LAKE WARDEN NATURAL DIVERSITY RECOVERY CATCHMENT

HYDROLOGY PROGRAM SYNOPSIS 1997 – 2015

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DEPARTMENT OF PARKS AND WILDLIFE

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# 1 Introduction

## 1.1 Background

On 7th June 1990, the Lake Warden and Woody Lake Nature Reserves, as well as a portion of Mullet Lake Nature Reserve, Esperance, were recognised internationally under the Ramsar Convention as wetlands of importance to migratory waterbirds (Department of Conservation and Land Management 1999a). The area encompassed by the Lake Warden Wetland System (LWWS) provides significant waterbird feeding, breeding and refuge habitat. Waterbird species listed under the international migratory agreements CAMBA (China – Australia Migratory Bird Agreement), JAMBA (Japan – Australia Migratory Bird Agreement), ROKAMBA (Republic of Korea–Australia Migratory Bird Agreement) and CMS (Convention on the Conservation of Migratory Species of Wild Animals) have been observed at the site. Seventy three waterbird species have been recorded, including 25 migratory species which are specially protected by the Commonwealth *Environment Protection and Biodiversity Conservation Act* (1999). The Lake Warden Wetland System has also been listed locally on the National Estate Register in recognition of its significance for waterbird conservation.

Under the Ramsar Convention, Australia is obliged to promote the conservation and wise use of wetlands, which includes a commitment to maintain and protect the ecological character of listed Ramsar sites. For a wetland to be included on the List of Wetlands of International Importance it must meet at least one of the following nine Ramsar Criteria (Department of Environment and Conservation 2009b):

1. Representative, rare or unique wetland type.
2. Supports vulnerable or endangered species, or threatened ecological communities.
3. Supports species important for maintaining biodiversity.
4. Supports species at a critical life cycle stage, or provides refuge.
5. Regularly supports 20,000 or more waterbirds.
6. Regularly supports one per cent of the individuals in a population of one species of waterbird.
7. Supports a significant proportion of indigenous fish.
8. Important source of food for fishes, spawning ground, nursery or migration path for fishes.
9. Regularly supports one per cent of the individuals in a population of one species of wetland-dependent non-avian animal species.

In order to meet Australia's obligations under the Ramsar Convention and those of both Commonwealth and State legislation, the Department of Parks and Wildlife (known as CALM until 2006 and DEC until 2013) is required to continue to manage some of the wetlands in the LWWS (Lake Warden, Woody Lake and a portion of Mullet Lake Nature Reserves) to ensure the ongoing ecological character of the wetlands are maintained. For the LWWS this is specifically criteria 1, 4 and 6 (Department of Environment and Conservation 2009a).

In 1996, the Western Australian Government implemented the Salinity Action Plan (SAP) to address the problems of landscape salinization (Agriculture Western Australia et al. 1996). The SAP provided funds for the management of biodiversity assets threatened by salinity (Wallace et al. 2011). Under this funding, several programs were developed, including the Natural Diversity Recovery Catchments

Program. Six catchments were named under the Natural Diversity Recovery Program, one of which was the Lake Warden Catchment (LWC). In addition to this program, Lake Wheatfield was identified as a key site in which biodiversity would be monitored as a means of evaluating if the biodiversity conservation goals developed for the SAP were being achieved (Cale et al. 2011). Lake Wheatfield was included in the State Salinity Strategy Biodiversity Monitoring program because it has a high conservation value, is actively managed as part of the Lake Warden Natural Biodiversity Recovery Catchment and was an example of a naturally saline wetland (Cale et al. 2011).

The 2009 Ecological Character Description of the LWWS Ramsar Site identifies that the clearing of native vegetation for agriculture has altered the hydrological regime in the LWC (Department of Environment and Conservation 2009a). Clearing, along with encroaching urbanisation are the two greatest threat to the assets of the LWWS, and have resulted in rising water tables and increased surface water runoff, directly impacting the wetlands within the Ramsar site (Short et al. 2000, Halse and Massenbauer 2005). Hydrological modelling has indicated that approximately 27% of the LWC will be at risk from salinity by 2020, increasing to approximately 45% by 2050 (Short et al. 2000). More recent unseasonal episodic rainfall events such as those which occurred in 1999, 2000, 2007 and 2009, have exacerbated the effects of clearing and contributed to altered hydrological regimes within the LWC (Department of Environment and Conservation 2009a).

From 1999 through to 2009, the lakes in the LWWS were managed under the Esperance Lakes Reserves Management Plan 1999 – 2009 (Department of Conservation and Land Management 1999a). This Management Plan was developed specifically for the nature reserves in and around the LWWS including reserve numbers A32257 - Lake Warden, A15231 – Woody Lake, A23825 – Mullet Lake, A31197 – Shark Lake and C24511 – Pink Lake. The Plan recognised that the Reserves provided valuable habitat for a variety of waterbirds. It also acknowledged that increased volumes of runoff with poor water quality (i.e. water contaminated with salt, excessive nutrients and sediment) in the LWWS catchment was adversely impacting on the values of the lakes in the system. Under this plan, a number of recommendations were made and implemented in relation to water management and monitoring, but the primary focus from a hydrological perspective was to *'further investigate the relationship between the lakes and groundwater supplies, and the impacts of groundwater use on the lakes. Encourage regular monitoring of groundwater quality, and maintain awareness of monitoring results.'* (Department of Conservation and Land Management 1999a).

The Esperance and Recherche Parks and Reserves Draft Management Plan was developed in 2012 (Department of Environment and Conservation 2012). This plan acknowledged that altered hydrological regimes continued to affect the assets and key values of the LWWS. It provided a number of management actions related to hydrological processes, but specifically recommended the continued monitoring of hydrological regimes to improve knowledge of the wetland hydrological processes as well as to evaluate the revegetation and engineering programs.

Several iterations of the Lake Warden Natural Diversity Recovery Catchment (LWNDRC) Recovery Plans were made in 1999 (Department of Conservation and Land Management 1999b) and later in 2005 — 2006 (Department of Conservation and Land Management 2006). Each attempt recognised that the major threats to the wetlands, native vegetation communities and productive farmland in the LWC area were due to alterations to the surface and groundwater hydrological cycle and its influence on salt stored in the landscape. Investigations into various options for the management of water within the LWWS led to the drafting of the second Recovery Plan in 2005, which resulted in an engineering assessment process including a feasibility study (Maunsell 2006), Environment Impact Assessment (Maunsell 2008) and strategic resource capabilities.

The aim of the approach was to dewater the LWWS using engineering, with the ultimate aim of restoring the natural hydroperiods of the lakes in the LWWS to improve the available habitat for wading birds and the condition of riparian vegetation. The Plan also provided various recommendations in relation to water and biodiversity monitoring. Neither Recovery Plan was finalised, however a number of actions identified in the draft plans have been implemented.

Management of the threats in the LWC has included targeted revegetation as part of the 2000 LWC Recovery Farm Kit (Massenbauer 2000), planting of perennial crops and engineered dewatering of the Ramsar wetland suite (Wallace et al. 2011). Targeted revegetation aimed to reduce salinity, nutrient and sediment loads of surface water flows to the lakes (Massenbauer et al. 2009). In the period 1996 to 2006, 403 hectares of land was purchased to expand the conservation estate, over 1,500 hectares of land was revegetated or rehabilitated incorporating over 2 million seedlings (Massenbauer et al. 2009). In addition, over 4,200 hectares of remnant vegetation was fenced (Department of Environment and Conservation 2006, Massenbauer et al. 2009) and large areas of pasture land was converted to AgroForestry.

In 2014 the Department of Parks and Wildlife commenced the development of a new recovery plan for the LWWS. Part of the program involved a variety of workshops that examined the human values that the LWWS provide and the elements that support these values. A key outcome was to elicit how the local community and other stakeholders value the LWWS and associated areas. The information gathered from the workshops aimed to provide the basis for determining the key biological assets of the LWWS and the management actions needed to deliver the priority values. Ideally, all perceived threats to the assets would be managed, however, it was recognised that decisions will need to be made according to available budget, legislative requirements and what can be realistically achieved.

The 2014 draft recovery plan revised the goal of the LWNDRC Recovery Plan to:

*"Until 2035 the Lake Warden Wetland System delivers the four cultural values of knowledge and education, personal amenity, leisure and spiritual/philosophical/intrinsic values by maintaining and improving the biological assets required to deliver these."* (LWNDRC Human Values/Biological Elements Workshop, Feb 2013).

The aim was to refine the goal during the development of the recovery plan, however in 2014 progress on the recovery plan was stalled and no further progress has been made.

## 1.2 Purpose and scope

The purpose of this report is to provide a summary of all hydrological projects and associated reports that were conducted in the LWC between 1997 and 2014 involving the Department of Parks and Wildlife (and its predecessors). This document also aims to detail the evolution of hydrological knowledge in the region. The information can be used as a basis for future hydrological programs and for the development and implementation of a recovery plan for the LWC and other similar catchments. Whilst it is acknowledged that considerable information is available for the LWS, this summary is restricted only to published documents.

This report also aims to identify shortcomings, knowledge gaps and positive outcomes from previous projects, so that future projects can effectively build on this knowledge. Information gaps identified may not reflect the current values of the LWC and therefore they are only a guide to potential areas in which future research could be considered. Prioritisation of the knowledge gaps will be highly dependent on the values identified in any future recovery plan and associated budget allocations. Ultimately, this report will assist in ensuring future projects are designed and planned to provide desired outcomes and ensure that the long-term aims of hydrological research meet those identified human values of the LWC.

## 1.3 Site Location and Description

The LWC encompasses over 212,000 hectares of land over four sub-catchments (Appendix 1). It is located approximately 600 km southeast of Perth, near the coastal town of Esperance on the south coast of Western Australia. The LWC encompasses the coastal floodplain, with the upper catchment extending onto the granite escarpment to the north. Approximately 80 – 90 % of the pre-European native vegetation has been cleared within the four sub-catchments (Government of Western Australia 1996, Penn 1999), with approximately 148,000 hectares dedicated to farming (based on figures provided in Massenbauer (2005)). Beef, sheep and cropping dominate the farm industry in the area, with some agro-forestry present within the catchment (Government of Western Australia 1996).

Within the LWC is a chain of coastal wetlands collectively called the LWWS which situated in the Esperance Sand Plain Biogeographic Region on the coastal floodplain covering an area of 1,999 hectares (Department of Environment and Conservation 2009a). The LWWS incorporates eight major lakes (from east to west): Ewans Lake, Mullet Lake, Station Lake, Lake Wheatfield, Woody Lake, Lake Windabout, Lake Warden and Pink Lake and over 90 overflow or satellite lakes (Marimuthu et al. 2005a; Figure 2). These wetlands are further grouped according to hydrological connectivity, providing three primary hydrological suites: the eastern suite — Ewans, Mullet and Station lakes; the central suite — Lake Wheatfield, Woody Lake and Lake Windabout; and the western suite — Lake Warden and Pink Lake (Maunsell 2008).

Pink Lake was likely historically connected with Lake Warden; however the installation of a rail line and the South Coast Highway sometime in the early to mid 1900's resulted in the isolation of Pink Lake from surface flows from the remainder of the LWWS. Research indicates Pink Lake most likely still has groundwater connection with Lake Warden (Street and Abbott 2004b, Johnson 2014). Mining and mineral exploration has occurred on Pink Lake for many years, with a mining lease for the production of salt over the north east section of the Lake (Department of Environment and Conservation 2009a).

In the 1980's there was a request to increase salt production including the harvesting of algae used for vitamin production. Approval was given for harvesting up to 14,000 tonnes/annum for 10 years, at which time extraction volumes were to be reviewed (Department of Conservation and Land Management 1986), and in 2002 approval was received to increase production to 20,000 tonnes/annum (Harnsard 2002). WA Salt has now relinquished the mining lease and is in negotiations with Parks and Wildlife and other stakeholders to establish rehabilitation requirements.

### 1.3.1 Hydrological Investigations

The Esperance Lakes Reserves Management Plan 1999 – 2009 (Department of Conservation and Land Management 1999a) identified that the major driving point for management of the LWWS was the loss of habitat available for use by waterbirds on the lakes, particularly the area of exposed shore and areas of shallow water. Increasing water levels has limited the available wading bird habitat in the wetlands resulting in fewer birds and a decline in the health and extent of fringing vegetation. Increasing water volumes in the lakes have also indirectly impacted on the water quality and food source availability for birds. The primary aim of most of the conservation effort until recently was to increase waterbird numbers at the lakes to their 1980's benchmark condition by 2030. In order to effectively manage this issue, it was determined that a more detailed understanding of how water moved through the catchment and the wetlands was required, and so a number of hydrological research projects were developed. As the rising water levels appeared to be the primary threat to the maintenance of water bird numbers, the fundamental aim of the groundwater drilling program (at least post 2000 and to 2012) was to estimate the groundwater input to the water balance of the lake system. Research was therefore conducted to improve the understanding of the LWWS lithostratigraphic units, groundwater levels and water quality fluctuations, the identification of recharge and discharge zones, groundwater flow system, and lake flow characteristics. The primary objective for the majority of the hydrological programs in the LWWS was to understand the integration of groundwater and surface water processes to provide a basis on which ecological functioning within the system could assessed, and better inform future restoration plans.

## 1.4 Groundwater Investigations

### 1.4.1 Farm Water Supplies

Early investigations in the Esperance region were mainly carried out to assess the value of local groundwater for use in agricultural activities (Berliat 1952, Morgan and Peers 1973). Extensive hydrogeological investigations were later conducted to the south-southwest of Pink Lake (Baddock 1995, Johnson and Baddock 1998) with the primary objective of determining its value for a town water supply. The Department of Agriculture and Food, AgBore database has records of 410 groundwater monitoring bores within the Esperance Lakes Catchment with 60 % of these still in operation in 2006 (Massenbauer 2007). Depth to groundwater is variable ranging from ground level to 18 m with a median depth of 2.4 m (Massenbauer 2007).

### 1.4.2 Parks and Wildlife Hydrological and Salinity Investigations

From 1998 to 2012, the Department of Parks and Wildlife installed 63 groundwater monitoring bores throughout the LWWS. Nested groundwater monitoring bores were installed around LWWS in 2001 – 2003 to improve the understanding regional groundwater flow. Shallow observation bores were mainly installed in the superficial aquifer, the intermediate and deeper bores were either screened in the Tertiary Pallinup Siltsone, Werrilup Formation or saprolite aquifers. All these bores were monitored regularly for groundwater level and water quality. Data loggers were installed in nine of these bore holes to measure water levels at sub-daily frequency. Tilo Massenbauer (Recovery Catchment Coordinator) managed all hydrological monitoring programs in the period 1998 to 2009 and John Lizamore (Conservation Officer — Catchment) from 2008 to 2014.

#### 1.4.2.1 SAP Wetland Monitoring Program (1998)

In 1998, a series of groundwater monitoring bores were established by the Department in and around the Woody Lake Nature Reserve and Lake Wheatfield as part of the SAP Wetland Monitoring Program (Department of Conservation and Land Management 1999a). The aim of the SAP Wetland Monitoring Program was to monitor trends in water chemistry, groundwater levels, salinity, waterbirds and aquatic invertebrates and relate these trends to patterns of surrounding land-use, management actions and historical data on wetland condition

Seven shallow bores (LW B 001 OB to LW B 007 OB) were installed in July 1998 to a depth of approximately 3 to 6 m below ground level (bgl) around the perimeter of Lake Wheatfield. A further six shallow bores (< 5 m bgl) were drilled in October 1998 around Woody Lake (LW B 008 OB and LW B 009 OB), to the north-west of Woody Lake on the Esperance to Coolgardie Hwy (LW B 010 OB and LW B 011 OB) and on Lakes Rd (LW B 012 OB and LW B 013 OB).

Reports detailing information collected from specific bores are limited. Data collected from bores LW B 001, 002 and 003 were reported in the Initial Environmental Impact Assessment (Maunsell 2008) and data from LW B 001 to LW B 004 were used as part of the Esperance Area Acid Sulphate Soil Hazard Mapping (Galloway and Clarendon 2009). It is also likely that the information gathered from these bores were used in studies on the natural biota of wetlands in the LWWS. Cale et al. (2004), provided summary information on the groundwater and surface water chemistry data collected as part of the SAP Wetlands Biodiversity Monitoring Program from 2000 to 2001. A recent summary of data collected at Lake Wheatfield which included GPS locations and bore names was reported in Cale et al. (2011). No reports could be found that refer directly to the remaining eight bores that were installed around Lake Wheatfield, Lake Woody and Lake Warden.

Data from five of the bores (LW B 001 to LW B 005) in close proximity to vegetation transects established at Lake Wheatfield in 1997 were used to assess if changing groundwater levels or water quality was impacting on the health of wetland vegetation communities (Cale et al. 2011). The bores were monitored monthly from September 2000. Depth to groundwater was measured with an electrical continuity dipper tape, and electrical conductivity (EC) and pH, were measured with a TPS WP-81 metre from the second sample withdrawn using a 0.5 L stainless steel bailer (Cale et al. 2004).

According to Cale et al. (2004), the location, construction and depth details for each bore are recorded in the SAP Wetlands Database. This database however is understood to be a series of excel spreadsheets, based upon data collected by District staff, therefore no additional details are known. Groundwater measurements were taken frequently to maximise the probability of capturing seasonal variability (Cale et al. 2011) and to provide a baseline dataset for the implementation of water management options, such as the removal of excess water from Lake Wheatfield via the gravitational pipe.

Six bores were installed in July 2001. This included two observation bores (LW B 014 OB and LW B 015 OB), less than 10 m deep in the superficial aquifer, and four deep bores. Two of the deep bores were placed in association with existing observation bores (LW B 010 and 013), one with the new LW B 014 observation bore and a single deep bore (without an observation bore) north of the wetlands on Myrup Rd (LW B 016D).

A report could not be sourced that directly linked the implementation of the two transects with specific aims or outcomes, however, a report (Department of Environment and Conservation 2009a) noted that a number of bores were established in and around the Lake Warden Ramsar sites in 2001 to monitor groundwater influences on the lakes. This report indicated that the groundwater measured from the bores installed in 2001 in the vicinity of the Ramsar site ranges from fresh to saline and refers to an unpublished document by DEC (2009; Esperance District Office raw physical-chemical data 2001 – 2009 for the Lake Warden wetlands.). The report indicates that the groundwater in the vicinity of the site has pH ranging from 5.4 to 8.6 (Department of Environment and Conservation (2009a).

#### 1.4.2.2 University Western Australia & CALM ARC Linkage Grant Research (2002-2007)

In 2002, CALM became an industry partner with the University of Western Australia's Centre for Water Research under an Australian Research Council Linkage grant (ARC). This culminated in a four year research project to understand the integration of surface water and groundwater processes in a coastal wetland system — the LWC was chosen for the case study. Consequently, the hydrology monitoring program was expanded in the LWC, with the installation of a network of groundwater monitoring bores and automated groundwater data loggers to support a PhD student, Selva Marimuthu (see Marimuthu 2005).

Investigations and research undertaken included hydraulic, geochemical and stable isotope analysis of groundwater, creeks and the lakes within the wetlands system to assist in developing and refining conceptual hydrological models of the LWWS (Marimuthu et al. 2005a, Marimuthu et al. 2005b). The hydrological processes in the LWWS was also modelled to understand the thresholds to storm response, the occurrence and magnitude of lake overflows and the implications of flood frequency on lake chain system (Kusumastuti et al. 2007 and Kusumastuti et al. 2008). In order to quantify groundwater input to the wetlands system the groundwater flow and transport numerical model (FEFLOW) was utilised (Marimuthu 2006 and Stevenson 2007) (see Section 5.3.2). A substantial body of work was produced during this period providing the basis for future research and management programs and the groundwater and surface water in the catchment was extensively monitored during this period. Data collected was to be used to assist with the establishment of management targets and actions which addressed the primary threat of excess water and ultimately aimed at ensuring waterbird numbers at the site improved. Other projects were undertaken during this period including airborne electromagnetic (EM) surveys (Street and Abbott 2004b) (see Section 4.2), and bathymetric surveys for lake volume calculations (Warren King and Company and Midland Survey Services 2006) (see Section 1.5).

Ten (10) groundwater monitoring bores were commissioned in May 2002. Five of these sites were established at four new locations (LW B 017 to LW B 020, two were placed at LW B 018), while the remaining five were commission to pair with existing sites (LW B 008D, LW B 008WD, LW B 010 DB and LW B 015D and DB). The bores vary in depth from between 12 – 33 m bgl. The groundwater monitoring infrastructure formed two transects which bisected the Lake Warden wetland system. In addition, nine sites were fitted with data loggers (fitted with capacitance probe sensors) to measure the water level on an hourly basis. S. Marimuthu collated data from these bores as well as bores installed in 2003 and prior to 2002. This drilling program had two aims: firstly, to complete the two transects which had commenced in 2001; and to add additional sites requested by the PhD candidate S. Marimuthu for the development of a regional conceptual model and a Lake Warden water balance for his PhD. This drilling program enabled the collection of new geological and hydrogeological data, and the collection of data from this infrastructure lead to an understanding of regional groundwater flow and lake flow characteristics (Marimuthu et al. 2005a). .

A number of drilling programs were conducted in 2003:

- A single shallow observation bore (LWB 016 OB) was installed to pair the existing deep bore at the same location and two mini piezometers (Pink Lake 1 and 2) were commissioned.
- Five bores (LW B 017 – LW B 019 and LW B 021 –LW B 022) were commissioned in April, with LWB 021 and LW B 022 being new sites on the north western side of Lake Warden.
- In June a single observation bore was paired with a deep bore established in 2002 (LW B 020).
- Eight mini-piezometers (Warden 1, Warden 2, Ewans, Mullet, Station, Woody, Windabout and Wheatfield) were commission, most likely in September, however no details on construction, lithology or location could be found.

Most of the bores commissioned in 2003 were less than 5 m deep; the only exception being LW B 016 OB, which was drilled to almost 11 m bgl (unpublished data). A number of the shallow observation wells were drilled to pair up with the deeper piezometers drilled in 2001 and 2002 for the cross sectional, north-south and east-west transects (Appendix 3).

There are a total of nine bores forming the two transects: four bores run east-west through the wetland system (east-west transect), with a number of associated observation bores; and five bores, including the central piezometer (also part of the east-west transect), intersect the wetlands in a north-south cross-section (north-south transect). The east-west transect commenced east of Ewans Lake on Merivale Rd intercepting the major Lakes to the western side of Lake Warden; and the North-South transect commences at Myrup Rd running south through Woody Lake and into the Esperance township on Fisheries Rd (Massenbauer 2005).

All of these bores were operational in 2015, and most continued to be monitored until March 2015. Bores LW 14 OB, LW 14 D, LW 11 OB and LW 9 OB, were redrilled/reconstructed in the same location after they were damaged. The mini-piezos are no longer in use. A number of papers and reports have been produced as a result of the data collected from the bores commissioned between 1998 and 2003, including Marimuthu (2005) and Marimuthu et al. (2005a; 2005b).

In 2012, an additional 17 bores were drilled: four deep bores and four shallow observation bores around Pink Lake; three deep bores and four shallow bores in close proximity to Lake Warden; and another two in association with Windabout Lake. The primary purpose of this drilling program was to augment the existing bore network and refine the water balance. Drill results are yet to be reported.

A brief summary produced by Parks and Wildlife, Esperance provided sampling frequencies for groundwater and surface water in the district in 2004, identifying the number of sites sampled, frequency and information collected (Department of Conservation and Land Management 2004). In 2012, correspondence indicated that a total of 54 bores in 32 locations continued to be monitored for water levels and quality in the region, but the monitored bores were not identified. Based on the 2013 data set provided by Parks and Wildlife, Esperance (Department of Parks and Wildlife 2013), most bores have been monitored monthly from the date of installation until November 2013. Water quality parameters measured included: pH, temperature, Redox (Eh), Electrical Conductivity (EC), Nutrients (TN, TP, N and $PO_4$) and Total Alkalinity (as CaCO3) have been monitored monthly in bores associated with Lake Warden since 2010 and Pink Lake since 2012. The remaining groundwater monitoring bores in the network are monitored for EC, pH and Redox. A preliminary review of geochemistry data for the LWS provides a summary of the adopted sampling methodology (Carr 2014).

### 1.4.3 Summary of Groundwater Infrastructure

A summary of the groundwater monitoring infrastructure is detailed in Table 1 below:

**Table 1: Summary of drilling programs that have been completed in the Lake Warden NDRC**

| Drilling Program Custodian | Year | Bore Logs | Bore Construction | Drilling Report | Pump Test Report | Related Report | Number of Bores | Appendix No. |
|---|---|---|---|---|---|---|---|---|
| SAP Wetland Monitoring Program/CALM | 1998 | | | | | Department of Conservation and Land Management (1999a); (CALM 1999);(Wallace, 2001); Cale et al. (2004); Cale et al. (2011) | 13 | Appendix 3 |
| CALM | 2001 | | | | | Department of Conservation and Land Management(2004) | 6 | |
| CALM | 2002 | | | | | | 10 | |
| DEC | 2003 | | | | | | 7 | |
| Parks and Wildlife | 2012 | | | | | Department of Parks and Wildlife (2013) | 17 | |

Information available
No information available
Not applicable

## 1.5 Surface Water Investigations

The draft Recovery Plan's (2005 – 2030) monitoring objectives included the monitoring of water quality and quantity on the coastal floodplain to obtain an extensive dataset which would enable the identification of hydrological change within the LWC as a result of land use and vegetation changes (Department of Conservation and Land Management 2006). The Plan also outlined a number of knowledge gaps that it would be essential to fill for effective management of key assets. Although the list was likely to be incomplete, the key recommendations in relation to knowledge gaps that specifically related to hydrological research were:

- Further research to better understand Pink Lake;
- Environmental Impact Assessment of engineering options;
- Nutrient, sediment, and salt transport;
- Riparian vegetation condition modelling;
- Eastern Wetland Suite — Hydrological target ranges to be set to enable the development of an engineering option. (This option is now obsolete as the redesign of the Bandy Creek Harbour Weir alleviated many of the previous issues);
- Ongoing research to better understand the relationship between waterbirds, hydrology and wetland ecosystem thresholds (Lizamore PhD in prep);
- Refine AGET GIS model to update agro forestry water use and link this with LWWS hydrology model (this has not been completed and final figures are complicated by the current clear-felling of much of the agroforestry in the region);
- Refine and implement a catchment scale surface groundwater model;
- Update the LWWS water balance model (Model update is pending funding);
- Develop a coastal flood plain groundwater DEM;
- Flood plain hazard mapping.

### 1.5.1 Surface Water Infrastructure

The surface water depth's, pH and salinity of Lake Warden and Station Lake have been monitored every September and November since 1979 as part of the South-West Wetlands Monitoring Program (SWWMP) (Lane 2011a, b, Lane et al. 2015) (Table 2). In 1997 funding from the Salinity Action Plan, enabled the expansion of an earlier program of monitoring depth and water chemistry in selected south-western, Western Australian wetlands (Lane and Munro 1983). This South-west Wetland Monitoring Program (SWWMP) currently monitors 104 wetlands (Lane et al. 2015). This program led to the installation of a permanent depth gauge in Lake Wheatfield in November 1999 (Cale et al. 2011), with lake depth readings commencing in this Lake in April 2000 (Lane 2011c). Details of gauge installation in Warden, Station and Wheatfield's lakes could not be sourced. Additional lake depth gauges were also installed in Ewans, Mullet, Woody and Windabout Lakes on 24 September 2002 by Alan Clarke and Cameron Hennessy using a Wild dumpy level and staff (Clarke 2002). Attempts were made to ensure depth gauges were installed at the deepest point of both Mullet and Station Lakes. Locations of the 'deepest' point were based on the bathymetric survey measurements conducted in 2002 (Warren King and Company and Midland Survey Services 2006).

Stream gauges were established in Coramup and Bandy Creeks in 1997 to 1998, however; the gauges were damaged in the 1999 flood (Janicke 1999). New stream gauges were installed at these sites in 2002. Additionally, a stream gauge was also installed in Bandy Creek harbour weir in June 2002 to calculate flow leaving the wetlands system. This infrastructure was later washed away in the January 2007 storm and not replaced until January 2012. The stream gauge at Coromup Creek is 4.5 km from Lake Wheatfield, while the Bandy creek gauge is located 7 km upstream of Ewans Lake. A number of automated loggers were installed in Ewans Lake, Mullet Lake, Station Lake, Lake Wheatfield, Lake Windabout, and Lake Warden in 2008, with water levels being recorded every five minutes. A total of 14 loggers were in use as of September 30, 2014 (Appendix 4) all of which are now understood to have been removed.

The Water and Rivers Commission (now Department of Water) installed automatic water quality and flow recording stations at four monitoring points within the catchment. These are located in Bandy Creek, Coramup Creek, Neridup Creek and Melijinup Creek (Department of Conservation and Land Management 2006). Loggers were also installed at D1 Lakes West Rd (RB0020), D2 Lakes Rd Manners (RB0016), D3 Stearns Rd (RB0019), D4 Buckenerup Rd (RB0030), D5 Ravensthorp Road (RB0026), D8 Fisheries Rd (RB0028), D9 Fisheries Rd Wheatfield (RB0027), and D11 Lakes Rd Wheatfield (RB0022). Based on logger download files it appears these loggers were installed in 2009 and depths are logged every 5 minutes. Both Neridup and Melijinup Creek stations are no longer operational.

A draft report produced by Janicke (2004) details that surface flows in four of the main creeks (Coramup, Bandy, Neridup and Melijinup (aka Stearne's Creek)) were monitored daily at gauging stations from 1998 through to 2003. In addition, water quality including nutrients, salinity, turbidity and pH of the surface flow in each of the creeks was monitored. The data collected provided preliminary estimates of the volumes of water and the load of nutrients and sediments each creek contributed to the Lake system. The report indicated that Melijinup (aka Stearne's) Creek contributed substantial loads of nutrients to the lakes, and that nutrient management efforts should be particularly rigorous in the Melijinup catchment (Janicke 2004). The report did however indicate that a minimum of 10 years of data would be required to fully understand the influence of flows and water quality of the LWWS.

Surface water sampling occurred on a fortnightly basis at 16 surface water sites. Lake levels and water quality were monitored fortnightly until November 2014, since then monitoring for depth, pH, Eh and EC has been monthly with major nutrients (TN, N, TP and $PO_4$) measured quarterly. Locations of all surface water sites are provided in **Appendix 5**. Water quality parameters measured in Lake Warden, Pink Lake, Lake Wheatfield and Bandy Harbour include pH, EC, TN, N, TP, $PO_4$, Redox (Eh), alkalinity (as CaCO3), as part of a legal requirement during the operation of the pipeline.

Actions that were implemented based on the first draft Recovery Plan (Department of Conservation and Land Management 1999b) included a feasibility and engineering options report completed by Maunsell (2006) to look at the capacity of a gravity system and/or pumping water to manage the water levels of both Lake Warden and Lake Wheatfield. Each engineering option was assessed according to its capacity to meet the lake depth thresholds for the maintenance of waterbird habitat determined by Robertson et al. (2005) and later stated in the second draft Recovery Plan (Department of Conservation and Land Management 2006).

In addition to the assessment on engineering options, Walshe et al. (2007) and Walshe and Massenbauer (2008) undertook a study using a Bayesian Belief Network probability analysis to determine what single or combined options were going to provide the best short, medium and long-term solution to the key threatening processes. The research determined that the most effective way to immediately manage the excess of water in the lakes was through engineering combined with perennial revegetation (Walshe and Massenbauer 2008). As perennial revegetation options (including tree farms and biodiversity plantings) were likely to only be effective in the medium to long-term in lowering groundwater tables and runoff, Walshe and Massenbauer (2008) determined that the most effective short-term management option that would ameliorate immediate threats was via engineering.

**Table 2: Summary of surface water engineering infrastructure and monitoring stations that have been installed in the Lake Warden NDRC**

| Program Custodian | Year | Surface Water Infrastructure e.g. drains | Surface Water Gauging Stations and Loggers | Design Report | Monitoring Report | Comments |
|---|---|---|---|---|---|---|
| CALM | 1979 | | | | (Lane 2011a, b) | First known depth recording made on 8 November 1979. |
| Water and Rivers Commission (Ribbons of Blue) | 1997-1998 | | | Janicke (1999) | | Stream gauges were established in Coramup and Bandy Creek and later Melijinup and Neridup |
| SAP wetland monitoring program | 1999 | | | Cale et al. (2011) | Lane (2011c) | A permanent depth gauge was installed in Lake Wheatfield in November 1999. An artificial channel diversion of a portion of Coramup Creek to Station Lake was created (Parkins pers. com., 1999) |
| WRC | 2000 | | | | | Flow gauging at Melijinup and Neridup Creeks due to unreliable data. |
| WRC | 2002 | | | Marimuthu et al. (2005b) | | Replacement stream gauges were established in Coramup and Bandy Creeks and a new gauge in Bandy Creek harbour weir. |
| SWWMP/DEC | 2002 | | | Clarke (2002) | | Lake depth gauges were installed in Ewans, Mullet Woody and Windabout Lakes on 24 September 2002. |
| DEC | 2008 | | | | | Automated loggers were installed in Lake Warden and Ewans, Mullet, Station, Wheatfield and Windabout Lakes. |
| DEC | 2008 | | | Lizamore (2010) | | A gravitational pipeline was constructed connecting Lake Wheatfield to Bandy Creek. |
| DEC | 2009 | | | | | Creek loggers appear also to have been installed at: D1 Lakes West Rd, D2 Lakes Rd Manners, D3 Stearns Rd, D4 Buckenerup Rd, D5 Ravensthorp Road, D8 Fisheries Rd, D9 Fisheries Rd Wheatfield, and D11 Lakes Rd Wheatfield. |
| DEC | 2010 | | | O'Brien (2010); Davies (2011) | | The Bandy Creek Harbour Causeway was redesigned and installed. |
| DEC | 2010 | | | Lizamore and Davies (2012) | | Fisheries Rd culvert was upgraded. |

Information available
No information available
Not applicable

The Department commissioned Maunsell to complete an Environmental Impact Assessment (EIA) for the preferred engineering option for water management in Lake Wheatfield (Maunsell 2008), investigating the potential impacts of a gravitational pipeline from Lake Wheatfield to Bandy Creek designed to remove excess water from the Lake. Investigations covered potential impacts to Lake Warden, Lake Wheatfield, the disposal site (Bandy Creek), as well as impacts associated with the pipeline route, operational issues and social impacts.

In addition, the initial EIA assessed the impacts of:

- Pumping water from Lake Wheatfield and disposing of it 6.9 km away via a pipe into the Bandy Creek Boat Harbour;
- Establishing a culvert flow management system to temporarily prevent water from flowing from Lake Windabout into Lake Warden.

The report grouped the proposed actions into two stages, Phase 1 – Lake Wheatfield component; and Phase 2 – Lake Windabout/Warden component, with approval to be sort for each component separately due to the timing of works and budgets. It concluded that the engineering intervention would be a minimal disturbance approach using a buried pipe to pump and gravity feed water safely to their disposal sites. The pipe system allowed accurate dewatering to prevent excess drawdown and to manage flood events. Environmental risks associated with the dewatering process were identified (Maunsell 2008), however the Environmental Protection Agency (EPA) determined that the environmental risk associated with Phase 1 did not require assessment (Environmental Protection Agency 2008). Phase 2 has not yet been actioned.

Based on the analyses by Robertson et al. (2005) and the assessment of various management options to ameliorate the problem, in 2008 a gravitational pipeline was constructed connecting Lake Wheatfield to Bandy Creek, to assist in reducing surface water levels in Lake Wheatfield (Lizamore 2010). Since construction, the pipeline has been opened numerous times (details of which are outlined in Table 3). Due to ongoing technical issues with the automated flow gauge, the volume of water removed during this period have been approximated using flow measurements from discrete time periods and extrapolating this data (see Appendix 6). The initial aim was to remove between 1.2 and 2.4 GL of water which was estimated to drop water levels in the Lake sufficiently to increase the exposed shore and shallow water habitat available to wading birds. Estimates suggest that less than 1.5 GL of water had been removed by from Lake Wheatfield by November 2010 yet water levels were the lowest (ca. 1.2 m) that had been in Lake Warden since monitoring began in 2000 (Lane et al. 2015). This was subsequently followed by a low of 0.29 m in February 2013. Unforeseen adverse impacts to the water quality caused by the reduced water levels prompted local catchment managers to temporarily ‘flood’ the central suite of wetlands by delaying the opening of the gravity pipe in winter 2013, and water removal via the pipeline recommenced in June 2013.

In addition, an artificial channel diversion of a portion of Coramup Creek to Station Lake (via a series of unnamed satellite lakes) was created in 1999 and the Bandy Creek Harbour Causeway was redesigned and installed in 2010 (O'Brien 2010), and the Fisheries Rd culvert was upgraded in 2010 (Lizamore and Davies 2012).

**Table 3: Discharge periods and volumes since commissioning in April 2009 for the Lake Wheatfield Pipeline (Lizamore 2015).**

[Note: discharge volumes are an estimate only. Values have been calculated based on manually measured discharges rates and extrapolated using discharge curves and a series of associated assumptions. See Appendix 6 for details].

| Open | Closed | Total discharge ($m^3$) |
|---|---|---|
| 28 Apr 2009 | 19 Jan 2010 | 889 291.72 |
| 26 May 2010 | 22 Dec 2010 | 650 166.09 |
| 25 May 2011 | 30 Aug 2011 | 124 199.08 |
| 28 Sep 2011 | 23 Feb 2012 | 234 591.18 |
| 20 Jun 2012 | 07 Jan 2013 | 552 275.54 |
| 12 Jun 2013 | 11 Feb 2014 | 818 159.88 |
| Total | | 3 268 683.50 |

## 1.6 Climate

The climate is temperate with cool wet winters and dry warm summers**.** Regional rainfall data collected by the Australian Bureau of Meteorology (BOM) at several stations in the Esperance district indicates that annual rainfall varies from 610 mm in the south at Esperance to 420 mm at Scaddan, located ~20 km to the north (Massenbauer 2007). July is on average the wettest month in the region, Esperance averaging 95 mm and Scaddan averaging 55 mm, while both Esperance and Scaddan average only about 20 mm in December (Massenbauer 2007). Between two-thirds and three-quarters of the rain falls during the growing season (May — October) and evaporation is also lowest in these months (Massenbauer 2007). The driest year since 1975 was 1994, when the area received less than two-thirds of the average annual rainfall. The highest annual rainfall for Esperance occurred in 1999 with 260 mm more rainfall than the annual average.

### 1.6.1 Climate monitoring Infrastructure

In addition to the network of rain gauges managed through the BOM, rainfall data was also collected using automated loggers in the Speddingup Lake's area for a number of years by the former Recovery Catchment Officer, Tilo Massenbauer. Two automated rainfall gauge stations were mentioned in the 2004 monitoring program, although the specific details are not known (Department of Conservation and Land Management 2004). Six evaporation pans and associated rainfall gauges were established around the lakes in June 2012 by the Department in order to address earlier identified knowledge gaps in water balance parameters. Locations for these sites are detailed in **Appendix 5**. No other details were known at the time of this report.

## 1.7 Water quality (salt balance)

In 1994, the Science Department of the Esperance Senior High School in conjunction with CALM implemented a Ribbons of Blue Project at the LWWS. The aim of the project was to establish a program which would enable students to monitor the health of local wetlands, and increase the awareness of the values of the lake system and the threats to their continued health. The monitoring program examined nutrients (N and P), turbidity, EC and pH at Lake Warden, Wheatfield and Station

Lakes quarterly from September 1994 to November 1999. However, the program ceased due to inflexible time requirements (CALM 2006b).

Measurements of salinity in both soil and water in and around the LWWS have been collected for a number of years under the SAP and SWWMP programs (see Section 1.5.1). The programs collected surface water salinity and shallow soil salinity around Lake Warden, Station Lake, and Lake Wheatfield from 1979, 1980, and 1999, respectively, to the present (Lane et al. 2015).

Over an 18 month period from May 2002 to November 2003, weekly chemical isotope samples were taken from the five major surface water sites (Warden, Wheatfield and Station Lakes and Bandy and Coramup Creeks). Rain samples were also collected during rainstorm events and cumulated to a weekly/monthly monitoring total (Marimuthu 2005). Information collected as part of this study was used to determine the interaction between surface and groundwater within LWWS. Cale et al. (2011), also analysed water chemistry parameters for Lake Wheatfield as part of monitoring conducted between 1997 and 2009.

Between August 2006 and April 2008 the WA Water Corporation conducted fortnightly surface water quality sampling at 12 sites in the Esperance district measuring major nutrients, salinity (electrical conductivity), turbidity, sediment, pH and river flow (May 2008). Bandy and Coramup Creeks along with Station, Wheatfield and Warden Lakes were sampled.

Some of the wetlands within the LWS are frequently used for recreational pursuits such as water skiing (Department of Conservation and Land Management 1999b). On a number of occasions bad odours, toxic blooms or fish kills were observed (Phytoplankton Ecology Unit 2001, 2003, 2004, and 2009). In some instances wetlands were deemed unsuitable for recreational use due to the presence of pathogens above those of the relevant guidelines (Phytoplankton Ecology Unit 2003). Specific details about the monitoring rationale, frequency or sampling methodology are unknown.

In addition to the above programs, salinity (EC) data was collected from all surface water sites in the lakes and contributing creeks as well as from all monitoring bores within the wetland system as part of regular monitoring by the Esperance Parks and Wildlife office (Lizamore 2013). Due to the depth of many of the bores, only limited EC data (a total of four bores in association with the lake system) has been collected in the deeper Werrilup Formation. Salt stores in the landscape need to be linked to surface, sub-surface and groundwater flow processes to adequately represent how salt enters the lake. As such, measurements used for the development of the water balance model needs to be sufficiently distributed to capture the heterogeneity of the salt store and mobilisation processes (Vaze et al. 2004).

To date, no report or model has examined the salt balance in the LWWS. Given that there is concern that increasing salt levels in Lake Warden and Wheatfield may have a detrimental effect on aquatic invertebrate communities, and impact on the value of the wetlands as a feeding site for wading birds (Davies and Lizamore 2013), understanding the origins of the salts and the ecological impact of these will be important in developing appropriate management strategies to ameliorate this threat. There is a currently a proposed feasibility study, aimed at examining and potentially restoring the Pink Lake to Lake Warden surface flows which will partly address this issue, however the project is dependent upon allocation of funding.

It is important to note that salinity and changes to the hydrological regime of wetlands are not the only cause of changes in the biodiversity values of Wheatbelt wetlands (Cale et al. 2004). Factors including eutrophication, variations in pH, loss of fringing vegetation, etc., are all likely to affect diversity and may have synergistic effects on wetland biodiversity when combined with other disturbance factors, the complexity of which is little understood. Few species have predictable monotonic responses to disturbances (Cale et al. 2004) and therefore it is vitally important that monitoring continues to measure physical as well as biological responses to catchment disturbances.

### 1.8 Revegetation

The On-ground Works Statistical Output Summary 1997 – 2005 report, noted that a total of 1,304,600 seedlings were planted over 1,050 hectares encompassing 110 properties from 1997 to 2005. At the time of writing this report there was no available documentation on the ongoing monitoring of revegetation works, such as the Farm Kit revegetation program (Massenbauer 2000), to assess the success of the implemented revegetation programs.

# 2 Land Surveying

### 2.1 Ground Surveying

On ground surveying work can provide precise elevation details, which are normally only undertaken for particular areas of interest, such as for engineering works, and can be used to verify information from Digital Elevation Models (DEMs) or other similar products. Numerous ground surveys have been completed in the LWC for the installation of bores and gauge plates etc. to establish its position above sea level or Australian Height datum (AHD) (e.g. Clarke 2002). Bathymetric surveys for lake volume calculations were conducted in 2002 (Warren King and Company and Midland Survey Services 2006). An update of the bathymetric surveys for the eastern suite, Lake Wheatfield and the eastern section of Lake Warden were completed recently by Parks and Wildlife staff, Esperance, to address some identified inaccuracies with the survey data, with aims to do the same for the remainder of the system. In 2011, Recovery Catchment Coordinator John Lizamore identified some projection issues with the survey benchmarks when working in ArcGIS. It is understood that all benchmarks associated with Parks and Wildlife bores were resurveyed (Table 4). At the time of writing this review there was no available supporting documentation or datasets for the resurvey of benchmarks or update to the wetland bathymetry.

### 2.2 Digital Elevation Models (DEMs)

Robertson et al. (2005), created a 5 m Digital Elevation Model (DEM) of the wetland's bathymetry using ArcInfo Geographic Information System (GIS) software to relate depth gauge data to water volumes and areas of differing depth ranges, representing waterbird habitat types. The DEM was generated from a Real-Time Kinematic Differential Global Positioning System (RTK DGPS) bathymetric survey and an Airborne Laser Scanning (ALS) survey. A 5 m DEM for the entire LWC was created by the Departments GIS section in 2007 which integrated data from a number of existing DEM's and newly acquired datasets (Robertson 2007). These datasets included LiDAR survey undertaken in May 2005, LiDAR survey in March 2007 (Fugro Spatial Solutions 2007) and RTK GPS data capture along Bandy Creek. It is understood that a more recent DEM was produced in 2014 covering Pink Lake (Table 4), but not the eastern suite, although no supporting documentation was available at the writing of this review.

## 2.3 Summary of Surveying

A summary of ground survey and acquisition of airborne data are summarised in Table 4 below:

**Table 4: Summary of ground and aerial surveying undertaken in the Lake Warden NDRC**

| Program Custodian | Year | Ground Surveying | DEM's | Related Report | Reason Undertaken | Comments |
|---|---|---|---|---|---|---|
| DEC | 2002 | | | Warren King and Company and Midland Survey Services (2006) | Lake volume calculations | Bathymetric survey |
| DEC | 2005 | | | Robertson et al. (2005) | To relate depth gauge data to water volumes and areas of differing depth ranges | Bathymetric survey |
| DEC | 2007 | | | Robertson (2007) | | Mosaiced DEM for the LWC |
| DEC | 2010 – 2011 | | | None only Shapefiles | To ensure that bore coordinates and elevations were accurate | Benchmarks associated with Parks and Wildlife bores were resurveyed |
| DEC/ Parks and Wildlife | 2012 – 2013 | | | None only Shapefiles | To ensure that bore coordinates and elevations were accurate | Benchmarks established for new bores established in 2012 and 2013; |
| Parks and Wildlife | 2014 | | | None only Shapefiles produced with revised bathymetry | | Bathymetric survey |

Information available
No information available
Not applicable

# 3 Remote sensing

### 3.1.1 Hyperspectral Surveys

Multi-spectral data was acquired by SpecTerra Airborne Remote Sensing in 2004, 2007, and 2014 to assess riparian vegetation condition change (an indicator of biodiversity) within the LWWS (Massenbauer et al. 2009). A report comparing these datasets is currently being prepared by Parks and Wildlife GIS specialists. This data can be combined with vegetation surveys completed by DEC staff in 1999, 2001, 2004 and 2007 to assess impacts of management actions on the vegetation. A draft report on the remote sensing data indicates there was further vegetation loss and degradation at some of the lakes from 2007 to 2014, but provides no explanation for the reasons for the declines.

# 4 Geophysical surveys

## 4.1 Borehole geophysics

Geophysical logs (down-hole EM and gamma) were acquired and assessed from a number of bores to calibrate the HoisTEM Airborne Electromagnetic (AEM) surveys (Street and Abbott 2004a, b). The sites included bores: LW08, LW13, LW14, LW15, LW16, LW17, LW18, LW19, and LW20.

## 4.2 Airborne Geophysics

### 4.2.1 HoisTEM(2004)

HoisTEM Airborne Electromagnetic (AEM) surveys were used by Street and Abbott (2004a). AEM conductance assessment surveys identified that there were large salt stores under many of the lakes in the LWWS and within the deeper zones along the metamorphic bands in the coastal plain. Of particular note was a large salt area immediately north of Pink Lake, showing the highest salt stores in the catchment (Street and Abbott 2004a).

Street and Abbott (2004a) used the HoisTEM Airborne Electromagnetic (AEM) surveys together with CALM and Water Corporation bore data, to determine palaeochannel formations, groundwater connections between the upper catchment and the lower floodplain of the LWC and to estimate the groundwater storage volume of the coastal floodplain (where the LWWS is located). Results from the AEM indicate that there is strong geological control on the position of the lakes and other features within the study area. Based on the basement and surface features, Street and Abbott (2004a) concluded that the LWWS can be divided into three sections.

1. The western lakes area comprising Pink Lake and Lake Warden within the Biranup Complex;
2. The central northern lakes area, encompassing the northern section of the Woody Lakes Reserve and the north eastern portion of Lake Warden within the Biranup Complex; and
3. The eastern catchment comprising Ewans, Mullet, Station, Wheatfield, Woody and sections of Lake Windabout within the Nornalup Complex.

The report indicated that Pink Lake and the south western portion of Lake Warden comprise an isolated western suite of wetlands with no groundwater connection between this suite and those in the central suite. It identified that there was currently no surface flow connection between the two lakes in the western suite but there was groundwater throughflow, maintaining a groundwater connection between Pink Lake and Lake Warden, and that basement rock prevents deep drainage to Lake Warden from the north. Assessments could not identify any major groundwater discharge from Pink Lake to the south; however a minor pathway running via Esperance was identified.

The AEM survey identified that salt storage increases downslope from the escarpment towards the area under Lake Windabout Lake and the conductivity data suggests that most of the deep drainage from Coramup Creek catchment appears to flow to this point (Street and Abbott 2004a). Further east, salt storage indicates groundwater moves south towards areas under Mullet and Station Lakes.

Street and Abbott (2007) noted that noise in the AEM data from infrastructure and radio transmitters gave spurious results which, despite various filters, could not be rectified. In addition, the laser altimeter employed to give altitude of the HoisTEM loop did not give accurate measurement over the lakes. Conductivity logs of deep bores, more detailed geophysical logs and correction of the Altitude using a different DTM would be required to further refine the model (Street and Abbott 2004a, 2007).

# 5 Hydrological Assessments

## 5.1 Groundwater

Sixty per cent of the LWC consists of valley floors and groundwater modelling suggests that shallow (< 2 m below surface) saline groundwater tables will develop over most of these floors (Short et al., 2000). Shallow water tables have already detrimentally affected many wetlands in the northern parts of the catchment. There has been substantial death of littoral vegetation as a result of waterlogging (Wallace et al. 2011). Whilst the high watertable was partly the result of a series of high rainfall years, the primary cause was the enhanced groundwater recharge and volume of run-off being generated in the catchment as a consequence of clearing (see Short 2000, Halse et al. 2003).

Simons and Alderman (2004), provide a description of groundwater trends, risk of shallow watertables and the technical feasibility of salinity management in the soil-landscape zones in the Esperance region. The document provides a synthesis of information collected over a number of projects including groundwater monitoring of Department of Agriculture bores, Land Monitor Project and information collected by Short and McConnell (2001). Interpretation of groundwater trends across the eastern south coast, which includes the LWC area, indicated that rising groundwater trends were dominant over the analysed period (pre-2000 and 2000 to 2006) (George et al. 2008). The most recent analysis, since 2007, indicates that rising groundwater trends accounts for just over half of the analysed sites within the Esperance Sandplain Hydrozone (includes the LWS) (Raper et al. 2014). Since 2007 the number of bores with rising trends has fallen by 14%, the number of falling trends declined by more than 50% and the number of steady trends increased by 2%. Rising trends occur outside of the Esperance area (Munglinup area or north and east of Condingup), whereas falling or stable trends generally occur in those bores where water tables are observed respond seasonally or to episodic events (Raper et al. 2014).

Analysis of groundwater data by the Department of Environment and Conservation (2009a), indicated that the groundwater level surrounding the Ramsar site was less than 3.0 m bgl and the groundwater levels recorded from observation bores in the area suggested that some of the aquifers surrounding the Ramsar site had reached full capacity in 2008 (Department of Environment and Conservation 2009a). Cale et al. (2011) noted that groundwater levels had risen in observation bores in direct association with the Lakes between 2000 and 2009. In the same period, the water depth at Lake Wheatfield averaged 1.6 m, rarely falling below 1 m and being notably much deeper than historically recorded.

The most recent analysis of groundwater in the LWC was conducted by Johnson (2014). In their study, all available hydrogeological data was examined. The stratigraphy for all bores was reinterpreted and hydrogeological units were confirmed across a number of north-south cross sections. Hydrographic analysis and interpolation of minimum and maximum regional water table contours were combined with hydrogeological interpretations to gain an understanding of the functioning of wetlands in the LWWS, with respect of groundwater.

Groundwater was generally found to flow towards the coast in a southerly direction and there was no evidence of substantial easterly or westerly groundwater flow, although groundwater throughflow from Lake Warden to Pink Lake was confirmed. This contrasts with the variable nature of surface water flows, which are dependent on factors such as connectivity of wetlands, flow rates and the prevailing winds. Groundwater levels were found to be dynamic and highly influenced by groundwater recharge. Changes to groundwater levels were most evident over the period 2009 to 2012 in association with a period of lower rainfall. Localised change was also evident in areas associated with the release of surface water via the Lake Wheatfield gravitational pipeline. Groundwater-surface water interactions in the LWWS wetlands was generally considered relatively simple, however the hydrogeological setting and hydrodynamics meant that the management of groundwater and surface water for the LWWS is complex.

## 5.2 Surface Water

The salinity of water within Lake Warden have varied considerably since monitoring commenced and different research/monitoring groups have reported different concentrations in the Lake. The highest recorded concentrations prior to 2012 occurred in 1983, when salts (Total Dissolved Solids, TDS) exceeded 200 parts/thousand (ppt), followed by relatively low concentrations of 20 ppt the following year, when lake levels returned to > 1m in depth (Lane et al. 2015). Salinity concentrations again rose to levels more closely representing historical concentrations in the 2012 and 2013 period, most likely due to the low water levels in the lake associated with the artificial removal of surface water from Lake Wheatfield via the gravitational pipeline to Bandy Creek (Davies and Lizamore 2013) as well as the drier climate in this period compared to the previous 10 years. Davies and Lizamore (2013) reported substantially different salinity concentrations to that of Lane et al. (2015) over the same period. The cause of these discrepancies have not been investigated, although factors such as the sampling location and methodology, timing and frequency are possible explanations.

Lake Wheatfield is naturally brackish, with salinity (TDS) ranging from 4 to 15 ppt since recordings began in 1997 (Lane et al. 2015)(Department of Parks and Wildlife 2013). Water levels in the lake have steadily declined since the commencement of monitoring, and there has been an associated increase in salinity concentrations (Lane et al. 2015). Station Lake, like Lake Wheatfield, is classified as naturally brackish, with salinity concentrations prior to 2010 ranging from < 10 ppt up to 50 ppt, the single exception being in 1983 when low water levels in the Lake resulted in salinity concentrations of > 200 ppt (Lane et al. 2015). However, Lizamore (2014) reports that following the redesign of the Bandy Creek Weir and the drier conditions now being experienced in the Esperance region that the Lake continually reaches salinity concentrations > 200 ppt when drying.

May (2008), reported that during the period from May 2002 to November 2003, Coramup Creek recorded relatively low EC and classified the river as brackish, while Bandy Creek near Fisheries Rd was a predominately saline system with major saline fluxes occurring during autumn and winter flows in 2007. May (2008), noted that Station and Warden Lakes in the period August 2006 to April 2008 would be classified as saline, with EC concentrations in Lake Warden on occasion (e.g. April 2008) reaching hypersaline levels. Station Lake EC concentrations were higher than Lake Wheatfield with summer samples rising up to 65,450 mg $L^{-1}$ (65 ppt) in April 2008 (May 2008). Notably, Lake

Warden is considered naturally hypersaline, indicating that water levels in the lake during this period were relatively high. Lake Wheatfield during this period was classified brackish to saline.

The installation of the gravity feed pipeline at Lake Wheatfield provided further evidence that Lake Wheatfield is hydrologically connected to Woody, Windabout and Warden Lakes via surface water. Between November 2009 and November 2010, water levels in Lake Warden declined by approximately 0.6 m, and this is thought to be partly due to the artificial lowering of water levels in the central suite.

In 2003, sediment cores were extracted from Lake Warden, Lake Wheatfield and Station Lake to profile the environmental changes in the region and to determine contemporary and historical rates of sedimentation (Wilson 2004). A similar study was conducted at the nearby Lake Gore (Wilson 2003). The analyses identified that rates of sedimentation in all three lakes have significantly increased since agricultural expansion in the area in the 20$^{th}$ century, presumably in response to clearing of native vegetation. However, Wilson (2004) also noted that eutrophication appears to have occurred in Lake Wheatfield some 600 years ago. This indicates that high nutrient loads in the system occurred prior to European settlement, but rates of nutrient accumulation in the lake have increased since European development in the region (Wilson 2004).

For the periods August 2006 and April 2008, monitoring conducted by the WA Water Corporation found that total nitrogen was in general very high in all three lakes, however Station Lake consistently recorded concentrations lower than the State-wide River Water Quality Assessment Classification (Department of Water 2008) and ANZECC 2000 guidelines. Lakes Warden and Wheatfield consistently recorded Total Phosphorus (TP) concentrations above the recommended guidelines, but the Soluble Reactive Phosphorus (SRP: bioavailable form) was in general, low. Station Lake recorded low concentrations of both TP and SRP (May 2008).

Total nitrogen in both Bandy and Corumup Creeks varied over the sample period but the median concentrations were well below ANZECC 2000 guideline concentrations, with both Soluble Reactive Phosphorus and Total Phosphorus generally below guideline concentrations, the only exceptions being after storm events. Coramup Creek in general had relatively high loads of Total Suspended Solids and high readings for turbidity with these readings peaking after storm events. Bandy Creek, in contrast, recorded low to moderate levels for both parameters, the exception being after storm events (May 2008). The report did not detail the specific impacts of these nutrient or sediment concentrations on the respective ecosystems, providing only a general synopsis of the impact of each of the measured parameters at the start of the document, nor any details on the need to manage nutrients or sediment flows along rivers or within the lakes.

Like Street and Abbott (2004a), Marimuthu et al. (2005a) concluded that Pink Lake is a sink or terminal lake, with no existing surface water connection to the other lakes in the system. Marimuthu (2005) noted that, although the path analysis has captured the general flow systems within the study area, full confidence in the understanding of the interaction of flows within the wetlands system is constrained by sparse hydraulic data and the complexity of the site. The report indicated the need to monitor local evaporation rates, establish more reliable and accurate measures of stream flow and monitor additional groundwater sites to develop more accurate models.

As a consequence of this initial research, a number of follow on projects were initiated, including those by Stevenson (2007) described below (Section 5.3). Although water balance models developed by Marimuthu et al (2005c), Stevenson (2007), Kusumastuti et al. (2007) and Kusumastuti et al. (2008a) functioned well in preliminary testing, the models were developed when there was unusual climatic conditions (three 1:100 year floods in the decade ending 2010: Lizamore and Davies, 2012 Draft). Lizamore and Davies (2012) therefore suggested that the models require recalibrating or an alternative model developed that incorporates recent variations in the climate (in prep Lizamore and Davies 2012).

Lane et al. (2011), provided a review of the depth data collected for Lakes Warden and Wheatfield from 1977 to 2010. Water levels in Lake Warden were unusually high (ca. 2.0 – 2.7 m) for an extended period between 1999 and 2009. Lane et al. (2011) suggests that the high water levels in Lake Warden were due to a combination of catchment clearing (resulting in increased runoff and groundwater rise; Marimuthu *et al.* 2005) and extreme rainfall events (Kusumastuti 2006). Rises in groundwater levels were noted to directly impact on the wetlands by prolonging the inundation period from about 1986 onwards (Robertson & Massenbauer 2005).

Robertson et al. (2005), analysed historical waterbird and surface water depth data from the previous 25 years and examined relationships between waterbird diversity and water depths in the LWWS. Simple scatter plots identified a negative relationship between lake depths and water bird diversity for Lake Warden, with a notable decline in waterbird abundance at depths above 1.4 m. These relationships coincided with the loss of exposed shore and shallow water habitats, quantified by the DEM used. Lake Warden had lost approximately 65 hectares of wading habitat (defined as depths < 25 cm) and 100 hectares of exposed shore habitat in the period between the early 1980s and 2005. The loss of shorebird habitats was not as pronounced for other lakes in the system, owing to more complex bathymetry and some surface outflow connectivity with the Southern Ocean (Robertson et al. 2005).

Initial assessment of the gravitational pipe system to remove excess water in Lake Wheatfield, which commenced in 2009, indicated that it is effectively removing excess water from Lakes Wheatfield, Woody and Windabout. The reduced water levels in the central suite has resulted in reduced flows entering Lake Warden from the East and the pipeline has therefore indirectly resulted in reduced waterlogging of the fringing vegetation and the subsequent exposure of the Lake Warden's shoreline. This has improved recruitment levels in shoreline vegetation and the numbers and species of wading birds using the wetlands (Davies 2011). However, while there was an observed increase in the richness of small waders in February 2010, abundance was generally low and there was insufficient evidence to suggest a major change in community composition at that time (Cale et al. 2011). More recent data indicates that bird numbers are starting to increase in the system when salinity levels start to decline below 180 g $L^{-1}$.

Non-target impacts associated with the lower water levels was an increase in salt loads in Lake Warden and Wheatfield. Davies and Lizamore (2013) noted that macroinvertebrate numbers declined dramatically in Lake Warden in the summer of 2012/2013, seemingly in response to increasing salinity in the water. In January 2013 it was confirmed that salinity concentrations had reached such a level that Lake Warden had turned pink, with the appearance of *Dunaliella salina* (the halophilic green algae responsible for the pink colouration) in surface water samples from the lake (Davies and Lizamore (2013).

Pinder et al. (2012a) and Pinder et al. (2012b) provide a detailed summary of waterbird richness in the LWWS from the 1980's to 2012. A survey in spring of 2012 recorded the highest number of waterbirds for the last two decades in the wetlands. Notably, however there was an almost complete loss of macroinvertebrates in Lake Warden by the summer of 2013 (Davies and Lizamore 2013) and a massive reduction in bird species diversity in the summer of 2013 compared to the 2012 data (Davies and Lizamore 2013). This was thought to be a result of increased salinity. Recent research by Lizamore has shown that when salinity levels exceed 180 g $L^{-1}$ water bird abundance decline rapidly with water bird abundance maximised at salinity levels < 150 g $L^{-1}$.

In a report produced before the 2013 declines in the invertebrate community, Cale et al. (2011) noted that in the 2009 sampling period, water chemistry parameters for Lake Wheatfield that were tested during invertebrate sampling had few apparent effects on the invertebrate community composition. They further indicated that active management to lower water levels (e.g. the gravitational pipeline from Lake Wheatfield) was unlikely to impact on invertebrate communities provided the annual hydroperiod includes a range of water depths and salinities, similar to those already observed, in which these diverse communities can periodically develop.

## 5.3 Modelling

### 5.3.1 Short et al (2000)

A hydrogeological conceptual model for the LWC was developed by the Department of Agriculture and Food, Western Australia (Short 2000). This conceptual model formed the basis for numerical modelling undertaken by Short et al. (2000). Numerical modelling was used as a predictive tool to assess the likely future extent of salinity under different land uses. A number of different models were applied in their study, comprising of: the simple one-dimensional groundwater model FLOWTUBE; HARSD, which is a set of procedures for modelling groundwater behaviour to delineate areas of recharge, discharge and transmission; WAVES water balance model used to partition runoff, shallow subsurface lateral flow and deep drainage; and the farming system models APSIM and GRASSGRO which were used to assess recharge rates under different farming systems. Specifically the study attempted to identify:

- areas of the catchment where changes in recharge will most affect catchment salinity;
- the magnitude of recharge reduction required in those areas to produce a given level of salinity management (*e.g*. percentage reduction in area of salt-affected land);
- land use and farming system options for producing recharge reductions of sufficient magnitude to achieve salinity management;
- information on which to base a cost benefit analysis and viability of the options for change; and
- constraints to achieving required change for each catchment.

The report noted that the models produced in the study were able to:

- identify areas of the catchment where changes in recharge will most affect catchment salinity;

- identify the magnitude of recharge reduction required in those areas to produce a given level of salinity management (e.g. percentage reduction in area of salt-affected land);
- identify constraints to achieving required change for each catchment;
- identify that farming system options were unlikely to produce recharge reductions of sufficient magnitude; and
- provide information on which to base a cost benefit analysis and viability of the options for change.

Simulations conducted by Short et al. (2000) found that under current winter cropping systems and annual pastures that rainfall for most years exceeded the amount of water that can be used by these farming systems. In particular rainfall occurring in April and May fully recharges the plant available water capacity (PAWC), creating conditions conducive to groundwater recharge or surface water runoff. The farming systems modelling indicated that to achieve catchment-wide recharge reductions to 90% of present rates, all pasture land and 90% of cropped land would need to be replaced by trees. However, by replacing all pasture land with perennial pasture (kikuyu or lucerne) and at least 50% of cropped land by perennial pasture or trees, recharge reductions of 50% or more could be achieved.

Short et al. (2000) noted that in order to develop a defensible conceptual model of the catchment hydrogeology, sufficient groundwater level information needs to be available to construct a groundwater flownet for the catchment. Stratigraphical descriptions and bore details need to be available parallel and perpendicular to the main groundwater flow paths in the catchment. Information also needs to be available regarding characteristics of the hydrogeological units, ideally from pumping tests within the catchment, but also from relevant hydrogeological units outside the catchment if necessary. Groundwater hydrographs also need to be available from bores representative of the range of hydrogeological and geomorphic variation in the catchment, and a map of the current of extent of salinity needs to be made available.

### 5.3.2 XP-Storm (2006)

Annual dewatering targets were tested by Maunsell using a dynamic water balance model in XP-Storm (Maunsell 2006). This model enabled the outflow component of the LWWS water balance for 2002 – 2006 (derived from Marimuthu et al. 2005a) to be adjusted to replicate the effect of implementing one or more of the engineering options being investigated as part of an feasibility and engineering options report (Maunsell 2006).

### 5.3.1 Rainfall-runoff modelling (2006-2008)

Kusumastuti (2006) and others (Kusumastuti et al. 2007, Kusumastuti et al. 2008a, Kusumastuti et al. 2008b) conducted conceptual rainfall-runoff studies for the LWC, with the aim of understanding climatic and landscape controls upon the surface runoff behaviour in the LWC. It was identified that summer storm characteristics and the interaction between winter rainfall and evaporation which affect the antecedent catchment conditions for summer storm events strongly impacts the occurrence and magnitude of the flood events. The lake storage deficits along with the spatial organisation of the lakes in the LWC all contribute to the capacity of the landscape to naturally mitigate potential flood conditions (Kusumastuti et al. 2008a). However, the model’s capacity was limited by the availability of climatic and hydraulic data for the catchment and the model could not be validated (Kusumastuti et al. 2007).

### 5.3.2 FEFLOW (2005, 2007 and 2012)

Physical hydrological, hydrochemical and stable water isotopic methods were applied to the wetlands of the LWC to define their hydrological functioning (Marimuthu et al. 2005a, Marimuthu and Reynolds 2005, Marimuthu et al. 2005b, Reynolds and Marimuthu 2007). Groundwater, surface water from creeks and wetlands, plus rainfall data was compiled to resolve an annual water cycle for the areas wetlands. The key methodologies applied in these studies included the use of mass-balance mixing models to determine relative contributions from surface water, groundwater, and rainfall to wetland water balances. Hydraulic, chemical and stable isotopic data was used as the basis to develop a finite element numerical model, FEFLOW (Marimuthu and Reynolds 2005).

Particle path analysis modelling indicated that Wheatfield, Woody, Windabout and Warden lakes are hydraulically connected to each other, but are isolated from the eastern group (defined as Ewans through to Station); results that are supported by weekly isotope results which show that the eastern suite are significantly different, from a compositional standpoint, to the lakes on the western side of the group (Marimuthu et al. 2005a). These results differed from those provided by Street and Abbott (2007). The bathymetric survey of the wetlands system, however, indicated that the lakes are connected by small channels and form a cluster. As noted by Marimuthu et al (2005a), further investigations were required to understand the full complexities of the system. Isotopic composition analyses conducted by Marimuthu et al. (Marimuthu et al. 2005a) supported the theories of Short (2000), indicating that Bandy Creek fed into Station Lake while Coramup Creek fed Lake Wheatfield, with no apparent mixing between the two lakes.

Stevenson (2007) refined the previous modelling undertaken by Short (2000) and Marimuthu (2005). A FEFLOW numerical model was developed, providing revised surface groundwater interaction modelling for the LWWS using updated basement data and revised model boundaries. Stevenson's (2007) model was able to satisfactorily calibrate groundwater levels in the tested boreholes, but it was unable to model surface flow and the fluctuations in the lake levels accurately. Stevenson (2007), noted that the surface flow recharge functions were not adequate for the model and postulated the same conclusion of Marimuthu (2005) that two of the lakes (Ewans and Mullet) were most likely fed predominately from groundwater. Stevenson's (2007) model found that the other five lakes only showed a slight change upon removal of the surface flow component. The model mostly overestimated the water levels in these lakes, showing an increasing trend in the water levels over time, which is not reflected in the measured data.

Stevenson (2007) concluded that the model was not useful in answering any urgent questions in regards to the management of the lakes and that it was limited by a lack of accurate evaporation data and limited groundwater data from only part of the LWWS. Stevenson (2007) suggested that collection of local evaporation data, as well as additional bore data from a wider catchment area incorporating Pink Lake, would assist in improving the capacity of the model to accurately predict lake level variations.

In 2012, the groundwater flow model (FEFLOW) previously developed by Marimuthu (2005) was revised and recalibrated (MS Groundwater 2012). This revision occurred to assess existing management boundaries in the Esperance Groundwater Area. Previously applied datasets were updated and additional data were applied to run and recalibrate the model. Steady-state and transient calibrations were performed using data for the period 2002-2006 and data for the period 2007-2011 used for model validation.

Modelling by MS Groundwater Management (2012) revealed that there was no significant long-term decline of groundwater level across the study area. Quantification of lake inflow and outflow regimes indicated that the ratio of inflow to outflow was variable, although the dominant trend was for groundwater inflow to be greater than outflow. The majority were interpreted to be flow-through lakes, whilst the exception was Pink Lake, which acts as a groundwater sink. Modelling under different climate scenarios indicated that all the lakes except Mullet Lake show positive net groundwater flow. Mullet Lake shows negative net groundwater flow during the dry period.

The steady-state FEFLOW model was successful overall in simulating observed groundwater level levels across the model domain (MS Groundwater Management 2012). Site-specific differences were however evident, which is most likely attributed to local-scale features, which in some cases are poorly represented. Calibration of the transient model was considered satisfactory, although in some areas the simulated hydraulic head was lower than observed. In cases where large error between simulated and observed groundwater levels occurred, particularly to the north of the wetlands system, then the installation of additional infrastructure in these areas is suggested. Conclusions and Knowledge Gaps

## 5.4 Water balance

Since hydrogeological monitoring and investigations commenced in the LWC in 1998, and from assessments including Short (2000), Marimuthu et al. (2005a), Marimuthu et al. (2005b), Stevenson (2007), and MS Groundwater Management (2012) the understanding of groundwater flow, characteristics of aquifers, and the contribution of groundwater to the lake suites has improved significantly. The recent Groundwater Review re-assessed the hydrogeological processes associated with the LWWS (Johnson 2014). The available groundwater level datasets show that groundwater levels are dynamic and influenced by recharge rates, but on average groundwater flow is generally towards the south and coast. Groundwater-surface water regime appears to behave differently with respect to flow dynamics (Marimuthu et al. 2005a, Johnson 2014). From 2009 – 2012 hydrological change was observed from lower rainfall during this period (Johnson 2014).

Increased water depth and the loss of shorelines and shallow feeding areas were noted as the major threatening process to waterbird communities in the LWWS. The hydrogeological data collected since 1998 has provided some information to assist in determining management targets for the LWWS. In 2008 a gravitational pipeline was constructed connecting Lake Wheatfield to Bandy Creek, to assist in reducing surface water levels in Lake Wheatfield. Preliminary results suggest the pipeline is achieving the objective of lowering lake levels. The construction of the Lake Wheatfield gravitational pipeline has resulted in some positive results for wildlife, however unanticipated high salinity concentrations in Lake Warden have occurred. This change corresponds to considerable reductions in invertebrate populations and a large decrease in the diversity of water birds at the LWWS. At this point it is unclear if this decline is related or due to other environmental factors (e.g. limited seasonal variation in water levels, high nutrient loads, etc.) or a combination.

## 5.5 Salinity

To date there has been limited analysis of salt, both in terms of stores and mobility, in groundwater and surface water. The unanticipated increases in salinity in Lake Warden following the installation of the Lake Wheatfield gravitational pipeline suggests further investigations are required to understand further the hydraulic connectivity between deeper aquifers and surface water hydrology within the LWWS. The collection of salinity data by the LWC program as well as the SAP, SWWMP and other projects in the area provide an opportunity to identify major salt pathways to the wetlands. This data, in combination with data on aquatic invertebrates, birds and vegetation could potentially be used to better understand the biological response to changing salt loads. Review of the existing data should be undertaken to provide preliminary models of the salt balance and determine what additional information might be required to refine the current understanding and reduce uncertainty.

In order to ensure the ongoing value of the LWWS for both migratory and local bird populations, it is vital that the complex interactions between the availability of wading habitat, health of the fringing vegetation, available food sources and water quality are clearly understood. A greater understanding of groundwater-surface water interactions and how salt stores impact on salinity loads in the wetlands is required to set water balance targets which are linked to biodiversity targets.

In the draft 2005-2030 preliminary Recovery Plan (Department of Conservation and Land Management 2006), it was noted that further research was required to better understand Pink Lake. Although Pink Lake is not part of the Ramsar wetland suite, there are potential tourism and recreation values associated with the lake that suggest it may be valuable to understand and manage salt levels in the lake to ensure the pink colouration is maintained.

## 5.6 Sedimentation and nutrients

In the draft 2005 – 2030 preliminary Recovery Plan, one of the key recommendations was to undertake nutrient, sediment, and salt transport modelling in the LWWS, but to date it appears only limited analyses of the data has occurred. As identified by Wilson (2004), sedimentation rates and nutrient loads to Lake Warden have increased significantly in recent years, however only a few preliminary reports discuss these issues. Bathymetric surveys have been commissioned twice in the LWWS, however no report could be identified that discussed variations in the bathymetry between the two surveys to assess recent sediment loads. Although nutrient levels and turbidity in both surface water and groundwater have been monitored since the late 1990's, only preliminary reports that discuss the major sources of nutrients to the creeks and lakes were produced.

A number of reports investigating the relationship between aquatic invertebrates and various physical parameters in Lake Warden and Lake Wheatfield have been produced. However, most examine individual relationships between either species richness or functional groups and do not examine multiple interactions between various physical parameters (e.g. salinity and high phosphorus and species diversity or salinity and hydroperiod and species diversity) in any detail. The aquatic invertebrate monitoring was not designed to answer these more complex questions and since monitoring commenced, water quality parameters have not fluctuated sufficiently enough to be able to tease out possible relationships. Recent changes in hydroperiods from the gravitational pipeline provide an excellent opportunity to determine if there are more complex ecological interactions.

Preliminary research has indicated that the life-cycle of some salt-tolerate aquatic invertebrates may be strongly linked to changed salinity and flooding patterns and modifications to the hydroperiod and the timing of peak salinity may provide unfavourable cues and conditions for hatching and the development of invertebrates (Halse et al. 2003). Further research is needed to understand the invertebrate breeding ecology in these secondary salinized wetlands before we can fully understand the impact managing water levels will have on the wider ecology of the system.

## 5.7 Revegetation

A number of programs have been initiated that involved the establishment of perennial plants (both native and crop species) in key recharge areas of the LWC. However, it is unclear how these programs have developed and if any analysis of the success of these programs has been conducted. Initially, the establishment of perennial plants in the LWC was intended to provide medium to long-term solutions to the management of water in the LWWS as well as long-term management of localised salinity problems. However, no documentation could be sourced that discussed the initial level of success of programs, the long-term maintenance of these or any investigations on the potential impact these programs are having on the key threats they were initiated to address (e.g. localised reduction in salt loads, reduction in local and downstream water loads, nutrient and sediment loads to LWWS, etc.). The draft 2005-2030 preliminary Recovery Plan (Department of Conservation and Land Management 2006) recommended that investigations should be conducted on the local effect of revegetation works and remnant vegetation rehabilitation on hydrology. It is unclear at this stage if steps were taken to evaluate this.

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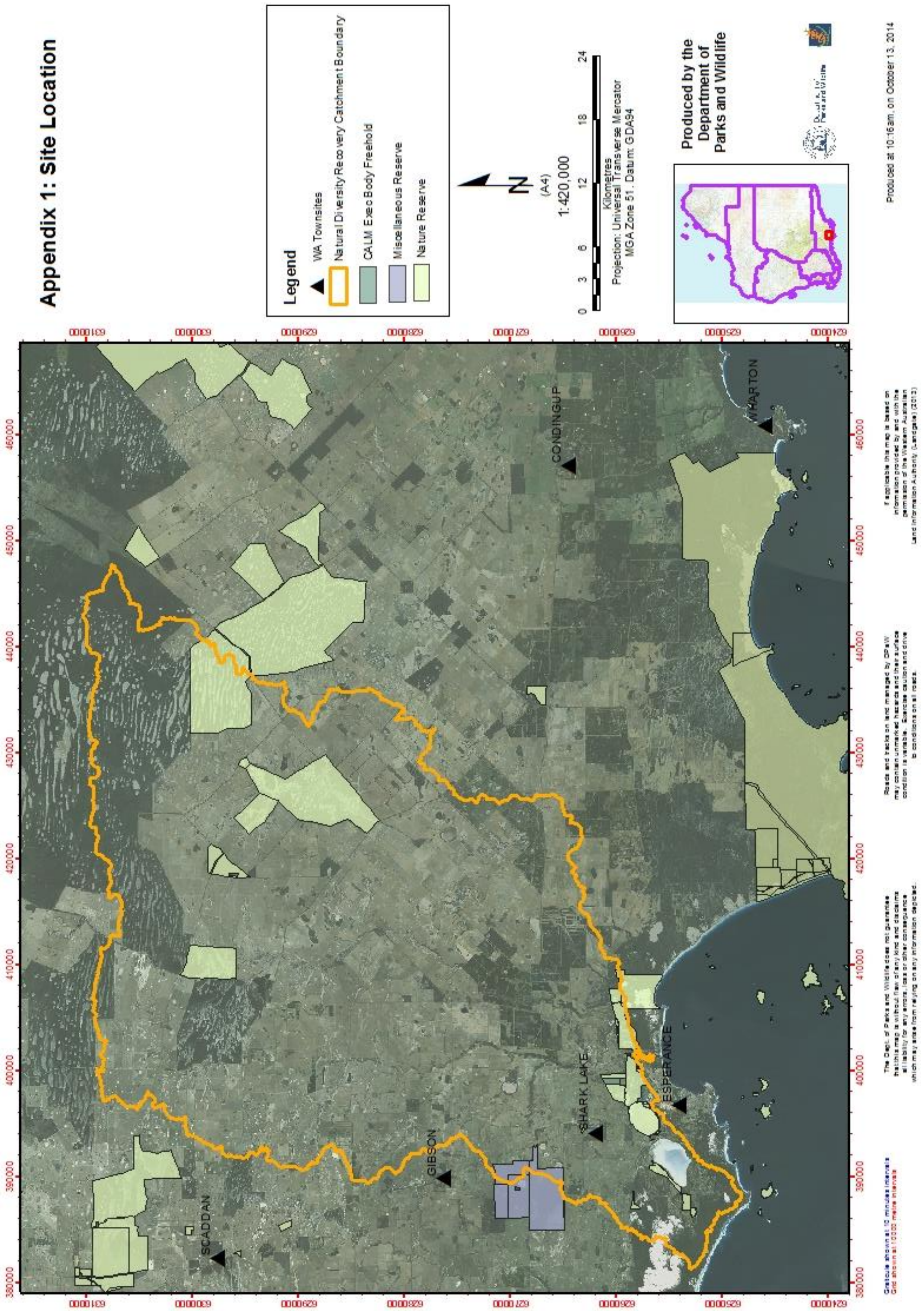
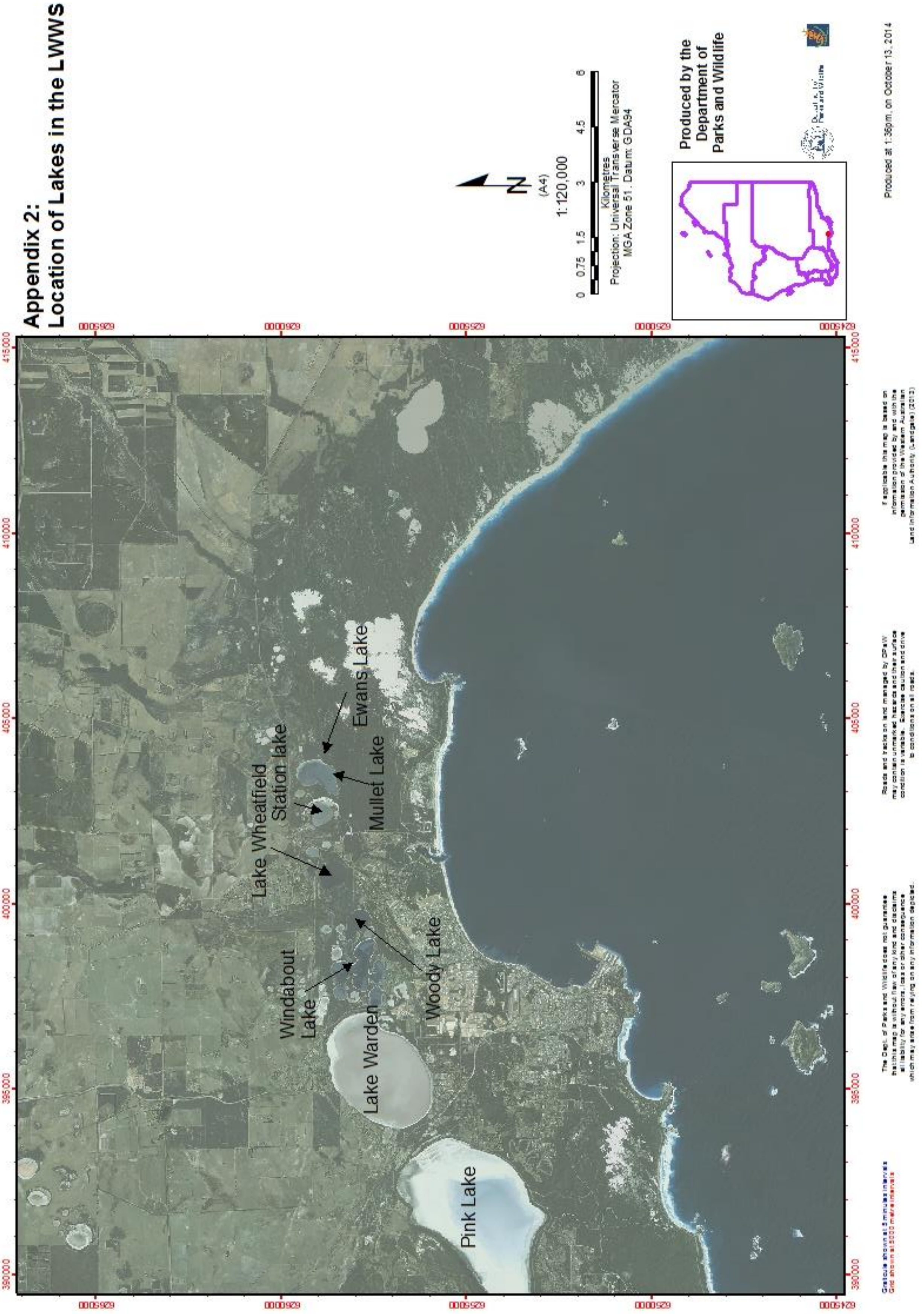
# 7 Appendices

## Appendix 1: Site Location

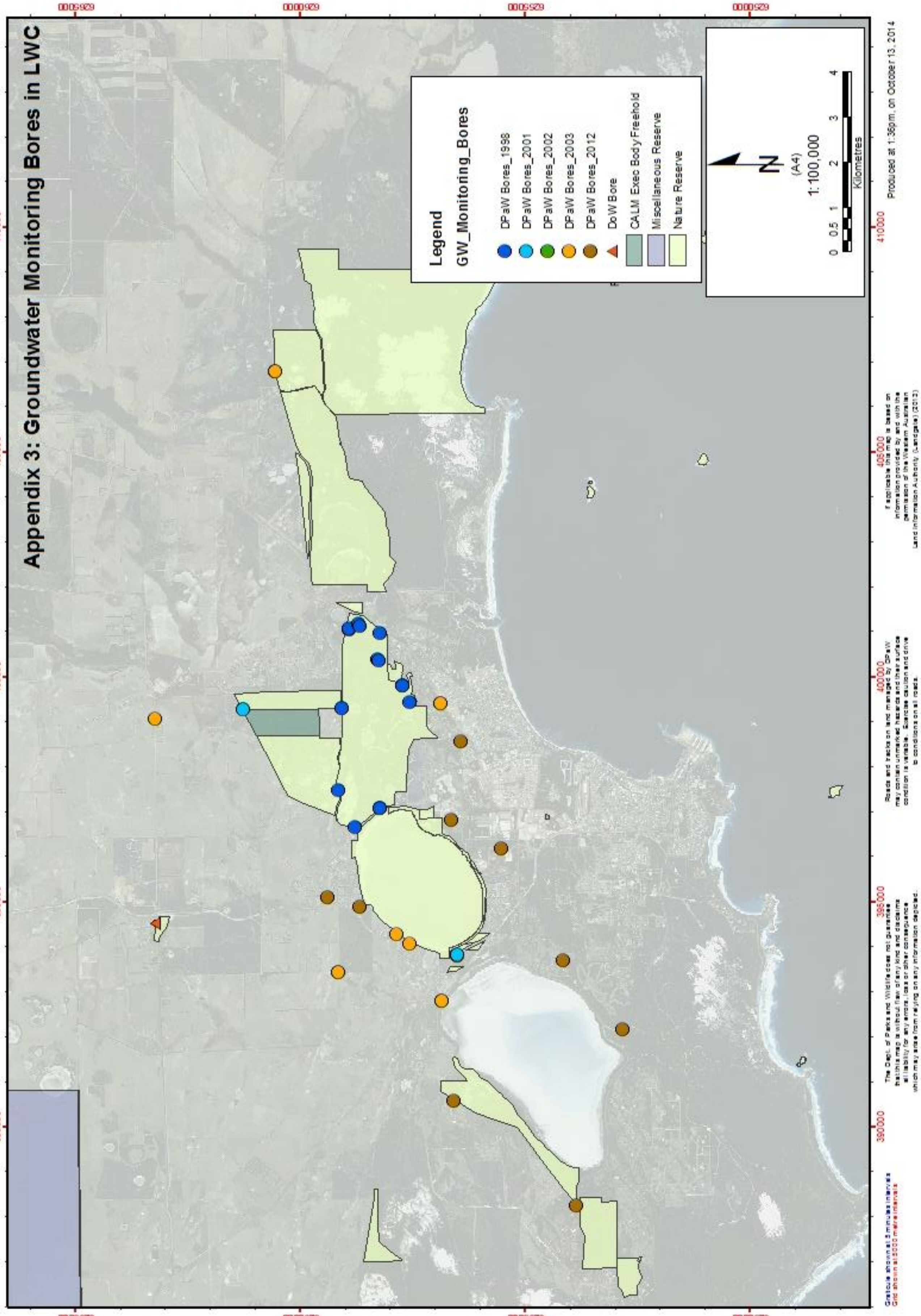

Appendix 1: Site Location
Legend
WA Townsites
Natural Diversity Recovery Catchment Boundary
CALM Exec Body Freehold
Miscellaneous Reserve
Nature Reserve
N
(A4)
1:420,000
0 3 6 12 18 24
Kilometres
Projection: Universal Transverse Mercator
MGA Zone 51. Datum: GDA94
Produced by the
Department of
Parks and Wildlife
Produced at 10:16am, on October 13, 2014
SCADDAN
GIBSON
SHARK LAKE
ESPERANCE
CONDINGUP
WHARTON

## Appendix 2 : Lakes within the Lake Warden Wetlands System

## Appendix 2: Location of Lakes in the LWWS



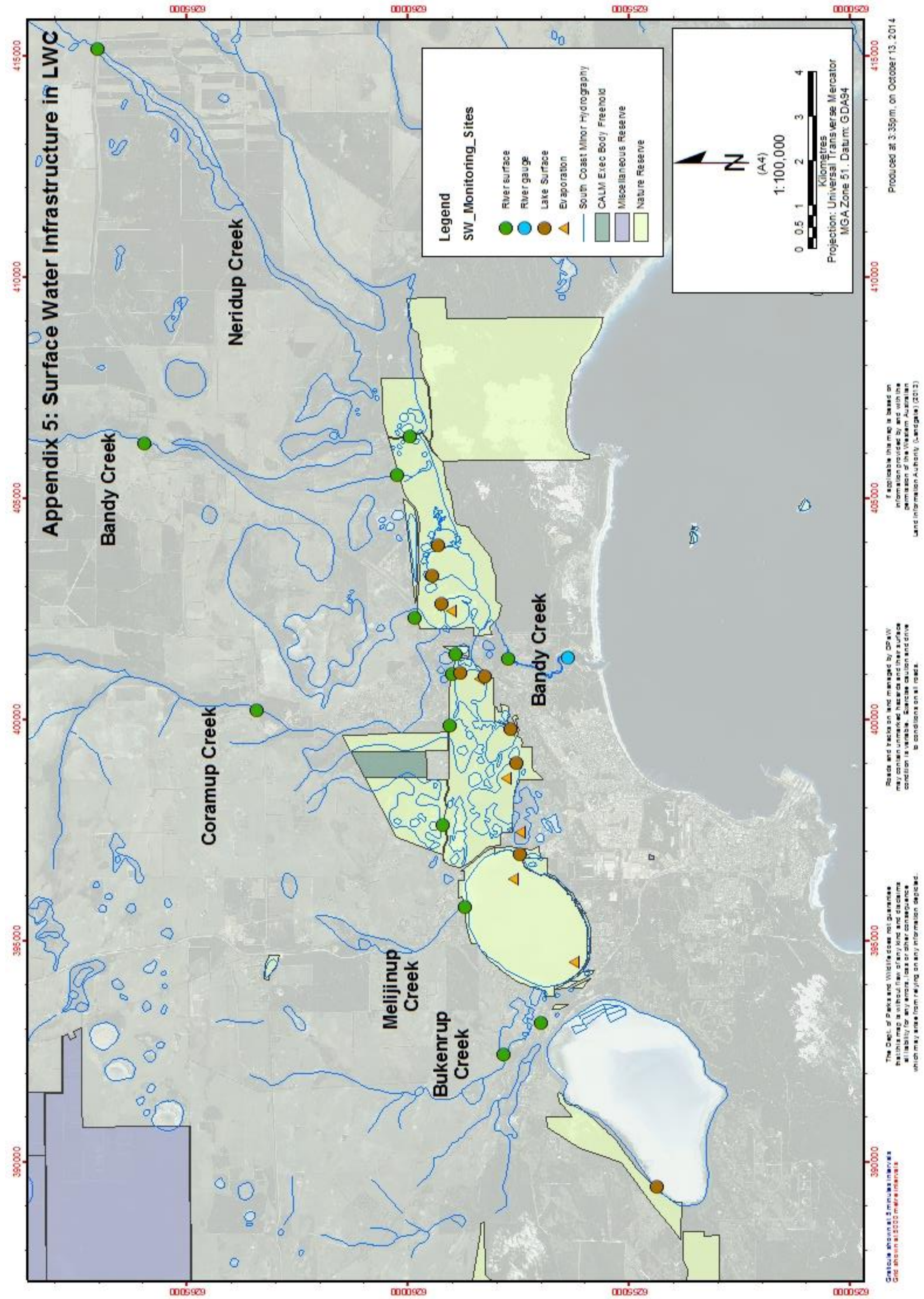
# Appendix 3: Groundwater Monitoring Intrastructure in Lake Warden Catchment


Appendix 3: Groundwater Monitoring Bores in LWC
Legend
GW_Monitoring_Bores
DPaW Bores_1998
DPaW Bores_2001
DPaW Bores_2002
DPaW Bores_2003
DPaW Bores_2012
DoW Bore
CALM Exec Body Freehold
Miscellaneous Reserve
Nature Reserve
N
(A4)
1:100,000
0 0.5 1 2 3 4
Kilometres
Produced at 1:36pm, on October 13, 2014

## Appendix 4: Logger locations as on 30th September 2014 (now all decommissioned)

| Location | Logger number |
|---|---|
| Bukenrup Creek (D4) | RB0022 |
| Corrumup Creek at Lakes Rd | RB0019 |
| Ewans Lake | RB0008 |
| Fisheries Rd (catchment off Quarry Rd discharging to Station Lake) | RB0025 |
| Lake Gore | RB0018 |
| Lake Kubich | RB0023 |
| Mullet Lake | RB0014 |
| Lake Quallilup | RB0029 |
| South Coast Hwy (discharging to Lake Warden) D5 | RB0025 |
| Stearne’s Creek at Stearne’s Rd | RB0024 |
| Station Lake | RV0001 |
| Lake Warden | RB0009 |
| Lake Wheatfield | RB0011 |
| Lake Windabout | RB0007 |

# Appendix 5: Surface water and climate monitoring infrastructure in Lake Warden Catchment


Appendix 5: Surface Water Infrastructure in LWC
Bandy Creek
Neridup Creek
Coramup Creek
Bandy Creek
Melijinup Creek
Bukenrup Creek
Legend
SW_Monitoring_Sites
River surface
River gauge
Lake Surface
Evaporation
South Coast Minor Hydrography
CALM Exec Body Freehold
Miscellaneous Reserve
Nature Reserve
N
(A4)
1:100,000
Kilometres
Projection: Universal Transverse Mercator
MGA Zone 51. Datum: GDA94
Produced at 3:35pm, on October 13, 2014
415000
410000
405000
400000
395000
390000

# Appendix 6: Wheatfield Discharge Review (Lizamore 2015)

# Lake Wheatfield gravity pipeline discharge review

## Lake Warden Natural Diversity Recovery Catchment

*Prepared for*

## Department of Parks and Wildlife

Esperance District and Science and Conservation Division

14 April 2015

Locked Bag 104
Bentley Delivery Centre; Bentley 6983
Western Australia

*Prepared by*


**John Lizamore**

**Esperance District Office**

PO Box 234, Esperance 6450
Western Australia

Index:

## 1 Introduction:

Altered hydrology as a result of large-scale land clearing resulted in the flooding of the Lake Warden Wetland System and engineering interventions proposed (Maunsell-Aecom 2008). As part of approved mitigation measures, the Lake Wheatfield gravity pipeline construction was completed and tested on 02 April 2009. Discharge operations commenced on 28 April 2009. As a result of endless technical difficulties experienced with the installed flow rate measurement equipment in the pipeline to monitor the releases, it was decided to manually measure discharge and use the empirical values to calculate a discharge curve for the system and calculate the discharged volumes.

## 2 Methodology:

John Lizamore and Sarah Davies undertook several flow measurements within the pipeline during various flow conditions. Flow measurements were undertaken with a Valeport Electromagnetic Flow Meter (model 801 flat) and a Valeport Mechanical Flow Meter (model 2) during the period of November 2011 to December 2012. Flow regimes included full pipe flow and half-pipe flow. All measurements were taken approximately 30m from the pipeline inlet through an open manhole cover installed in the pipeline.

## 3 Calculations:

The Lake Wheatfield pipeline, as constructed, differs from the designed parameters. These changes came as a result of route reallignements and construction difficulties experienced. Final relevant specifications for all calculations are:

- Length = 850m
- Internal diameter = 368mm (pvc pipe)
- Inlet height to discharge height $\approx$ 1.7 - 2.5m (depending on tidal effect experienced at discharge point at water level in the creek)

All calculations were based on the following assumptions:

- Formulaes & equations used: Gauckler-Manning, Bernoulli and Darcy-Weisbach.
- Laminar flow (not turbulent)
- Static hydraulic head of 2m (Tidal effect should cancel out over period. Higher water levels in creek (and resulting reduced head) will cancel out as a result of increased flow downstream which will result in negative pressure and increased suction through the venturi principle)
- Manning roughness coefficient of 0.016
- No allowances were made for differences in viscosity and/or relative density as a result of salinity changes.
- Averages of maximum flow velocities were used for most representative measurements taken (10 November 2011 and 8 December 2012).
- For half-pipe flow, open channel flow equations and principles were used.
- When the pipeline is flowing at more than ¾ full, flow tends to alternate between full and partial flow. No allowance was made for this, as there is no way to know when the pipe was experiencing full and when partial flow during a 24-hour flow cycle. It was assumed that the effects will cancel itself out.
- Friction constants were caculated for full and partial flow based on emperical flow measurements and was used as 0.139876948 and 0.30692317 respectively.

## 4 Results:

Discharge table indicated in Figure 1 below. The combined discharge volumes for pipeline operations since April 2009 were calculated as:

| Date opened | Date closed | Total discharge ($m^3$) |
|---|---|---|
| 28-Apr-09 | 19-Jan-10 | 889291.72 |
| 26-May-10 | 22-Dec-10 | 650166.09 |
| 25-May-11 | 30-Aug-11 | 124199.08 |
| 28-Sep-11 | 23-Feb-12 | 234591.18 |
| 20-Jun-12 | 7-Jan-13 | 552275.54 |
| 12-Jun-13 | 11-Feb-14 | 818159.88 |
| | Total: | 3268683.50 |

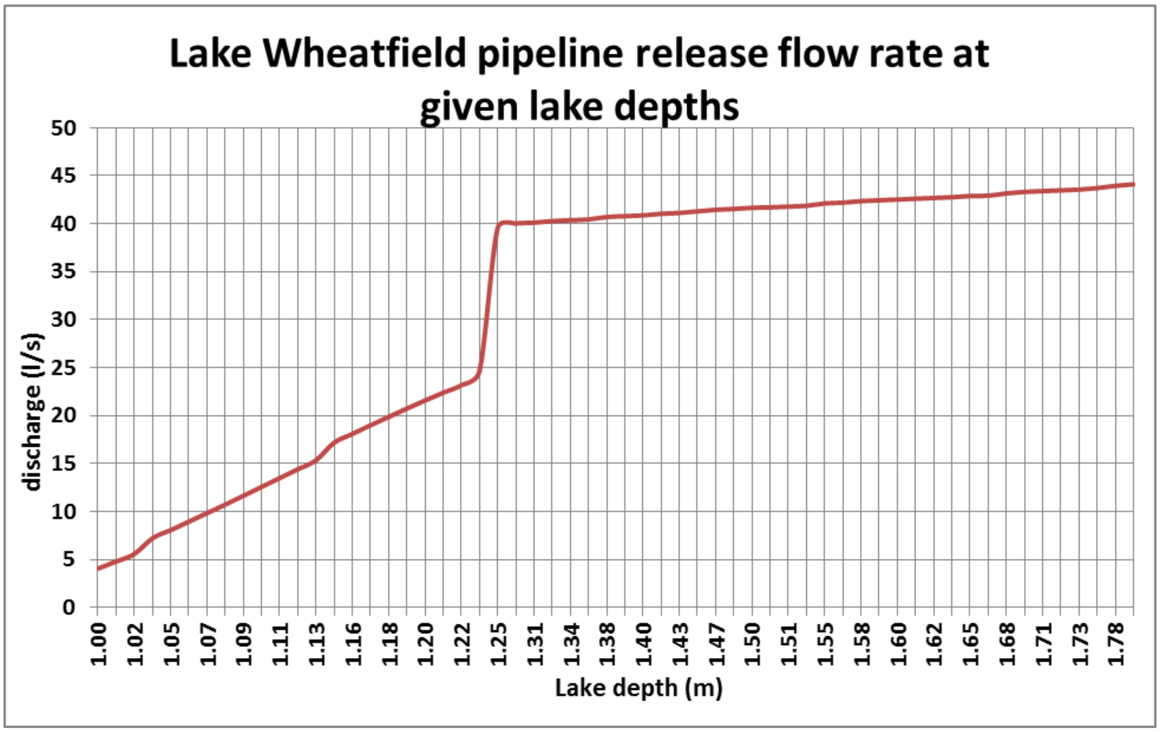



Figure 1: Discharge tables as calculated.

## 5. Acknowledgements:

This work would not have been possible without the guidance and assistance of Nathan Rugless, Lance Mudgeway, John Simons, Lindsay Bourke, Mick Rose and Sarah Davies.

## 6. References:

Maunsell-Aecom (2008). *Lake Warden Wetland System, Esperance. Initial Environmental Impact Assessment.* G. M. Prepared by Steven Thomas, Lisa Chappell, ELisabeth Zajc, Shirley Connelly, Lara Jefferson, Tilo Massenbauer (DEC), T. M. D. Reviewed by Steven Thomas, Troy Collie and A. b. S. S. T. L.-P. Advisory). Perth, WA, Department of Environment & Conservation.