/09/2012 4:45 AM
1B	Wet	4	16/06/2012 4:45 AM to 16/07/2012 4:45 AM
2A	Dry	2	22/08/2012 4:45 AM to 22/09/2012 4:45 AM
2B	Wet	2	16/06/2012 4:45 AM to 16/07/2012 4:45 AM
3A	Dry	3	22/08/2012 4:45 AM to 22/09/2012 4:45 AM
3B	Dry	3	22/08/2012 4:45 AM to 22/09/2012 4:45 AM

The depth of inundation across the Big Swamp floodplain is presented at the select time steps and tidal heights listed in Table 5-3, for "dry" model runs and Table 5-4, for "wet" model runs. These times were selected as they align with the tidal plane levels calculated by MHL for Croki during typical dry periods and the maximum inundation area following a wet event. The tidal heights recorded at Croki represent the model boundary conditions for the simulation periods listed in Table 5-2 and are provided in Figures 5.7 and 5.8. Further information on the tidal planes for Croki is provided in Appendix B.

Contour maps for each model run showing inundation extents and the increase in inundation compared to the existing site are provided in Figures 5.9 to 5.27. As there was no inundation observed for the dry existing site, the remaining dry model runs represent the increase in inundation across the floodplain compared to the existing site. Floodplain inundation areas and volumes for dry model runs are summarised in Table 5-6, with corresponding depths provided in Table 5-7 at the end of this section.

In addition to inundation extents, a time-series of water depths has been extracted for a range of sites across the Big Swamp floodplain (Figure 5.28) to assess the wet model runs. Water depth time-series are provided in Figure 5.29. A summary table of the maximum and average water depths for each model run at the six locations across the Big Swamp floodplain is provided in Table 5-8. These model predictions show that on-ground works at Big Swamp will not measurably impact flood levels outside of the immediate area of the works.

Table 5-3: Selected Time Steps and Elevations for Display of 2D Modelling Results (Dry Period)

Reference ID	Selected Time Step	Tide Elevation (m AHD)
D1	01/09/2012 22:45	0.720
D2	03/09/2012 11:45	0.411
D3	06/09/2012 07:45	-0.253

Table 5-4: Selected Time Steps and Elevations for Display of 2D Modelling Results (Wet Period)

Reference ID	Selected Time Step	Tide Elevation (m AHD)
W1	04/07/2012 22:45	1.123
W2	06/07/2012 23:45	0.856
W3	10/07/2012 02:45	0.338

5.2.1 Scenario 1: Existing Site

This scenario replicates the existing tidal exchange conditions through Pipeclay Canal where all existing floodgated culverts included in the model setup are operational. The model used is identical to that presented in the calibration. Details of the climate and boundary input conditions for the two existing model setups are provided in Appendix C. The model simulation periods have a duration of 31 days (Table 5-2) that cover two spring and neap tidal cycles as recorded at Croki. Modelling of the existing conditions enables the impact of further scenarios to be quantified.

Model predictions for the existing site vary between the dry and wet model runs. Predictions for the dry model run shows that no inundation occurs across the Big Swamp floodplain (Figure 5.9). For the same site conditions, predictions from the wet model run confirm that the site is extremely flat with shallow surface water becoming isolated across the floodplain as the site drains. An example of this is shown in Figures 5.10 to 5.12. It is worth noting that the model assumes 100% runoff occurs during a rainfall event and does not include groundwater infiltration that will reduce puddling across the site.

Further, the wet model run predictions confirm that the site stays wet for several days following a rainfall event. It is worth noting also that for the selected "wet" time steps, excess rainfall is concentrated along the eastern side of Pipeclay Canal, extending from Cattai Creek to the north-east section of the floodplain. This appears to be along the alignment of the relic Freshwater Creek (Figure 2.3). The model predicts average depths in this area of less than 0.2 m, reducing only marginally after 10 days of the maximum water level being recorded at Croki.

5.2.2 Scenario 2: Full Remediation

Compared with the model setup in Scenario 1, the full remediation scenario is indicative of the maximum tidal inundation possible for the site without on-ground reshaping works and is achieved by the removal of all floodgates. Note that the remainder of the site is unchanged including levee heights, drain invert levels, total number of culverts, off-line storage and the conveyance capacity of Pipeclay Canal. Furthermore, boundary and input conditions to the model remain as applied in Scenario 1.

In general, the model results for the fully open scenario suggests that the south-west corner of the site is the key area for tidal inundation due to its proximity to Cattai Creek, the nearby Cattai Wetlands and low-lying topography (surveyed at or below 0.4 m AHD). The field data highlights this area as the worst zone for the deposition of ASS by-products across the entire Big Swamp floodplain. This is evident in aerial photographs and ground surveys showing expansive acid scalding of the ground surface.

As such, allowing for tidal inundation in the south-west area will be beneficial for the following reasons:

1. Immediate and effective acid neutralisation through shallow tidal overland flows with minimal on-ground works required;
2. Limited impact (flooding or otherwise) on upland landholders;
3. Opening this area to a seasonally-based dynamic combination of salt/ freshwater wetlands;
4. Increasing the possibility of re-establishing a connection between Cattai Wetlands and the south-west paddocks of Big Swamp; and
5. Flood detention.

Model predictions for the fully remediated site show similar inundation extents in the south-west floodplain area between the dry and wet model runs. For the dry model runs, the selected reporting time steps predict an increased floodplain inundation area compared to the existing site, as provided in Table 5-6 and Figures 5.13 to 5.15. The inundation extent and depths of coverage are increased for water levels closer to HHWSS, when compared to MHW and ISLW. For example, average inundation depths were 0.18 m for D1, 0.15 m for D2 and 0.14 m for D3. In all three cases, limited inundation area is predicted for depths greater than 0.3 m. Based on these model predictions and field observations, the majority of the overland inundation occurs via the 'D/S West Section Drain 002' and 'D/S West Section Drain 003' drains. Note that the model predictions show no further inundation occurs across the remainder of the site.

For the wet model runs, model predictions indicate that the inundation extent and depths of coverage are increased for the maximum recorded tide during the simulation period when compared to peak tides recorded two and six days later. Predicted water depths throughout the simulation period are provided in Figure 5.29 as a time-series of water depths for the selected locations shown in Figure 5.28. Average predicted depths in these areas generally do not exceed 0.5 m, except for Location 6, which is in a low-lying area of the topography to show representative water depths possible for that location.

The predicted floodplain inundation area provided in Figures 5.16 to 5.18 shows the increase in water depth compared to the existing site. This analysis shows that some inundation occurs across the remainder of the site during the wet simulation period. This runoff concentrates in the areas opposite Long Point and in the north-west paddock adjacent to Pipeclay Canal. It is surmised that the increase in inundation from W1 to W3 in these areas is due to the floodplain draining following the rainfall event. Predicted depths in these areas do not exceed 0.2 m.

5.2.3 Scenario 3A: Partial Remediation – Option 1

As Scenario 2 requires the removal of all floodgates along Pipeclay Canal, Scenario 3A simulates on-ground works for the proposed acquisition areas only. The recommended on-ground works for the south-west corner are provided in Figure 5.19. In summary, these include:

1. All existing culverts and floodgates within the proposed acquisition area should be removed.

2. All drains shown in red (Figure 5.19) should be infilled to the level of the existing ground elevations (approximately 0.4 m AHD).

3. A key component to the management of the site hydrology in Scenario 3A involves improving the hydrological exchange of the south-west corner of the site with Cattai Creek. This involves encouraging a natural balance of saltwater/freshwater overland exchange, as it is the only area across the site that benefit from a neutralisation remediation strategy. This can be achieved by overall modification to the depth, connectivity and conveyance of the most southern south-west drainage channel in the acquisition area (D/S West Section Drain 003). Construction of a shallow swale drain (or slight ground-surface depression) should include reducing the depth of the channel to approximately 0.2 m AHD and widening the drain to approximately 40 – 60 m (where appropriate). The method of construction should utilise available laser levelling technology to ensure that the depth of excavation is precise and minimised at all times. The swale channel should follow the natural drainage line of the area and form a preferential flow path for freshwater flows to discharge from the site during wet periods.

   The recommended changes would maintain the capacity of the drain while ensuring the equivalent conveyance to the existing channel (i.e. a ratio of discharge between the modified drain and original drain of approximately unity) (Table 5-5). This design will allow regular shallow tidal flushing and periodical inundation of the surrounding landscape under larger tides. This will ensure that the lowest lying areas will be wet more often and the other areas only wet on larger tides during dry periods. It is also recommended that the channel remains connected with the drainage line around Long Point (via a tidal floodgate).

4. A new floodgated culvert in the north-west corner of the proposed acquisition area is recommended to allow floodwaters to escape from the north-west paddocks, while containing any water within the south-west paddocks.

5. To complete the remediation works, a new shallow swale drainage line is recommended running south-east along the northern boundary line of the acquisition area. A new floodgated culvert would be required at the confluence of the drainage line with Pipeclay Canal. As drains should not permanently contain ponded water, the swale drain design should maintain an invert shallower than the invert of the floodgate. Further design of this drainage line is required before construction commences. A small berm with a design crest elevation of approximately 1.0 m AHD (less than the height of the existing levee along Pipeclay Canal) is recommended on the southern side of the swale drain. This is required to hold back initial floodwaters before release into the proposed land purchase area or Pipeclay Canal. This would also hydrologically separate the south-west corner of the site from the adjacent properties to the north.

Table 5-5: Hydraulic Radius Calculations for New Drains

Parameters	Symbol	Original Drain [1]	Modified Drain [2]
Height (m)	H	2.4	0.4
Bottom Width (m)	B1	3	45
Top Width (m)	B2	5	50
(B1-B2)/2 (m)	X	1	2.5
Side Length (m)	S	2.60	2.53
Trapezoidal Area (m^2)	A	9.60	19.00
Perimeter (m)	P	8.20	50.06
Hydraulic Radius (m)	R_h	1.17	0.38
	v	1.24	0.59
	Q	11.92	11.14
Statistics	A2/A1		1.98
	R_h2/R_h1		0.32
	v2/v1		0.47
	Q2/Q1		**0.93**

An alternative approach to remediating the south-east corner of the site is required and is limited by several constraints. These include:

1. Acid production and export is the most severe in the south-east corner;
2. Tidal buffering is limited due to topography (i.e. the south-east corner is generally higher in elevation than the south-west corner); and
3. Containment remediation strategies are limited as several properties adjacent to the acquisition zone could be affected if the overall drainage capacity of the area is restricted or significantly reduced.

As a result, several on-ground works are recommended for the south-east corner of the site and these works aim to minimise acid production and export from this area. Note that there remains a high priority in the future to purchase key properties adjacent to the proposed acquisition area that are potentially impacted by a containment strategy or infilling of the existing primary ring drain.

The modifications introduced into the model setup (Figure 5.20) and tested under Scenario 3A include:

1. Infilling all drains shown in red (on Figure 5.20), as well as isolated depressions within the proposed acquisition boundary, to a level consistent with the existing ground elevations;
2. Removal of the existing east-west drain along the northern boundary line of the property; and
3. Removal of notches for the relevant sections of the levee (shown in pink) to a set height of approximately 0.4 m AHD. Where possible, grading of the ground surface inside the notches would encourage shallow overland flows (e.g. tidal/fresh), while primarily being contained within the acquisition boundary. This should be carried out using laser levelling and supervised to ensure excavation is minimised. Removal of the internal levee along the ring drain of the property boundary requires access to plant machinery. Note that any cut material would need to be stockpiled and treated for acid sulfate soils.

Model predictions of inundation extent and depths of coverage increased for Scenario 3A in the south-west floodplain area, compared to the full remediation and the existing site. Predictions were shown to increase water levels closer to HHWSS, when compared to MHW and ISLW, as provided in Table 5-6 and Figures 5.21 to 5.23. For example, average inundation depths were 0.18 m for D1, 0.15 m for D2 and 0.15 m for D3. In all three cases, residence time had increased from previous runs, with more areas inundated for longer. This is a desired outcome for the treatment of ASS production and export. The model predicts limited inundation areas for depths greater than 0.3 m.

Limited inundation of the south-east corner of the site was observed during dry periods when compared to other cases.

5.2.4 Scenario 3B: Partial Remediation – Option 2

Following discussions with stakeholders throughout the model development phase, the proposed on-ground works for Scenario 3B were refined with the aim of achieving better remediation outcomes through equivalent on-ground effort. The recommendations listed below only apply to the proposed acquisition area in the south-west corner of the site (Figure 5.24). Recommendations for the south-east corner remain unchanged from Scenario 3A.

For Scenario 3B, the on-ground actions include:

1. All existing culverts and floodgates within the proposed acquisition area should be removed;
2. All drains shown in red (Figure 5.24) should be infilled to the level of the existing ground elevations (approximately 0.4 m AHD);
3. Removal of a section of the existing Pipeclay Canal levee in the location shown (Figure 5.24) (approximately 300 m in length);
4. For this option, it is recommended that two new swale drains are constructed in the locations shown. In summary:
    a. The most southern swale drain should expand a palaeochannel drain and allow unimpeded tidal exchange to the south-west corner of the floodplain directly from Cattai Creek. This would encourage overland tidal inundation during dry periods and a preferential drainage path for floodwaters during wet periods. It is recommended that the invert of the swale drain is excavated to above the AASS layer (approximately 0.2 m AHD) and widened to approximately 50 m (where possible);
    b. It is recommended that the existing south-west drainage channel along the western boundary of the proposed acquisition area be infilled to approximately 0.2 m AHD. This would create a shallow swale drain connected to the drainage network around Long Point (via a one-way floodgate) as proposed in Scenario 3A. A key difference recommended for Scenario 3B is that the drainage line terminates in a wide, graded delta area to encourage upland catchment overland flows to spread into the proposed acquisition area, rather than a single preferential flow path through the landscape. It is anticipated that during earthworks the land will be generally graded to remove any internal levees or depressions within the proposed boundary lines (consistent with elevations of approximately 0.4 m AHD). Similar construction techniques for these works are advised as highlighted in Scenario 3A. The aim is to allow initial floodwater runoff, with the remaining water forming a shallow freshwater pond to encourage organic matter deposition and an anaerobic environment; and
5. To complete the restoration works a swale drain should be constructed running south-east along the northern boundary line of the acquisition area (as previously detailed in Scenario 3A).

Model results for Scenario 3B indicated a moderate increase for inundation extent and depths of coverage in the south-west floodplain area, compared to previous model runs. Predictions were shown to increase for water levels closer to HHWSS, when compared to MHW and ISLW, as provided in Table 5-6 and Figures 5.25 to 5.27. For example, average inundation depths were 0.21 m for D1, 0.19 m for D2 and 0.18 m for D3. In all three cases, residence time increased from previous runs, with more area inundated for longer. The model predicts limited inundation area for depths greater than 0.3 m, except in areas where relic drains have been modified in the model topography to an invert of 0.2 m AHD.

Note for both Scenario 3A and Scenario 3B, the model predictions show that no inundation occurs across the remainder of the site, except along the boundary of the proposed acquisition area in the south-east paddocks off Pipeclay Canal. In this area, the model predicts average water depths of less than 0.03 m for the selected time steps. The nature and extent of inundation here is an artefact of the modifications made to the model topography and was intended to represent an access route for machinery to remove the internal levee along the ring drain. Nonetheless, the model results indicate that some tidal exchange is possible along the ring drain.

Table 5-6: Summary of Model Inundation Areas and Volumes for Dry Model Runs

Model Run	D1 (HHWSS)		D2 (MHW)		D3 (ISLW)	
	Area (m^2)	Volume (m^3)	Area (m^2)	Volume (m^3)	Area (m^2)	Volume (m^3)
1A	No Inundation		No Inundation		No Inundation	
1B						
2A	450,400	79,664	349,800	52,646	319,600	45,733
2B						
3A[1]	523,000	93,451	444,200	66,713	425,900	62,005
3B[1]	597,600	124,310	659,300	123,201	640,700	114,672

[1] Note inundation depths, areas and volumes were calculated for the south-west paddocks off Pipeclay Canal only.

Table 5-7: Summary of Model Inundation Depths in South-West Paddock Area off Pipeclay Canal for Dry Model Runs

Model Run	D1 (HHWSS)	D2 (MHW)	D3 (ISLW)
	Avg. Depth (m)	Avg. Depth (m)	Avg. Depth (m)
1A	No Inundation	No Inundation	No Inundation
1B			
2A	0.18	0.15	0.14
2B			
3A	0.18	0.15	0.15
3B	0.21	0.19	0.18

Table 5-8: Summary of Maximum and Average Water Depths for All Model Runs

Location	Dry Existing Site (Scenario1A)		Dry Full Remediation (Scenario2A)		Wet Existing Site (Scenario1B)		Wet Full Remediation (Scenario2B)		Dry Remediation Option 1 (Scenario3A)		Dry Remediation Option 2 (Scenario3B)	
	Max	**Mean**	**Max**	**Mean**	**Max**	**Mean**	**Max**	**Mean**	**Max**	**Mean**	**Max**	**Mean**
1	0	0	0	0	0.29	0.26	0.53	0.37	0	0	0	0
2	0	0	0	0	0.16	0.08	0.15	0.08	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0.15	0.13	0.35	0.27	0	0	0	0
6	0	0	0.94	0.75	0.85	0.72	1.09	0.81	0.97	0.83	0.97	0.91

6. Discussion of Remediation Options

Model runs of the existing site conditions provided a baseline for comparison with the proposed remediation options. These scenarios were undertaken using a systematic approach, starting with the full tidal remediation to investigate the maximum inundation possible for the site and progressing with a series of on-ground works tailored to either control or divert tidal/freshwater flows across these areas. The partial remediation options were developed and tested in line with the outcomes of the conceptual model, priority assessment methodology and full remediation scenario.

For dry conditions, model predictions for the remediated site were compared to the existing site assessment. The comparison indicates that increased inundation extent and depths of coverage will occur in the south-west floodplain area. In this area, for all water levels tested, the partial remediation Scenario 1 predicts:

1. Increased inundation area and floodplain storage of more than 15% compared to the fully remediated site; and
2. Average inundation depths across selected floodplain locations were less than 0.18 m.

Similarly, for all water levels tested, the partial remediation Scenario 2 predicts:

1. Increased inundation area of more than 25% compared to the fully remediated site;
2. Increased floodplain storage of more than 35% compared to the fully remediated site;
3. Increased inundation area of more than 12% compared to the partially remediation Option 1;
4. Increased floodplain storage of more than 25% compared to the partially remediation Option 1; and,
5. Average inundation depths across selected floodplain locations were less than 0.21 m.

The hydrodynamic modelling predictions therefore indicate that well-planned on-ground works, within the proposed land acquisition zones, have the potential to immobilise acid stored in the soil profile. This will be achieved through reinstating a natural flushing regime to the remediated area to promote the regeneration of a dynamic seasonal saltwater/freshwater wetland vegetation complex. Ultimately, these results align with the objectives set out in Section 4.

Following consultation with stakeholders and analysis of the model results, a second partial remediation option was tested. These results were similar to those recommended for partial remediation Scenario 1. The proposed remediation works for Scenario 2 include three key differences to Scenario 1, including:

1. Removing a heavily vegetated levee section along the right bank of Cattai Creek, near its confluence with Pipeclay Canal;
2. Removing a section of levee along the right bank of Pipeclay Canal, extending approximately 300 m upstream from its confluence with Cattai Creek; and
3. Limited drain connectivity is proposed in the south-west acquisition area.

A short discussion of the implications of these changes is provided below:

1. Safe access to remove a heavily vegetated levee section along the right bank of Cattai Creek is not guaranteed and undertaking the on-ground works in the proposed location may prove difficult;

2. Removing a section of levee along the right bank of Pipeclay Canal would involve reducing the levee height to an elevation of 0.4 m AHD level with the existing floodplain. There are several advantages in removing this section of levee including:

    a. Ease of access;
    b. Increased effective area for tidal flows; and
    c. Increased off-line storage of backwater flooding from the Manning River.

    An implication of these works is access to this area for future maintenance of Pipeclay Canal may be difficult on a normal high tide. Alternatively, this section of Pipeclay Canal can be accessed from the left bank; and

3. The implications of limited drain connectivity in the proposed south-west acquisition area may increase the likelihood of isolated ponding or stagnant water if regular flushing freshwater or brackish estuarine water does not occur.

Note that all on-ground works should be undertaken in-line with the NSW ASS Manual.

7. Recommendations

The quantities of acid that can be discharged from the Big Swamp floodplain following a catchment-based rainfall event can severely impact the Manning River estuary ecology, aquaculture and fishing (Sammut et al., 1995; Dove, 2003). The altered water balance of the floodplain is a key factor in controlling the export of acid. Restoring the natural water balance by remediating the entire site would be the ideal option to the long-term management of acid production and export. As such, managing the hydrological regime to minimise the production and export of acid at the Big Swamp floodplain should be an ongoing priority.

7.1 On-ground Works

The prioritisation assessment method identified the south-west and south-east areas of the site as high acid export zones requiring immediate priority remediation (Section 3.2). In particular, the south-west paddock areas are subject to twice daily tidal exchange as shown in the modelling results (Section 5.2). This provides an effective and economically viable treatment strategy to prevent further oxidation of acid soils by changing the hydrological regime through removal of floodgates and land reshaping.

To achieve the required objectives of the Big Swamp rehabilitation project, the proposed on-ground works should be in accordance with Scenario 3A (as presented in Section 5.2.3), in addition to removing a section of levee along the right-bank of Pipeclay Canal. This option was selected in preference to Scenario 3B as the recommendations adhere to natural contours of the land and impose less environmental damage to the landscape, while still achieving the immediate remediation outcomes. The following section broadly discusses the recommended on-ground remediation actions and should be read in conjunction with the detailed recommendations highlighted throughout Section 5 of this report.

1. Removal of existing floodgates and culvert structures

Removal of existing floodgates and culvert structures in the remediation zone is a key recommendation resulting from this study. All existing floodgates and culverts structures within these areas are to be removed and the drains infilled to levels above the ASS layer.

2. Removal of existing levees

Based on the outcomes of Scenario 3B, it is recommended that a section of levee along the right-bank of Pipeclay Canal, extending approximately 300 m upstream from its confluence with Cattai Creek, be removed to the existing ground level at the site. Additional minor levees along secondary and field drains within the acquisition area should be infilled as appropriate.

3. Modification of existing drains and construction of new drains

A strong preference is to reduce the overall number and depth of drains and where possible, reconfigure existing drains to immobilise acid production and discharges from the Big Swamp floodplain. Existing deep drains should be shallowed and widened as highlighted previously. Modification of existing drains must be in accordance with the Drainage Guidelines in the NSW ASS Manual.

There is strong justification for the construction of wide, shallow low slope drains at Big Swamp. These drains should be designed to provide a preferential flow path for tidal/freshwater overland flows to the remediation areas and prevent any measurable impact to landholders outside of these areas. It is important to note that any new drainage works for such landscapes should be undertaken carefully and must ensure that no further acid is produced or discharged as a result of their construction, operation or maintenance. As such, levelling of the drained area using small cuts from the surface (< 0.3 m) is an effective way of increasing the efficiency of surface drainage and preventing localised waterlogging (White et al., 1997). Further, as the proposed swale drains at Big Swamp will require culverts, the drains should not permanently contain ponded water and should be shallower than the invert of the floodgate or the PASS layer.

4. Land grading

The land should be graded to increase the drainage efficiency across the floodplain using a laser level or other precision excavation method. This land shaping is required to remove isolated depressions and achieve an adequate drainage slope, while minimising PASS disturbances. Some of the main benefits of improved surface drainage by land grading include reduced drainage density and length of drains for a given paddock and thus, reduced acid flux. Land grading also improves water quality across the site by efficiently shedding local rainfall, rather than allowing surface water infiltration into the soil and subsequent acidification (Tulau, 2007).

Note that works should be carried out in accordance with the NSW ASS Manual. In all cases involving earthworks, the management plan should be designed so that subsurface pyritic materials are not exposed during land forming.

5. Removal of livestock

A key component to the success of any effective management technique for the Big Swamp floodplain is to ensure that remediated areas are fenced off to livestock. The recovery of the land when cattle are removed can be dramatic in the short term due to the encouraged growth of native grasses and macrophytes. The recovery of grasses will assist in providing the organic material necessary to form anaerobic conditions and encourage acid reduction.

The key outcomes of the proposed works, if they are undertaken on-site, will include:

1. During dry periods, tidal buffering will neutralise existing acid stores, limit acid formation and prevent acid reservoirs;
2. High drain invert levels will reduce groundwater drawdown;
3. With less acid in the system, acid export should be reduced during wet events. It is important to note that acid discharges will not be entirely eliminated due to the bank of acid stored in the soil matrix;
4. Ensuring cattle are clear of the land, will encourage the regeneration of native grasses and macrophytes; and
5. With time, organic matter will accumulate and decay, encouraging anaerobic (i.e. reducing) conditions and the dissociation of acidic soil by-products.

7.2 Future Monitoring

Every ASS remediation project should include a monitoring program designed to provide feedback on the effectiveness of the management strategy. The monitoring should provide an early warning of any environmental degradation and be adaptable to evaluate and modify the management of the project as necessary (Tulau, 2007 uncited in Ahern et. al., 1998a).

Quantifying soil and water quality changes and relating these to on-ground works requires systematic monitoring pre- and post-work. Monitoring must commence prior to works or changes to groundwater, drain and/or land management implementation to compile a statistical baseline of existing conditions. While an extensive field survey and monitoring program was undertaken for this project, due to the climate variability (wet/dry) and the hydraulic properties of the soils, the limited length of the monitoring period can only be considered indicative. A definitive understanding of the relationships between water quality and hydrology is difficult to achieve over short periods and further monitoring pre-works is required.

At a minimum, the following monitoring is recommended based on the ASS Remediation Guidelines for Coastal Floodplains in NSW (Tulau, 2007):

1. At least three (3) water quality monitoring stations measuring a suite of chemical parameters may include pH, DO, EC, temperature and water levels;
2. At least three (3) discharge monitoring stations including a permanent flow meter installed at the bottom of Pipeclay Canal to measure total site discharge flux; with
3. At least four (4) groundwater piezometers with detailed soil reports at the piezometer location, including K_{sat} and groundwater pH, EC and water level measurements;
4. Supplementary monthly spot water quality sampling; and
5. A photographic archive from fixed photo points.

To achieve optimal outcomes from the monitoring program, short-term deployable multi-parameter devices are recommended, in addition to monthly spot measurements, for their value in:

(i) providing a complete data set over a range of climatic (i.e. drought/flood) and environmental conditions (i.e. spring/neap tidal cycles);
(ii) allowing for continuous monitoring of range of critical parameters within a single unit/station;
(iii) allowing for comparison between key locations within one remediation site and between another; and
(iv) providing coordinated measurements spot measurements.

Prior to finalising a targeted monitoring program for Big Swamp, stakeholder discussions on setting clear objectives and outcomes for the program including design, security, maintenance, analysis and reporting should be undertaken.

7.2.1 Water Quality Monitoring

Water levels and water quality are two fundamental monitoring requirements. The water quality monitoring should provide a better understanding of the relationships between the drain and surface water levels, chemistry and relate these to groundwater levels, dynamics and chemistry.

Monitoring sites should be located upstream of the site, within the site and immediately downstream of a remediation discharge point. The downstream point is the most critical, as it provides the best measure of overall performance of the remediation project. Control and reference sites are also encouraged, where feasible.

Short-term deployable water quality measurement devices (recording at 15-minute intervals) are recommended for this monitoring. Multi-parameter water quality sondes capable of measuring pH, temperature, conductivity (EC), turbidity and dissolved oxygen (DO), in addition to several water level sondes, should be deployed across the site and downstream of the remediated areas. Similar equipment was temporarily installed during the wet and dry field investigations for this project.

7.2.2 Discharge Monitoring

Flow data is fundamental to the calculation of acid discharge. Installation of discharge monitoring stations including a permanent flow meter recording at 15-minute intervals is recommended. Acid discharge patterns from ASS are highly variable due to temporal variations in rainfall, tidal flows, interactions between soil chemical properties and vegetation, and biologically mediated iron redox reactions (Tulau, 2007). Given this complexity, the data requirements to accurately estimate acid discharge from backswamps are considerable. An alternative approach is to model the two components of acid discharge: acid discharge via groundwater seepage to drains and acid discharge in surface run-off (Tulau, 2007).

7.2.3 Supplementary Data

Groundwater seepage into drains is the most significant pathway for acid discharge from ASS soil landscapes (Johnston et. al., 2004). The manipulation of groundwater levels is often a key objective of ASS remediation projects, so the monitoring of groundwater dynamics is of crucial importance. Groundwater chemistry can respond quickly to changes produced by watertable manipulation and the hydrological and chemical components of groundwater monitoring should be closely linked (Tulau, 2007).

For groundwater monitoring, at least four (4) groundwater piezometers with sondes equipped to monitor groundwater levels, pH and EC, preferably at least hourly are recommended. The Groundwater Guidelines in the ASS Manual should be consulted for the most effective installation and monitoring of groundwater piezometers. Detailed soil reports at the piezometer locations including K_{sat} and groundwater pH measurements would also be required.

WRL also recommends complementing continuous insitu monitoring of water with spot sampling at several locations to provide a greater understanding of the dynamics and processes of acid discharge. Areas with ponded surface waters will also need to be monitored. Based on the findings presented in this report and the field snapshots undertaken, WRL recommends supplementary spot water quality sampling to be carried out monthly during low flow periods. Sampling would be increased to daily during wet events. The sampling sites would be located according to the remediation works being undertaken. Laboratory analysis on various water quality samples would be required throughout the monitoring program for a more detailed analysis (if required).

The installation of digital cameras in the remediation areas is recommended to enhance the monitoring program, observe the long-term evolution of the site following remediation and allow for offsite management (Figure 7.1). The camera should be installed in a fixed position and should be set to take several images per day. A system should be developed to transfer the images via the 3G/4G network for viewing and archiving.

The images could be used for several purposes, these include:

- Assessing the coverage of tidal water with time;
- Determining the hydro-period and related plant species;
- Assessing the type and quantity of birds onsite throughout the day;

- Determining the impact of large rainfall events on the site and drainage patterns;
- Reducing vandalism onsite;
- Calculating the evolution of vegetation; and
- Determining if cattle or exotic species are gaining access to the site.

Additional images can be taken as required throughout the day. Onsite field measurements of discharge and water level may be used in conjunction with the camera to determine the flux of key surface water quality constituents.

7.3 Multi-Stage Restoration Approach

A Big Swamp Management Plan is recommended for Big Swamp floodplain describing how the proposed on-ground works are to be carried out. The Big Swamp Management Plan should outline the phases of restoration and when they should occur. Ongoing management through on-site monitoring (as described in Section 7.2) and maintenance should be included. The Big Swamp Management Plan should also include discussions on climate change and potential future changes to the management of the Manning River estuary entrances, as well as the possible implications on the future management of the Big Swamp floodplain.

7.3.1 Long-Term Management Strategy

Due to the social and economic costs it is not possible, in the immediate future, to return Big Swamp floodplain to a pristine condition. The challenge in the immediate future is to encourage the implementation of better drain management techniques, by existing landholders, in an attempt to reduce acidic outflows until further acquisition is possible. The Restoration Management Plan for the floodplain should include a long-term strategy to initiate future land purchases for the remainder of the site, as the full restoration of the Big Swamp floodplain is strongly recommended. In the absence of any other on-ground engineering works that are already suggested, future remediation recommendations should include:

1. Reducing the overall drainage density of the floodplain;
2. Removal of all floodgates and flow control structures;
3. Tidal buffering in areas with elevations less than 0.4 m AHD;
4. Infilling (or weir installations) of deep drains including all primary drains to above the PASS layer;
5. Encouraging regeneration of native vegetation to provide organic material buffering in the form of a thick retardant layer on the ground and drain bed surface; and
6. Encouraging semi-containment management strategies (such as weirs) where there is no other way to raise the invert level of a critical acid generating primary drain.

8. Conclusion

The Water Research Laboratory of the School of Civil and Environmental Engineering at The University of New South Wales was commissioned by Greater Taree City Council to undertake a hydrologic assessment of Pipeclay Canal, the adjoining Big Swamp floodplain and adjacent areas. This study provides an understanding of the local hydrology and determines how on-ground remediation works would potentially alter the existing hydrology. The remedial works are required to combat acid sulfate soils and poor water quality. For this study, the term hydrology is used in a broad sense to include upland, onsite and downstream surface water and groundwater quantity and quality.

This project was undertaken in a staged manner. Initially, hydrology literature was collated and reviewed. Available data was used in conjunction with targeted field investigations to develop historical and existing conceptual models of the site hydrology (Section 2). This research highlighted that the entire Big Swamp floodplain is strongly acidic and that rainfall/flooding events can transport acid waters from Pipeclay Canal into Cattai Creek and downstream waters.

An evidence based assessment method was then applied to determine which sub-catchments of the floodplain should be prioritised for remediation (Section 3). This was undertaken as insufficient funds and landholder support was available to remediate the entire site and thus, only the highest priority areas available could be immediately remediated. The assessment method included various factors such as groundwater acidity, surface water transport, sub-catchment size and potential restoration methods. Sub-catchment zones in the south-western and south-eastern areas of the Big Swamp floodplain were rated the highest priority areas. Private properties located within these zones were acquired during this study or are currently going through the acquisition process.

A series of on-ground remediation works were recommended for the nominated properties (Section 7). These works are focused on reducing acid production, limiting acid transport, neutralising and diluting acidic waters, and removing hydraulic structures, where feasible. As only a portion of the site will be remediated, the works were also designed to not impact other properties.

A computer model of the Big Swamp Floodplain, Pipeclay Canal and Cattai Creek system was developed and validated for this study. The model was designed to quantify the hydrology and hydrodynamics of the entire floodplain and test specific proposed remediation strategies (Section 5). The modelling results indicated that removing all tidal floodgates along Pipeclay Canal would impact a limited area of the Big Swamp floodplain and inundation would be largely focused in the south-western paddocks. As this is a prioritised zone, further scenario modelling was undertaken to test on-ground remedial works and ensure that the paddocks to the north remain in their current state. Scenario testing of remedial works was also undertaken for the prioritised south-eastern areas.

The computer modelling results have direct implications for land management and remediation strategies (Section 4). The results indicate that the proposed on-ground works should achieve the stated aims by reducing acid generation and transport in the south-western properties. This would be achieved through a combination of tidal inundation, retaining shallow surface waters onsite, encouraging organic matter decomposition, removing/altering existing drains and floodgates, and hydrologically isolating the restored areas from the arable land to the north. Conversely, limited on-ground works are proposed for the south-eastern properties, as several landholders remain upstream of the acquired properties and still require the drainage network for flood mitigation purposes. In this area, the primary recommendation is to remove internal levee bunds along the tidal drains and encourage rewetting and overtopping during small floods.

Ultimately, undertaking the proposed on-ground works is an effective approach to manage acid production and export at the site. In the short-term to medium-term, re-flooding, tidal buffering and drain infilling (or using weirs) to raise drain invert levels will limit acid formation, reservoirs and export. However, it is important to note that these strategies will not entirely ameliorate the acid problem due to the significant amount of acid stored in the soil profile. Ongoing management and monitoring, ensuring cattle are clear of the land and regeneration of a dynamic seasonal saltwater/freshwater wetland vegetation complex, will continue to foster the reduction of acid on the floodplain by encouraging the formation of anaerobic conditions. The combination of these strategies in the short and medium term will ensure a better long-term result of improving water quality discharges spanning both dry and wet seasons.

The report provides a summary of important findings (Section 6) and recommendations for the future (Section 7). Important recommendations include detailed on-ground works, onsite monitoring, a staged works program and a high priority for future land purchases as part of a long-term management plan to remediate the entire Big Swamp floodplain. The onsite monitoring highlights the need for continuous monitoring to ensure that the acid discharge events following rainfall/floods are measured. Photo points and/or remote cameras are also recommended to track the onsite changes with time.

A large volume of information relevant to the study was included as appendices to the report. This information includes additional literature, field monitoring data and numerical modelling details. It is also worth noting that research examining the fate and transport of acid and related heavy metals discharged from Pipeclay Canal during the February 2013 wet event is on-going and will assist in further understanding the catchment hydrology.

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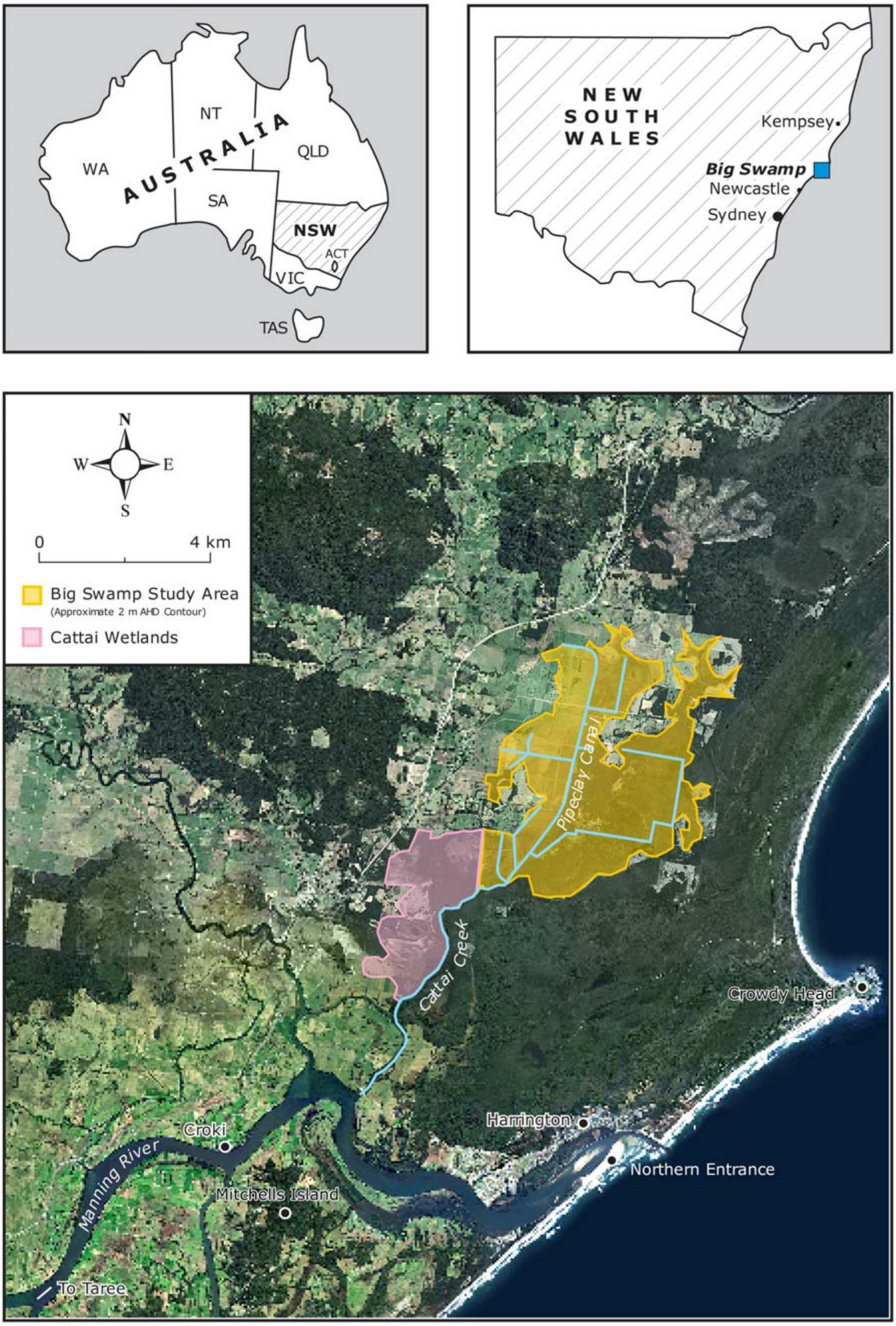
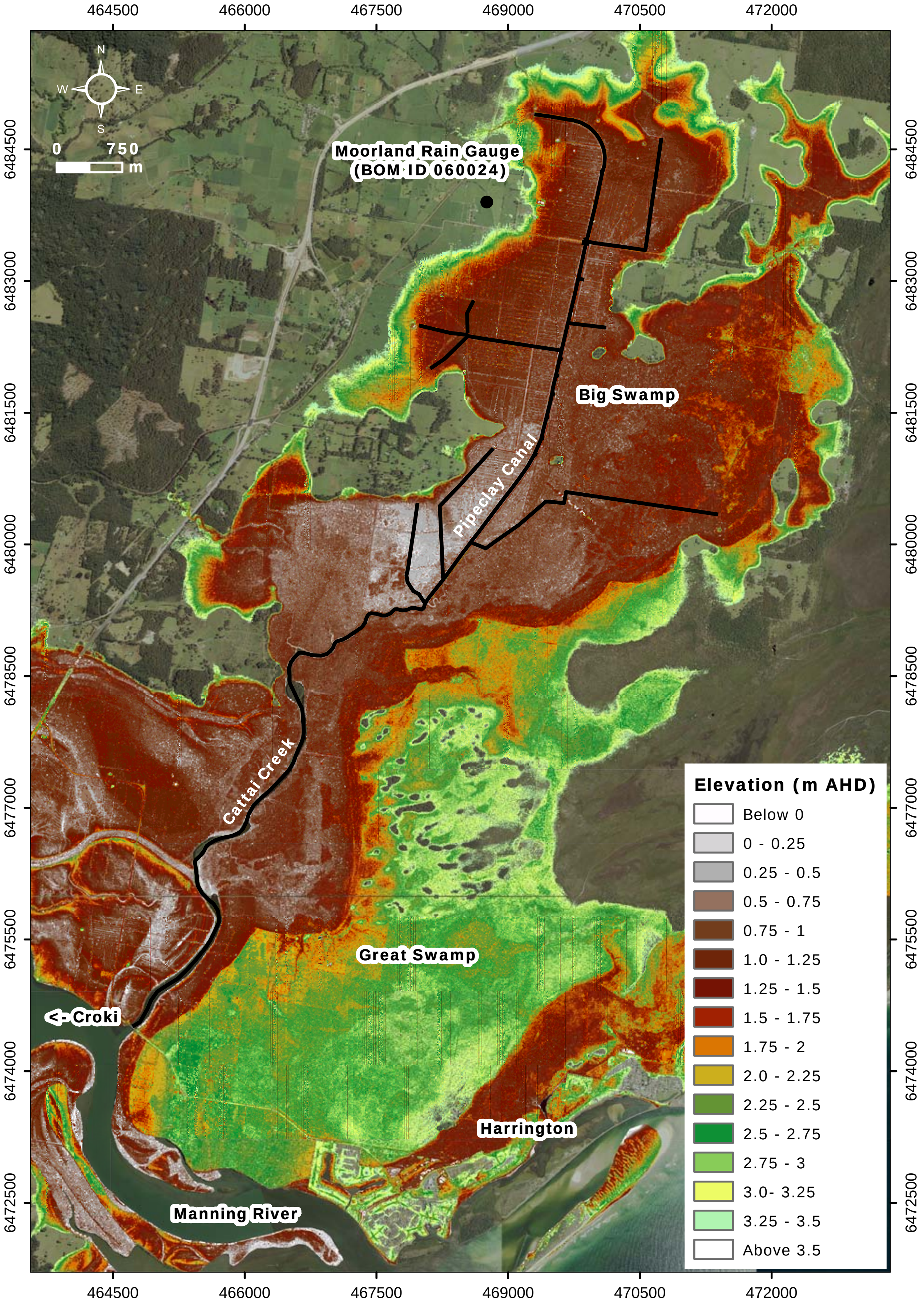
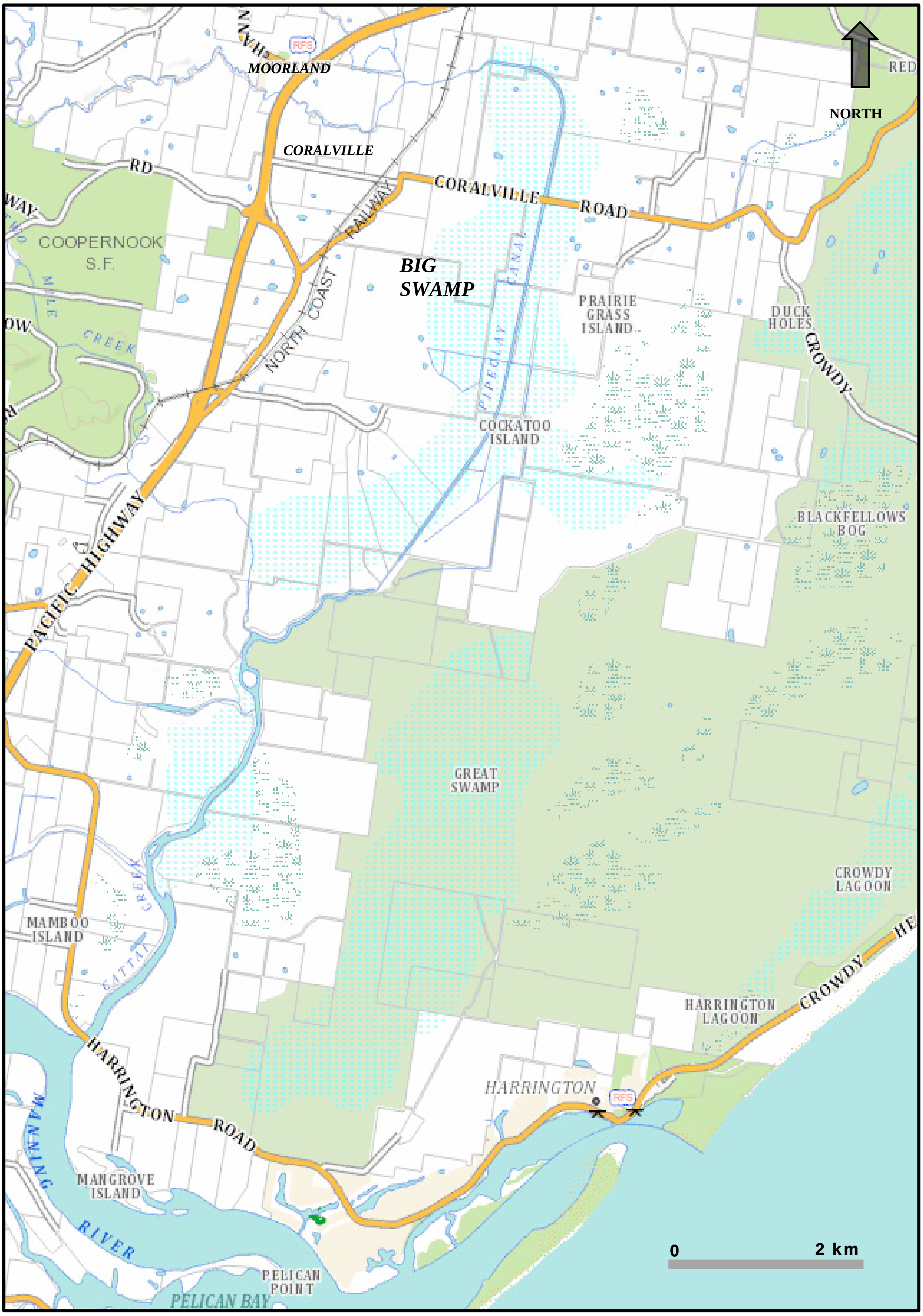


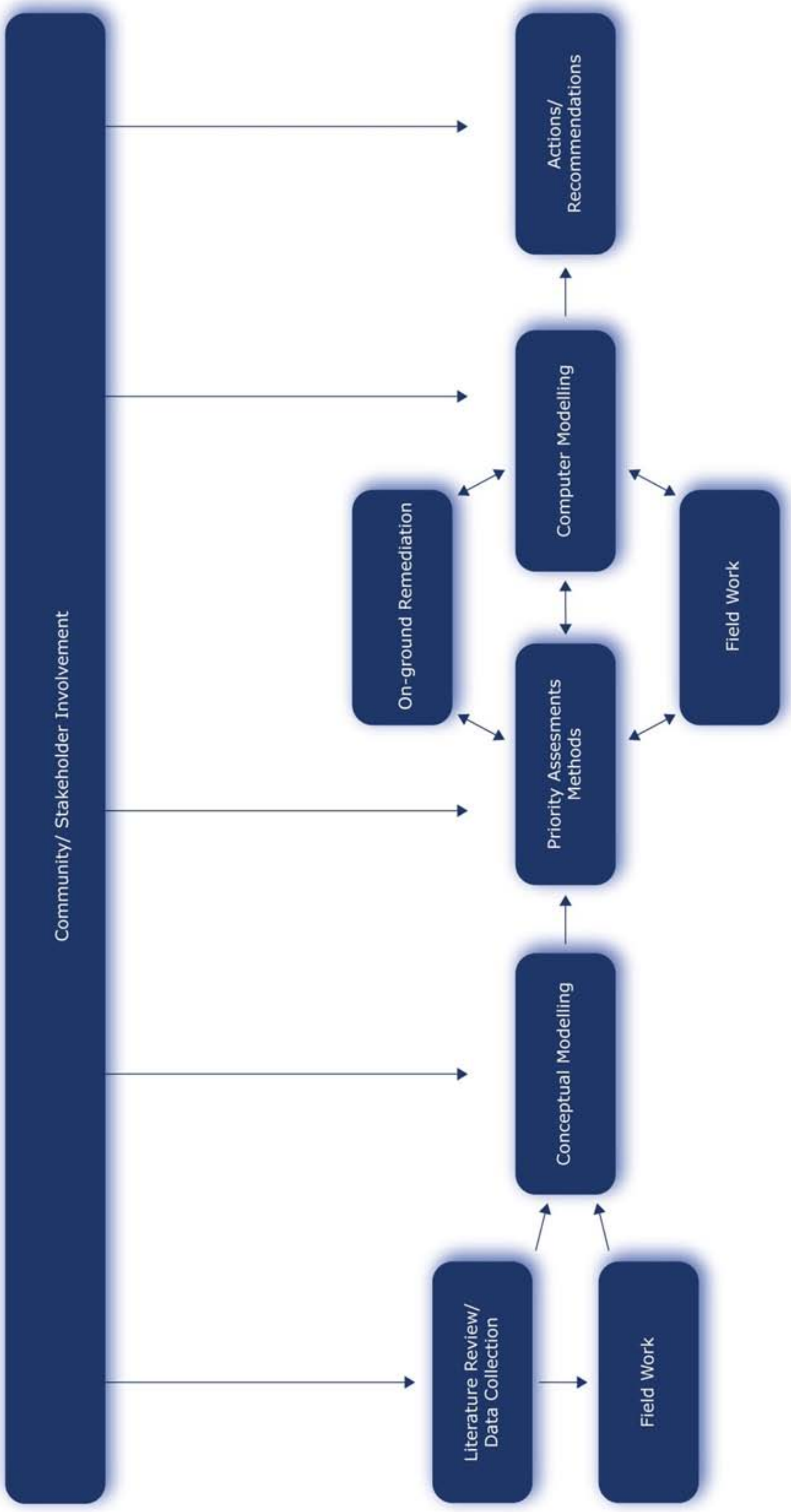
Pipeclay Canal and Big Swamp Floodplain Study Domain



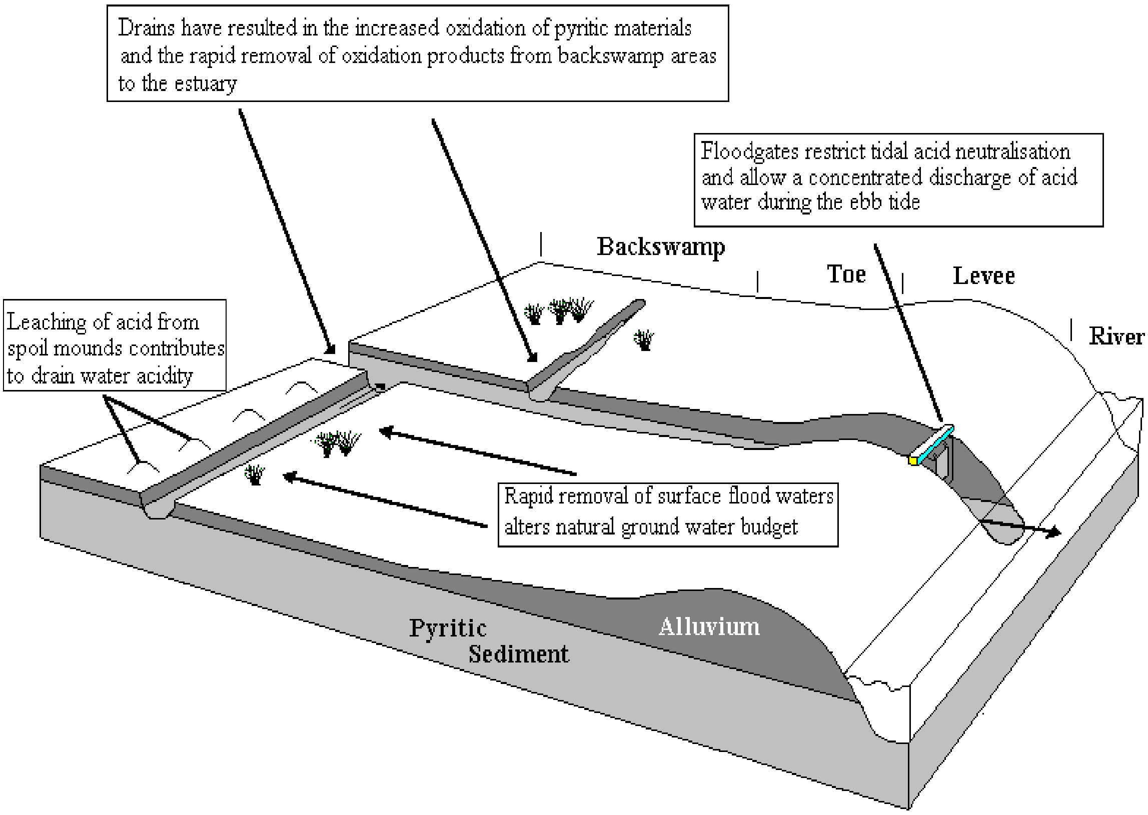
Topography for the Big Swamp Floodplain Study Domain.



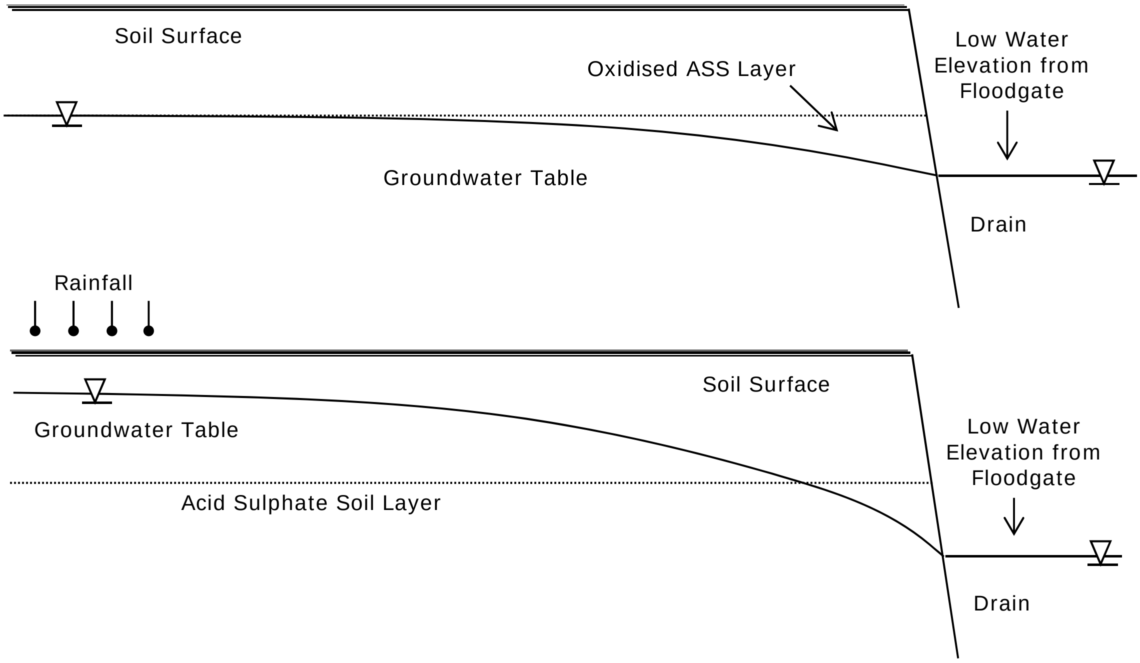
Location and Place Names



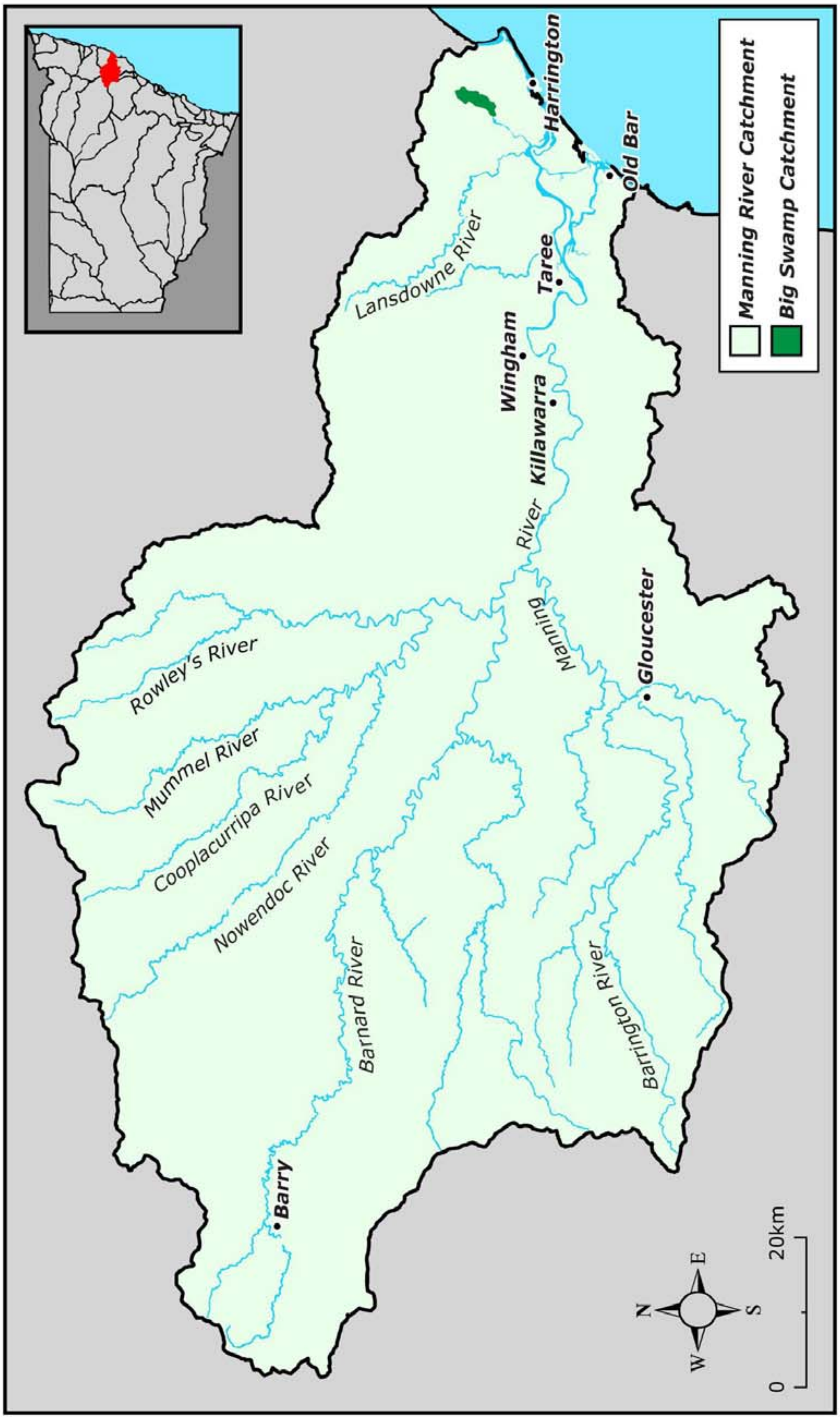
Conceptual Model of the Project Emphasising the Interlinkages Between Model Development and Prioritisation Actions



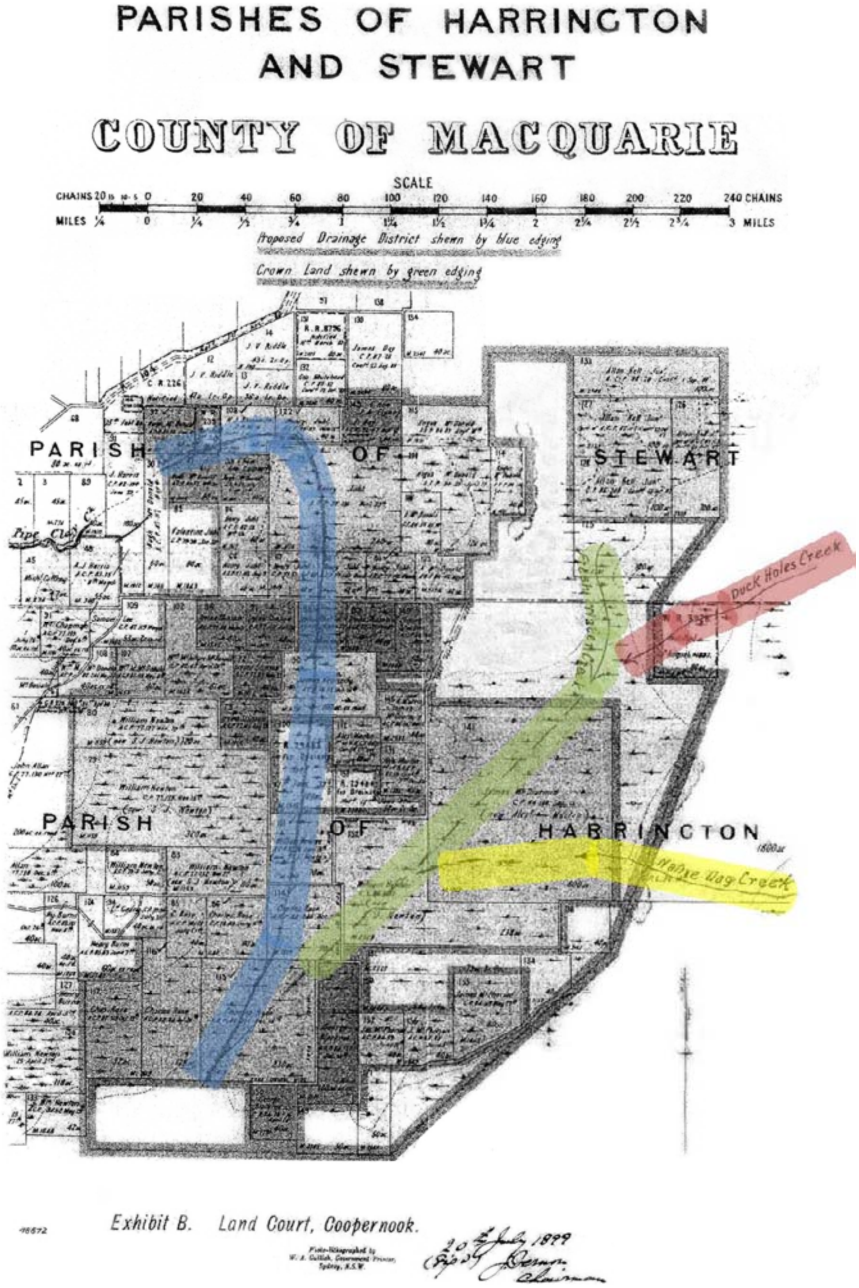
Schematic of a typical drained coastal floodplain showing levee banks and backswamps with one-way floodgates, straightened and cleared drainage canals and excavated side drains (Naylor et al., 1993; Tulau, 1998)



Influence of One-Way Floodgates on Groundwater Elevation Under Normal (Top) and Flood (Bottom) Conditions (Adapted from Glamore, 2003)



Comparison of Manning River Catchment and Big Swamp Catchment



Historical Map of the County of Macquarie from 1899 with Pipeclay Canal and Original Flow Paths Noted (PWD, 1901)

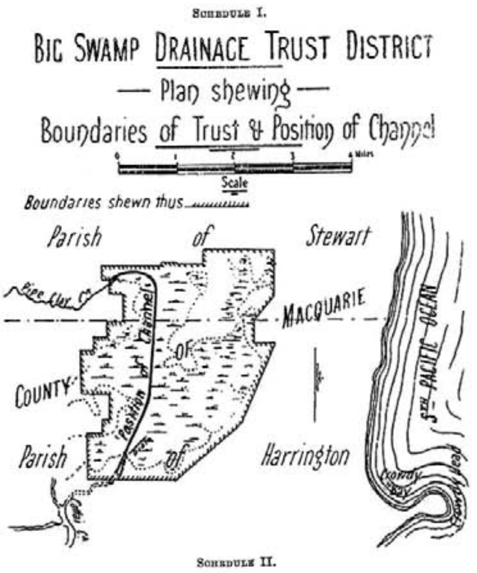


Fig 1.

Fig 2.

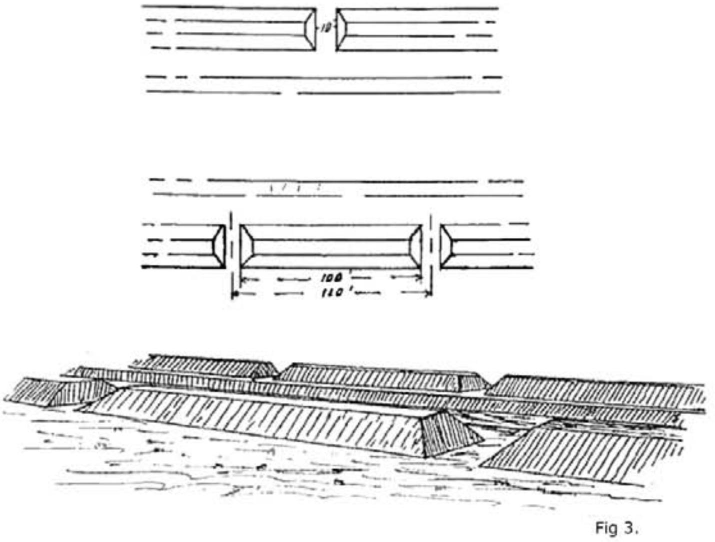
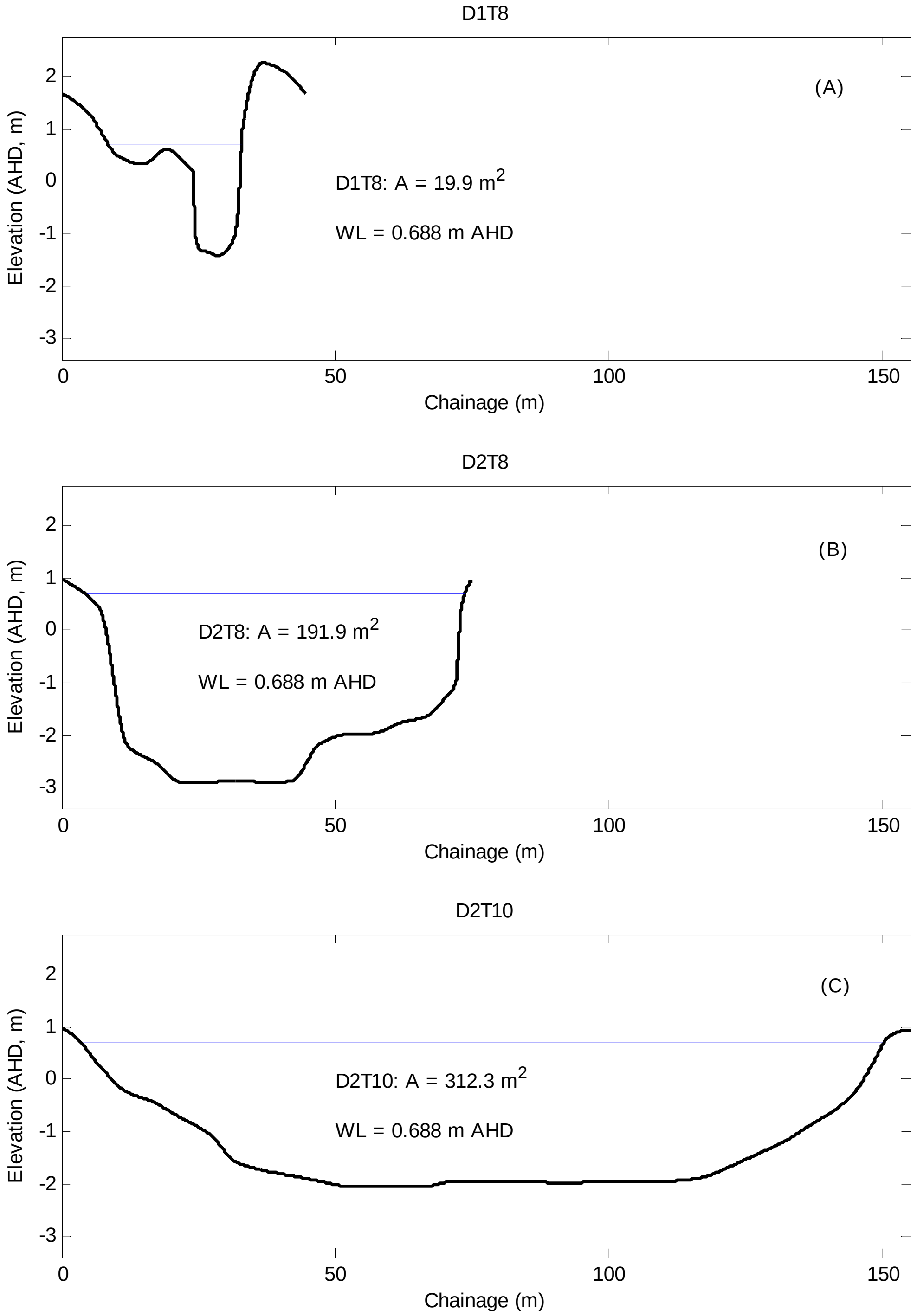
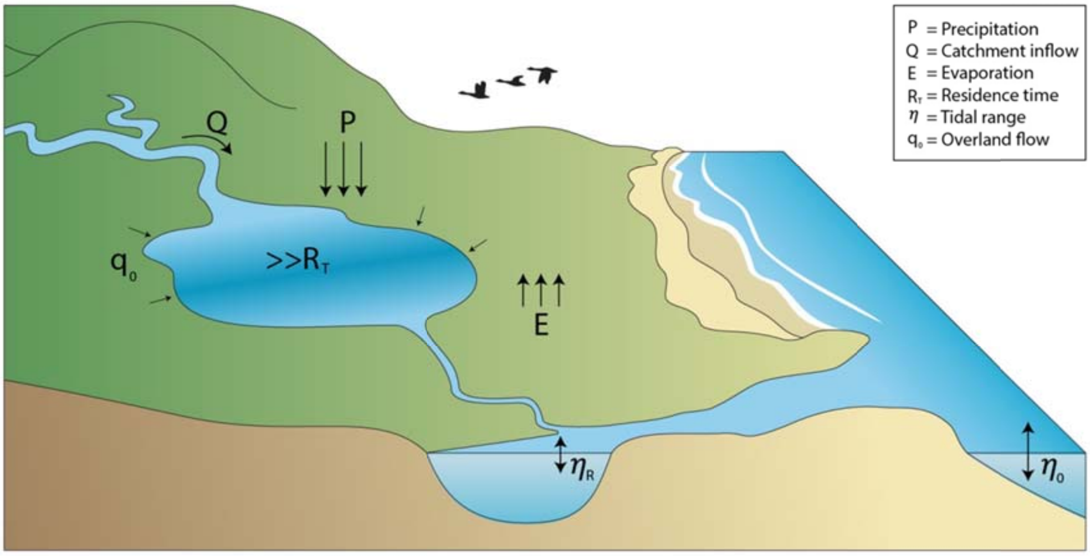


Fig 3.

Historical Figures of the Proposed Big Swamp Drainage Scheme Including (Fig 1.) Design of a Large Central Drain with Continuous Levees on Both Sides (Fig 2.) and Proposed Modifications to the Original Levee Design to Improve Site Drainage and Connectivity (Fig 3.) (PWD, 1901)

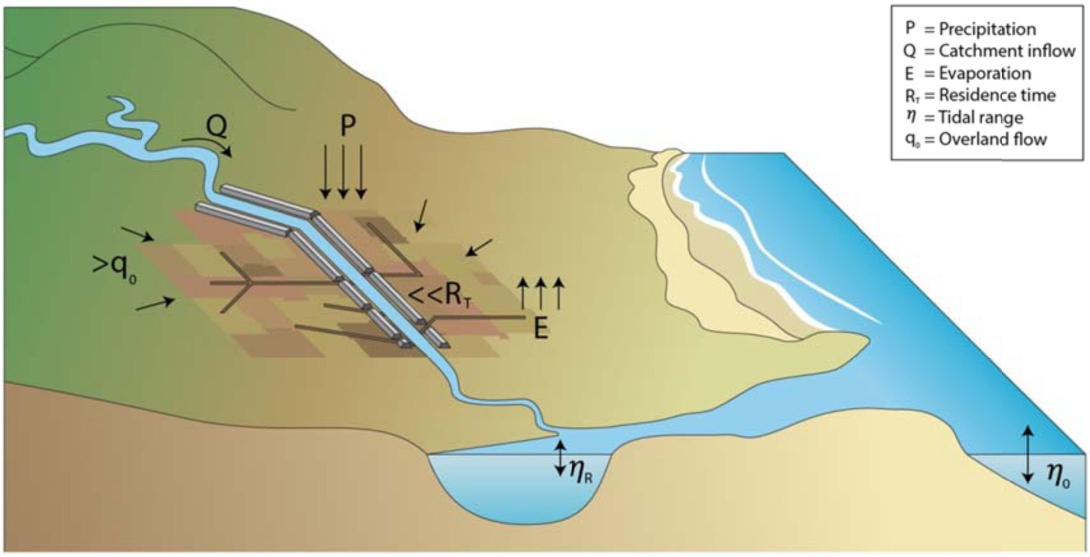


Representative Surveyed Cross Sections:
Pipeclay Canal (A), Top of Cattai Creek (B) and Entrance to Cattai Creek (C)



Historical Site

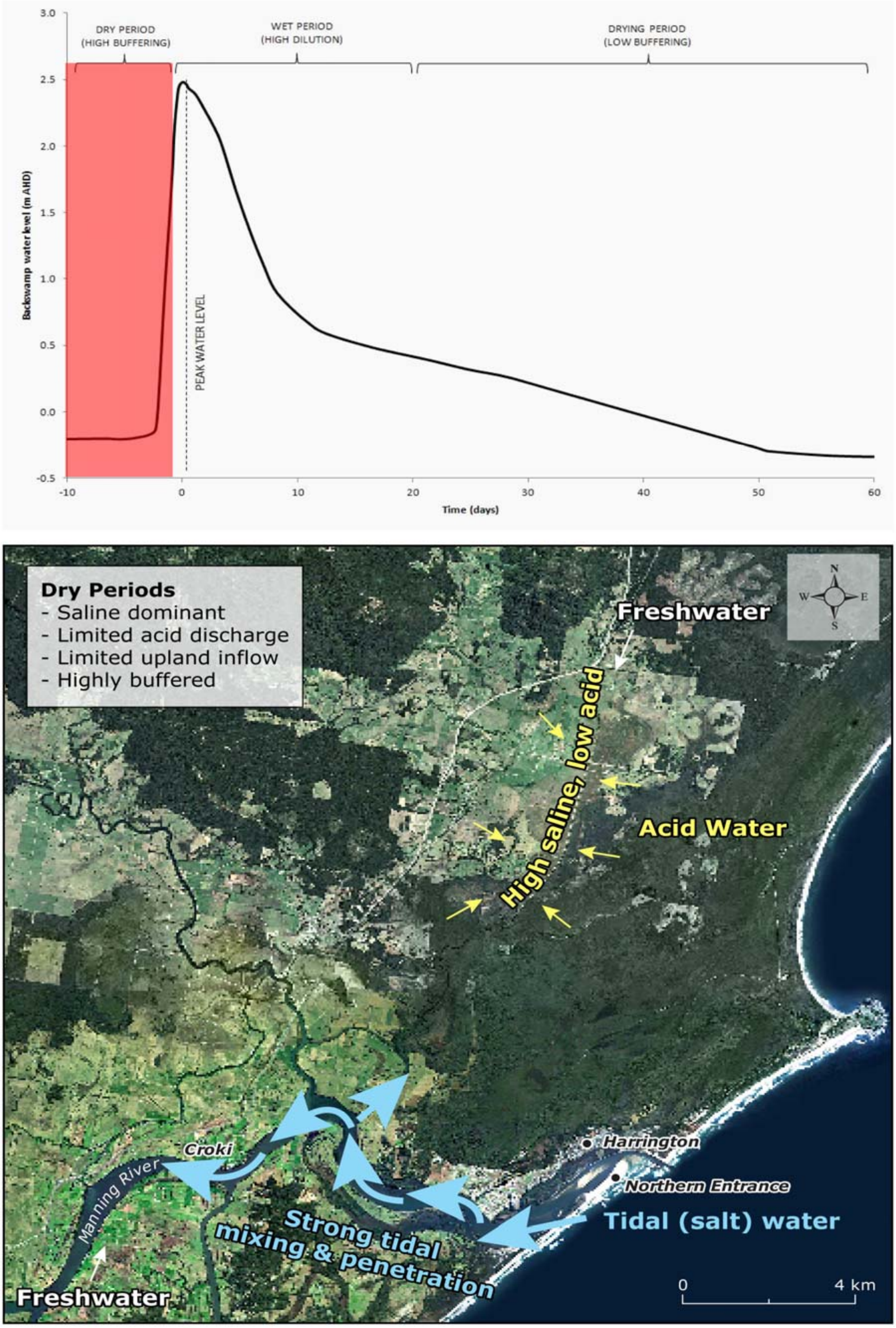
- Natural water balance, drainage paths and surface water-ground water interactions
- High residence time (R_T) with natural organic decomposition of floodplan sediments
- Natural geomorphological change with estuary evolution



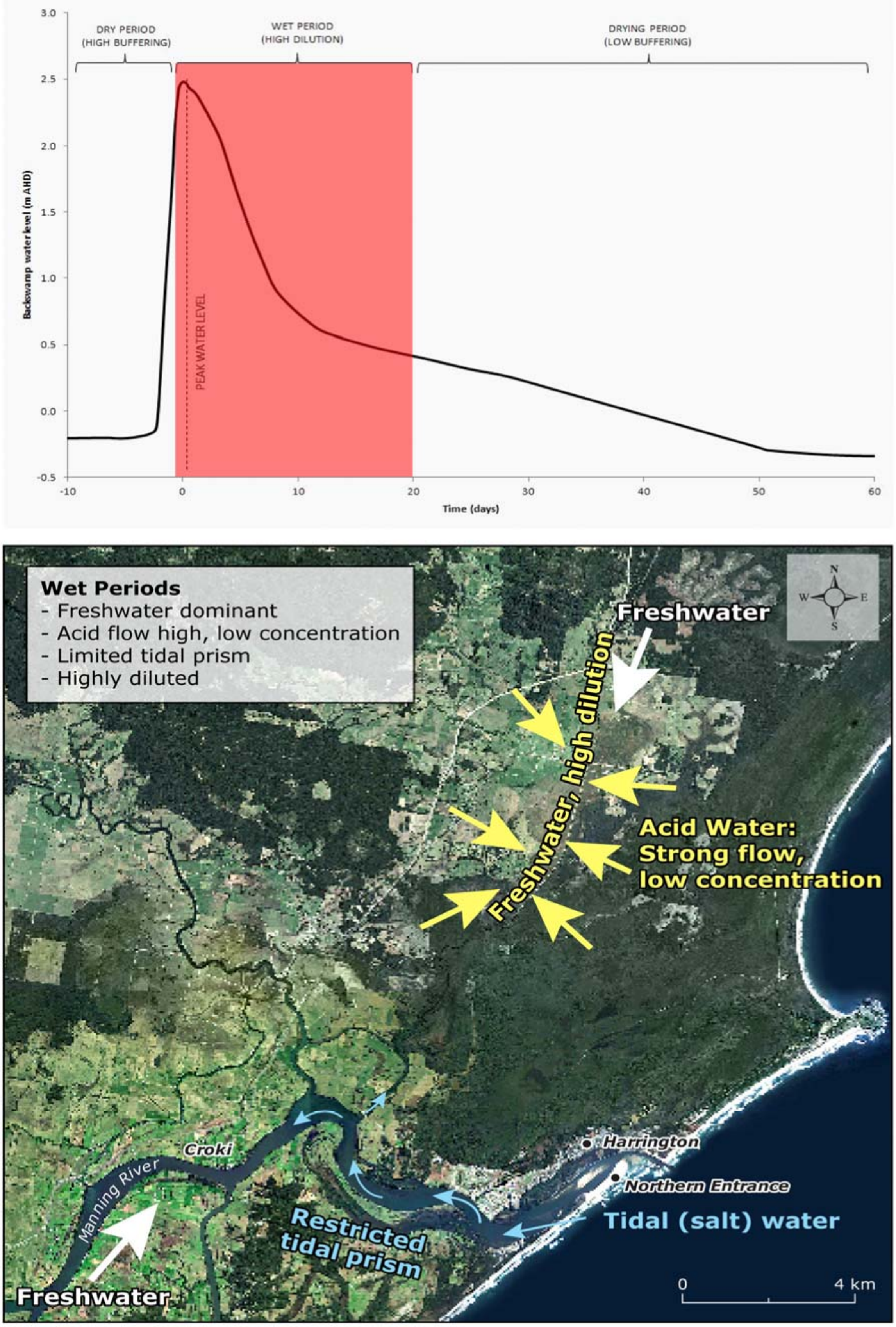
Post 1905 (Pipeclay)

- Rapid removal of surface flood waters altered natural groundwater budget and site hydrology
- Drainage increased oxidation of pyritic material with rapid export from backswamp to estuary
- Flow control structures restrict tidal acid neutralisation and allow a concentrated discharge of acid water during ebb tide

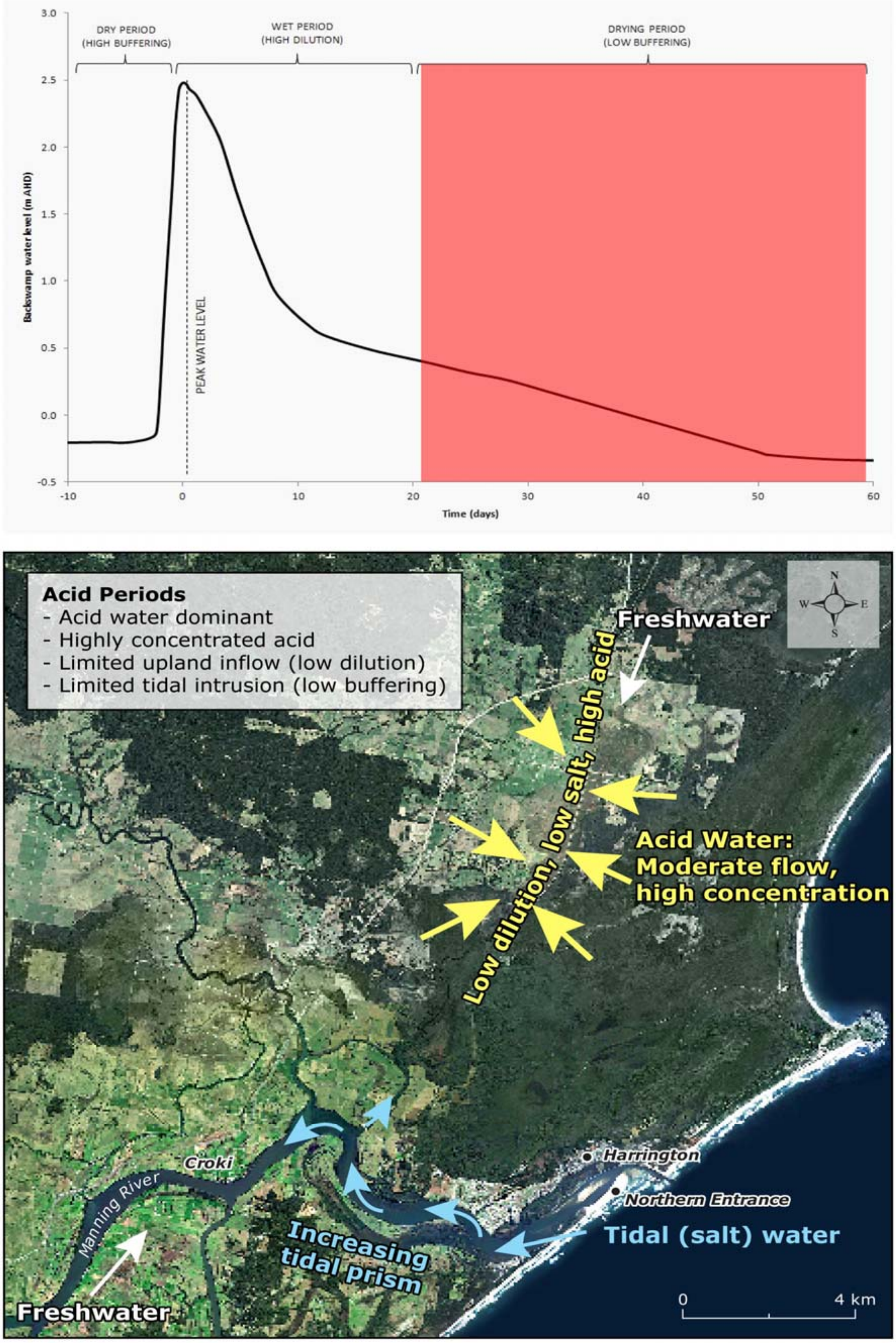
Conceptual Model of Site



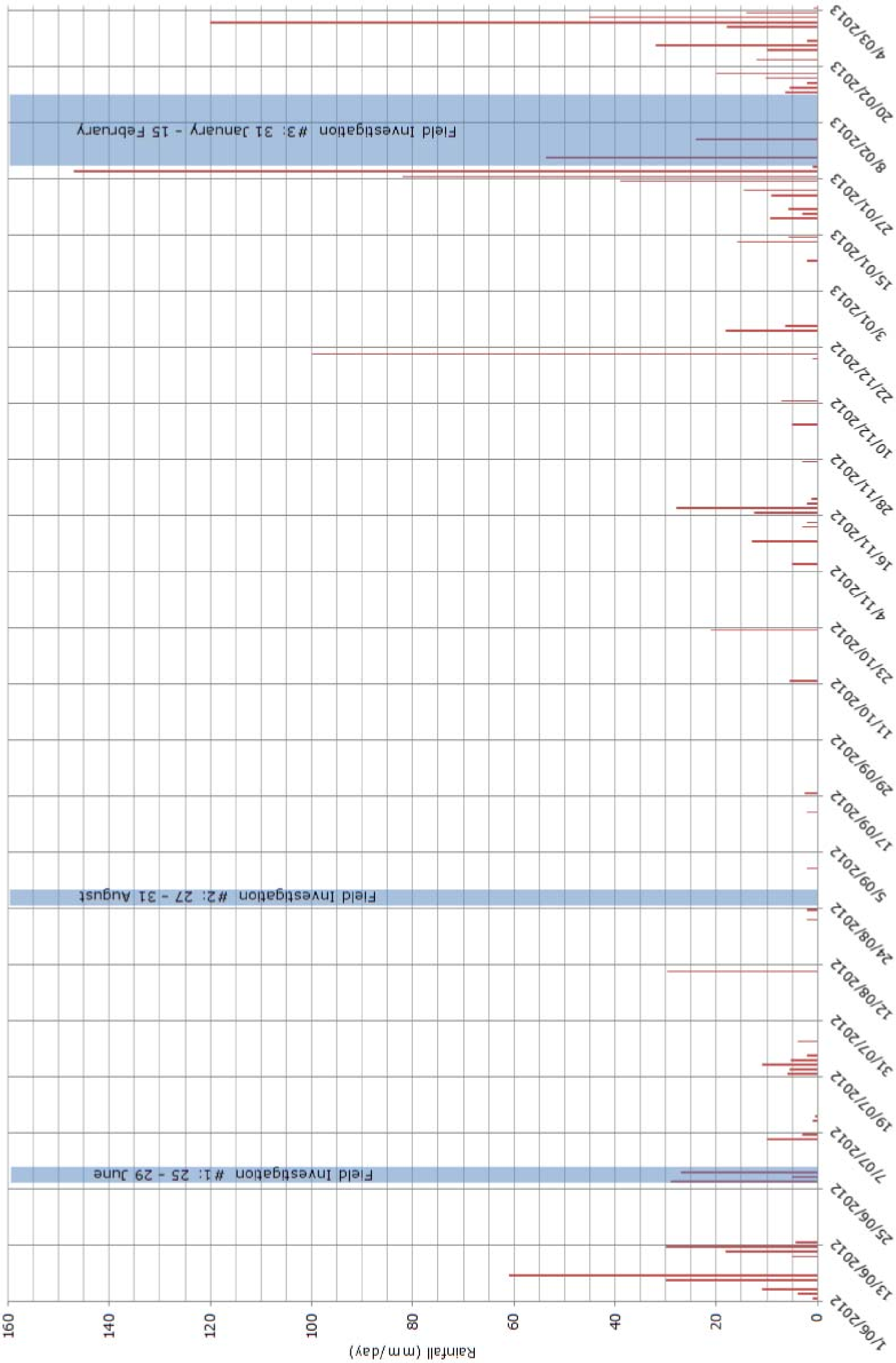
Dry Hydrograph Periods Characterised by High Acid Buffering



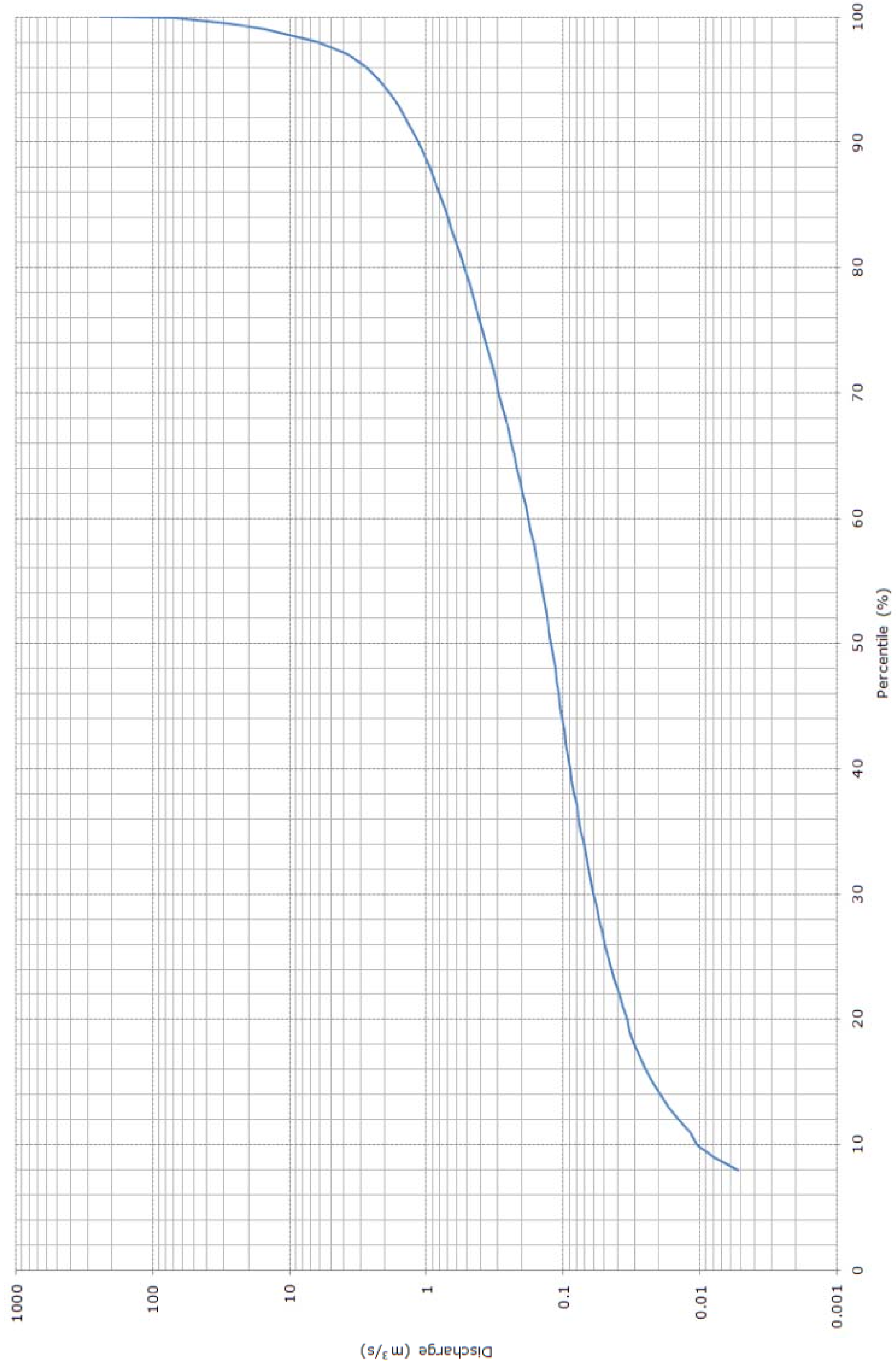
Wet Hydrograph Periods Characterised by High Acid Dilution



Draining Hydrograph Periods Characterised by High Acidity

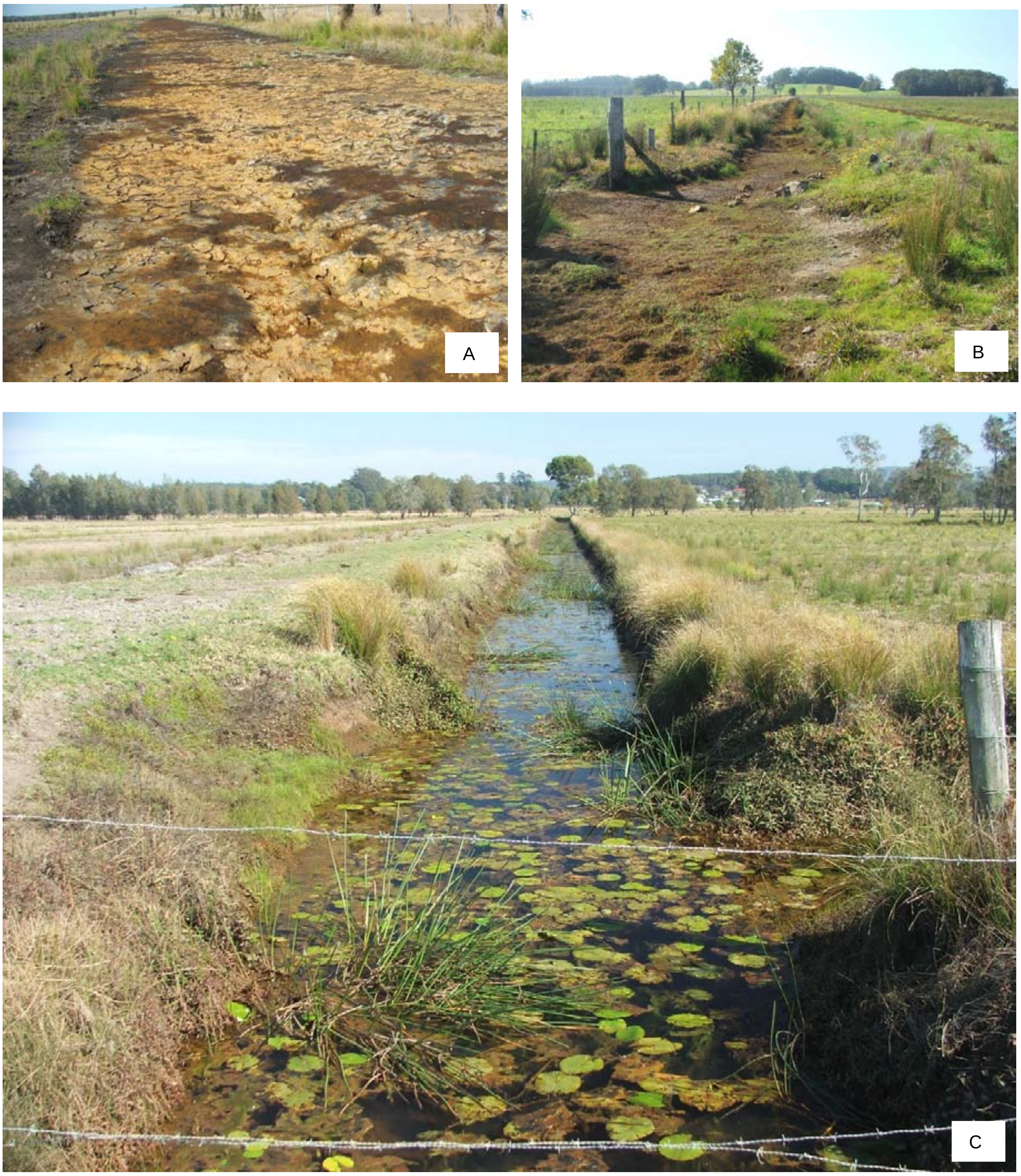


Summary of Field Investigation Periods and Rainfall as Recorded at Moorland

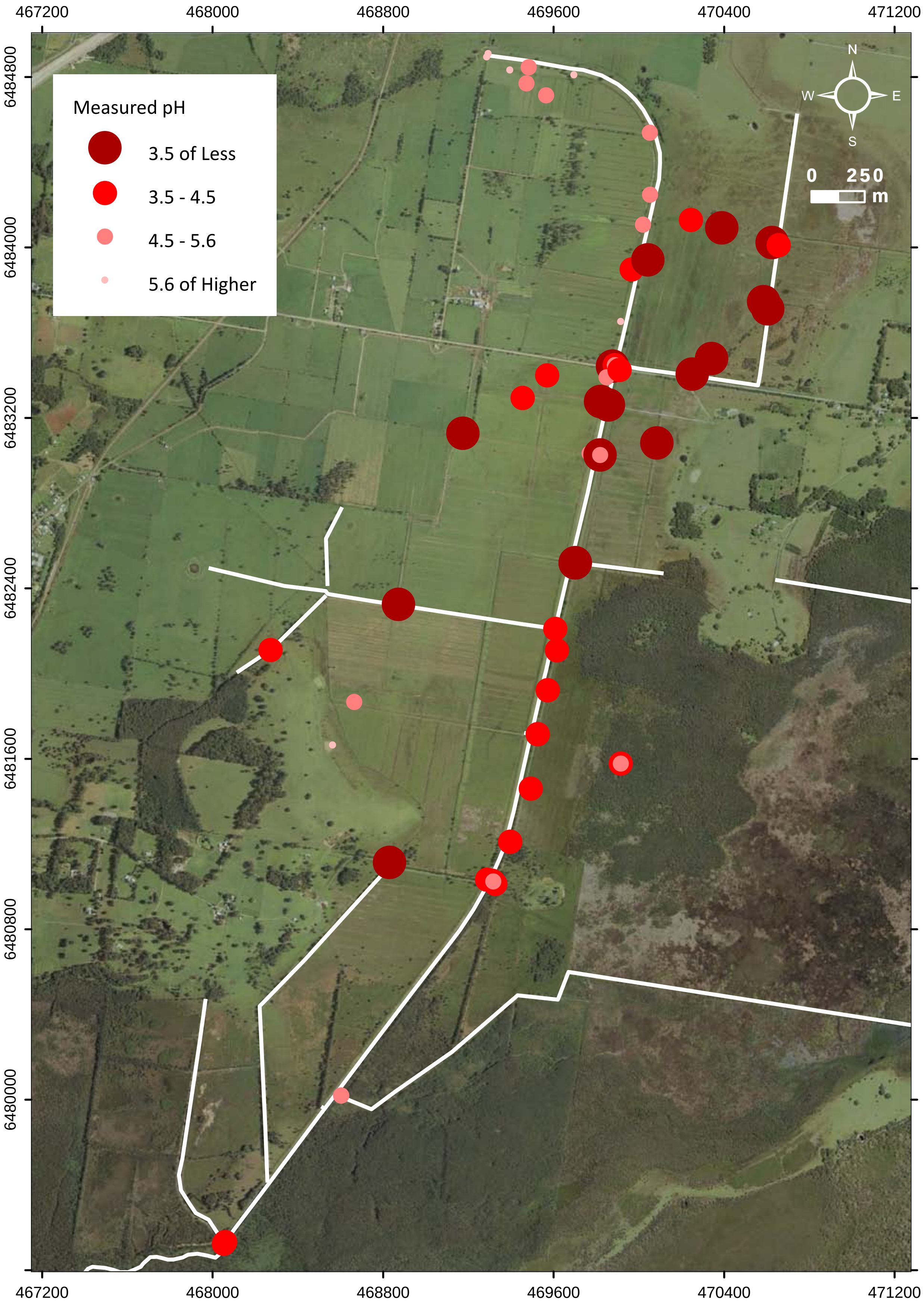


Simulated Flow Duration Curve using Moorland Rainfall (1912 - 2012)

Dry Paddocks West of Pipeclay Canal (A) vs. Boggy Paddocks East of Pipeclay Canal (B)

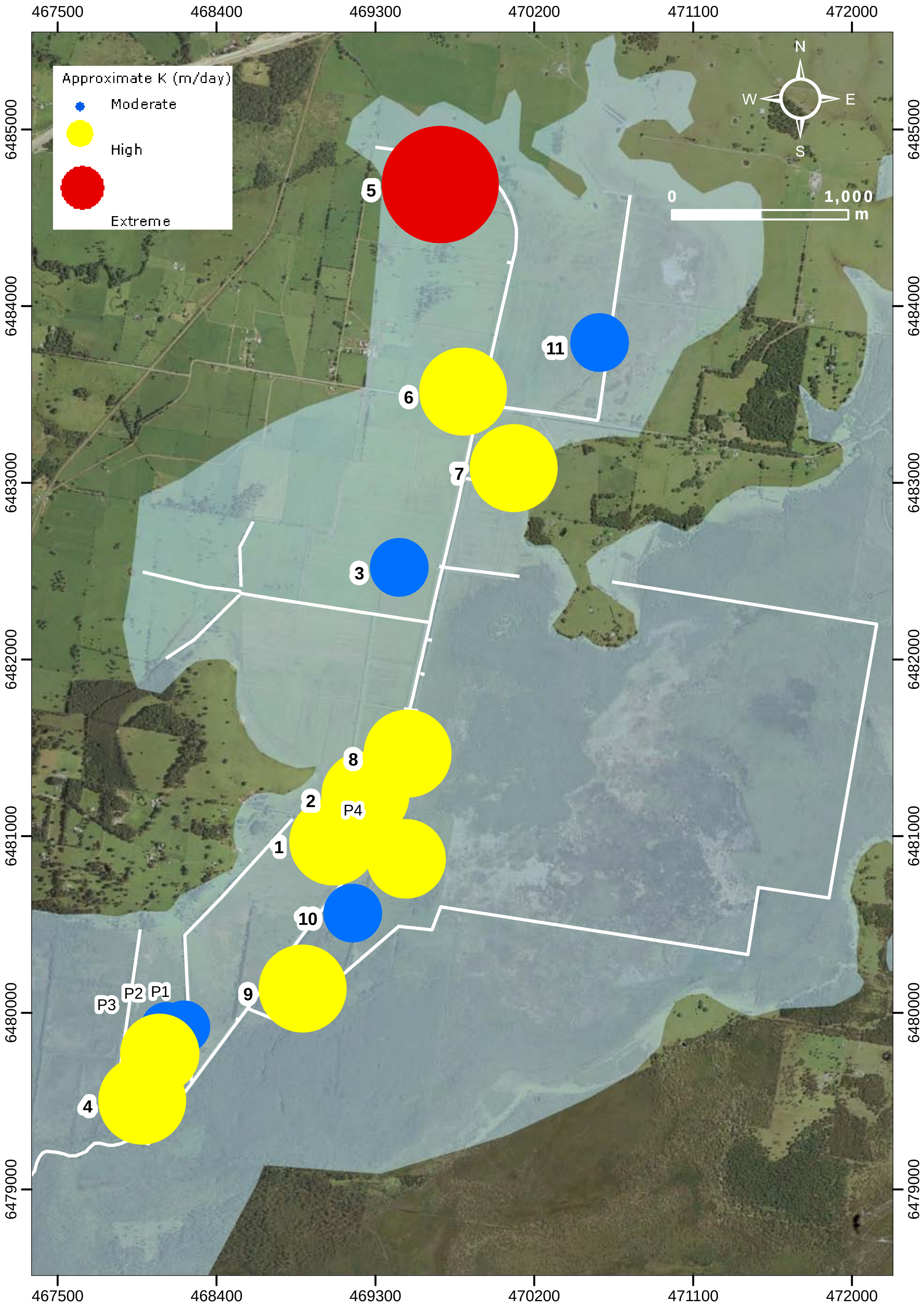


Dry shallow Field Drains Observed to Have Extensive Ferric Iron Staining (A,B) and Weed Infestation (C)

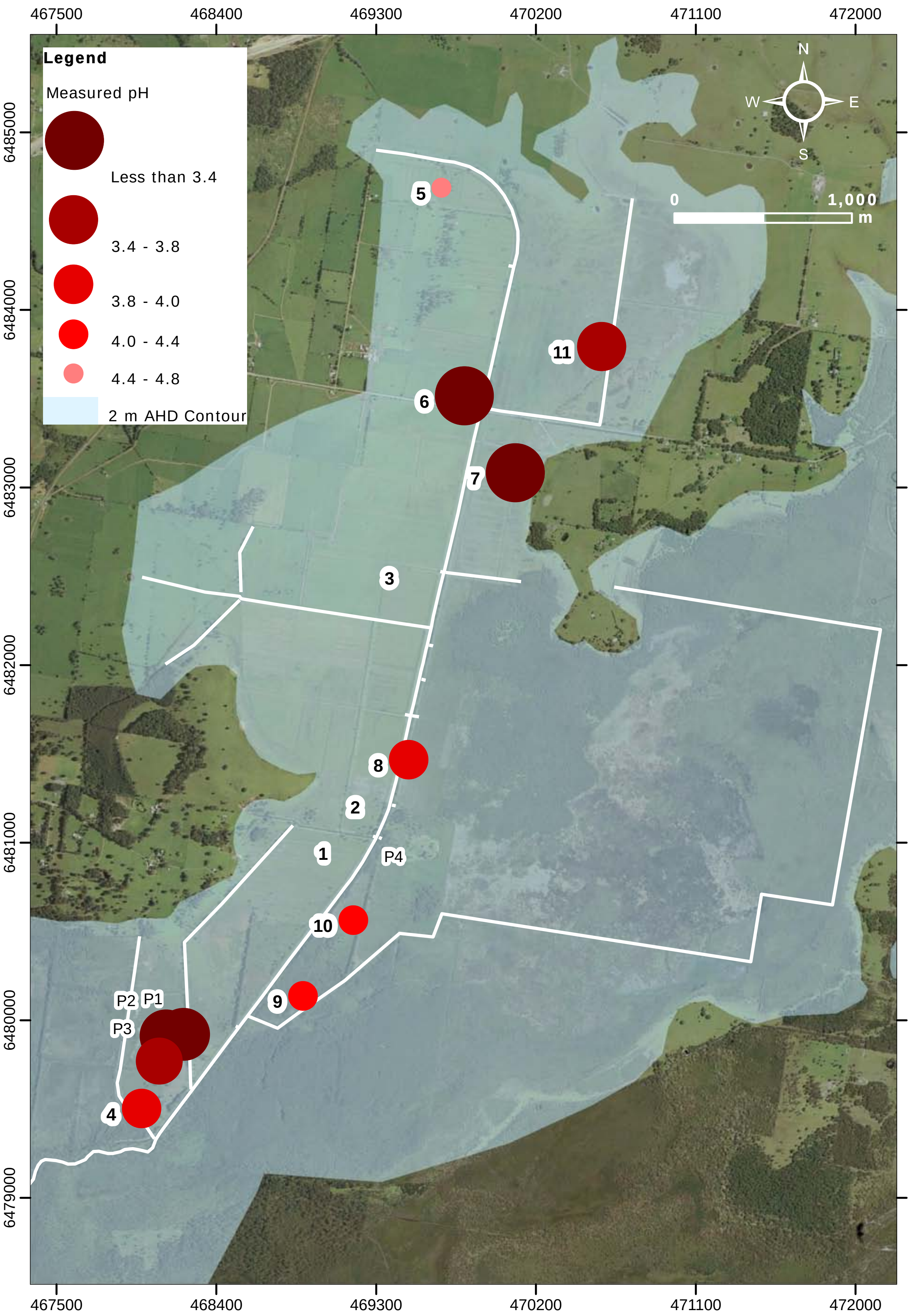


Location of pH Measurements Taken During the 'Dry Snapshot' on 29th August 2012. Map Projection is MGA-56.

Location of Flow Measurements Taken During the 'Dry Snapshot' on 29th August 2012. Map Projection is MGA-56.

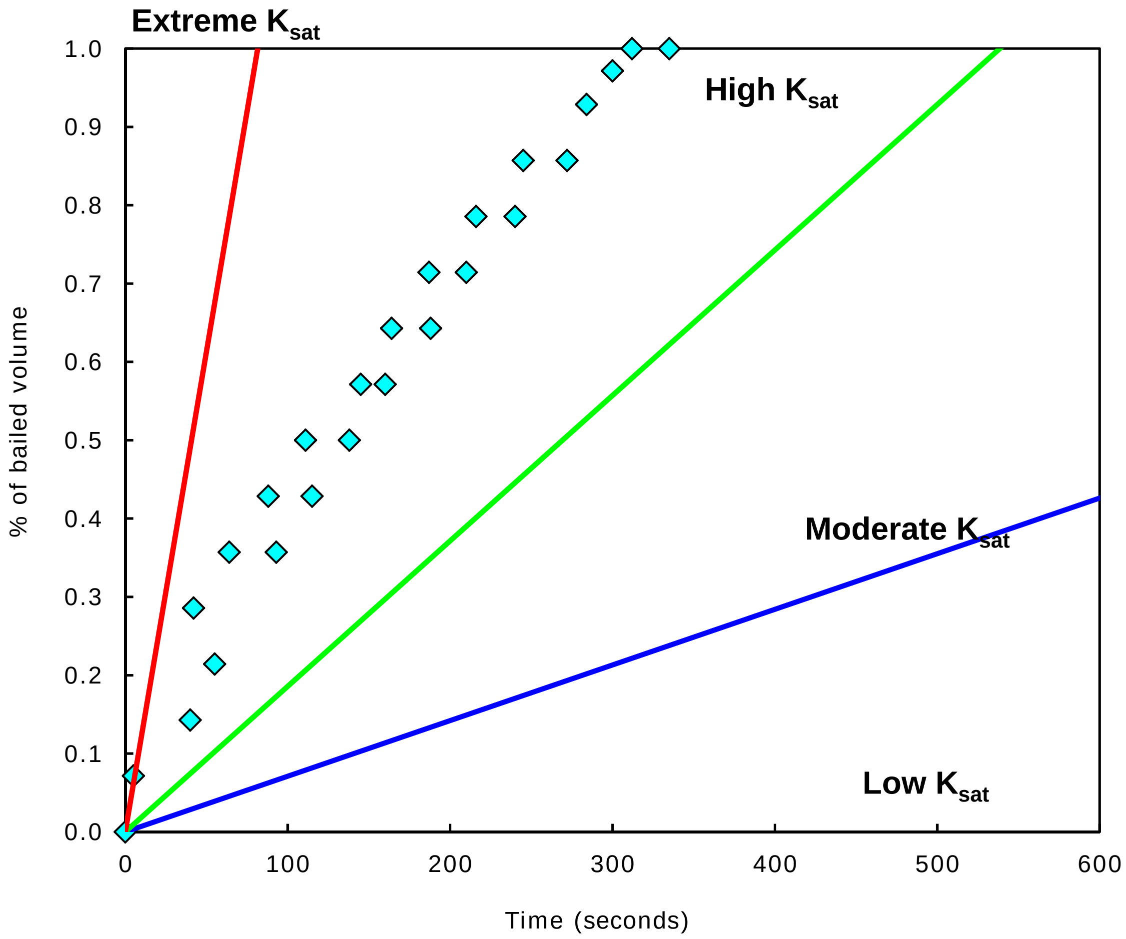


Approximate Hydraulic Conductivity of the Groundwater at Big Swamp.



Measured pH of Groundwater at Big Swamp Including WRL and Jonston (2007) Test Pits.

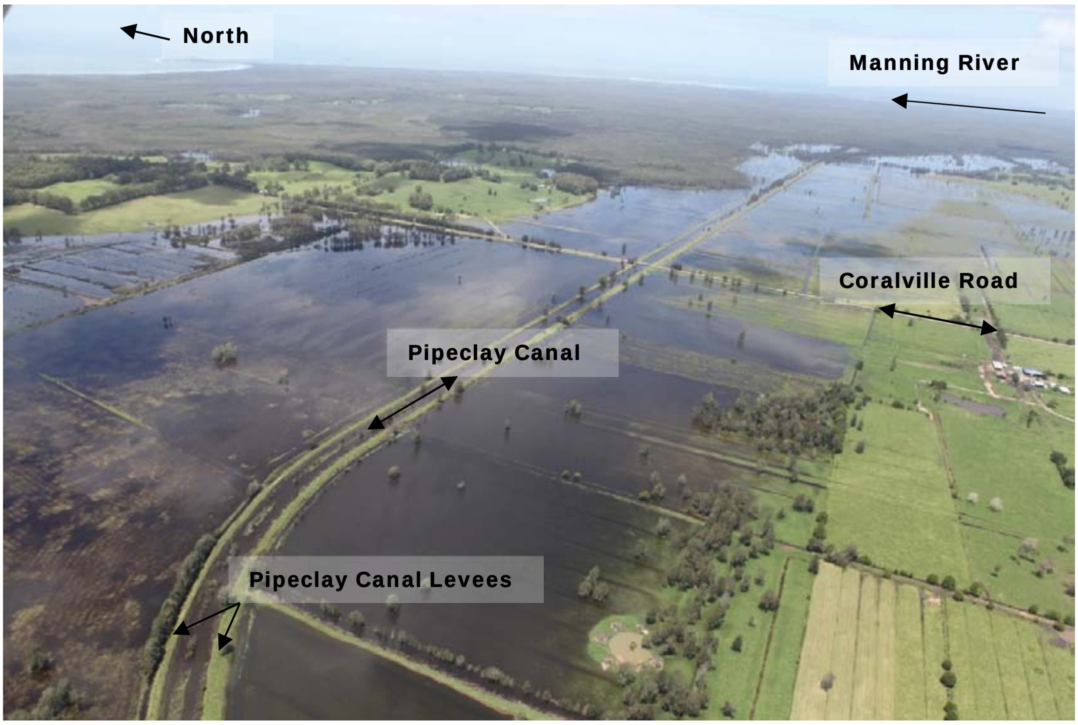
Representative Test Pit (A) Showing Dark Organic Loams Overlaying a Pale Grey to Greyish-Brown Silty-Clay Sulfuric Horizon (Actual ASS), with Extensive Iron (Fe) Mottling and Pale Jarosite Mottling (B)



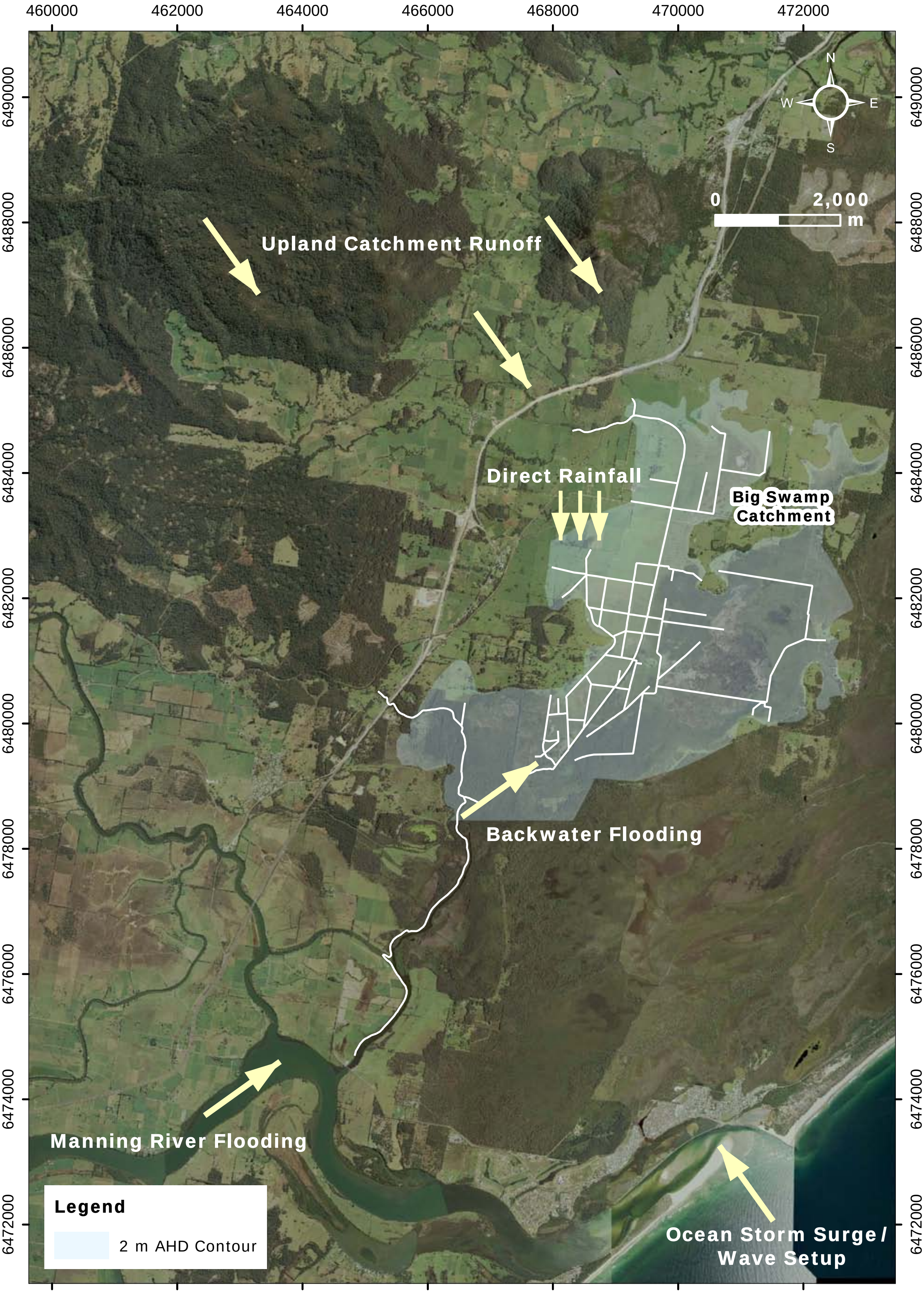
Classification	Approximate K_{sat} (m/day)
Extreme	~100
High	15 to 100
Moderate	1.5 to 15
Low	< 1.5

Bulk Hydraulic Conductivity Test Pit: 1

Hach Meter Reading Low pH Values in Infield Drains Having Stagnant Water

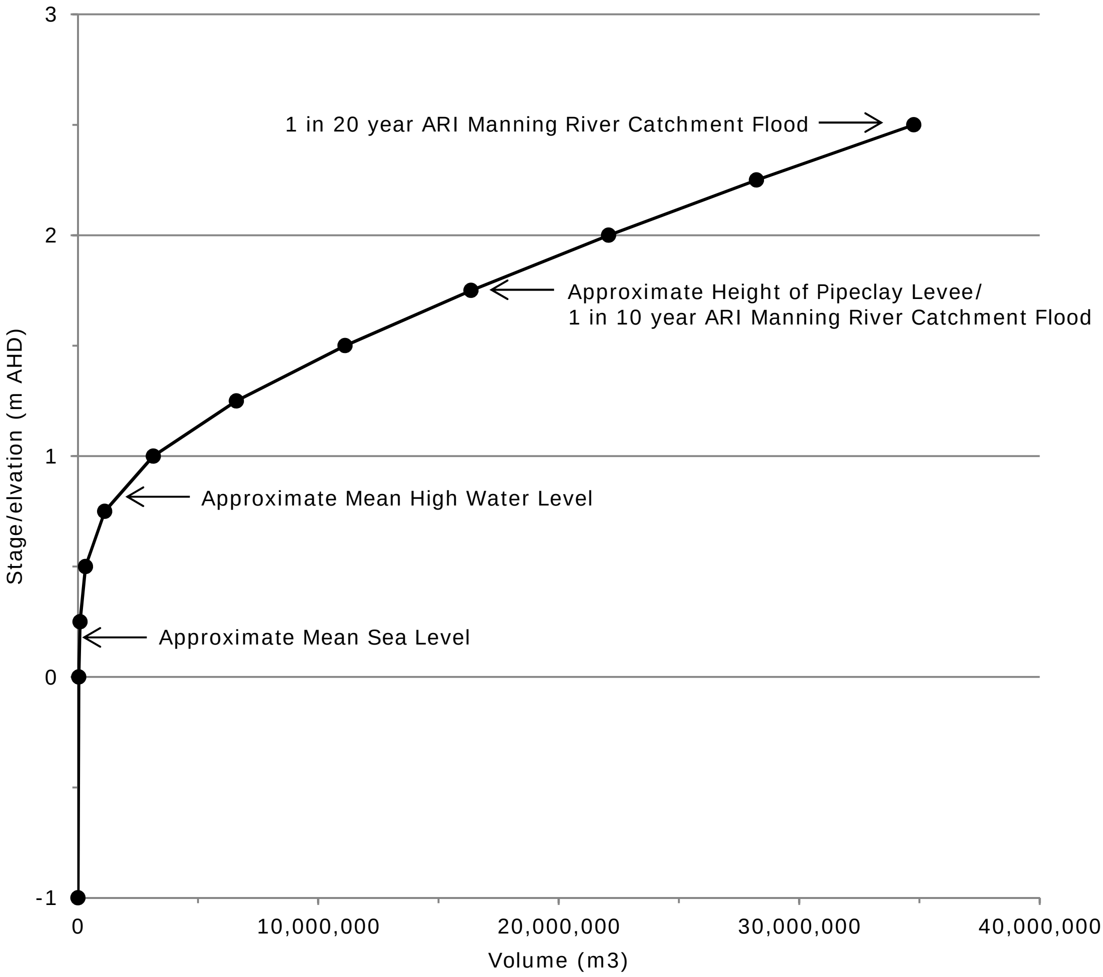


The Big Swamp Catchment After 5-days of Rainfall from the 24th January to 28th January Causing Flooding of Pipeclay Canal to a Bankfull State and Inundating the Surrounding Landscape (GTCC, 2013)

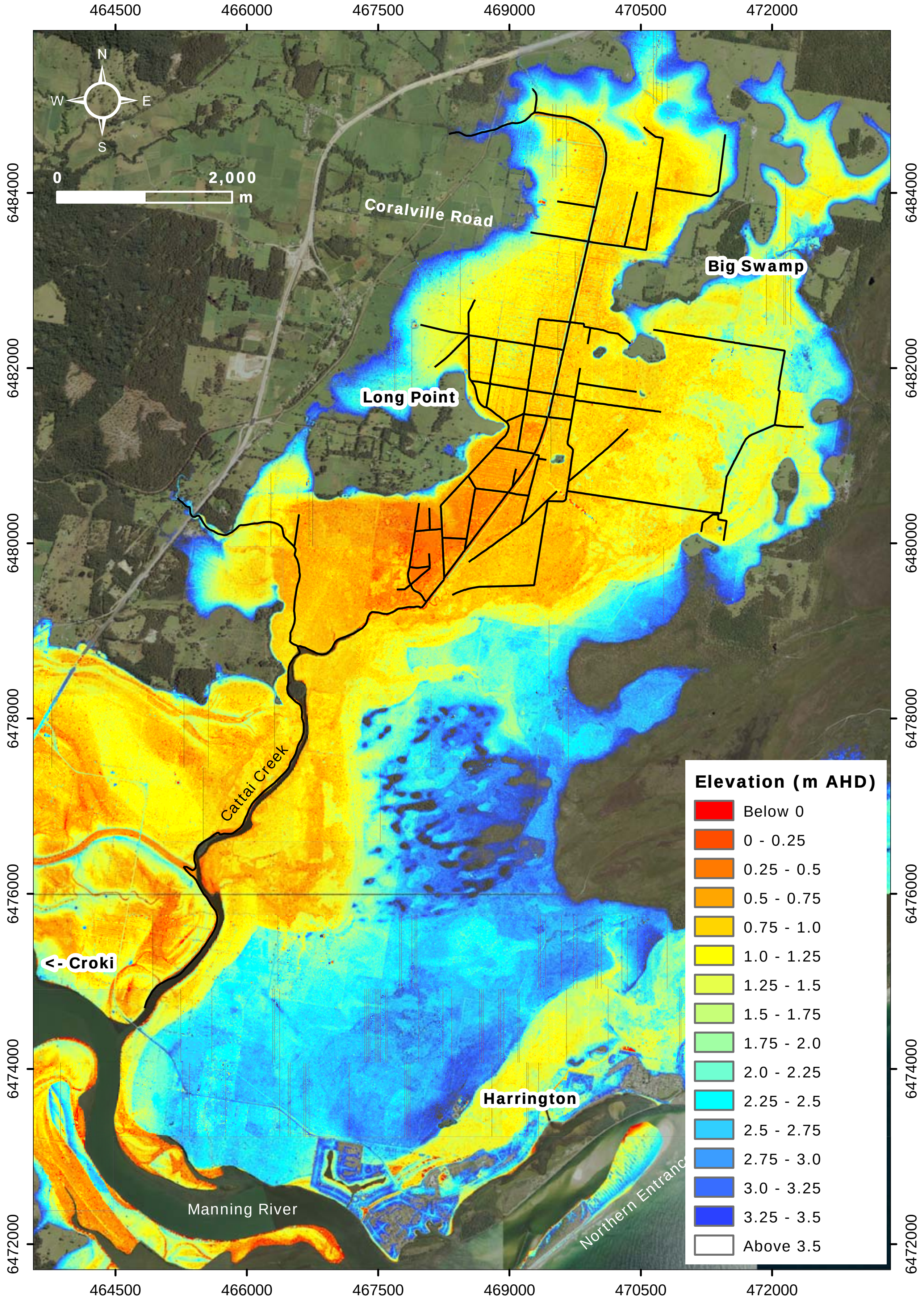


Conceptual Process of Possible Flooding Mechanisms at Big Swamp

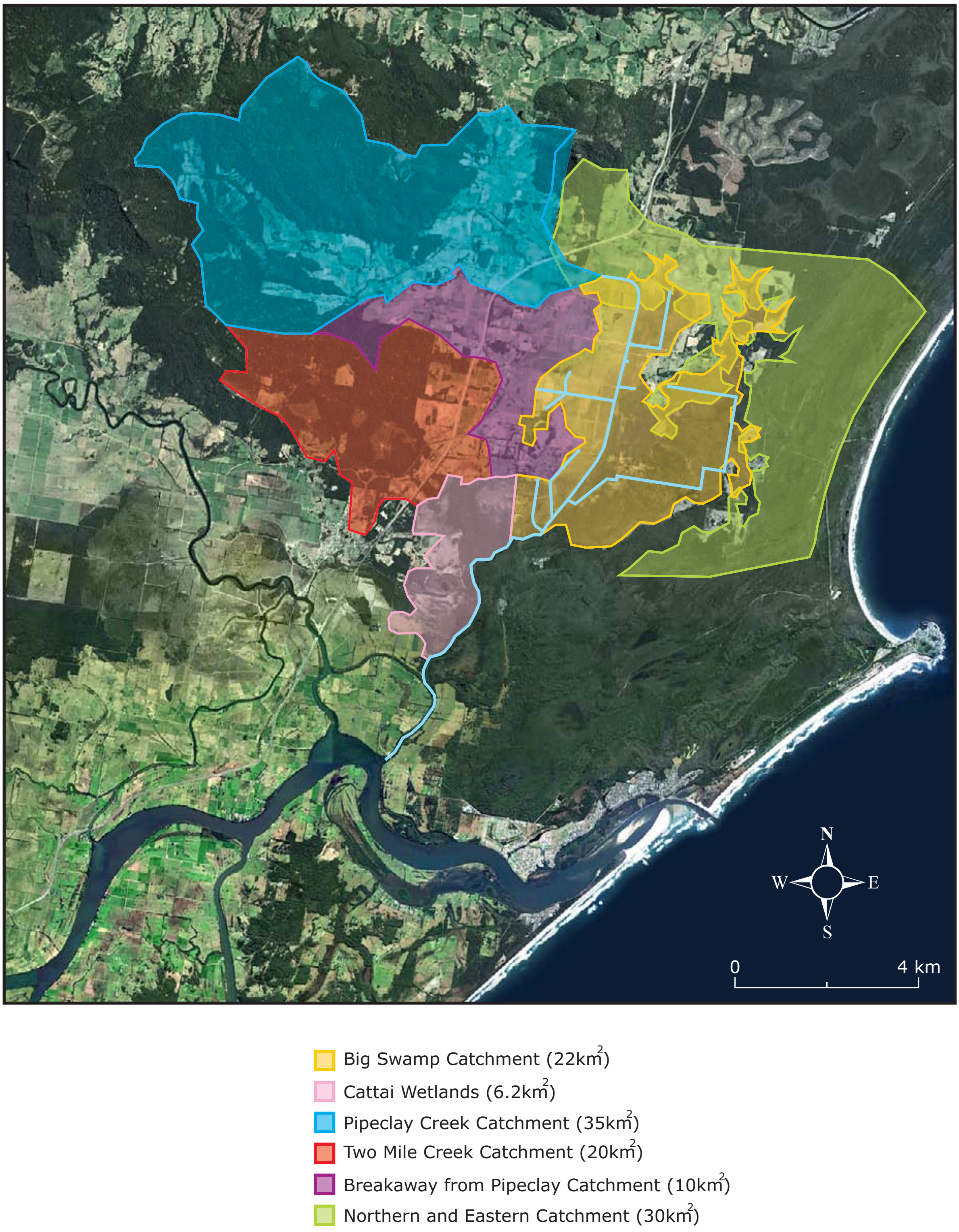
Figure 2.23



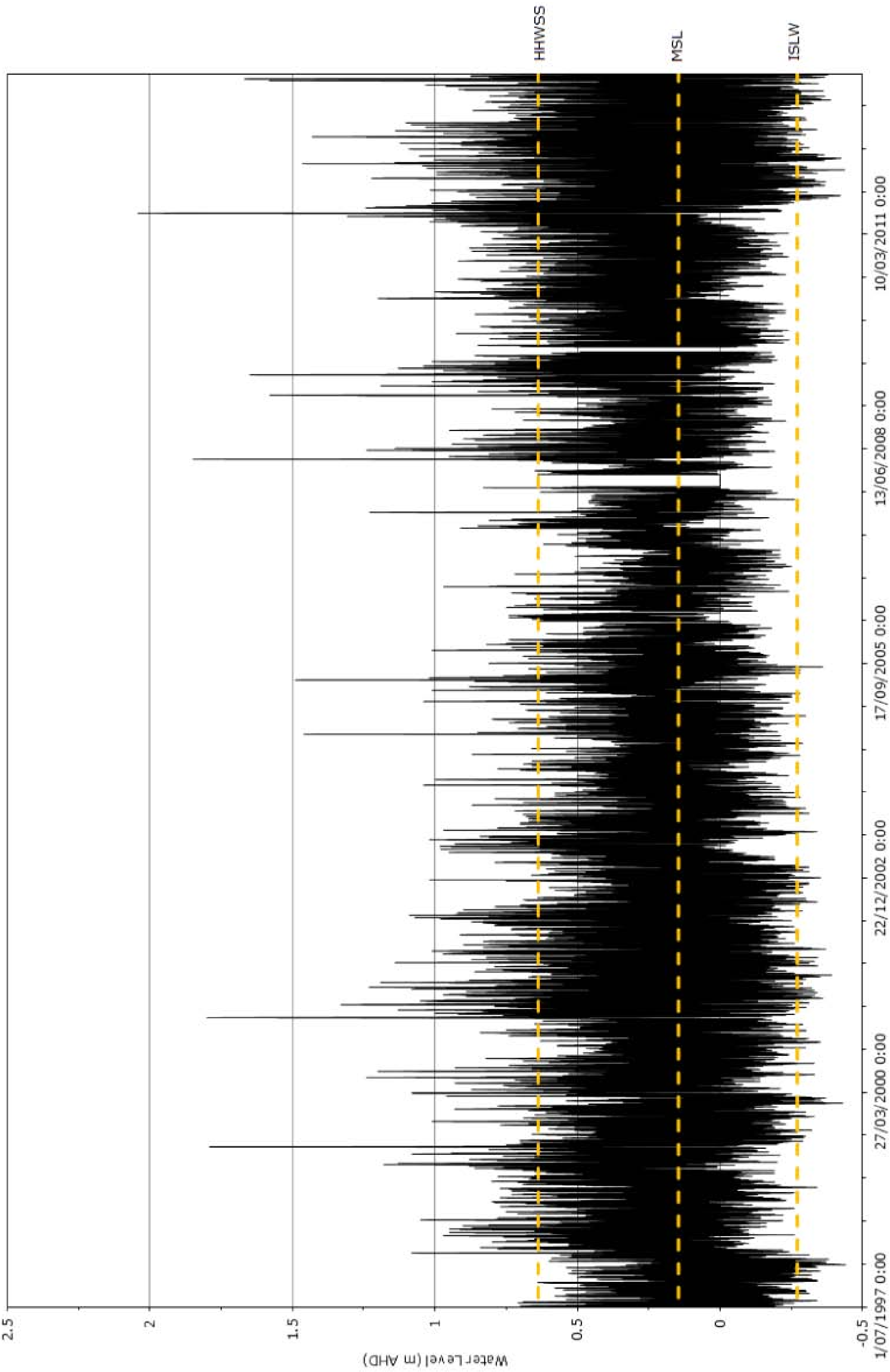
Big Swamp Stage-Volume Analysis



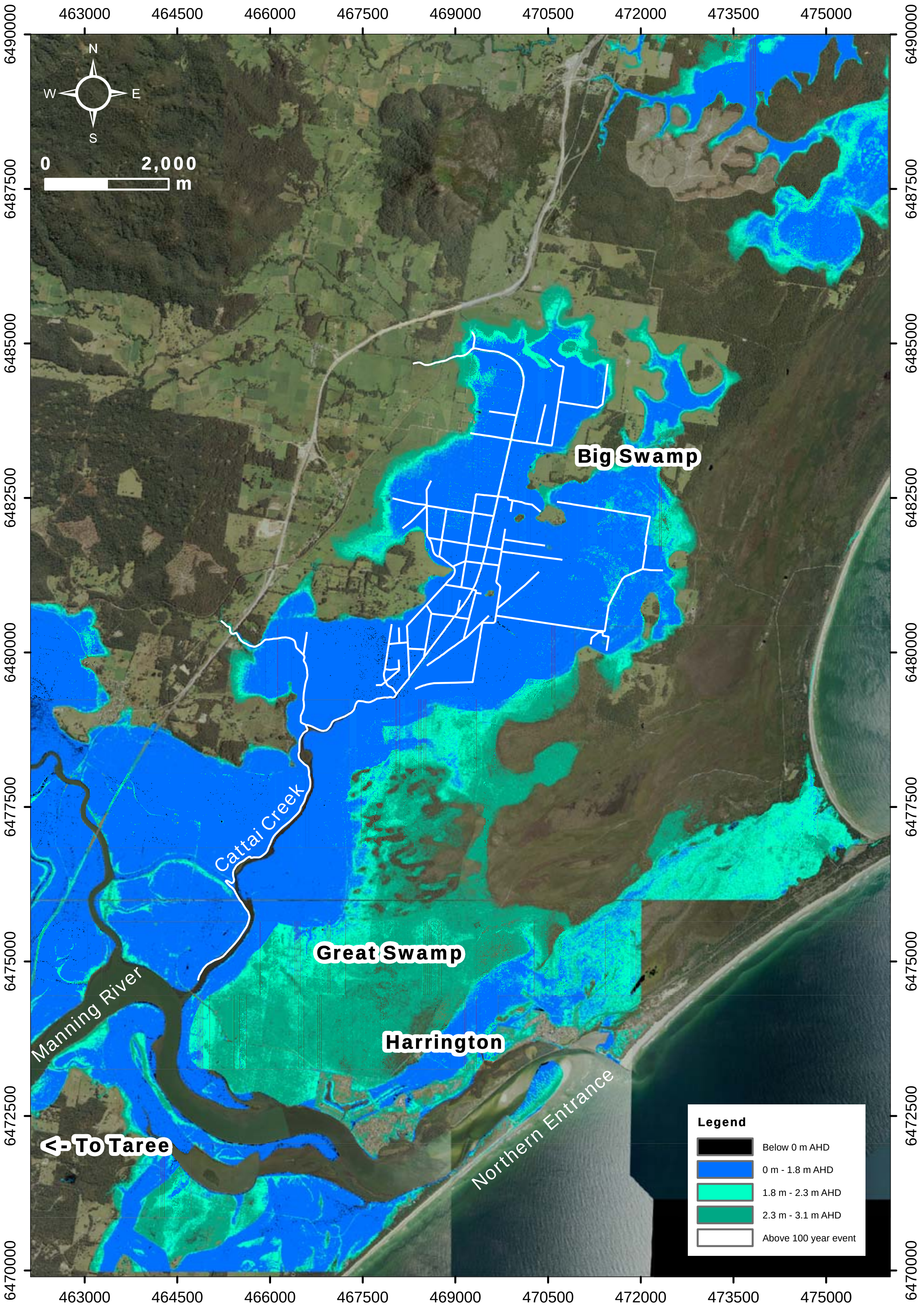
Key Hydrologic Features of the Site Using Topography



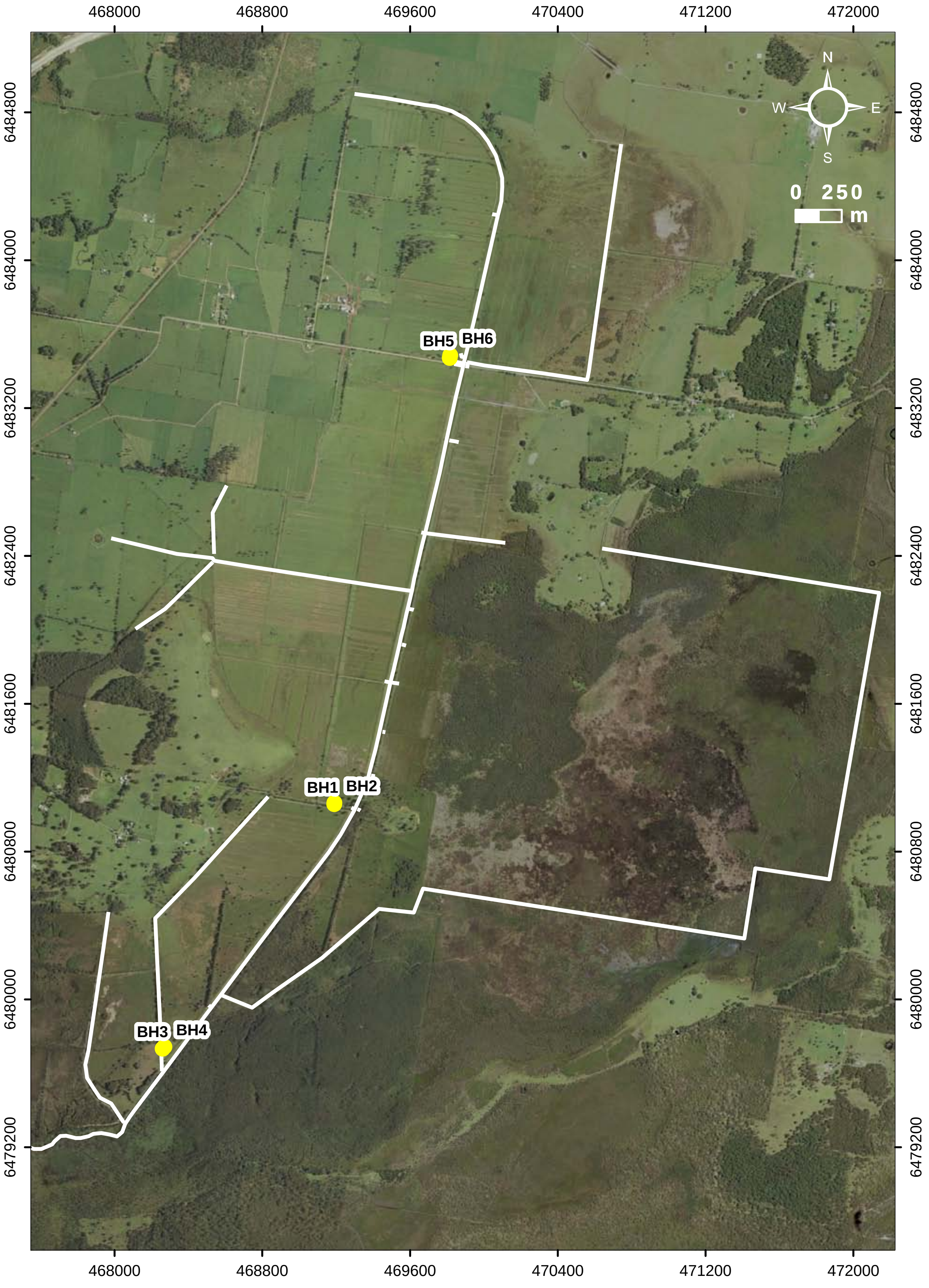
Approximate Sub-Catchments in the Big Swamp Region



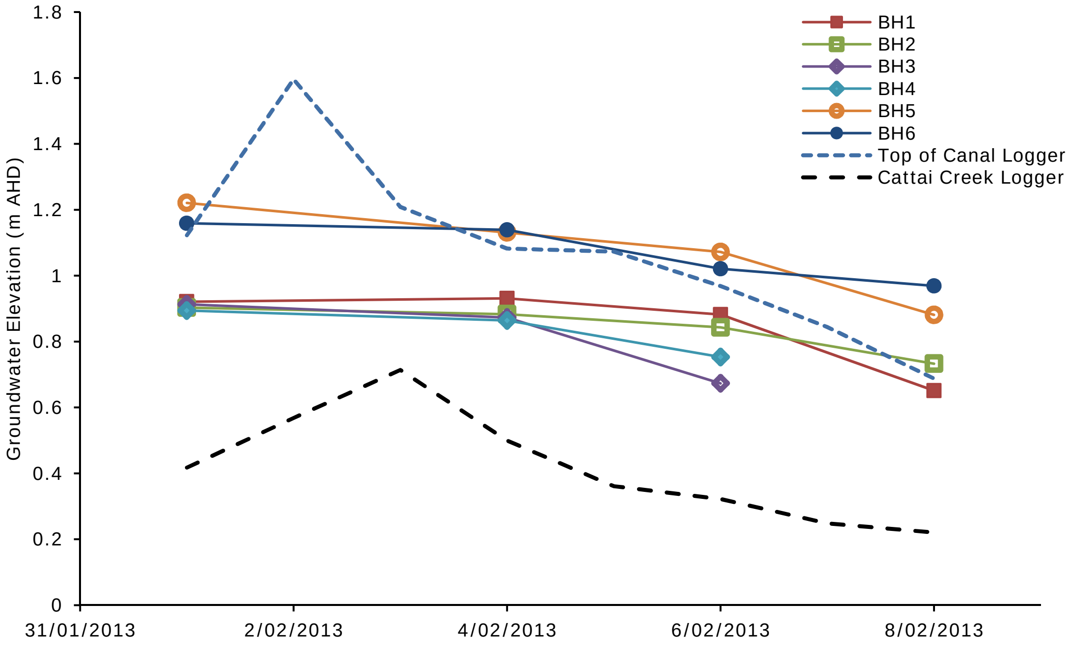
Historical Water Levels at Croki, Manning River (with Tidal Planes as per MHL, 2013)



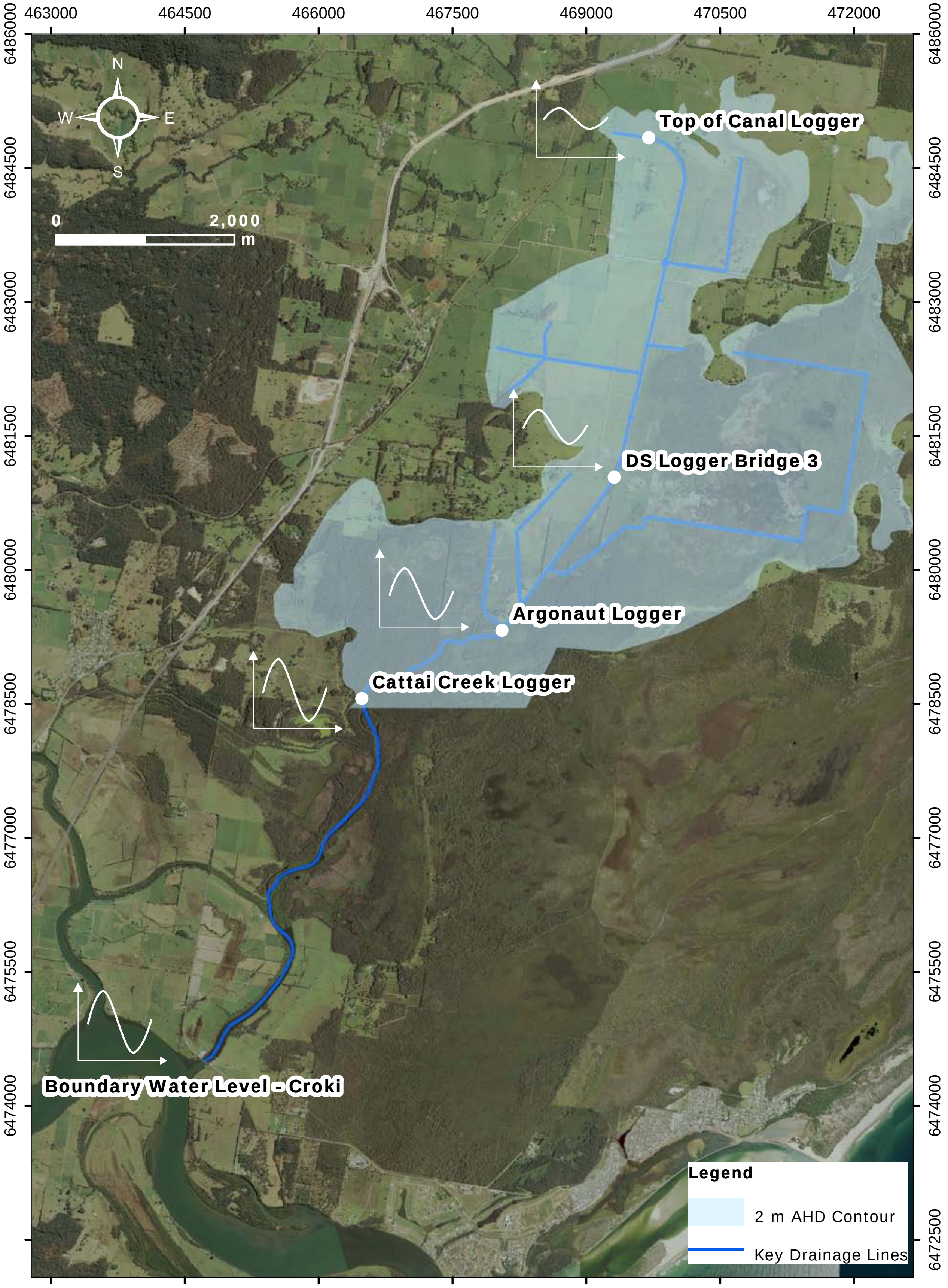
Inundation for Minor (1.8 m AHD) and Major (3.1 m AHD) Flood Levels at Croki



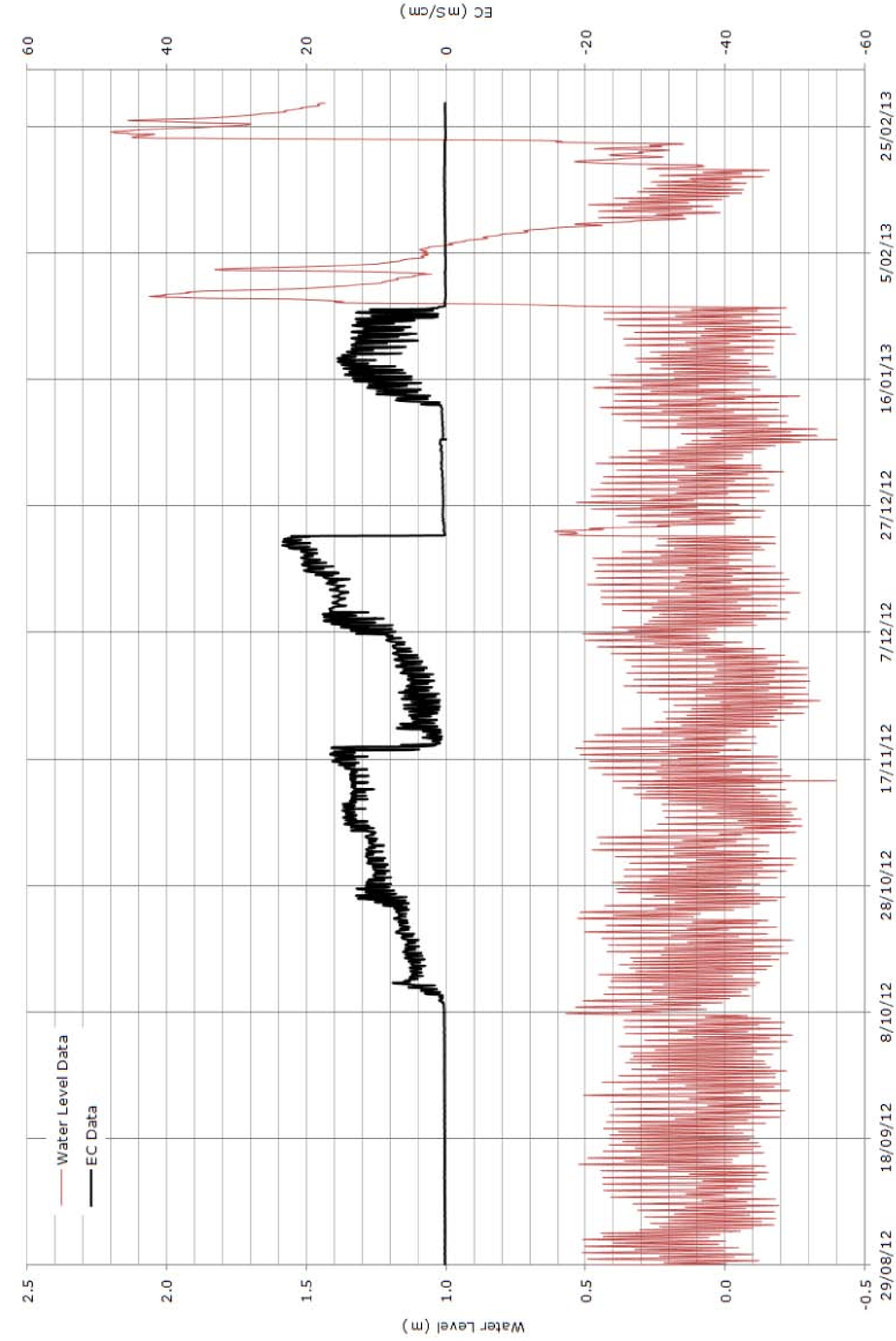
Location of Short-Term Groundwater Measurements From 1st to 8th February 2013



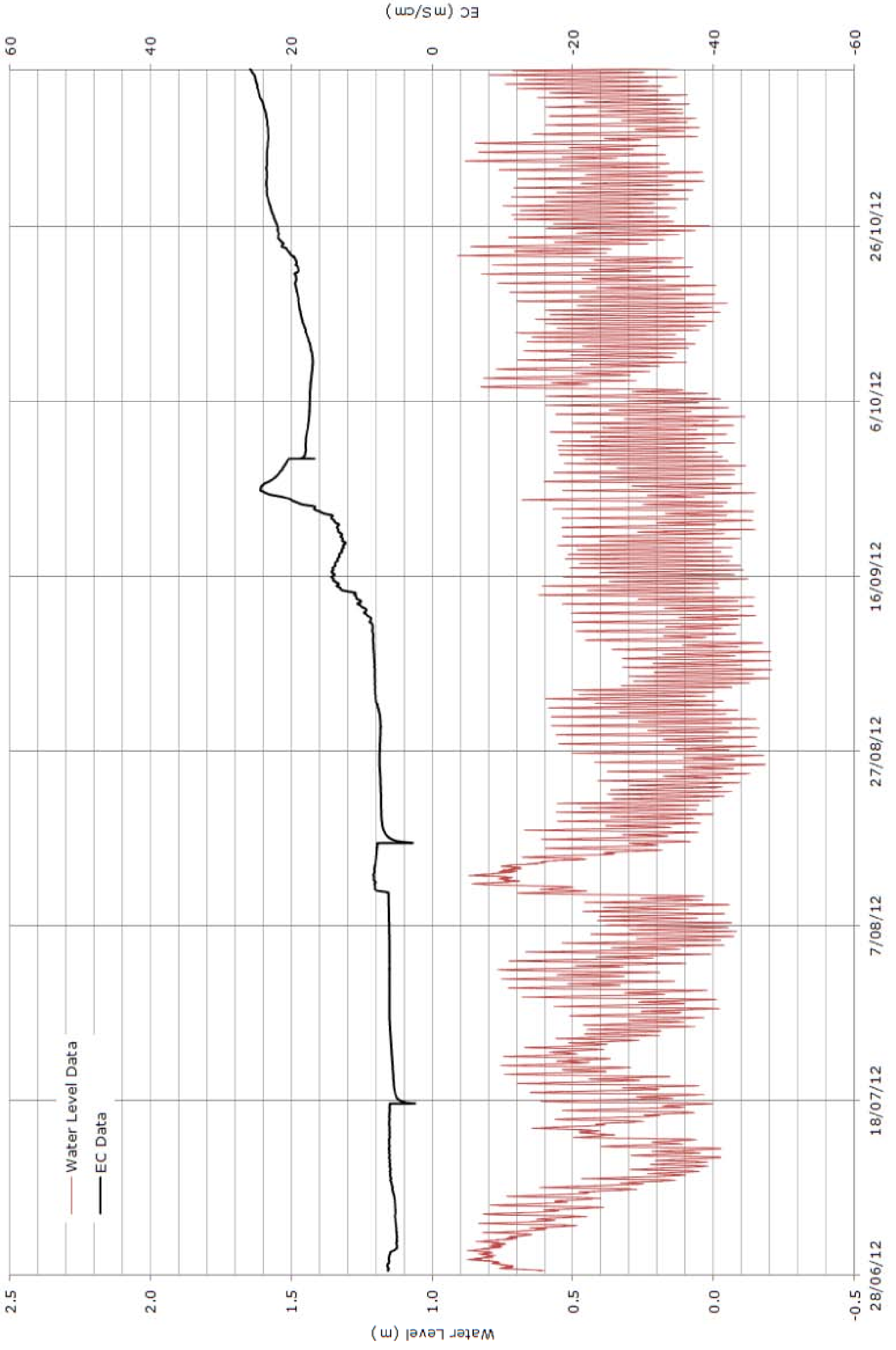
Groundwater Measurements Observed Over a 7-day Period Following a Catchment Rainfall Event at Big Swamp Including Daily Averaged Water Levels at Two Water Level Stations



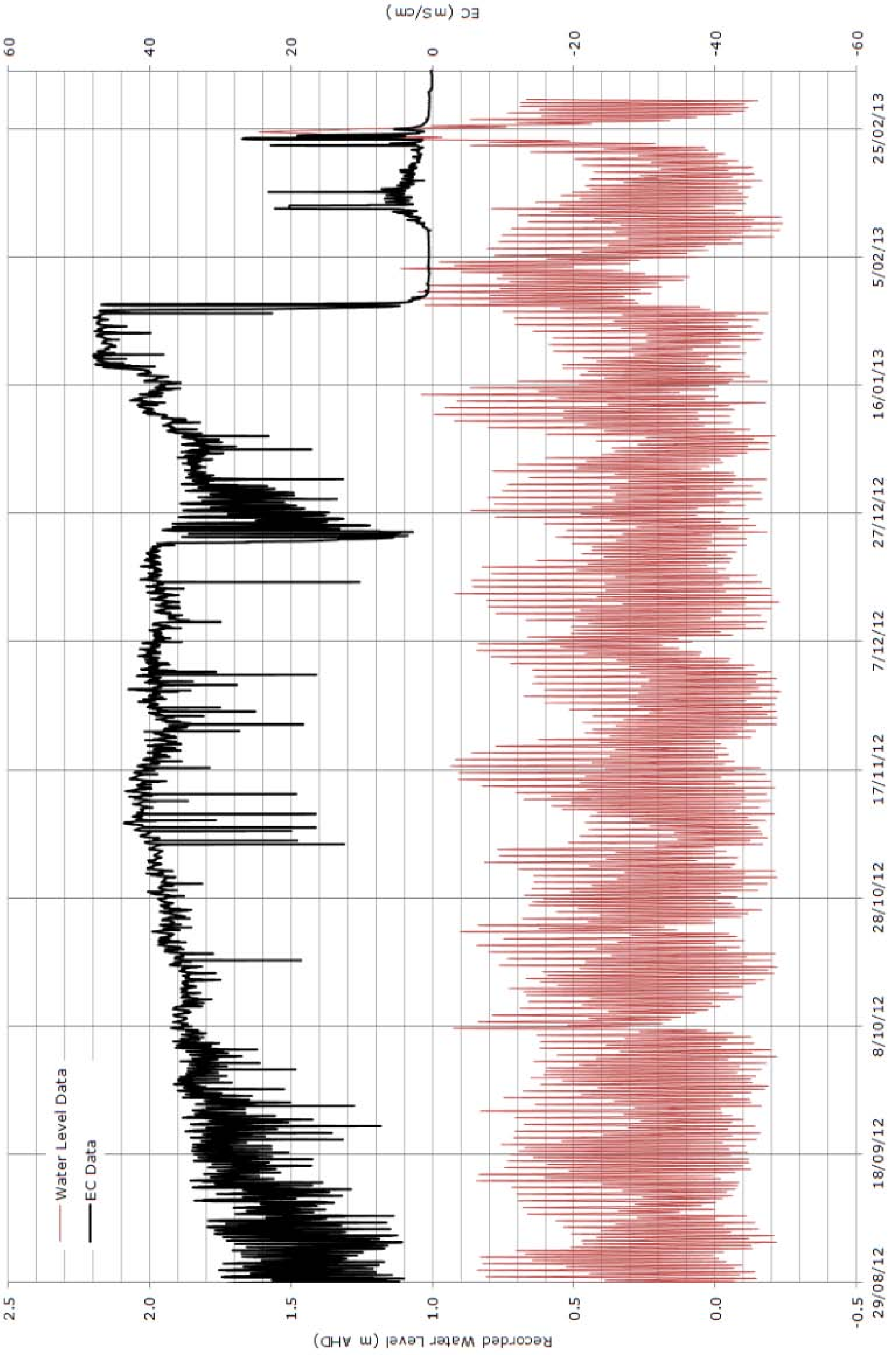
Location of Water Level Recording Stations



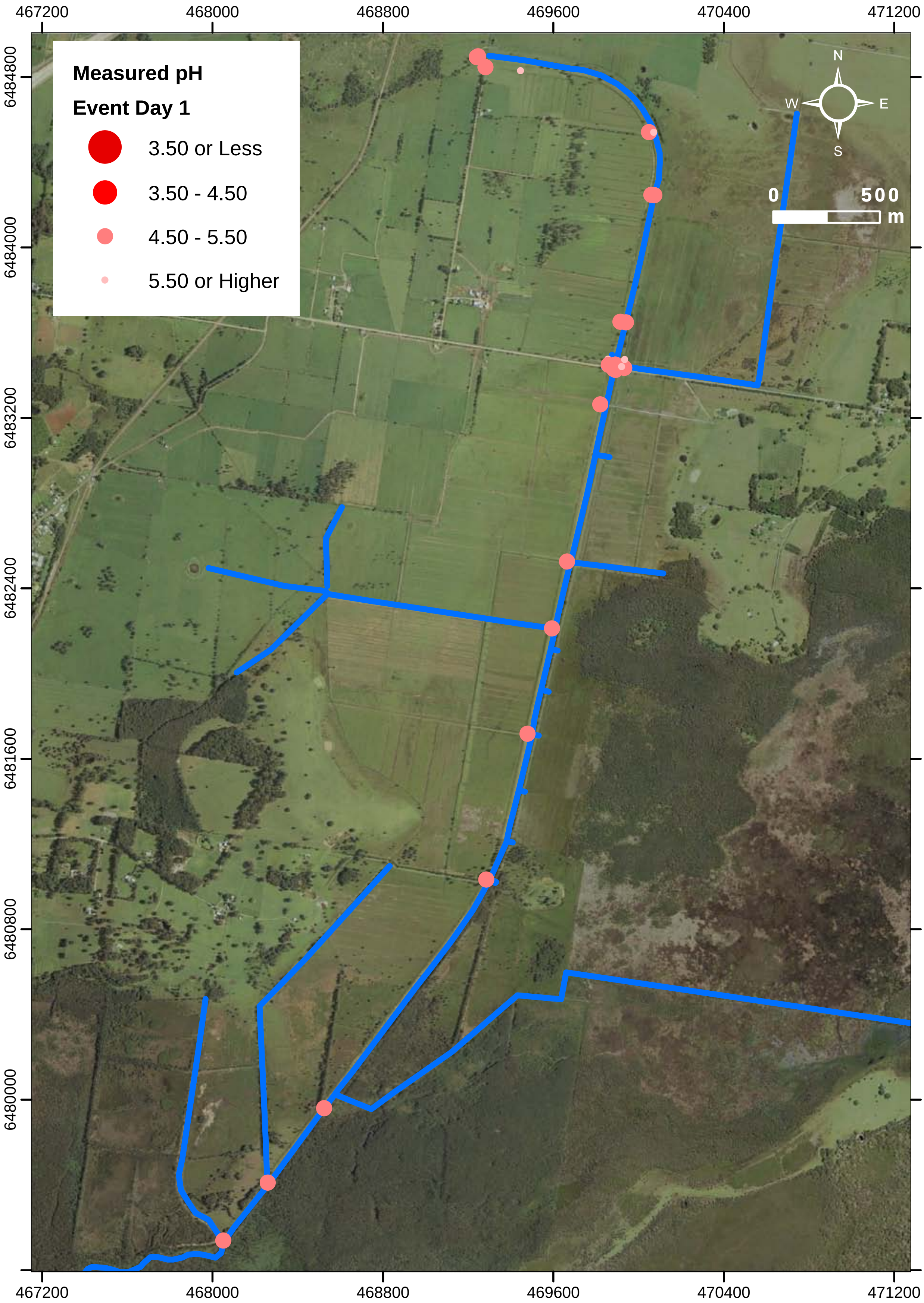
Barometrically Corrected Recorded Water Levels at the Northern End of Pipeclay Canal Including Recorded EC (27/8/2012 – 28/2/2013) ("*Top of the Canal*")



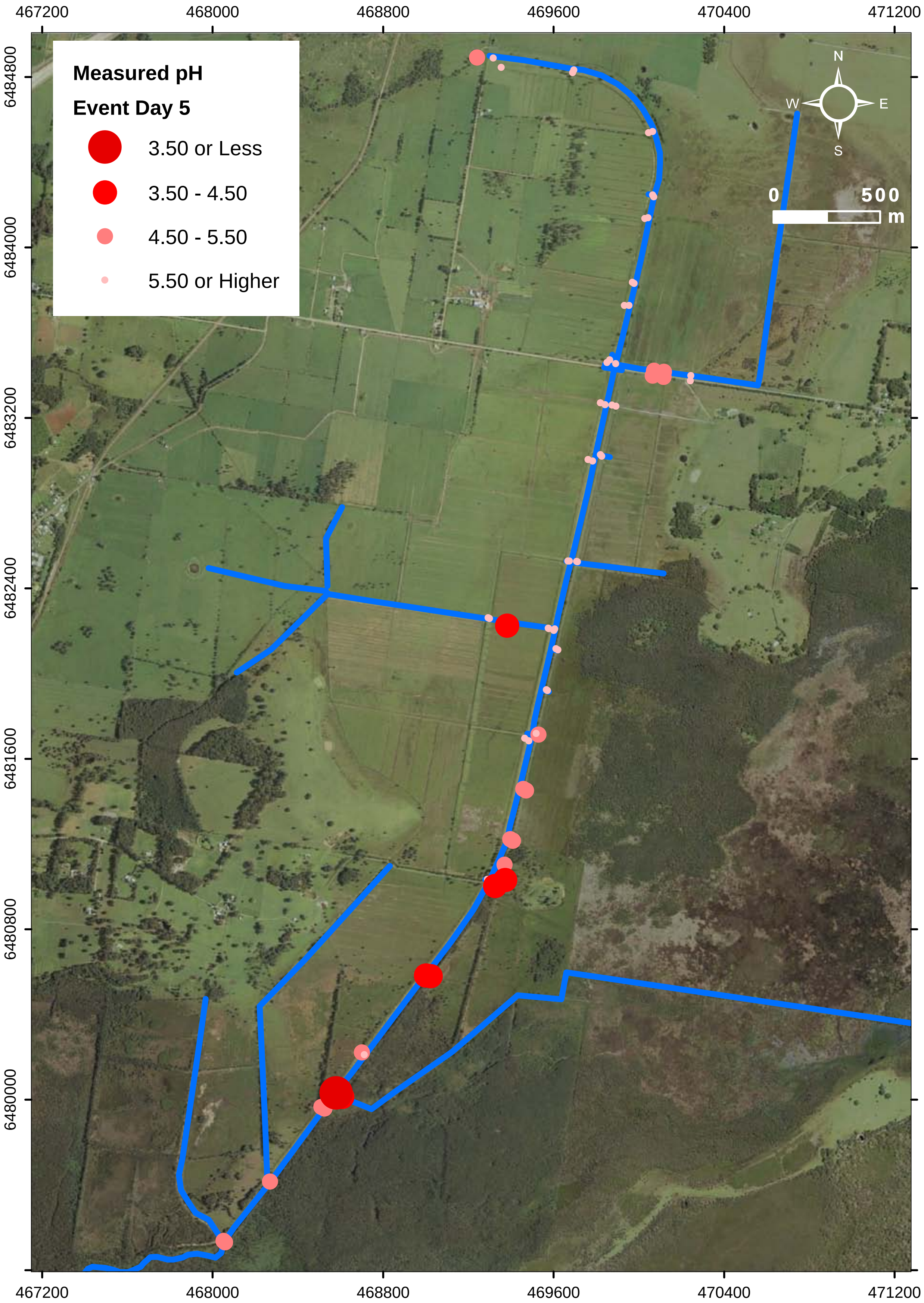
Barometrically Corrected Recorded Water Levels in the Bottom Section of Pipeclay Canal Including Recorded EC (28/6/2012 – 13/11/2012) ("*Downstream Logger*")



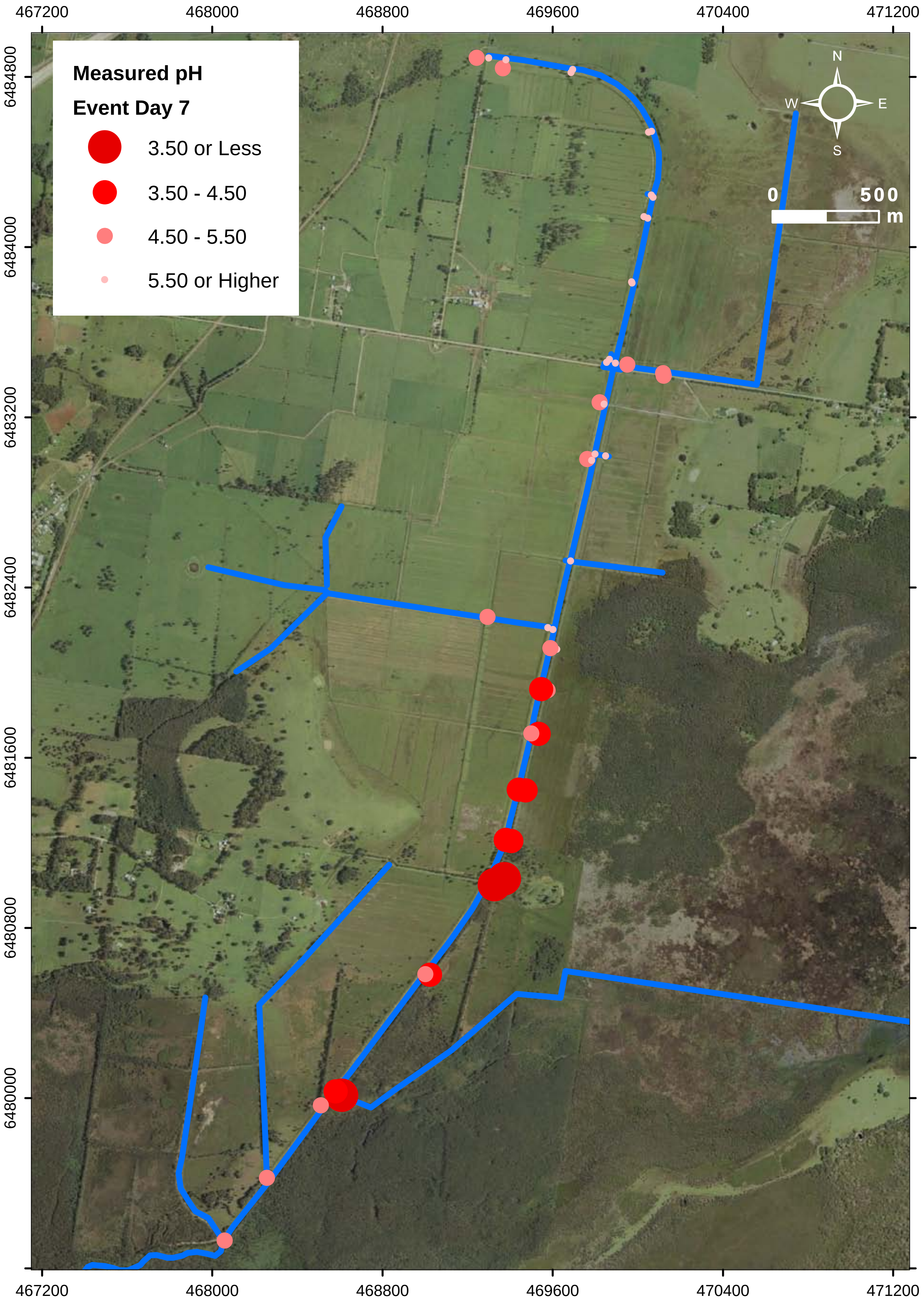
Barometrically Corrected Recorded Water Levels in Cattai Creek Including Recorded EC (27/8/2012 – 28/2/2013) (“*Cattai Logger*”)



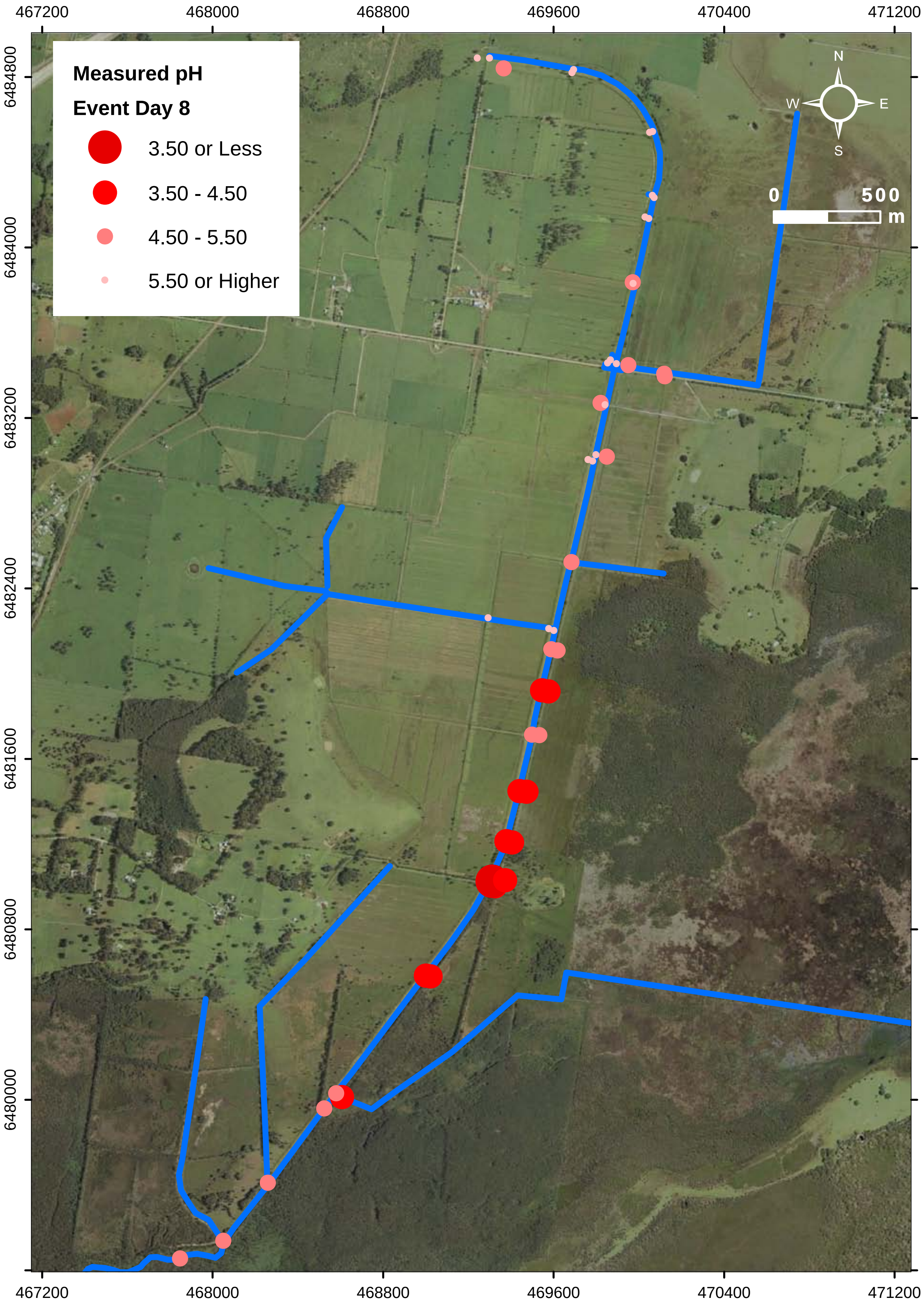
Location of pH Measurements Taken During the 'Wet Event' on 31st January 2013.



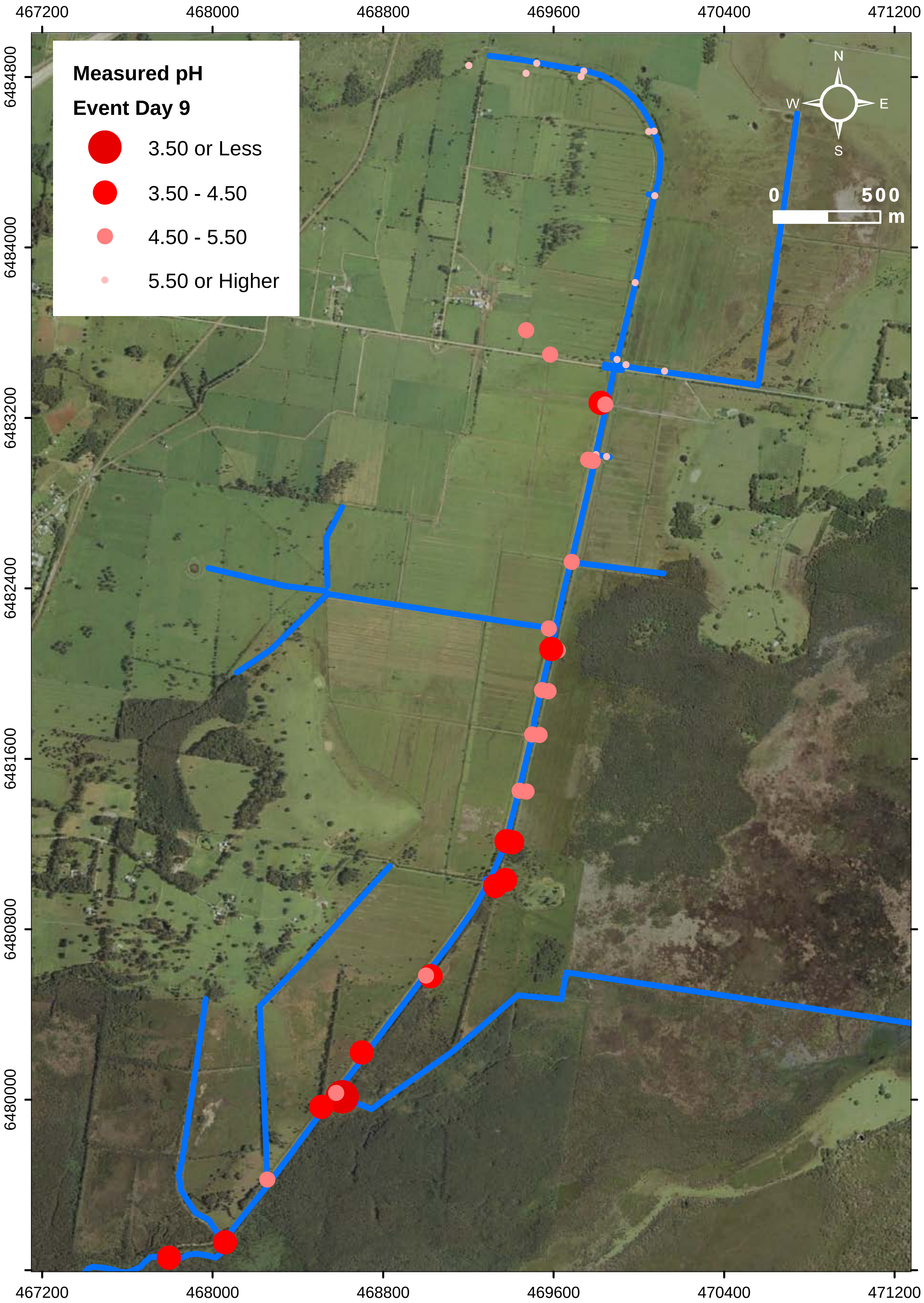
Location of pH Measurements Taken During the 'Wet Event' on 4th February 2013.



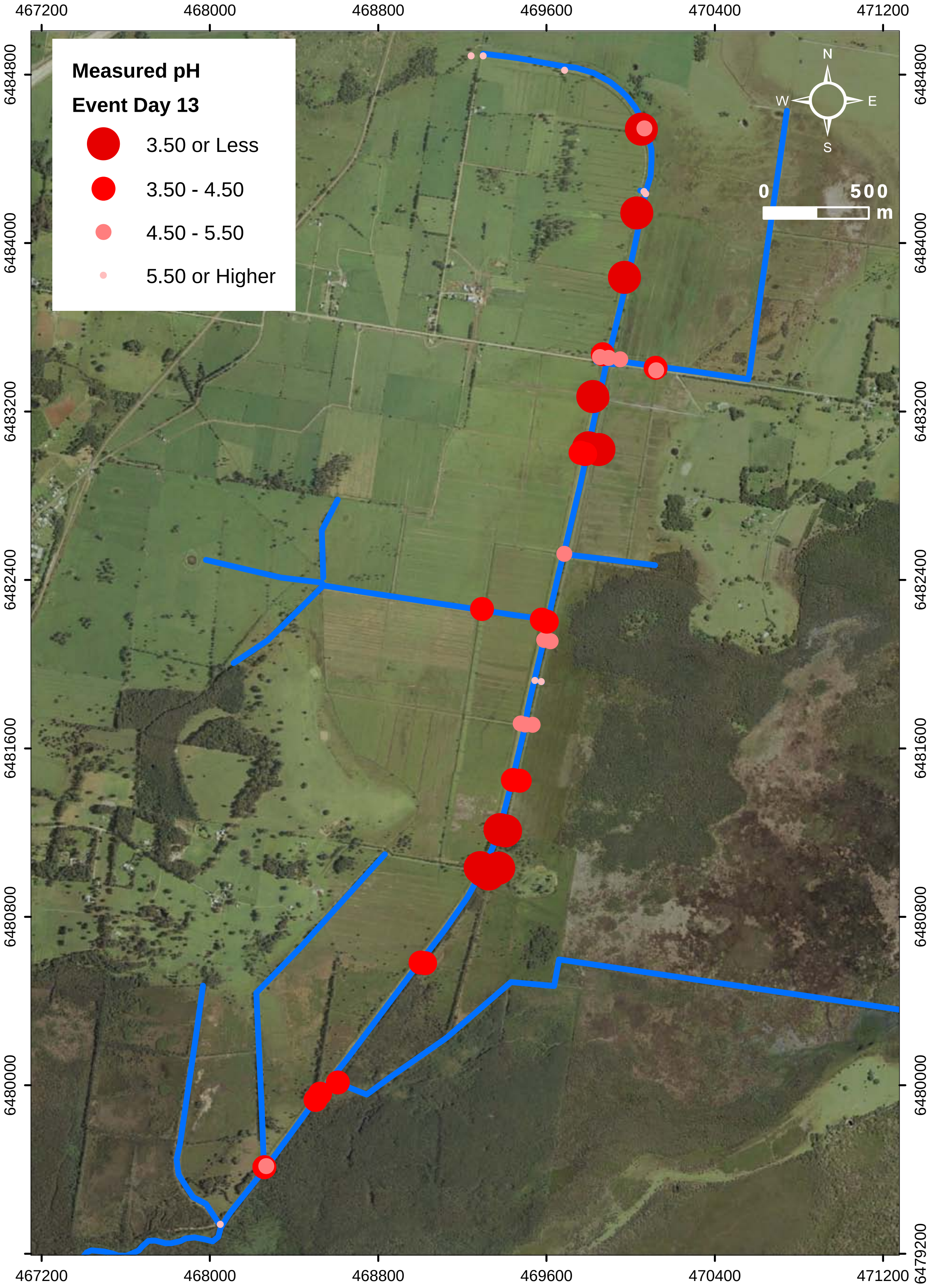
Location of pH Measurements Taken During the 'Wet Event' on 6th February 2013.



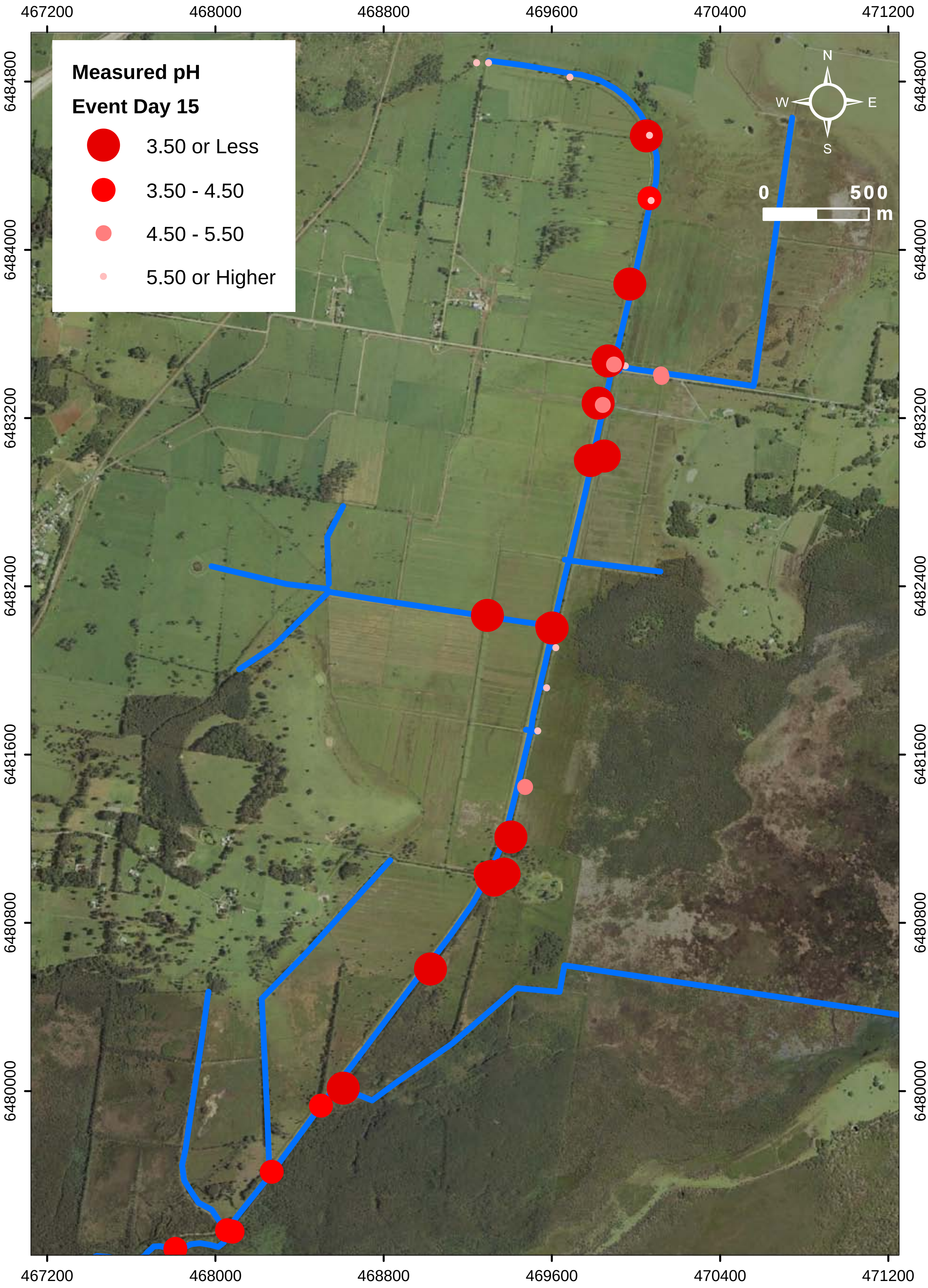
Location of pH Measurements Taken During the 'Wet Event' on 7th February 2013.



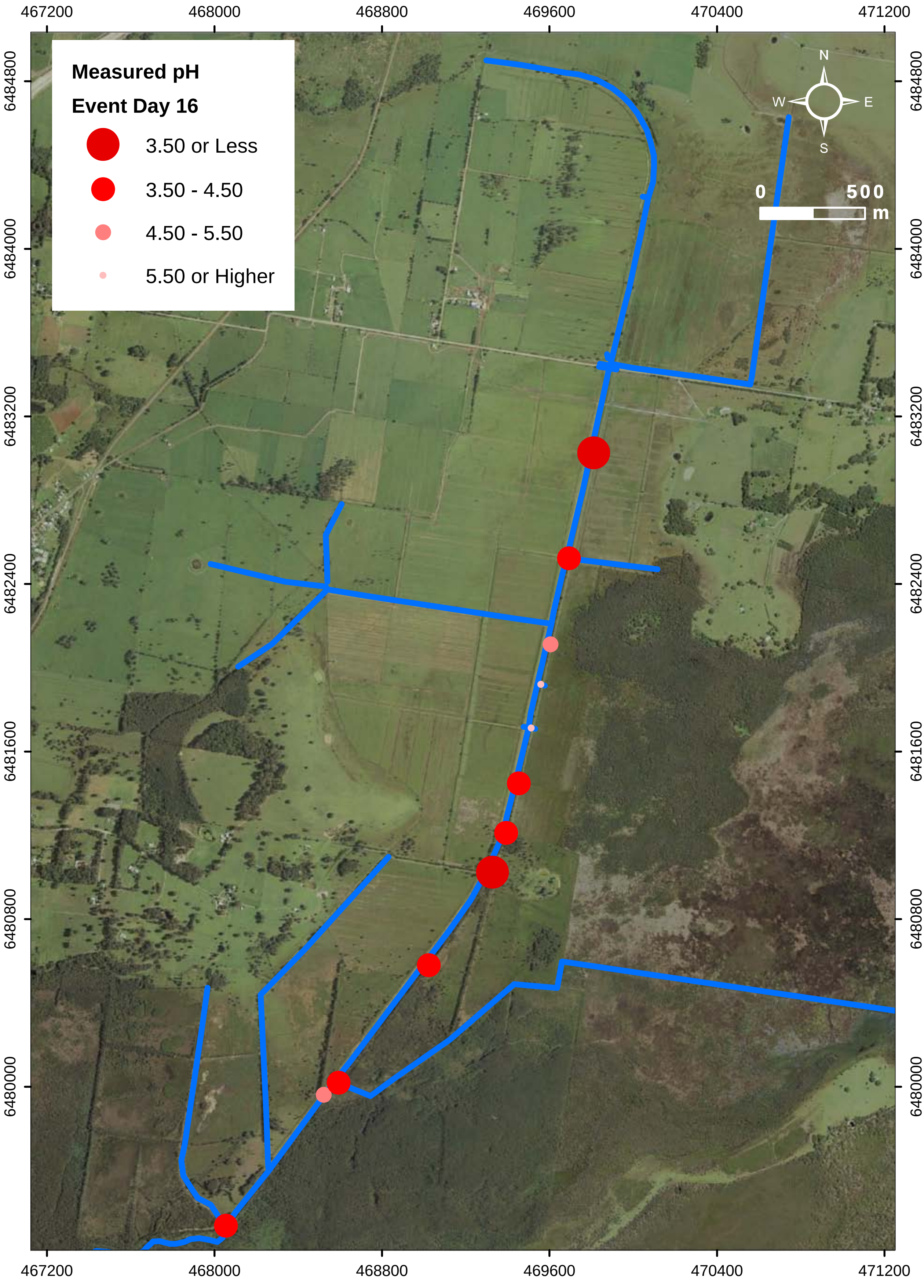
Location of pH Measurements Taken During the 'Wet Event' on 8th February 2013.



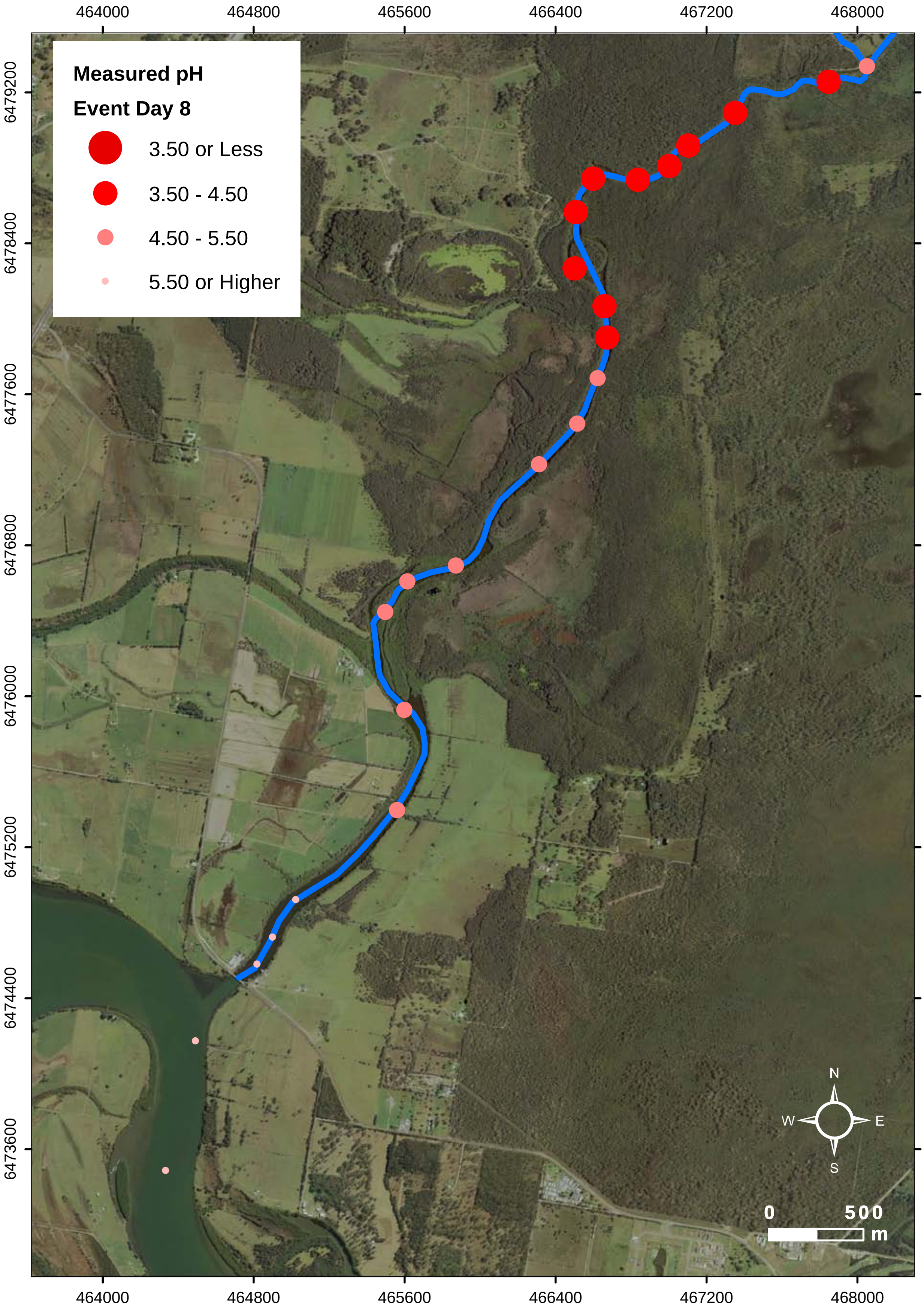
Location of pH Measurements Taken During the 'Wet Event' on 12th February 2013.



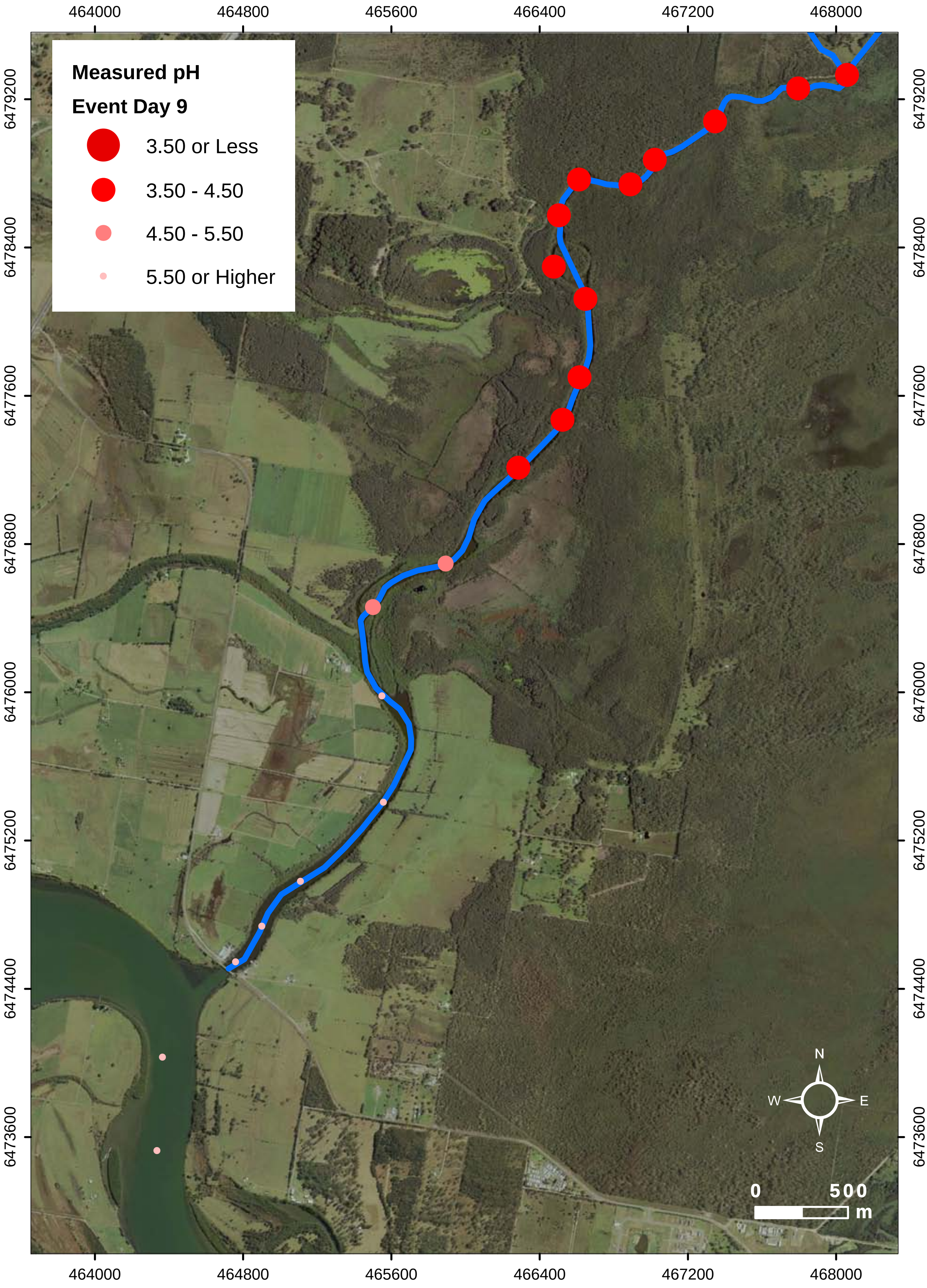
Location of pH Measurements Taken During the 'Wet Event' on 14th February 2013.



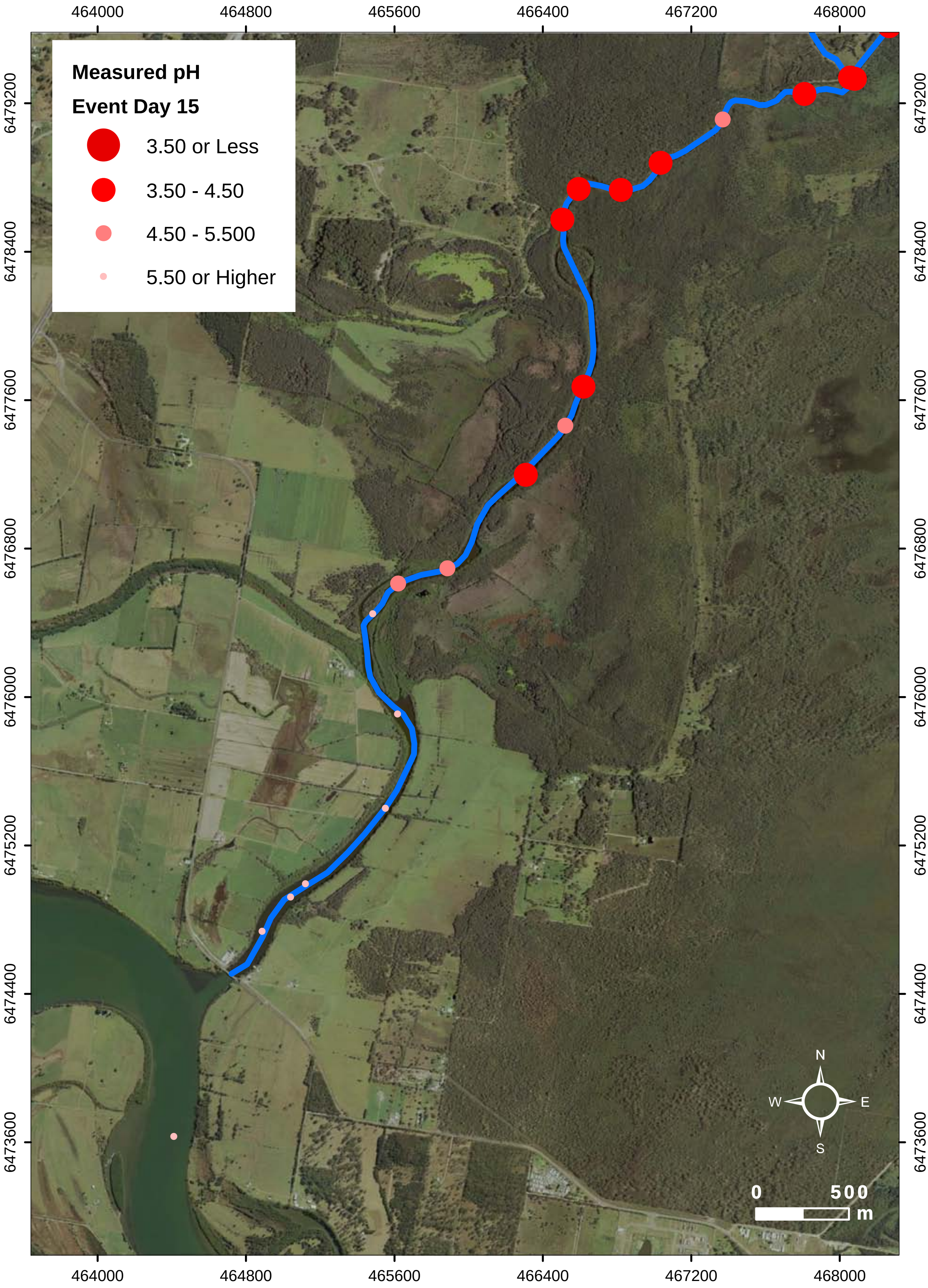
Location of pH Measurements Taken During the 'Wet Event' on 15th February 2013.



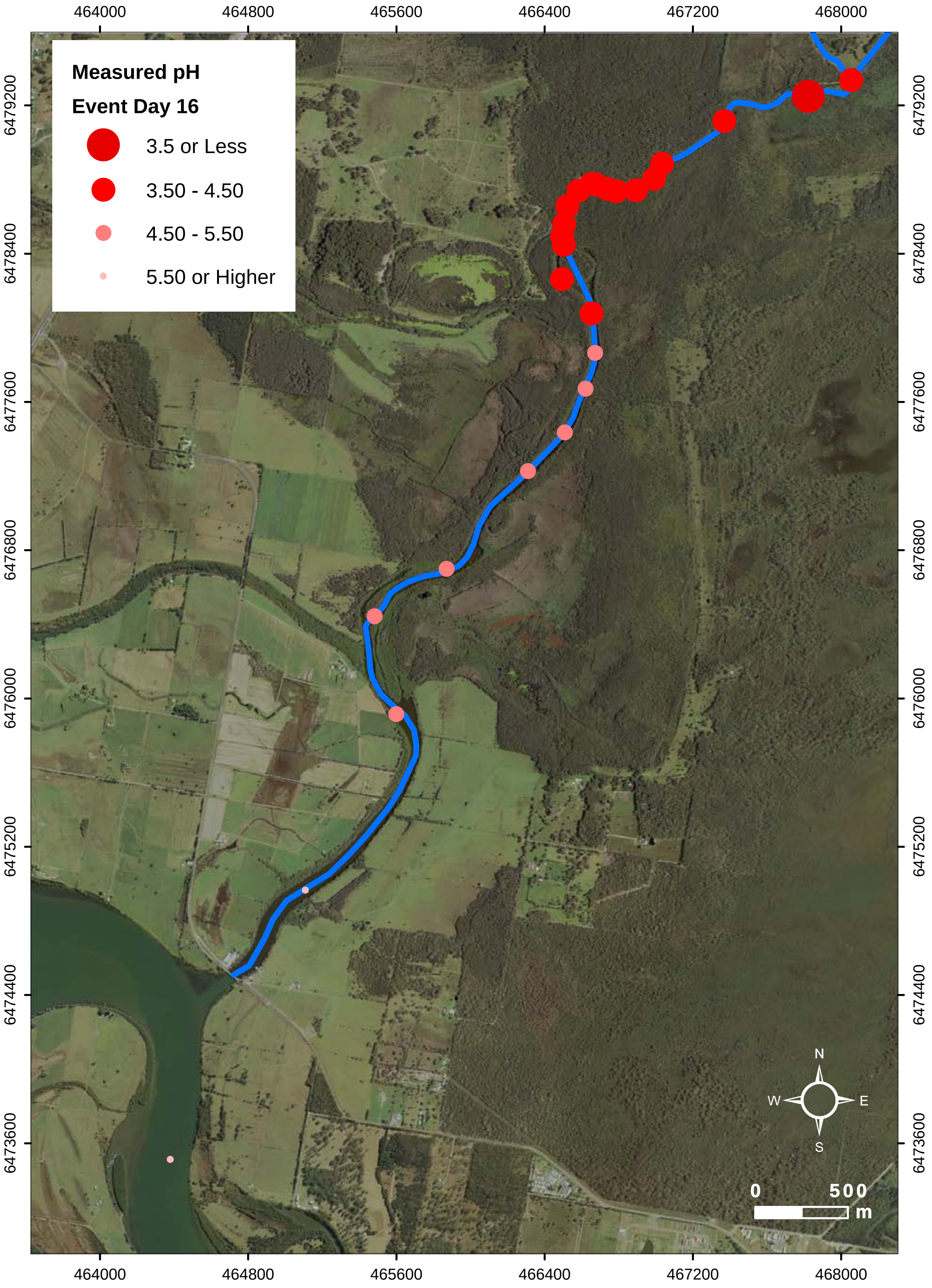
Location of pH Measurements Taken During the 'Wet Event' on 7th February 2013.



Location of pH Measurements Taken During the 'Wet Event' on 8th February 2013.



Location of pH Measurements Taken During the 'Wet Event' on 14th February 2013.

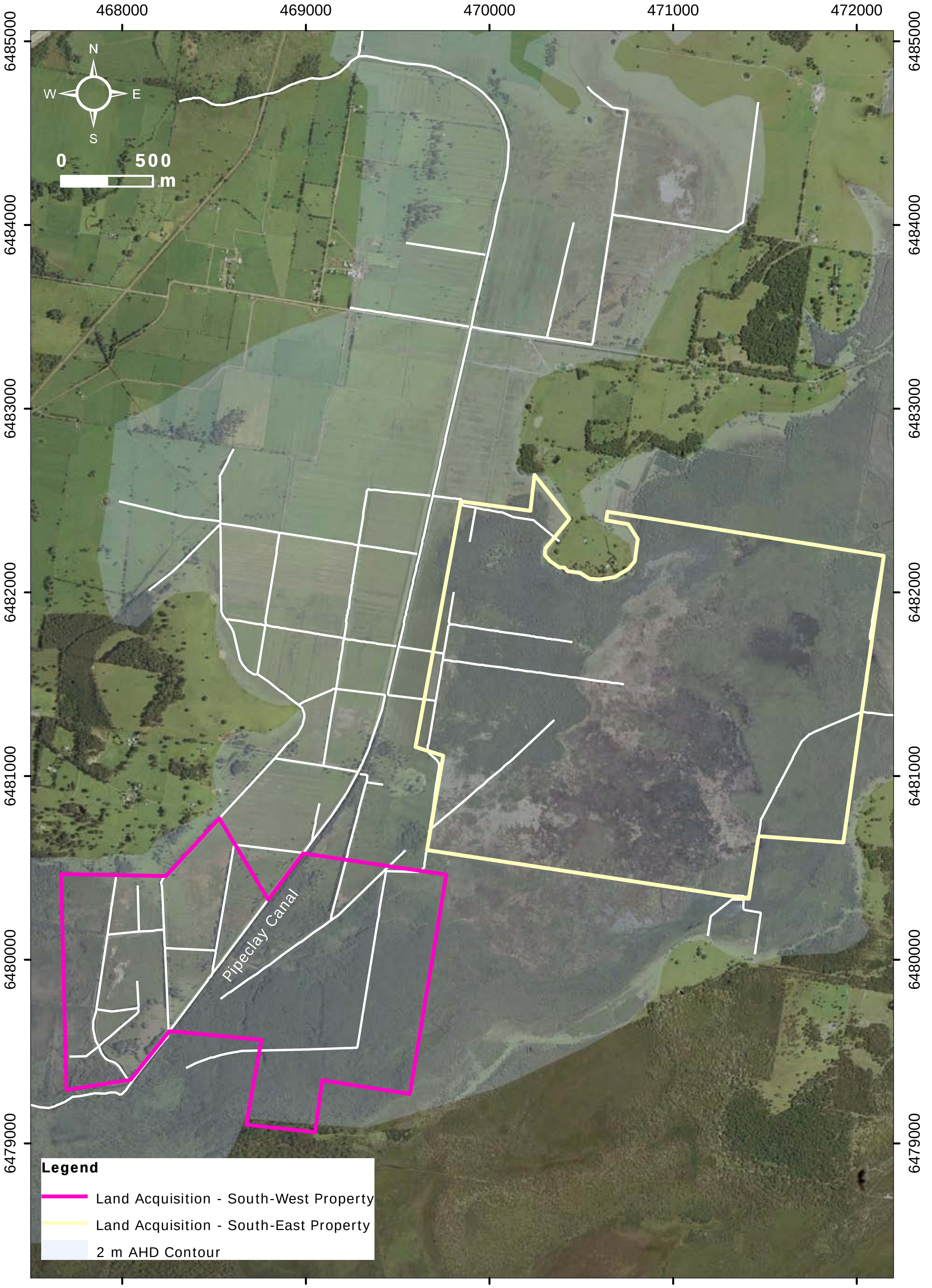


Location of pH Measurements Taken During the 'Wet Event' on 15th February 2013.

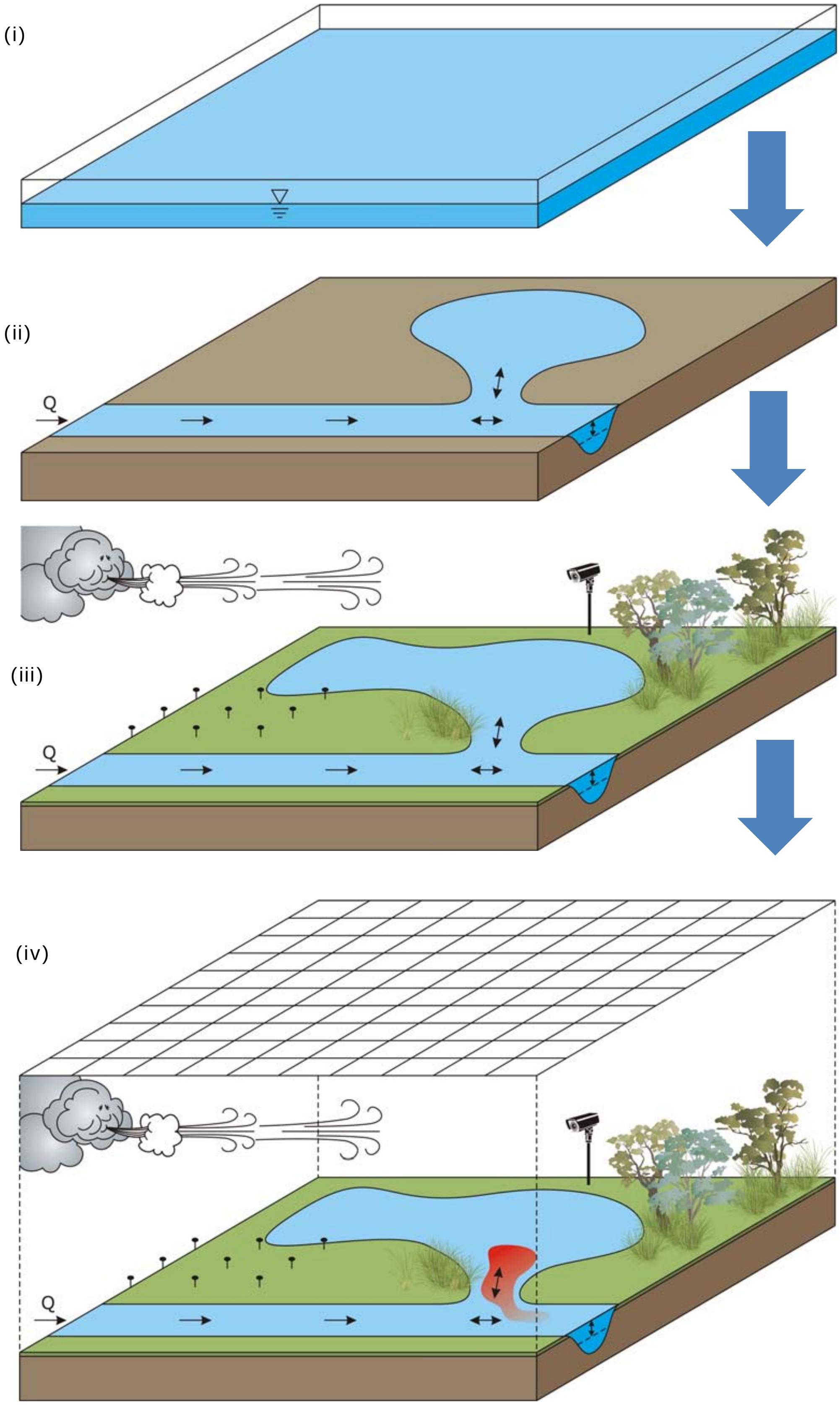
Image Captured During Day 16 (15th February 2013) Showing Acid Plume By-products being Transported within Cattai Creek Towards the Manning River

Image Captured (31st January 2013) Showing Acid Plume By-products being Discharged to the North Arm of the Manning River

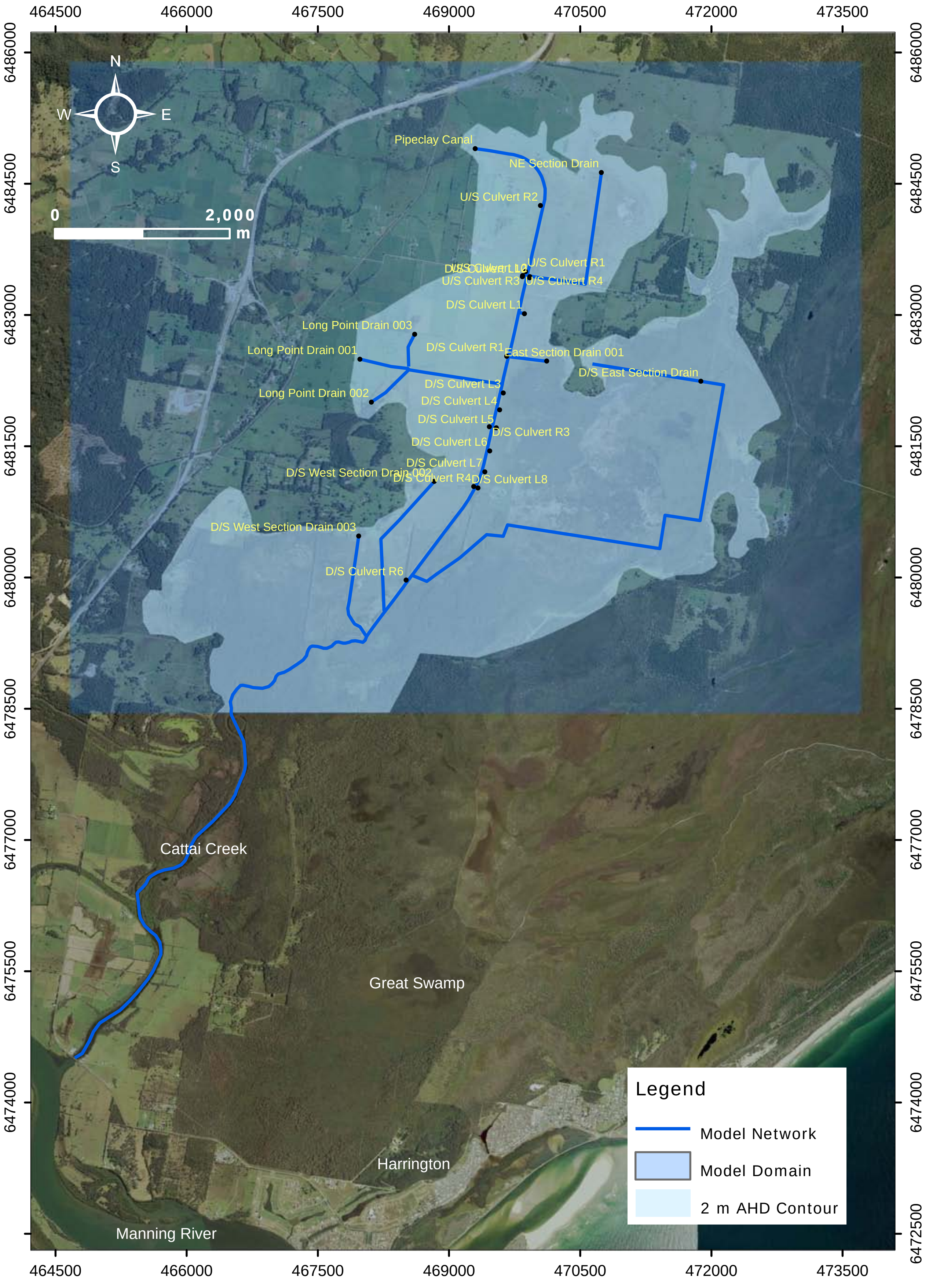
Prioritisation Zones for Floodplain Remediation



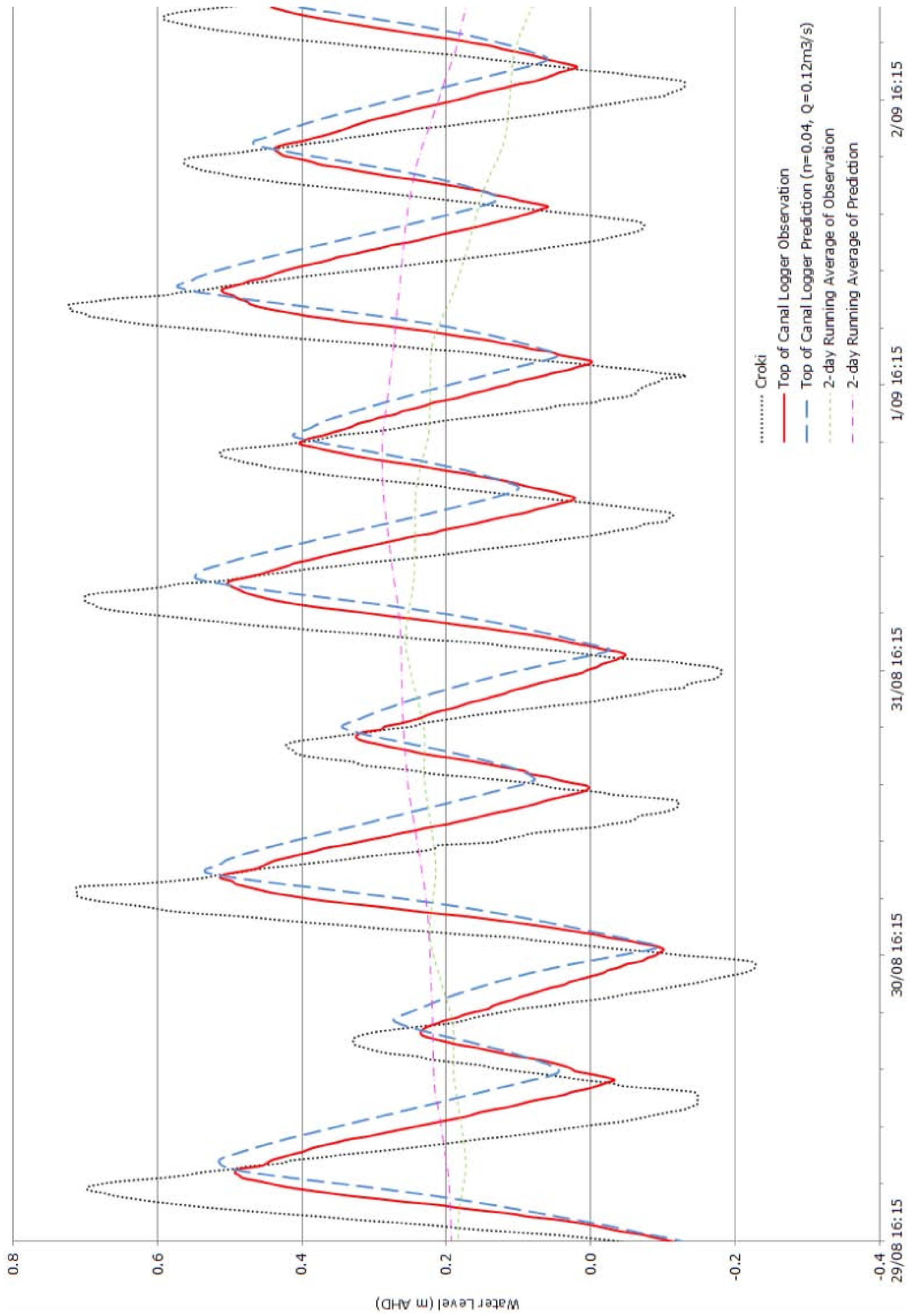
Selected Properties Currently Going Through Acquisition and Supported by Priority Assessment



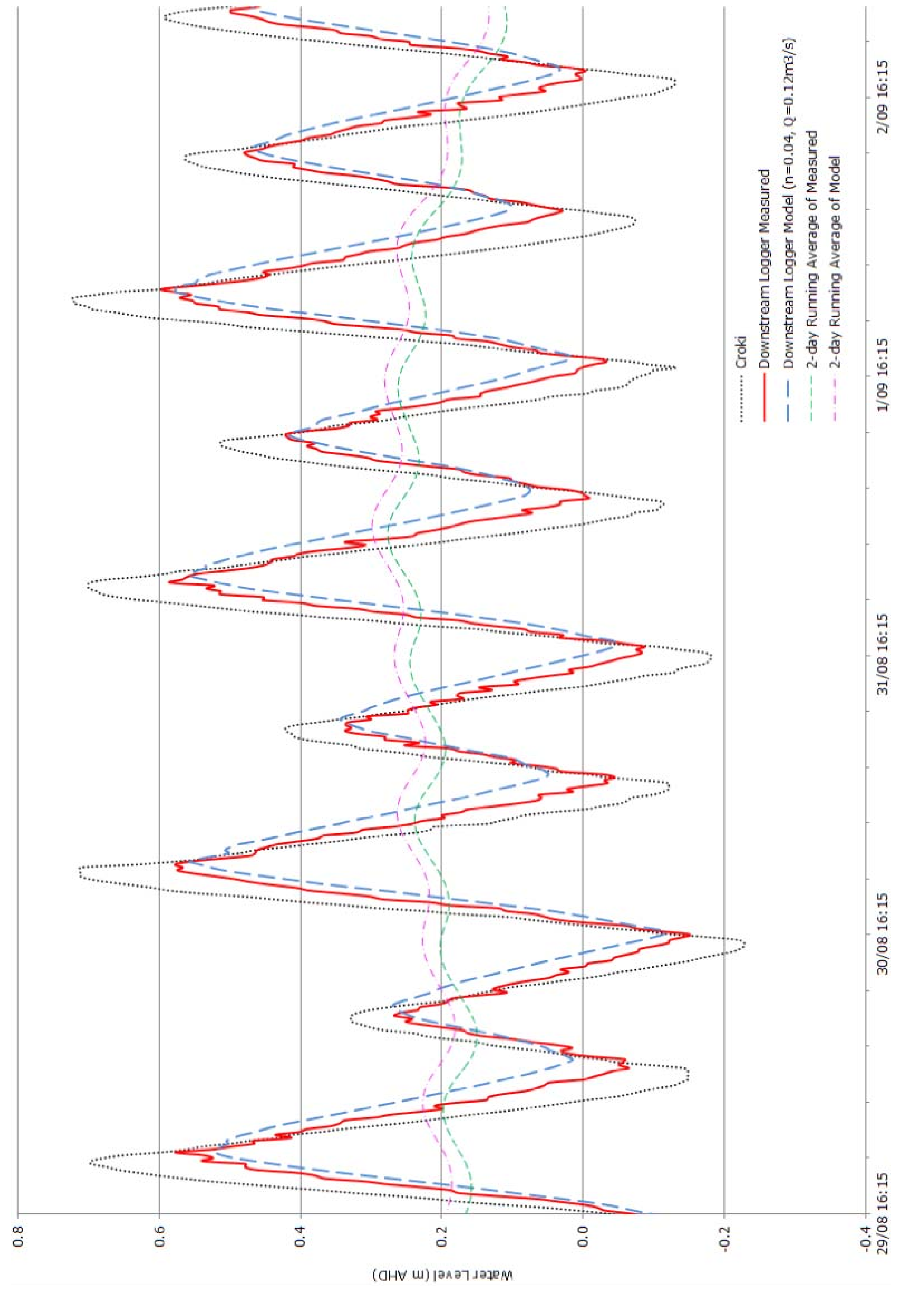
Conceptual Process of Building a Computer Model with Increasing Complexity



MIKE FLOOD Model Domain.
Map Projection is MGA-56.



1D Model Calibration. Location: Top of Canal; Conditions: n = 0.04, Q = 0.12 m^3/s
(29/08/2012 4:15 PM – 03/09/2012 12:00 AM)



1D Model Calibration. Location: Middle Canal; Conditions: n = 0.04, Q = 0.12 m^3/s
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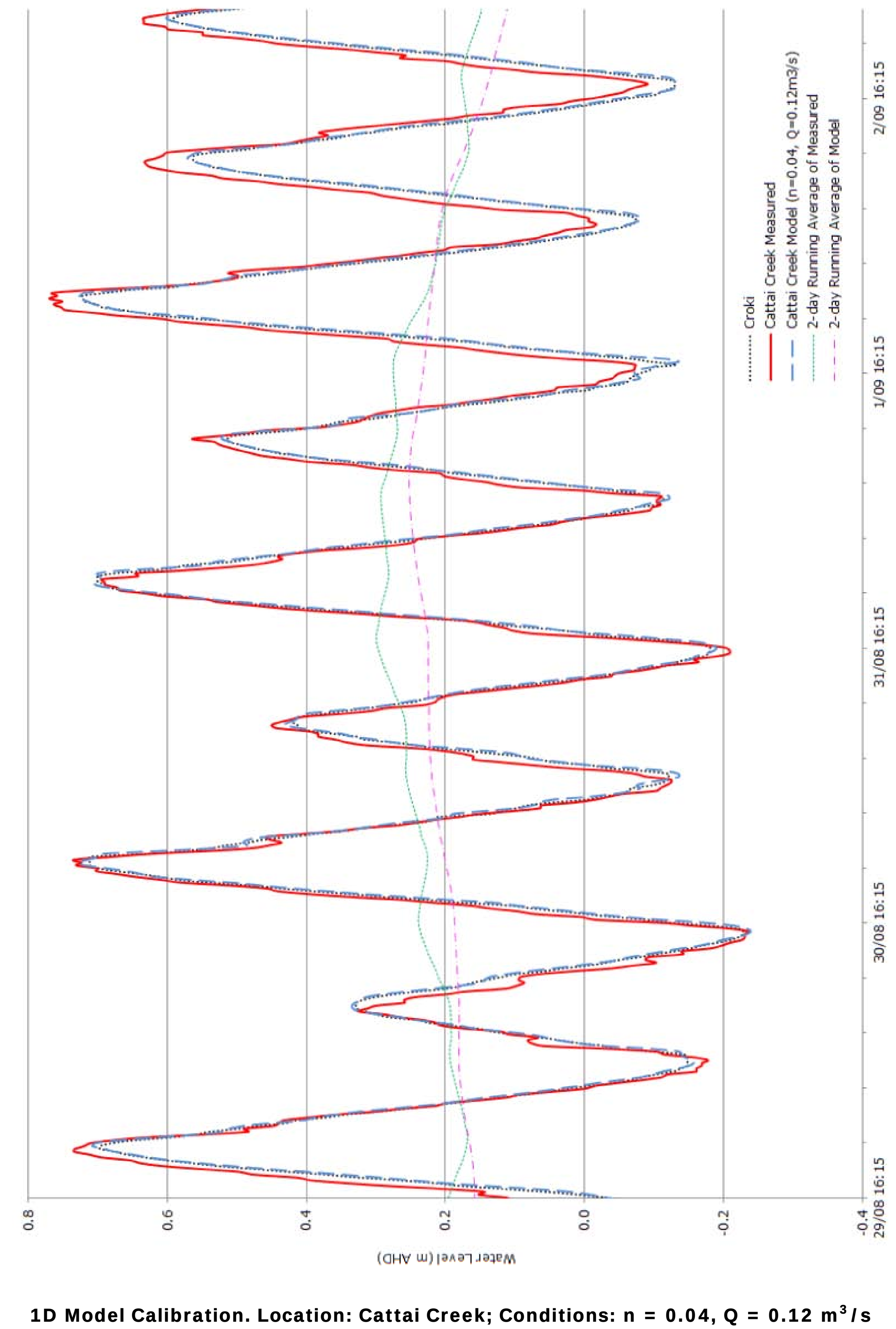
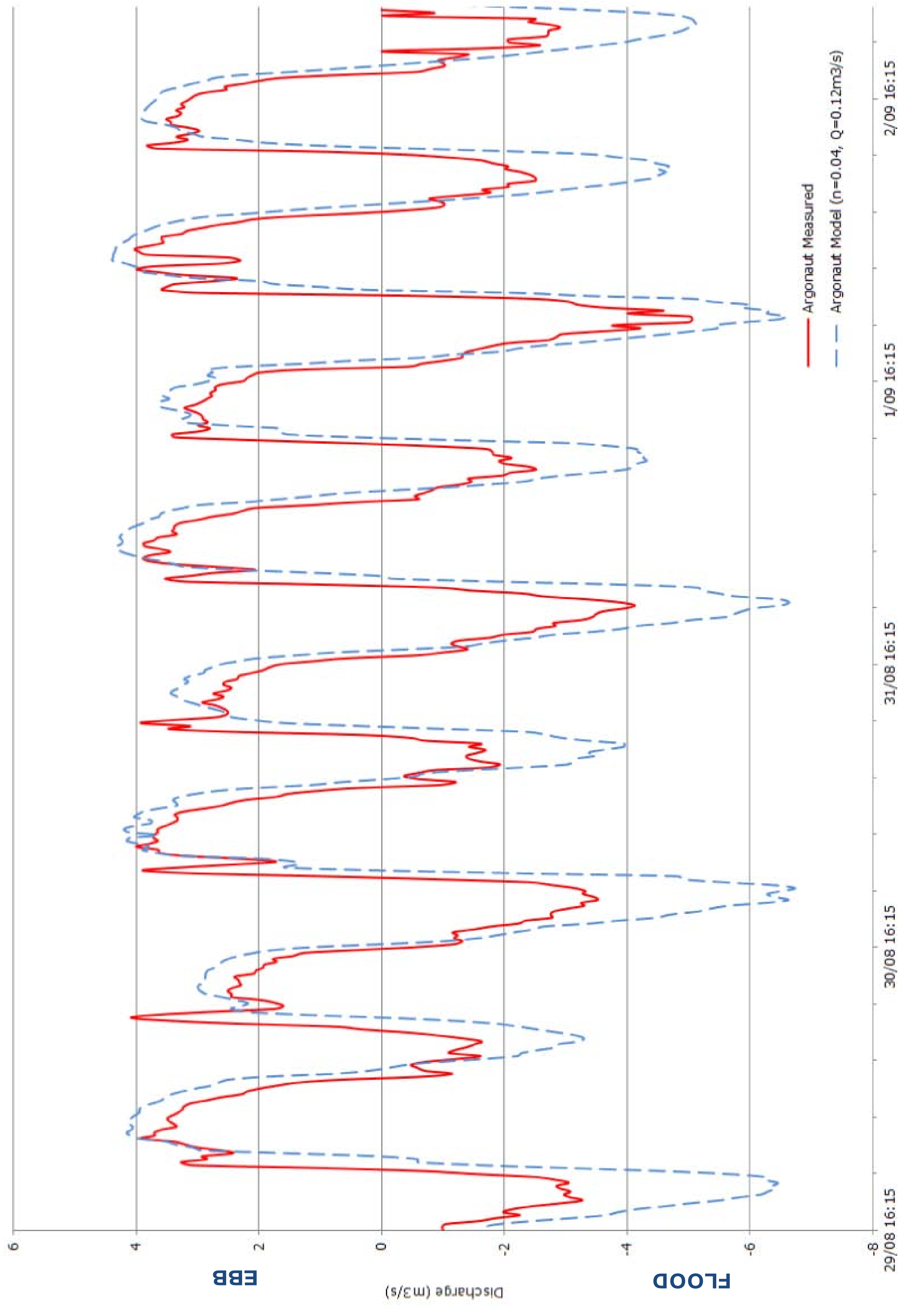
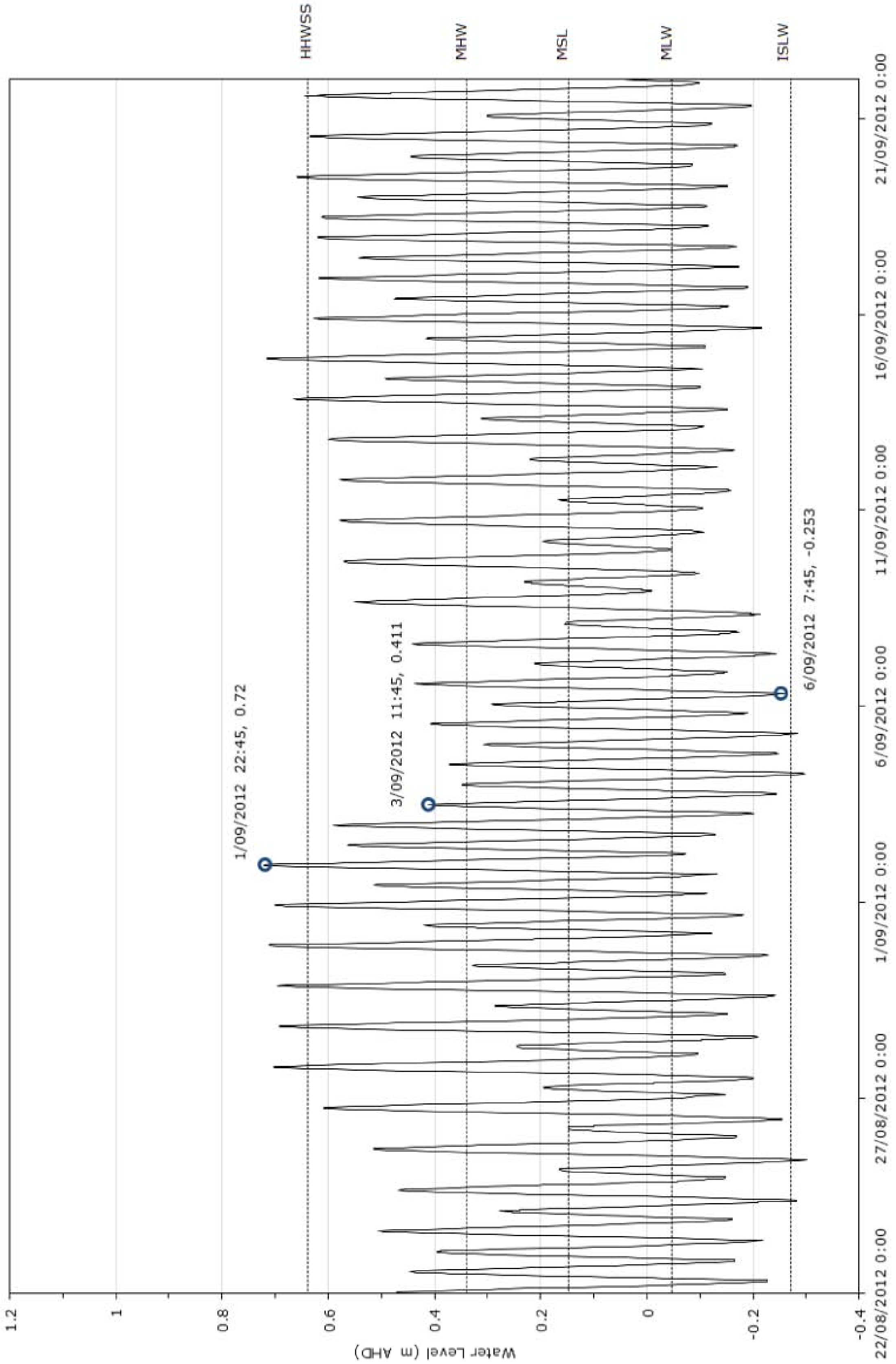


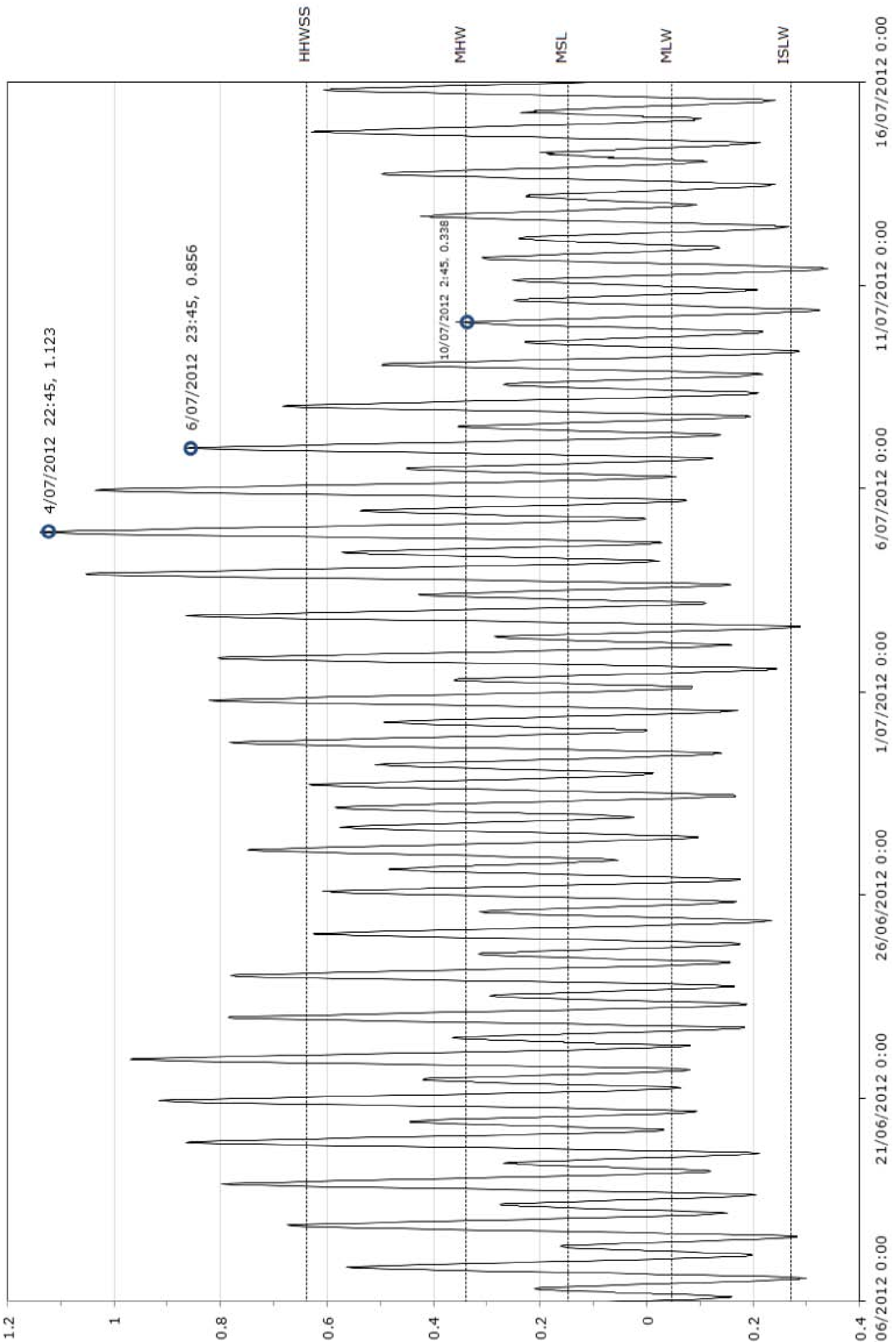
1D Model Calibration. Location: Cattai Creek; Conditions: n = 0.04, Q = 0.12 m^3/s (29/08/2012 4:15 PM – 03/09/2012 12:00 AM)



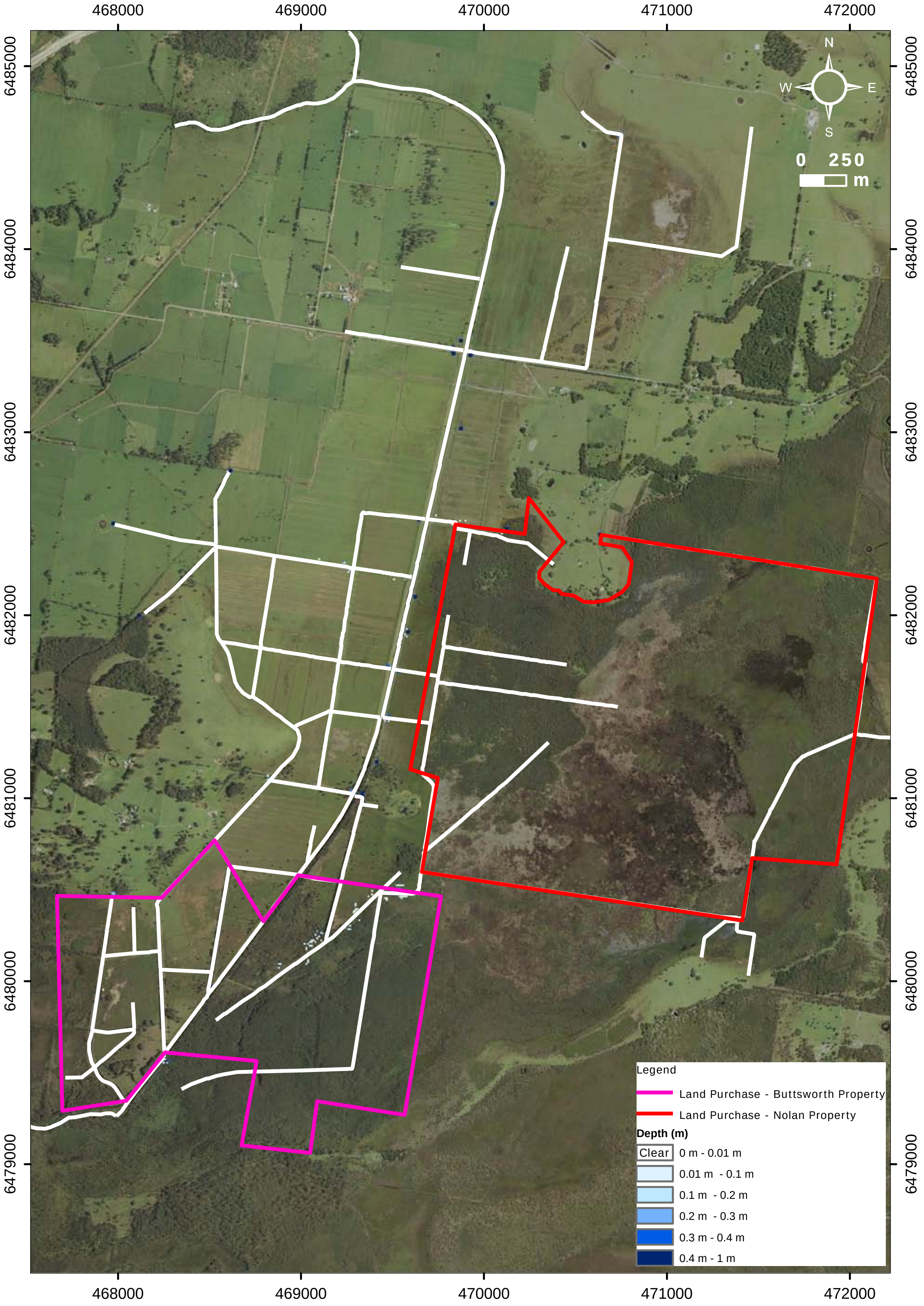
1D Model Calibration. Location: Bottom of Canal; Conditions: n = 0.04, Q = 0.12 m^3/s (29/08/2012 4:15 PM – 03/09/2012 12:00 AM)



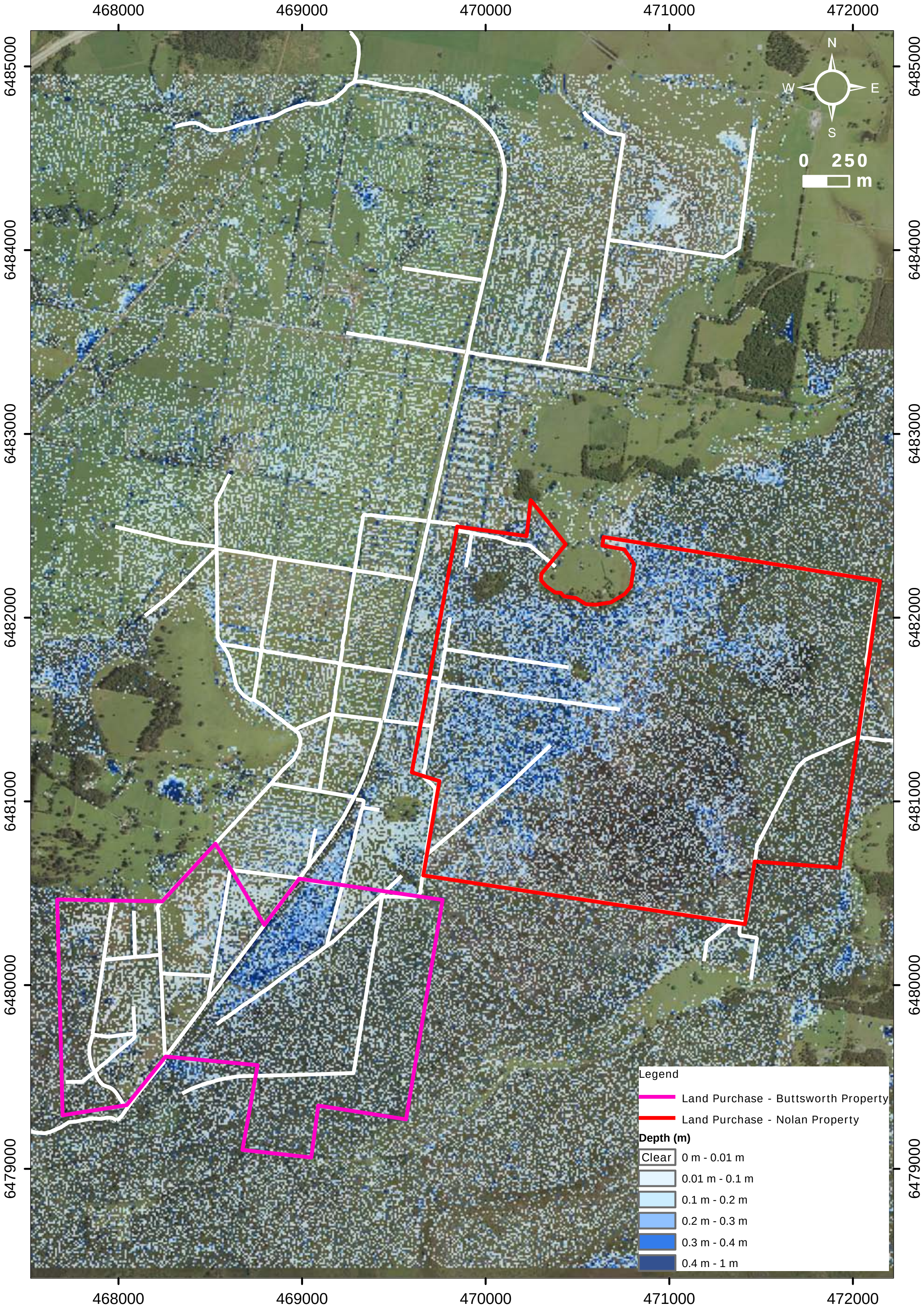
Boundary Tidal Levels "Dry Period" And Selected Periods To Display 2-D Results



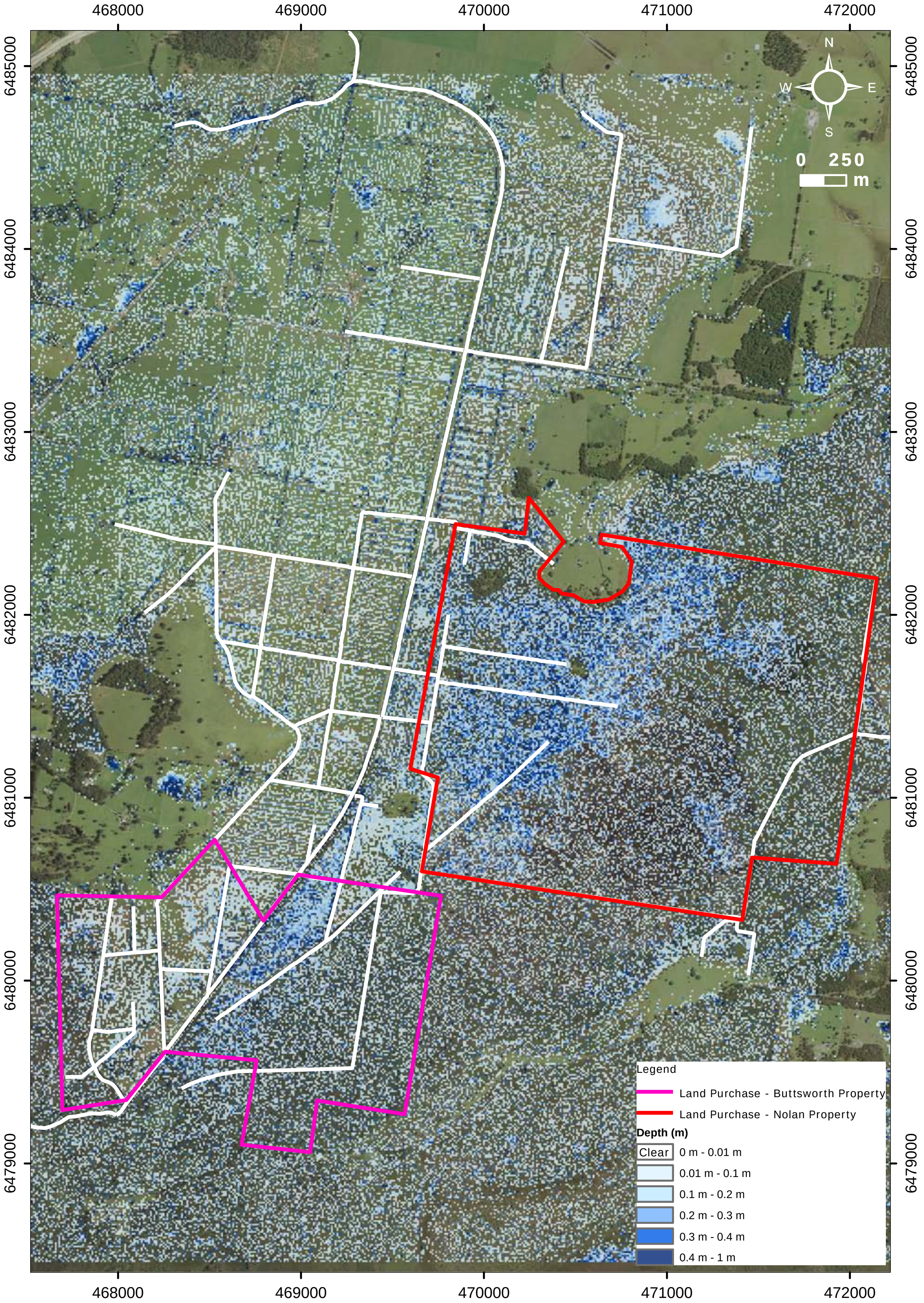
Boundary Tidal Levels "Wet Period" And Selected Periods To Display 2-D Results



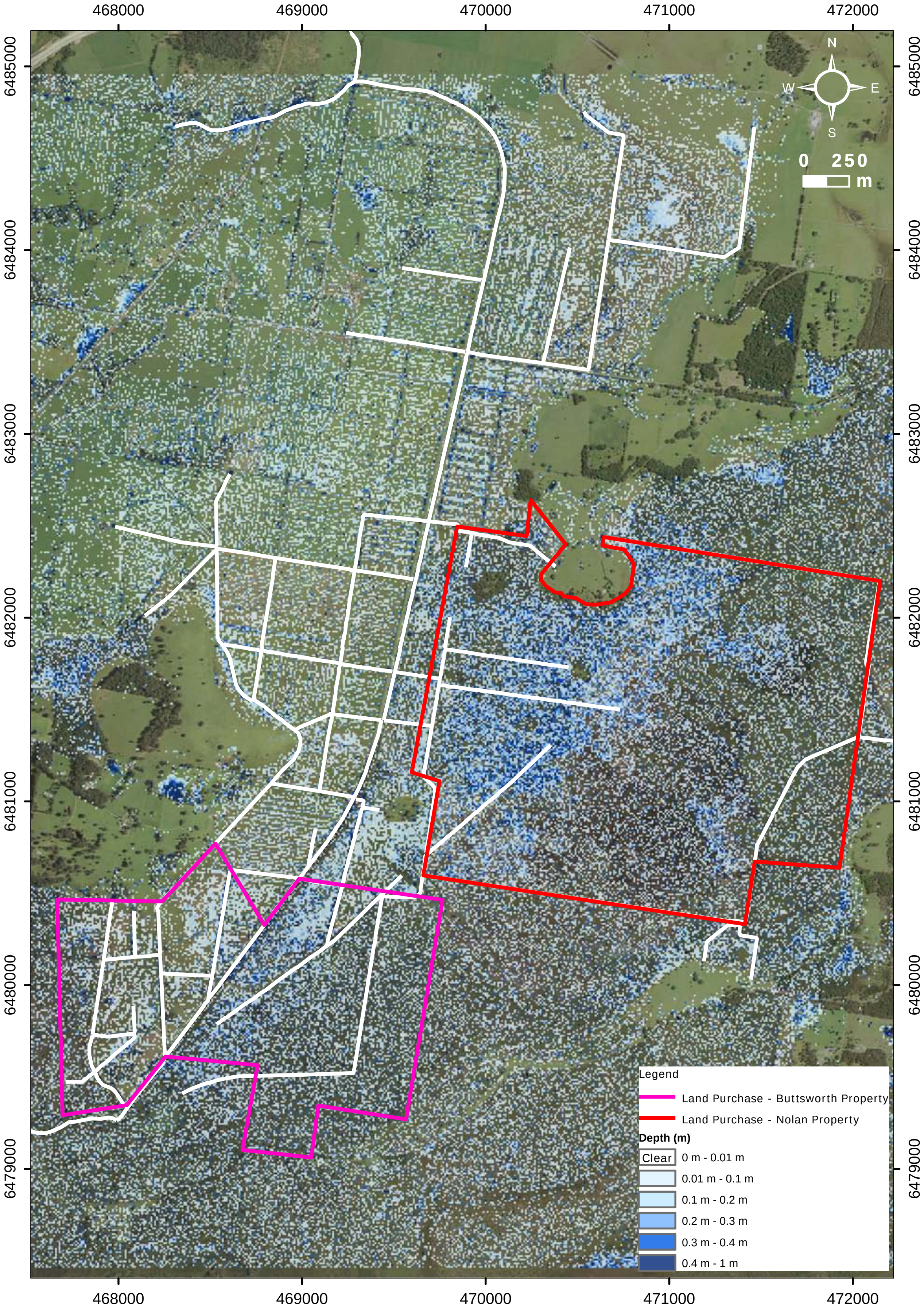
Model Run #1A: Existing Conditions Dry Periods
No Inundation



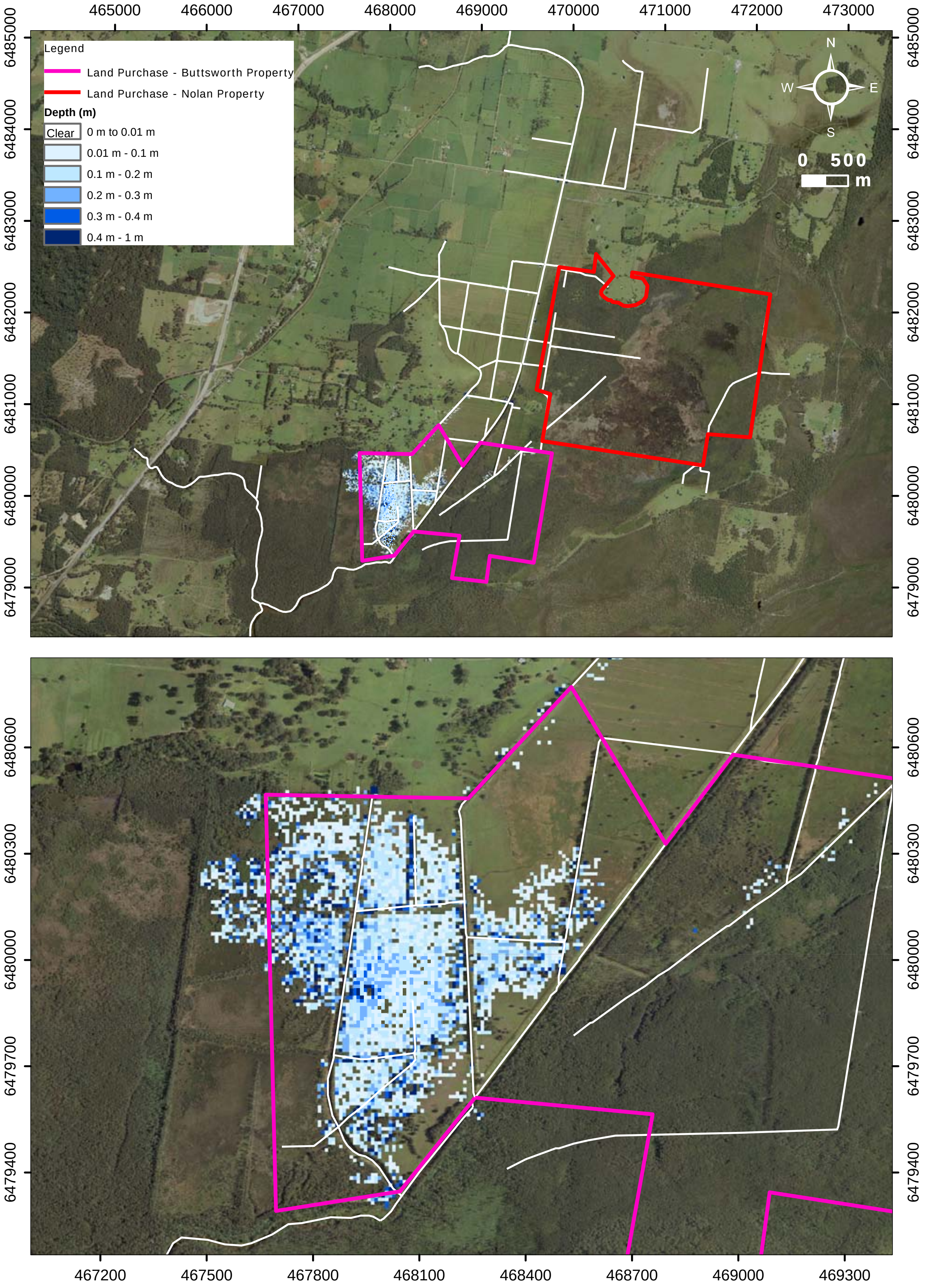
Model Run #1B Inundation: Existing Conditions Wet Periods
4/7/2012 10:45 PM



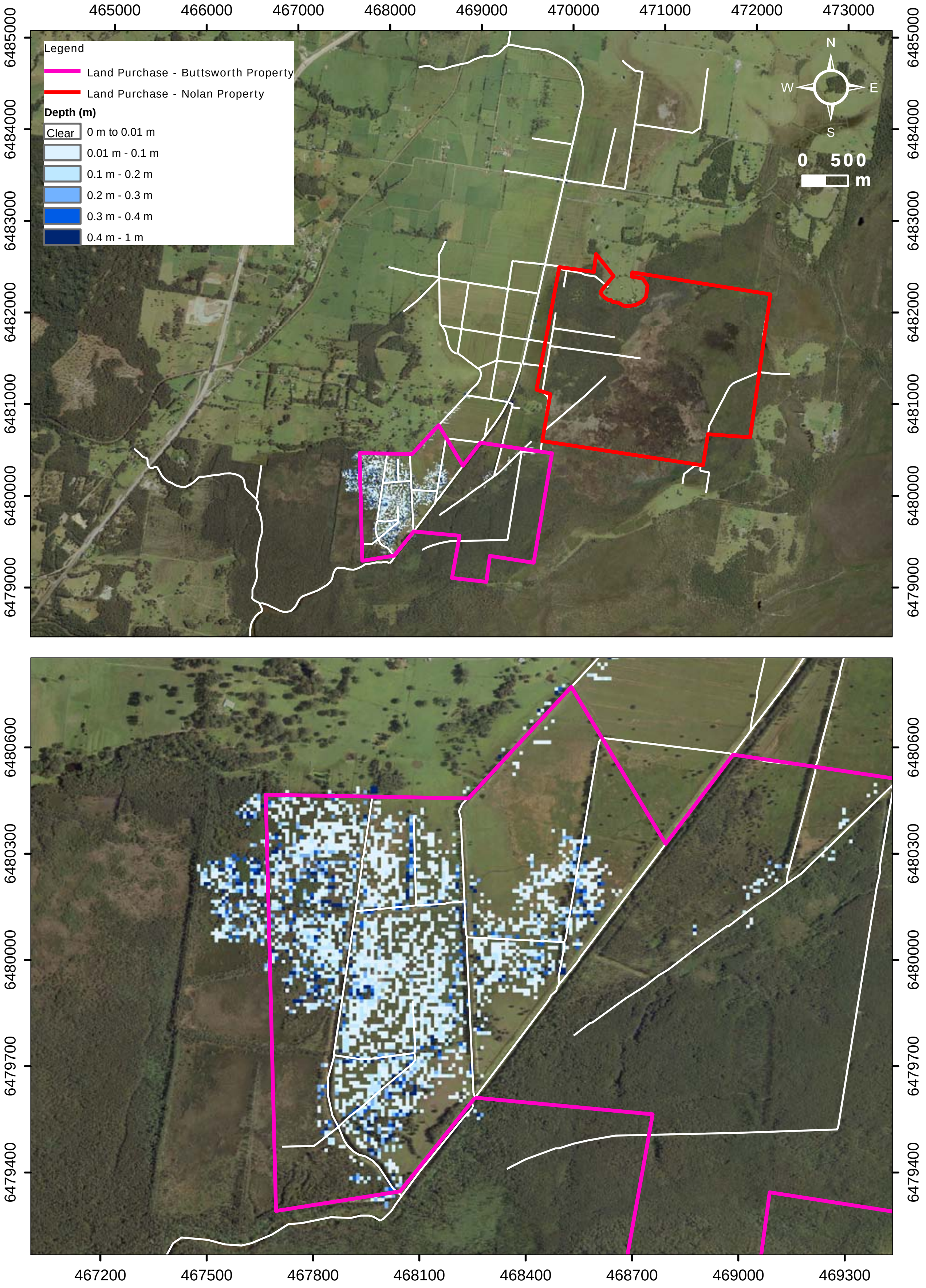
Model Run #1B Inundation: Existing Conditions Wet Period
6/7/2012 11:45 PM



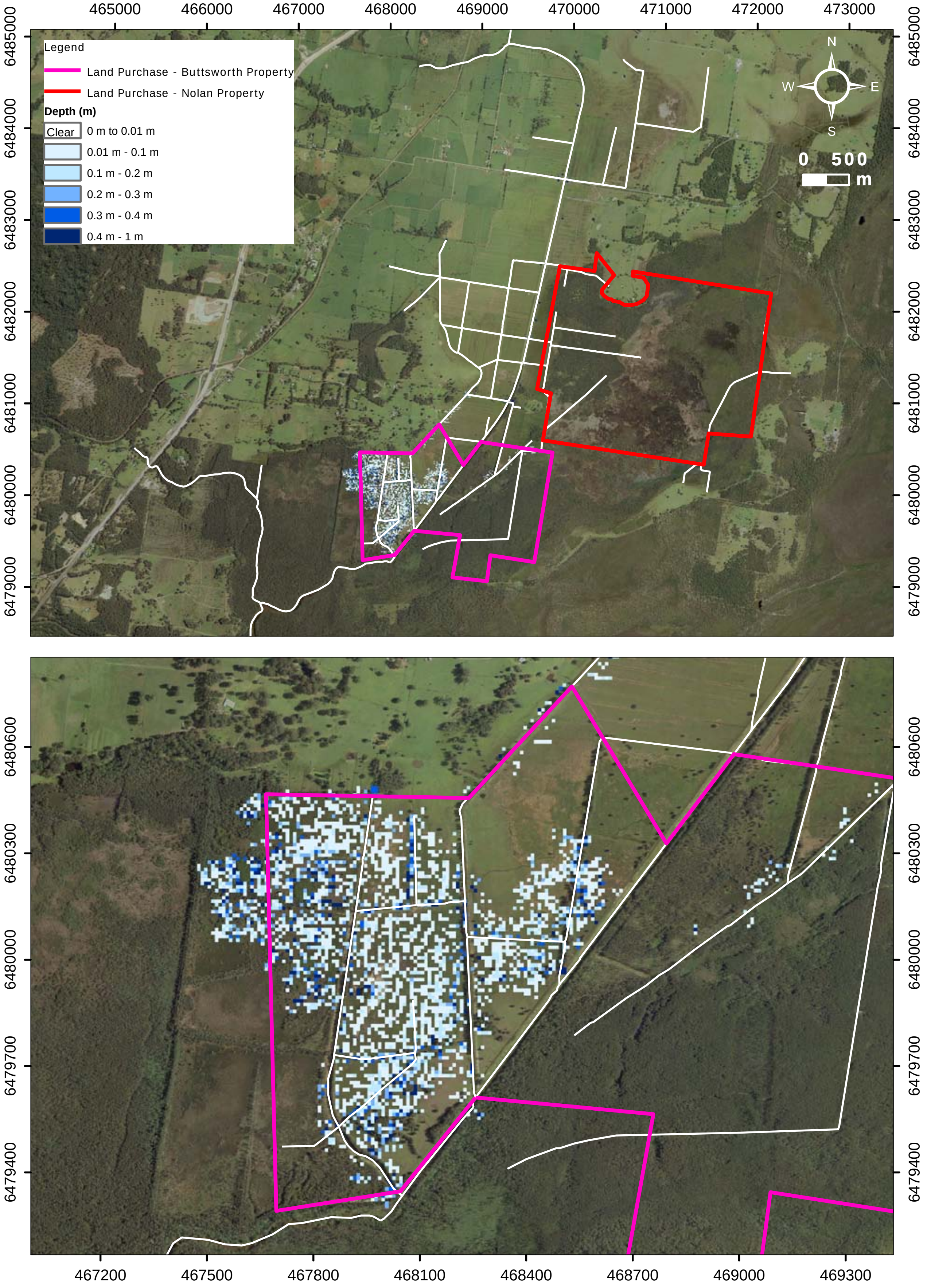
Model Run #1B Inundation: Existing Conditions Wet Conditions
10/7/2012 2:45 AM



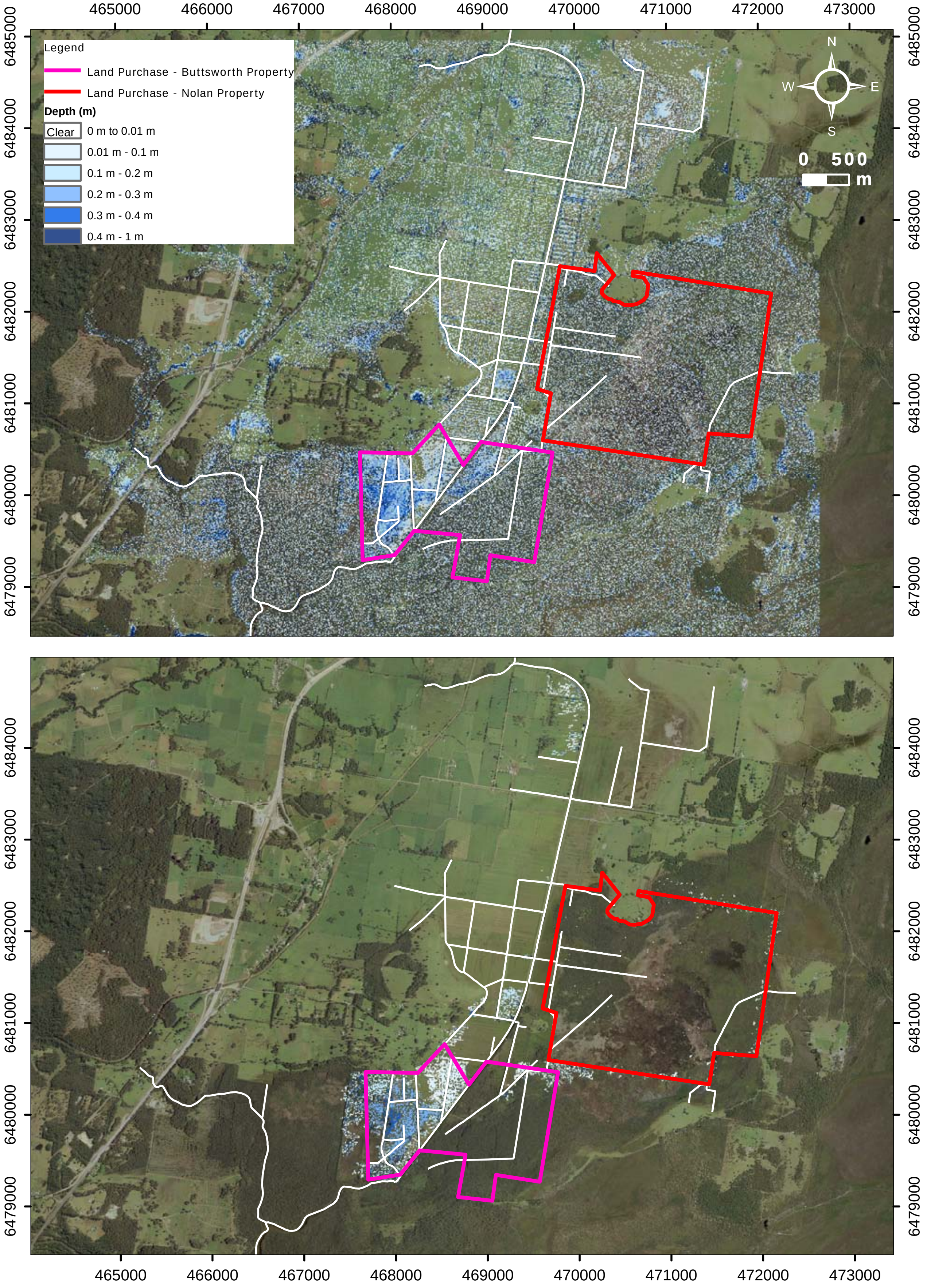
Model Run #2A Inundation
1/9/2012 10:45 PM



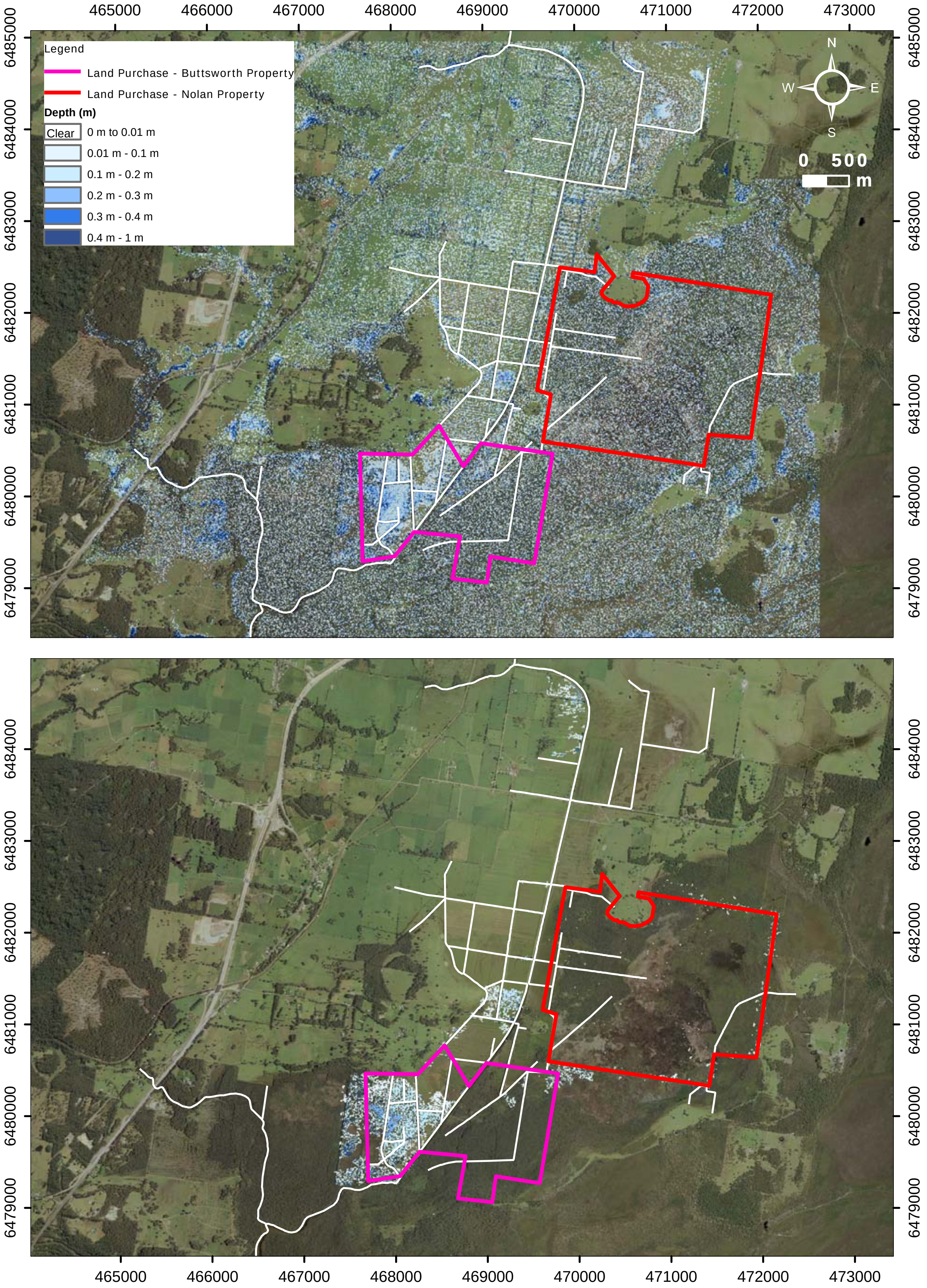
Model Run #2A Inundation
3/9/2012 11:45 AM



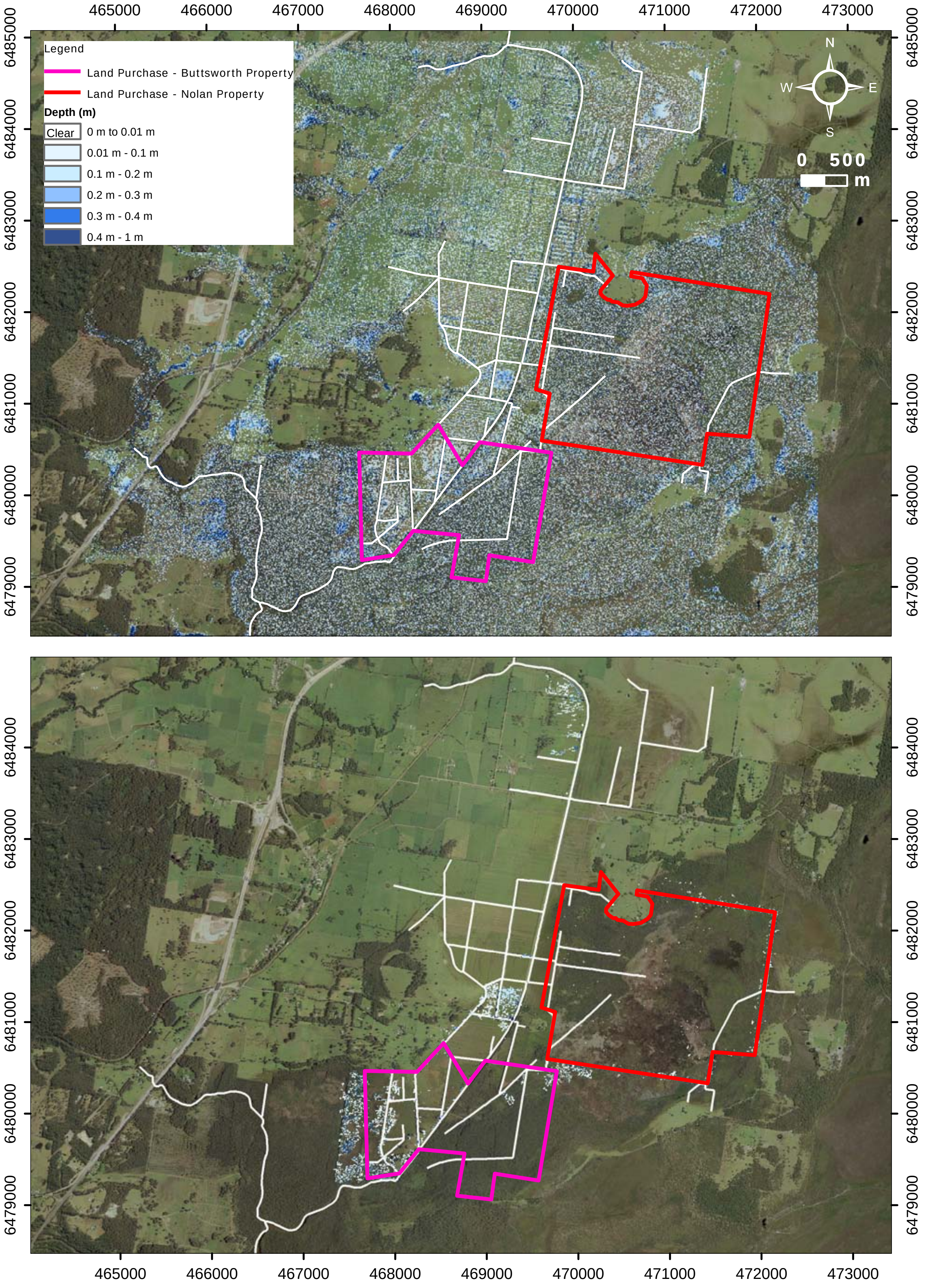
Model Run #2A Inundation
6/9/2012 7:45 AM



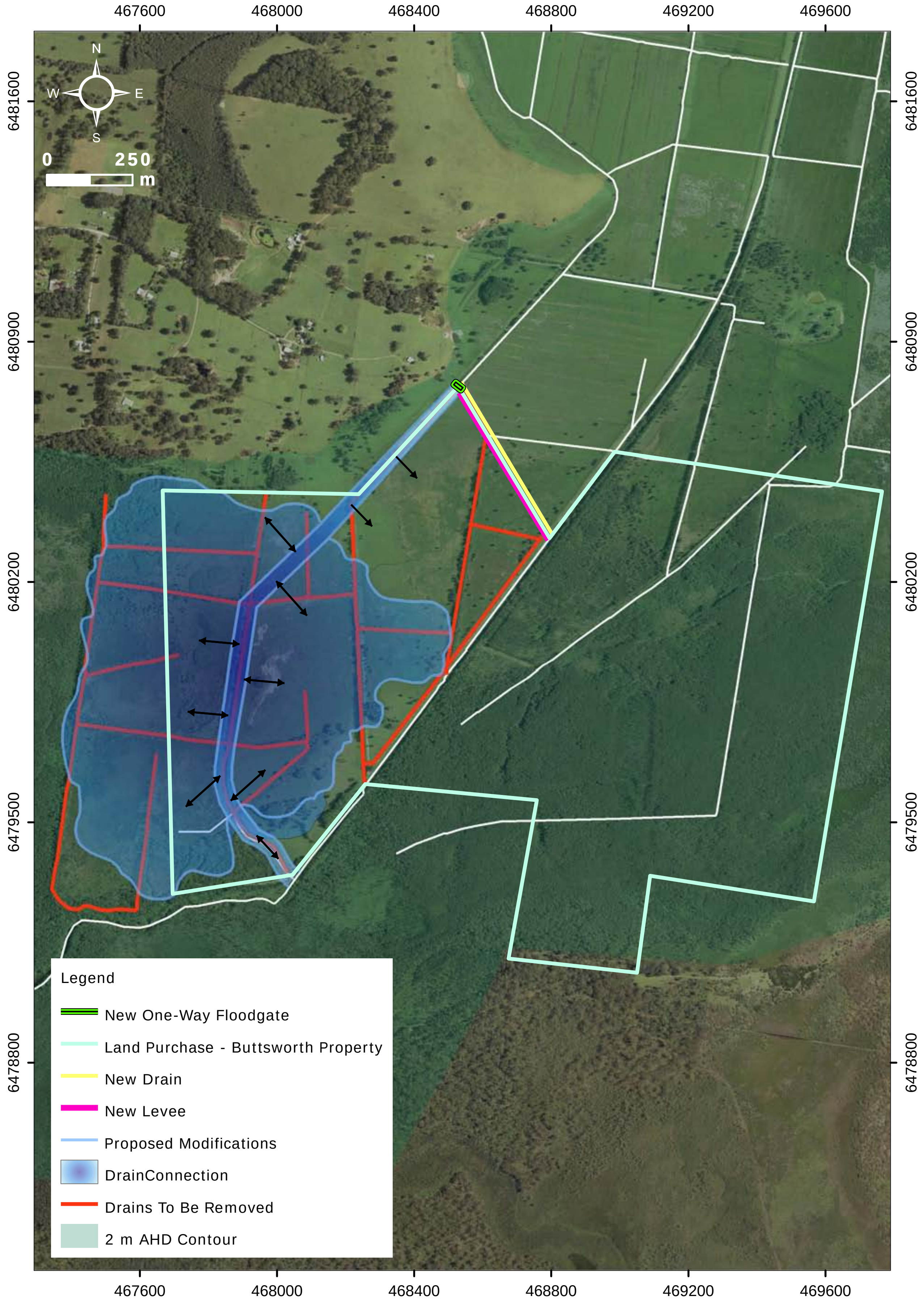
Model Run #2B Inundation (Top) and Increase in Water Depth Compared to Model Run #1B (Bottom)
4/7/2012 10:45 PM



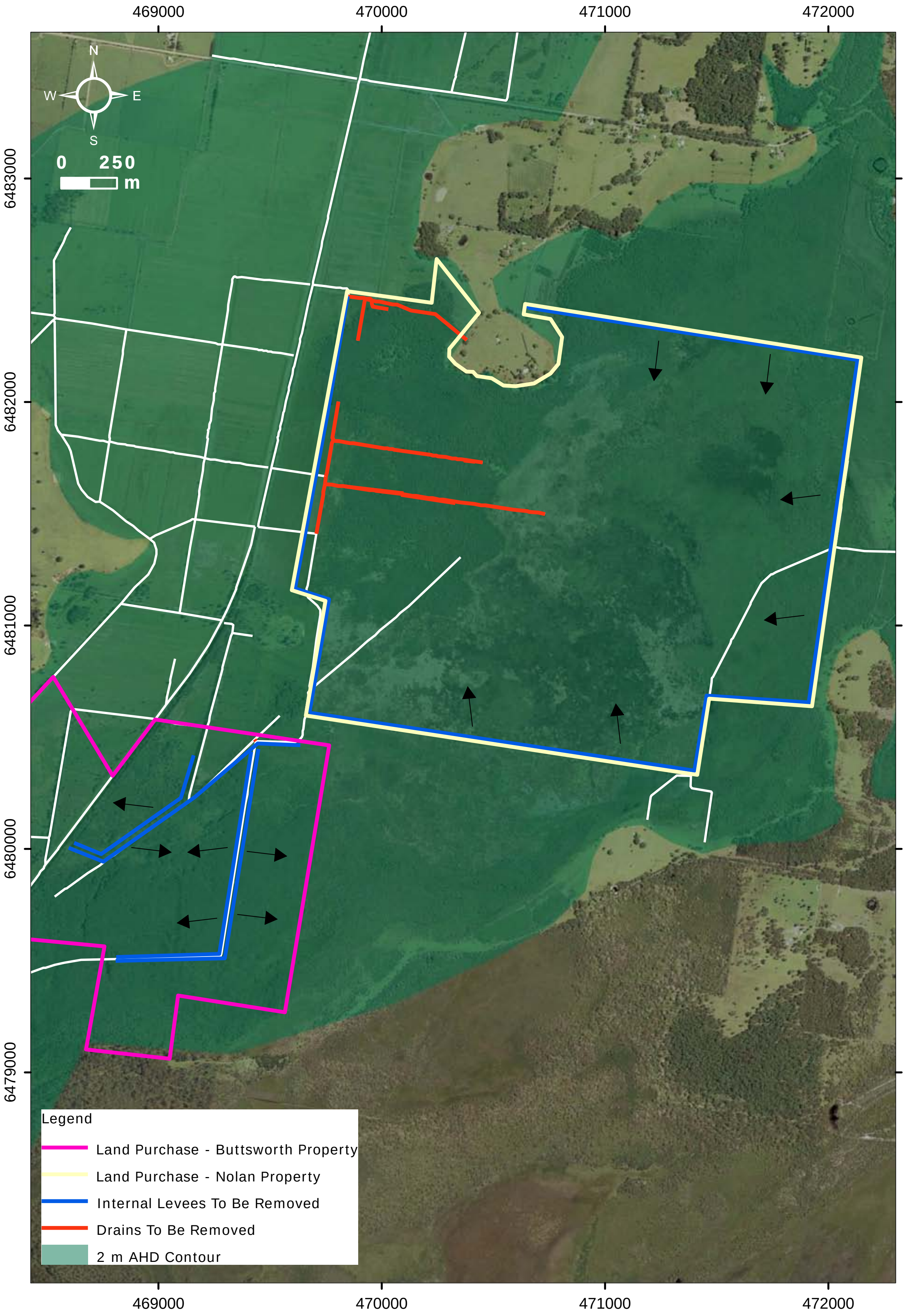
Model Run #2B Inundation (Top) and Increase in Water Depth Compared to Model Run #1B (Bottom)
6/7/2012 11:45 PM



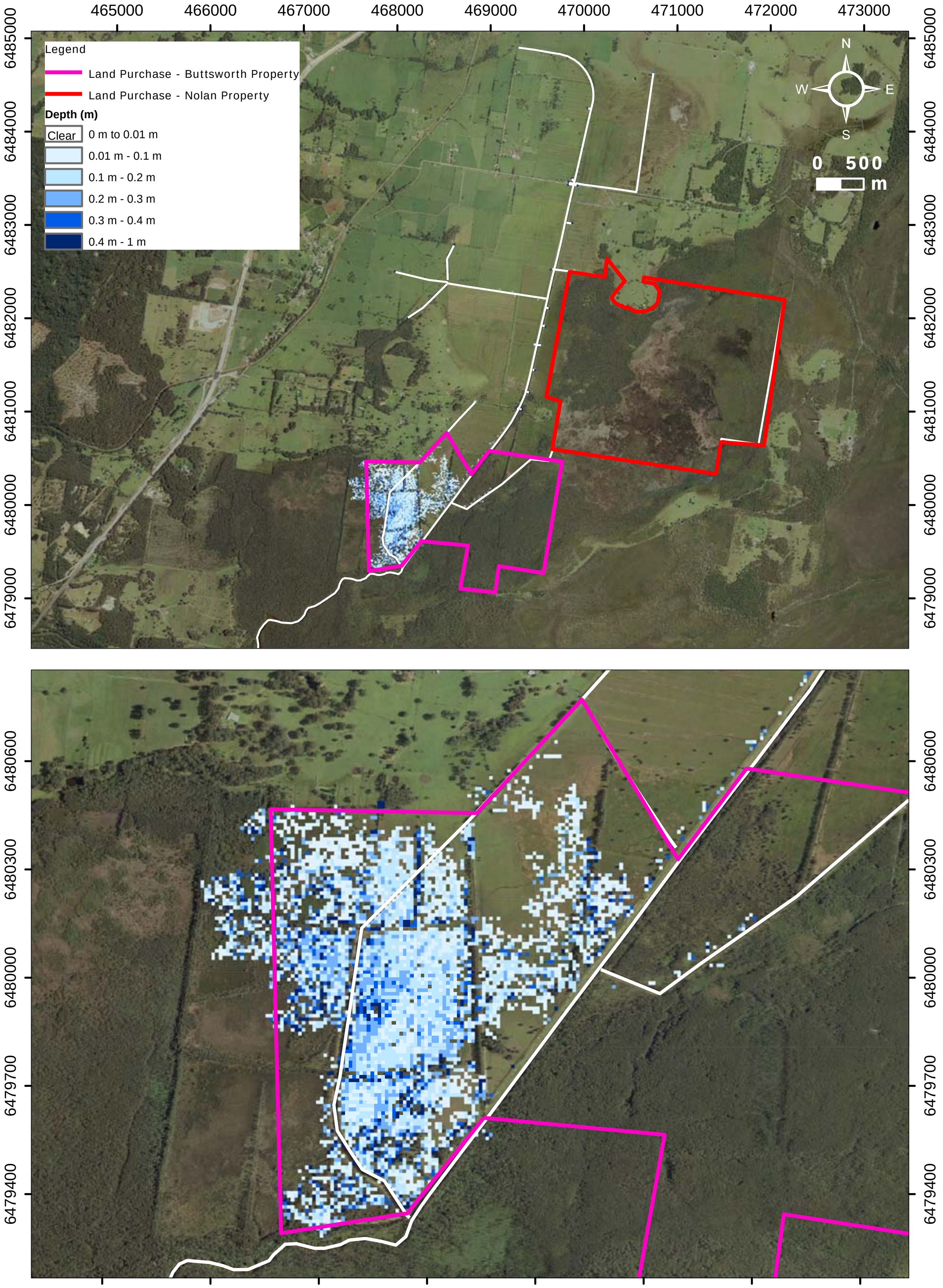
Model Run #2B Inundation (Top) and Increase in Water Depth Compared to Model Run #1B (Bottom)
10/7/2012 2:45 AM



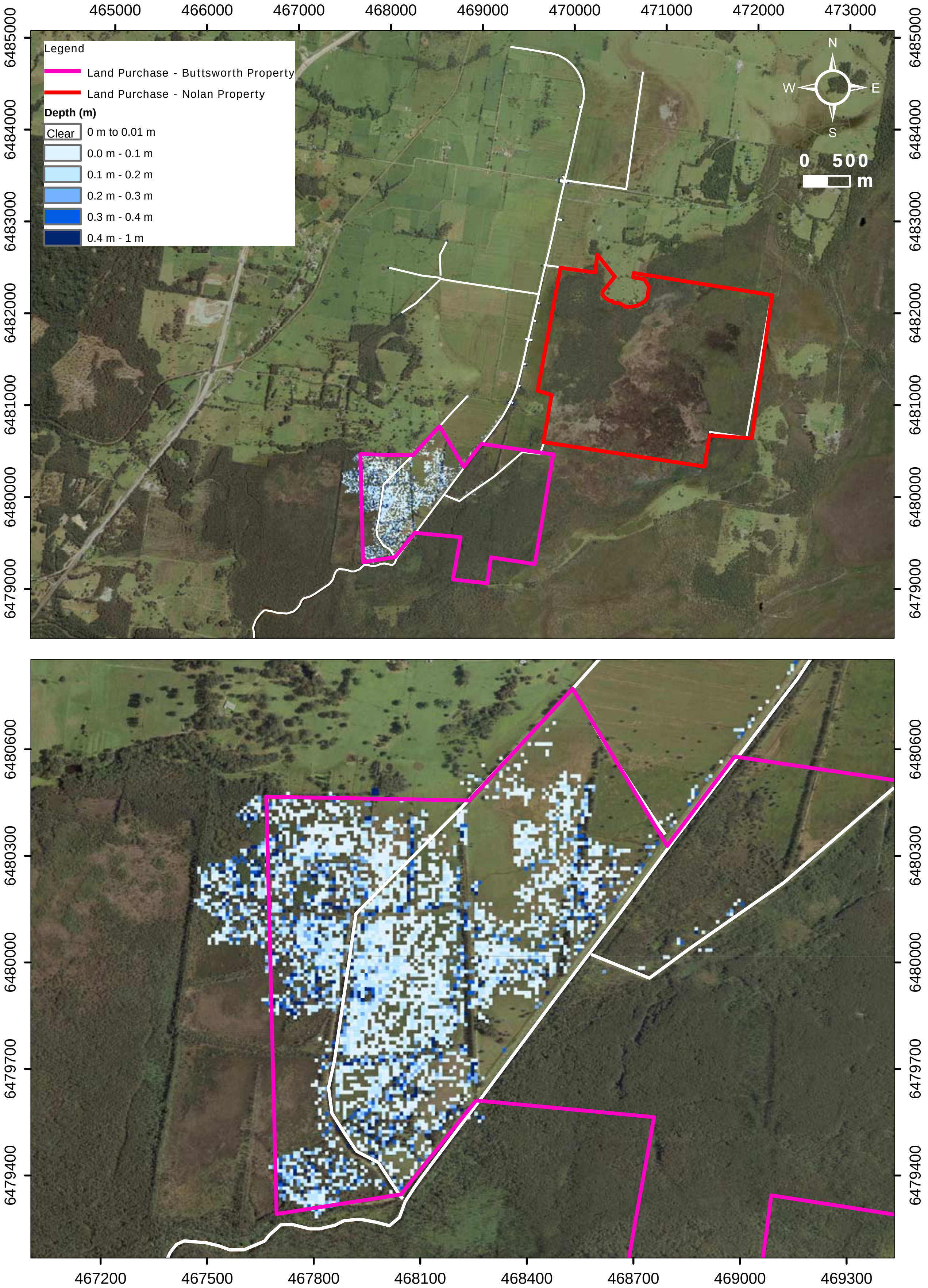
Conceptual Restoration Option 1 - South-West Property



Conceptual Restoration Option 1 - South-West Property.

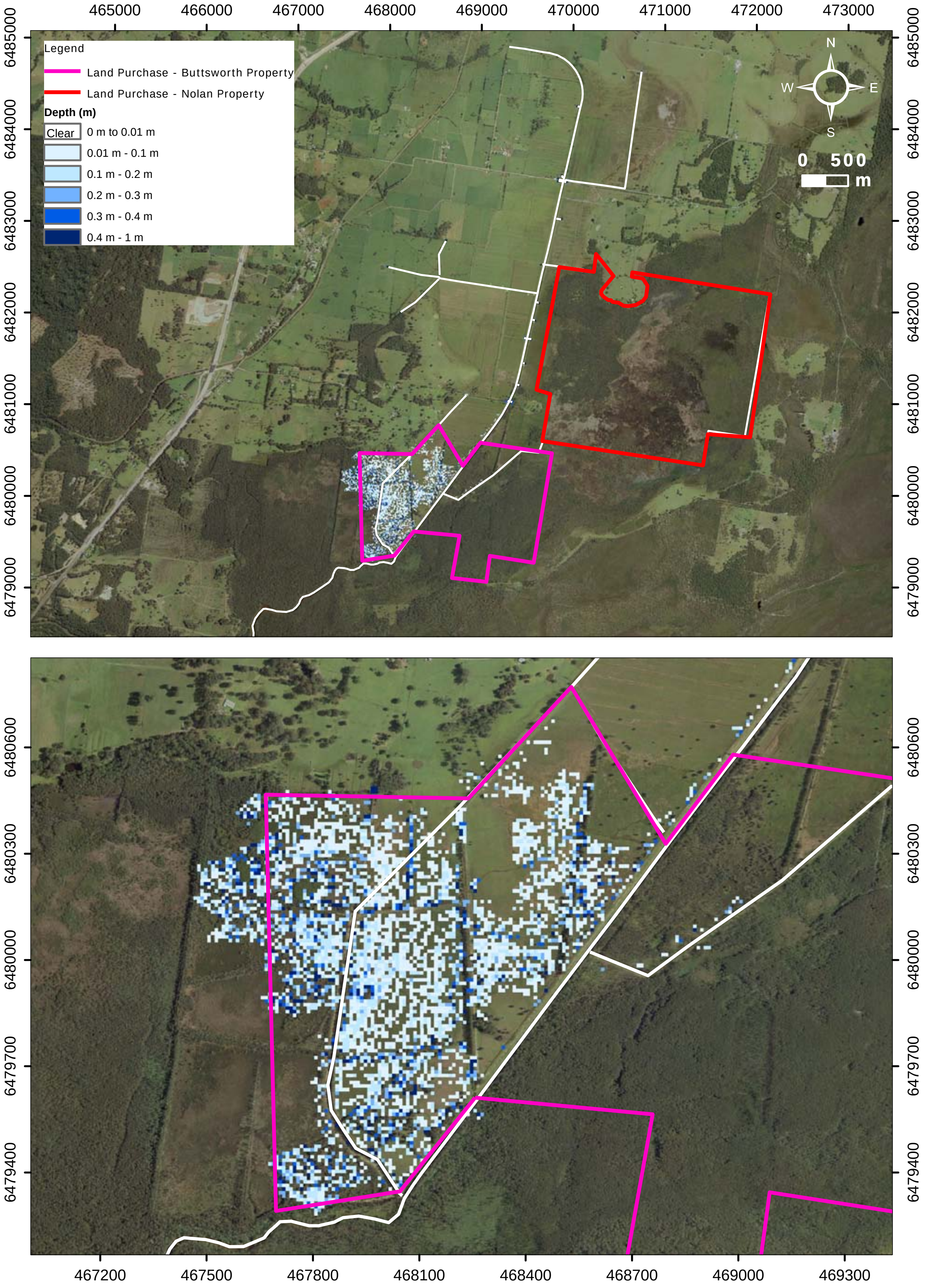


Model Run #3A Inundation
1/9/2012 10:45 PM

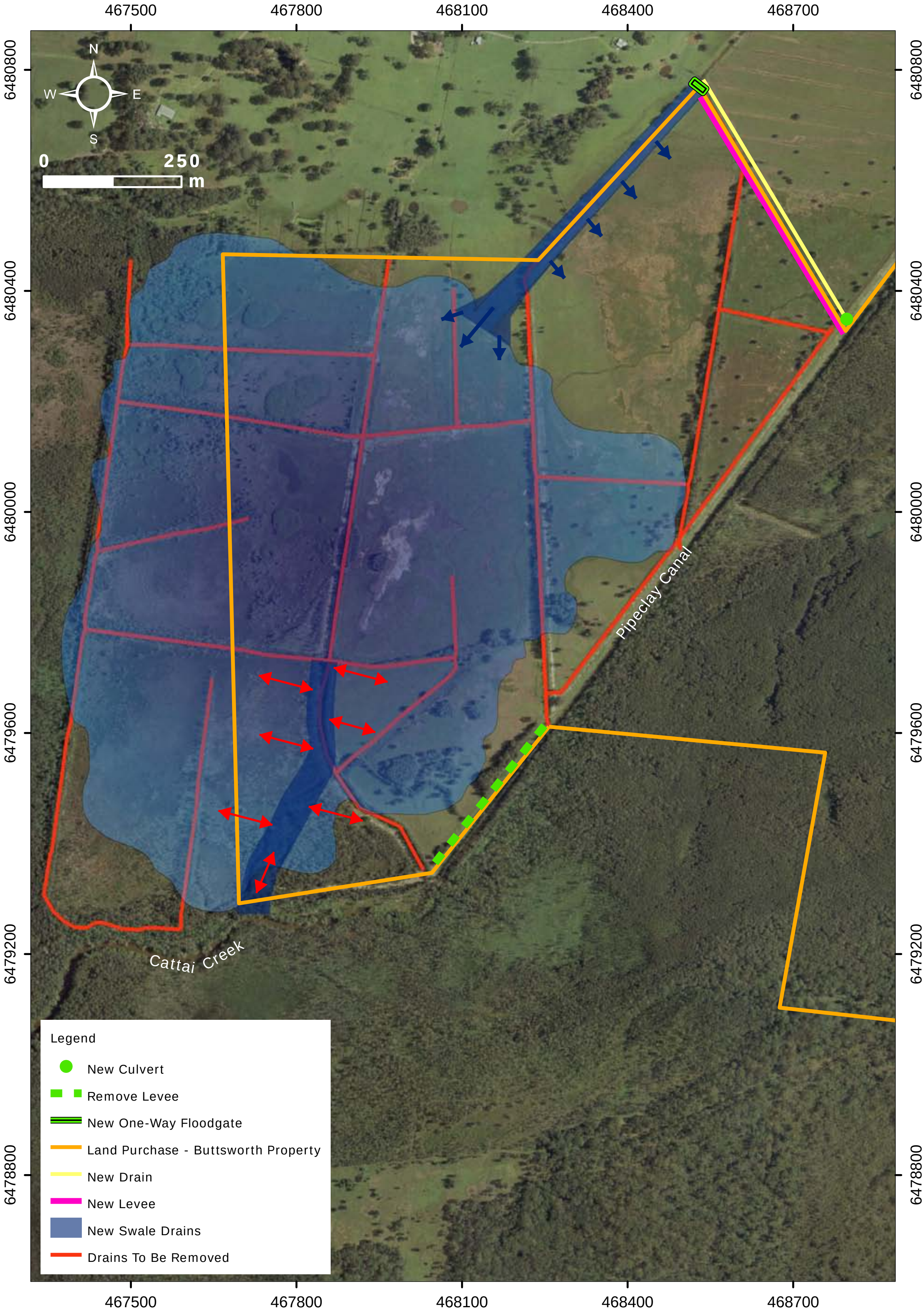


Model Run #3A Inundation
3/9/2012 11:45 AM

Figure 5.22

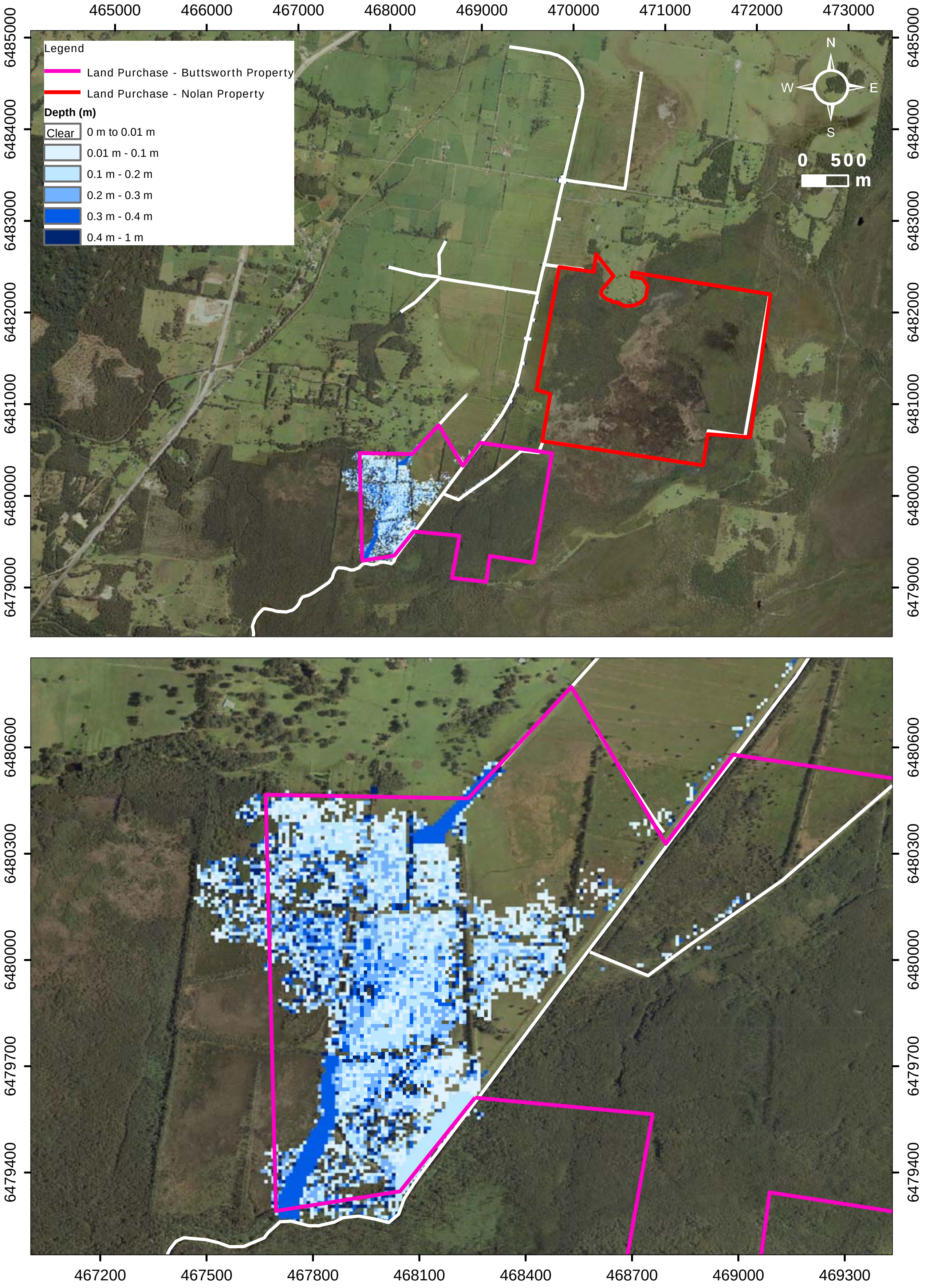


Model Run #3A Inundation
6/9/2012 7:45 AM

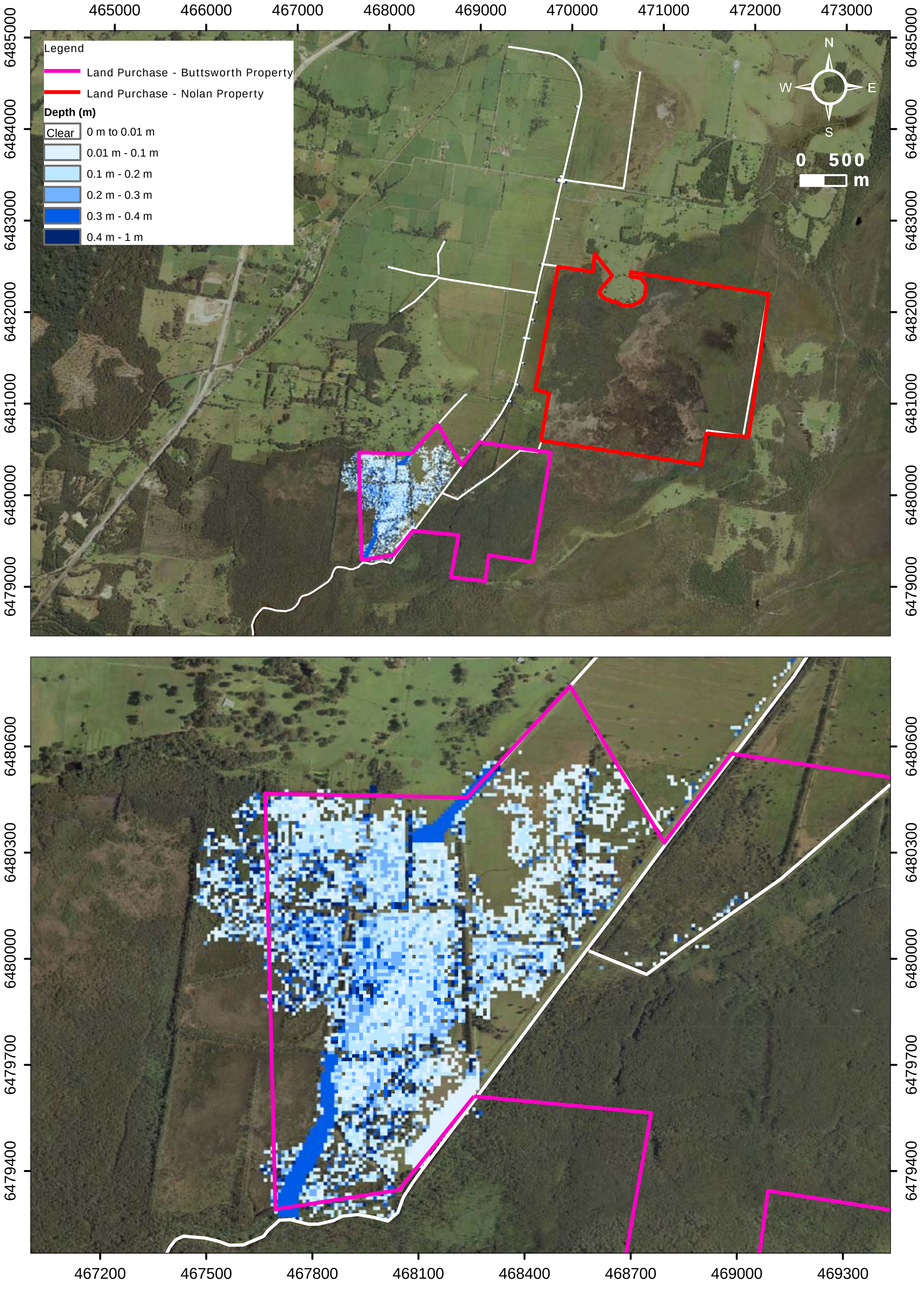


Conceptual Restoration Option 2 - South-West Property

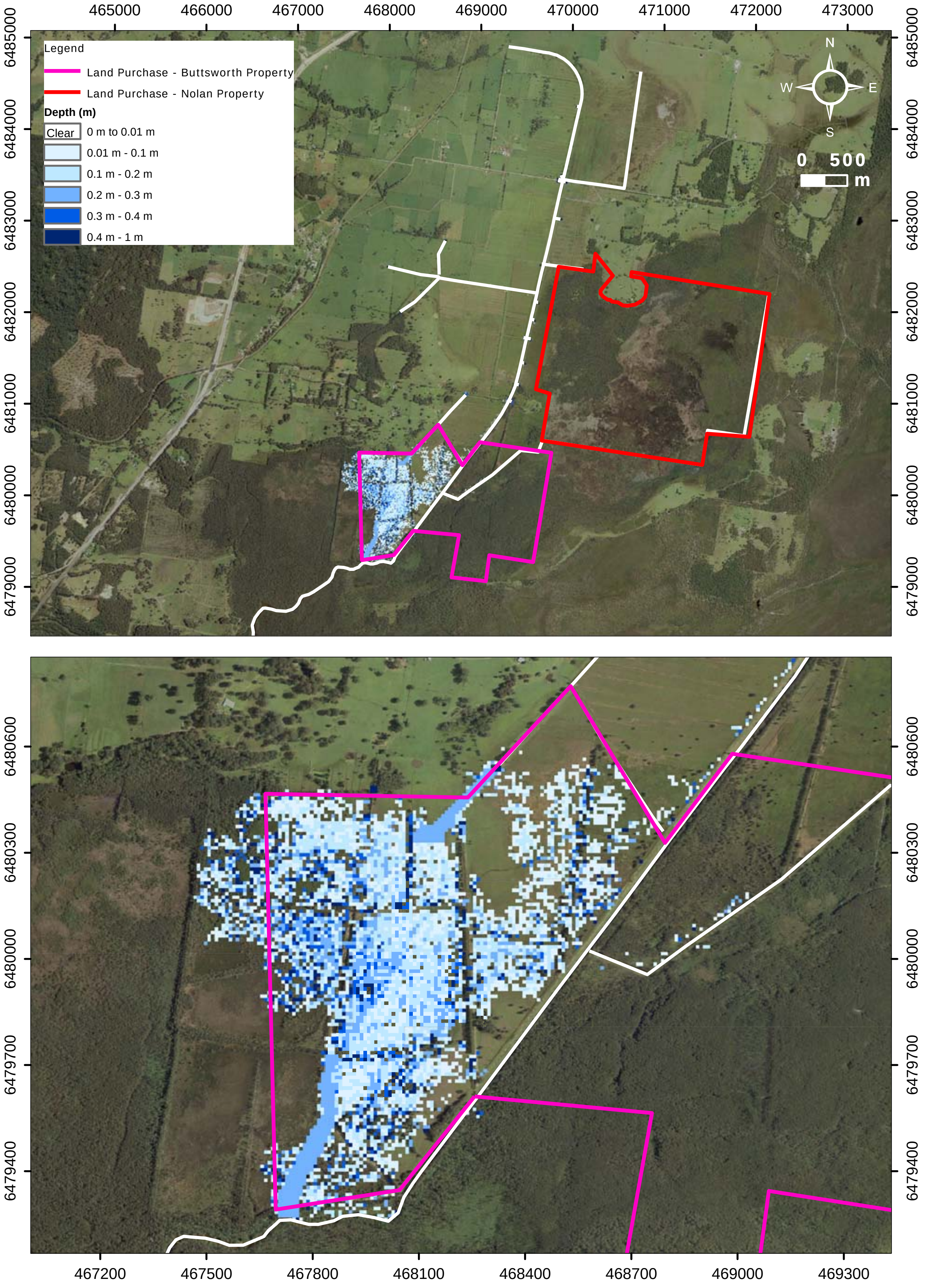
Figure 5.24



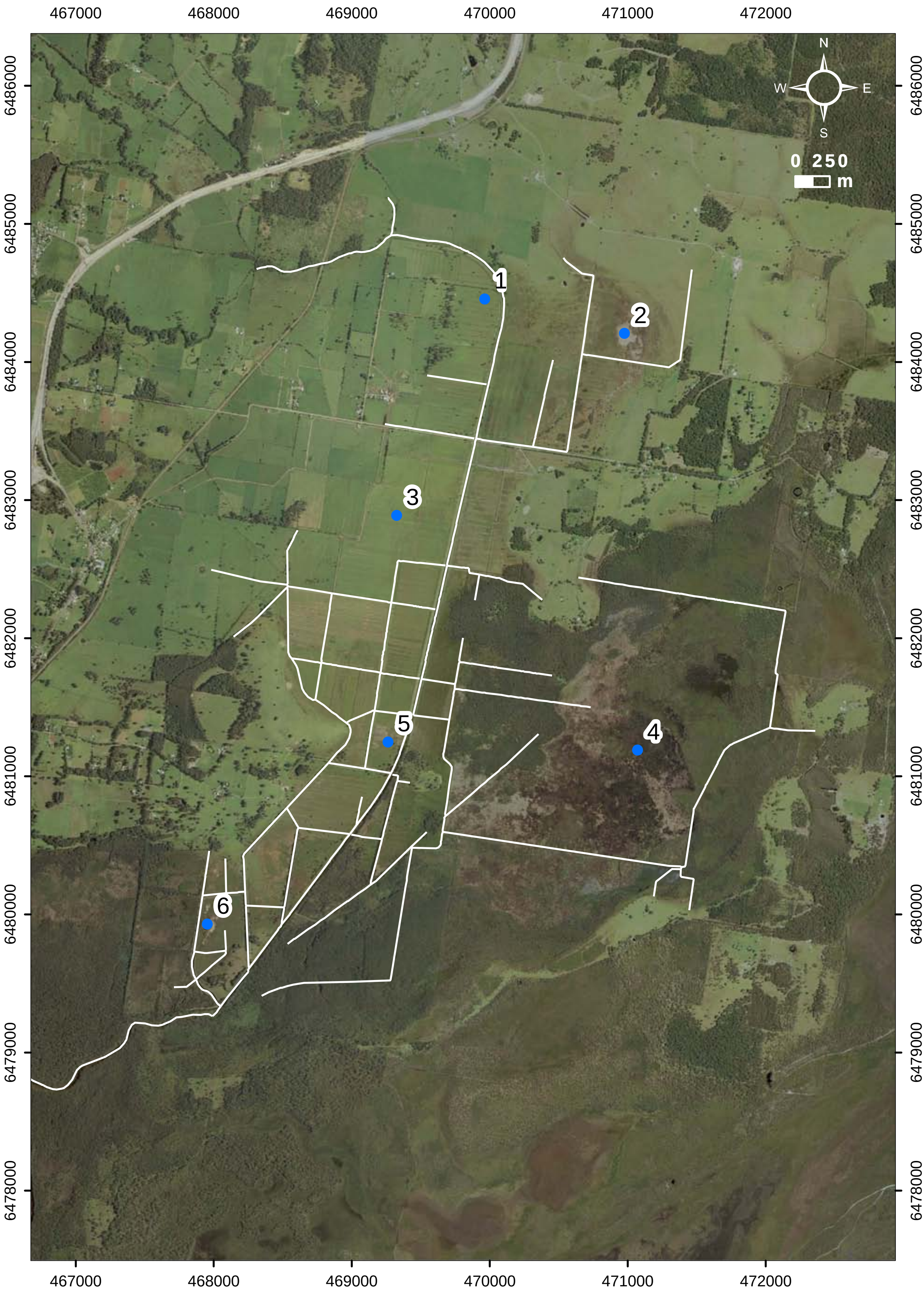
Model Run #3B Inundation
1/9/2012 10:45 PM



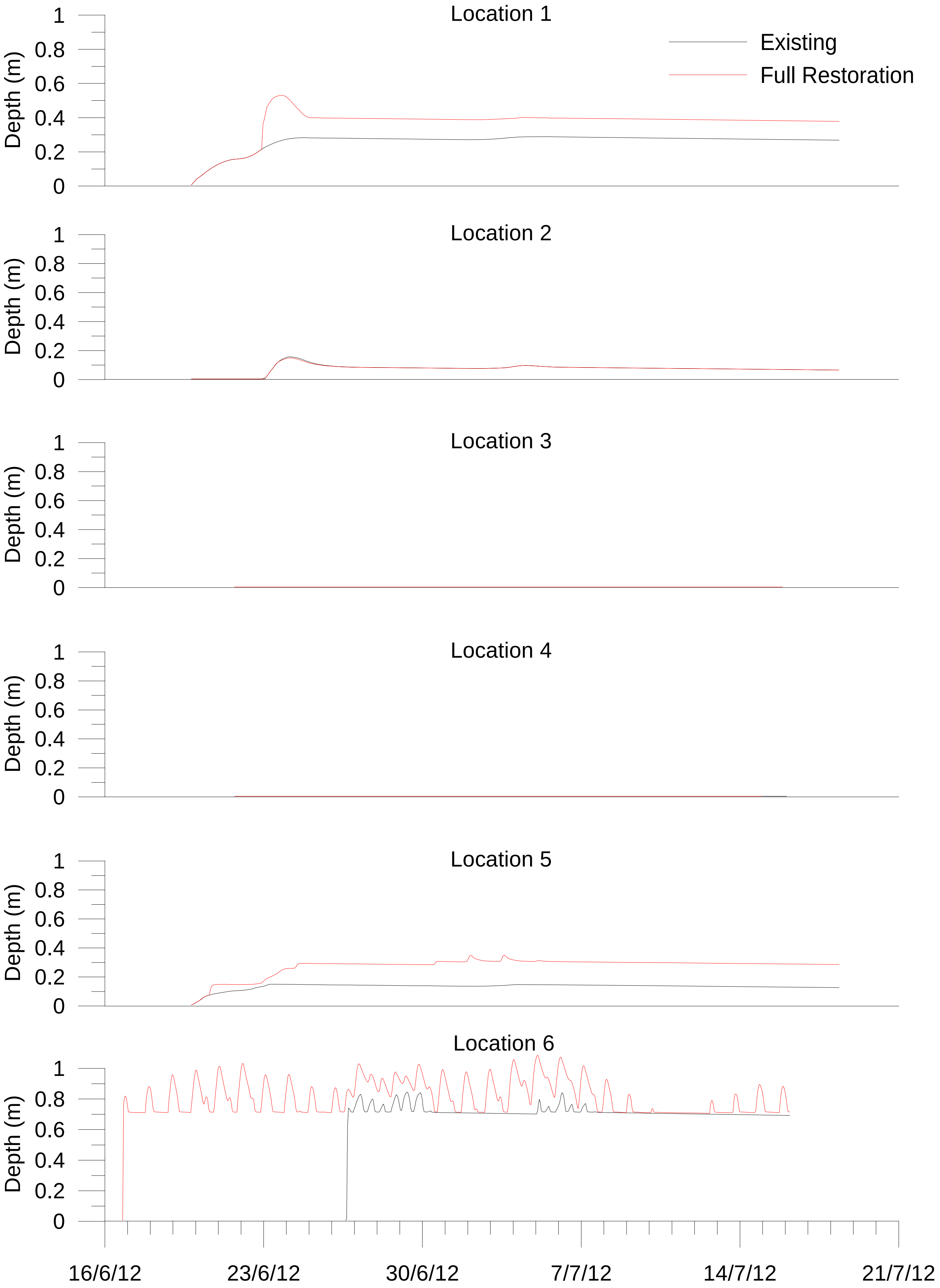
Model Run #3B Inundation
3/9/2012 11:45 AM



Model Run #3B Inundation
6/9/2012 7:45 AM



Model Result Timeseries Locations



Comparison of Inundation Depths For Selected Sites

Installing A Camera on 18 m High Pole at Tomago Wetlands, NSW

Appendix A: Literature

Table A-1: Studies that have Investigated Water Quality Associated with ASS Problems in the Manning River Estuary

Source	Brief Details
Australian Institution of Engineers (1987)	Background information for estimation of design flood characteristics in Australia.
ANZECC (2002)	A framework for conserving ambient water quality in Australian and New Zealand rivers, lakes, estuaries and marine waters.
Atkinson et al. (2003)	Briefly describes priority areas for the management of ASS in the lower Manning River floodplain including Cattai-Pipeclay Canal in terms of drainage, policy and management and water quality.
Birrell, W.K. (1987)	Background to the lower Manning estuary pre-settlement.
BOM (2013)	Climate data used during this study.
Boughton, W. (2004)	Background information on the development and model structure.
Burkitt et al. (2009)	Extensive testing for ASS was carried out over the entire length of the project and was used as background information to this study.
Coode, S.J. (1989)	Background to the history of the Manning River and its' estuary.
Chow (1959)	Provided indicative values for channel and floodplain roughness parameters.
DERM (2009)	Background information on ASS.
Dent, D. (1986)	Background information on ASS.
Dove, M.C. & Sammut, J. (2007)	This study investigated estuarine acidification, associated with drainage and excavation of acid sulfate soils, in areas used for commercial cultivation of Sydney rock oysters. Regular measurements of pH and electrical conductivity were collected in oyster cultivation areas and acidified reaches of the Hastings River estuary and Port Stephens estuary. Water quality information from acidified floodplain drains was also collected in the Hastings River following heavy rainfall.
Dove, M. C. (2003)	Identification, measurement and investigation of sources of acidification and its' spatial and temporal characteristics in the Manning and Hastings Rivers.
Smith & Dove (2001)	Water quality study (February 1999 to August 2001) of drains on North Oxley Island which measured persistent acidic conditions.
EPA (1999)	Water quality and river flow interim environmental objectives: guidelines for river, groundwater and water management committees in the Manning River catchment.
Evangelou, V.P. (1995)	Background information on ASS.
Gates, G. (1978)	Background report on groundwater trends in the lower Manning River estuary.
Glamore, W. (2003)	Background information on ASS and remediation by tidal buffering.
Goodrick, G. (1970)	A report on a collaborative project of the National Parks and Wildlife Service of New South Wales and the CSIRO Division of Wildlife Research. This report provided general coastal wetlands classification in NSW and noted Great Swamp as a freshwater swamp.
GTCC (2010 – 2011)	Short-Term Monitoring of Pipeclay Canal and Cattai Creek Following Acid Plume Event in May, 2010.
GTCC (2010)	Background information to the Big Swamp floodplain. This report identified outcomes for the remediation works.
GTCC (2009)	Background to the management of the lower Manning River estuary based on the outcomes of the estuary processes study.
GTCC (2005)	A short summary on the history and current issues of the Big Swamp floodplain is provided.
GTCC (1997)	A comprehensive report on the physical, chemical and biological condition of the estuary that will enable appropriate management decisions to be made in the future. Short-term spot testing of drains and tidal waters in the Cattai

	Creek, Lansdowne River and Ghinni Ghinni Creek (in August 1995 and August 1996) that identified acidic drains and tidal waters.
GTCC (1996)	Background to the management of the lower Manning River estuary based on the outcomes of the estuary processes study.
Heggie & Skyring. (1999)	Background information on physical flushing processes of the Manning River estuary.
Jenks (1982)	Background information on the past geomorphology of the Manning River estuary.
Johnston et al. (2009)	The saturated hydraulic conductivity of sulfuric horizons was assessed on seven major coastal floodplains of eastern Australia using an in situ recovery technique conducted in ~0.4–0.65 m deep pits. Duplicate recovery tests were conducted in a total of 148 pits located in 32 separate geomorphic units across the seven coastal floodplains. Most pits were constructed in clay soils with acidic (pH <4.0) shallow groundwater.
Johnston, S. (2007)	Preliminary ASS Assessment.
Johnston et al. (2003)	Comprehensive remediation guidelines to manage coastal floodplain drainage systems.
Johnston & Slavich (2003)	Methodology to undertake insitu bulk hydraulic conductivity measurements.
Laxton (1984)	Short term water quality monitoring in the Dawson's River and Manning River estuary upstream Cattai Creek.
Kaliska, A. (1994)	Water quality data in the tidal section of the Manning River was obtained as a result of Greater Taree City Council "River Monitoring Program". Extension of previous work undertaken by the EPA and GTCC. Water quality monitoring sites were taken several kilometres upstream of the confluence of Cattai Creek with the Manning River.
Kazimierczuk, E. (1965)	A report on planning and actions to reduce the effects of flooding in the lower Manning River estuary.
Knutzen, J. (1981)	A review of the literature on pH tolerance of marine organisms.
Laurie, Montgomerie & Pettit. (1980)	Overview of the land drainage of the lower Manning River estuary, with specific reference to the Big Swamp floodplain. The report recommended soil type surveys and water quality monitoring to be undertaken in the lower estuary.
Lawrie, R. (1996)	Short-term spot testing of drains in the Pipeclay Creek Canal and Lansdowne River areas that noted very acidic drains.
Lines-Kelly, R. (Date Unknown)	The principles and strategies which can be employed to improve the environmental performance of coastal floodplain drainage systems by drain redesign.
MHL (2013)	Most recent tidal planes analysis undertaken at Croki.
MHL (1999)	Channel cross-sections taken in Cattai Creek and the north arm of the Manning River.
Miller, B. & Tarrade, L. (2010)	Background and modelling investigations on the saline dynamics in the Manning River estuary under various extraction scenarios.
Naylor et al. (1995)	Guidelines for the use of ASS risk maps.
NSW Office of Water (2012)	Office of Water groundwater monitoring bores for levels and groundwater quality at several sites in the Manning River estuary.
NSW Department of Natural Resources (2005)	A report helping to consider community values for water quality in decision making. Water Quality Objectives have been agreed for Fresh and Estuarine surface waters. The River Flow Objectives are the agreed high-level goals for surface water flow management. They identify the key elements of the flow regime that protect river health and water quality for ecosystems and human uses.
NSW DPI (2007)	Initial Monitoring of Drains on Buttsworth Property.
NSW Government (2005)	The manual highlights the government's ongoing commitment to managing

	the risks resulting from natural hazards to reduce their impacts on the people of NSW.
NSW Department of Land and Water Conservation (2000)	Report on the health of some NSW estuaries. A broad look at the state of the rivers so we can focus future investments where they can be most effective to preserve the health of the estuaries.
NSW Public Works Department (1991)	The report presents the results of numerical modelling to assess the flood impacts on the lower Manning River estuary. This report was used in justifying that there would be no measureable impact on upland/downstream flooding as a result of on-ground remediation works being undertaken on the Big Swamp floodplain.
NSW Public Works Department (1981)	A comprehensive review of the flood history of the Manning River between 1831 - 1979.
NSW Public Works Department (1980)	A report reviewing the existing data adequacy and data and information needs for the Manning River Estuary Management Plan. The scope of this report is generally limited to the collation and review of data and information sources by 1980.
NSW Public Works Department (1911)	Background to the drainage history of the Big Swamp floodplain.
Rayner, D.S. (2010)	This report was a research project investigating the buffering dynamics of acid plumes in the Shoalhaven River estuary. This report provided a comprehensive background to ASS and remediation by tidal buffering.
Revitt, J. (1979)	Background on the development of the Manning River floodplain.
RTA (2007)	Summary of ASS in vicinity of the projects.
Roy et al. (2001)	Background to the structure and function of the Manning River estuary.
Roy, P.S. (1984)	Background to the characteristics and geomorphological classification of NSW estuaries.
Ruprecht, J., Glamore, W. & Rayner, D. (2012)	Empirical hydraulic geometry relationships for tidal marsh channels are a practical geomorphically based design tool that can assist in the planning of tidal wetland restoration projects. This study provides hydraulic geometry relationships for predicting the depth, width, and cross-sectional area of mature tidal channels as functions of contributing marsh area or tidal prism. The relationships are based on data from the Hunter Wetlands National Park.
Ruprecht, J. E. & Peirson, W. L. (2011)	Background to estuary processes in the lower Manning River estuary.
Sammut, J. (1998)	Results from this study highlight the rapid deleterious effects of reduced pHs to fish and the impacts of iron and aluminium contained in ASS-affected waters.
Sammut et al. (1996a)	This paper examines the acidification of a tidal reach on the Richmond River, New South Wales. Acid discharge is controlled by the floodplain water balance, drainage of shallow acid groundwater, and tidal floodgate operation.
Sammut et al. (1995)	In the Richmond River estuary, northern New South Wales, flood mitigation, drainage works and floodplain excavations have augmented acid sulphate soil formation by increasing pyrite availability for oxidation. These engineering works have facilitated the transport of acidified water and have impeded recovery from tributary acidification. Fish kills have been recorded from acidified sites in the estuary.
Sammut et al. (1994)	This paper reports on the physical, chemical and ecological changes within drainage channels caused by altered hydrology. Unusual stratification in an acidified drain during a dry period is described.
Silcock, S. (1998)	Soil study that included spot testing of drains on North Oxley Island, measured drains with pH < 4.5.
Smith, B. & Dove, M. (2001)	Identification and remediation options of ASS for the management of agricultural drains on Oxley Island.
Smith, B et al. (1999)	Background to ASS production and export in the Manning River estuary and

	the associated impacts on the local oyster industry. Some water quality data was presented.
Sonter, L. (1999)	Water quality study (March to June 1999) in Pipeclay Creek Canal and Cattai Creek that measured acidic drain and tidal waters. Spatial and temporal variability.
SPCC (1986)	Water Quality in the Manning River.
Stumm & Morgan (1996)	Background chemistry to the formation and reduction of ASS.
SMH (1917)	Short article highlight the apparent failure of the Big Swamp drainage scheme with clear indications of the effects of ASS.
Tulau, M.J. (2007)	The approach taken in these Guidelines is that the remediation strategy adopted should flow from the characteristics and measurable properties of the landscape. The Guidelines examine the science underlying the remediation strategies discussed, and place the requirements of each strategy in the context of the physical limitations of the landscape. These extend the ASS Manual.
Tulau, M.J. (2001)	Discussion on the technical, regulatory and policy responses to ASS drainage in NSW estuaries.
Tulau, M.J. (1999b)	Identification of Cattai-Pipeclay, lower Lansdowne-Moto-Ghinni Ghinni Creek as ASS priority management areas.
WBM Oceanics Australia. (1998)	A short letter to GTCC regarding the Harrington Waters Estate flood impact assessment. This letter highlights that there is no hydrological connection between the Great Swamp and Harrington Waters below 2.3 m AHD.
West et al. (1985)	Fisheries oriented inventory that consists of tabular information and an atlas of estuarine wetlands describing 133 estuaries and embayments along the NSW (Australia) coast.
White et al. (1997)	Background to the production and export of ASS from coastal floodplains. Discussion of various remediation strategies to reduce the impact of acid discharges.
Willet, I. & Walker, P. (1982)	A transect of soils across a toposequence on the coastal flood plain of the Shoalhaven River (N.S.W.) was described. The toposequence comprised a backswamp, toe of levee, and levee, and was underlain by a pyritic estuarine deposit.
Williams et al. (2002)	Empirical hydraulic geometry relationships for tidal marsh channels are a practical geomorphically based design tool that can assist in the planning of tidal wetland restoration projects. This study provides hydraulic geometry relationships for predicting the depth, width, and cross-sectional area of mature tidal channels as functions of contributing marsh area or tidal prism. The relationships are based on data from San Francisco Bay coastal salt marshes ranging in size from 2 to 5,700 ha.

Appendix B: Data Collection

The ability of a numerical model to accurately simulate on-site conditions is highly reliant on adequately representing the site's geometry and boundary conditions. The following section describes the data available for model development. All site locations are referenced to MGA-56. The datum is Australian Height Datum (AHD).

Topographic Data

An Airborne Laser Scanning Survey (ALS or LIDAR) was undertaken by AAMHATCH for GTCC in 2005. The raw ground point cloud covering the entire Big Swamp catchment including the extent of Pipeclay Canal was supplied to WRL by GTCC and interpolated to a 1 m x 1 m grid using a spline function.

The 2005 LIDAR data was designed to have a vertical accuracy of 0.2 m. The resulting point could was validated by AAMHATCH to have a standard deviation of 0.071 m. The accuracy of the LIDAR data was checked against a number of observation points taken by WRL using an RTK GPS. An analysis of the LiDAR data and survey points undertaken by WRL along the Great Swamp swale (Figure B.1) showed that the LiDAR data is variable in accuracy with a relative mean error bias of + 0.19 m. A plot of the inspection of the LiDAR data versus the surveyed data is provided in Figure B.2. Although there is a clear bias in the error, this was not significant enough to warrant any modification of the data provided as this is in the range of uncertainty expected (± 0.2 m).

Rainfall Data

Daily rainfall data was obtained from the Bureau of Meteorology (BOM, 2012) website. Table B-1 summarises the rainfall stations and data durations available.

Table B-1: Rainfall Station Information

Station ID	Station Name	Easting (m)	Northing (m)	Dates Available
060024	Moorland (Denro-An) NSW	468755	6483901	1885 - Current
060030	Taree (Robertson Street)	447992	6470516	1881 - 2010

Evaporation Data

Mean daily evaporation data was obtained from the Bureau of Meteorology (BOM, 2012) website. Table B-2 and Figure B.3 summarises the station, duration and data available.

Table B-2: Evaporation Station Information

Station ID	Station Name	Easting (m)	Northing (m)	Dates Available
060141	Taree Airport	453661	6471652	1997 - Current

Water Level Data

A time series of water level data on the Manning River at Croki was obtained from Manly Hydraulics Laboratory on behalf of the NSW Office of Environment and Heritage (MHL, 2012). Table B-3 summarises the station and data duration available.

Table B-3: Croki Station Information Data

Station ID	Station Name	Easting (m)	Northing (m)	Dates Available
208404	Croki (Live)	461589	6473115	1997 - Current

Tidal Planes At Croki

A recent draft report by MHL (MHL2053, 2012) provides the most recent tidal planes for NSW and includes data for the Manning River at Croki. Data has been presented in Table B-4 for 1992 – 2001 and in Table B-5 for 2001 – 2010, as well as Figure B.4, which compares the tidal planes at Croki in descending order of tidal planes. It should be noted that the analysis is undertaken during a financial year rather than a calendar year.

Expanded tidal plane acronyms are as follows:

H.H.W.S.S – High high water spring solstice
M.H.W.S – Mean high water springs
M.H.W – Mean high water
M.H.W.N – Mean high water neaps
M.S.L – Mean sea level
M.L.W.N – Mean low water neaps
M.L.W – Mean low water
M.L.W.S –Mean low water springs
I.S.L.W – Indian spring low water

Table B-4: Croki Tidal Planes Data in m AHD (1992 – 2001)

Tidal Planes	1992-93	1993-94	1994-95	1995-96	1996-97	1997-98	1998-99	1999-00	2000-01
HHWSS	0.736	0.645	0.640	0.692	0.685	0.595	0.664	0.664	0.711
MHWS	0.418	0.357	0.364	0.396	0.391	0.329	0.391	0.386	0.435
MHW	0.367	0.312	0.320	0.352	0.349	0.293	0.355	0.345	0.390
MHWN	0.317	0.267	0.276	0.308	0.308	0.256	0.320	0.305	0.346
MSL	0.108	0.083	0.101	0.127	0.125	0.102	0.168	0.135	0.160
MLWN	-0.100	-0.102	-0.073	-0.053	-0.058	-0.053	0.002	-0.034	-0.025
MLW	-0.151	-0.147	-0.117	-0.097	-0.100	-0.089	-0.020	-0.075	-0.070
MLWS	-0.202	-0.192	-0.162	-0.141	-0.141	-0.126	-0.055	-0.116	-0.114
ISLW	-0.429	-0.398	-0.359	-0.353	-0.351	-0.315	-0.250	-0.314	-0.311

Table B-5: Croki Tidal Planes Data in m AHD (2001 – 2010)

Tidal Planes	2001-02	2002-03	2003-04	2004-05	2005-06	2006-07	2007-08	2008-09	2009-10
HHWSS	0.801	0.658	0.582	0.532	0.591	0.439	0.543	0.617	0.688
MHWS	0.485	0.389	0.348	0.309	0.379	0.266	0.350	0.390	0.412
MHW	0.433	0.348	0.314	0.278	0.350	0.245	0.326	0.360	0.373
MHWN	0.380	0.307	0.280	0.247	0.321	0.224	0.303	0.329	0.333
MSL	0.168	0.146	0.154	0.126	0.209	0.138	0.211	0.203	0.170
MLWN	-0.043	-0.015	0.028	0.006	0.097	0.052	0.120	0.078	0.007
MLW	-0.096	-0.057	-0.007	-0.025	0.068	0.031	0.096	0.047	-0.032
MLWS	-0.149	-0.098	-0.041	-0.056	0.039	0.010	0.073	0.017	-0.072
ISLW	-0.374	-0.290	-0.207	-0.216	-0.113	-0.113	-0.065	-0.145	-0.269

Tidal Planes Comparison – Entrance to Pipeclay Canal

A data set defining tidal variations in water level between Harrington and Pipeclay Canal during a monitoring period, from 2 November to 17 December 1998, by MHL (MHL968, 1999) is provided in Table B-6. The data collected in Pipeclay Canal was in the upper reaches of the Canal (469788 m E, 6483238 m N, AMG 56).

Table B-6: Pipeclay Canal Tidal Planes Data in m AHD (1998)

Tidal Planes	Croki [1]	Harrington	Pipeclay Canal
HHWSS	0.638	0.895	0.541
MHWS	0.378	0.524	0.292
MHW	0.339	0.429	0.243
MHWN	0.302	0.334	0.195
MSL	0.146	0.055	0.054
MLWN	-0.009	-0.223	-0.087
MLW	-0.047	-0.319	-0.136
MLWS	-0.085	-0.414	-0.184
ISLW	-0.271	-0.679	-0.363

[1] Long term averages for comparison based on *Draft* MHL2053 Report, 2012.

Field Data and Instrumentation

Several field data gathering campaigns were undertaken by WRL throughout the project to collect the necessary data for developing a numerical model and to enhance/ground-truth the conceptual hydrologic model. The field campaigns were designed to:

1. Gather sufficient topographic, surface and groundwater data to understand the key hydrologic processes;
2. Survey key structures such as culverts and weirs in the system as they can regulate the flow regimes; and
3. Survey primary drain locations and cross-sections.

Short-Term Instrumentation

Various field equipment was used by WRL during this study including an RTK-GPS, quad bikes equipped with RTK-GPS stands, flow measurement devices, groundwater sampling equipment and bathymetric survey equipment. In addition to this equipment, WRL installed several short-term data loggers to gain overlapping data sets of water height and flow measurement of tidal exchange in Pipeclay Canal.

Conductivity-Temperature-Depth (CTD) probes were used to measure water levels and salinity along Pipeclay Canal and Cattai Creek. Changes in water level were obtained by compensating the probes for atmospheric pressure fluctuations using mean sea level pressure observations drawn from Taree Airport AWS (BOM station 060141).

Preliminary 2-D velocity measurements (using 2 acoustic beams: along channel and vertical velocity components) at the junction of Pipeclay Canal and Cattai Creek were captured using a Sontek Argonaut-SW. The Argonaut-SW also measures water levels using a vertical acoustic beam. Cross-sectional area for each water level in the time series was calculated using the surveyed channel geometry at the location of the Argonaut-SW. Cross-sectional area and velocity were then used to calculate time series of discharge. All instrumentation was set to sample at a frequency of 15 minutes. This unit was decommissioned after the field investigation undertaken on 27th – 31st August 2012 due to unknown equipment failure.

Additional flow, water level and water quality logging equipment was temporarily installed on-site during the 16-day field investigation from 30th January to 15th February 2013, to capture coordinated data sets across the Big Swamp catchment following a flood event. The field program involved installation of various short-term deployable flow and water quality measurement devices, including:

- Two Gamet auto-samplers set up to monitor at a 6-hourly interval. The sampling locations were positioned just upstream of Coralville Bridge and just downstream of Cattai Creek – Pipeclay Canal confluence;
- A Sontek Argonaut-IQ real-time acoustic doppler flow logger set up to monitor at a 15 minute interval to determine continuous discharge from the site.; and
- Installation of a Sontek 6600 V2 Multi-Parameter Water Quality Sonde, capable of measuring pH, temperature, conductivity (EC), turbidity and dissolved oxygen (DO) and set up to monitor at a 15 minute interval.

Table B-7 provides a summary of the site information relating to the field instrumentation installed along Pipeclay Canal (Figure B.5) during the various field experiments.

Table B-7: Summary of Field Instrumentation Data Information

Installation Dates		**Project Stage**	**Data Type**	**Instrument Location**		**Site Description**	**Record Length (days)**	**Status**
Start	**Finish**			**Easting (m)**	**Northing (m)**			
25/06/2012	13/11/2012	Inception	CTD[5]	469310.497	6481037.235	*Downstream Bridge #3*	138[1]	Closed[3]
			CTD[5]	469844.146	6483259.886	*Downstream Bridge #2*	92[1]	Closed[3]
27/08/2012	13/03/2012	Pilot Model/ Dry Snapshot	CTD[5]	469696.918	6484836.922	*Top of Pipeclay Canal*	197[1]	Open[2]
			CTD[5]	466483.074	6478559.720	*Cattai Creek/ Wetlands*	197[1]	Open[2]
27/08/2012	31/08/2012		Discharge	468052.139	6479324.808	*Top of Cattai Creek*	4[1]	Closed[3]
29/09/2012	29/09/2012	Detailed Model	Discharge	468052.139	6479324.808	*Top of Cattai Creek*	-	Closed[3]
4/02/2013	23/02/2013	Detailed Model/ Wet Snapshot	Discharge	468037.010	6479287.806	*Top of Cattai Creek*	13[1]	Open[2]
7/02/2013	13/03/2013		Water Quality	468037.010	6479287.806	*Top of Cattai Creek*	34[1]	Open[2]
7/02/2013	20/2/2013		Auto-sampler	469879.429	6483439.334	*Coralville Bridge*	14[1]	Open[2]
7/02/2013	20/2/2013		Auto-sampler	468037.010	6479287.806	*Top of Cattai Creek*	14[1]	Open[2]

1. Record length calculated from the date of installation, unless the site was closed prior or logging was interrupted.
2. An “open” site refers to an uninterrupted data record, these stations have since been decommissioned on 13/03/2013.
3. A “closed” site refers to a suspended data record due to instrument failure or appropriated equipment
4. “CTD” stands for Conductivity-Temperature-Depth.

Key Structures

A field investigation was undertaken by WRL on 25th – 29th June 2012 to obtain elevations and dimensions of critical structures/landforms. The survey was undertaken using a Trimble 5800 RTK-GPS (real-time kinematic global positioning system) accurate to ± 20 mm vertically and horizontally. All structures were surveyed with the obvert height and cross-sectional dimensions measured. Flow restrictions such as one-way flaps were noted as 'flap gates'.

A summary of the surveyed culvert structures located in Pipeclay Canal is presented in Table B-8. Locations of the surveyed structures can be seen in Figure B.6.

Table B-8: Surveyed Culvert Structures Along Pipeclay Canal

Location I.D.	Co-ordinates (m) (MGA56 UTM 56S)		Valve Regulation	Upstream Invert (m AHD)	Downstream Invert (m AHD)	Internal Dimension (m) x Length (m)
	Easting	Northing				
U/S Culvert R2	470069	6484246	Flap Gate	0.18	0.18	0.9 x 4.0
U/S Culvert R1	469893	6483475	Flap Gate	0.00	0.00	0.9 x 4.0
D/S Culvert L1	469824	6483023	None	0.07	0.12	1.5 x 4.0
East Section Drain 001	469701	6482521	None	-0.08	-0.13	0.9 x 5.0
D/S Culvert R1	469677	6482524	Flap Gate	-0.05	-0.01	0.9 x 4.0
Long Point Drain 001	469600	6482211	None	-0.79	-0.79	1.2 x 6.5
D/S Culvert L3	469616	6482109	None	-0.13	-0.13	0.9 x 7.0
D/S Culvert L4	469572	6481917	None	-0.01	0.02	0.9 x 7.5
D/S Culvert L5	469516	6481712	None	-0.10	-0.10	0.9 x 6.0
D/S Culvert R3	469492	6481715	Flap Gate	-0.19	-0.20	0.9 x 6.0
D/S Culvert L6	469458	6481447	None	0.02	0.02	0.9 x 6.0
D/S Culvert R6	468519	6479962	Flap Gate	0.05	0.05	1.0 x 4.0
D/S West Section Drain 002	468256	6479629	Flap Gate	-0.56	-0.56	2.0 x 4.0
D/S West Section Drain 003	468041	6479346	Flap Gate	-0.82	-0.82	1.5 x 7.0
D/S Culvert L7	469396	6481211	None	0.02	0.02	0.7 x 8.0
D/S Culvert L8	469328	6481023	None	-0.47	-0.47	1.5 x 6.0
D/S Culvert L9	469316	6481023	None	-0.26	-0.26	0.9 x 8.5
D/S Culvert R4	469287	6481035	Flap Gate	-0.47	-0.47	1.5 x 6.0
D/S Culvert R5	469287	6481029	None	-0.26	-0.26	0.9 x 6.0
U/S Culvert R4	469875	6483445	None	0.08	0.10	0.6 x 6.0
U/S Culvert R3	469882	6483430	None	0.08	0.10	0.9 x 6.0
U/S Culvert L2	469923	6483437	None	0.29	0.24	0.9 x 6.0
D/S Culvert L10	469908	6483427	None	0.07	0.07	0.9 x 6.0
NE Section Drain	469919	6483466	Flap Gate	-0.39	-0.39	1.5 x 7.0

Channel Survey Data

As the LiDAR is unable to penetrate water, channel geometry in and around Pipeclay Canal was surveyed as part of the initial field investigation on 25th – 29th June 2012. WRL surveyed 19 cross-sections along Pipeclay Canal, 6 cross-sections along Cattai Creek and 8 cross-sections of internal trunk drains on the floodplain that connect to Pipeclay Canal. Locations of the surveyed drain cross-sections are provided in Table B-9 and Figure B.7. Cross-sections are detailed in Figures B.8 to B.14. The survey was undertaken using a Trimble 5800 RTK-GPS, survey equipment and a kayak or boat. During each cross-sectional survey, the RTK-GPS was initially used to establish a water level bench mark. Once the bench mark was determined, a survey pole was submerged from a kayak at known intervals across the channel to measure the depth of the channel and relate the depth back to real-world coordinates (Figure B.15). Bed elevations were recorded every 0.5 – 2 m, with closer spacing for steeper slopes. The deepest point on the cross-section was always surveyed and widths were measured at the elevation of an effective bank full state. The right and left banks of the channels surveyed rarely were of equal elevations, therefore, the effective bank full state was assumed to be that below the lower of the two banks, above which "overbank flow" would occur. To estimate cross-sectional area, the surveyed cross-section was first interpolated to a 0.1 m cross-channel grid and then the area below a given water level integrated.

Table B-9: Locations of Surveyed Channel Cross-Sections

Survey ID	Location	Easting (m)	Northing (m)
D1T1	Pipeclay Canal	469912.623	6483412.059
D1T2	Pipeclay Canal	469838.317	6483270.732
D1T3	Pipeclay Canal	469827.021	6483034.309
D1T4	Pipeclay Canal	469752.795	6482857.400
D1T5	Pipeclay Canal	469676.631	6482524.397
D1T6	Pipeclay Canal	469635.166	6482201.396
D1T7	Pipeclay Canal	469492.460	6481715.383
D1T8	Pipeclay Canal	469395.957	6481210.546
D1T9	Pipeclay Canal	469315.864	6481022.987
D1T10	Pipeclay Canal	469916.171	6483443.982
D1T11	Pipeclay Canal	469965.220	6483822.630
D2T1	Pipeclay Canal	468512.057	6479959.736
D2T2	Pipeclay Canal	468241.464	6479620.006
D2T3	Pipeclay Canal	468093.680	6479402.043
D2T4	Pipeclay Canal	468040.686	6479345.986
D2T5	Cattai Creek	467859.139	6479268.283
D2T6	Cattai Creek	467323.560	6479056.107
D2T7	Cattai Creek	466566.261	6478725.203
D2T8	Cattai Creek	466572.383	6477589.958
D2T9	Cattai Creek	465444.000	6476435.000
D2T10	Cattai Creek	464772.948	6474594.544
D3T1	Pipeclay Canal	469301.243	6484894.683
D3T2	Pipeclay Canal	469679.632	6484834.961
D3T3	Pipeclay Canal	470061.688	6484508.613
D3T4	Pipeclay Canal	470062.803	6484246.336
D4T1	Internal Trunk Drains	469087.965	6481069.468
D4T2	Internal Trunk Drains	469087.965	6481069.468
D4T3	Internal Trunk Drains	469274.148	6481040.010
D4T4	Internal Trunk Drains	469575.190	6482201.133
D4T5	Internal Trunk Drains	469595.148	6482214.224
D4T6	Internal Trunk Drains	469644.065	6482513.478
D4T7	Internal Trunk Drains	469761.432	6482999.951
D4T8	Internal Trunk Drains	469826.027	6483273.108

Flow and Surface Water Quality Data

A field investigation was undertaken by WRL on 27th – 30th August 2012 to provide additional information on how Pipeclay Canal functions during a typical dry weather period. A 'dry snapshot' survey was conducted on 29th August 2012 to obtain a coordinated set of flow measurements from the various field drains during typical dry weather conditions. Surface water quality parameters were also measured. The data shows that minimal-low flows across the site occur during dry weather conditions, while the whole landscape is evidently acidic.

A summary of the surveyed data located in Big Swamp catchment is presented in Table B-10. Several methods were employed to collect the measured discharge data, these techniques are noted for each data point. Locations of the surveyed data during the 'dry snapshot' can be seen in Figures 2.11 to 2.12.

Table B-10: Locations of Measured Discharge and Surface Water pH Data

Location ID	Easting (m)	Northing (m)	Date-Time	Measured Discharge (m^3/s)	pH	EC	Field Comments
A1	469293	6484910	29/08/12 9:20	0.1[1]	6.5	-	minimal flow, canal
A2	469286	6484895	29/08/12 9:27	0.0[3]	6.4	-	no flow, water
A3	469394	6484833	29/08/12 9:34	0.0[3]	6.7	-	dry test
A4	469472	6484770	29/08/12 9:39	0.0[3]	5.3	-	dry test
A5	469564	6484714	29/08/12 9:49	0.0[3]	5.0	-	dry test
A6	469482	6484846	29/08/12 9:54	0.0[3]	4.9	-	dry test
A7	469695	6484810	29/08/12 10:05	0.0[3]	6.2	-	pond
A8	470051	6484539	29/08/12 10:19	0.0[3]	5.0	-	dry test
A9	470052	6484248	29/08/12 10:30	0.0[3]	5.1	-	no flow, water
A10	470019	6484107	29/08/12 10:42	0.0[3]	5.6	-	no flow, pipe culvert
A11	469966	6483897	29/08/12 11:00	0.0[3]	3.8	-	no flow, water
A12	469915	6483652	29/08/12 11:00	0.1[1]	6.0	-	minimal flow, canal
A13	469876	6483443	29/08/12 11:20	0.0[3]	3.3	-	no flow, water
A14	469887	6483448	29/08/12 11:27	0.0[3]	4.4	-	dry test
A15	470042	6483942	29/08/12 11:35	0.0[3]	3.2	-	no flow, water
A16	470244	6484129	29/08/12 11:58	0.0[3]	3.7	-	no flow, water
A17	470389	6484092	29/08/12 12:11	0.0[3]	3.5	-	dry test
A18	470625	6484023	29/08/12 12:19	0.0[3]	3.0	-	dry test
A19	470656	6484011	29/08/12 12:27	0.0[3]	3.9	-	dry test
A20	470585	6483746	29/08/12 12:31	0.0[3]	3.5	-	no flow, water
A21	470604	6483712	29/08/12 12:39	0.0[3]	2.6	-	no flow, water
A22	470341	6483479	29/08/12 12:45	0.0[3]	2.8	-	no flow, water
A23	470250	6483406	29/08/12 12:57	0.0[3]	3.1	-	no flow, water
A24	470084	6483083	29/08/12 13:05	0.0[3]	3.3	-	no flow, water
A25	469492	6481460	29/08/12 16:30	0.0[3]	3.8	-	no flow, water
F1	469324	6484891	29/08/12 9:05	0.8[1]	-	-	u/s canal
F2	469324	6484891	29/08/12 10:03	0.8[1]	-	-	u/s canal
F3	470019	6484108	29/08/12 11:00	0.7[1]	-	-	u/s canal
F5	469888	6483449	29/08/12 13:15	0.7[1]	-	-	Coralville Bridge

Location ID	Easting (m)	Northing (m)	Date-Time	Measured Discharge (m^3/s)	pH	EC	Field Comments
F6	469888	6483449	29/08/12 13:45	0.5^1	5.8	-	Coralville Bridge
F7	469888	6483449	29/08/12 15:00	0.4^1	-	-	Coralville Bridge
F8	469888	6483449	29/08/12 15:45	0.4^1	5.0	-	Coralville Bridge
#1	469848	6483391	29/08/12 8:53	0.0^3	5.3	1496	no water flowing
#2	469821	6483278	29/08/12 8:55	0.0^3	2.9	2083	no water flowing
#3	469849	6483267	29/08/12 8:58	0.0^3	5.1	237	no water flowing
#4	469570	6483401	29/08/12 9:15	0.0^3	3.6	1291	no water flowing
#5	469174	6483129	29/08/12 9:45	0.0^3	2.7	2015	no water flowing
#6	468872	6482325	29/08/12 10:00	0.0^3	3.5	338	no water flowing
#7	468272	6482111	29/08/12 10:03	0.0^3	3.8	434	no water flowing
#8	468665	6481867	29/08/12 10:10	0.0^1	5.1	206	minimal flow
#9	468563	6481666	29/08/12 10:15	0.0^3	6.1	67	no water flowing
#10	468830	6481115	29/08/12 10:45	0.0^3	3.4	575	no water flowing
#11	469287	6481033	29/08/12 11:00	0.1^1	3.8	656	low flow
#12	469327	6481014	29/08/12 11:15	0.1^1	3.8	375	low flow
#13	469768	6483034	29/08/12 11:24	0.0^3	5.5	80	tide going out
#14	469857	6483262	29/08/12 11:47	0.1^1	3.5	600	low flow
#15	469608	6482211	29/08/12 11:50	0.0^3	3.7	550	no flow
#16a	468051	6479338	29/08/12 12:15	0.8^1	5.9	3180	v ~ 0.1 m/s
#17a	468058	6479332	29/08/12 12:00	2.2^1	4.3	1333	
#17b	468058	6479332	29/08/12 13:00	2.9^1	-	-	
#18a	469309	6481028	29/08/12 14:45	0.4^1	3.9	307	low flow
#18b	469309	6481028	29/08/12 14:53	0.6^1	4.0	1970	low flow
#19a	468052	6479325	29/08/12 9:15	3.0^1	5.0	5900	
#19b	468052	6479325	29/08/12 10:00	2.3^1	5.0	2700	
#18c	469309	6481028	29/08/12 10:35	1.4^1	-	-	
#19c	468052	6479325	29/08/12 11:31	2.8^1	4.5	1100	
#16b	468051	6479338	29/08/12 11:31	0.4^1	-	-	Culvert half full
#19d	468052	6479325	29/08/12 11:58	2.2^1	-	-	
#18d	469309	6481028	29/08/12 13:25	1.0^1	-	-	
#18e	469309	6481028	29/08/12 14:45	1.0^1	-	-	
B1	469910	6483425	29/08/12 8:45	0.0^3	7.5	319	
B2	469819	6483027	29/08/12 9:00	0.0^3	3.0	1433	
B3	469701	6482520	29/08/12 9:22	0.0^3	3.2	829	
B4	469701	6482520	29/08/12 9:22	0.0^2	3.4	555	
B5	469615	6482109	29/08/12 9:34	0.2^2	4.0	330	
B6	469573	6481923	29/08/12 10:07	0.0^3	3.7	540	
B7	469526	6481717	29/08/12 10:11	0.0^3	4.1	652	
B8	469455	6483294	29/08/12 10:20	0.1^2	3.7	686	
B9	469397	6481211	29/08/12 10:30	0.1^2	4.0	273	
B10	469316	6481026	29/08/12 10:40	0.0^2	4.9	395	
B11	469316	6481026	29/08/12 10:40	0.1^2	-	-	
B12	469915	6481578	29/08/12 11:00	0.0^3	3.7	921	
B13	469915	6481578	29/08/12 11:10	0.0^3	5.0	382	

Location ID	Easting (m)	Northing (m)	Date-Time	Measured Discharge (m^3/s)	pH	EC	Field Comments
B14	469915	6481578	29/08/12 11:20	0.0^2	-	-	
B15	468604	6480021	29/08/12 11:28	0.0^3	5.3	683	
B1	469910	6483425	29/08/12 12:30	0.0^3	4.3	434	
B2	469819	6483027	29/08/12 12:30	0.0^3	5.4	342	
B3	469701	6482520	29/08/12 12:46	0.0^3	3.0	1511	
B4	469701	6482520	29/08/12 12:50	0.0^3	3.2	1123	
B5	469615	6482109	29/08/12 12:50	0.0^3	-	-	
B6	469573	6481923	29/08/12 1:00	0.2^2	4.0	339	
B7	469526	6481717	29/08/12 1:07	0.0^3	3.6	584	
B8	469455	6483294	29/08/12 1:12	0.0^3	3.8	298	
B9	469397	6481211	29/08/12 1:14	0.1^2	3.9	921	
B10	469316	6481026	29/08/12 1:20	0.1^2	3.9	290	
B11	469316	6481026	29/08/12 1:30	0.0^3	4.8	406	
B12	469915	6481578	29/08/12 1:30	0.0^3	-	-	
B13	469915	6481578	29/08/12 1:40	0.1^2	-	-	
B14	469915	6481578	29/08/12 1:50	0.1^2	-	-	
B15	468604	6480021	29/08/12 2:00	0.0^3	5.5	848	

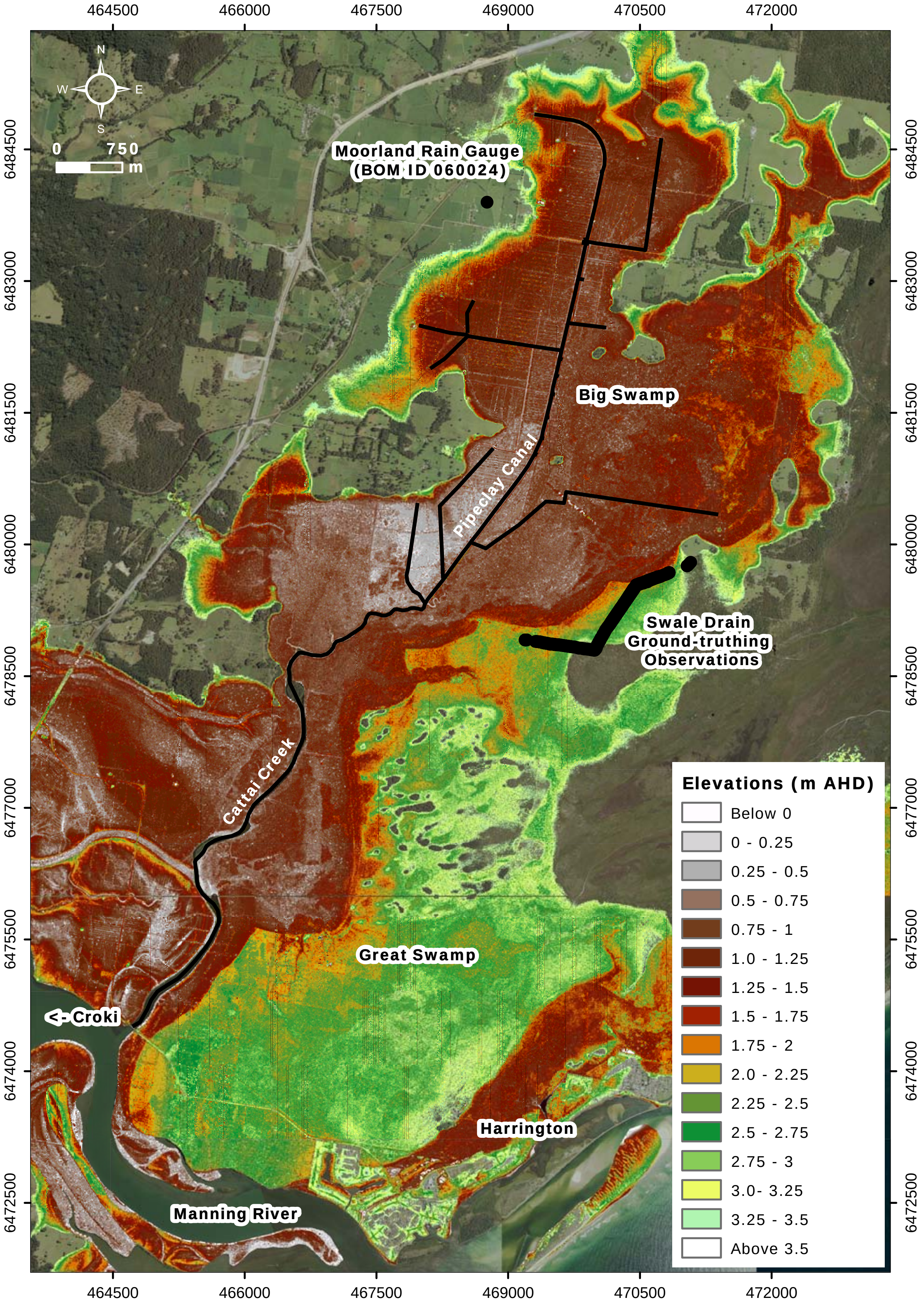
1. Flow measurement type 1: Orange passing between two points, time and distance is recorded.
2. Flow measurement type 2: Prop meter, propeller diameter and revolutions/ 100 sec recorded.
3. Flow measurement type 3: Observation only, no instrumentation.

In addition to the dry period field investigations, the 16-day field investigation from 30th January to 15th February 2013 was undertaken to capture water quality and flow measurements across the Big Swamp catchment and in Cattai Creek, following a wet period. Details of this field campaign are provided in Section 2.5.

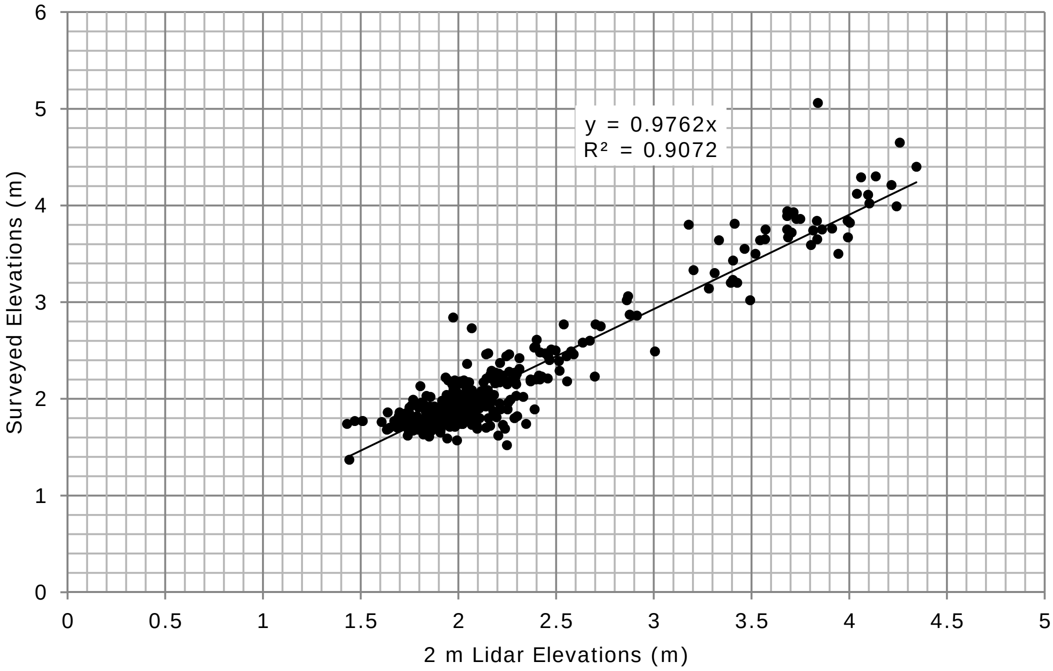
A range of short-term deployable water quality monitoring equipment was installed during the investigation. A summary of water quality data collected using the Sontek 6600 V2 Multi-Parameter Water Quality Sonde, including pH, conductivity (EC) and dissolved oxygen (DO) is provided in Figure B.16. Analysis of filtered/ unfiltered samples collected at Coralville Bridge and the confluence of Pipeclay Canal with Cattai Creek, was carried out by the UNSW Analytical Centre for the analyses. Results for selected constituents, iron and aluminium, are provided for Coralville Bridge in Figure B.17 and the Pipeclay Canal – Cattai Creek confluence in Figure B.18. The discharge recorded at the Pipeclay Canal – Cattai Creek confluence during the investigation is provided in Figure B.19.

Hydraulic Conductivity

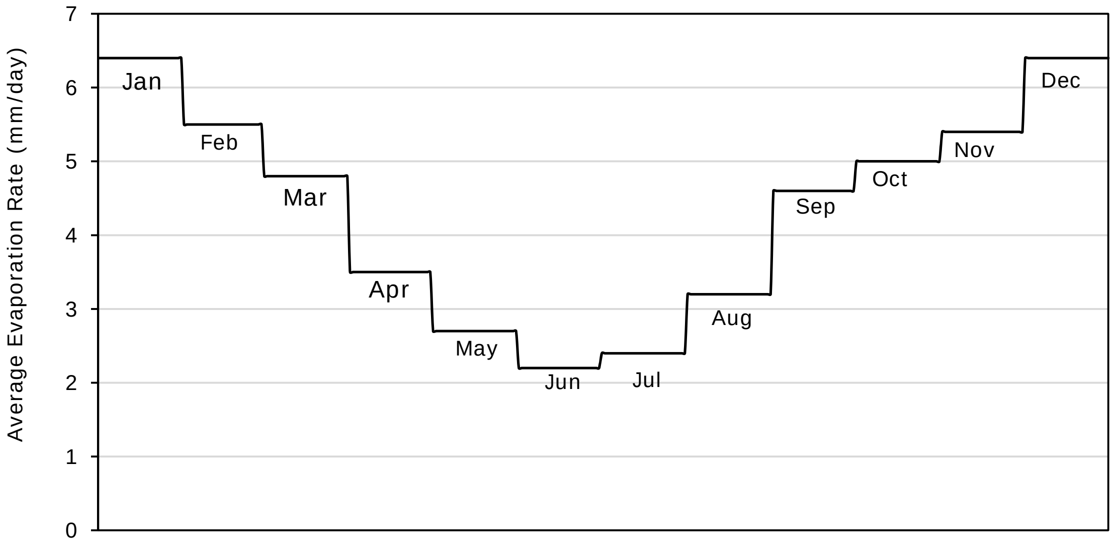
Spatial estimates of the hydraulic conductivity, groundwater levels and drain water levels during the recent field investigation has allowed for estimation of the transport rates of acid from the soil to the surface waters. Section 2.4.2 provides a detailed discussion on the field investigations and their implication at Big Swamp. The K_{sat} results for the remaining 10 test pits (test pit 2 to test pit 11) are provided in Figures B.20 to B.29.



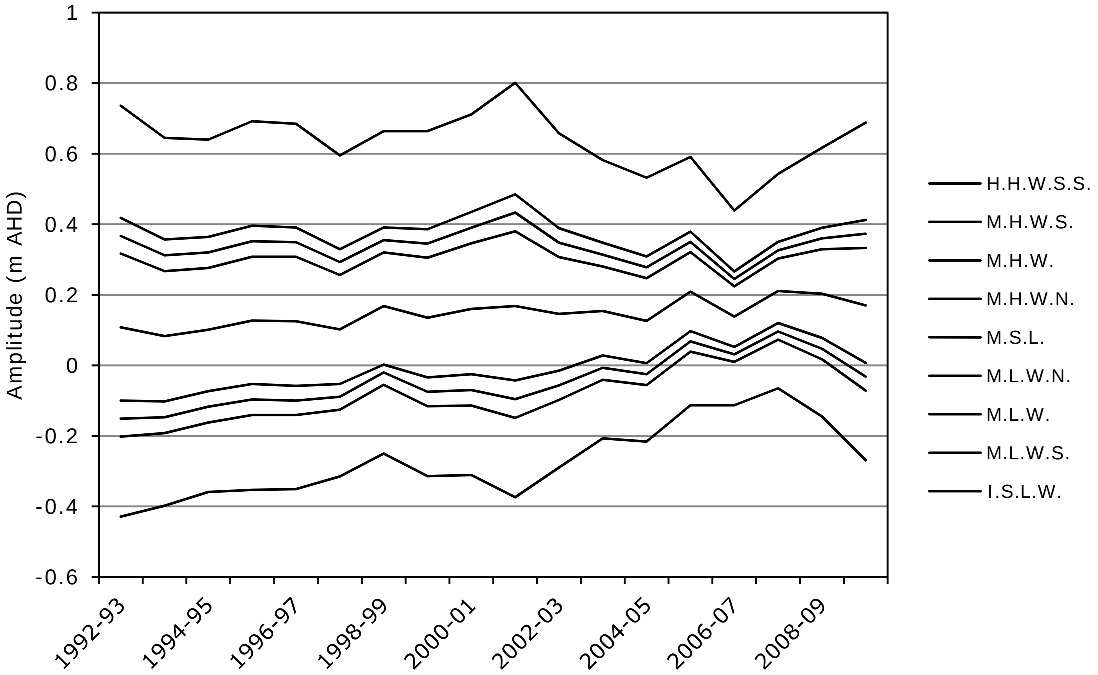
Topography Showing Swale Drain Ground-truthing Observations for the Big Swamp Floodplain Study Domain.



Scatter Plot of LiDAR Data and Ground-Truthing Observations

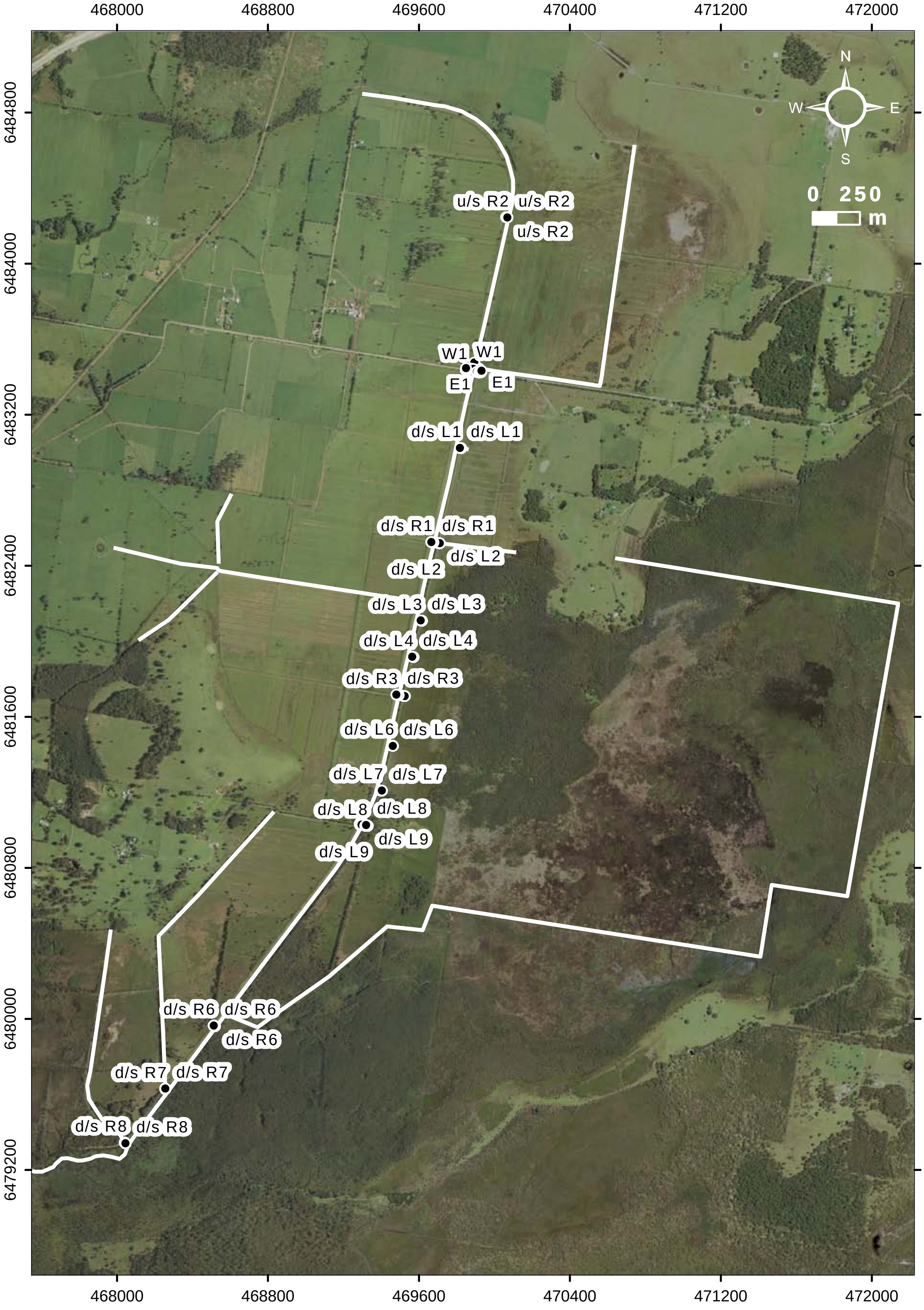


Monthly Averaged Evaporation Rates at Taree Airport (mm/day)

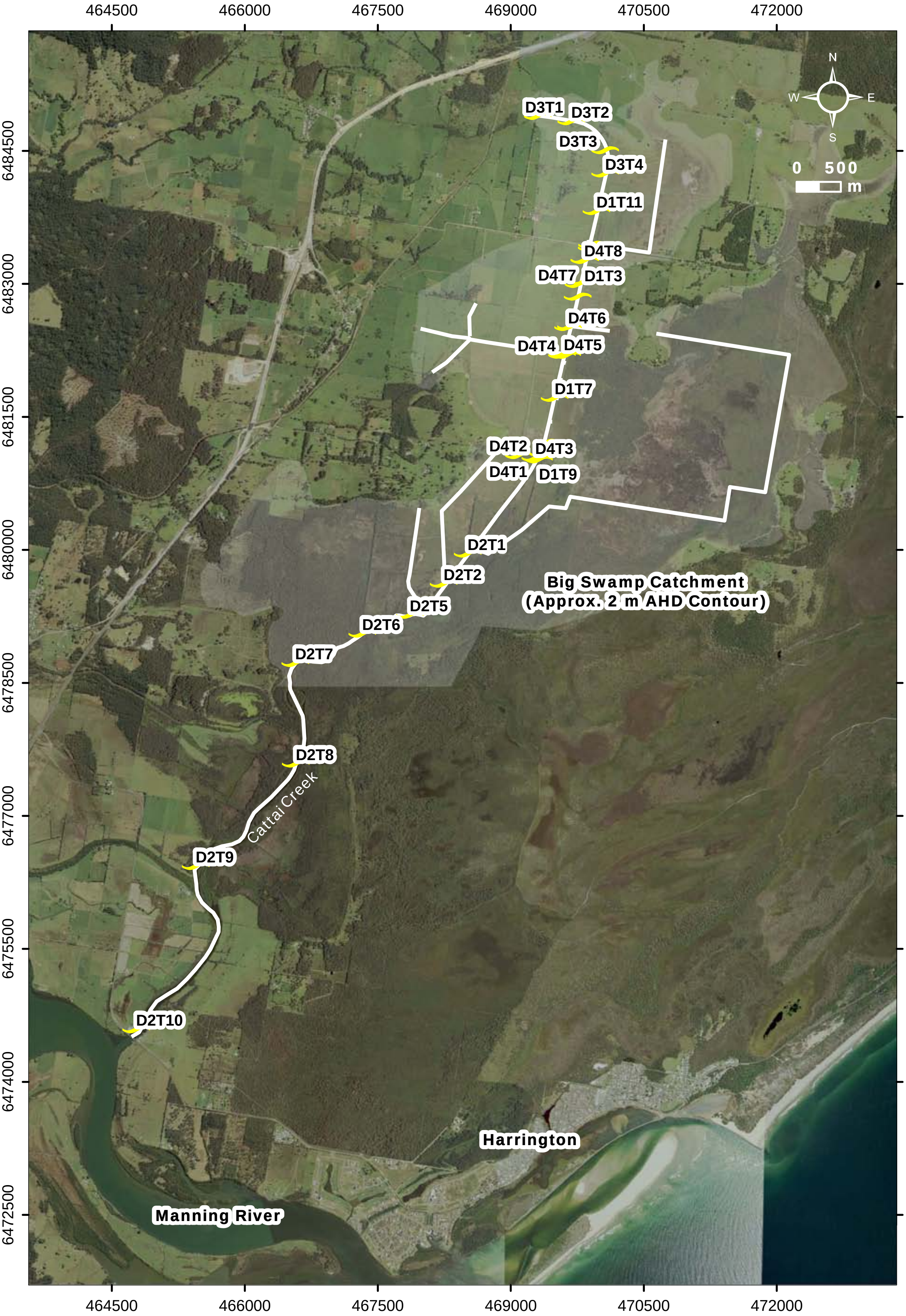


NSW Tidal Planes Analysis of Manning River at Croki (in Order of Tidal Planes)
(In Draft MHL2053 Report, 2012)

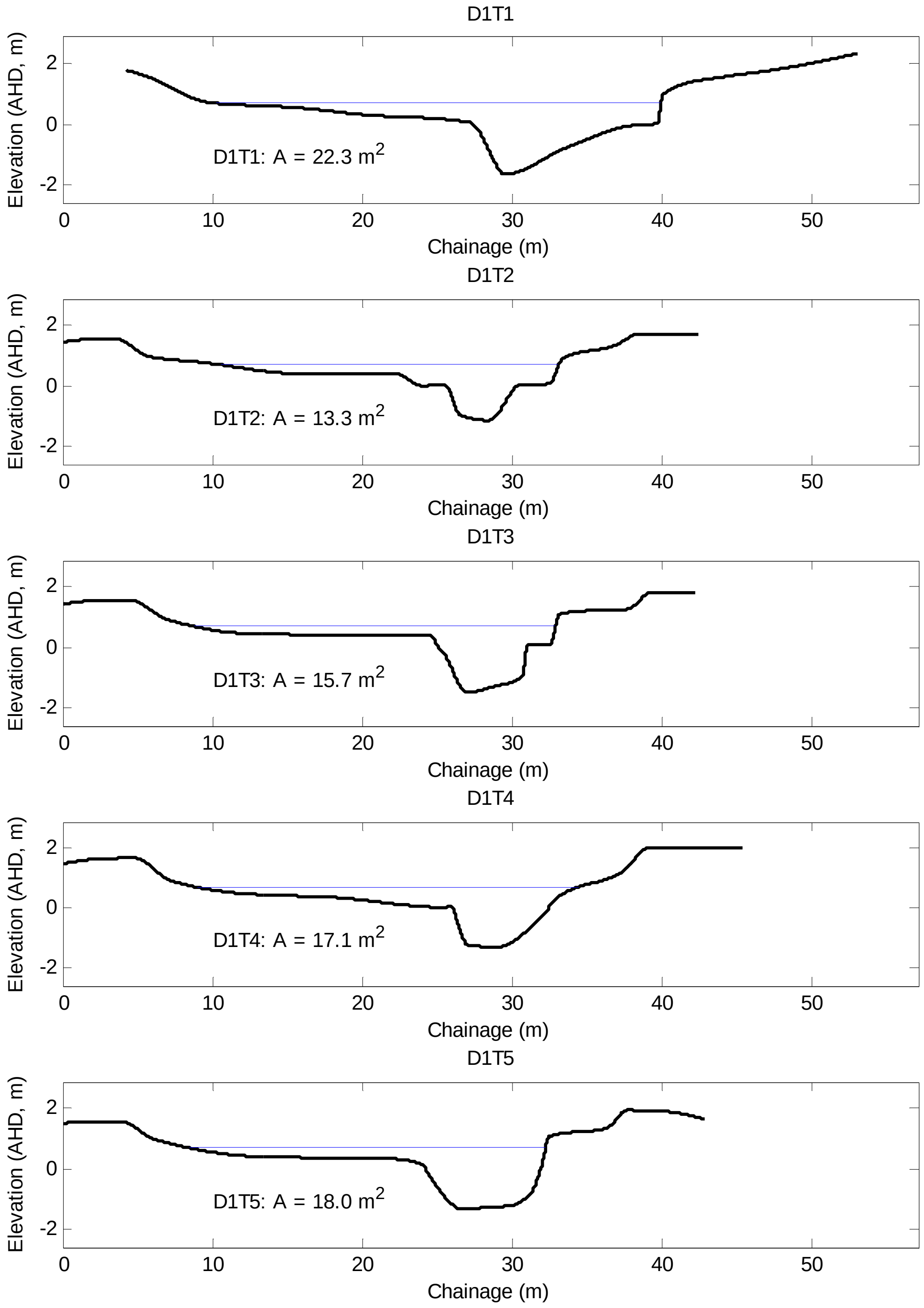
Instrument Installations at Top of Canal (A), Top of Cattai Creek (B) and Cattai Creek (C)



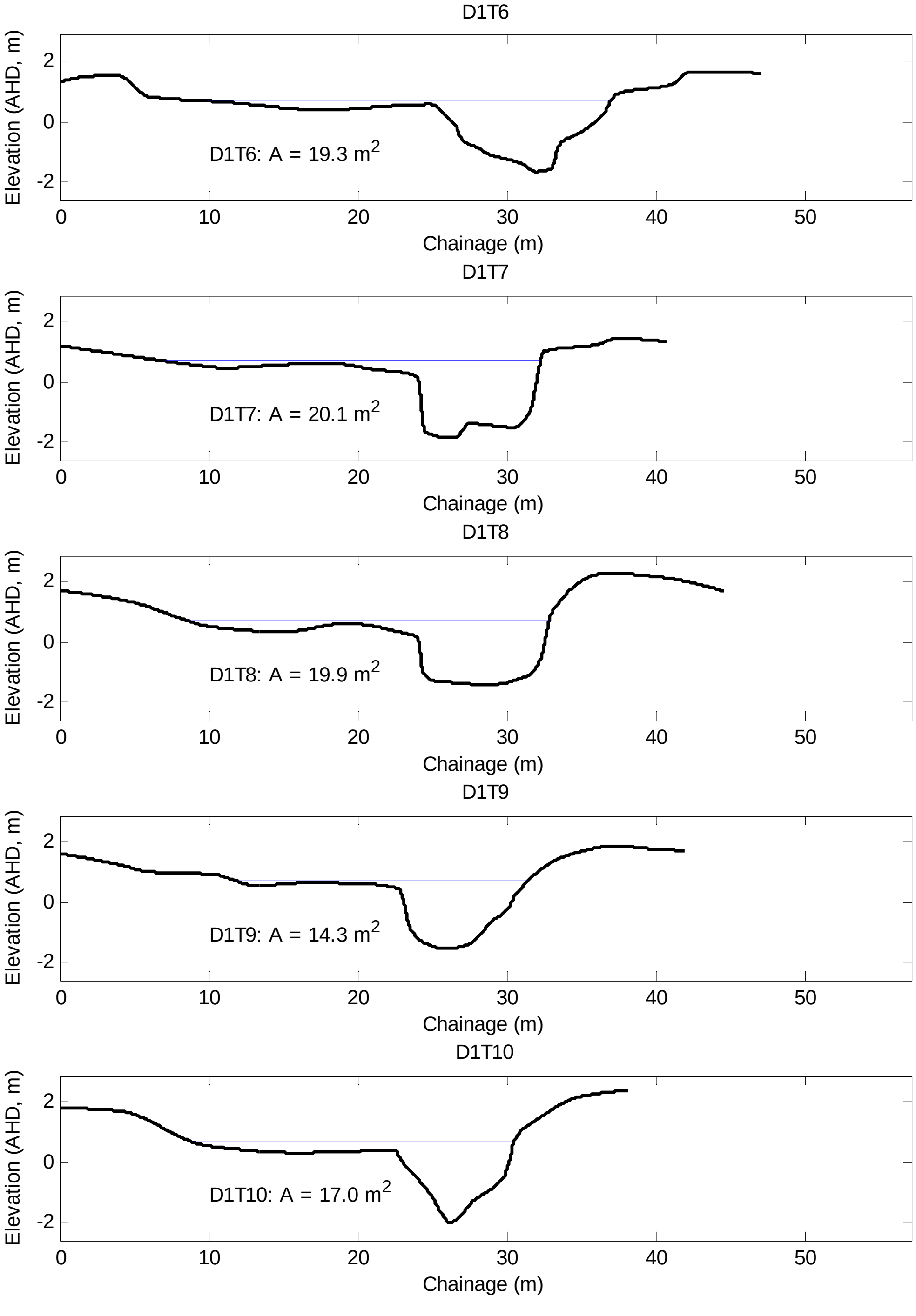
Key Structures and Drains Incorporated into 1D Network Model



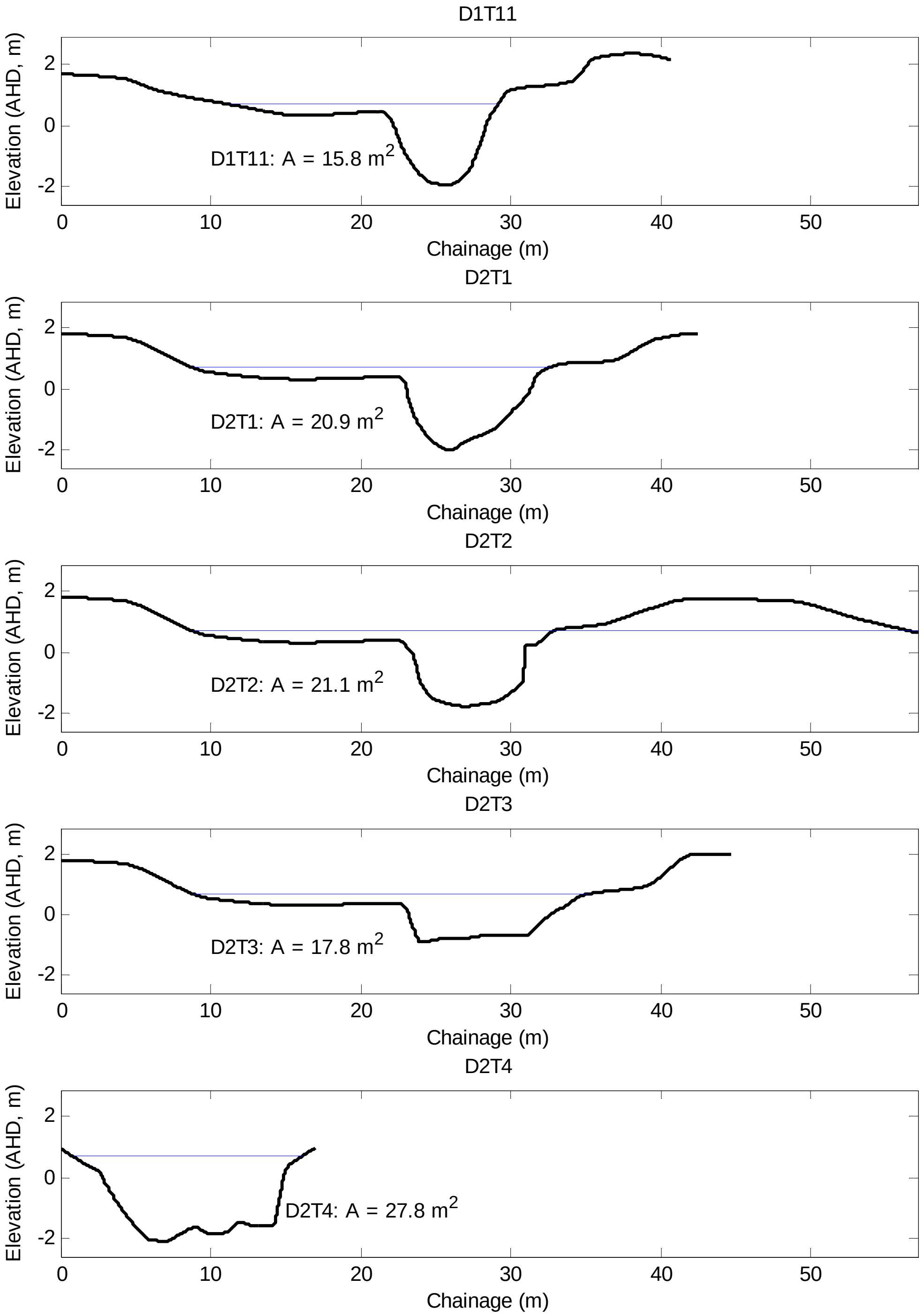
Location of Surveyed Channel Cross-Sections During Field Investigations (25th - 29th June)



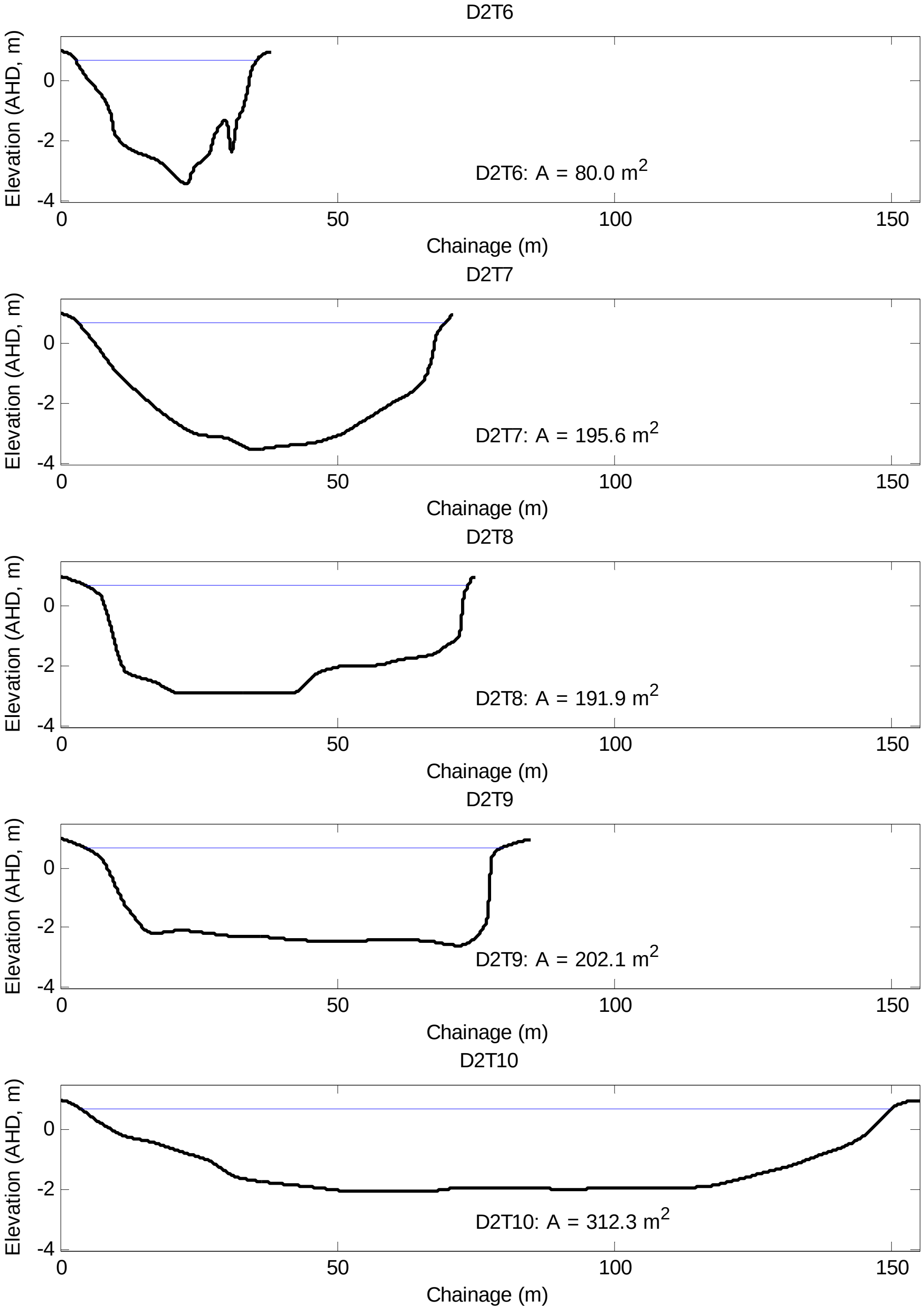
Surveyed Cross Sections



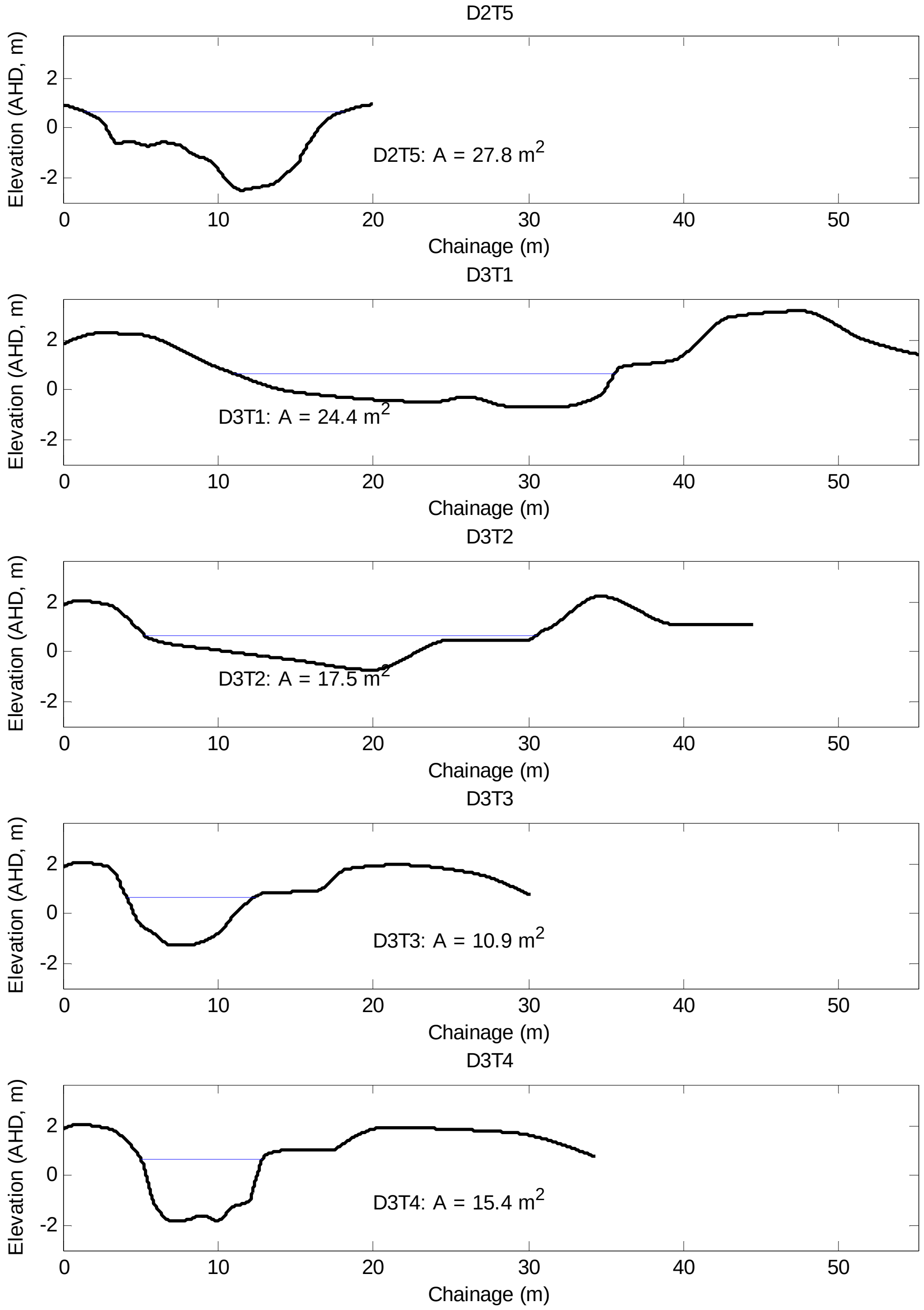
Surveyed Cross Sections



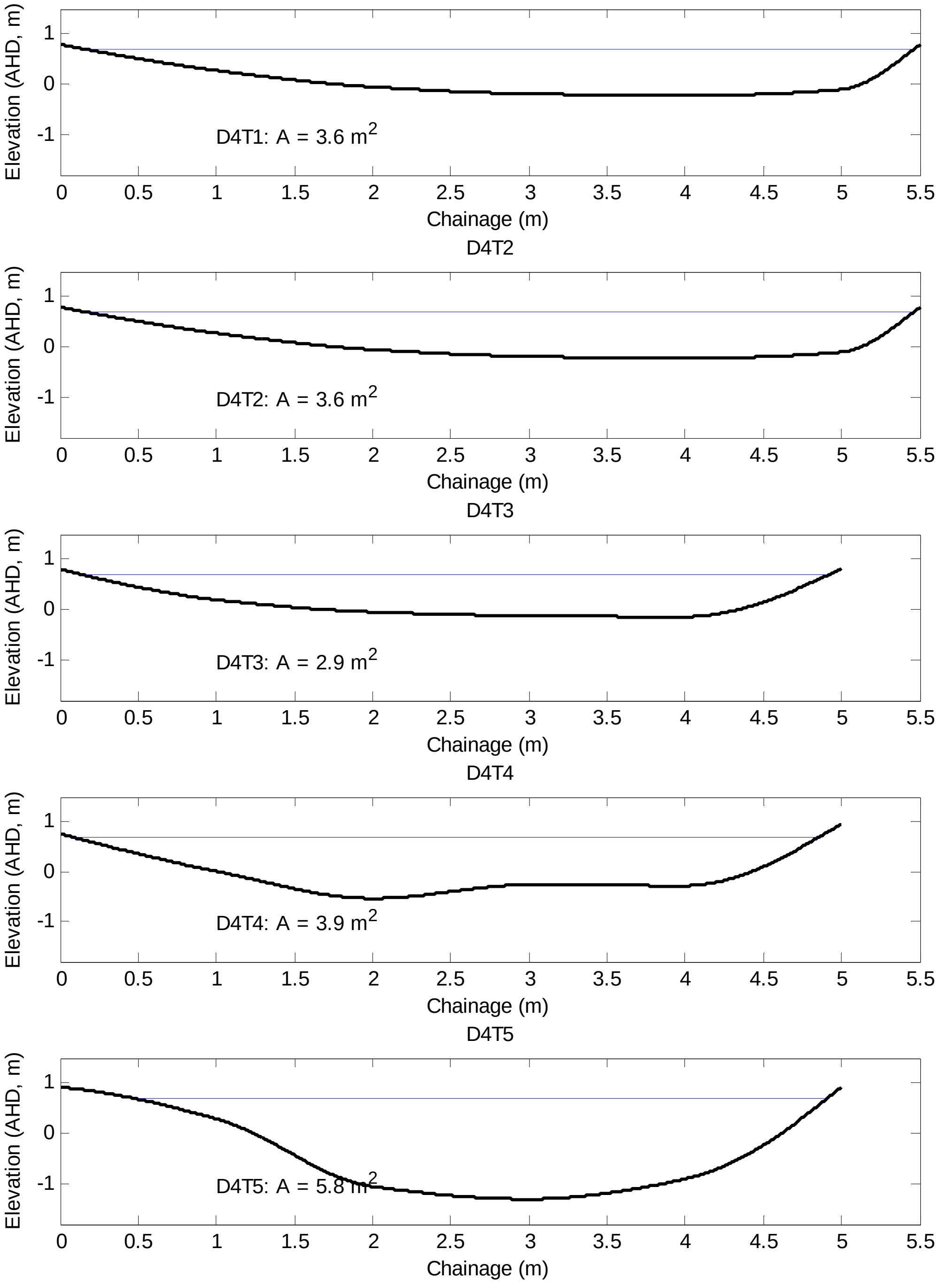
Surveyed Cross Sections



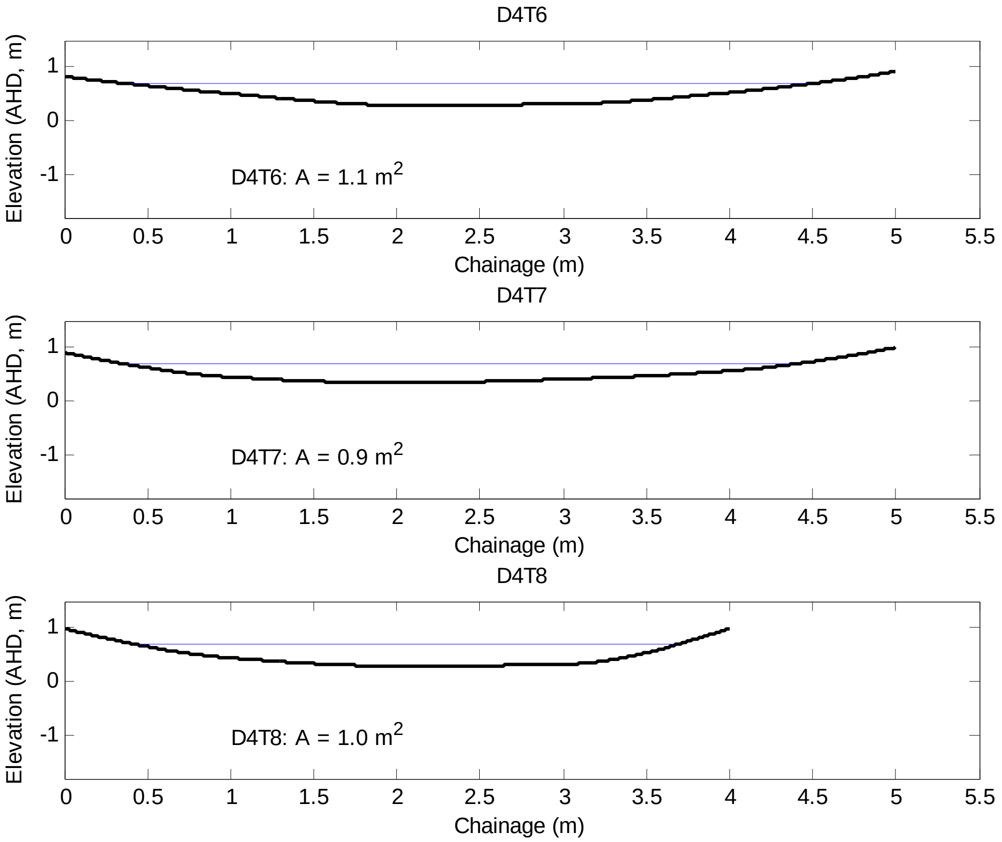
Surveyed Cross Sections



Surveyed Cross Sections

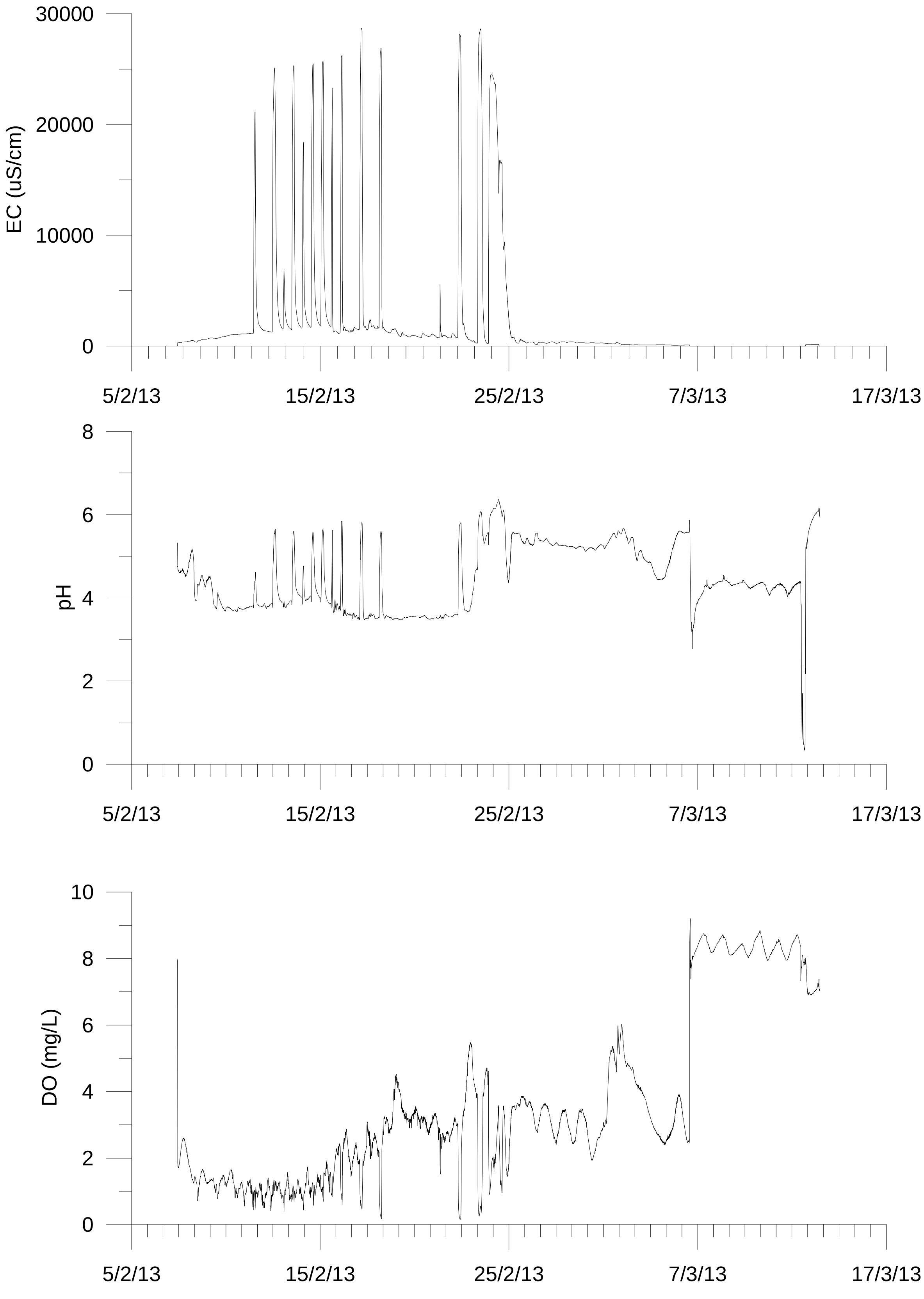


Surveyed Cross Sections

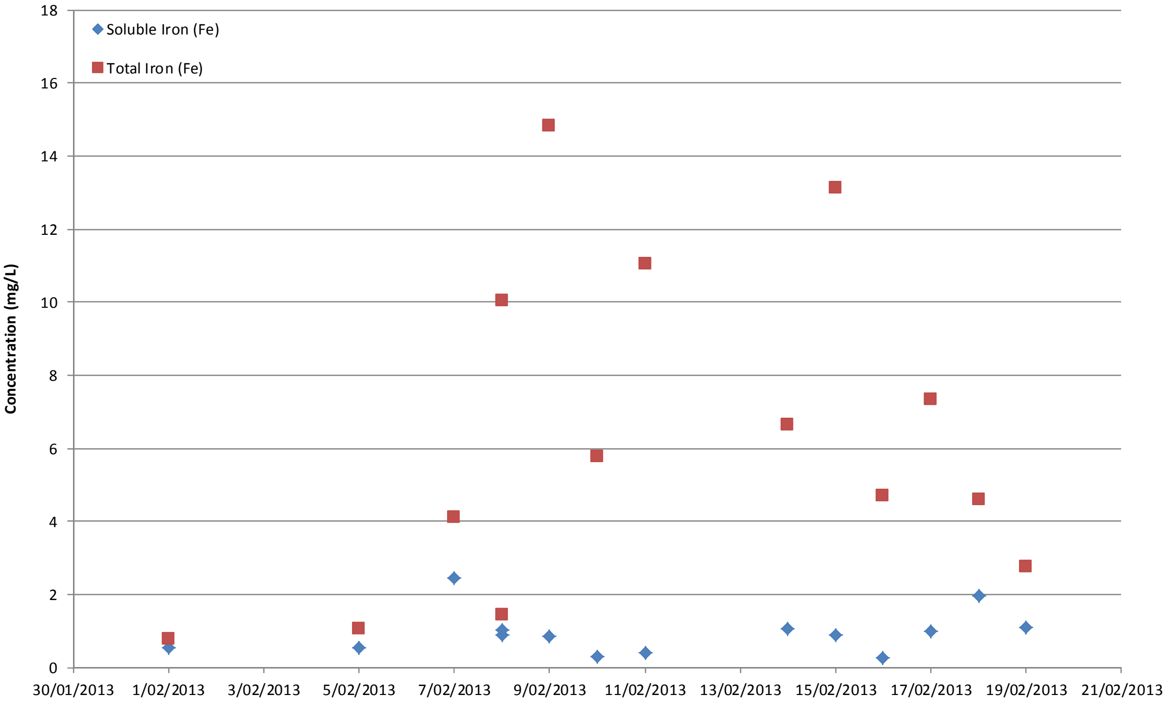


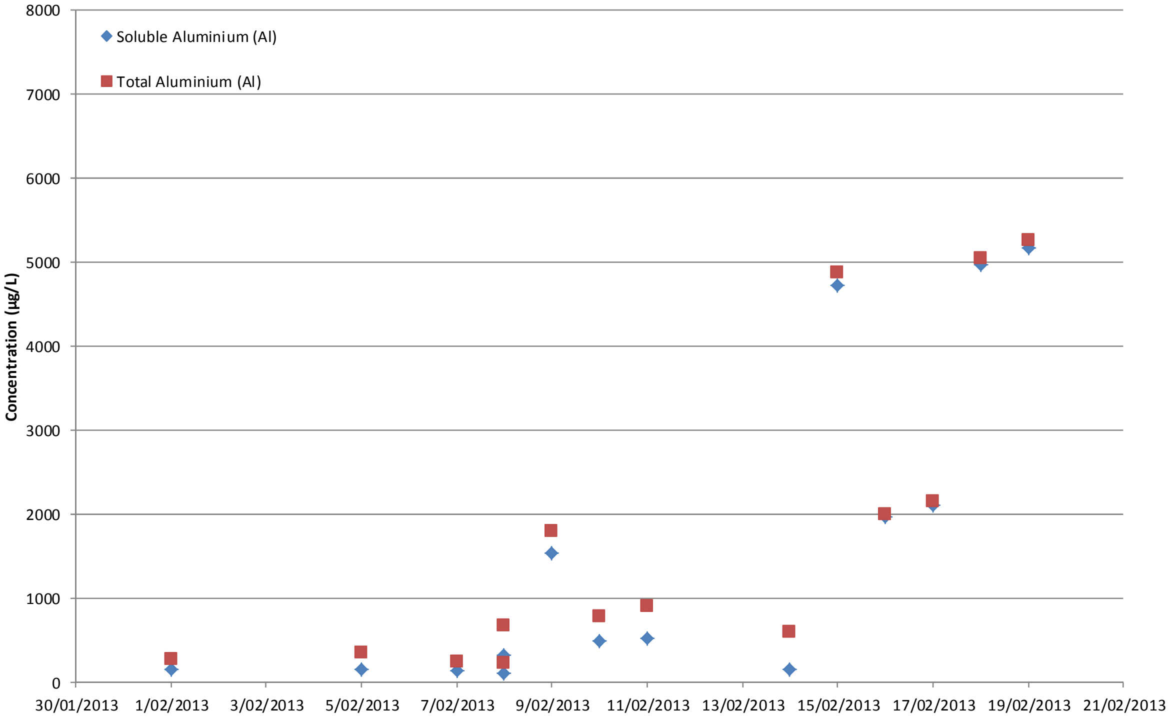
Surveyed Cross Sections

Channel Surveying Technique Using a Kayak

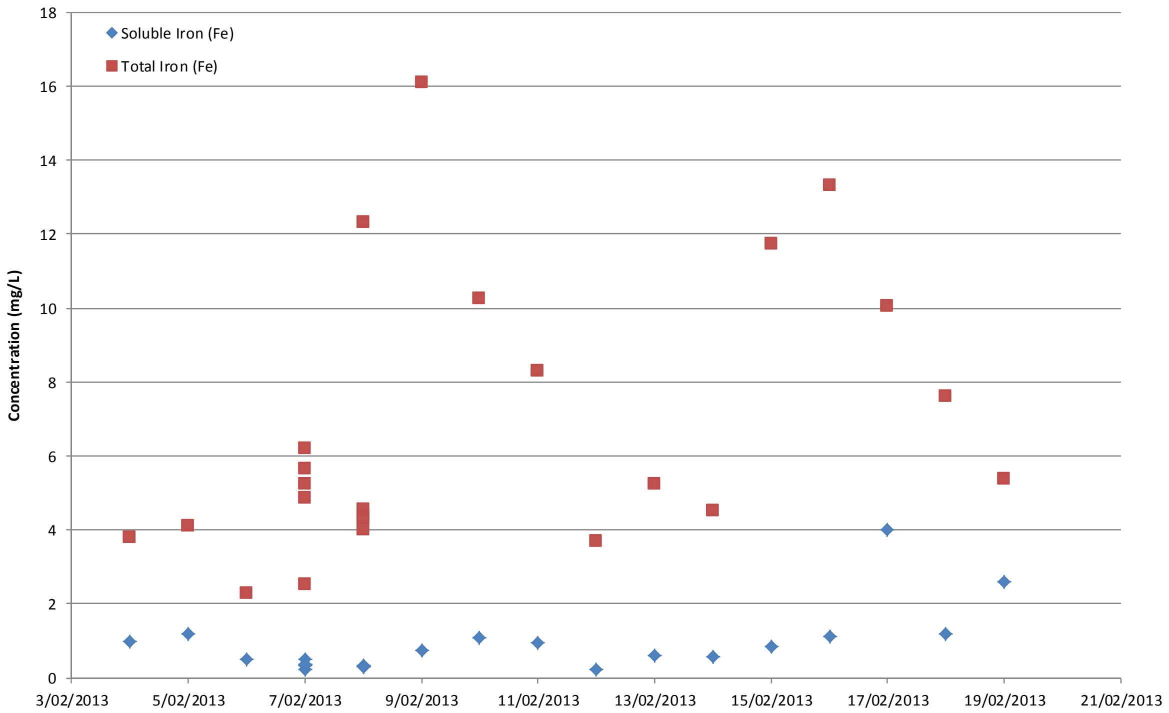


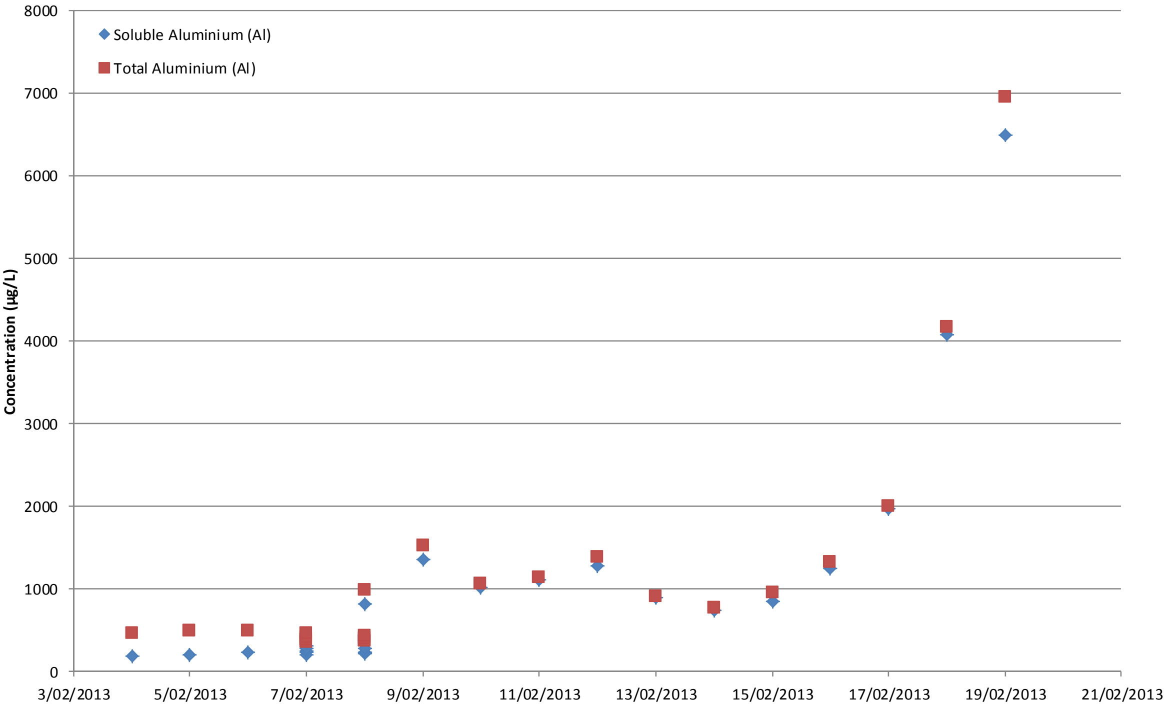
Measured Water Quality At Pipeclay Canal – Cattai Creek Confluence During Wet Period



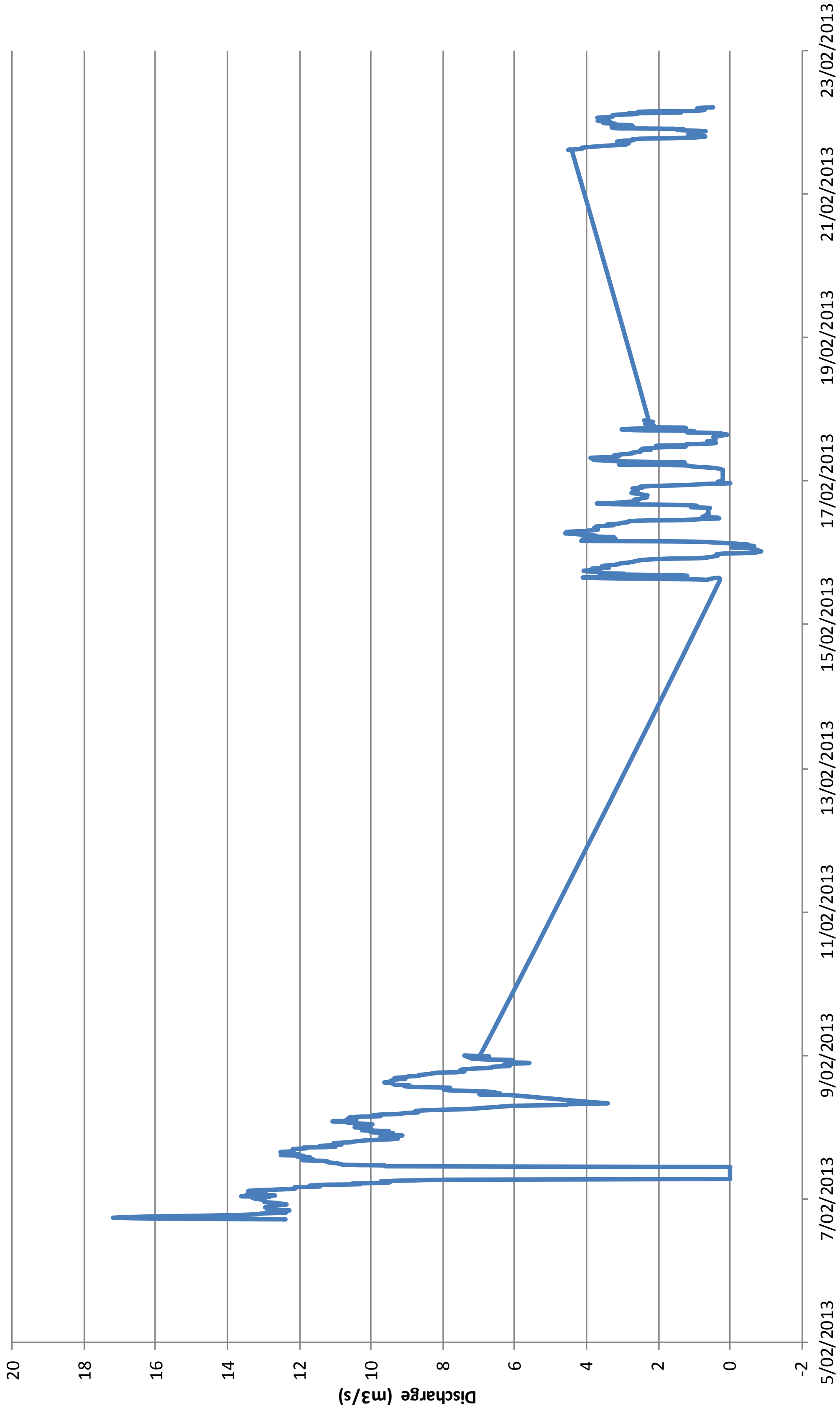


Coralville Road Bridge Heavy Metal Analysis

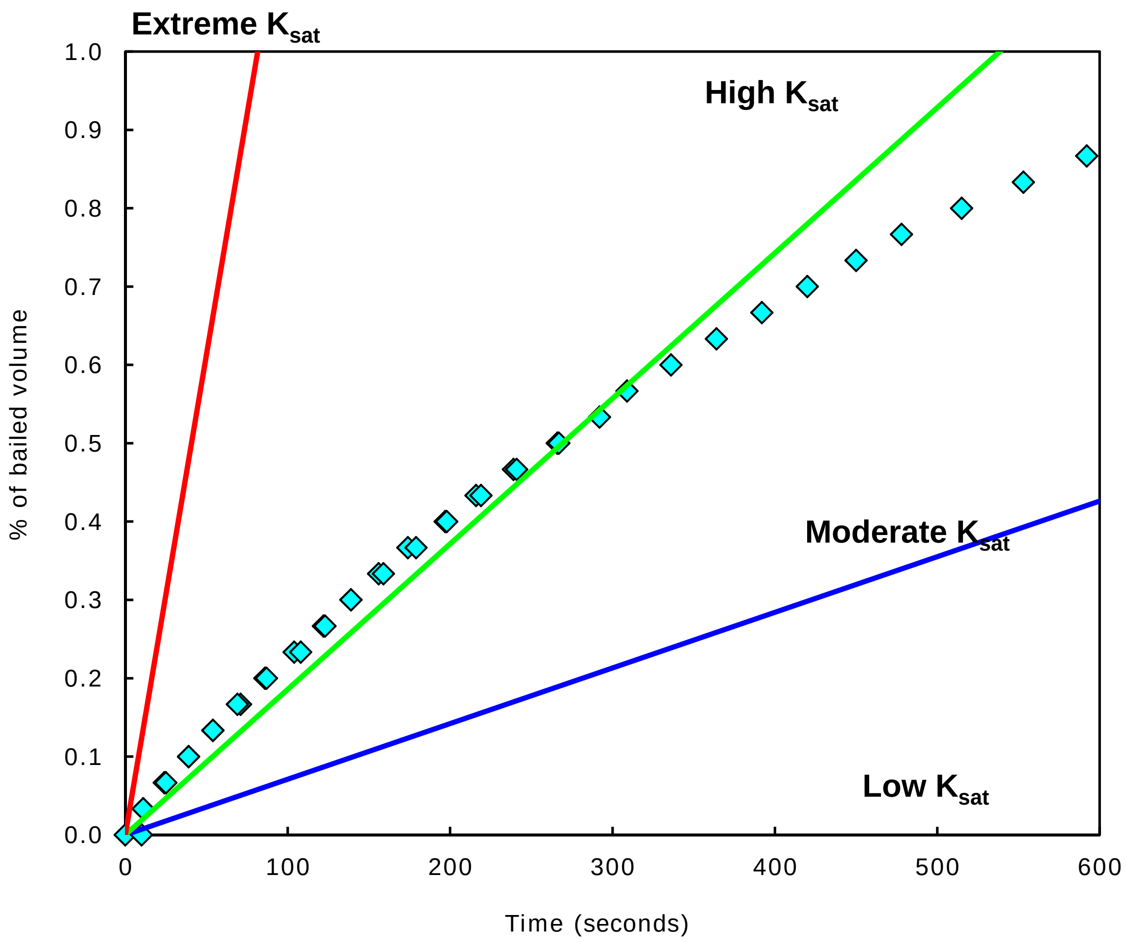




Heavy Metal Analysis Measured at the Pipeclay Canal – Cattai Creek Confluence

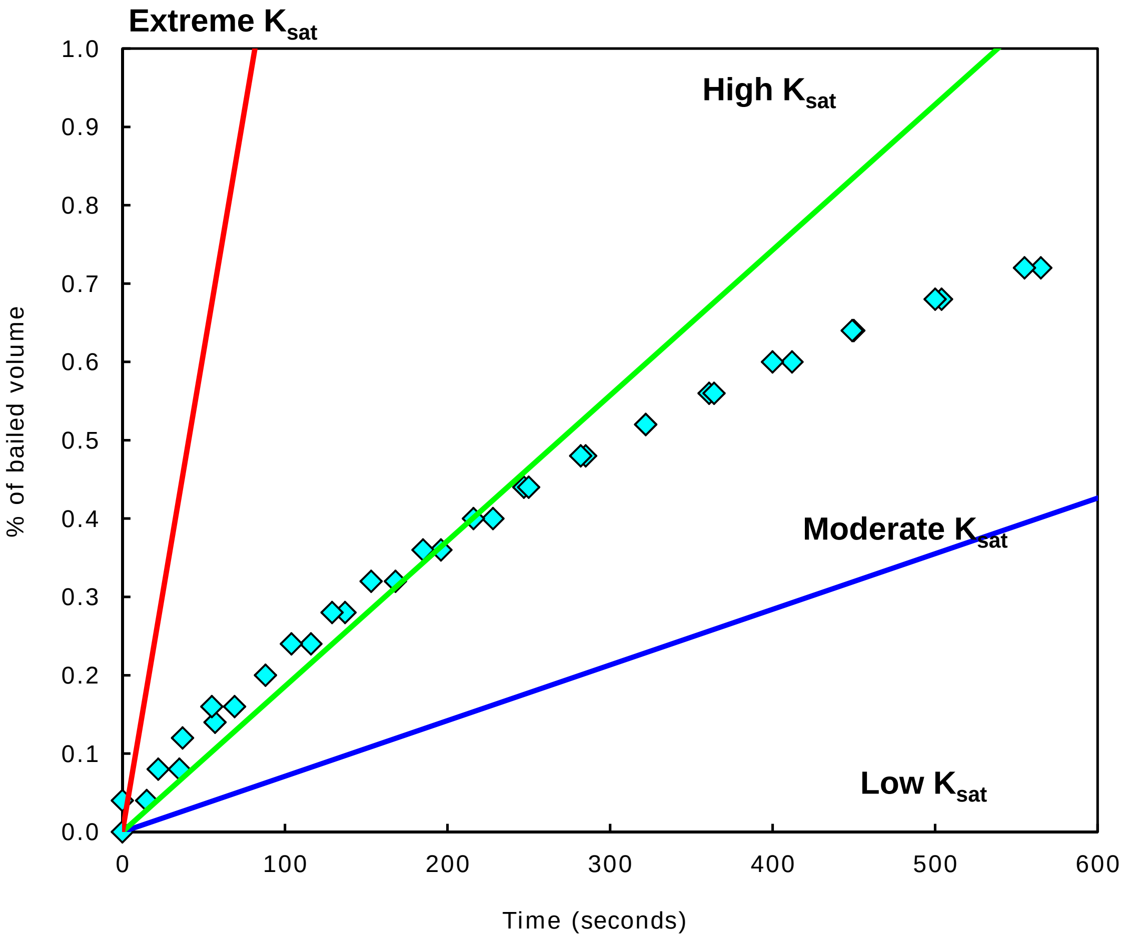


Measured Discharge at the Pipeclay Canal – Cattai Creek Confluence



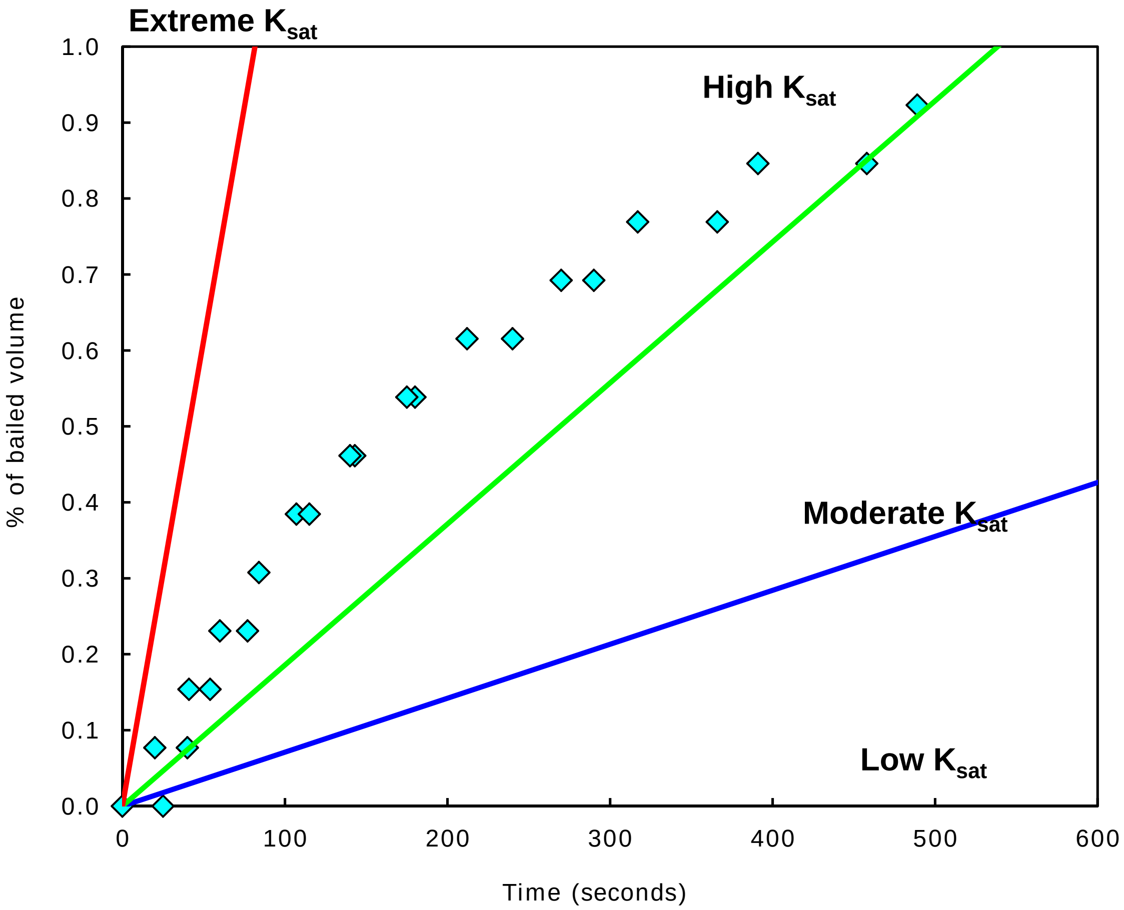
Classification	Approximate K_{sat} (m / day)
Extreme	~100
High	15 to 100
Moderate	1.5 to 15
Low	< 1.5

Bulk Hydraulic Conductivity Test Pit: 2



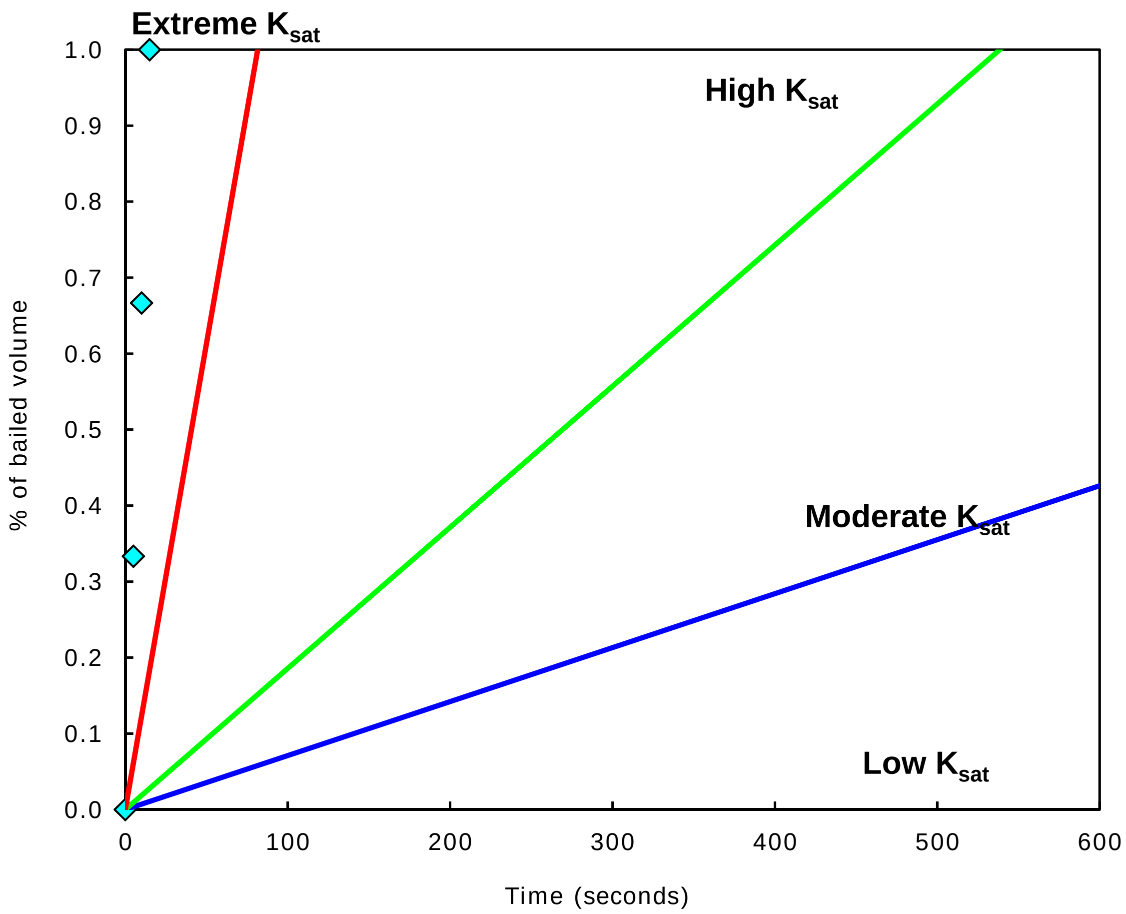
Classification	Approximate K_{sat} (m/day)
Extreme	~100
High	15 to 100
Moderate	1.5 to 15
Low	< 1.5

Bulk Hydraulic Conductivity Test Pit: 3



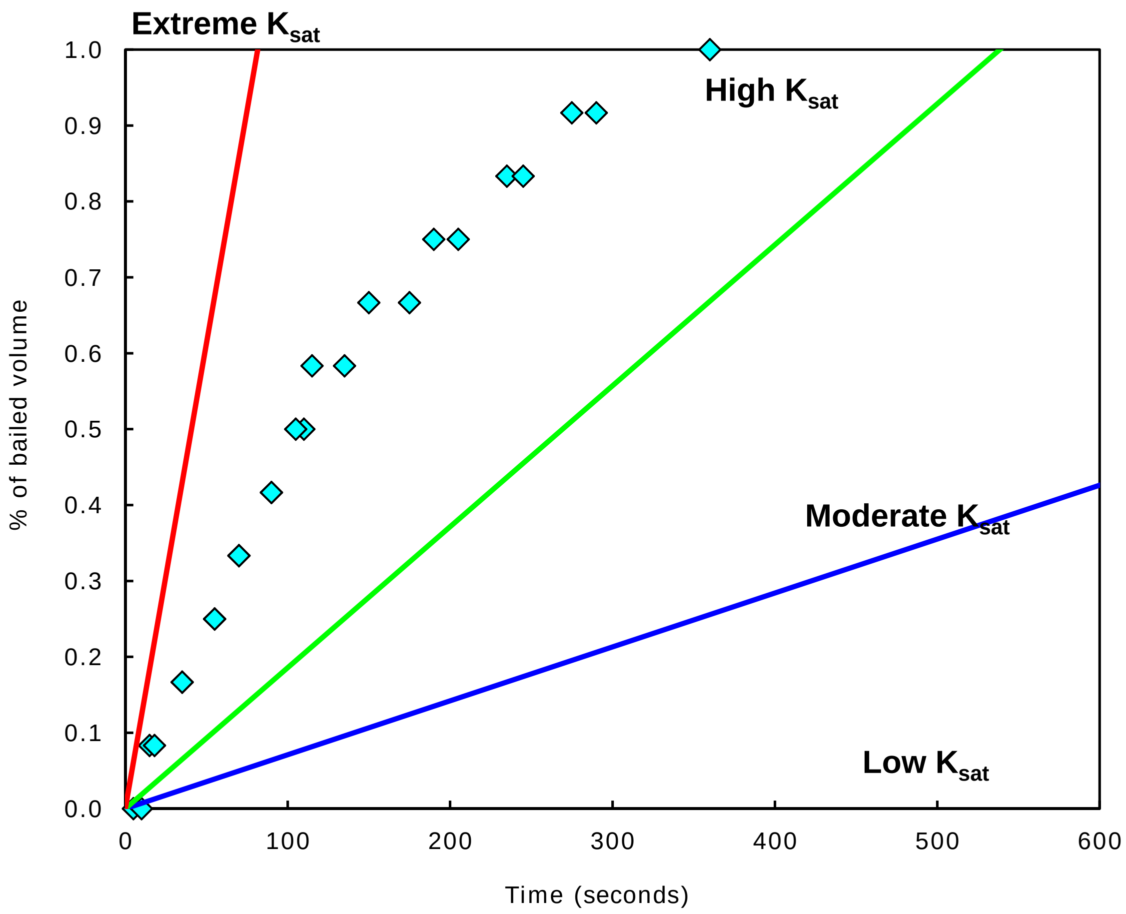
Classification	Approximate K_{sat} (m / day)
Extreme	~100
High	15 to 100
Moderate	1.5 to 15
Low	< 1.5

Bulk Hydraulic Conductivity Test Pit: 4



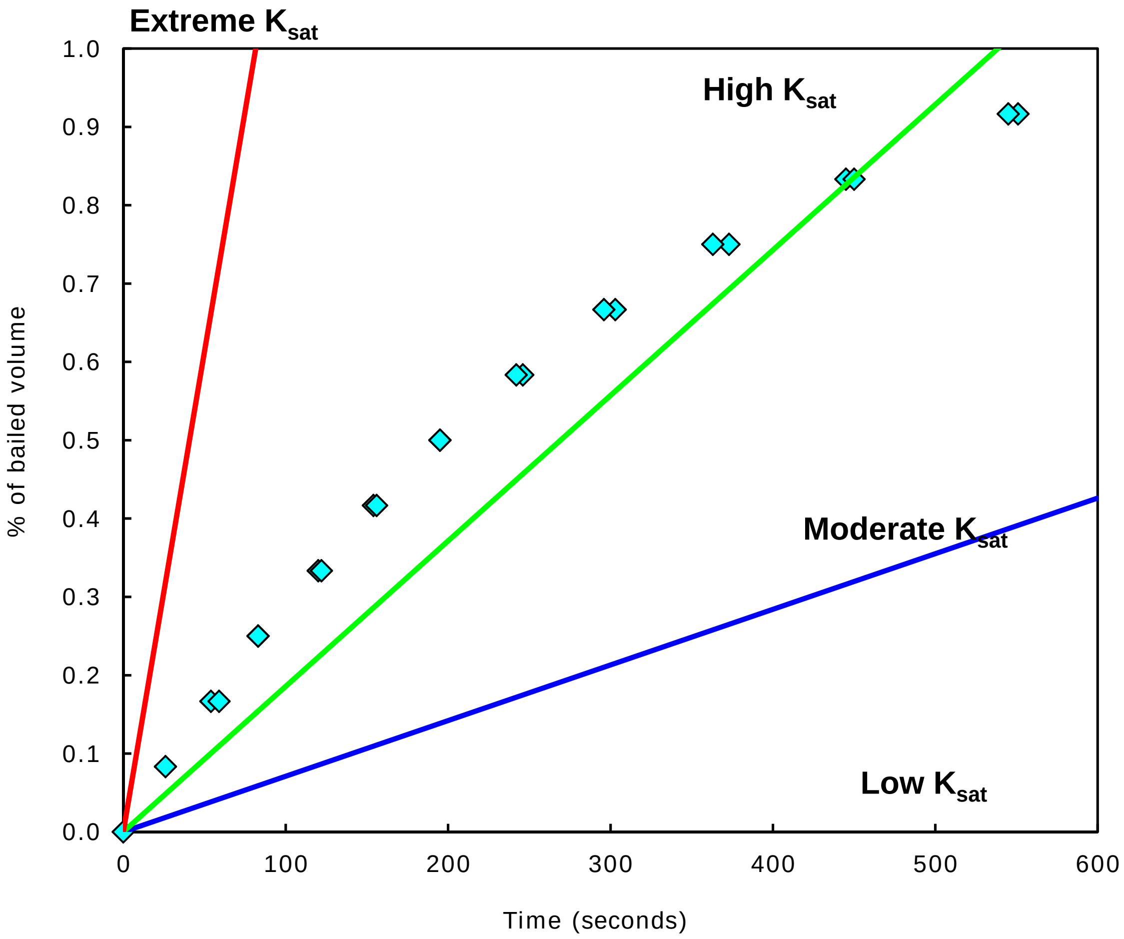
Classification	**Approximate K_{sat} (m / day)**
Extreme	~100
High	15 to 100
Moderate	1.5 to 15
Low	< 1.5

Bulk Hydraulic Conductivity Test Pit: 5



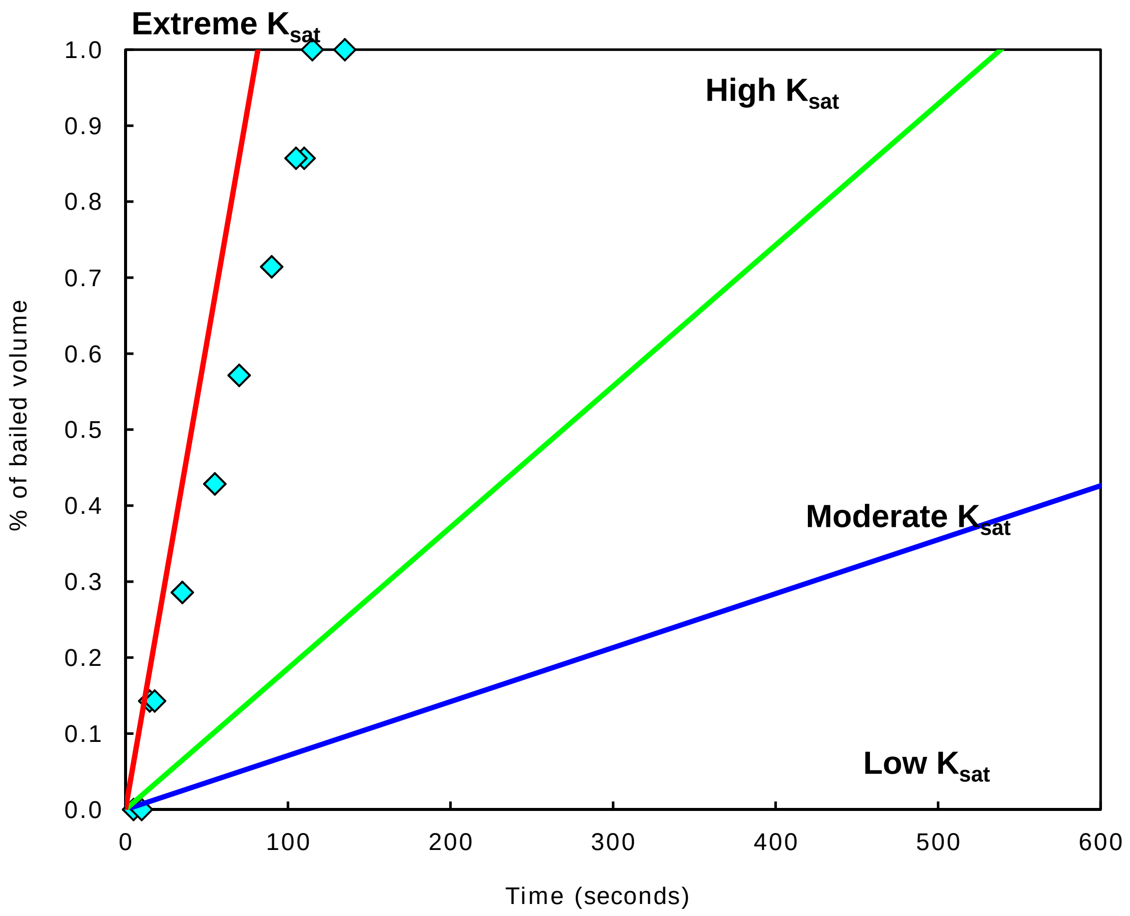
Classification	Approximate K_{sat} (m / day)
Extreme	~100
High	15 to 100
Moderate	1.5 to 15
Low	< 1.5

Bulk Hydraulic Conductivity Test Pit: 6



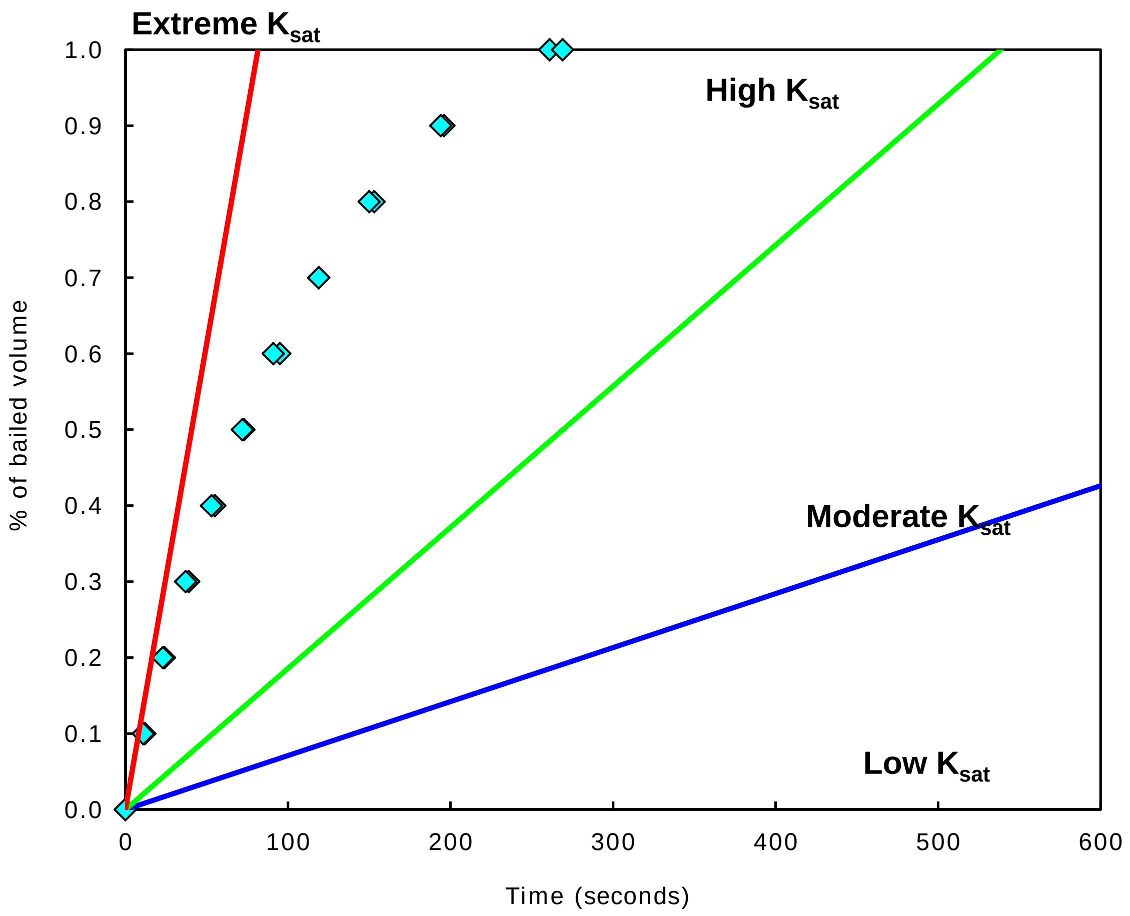
Classification	Approximate K_{sat} (m/day)
Extreme	~100
High	15 to 100
Moderate	1.5 to 15
Low	< 1.5

Bulk Hydraulic Conductivity Test Pit: 7



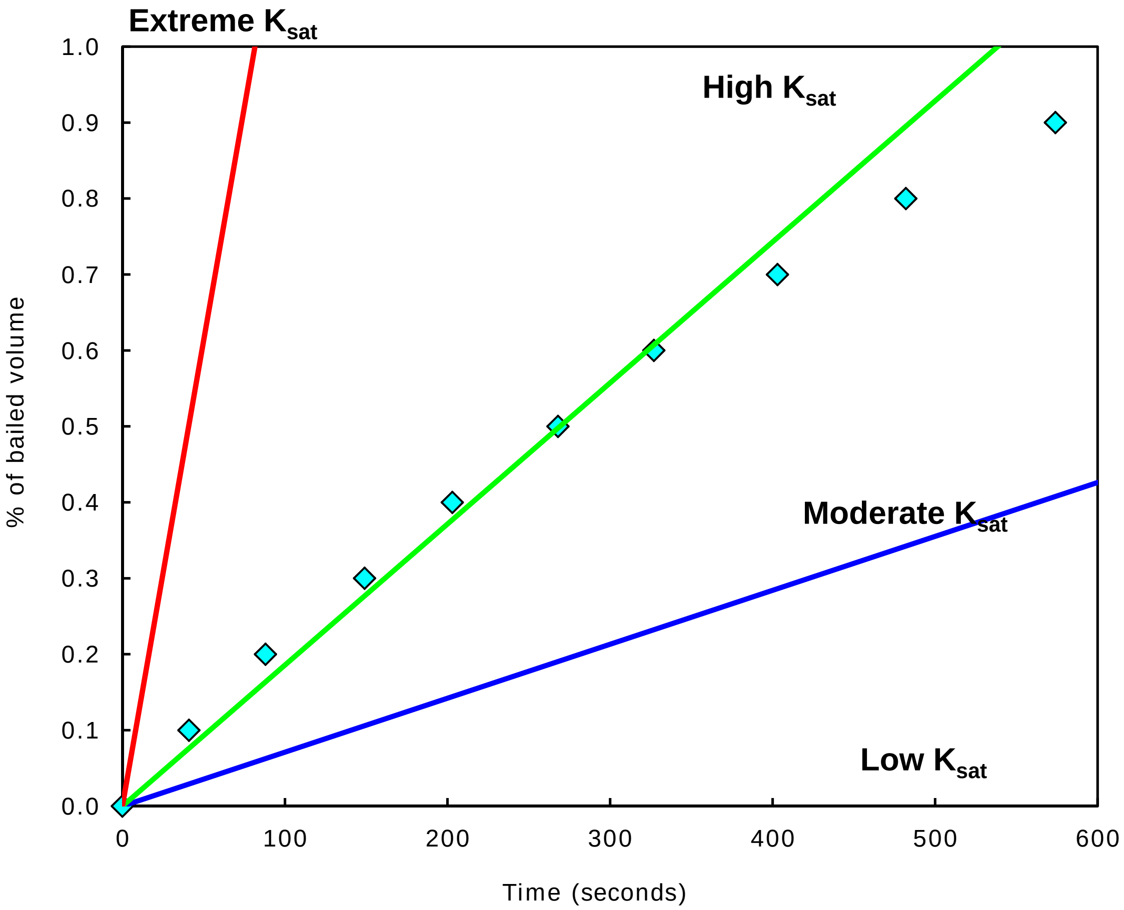
Classification	Approximate K_{sat} (m / day)
Extreme	~100
High	15 to 100
Moderate	1.5 to 15
Low	< 1.5

Bulk Hydraulic Conductivity Test Pit: 8



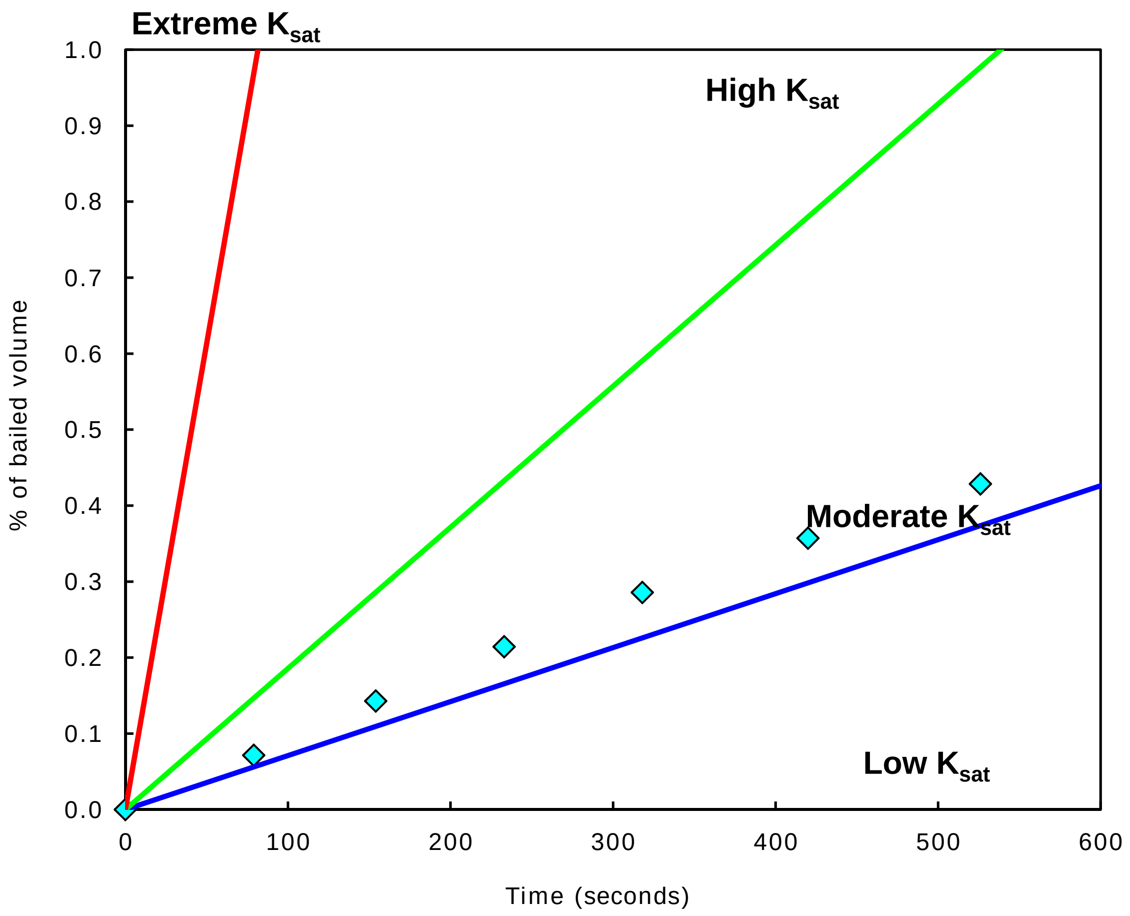
Classification	**Approximate K_{sat} (m / day)**
Extreme	~100
High	15 to 100
Moderate	1.5 to 15
Low	< 1.5

Bulk Hydraulic Conductivity Test Pit: 9



Classification	Approximate K_{sat} (m / day)
Extreme	~100
High	15 to 100
Moderate	1.5 to 15
Low	< 1.5

Bulk Hydraulic Conductivity Test Pit: 10



Classification	Approximate K_{sat} (m / day)
Extreme	~100
High	15 to 100
Moderate	1.5 to 15
Low	< 1.5

Bulk Hydraulic Conductivity Test Pit: 11

Appendix C: Hydrodynamic Model

Numerical models simulate hydrodynamic processes by using local data and relevant equations to represent physical processes. The model grid is constructed using site geometry and representative physical parameters such as bed roughness (or Manning's n). Boundary conditions are then applied (such as catchment inflows and tidal signals) and the model is calibrated using available real-world data.

A range of software programs are available for simulating complex hydrodynamic processes. For this study, the MIKE FLOOD v2012 (Service Pack 1) model was employed. MIKE FLOOD is particularly applicable to this site as it simulates one-dimensional/two-dimensional (1-D/2-D) overbank flow and wetting/drying efficiently. WRL has successfully used this model recently to simulate overbank inundation in the Anna Bay wetlands in Port Stephens, Yarrahapinni Wetlands in Northern NSW and Tomago Wetlands in the Hunter River Estuary.

This section details the modelling process including initial set-up of the 1-D and 2-D models, calibration and verification.

MIKE Modelling Suite

The MIKE models are a finite difference numerical modelling package. MIKE FLOOD allows a hybrid modelling approach, which combines both 1-D and 2-D modelling components to create the final model. For this study, MIKE-11 was used to simulate 1-D flows through the main channel network, including bridges, culverts and floodgates. MIKE-21 was used to simulate 2-D overland flow and wetting/drying of the floodplain. MIKE FLOOD linkage elements coupled the two models together to provide the completed model.

1-D Pilot Model

At the onset of this study limited information was available at Big Swamp to develop and calibrate/verify a numerical model. In particular, no channel surveys, tidal discharge volumes or water level information was available and little was known about the tidal extent and salinity/tidal dynamics in Pipeclay Canal. Consequently, an initial 5 day field campaign on the 25th – 29th June 2012, was undertaken to collect basic site data and information. The results of the field data collection programme were RTK-GPS survey levels of key structures that control flow (i.e. bridges, culverts and floodgates), cross-sections of important drains and installation of two water level sondes within Pipeclay Canal.

Using this information a 1-D pilot model was constructed and a range of sensitivity tests were undertaken to investigate the key parameters that influence water dynamics across the site. This approach was also used to identify further information that would be required to accurately simulate the hydrodynamic processes in Pipeclay Canal. Four key parameters were identified as:

1. Model roughness;
2. Upstream inflow;
3. Conveyance; and
4. Off-channel storage.

The initial pilot model proved to be sensitive to roughness, upstream inflow and conveyance, while being less sensitive to off-channel storage. The outcomes of these sensitivity tests were used to target field monitoring exercises.

Model Setup

The trunk drainage network in the Big Swamp region was simulated as a series of linked flow branches each capable of predicting flow represented in 1-D. The flow through this system is dependent on the drain geometry and any flow restrictions such as bridges and culverts. The extent of the 1-D network adopted for this study was taken from the top of Pipeclay Canal (E 469289 N 6484937) to the junction between Cattai Creek and the Manning River (E 468063 N 6479343), approximately 13.5 km in length. The 1-D network also includes several floodplain trunk drains that connect to Pipeclay Canal through culverts. To configure the 1-D model, channel geometry was required to be specified at every point in the system. For this study, the channel geometry was sourced from the cross-sections surveyed by WRL and supplemented by topography data. Where surveys were not taken, cross-sectional data was extracted from the topography. Drain geometry between surveyed locations was linearly interpolated using known cross-sections.

The locations of key flow control structures created by bridges, culverts and floodgates are instrumental in configuring a working 1-D network model. A series of three bridge structures and over 25 culvert structures, in and around Pipeclay Canal and the main floodplain drains, were observed during the initial field investigations at Big Swamp. The key culvert structures implemented into the model are shown in Table B-8.

1-D Model Calibration

A numerical model is as accurate as the data used to calibrate the model. Following the initial field campaign, there was limited calibration data available for Big Swamp and no coordinated data sets measuring water levels and flows from various locations concurrently. As a result, a field campaign was undertaken on 27th – 30th August 2012 to provide additional information on how Pipeclay Canal functions during a typical dry weather period ('dry snapshot'). The information collected was used to calibrate the 1-D network model including:

- Water levels within Cattai Creek and the top of Pipeclay Canal;
- Upstream and downstream discharge measurements in and out of Pipeclay Canal;
- Coordinated flow measurements from the various field drains; and
- Groundwater level measurements.

Data Available

Based on data availability, the 1-D network model was calibrated to water level and flow data only. A time series of recorded water levels at Croki on the Manning River was applied as the downstream boundary condition in the 1-D network model. The chosen calibration period (from 22/08/2012 12:00:00 AM to 17/09/2012 11:45 PM) followed the installation of two new water level loggers and the Argonaut-SW during the 'dry snapshot' field investigations on the 27th – 29th August 2012. Refer to Appendix B (Table B-7) for more detailed information on the installation of all data loggers.

Water level data was obtained from instrumentation installed by WRL at three locations within the 1-D network area. The three sites being:

1. Top of Pipeclay Canal;
2. Downstream Bridge #3; and
3. Cattai Creek.

Sites 1 and Site 3 were chosen to represent the extent of the 1-D network, while Site 2 was selected as representative of the internal conditions within the model.

Flow data was measured at the junction of Pipeclay Canal and Cattai Creek. This site was selected as being representative of the total flow moving in and out of the 1-D network model. Unidentifiable instrument failure following installation of the Argonaut-SW, resulted in only four days of reliable data (from 29/08/2012 4:15 PM to 02/09/2012 11:45 PM). WRL subsequently replaced the failed instrument, however, the new instrument also failed and this resulted in no additional data being collected.

Sensitivity Testing

For this study, values for roughness were chosen based on available literature. Chow (1959) suggests a value of 0.04 for straight and uniform channels with an earth bottom and 0.08 for conditions where the degree of vegetation is 'low'.

Calibration of the 1-D network model was chosen during a representative dry weather period and followed the 'dry snapshot' field campaign. There was no recorded rainfall for approximately 18 days preceding the field work. Based on this on-ground work, moderate inflows of approximately 0.5 m^3/s were recorded at the top of Pipeclay Canal and low inflows of approximately 0.1 m^3/s were recorded in the D/S East Section Drain (E 468610, N 6480029). The rest of the site recorded 'no flow'. It should be noted that 'no flow' may describe a floodplain drain in which there is a "stagnant" standing water level.

In the absence of gauged catchment data, a rainfall-runoff model was used to estimate typical daily runoff and baseflow values. A 'baseflow' value is representative of 50th percentile flow in a time series of runoff for a given site. For this study, approximately 100 years of rainfall data recorded at Moorland (3 km west of the study site) and a total catchment area of 113 km^2, was input into the Australian Water Balance Model v2002 (AWBM) (Boughton, 2004) to estimate the baseflow likely to be observed in the Pipeclay Canal. The observed 50th percentile flow calculated was approximately 0.1 m^3/s, which corresponds to the inflows recorded across the site during the 'dry snapshot'.

A combination of six cases between roughness and flow were trialled to test the sensitivity of the 1-D network model for the selected calibration period. Two roughness values were assumed in conjunction with three flow values; low, moderate and high, with respect to the dry weather conditions. The results showed that the model was highly sensitive to the chosen roughness value. A high roughness value of 0.08 caused increased water levels across the site, changes to the phasing of the tidal signal and influenced the filling and drainage time of the site. Similar results were also observed for the high flow case using a roughness value of 0.04. A better match between model and measured data was observed for low and moderate flows using a roughness value of 0.04.

Based on the sensitivity tests, a model roughness of 0.04 and inflow value of 0.1 m^3/s were adopted as the base calibration parameters for the 1-D network model. This was determined to be representative of the observations made during the 'dry snapshot' field investigations and the estimated baseflow value calculated using AWBM. A pivot table summarising the roughness-flow parameter combination adopted for the base calibration is shown in Table C-1.

Table C-1: Six Roughness-Flow Sensitivity Cases Trialled in the 1-D Model Calibration

		Model Roughness ‘n’	
Inflow Value (m^3/s)		**n = 0.04 (‘Normal’)**	**n = 0.08 (‘High’)**
‘Low’	0.0	✓	×
‘Moderate’	0.5	×	×
‘High’	1.0	×	×

Following the sensitivity testing of the roughness and inflow parameters, the model results for the calibration window indicated water levels to be higher in the model than measured onsite. At Site 1 and Site 3 in Pipeclay Canal, the differences observed were approximately 0.1 – 0.2 m above and below peak water levels for both the flood and ebb tides. In addition, the discharge observed in the model were generally in good agreement with the discharges recorded by the Argonaut-SW.

Further model refinement to better match the measured data could only be achieved through manipulation of the off-channel storage and conveyance parameters along Pipeclay Canal. Preliminary sensitivity work on the 1-D network model, investigating the effect of off-channel storage, suggested that large volumes of additional storage had minimal impact on influencing water levels along Pipeclay Canal. Moreover, there is no supporting evidence to suggest that above-ground off-channel storage areas exist within the Big Swamp floodplain, that have not already been accounted for in the 1-D network model. Conveyance however, becomes an important parameter influencing how water moves in and out of a system like Big Swamp. In particular, Pipeclay Canal has a main flow channel along its right bank and a 20 m wide bench above approximately 0.4 m AHD along its left bank, containing a mix of vegetation density the full length of the canal.

In these types of tidal systems where this low flow zone above the main flow channel exists, it is important to accurately represent the movement of water on to and off this area, as well as its conveyance properties. For this study, this zone is only “active” when water levels exceed 0.4 m AHD in Pipeclay Canal, therefore, it was assumed that this area provides limited conveyance along the system. As a result, the 1-D network model would need to reflect a channel geometry which provides zero conveyance, while still maintaining the storage area above 0.4 m AHD.

In Mike 1-D, generally, three “markers” are used to identify the left and right banks, as well as a bottom marker to indicate the bed level. These markers can be manipulated to change the channel geometry without changing the surveyed cross-section data. As a means to remove conveyance along the left-side bench of Pipeclay Canal, the left bank marker was shifted from the top of the left bank levy to an elevation of approximately 0.4 m AHD (representing the inner edge of the bench). Subsequently, additional storage area (represented as a ‘plan area’) was added at each surveyed cross-section above 0.4 m AHD and between Ch1657 m and Ch4515 m along Pipeclay Canal, to ‘replace’ an equivalent storage area “lost” through removing conveyance in these cross-sections. The estimated storage area was calculated at each cross-section using the following formula:

$$A = w \times \left(\frac{\Delta x_1}{2} + \frac{\Delta x_2}{2}\right)$$

Where w is the width of the bench,
Δx is the difference in chainage before (x_1) and after (x_2) the cross-section.

Refer to Table C-2 for the distribution of approximate storage area along Pipeclay Canal added to each cross-section.

Table C-2: Estimated Storage Areas Calculated to Replace the Equivalent Storage Area Lost Through Removing Conveyance at Each Cross-Section Chainage Listed

Cross-Section Chainage (m)	Estimated Storage Area (m^2)
1217	-
1657	10000
2003	5000
2030	500
2035	500
2048	500
2068	2000
2212	2000
2228	3000
2448	3000
2460	2500
2641	6500
2977	8000
3298	5000
3395	4000
3590	5000
3805	6000
4076	6500
4318	5500
4505	2500
4515	500
4525	-

Data Comparison

Figures 5.3 to 5.6 compare the calibrated model results to the measured field data at four locations including at the Argonaut-SW (Site 4). These figures show two separate frames at each water level recording site; the first highlights a four-day period, while the second frame shows the complete calibration timeframe. Water levels at Croki are also shown for reference. A 25-hour running average of both the model results and the measured data is shown to represent the mean water level for each data series.

The model was shown to be in good agreement with the available data measured onsite for infilling/rising and draining/falling tides in the lower sites of Pipeclay Canal. The magnitude of the peak water levels at Site 3 is particularly well simulated. However, upstream at Site 1, the model slightly over-predicts the peak water levels on the infilling/rising tide, which subsequently affects the draining rate of the system. Nonetheless, the difference between the modelled and measured data is approximately 0.1 m, which is considered to lie within the accuracy of the instrumentation and best practice techniques used in the field surveys.

Furthermore, the model was shown to over-estimate the discharges entering the model on the flood tide by approximately 1 – 2 m^3/s. This is equivalent to a velocity difference of approximately 0.05 - 0.08 m/s. It is considered that this difference could be associated with placement of the Argonaut-SW within the channel. The Argonaut-SW was installed just upstream of a bend at the junction of Pipeclay Canal and Cattai Creek, approximately 0.5 m from right bank and 2 m below the mean water level to ensure that the major field drains were included. As a result, the Argonaut-SW may not accurately capture the ebb tide velocities passing along the right bank, compared to the flood tide velocities which would focus on the left bank. It is anticipated that the variation in flood tide velocities across the profile of that section could be in the order of 0.1 m/s. Subsequent qualitative field inspections (but not quantitative) have been undertaken to support this assumption.

Model Uncertainties

Following completion of the 1-D network model, the remaining areas of concern are associated with additional off-channel storage. To assess the effect of adding off channel storage in the 1-D network model, an additional sensitivity test was compiled on the calibrated model. This involved taking the calculated storage areas provided in Table C-2 and adding this area to elevations between 0 – 0.4 m AHD (Figure C.1). This volume was assumed to be representative of infiltration to groundwater, leakage through culverts and evapotranspiration, processes not included as part of this study. The results showed that this additional storage improved the slope of the draining/falling arm of the tide and also restricted the model from draining below the measured peak ebb tide water level elevations. However, no data exists to justify any changes to the calibrated model and this additional scenario should be referenced when detailed investigation, of floodplain inundation are undertaken.

At this stage, the calibrated model results presented are considered to be *fit for purpose* as inflows and subsequently peak tidal water level in Pipeclay Canal will control the extent of floodplain inundation in the 1-D/2-D model.

MIKE FLOOD Model

Topography

The 2-D model topography was sourced directly from the LiDAR data. The 2 m gridded topography was re-sampled at a 10 m resolution in GIS and imported into MIKE 21. A 10 m x 10 m model grid was chosen to discretise the Pipeclay Canal floodplain region. This grid resolution ensured computational efficiency while still adequately representing the major landform features such as internal trunk drains and relic drains (Figure C.2). Furthermore, the grid resolution resulted in approximately 650,000 grid points with simulation times of between two days and six days for a 28 day simulation period. Run time varied due to rainfall being applied in the model.

Roughness

A constant Manning's *n* roughness of 0.04 was applied globally throughout the model domain. The 'roughness' of the vegetation has a significant impact on the spreading of water across the floodplain. It should be noted that model sensitivity to roughness was tested with a range of Manning's n.

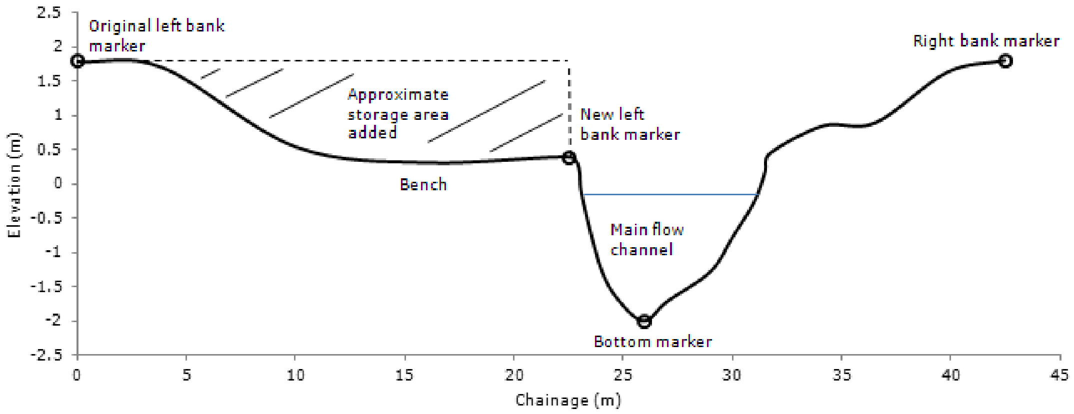
Lateral Linkage

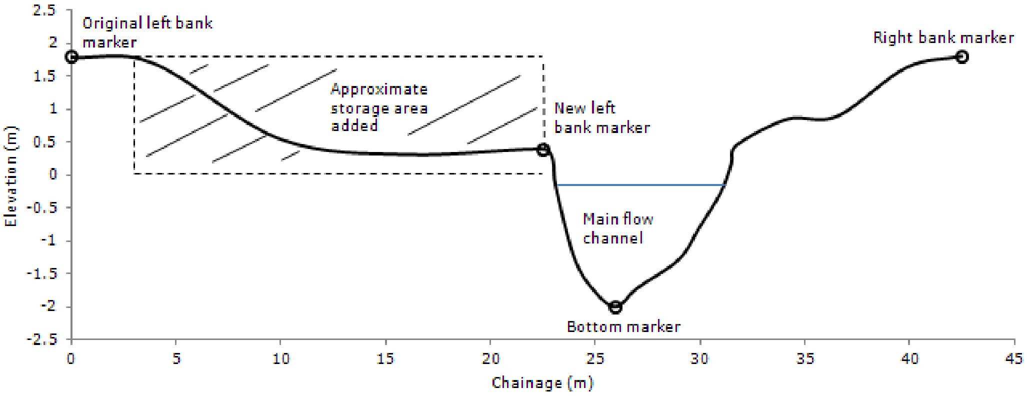
The 1D model is connected to the 2D bathymetry through lateral links inserted along the left and right levee banks of Pipeclay Canal and the internal trunk drains. Lateral links allow overbank flow from the 1D model into the 2D model bathymetry. Lateral links were input into the 1D-2D model as discrete files containing a series of chainages and elevations. A separate file defines the space between each branch structures in the 1D model. The chainages were defined upstream to downstream at 0.5 m spacing. Elevations were extracted from the topography using GIS.

Assumptions

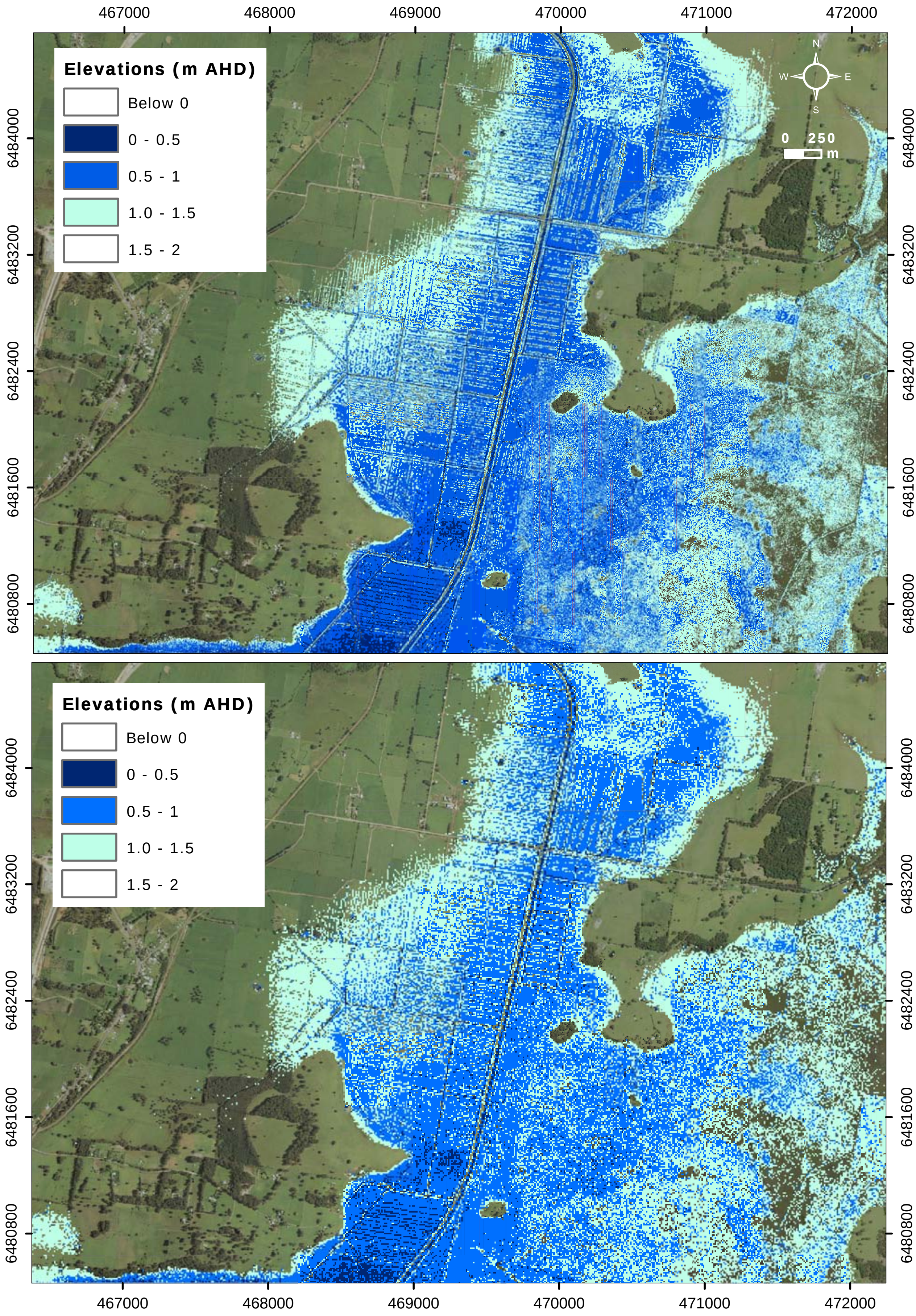
The following assumptions need to be considered when reviewing the model results:

- A single-point source representing Pipeclay Creek catchment inflows was applied at the top of Pipeclay Canal;
- Catchment inflows were derived using AWBM (refer Section 2.4.1). A constant catchment inflow was applied for the "dry" model runs and a time-series was applied for the "wet" model runs. As the AWBM model was developed for the whole Big Swamp catchment, the inflow time-series was reduced to account only for flows attributed to the Pipeclay Creek catchment (i.e. upstream of the point source);
- A water level time-series measured at Croki (MHL, 2013) provided the downstream tidal boundary conditions to the MIKE FLOOD model;
- No wind effects were applied across the model domain;
- A time-series of precipitation was reverse mean-step accumulated and applied globally on dry land. The rainfall time-series was applied assuming 100% runoff occurs but a continuing loss rate of 2.5 mm/day (PWD, 1991) was applied to the raw rainfall data to account for potential losses;
- A constant value of evaporation of 2.3 mm/day (refer Appendix B) was globally applied to the model;
- A constant value of Manning roughness of 0.04 (Chow, 1959) was used for all channels in the 1-D setup and applied globally to the 2-D model; and,
- A constant value of eddy viscosity of 1.0 m^2/s was applied globally to the 2-D model.





Typical Cross-Section Profile Along Pipeclay Canal Showing Marker Locations (A) and Representative Profile of the Additional Storage Area Added to the 1-D Calibrated Model as a Sensitivity Test on Off Channel Storage (B)



Comparison Between LiDAR Resolution: 2 m Interpolated LiDAR (Top) and 10 m Interpolated LiDAR (Bottom)