HYDROLOGY PROGRAM REVIEW 1977-2015:

TOOLIBIN LAKE NATURAL DIVERSITY RECOVERY CATCHMENT

Jasmine Rutherford, Kristy Ferguson, Natalie Horsfield and Mariajose Romero-Segura

DEPARTMENT OF PARKS AND WILDLIFE

HYDROLOGY REPORT

WCP-HR-2015-002

February 2015

For more information contact:

Jasmine Rutherford
Senior Hydrologist
Wetland Conservation Program
Department of Parks and Wildlife (DPaW)
17 Dick Perry Avenue
Kensington, Western Australia 6151

Disclaimer

Recommended Reference

The recommended reference for this publication is:

Rutherford, J.L. Ferguson, K. Horsfield N. and Romero-Segura, M. (2015). Hydrology Program Review 1977 - 2015: Toolibin Lake Natural Diversity Recovery Catchment. Department of Parks and Wildlife (DPaW), Wetlands Conservation Program Hydrology Report WCP-HR-2015-002, Kensington, Western Australia.

Acknowledgements

The following are acknowledged for their assistance at various stages during the development of this review: Ray McKnight, Maria Lee, Adrian Pinder, Richard George, Peter Lacey, Val English, Shawan Dogramaci and Darren Farmer.

Cover photo courtesy Mariajose Romero-Segura; Toolibin Lake 2014

Table of contents

Tables

Figures

Executive Summary

The Toolibin Lake Natural Diversity Recovery Catchment (TLNDRC) is located in the Western Australian Wheatbelt 250 km south-east of Perth. Toolibin Lake is one of a chain of nine lakes and is listed as a Ramsar Wetland of International Importance for its significance as a breeding habitat for native water birds. When the catchment was under native vegetation Toolibin Lake behaved as a freshwater-brackish ephemeral lake and was thought to historically fill in seven out of ten years. In the 1900s the expansion of broad acre agriculture changed the catchment water and salt balance and the lake and areas within the catchment's valley floor now have a more frequent connection with shallow saline groundwater. As a consequence lake evaporation has increased due to higher residence times of lake surface water and when ephemeral waterways flow, the water quality is generally saline.

The dominance of different hydrological processes has changed and this has altered biodiversity values within Toolibin Lake, as well as other biological assets in the TLNDRC. A recovery plan developed in 1994 included a set of initial hydrological criteria put forward to manage and measure success at restoring the lake and its surrounding nature reserves to a freshwater system suitable for waterbird usage. This report reviews progress made in the TLNDRC on understanding and measuring hydrological parameters, with a focus on the ability of projects to integrate results and information from previous work and provide confidence in the 1994 recovery plan hydrological criteria.

In the 1970s rising groundwater was identified as a threat to biodiversity in the TLNDRC and has been the subject of many investigations aimed at improving our existing knowledge of the water and salt balance. This was achieved through an assessment of groundwater recharge, aquifer connectivity and groundwater gradients, as well as the identification of priority management areas characterised by high water and salt fluxes. By the mid-late 1990s it became clear that considerable resources were required to understand the variable physical properties of the complex aquifer systems in the area and the rates of entrained water and salt movement. The need to manage water and salt beneath Toolibin Lake became paramount and the focus of investigations turned towards using the existing data to design a groundwater pumping and disposal scheme, with Lake Taarblin selected as the groundwater disposal site. Between 2000 and 2013, groundwater investigation and assessment work focussed on the effectiveness of groundwater management actions, notably the Toolibin Lake groundwater pumping system and nature reserve re-vegetation projects.

Similarly, for surface water investigations the initial work in the late 1970s was directed to fulfilling the objectives of understanding and developing a lake water balance by measuring rainfall, lake depth levels and ephemeral stream flow. This resulted in manual and automated measurement stations being installed within lakes and drainage lines across the catchment. In the 1990s the majority of surface water work focused on assessing the potential benefits of engineering works to divert flows and in the 2000s work covered the installation and performance assessments of major engineering structures (including the Toolibin Lake diversion, separator and outlet control) as well as researching the controls of catchment and sub-catchment water and salt fluxes. Many of the assessments were primarily theoretical, based on limited data and observations. This, in part, is

attributed to post 2000 rainfall events lacking the intensity to produce significant stream flow and subsequent lake inflows.

Limited research has been undertaken on the spatial distribution of rainfall and evaporation in the TLNDRC. Stations established to assess catchment scale rainfall variability in the early 2000s were installed after the major wet climate trend of the 1980s, but with the drying phase that followed they did not resolve significant spatial variability. Evaporation is likely to be an important parameter to understand and quantify, however it is also highly variable requiring supporting hydrological data to complete a robust quantitative assessment. As a result of these factors most studies source and use reference data from nearby Bureau of Meteorology (BoM) weather stations.

Investigations on the spatial distribution of regolith salt storages showed that they are spatially complex, change slowly and are characterised by high concentrations of salt. Combined, these factors make the measurement of changes in salt storage over short time frames problematic, with measurement error likely to be as high as the potential changes requiring quantification. Presently, the groundwater monitoring program does not include a regular program to assess changes in aquifer water quality. Long term low frequency monitoring using geophysical methods is required to increase confidence in the nature and transport of salt in the saturated and/or unsaturated zones. To-date progress on quantifying salt fluxes has been limited, particularly as surface water flows are very infrequent. Most recent research has focused on landscape and rainfall intensity as the main controls of higher salinity, with fresher flows tending to occur in upper landscape areas and following high intensity summer rainfall events.

Transpiration assessments in the TLNDRC have been based upon the presence and condition of vegetation (biomass estimates) combined with theoretical or direct measurements of plant water uptake. In the late 1970s vegetation structure and composition maps were produced for Toolibin Lake and adjoining nature reserves by combining field mapping with biomass measurements. Measurements of biomass to assess change in the 1990s and 2000s were produced at a local scale by monitoring vegetation plots/quadrats located in representative areas on Toolibin Lake. In the mid 2000s attempts were made to measure broader scale changes in biomass using remote sensing methods, with some success using high resolution hyperspectral data. At the same time finer scale water use assessments showing some species, such as *Melaleuca strobophylla,* were opportunistic in their water use, characterised by a very low water uptake during dry conditions but capable of using more water when inundated with low salinity water.

Geophysical data acquired over the past fifteen years from ground electromagnetic and airborne magnetic, radiometric and electromagnetic (AEM) surveys have assisted in the design of monitoring and groundwater abstraction programs. In the late 1990s airborne magnetic data were deemed to improve the geological understanding of the catchment while the spatially contiguous AEM data sets resolved the palaeochannel beneath Toolibin Lake and provided robust estimates of regolith salt stores, particularly within saturated regolith materials indicating the technology was useful in estimating regional scale groundwater salinities. In 2000 AEM data acquired from an improved system allowed for the better definition of the palaeochannel, but this system failed to improve resolution of salt stored in the unsaturated zone. Ground electromagnetic data acquired across Toolibin Lake to resolve spatial variations in near surface electrical conductivity and map areas where salt could be more mobile resolved interesting spatial patterns but were unverified due to limited sampling and monitoring of lake sediment water and salt content. In the mid 2000s a new AEM system was trialled across the Toolibin Lake and valley and modelling of these data combined with the acquisition of borehole Nuclear Magnetic Resonance data and lake substrate water and salt analyses provided a more accurate bedrock topography map and reliable estimates of total water and salt storage in aquifers and the unsaturated zone.

Hydrological numerical modelling has been mainly used as a tool to understand the success of managing groundwater through revegetation landscapes, dewatering Toolibin Lake and diverting surface and lake water. Groundwater modelling was undertaken using a MODFLOW saturated flow model in 1998 and 2000, with the latter model including the palaeochannel mapped by the AEM. In 2011 the MODFLOW model was again tested to assess the optimal configuration of pumping bores. In 2001 an analytical water and salt balance model was developed to assess disposing Toolibin Lake discharge water into Lake Taarblin, while a 2D flow tube model was developed to assess the catchment area required to be revegetated to mitigate salt mobilisation and shallow aquifer expansion.

In 2003 the lake and catchment water and salt balances were assessed using hydrograph, analytical and lumped parameter modelling methods. Results indicated that in the valley floor there was little or no net change in groundwater levels due to evaporation keeping pace with groundwater rises, resulting in the concentration of salts in the uppermost few metres. Catchment salt yields remained low due to landscapes and soils promoting a spatially complex pattern of salt mobilisation, retention and remobilisation zones. An analytical lake water balance model for Toolibin Lake successfully simulated the lake hydroperiod under the higher rainfall climate of the 1980s and 1990s. A catchment water balance model (MAGIC) showed that a high percentage of the catchment would need to be revegetated with perennial plants to effectively lower shallow water levels, results that were similar to those of the 2D flow tube modelling work.

In 2004 the analytical lake water balance model was re-run using fluxes produced from the catchment numerical model LUCICAT and incorporating aquifer head and the lake-bed conductance to account for groundwater losses. Results from this modelling study were similar to those reported in 2003 apart from losses of water and salt due to increases in lake seepage, which contradicted the findings of the 2000 MODFLOW modelling. In 2009 a statistical water and salt balance model assessed the benefits and threats of changing the inflow salinity threshold at Toolibin Lake from 1,000 to 5,000 mg/L TDS. Results from this dynamic Monte Carlo simulation model needed to be viewed as relative rather than absolute, with further monitoring being essential to calibrate and validate the model and reduce uncertainty.

HYDRUS-1D was used in 2010 and 2012 to model unsaturated zone water and salt fluxes in Toolibin Lake. The study indicated that the current lake system is characterised by low soil moisture and salt leaching, both of which are detrimental to vegetation health. Managed flushing was suggested as a mechanism to move stored salts deeper into the regolith profile. The likely success of this was tested under a number of climate scenarios that would influence the duration of lake inundation. Results showed that stored salts need to flush to improve water quality for the vegetation to establish and survive, with the flushing process needing to outpace the re-establishment of salt stores due to continued transpiration. Lags occur where sediments contained higher percentages of clay-sized material. Where the upward movement of salt occurred through diffusion, the flux was thought to be negligible compared to increases in salt storage due transpiration.

In 2015 a numerical model framework was developed that included a wetland water and energy balance 'bucket style' model with streamflow and salinity fluxes produced by quasi-three dimensional valley floor and uplands models. Rainfall-runoff modelling was undertaken using LASCAM, two dimensional valley floor surface water flow simulations using TUFLOW, while Toolibin Lake was modelled using WET0D, a lumped parameter radial flow model. A number of shortfalls and caveats were provided with the modelling results, with a recommendation that further modelling and assessments were required to remove uncertainty.

Research into groundwater and surface water hydrology in the Toolibin Lake NDRC has broadened the understanding of the how and when ephemeral wetlands in the Western Australian Wheatbelt adapt to changes in the water and salt balance. The broad nature of the TLNDRC hydrological research questions, or topics, has allowed researchers to develop projects and collect hydrological data to understand different water and salt balance parameters. Although progress on understanding the relevance of hydrological monitoring thresholds developed for the 1994 recovery plan has progressed, arguably it has also been hindered by a failure to fully incorporate the findings and information from previous work.

Knowledge gaps that remain are:

- Understanding what groundwater level beneath Toolibin Lake would be appropriate to protect the lake bed from threats of rising groundwater and long-lived lake inundation events,
- Identifying a maximum, or range, of lake water salinity levels to satisfy lake vegetation tolerances, composition and structure, as well as the lake salt balance,
- Measuring and mapping catchment-scale surface and groundwater processes responsible for changing surface water and salt fluxes into Toolibin Lake, and
- Determining an optimal hydroperiod for Toolibin Lake, under wet and dry climate regimes, to sustain vegetation composition, structure and biomass.

These gaps in large part reflect the absence of a robust quantitative hydrological conceptual model (e.g. questions remain on how water and salt is stored and how it moves under different seasonal and longer term climatic conditions). Available evidence suggests that sufficient hydrological data and information has been collected over the past forty years to help address these outstanding knowledge gaps.

To realise the full potential and value in these datasets, requires that they be quality assured and managed with the Department of Parks and Wildlife. Recognition of this potential has seen the Department invest considerable effort into these aspects over the past five years. Conclusion of this data quality work needs to be followed by the interpretation and integration of all available data to produce a quantitative hydrological conceptual model. This will achieve two things – recognition of the full value of the work done in the TLNDRC over the past few decades, and the development of a functional generic model that can used to manage Toolibin Lake and its catchment, as well as similar hydrological settings in the WA Wheatbelt.

1 Background

Toolibin Lake Natural Diversity Recovery Catchment (TLNDRC) has been the focus of many hydrological investigations since the 1970s. Commonwealth and a number of State Government agencies, universities and land care organisations have undertaken hydrological work to understand and restore Toolibin Lake, a Ramsar wetland located in southwest Western Australia.

Prior to the expansion of broad acre agriculture in the Wheatbelt of WA, Toolibin Lake behaved as a freshwater ephemeral lake and was an important bird breeding habitat. The lake and other areas in the catchment's valley floor now connect with saline groundwater and when ephemeral waterways flow, the water quality is generally saline. These hydrological processes have degraded the biodiversity values of Toolibin Lake and other biological assets in the TLNDRC.

Significant support was garnered in the 1970s to understand the deleterious processes occurring at Toolibin Lake. In 1977 the Northern Arthur River Wetlands Rehabilitation Committee (NARWRC) was established to assist research in the Toolibin Catchment by bringing together a group of scientific experts and stakeholders to drive research directions to restore the lake and its surrounding nature reserves as a healthy and resilient *freshwater* system, suitable for waterbird usage.

Toolibin Lake became a designated Ramsar site in 1990 (Department of Parks and Wildlife 2014) and was studied under the Salinity Action Plan (SAP) in 1996 (Agriculture Western Australia, Department of Conservation and Land Management *et al.* 1996). Commitments under the Ramsar convention require ecological values to be maintained to support bird life. Critical to this at Toolibin Lake is an understanding of groundwater and surface water hydrology, in particular the water and salt balance of the lake and connecting areas. To maintain Toolibin Lake Ramsar values, hydrological management currently involves catchment scale work aimed at lowering saline groundwater levels and reducing saline surface runoff in addition to the management of groundwater at Toolibin Lake through groundwater pumping and diverting saline surface water flows.

A recovery plan was developed for Toolibin Lake in 1994. This TLNDRC Recovery Plan (Toolibin Lake Recovery Team and Toolibin Lake Technical Advisory Group 1994) developed a set of five hydrological criteria to both manage and measure success at achieving these goals. These criteria, developed with hydrological data acquired since the late 1970s are detailed below.

1. The minimum depth to the water table beneath Toolibin Lake and Toolibin Flats in spring, when the lake is dry, should be 1.5m,
2. The maximum salinity of lake water when the lake is full should be 1,000mg/L Total Dissolved Salts (TDS),
3. The maximum salinity of inflow to the lake, measured at the Department of Water gauging station 609009 on the Northern Arthur River, should be 1000mg/L TDS during the winter months when the lake receives inflow,
4. The lake bed dries periodically by evaporation, on average once every three years,
5. The levels of nutrients within Toolibin Lake should not cause excessive growths of algae or other aquatic plants, or cause deleterious reductions in dissolved oxygen concentrations in the water. Total phosphorus levels in the water should not to exceed 100 µg/L TDS unless long-term monitoring indicates that this criterion may be modified.

1.1 Purpose and Scope

An understanding of where water and salt is stored and how it moves is critical in order manage biodiversity assets in the TLNDRC and assess progress on the five criteria listed in the Recovery Plan. This requires the development of a robust quantitative conceptual hydrological model of water and salt storages and fluxes, which can be tested and verified using numerical models.

The purpose of this report is to review the progress on the development of the conceptual hydrological model and its testing with numerical modelling. The review has involved:

- The sourcing of hydrological reports, papers and presentations (1977-2015),
- The division of the hydrological work into key elements (hydrological sub-disciplines) of water and salt balances (e.g. groundwater, surface water, climate, transpiration etc),
- Assessing the quality of the quantitative conceptual hydrological models developed and suitability and relevance of numerical modelling undertaken to test them and,
- Examination of the current status and reliability of the quantitative hydrological conceptual model (e.g. do we know where water and salt is stored and how it moves under different seasonal and longer term climatic conditions).

1.2 Site Location and Description

Toolibin Lake NDRC is located in the Shire of Wickepin in the Wheatbelt district, 250 km south-east of Perth (Figure 1). The catchment is 48,000 ha in size, and can be divided into 11 surface water sub-catchments (Toolibin Lake Recovery Team and Toolibin Lake Technical Advisory Group 1994). The majority of the Toolibin Lake NDRC has been cleared of native vegetation (91% cleared by the 1970s). Most of the heavy land (better class, valley floor clayey soils) was under cultivation by about 1934, with sandier soils developed in the late 1940s and 1950s (Northern Arthur River Wetlands Rehabilitation Committee 1978).

Toolibin Lake, one of nine in a chain of lakes, is located at the headwaters of the Northern Arthur River Catchment, which drains into the Blackwood River. Toolibin Lake is located in a valley filled with colluvial, fluvial and lacustrine sediments (Dogramaci *et al.* 2003). Overlying the valley fill sediments is a series of younger surficial sediments deposited mainly through fluvial, lacustrine and aeolian processes (Smith and Lee 2012).

Toolibin Lake is a fresh to brackish, ephemeral wetland and is thought to historically fill approximately seven out of ten years (Stokes and Sheridan 1985). It has been listed as a Ramsar Wetland of International Importance for its significance as a breeding habitat for native water birds.

2 Groundwater Investigations

Numerous groundwater investigations have been carried out in the Toolibin Catchment since the 1900s. Information on drilling programs carried out prior to 1977 is scarce but reported briefly in Furness (1977), Watson (1978) and the Northern Arthur River Wetlands Rehabilitation Committee (NARWRC) (1978). These documents provide some information on the search for potable water supplies in the by the Public Works Department (PWD). Most of the PWD exploratory drilling program bores have been destroyed and limited information exists on the investigation findings apart from the existence of lower salinity groundwater associated with lower yielding aquifers.

In the late 1970s the direction of groundwater investigations changed from water supply to natural resource management. This was prompted by observations of vegetation stress and death associated with the development of shallow saline aquifers following land clearing. State Government Agencies (e.g. Department of Fisheries and Wildlife, that became the Department of Conservation and Land Management (CALM) who became Department of Environment and Conservation (DEC) and now Department of Parks and Wildlife (DPaW), Geological Survey of Western Australia (GSWA), Department of Agriculture Western Australia (AgWA) now Department of Agriculture and Food (DAFWA), Water and Rivers Commission (WRC) now Department of Water (DoW) worked together to investigate, assess and help address this water and salt imbalance problem.

In the Toolibin Catchment there have been approximately nineteen drilling programs since the late 1970s, which has resulted in the installation of around 500 bores. In this report the groundwater programs are discussed within the three time periods; 1970-1989, 1990-1999 and 2000-2013.

Changes in investigation emphasis over this time have resulted in the engagement of different stakeholders and water professionals, variable experimental design and parameters measured and disparate information captured and reported. Many of the drilling programs were opportunistic and undertaken with limited time and resources. As a result information on geology intersected while drilling, hydrogeological observations, bore construction and reporting is highly variable, often incomplete and sometimes missing. Drilling programs covered in this report are summarised in Table 1, which also outlines the key hydrogeological information collected during groundwater investigations. Table 2 provides details on programs that carried out aquifer testing. Monitoring and pumping bore locations are displayed in Figure 2 through to 7.

2.1 1970-1989

In the period between 1970 and 1989 there was an expansion of drilling and groundwater monitoring programs for natural resource management in the Toolibin Catchment (Figure 3). The main purpose of the work was to gain a better understanding of the water and salt balance by assessing groundwater recharge, aquifer connectivity, groundwater gradients and salinity risks, both in the catchment and within Toolibin Lake. The desired outcome of the work was to effectively manage shallow and deep groundwater. Important investigations carried out during this time were Watson (1978), Martin (1987) and Martin (1990) (Table 1).

Work by Watson (1978) commenced in 1976 when the Department of Fisheries and Wildlife contacted the Department of Agriculture (AgWA) seeking advice on managing salt encroachment in the Northern Arthur River. The initial focus was on the Toolibin Catchment and lake. The investigation recommended carrying out a salt and water balance approach to understand the different contributions of the surface and groundwater systems on the development of shallow saline groundwater. During this investigation thirty bores were installed. Results reported that groundwater levels had risen beneath the lake and the water table was at approximately 1.5 metres below the ground surface. It was noted that more data was required to understand groundwater trends and a number of the bores installed in this program are part of the current groundwater monitoring program.

Table 1 Summary of TLNDRC drilling programs (1977-2012) (shaded cells indicates information is available)

Drilling Program Manager	Year	Lithological logs	Bore construction	Aquifer Testing	Bore completion report	Number of bores installed	Drilling program naming convention in DPaW database	See Figure in this report
AgWA	1977-1978				(Watson 1978)	30	77, TE, DW, DN, DS, F, N, TW, TS, 78	2 & 3
GSWA	1983-1984	■	■	■	(Martin 1987)	17	TO now TL11-TL16, LT2-4, Pump10	
AgWA	1985		■		No report located	30	85LTC	
CALM	1987				No report located	33	PM, GM, NS, RM, GD, GE, IE, NB, JC, BJ	
GSWA	1988		■	■	(Martin 1990)	33 (40 reported)	P9	
CALM	1989-90				No report located	25	TL01-10, LTC, JC, GD, KM, IE	
CALM	1995-1997				No report located	133 (TAFT trial)	D, W, RM	4, 5 & 6
AgWA	1995	■	■	■	(George and Bennett 1995) Limited aquifer testing	13 (6 production,7 monitoring)	Pump bores 1,2,3,4,7,8, SS95 (now TL)	
CALM	1996		■		No report located	13 (Lake Taarblin disposal site)	LTA, TL22-27	
AgWA	1997	■	■		(George 1998)	33	SS97, BW07-BW12	
WRC	1998	■	■	■	(De Silva 1999) Bores developed not tested	37	LT1-LT35	
WRC	1999	■	■	■	(Dogramaci 1999)	6 (5 production, 1 monitoring)	Pump bores P11-P15	
CALM	2000				No report located	8	T1-T4	7
WRC	2000	■	■	■	(Dogramaci 2000)	7	TL29-TL35	
DEC	2002				No report located	3	CB, JC	
AgWA	2003		■		No report located	11	SS03	
DEC	2009	■			(Noorduijn 2009)	22	PP, NS, EW, NW	
DEC	2012	■	■		(Smith and Lee 2012) Draft report	5	1A, 2A, 3A, LT07S, LT31S	

Table 2: Summary of TLNDRC aquifer testing (1983-2000)

Drilling Program Manager	Aquifer test date	Test Bore	Aquifer Airlift Results (m^3/d)	Aquifer Test Results (m^3/d)	Aquifer Testing Method
GSWA	1983-1984	Pump 10 (TP1)		34	Pump test (8 hours)
		TP2		<3	Low yield – limited testing
GSWA	1988	Pump 9 (1/88)		16	Pump test (11 days)
AgWA	1995	95/01S	2		
		Pump 1 (95/01P)	50.7		
		95/02I	11.1		
		Pump 2 (95/02P)	30.3		
		Pump 3 (95/03P)	68.6		
		Pump 4 (95/04P)	59.8		
		95/05D	5		
		95/05S	1		
		95/05H	1		
		95/06S	5		
		95/06I	10		
		Pump 7 (95/07P)	72.9		
		Pump 8 (95/08P)	61.4		
		95/11I	15.3		
WRC	1998	LT1	86.4		
		LT3	1		
		LT4	10.8		
		LT5	0.01		
		LT6	61.71		
		LT7	12		
		LT8	0.024		
		LT10	2.88		
		LT14	2.01		
		LT17	0.14		
		LT18	1.44		
		LT20	3.6		
		LT22	2.9		
		LT27	7.2		
		LT28	0.72		
		LT29	8.3		
		LT30	10.1		
		LT32	30.64		
		LT33	4		
		LT34	0.3		
WRC	1999	P11		259.2 (3L/s)	Pump test (10 hours; plus recovery test)
		P12		25.92 (0.3 L/s)	Pump test (18 hours, plus recovery test)
		P13		259.2 (3 L/s)	Pump test (18 hours plus step test: 52.6L/min, 84.5 L/min, 94.7 L/min
		P14		43.2 (0.5 L/s)	Pump test (21 hours plus step test 20L/min, 30 L/min, 40 L/min: plus recovery test.
		P15		259.2 (3 L/s)	Pump test (11 hours), plus recovery test
WRC	2000	TL31	43.2 (0.5 L/s)		
		TL32	43.2 (0.5 L/s)		
		TL33	129.6 (1.5 L/s)		
		TL34	43.2 (0.5 L/s)		
		TL35	8.64 (0.1 L/s)		

At the same time Watson (1978) was installing groundwater piezometers geologists from the Geological Survey of Western Australia (GSWA) were investigating the problem at the request of the Northern Arthur River Rehabilitation Committee (Furness, 1977). The work undertaken involved visual observations of lake substrate material for Toolibin, Taarblin, Dulbining and Footballer Lake (now known as Dulbining 3). Material was sampled using hand augering techniques at Toolbin, Taarblin and Footballer lakes. Analysis of samples showed salt concentrations to be highest at Taarblin, followed by Toolibin then Footballer lakes. It was noted that remnant vegetation that could root above the saline watertable was located on raised central gilgai mounds in Toolibin and a migrating central dune in Taarblin. Report recommendations included the acquisition of seismic data to appreciate the thickness of sediments beneath the lake, installation of additional piezometers to gain a better understanding of aquifer gradients and groundwater storages and commissioning an aquifer pump test to assess extracting and syphoning groundwater from Toolibin to Lake Taarblin.

From 1983 to 1985 the GSWA followed up recommendations made by Furness (1977) and carried out a drilling and pumping test program on the western margin of Toolibin Lake. The study was designed to assess the different aquifers beneath the lake by gaining a better understanding of “if, how and when” the aquifers connect with each other and the lake surface. Information on the bore construction details and results, including bore depths, screened intervals and salinity concentrations, are reported in Martin (1987). Groundwater contour maps were generated for discrete points in time (1978, 1982 and 1985). Results demonstrated that vertical (downward) groundwater gradients were dominant, local lateral gradients followed topography, moving from the topographically higher lake shoreline to the lake centre, with throughflow following the contemporary drainage direction, which is northeast to southwest, from Toolibin towards Walbyring and Lake Taarblin. The hydrogeology was noted to be complex and requiring a comprehensive drilling program to gain a greater understanding of gradients (Martin 1987).

Martin (1987) also reported that although groundwater levels had not reached the surface of the lake, aquifers within up gradient groundwater flow systems were continuing to fill in response to land clearing and the expectation was they would continue to rise, which could result in salinisation of the lake. Groundwater salinity measurements showed no obvious trends and averaged 18,000mg/L to 20,000mg/L TDS, with aquifers beneath Toolibin Lake showing highest salinities at around 60,000mg/L TDS (Martin, 1987). It was suggested that the higher salinity groundwater occurred at the watertable in shallow bores due to recharge water importing salts stores from the unsaturated zone that had been concentrated due to evapotranspiration.

The major conclusion of the work concurred with Furness (1977); that although high water use vegetation could lower groundwater levels, it would be contingent on mechanical pumping providing sufficient ‘freeboard’ (suitable unsaturated zone thickness) to allow the vegetation to become established. Questions that needed to be considered were the cost benefit of installing and operating an aquifer dewatering scheme and how successful revegetation efforts would be given the high salt soil storages.

During 1985 AgWA and CALM continued to supplement the shallow groundwater bore network, with the installation of the 85LTC monitoring series bores (Table 1) (Figure 2).

The GSWA recommenced work on the Toolibin Lake dewatering study in 1988 to 1989 following recommendations made in *The Status and Future of Toolibin Lake as a Wildlife Reserve* (Northern Arthur River Wetlands Rehabilitation Committee, 1987). The drilling and pumping program was designed to assess the effect of groundwater abstraction in lowering groundwater levels and as a consequence evaporation of near surface groundwater.

In this program a total of 39 bores were drilled as either prospective production or monitoring bores, with depth of drilling and bore construction ranging from 1.1 to 38 meters below ground level. Many sites drilled through low water yielding clay rich lithologies (e.g. dolerite, weathered mafic granite and migmatite) that didn't warrant the completion of a production bore. An exception was Bore 1/88 (now identified as P10) located on the western side of the lake, which was drilled to a depth of 35.5m and intersected higher, but still small, yielding sandy clays and clayey sands, likely to be derived from weathered felsic granites.

Martin (1990) includes some details on the aquifer testing of bore 1/88. The 1/88 aquifer test was carried out between the 28/06/1989-09/11/1989. Water levels were monitored fortnightly for the first month, and then reduced to monthly. The discharge rate ranged from 14.4-18.6m^3/day, with an average of 16m^3/day and an average groundwater salinity of 47,000mg/L TDS. Aquifer parameters calculated from the pump test produced a transmissivity of 4.92m^2/day, specific yield of 0.01 and hydraulic conductivity of 0.15m/day (Martin, 1990). Monitoring and test pumping results showed that groundwater levels only declined close to the production bore, within an approximate 30m radius.

Analysis of pump test data forecast that after 12mths of continuous pumping maximum drawdown would be 1.5m below ground level at a distance of around 35-40m from the production bore, with no drawdown at a distance of 650 metres. The 1.5 m below ground water level target on the western side of the lake, as set by the NARWRC, would require an additional eight production bores, with a further 16 required for the whole lake.

Martin (1990) proposed that due to the heterogeneity of the lithologies intersected during drilling that geophysical surveys should be carried out before designing the production bore field to ensure prospective higher yielding sediments suitable for pumping were mapped and targeted for drilling investigations.

2.2 1990-1999

This decade saw the expansion of the groundwater investigation and monitoring programs, including catchment scale drilling and the installation of pumping bores in Toolibin Lake. A groundwater pumping trial was commissioned at Toolibin Lake, with disposal via a pipeline to Lake Taarblin. The design of both the monitoring and groundwater abstraction programs were aided by modelled geophysical data acquired from airborne magnetic, radiometric and electromagnetic surveys (see Section 9). Monitoring bores installed during this time are shown in (Figure 4).

In 1992 CALM commissioned Gutteridge Haskins and Davey Pty Ltd (GHD 1992) to undertake a desk top study to evaluate the potential environmental impacts of diverting saline surface water and pumped groundwater from Toolibin Lake to Lake Taarblin. The study provided some preliminary estimates on the likely hydroperiod and salt balance changes to Lake Taarblin. Recommendations were made to monitor and collect data to verify the results. Additional data were collected and used in work undertaken by Actis Environmental Services in 2001 (see Section 10).

Recommendations put forward by Martin (1990) to increase dewatering in Toolibin Lake were inacted, with a drilling program commissioned to install six production bores and seven monitoring bores in the western and central part of Toolibin Lake. Prior to designing the drilling program, aeromagnetic data were acquired and interpreted to identify the distribution of magnetite in the basement rocks. Airborne magnetic data can assist groundwater investigations as areas with less magnetite tend to produce higher water yields relative to areas with high magnetite content (e.g. high magnetite is generally associated with mafic/dolerite dykes) (George 1992).

AgWA interpreted the aeromagnetic data and designed a drilling program and ensured that bores planned were located at a distance from high magnetic features that may represent low yielding aquifers and close to lower magnetic responses that may represent geological faults and higher groundwater yields (George and Bennett 1995). Two significant north-west and east-west trending dolerite dykes were identified in the dataset and these areas were avoided in the drilling plan. The orientation of the dykes were noted to cross cut the dominant north-south groundwater flow path, and as a consequence were thought to be restricting groundwater flow (George and Bennett 1995)

The 1995 drilling program installed bores to depths between 28 and 54 metres below ground level and noted variable formation water content and yields. Multiple screens were installed to maximise abstraction from the multiple aquifers observed while drilling. Bores were developed by airlifting for between two to four hours to estimate bore yields. Higher yields occurred in deeper bores (around 40m below ground level) installed in weathered bedrock aquifers. Six bores were thought to produce sufficient yields for production (95/01P (Pump 1), 95/02P (Pump 2), 95/03P (Pump 3), 95/04P (Pump 4), 95/07P (Pump 7) and 95/08P (Pump 8)) (Figure 5). A combined initial yield estimate of 344kL/day (estimated salt yield of 16t/day; 6,570t/yr) was proposed. Yields were likely to decrease by up to 50% once pumping rates stabilised and recommendations were made that a groundwater model be developed to simulate the aquifers and test the likely short and long term benefits of groundwater pumping (George and Bennett 1995). Nine production bores were commissioned in 1997 using Air-well pumping systems. Observation bores were installed in deep and shallow aquifers during this time to assess the spatial variability of groundwater drawdown.

The Water and Rivers Commission (WRC) and AgWA completed a drilling program to validate hydrogeological information in airborne electromagnetic data acquired through the National Airborne Geophysics Project (NAGP) (George 1998, Pracilio *et al.*, 1998). A total of 37 bores were installed and bore construction details, lithology data and drill core analysis results are reported in De Silva (1999).

An outcome of the NAGP work was the identification of a deeper zone of lower electrical conductivity on the eastern margin of Toolibin Lake. This feature was thought to be a sand sequence within a palaeochannel and therefore likely to have higher aquifer yields and represent a prospective groundwater pumping target. To test this idea a further five production bores (Pump 11-Pump 15) were installed in 1999 by WRC (Dogramaci 1999). Two of the five bores intersected palaeochannel sediments, production bores P11 and P15 were successfully installed in quartz sand dominated palaeochannel sediments. Production bore P13 was installed in weathered crystalline basement aquifers (Figure 6). Step tests were completed on P13, P14, recovery tests on P11 P13, P12, P14, P15 and short term continuous pump testing on P11, P12 P13, P14, P15. The results are tabulated in Table 2 and discussed in Dogramaci (1999).

In 1998 CALM completed a review of the recovery work undertaken at Toolibin Lake and reported that after twelve months of groundwater pumping that water levels in monitoring bores near Pump 10 that were previously near the surface were now greater than 2m below ground level (Smith and Wallace 1998).

During this period over 130 shallow piezometers (Figure 4) were installed as part of the Toolibin Alley Farming Trial (TAFT). The TAFT program was designed to assess the viability of alley farming, and how different vegetation densities could reduce groundwater levels. Noorduijn (2008) examined sparse groundwater data collected from the TAFT monitoring bores to determine the relative influence of revegetation and climate and concluded a decline in the groundwater levels was more likely to be attributed to decreased rainfall rather than the effect of the TAFT plantations.

2.3 2000-2013

This decade marked a decline in drilling investigations and monitoring bore installations and increased data interpretation and modelling phase (see Section 10). A number of factors influenced the decline in investigations. Fewer resources were available and lower average rainfall, particularly since 2005, reduced the frequency and extent of waterlogging and vegetation stress. As a result the 'visibility' of land and water salinisation declined and the sense of urgency to understand hydrological processes was relaxed. Monitoring bores installed between 2000 and 2013 are shown in Figure 7.

The Department of Environment and Conservation recommended the installation of 'fit for purpose' bores to monitor the effectiveness of the Toolibin Lake groundwater pumping. WRC completed seven bores in 2000 that were drilled to depths between 30 to 50m below ground level, with screens installed to monitor aquifers in the palaeochannel sediments and weathered granite (TL29-TL35) (Figure 7). The bore completion report for this drilling program includes information on bore construction, lithology, hydrogeology and groundwater salinity (Dogramaci 2000). A separate drilling program managed by DEC installed eight shallow observation bores, both within and on the margins of Toolibin Lake. No report was produced for the DEC drilling program.

In 2004-2005 a number of reports and papers were produced on the effectiveness of the Toolibin Lake groundwater abstraction program (George *et al.* 2004, Dogramaci *et al.* 2003). At this stage production bores P11, P13 and P15 had been pumped continuously for four years, while bores P1-P10 and P14 (installed in the weathered bedrock aquifer) had been operating for eight years. Reduced effectiveness due to poor water quality, in particular iron-reducing bacteria and subsequent corrosion was noted (Brown and Air Well Pumps Pty Ltd 2000). An average pumping volume was reported at 660kL/d, with an average salinity of 45,000mg/L TDS, with no comment on achieving pumping performance targets.

In 2009 thirty seven shallow monitoring bores were installed as part of the Cooperative Research Centre Future Farm Industry's (CRC FFI) BioRisk Project. Drill depths ranged from 2.8 to 9.6 metres below ground level and drill core was systematically sampled and regolith properties analysed, including particle size, moisture content, electrical conductivity and pH. The aim of this work was to establish relationships between vegetation condition, salt storage and waterlogging. A bore completion report summarises drilling and construction for a subset of these bores (Noorduijn 2009).

Solutions to control problems with iron-reducing bacteria and corrosion were researched in 2011 when a groundwater infrastructure condition assessment was undertaken (URS Pty Ltd 2011; CCA Industrial Pty. Ltd. 2011). Lake engineering infrastructure consisted of two transfer stations and eleven active and instrumented production bores; three bores with submersible pumps located in the palaeochannel on the southern and eastern margins of the lake, and to the west eight bores fitted with pneumatic pumps.

In 2012, the South West Catchment Council (SWCC) 'Return to Living Water Project' provided funding to DEC to install shallow monitoring bores to assess groundwater level change in response to vegetation in an area named Millers Block. Millers Block is located northeast of Toolibin Lake within the eastern tributary of the Toolibin Catchment. Salt storages and fluxes in this area are known to be high and details on bore construction, lithology and drill core properties analysed, including moisture content, electrical conductivity and pH are in a draft bore completion compiled by Smith and Lee (2012).

3 Surface Water Investigations

To manage a return of Toolibin Lake to a perched, ephemeral freshwater wetland system there is a need to understand the quantity and quality of surface water fluxes entering the lake. The TLNDRC Recovery Plan developed a water quality salt load threshold for Water Authority gauging station 609009 on the Northern Arthur River of 1,000 mg/L TDS (during the winter months when the lake is full) (Toolibin Lake Recovery Team and Toolibin Lake Technical Advisory Group 1994).

This section details the chronological investigations and results that led to the development of this criterion as well as continuing research to understand if it is achievable.

3.1 1977-1989

Surface water monitoring commenced in the TLNDRC in 1977 in order to fulfil objectives to understand and develop a lake water balance (Northern Arthur River Wetlands Rehabilitation Committee 1978).

An early study of rainfall and surface water flows suggested that the upper parts of the catchment may not produce runoff until a threshold of 30mm of rainfall is received (Northern Arthur River Wetlands Rehabilitation Committee 1978). To test this threshold a number of gauging stations were installed to measure ephemeral stream flow from tributaries of the Northern Arthur River into Toolibin Lake. Provision was also made to record lake water level measurements and this was done manually using depth boards.

Lakes with depth boards installed in the late 1970s and 1980s include Toolibin Lake, Lake Taarblin, Dulbining Lake and Walbyring Lake. Long term continuous surface water monitoring stations include Northern Arthur River (DoW gauging station 609010), at North West Creek, now Booloo Creek, (DoW gauging station 609013), and up gradient of Toolibin Lake (DoW gauging station 609009) (Figure 8). Rainfall data were collected at pluviograph monitoring stations 510254 (association with gauging station 609010) and 510253 (Froend and Storey 1996). Data collected for 609009 and 609010 commenced in 1977. Station 609010 is still operating, while gauging station 609009 ceased to operate in 2009 for three years before data collection recommenced in 2012 (Muirden and Coleman 2014). Gauging station 609013 operated from 1982-1984 before closing due to problems including poor quality of data, few flow measurements and site location (the site is prone to flooding) (Froend and Storey 1996). Data collection recommenced from 2012 to 2013 when weekly measurements were made (Muirden and Coleman 2014).

In the early 1980s the Water Authority of Western Australia) established five manual monitoring sites for surface water levels and water quality to assess relative surface water contributions from different sub catchment (Stations 6091024, 6091025, 6091026, 6091027, 6091028) (Stokes and Sheridan 1985) (Figure 8). Interpretation of data collected indicated the main surface water flows to Toolibin Lake were likely to be sourced from unregulated channels to the north of Toolibin Lake, (Northern Arthur River and North West Creek), with surface water flows into the lake being possible in seven out of ten years (Stokes and Martin 1986).

In 1987 a status report on Toolibin Lake produced by the NARWRC reported that between 1977 and 1984 the lake only received substantial inflows in two years (1981 and 1983) out of seven and that salt loads were variable, with winter flows delivering significantly higher salt loads. The report included water quality results from the lake and stream inflows, with stream flow salinities ranging from 100 to 8000mg/L TDS and lake surface water salinity increasing from 500mg/L to 6000mg/L TDS as the lake water evaporated. Little information on the sampling method and number of samples was provided. A graph of lake water quality against water volume suggested the relationship was derived from approximately six lake water samples (Northern Arthur River Wetlands Rehabilitation Committee 1987). It was recognised that lake surface water below the outflow was removed by either evapotranspiration or recharged groundwater. The process of evapotranspiration was noted to concentrate lake water solutes to salinity levels greater than 3000mg/L TDS when the lake water levels were at depths of around 1 metre. It was unknown if the food chain and bird breeding would be affected by salinities above 3000mg/L TDS.

Further monitoring was recommended to improve understanding of the variability in stream salt loads and the lake salt and water balance. As uncertainty existed regarding the health of the lake at salinities greater than 3000mg/L TDS, alternative methods to manage the lake water and salt balance were put forward. These management solutions included revegetation, pumping groundwater, controlling the volume of water within the lake and constructing a diversion channel to divert saline surface water and pumped groundwater (Casson and Atkins 1989).

3.2 1990-1999

The main focus of surface water work during this period was to investigate the potential benefits of proposed surface water control works and assess appropriate designs. Towards the end of this period the 1994 Toolibin Lake Recovery Plan was released, which included the criterion that “the quality of surface water entering the lake at gauging station 609010 should not exceed 1,000mg/L TDS” (Toolibin Lake Recovery Team and Toolibin Lake Technical Advisory Group 1994).

Harris and McIntosh (1990) proposed that prior to land clearing surface water flows were likely to have been less frequent and have lower salinities. However, periodic flooding and evaporation of surface water would have occurred due to the valley having a low variation in relief and drainage channels being braided and often poorly defined. A number of improved drainage options were presented to alleviate these problems, including a suggestion that low volume 'saline flows' should be kept in the chain of lakes north of Toolibin Lake; and larger, 'fresher flows' should continue on to Toolibin Lake (Harris and McIntosh 1990).

Recommendations for a more comprehensive surface water monitoring program to validate the relationship between surface flow and water quality were supported and implemented, and a drainage plan designed (Department of Conservation and Land Management and McIntosh 1990). Results from the 1990 surface water sampling program found that water quality was variable, with limited sampling suggesting there may be higher salinities in the first rainfall flush and lower salinities during flood events. A follow up study in the eastern catchment of the TLNDRC reported similar trends (McIntosh 1991). Sampling in both studies was carried out manually and not compared with data collected continuously from gauging stations.

In 1991 Negus was awarded a contract to develop a preliminary drainage design to drain waterlogged land in the *Toolibin Flats,* a semi-geomorphic term coined by McFarlane and others (1989). The design was intended to separate fresher surface flows from the north-west catchment from the more saline surface water flows sourced from the north-east (Negus 1991). This work drew on existing desk top studies (Greenbase Consulting 1991; Gutteridge Haskins and Davey Pty Ltd 1992).

Further drainage design was undertaken at Toolibin Lake, Toolibin Flats Drainage Options (Jim Davies and Associates 1994a) and Toolibin Lake, West Toolibin Flats Drainage (Jim Davies and Associates 1994b), where drainage options were assessed and a drainage design prepared. However, some uncertainty remained as to what effect these structures would have on Toolibin Lake due to a lack of data and as a consequence limited modelling. In 1995 two drains were constructed on north trending streams, these were named the eastern and western drains (Wallace and Toolibin Lake Recovery Team 1996). In 1999, DoW installed gauging stations to measure drain water levels and flows (609037 (East Drain) and 609038 (West drain)) (Figure 9). The drains were originally designed to convey 1 in 5 yr ARI events (Negus 1991), however the constructed drains convey 1 in 2 yr ARI events allowing overflow of the banks in 1 in 5 yr ARI, with a maximum velocity of 5.21 m^3/s (Jim Davies and Associates 1994a&b). The rationale behind the construction of the drains was to reduce groundwater recharge by removing surface water and decreasing the incidence and frequency of waterlogging in the Toolibin Flats, north of the Dulbinning Nature Reserve. This process would then allow perennial vegetation to become established and hopefully increase transpiration rates and as a consequence maintain lower groundwater levels.

The Toolibin Lake diversion 'separator' was conceptualised in the mid 1990s (George *et al.* 1996). The primary aim of the design was to divert early winter flows with higher salt loads with salinities over 1,000mg/L TDS away from Toolibin Lake (Jim Davies and Associates 1995). The drainage diversion was constructed in 1995 (Figure 9) and included an earthen waterway at the north of Toolibin Lake, a bund along the western edge of the lake and flow regulation and spillway structures. Regulation of surface water is from flood gates that are operated manually (e.g. inserting boards and allowing water into the Lake or opening the gate and diverting water south to Lake Taarblin). The system was designed to convey event flows of up to 6.0 m^3/sec upstream of North West Creek and 7.0 m^3/s downstream of North West Creek (Jim Davies and Associates 1995). The outflow control structure and outlet were numerically designed by Jim Davies and Associates (1999) was installed in Toolibin Lake in 2000 (Anonymous).

3.3 2000-2013

Surface water work during this period covered the installation and performance assessments of major engineering structures and continuing research on the controls of catchment and sub-catchment salt fluxes.

Unpublished surface water modelling results for the period 1979 to 1997 indicate the Toolibin Lake diversion channel and outlet could reduce lake salt loads by around 80% (8,000 tonnes), with 60% attributed to the channel and 20% to the outflow pipe (Dogramaci *et al.* 2003).

In the mid 2000's concerns were raised on detrimental effects produced by residual water in the lake following higher intensity incident rainfall and inflows. Seasonal waterlogging and the precipitation of salt on the ground surface was occurring in low lying areas within the lake. To address this problem a sump and pump design was proposed and constructed in 2009 (Mudgway 2009a). In 2009 a sump was excavated on the deepest part of the lake floor (at elevation of around 295.75 mAHD on the south western side of the lake) and a sump pump fitted to pump water into the diversion (Mudgway 2009a).

Between 2004 and 2011 the UWA Centre of Ecohydrology, included the former DAFWA Engineering Water Management Group, was involved in surface water data collection and interpretation. Surface water monitoring data are discussed in a number of reports and conference papers prepared by UWA Centre of Ecohydrology staff and students between 2006 and 2011 including Cattlin *et al.* (2004), Cattlin (2006), Callow *et al.* (2008), Barrett-Lennard (2008), Ovens et al (2010) and Callow *et al.* (2011).

Cattlin and others (2004) undertook an assessment with limited data and suggested understanding increased runoff in high intensity (72 hours), low to medium rainfall events (20-80 mm) could be important in managing the valley floor biological assets. The work also identified and documented spatial variability in streamflow salinity and potential issues associated existing drain discharge, in particular the eastern drain upgradient from the Dulbinning Reserve. A soil landscape map of relevance for low to medium rainfall-flow was developed and 17 management areas proposed. To validate these ideas an extensive network of continuous surface water data collection (depth and water quality) was recommended.

In 2006 Cattlin (2006) researched how the variable distribution of rainfall influences groundwater recharge and therefore salinity risk. The role of landscape slope and anthropogenic features (e.g. roads) were put forward as a major control on groundwater recharge, with areas of lower slope promoting higher residence time of surface water and hence groundwater recharge. The ideas presented were unverified as the work didn't complete a water balance or groundwater hydrograph analysis due to data being unfit for the purpose (e.g. insufficient robust and high frequency groundwater and surface water data). To address this issue, additional gauging stations were installed by the DAFWA-UWA Centre of Ecohydrology (Figure 10). Electrical conductivity (EC) probes were installed at 12 sites; ASWTLB01DEC, ASWTL03BRO001, 03TON, 05HAR, 10HAL, 11EDR, 12BRO, 13DUL006, 609038, 609037, 609010 and 609029. Stations were instrumented in 2004/05 but were not operational until 2007. Monitoring from these gauging stations was recorded in a number of reports (Callow *et al.* 2008; Ovens *et al.* 2010 and Callow *et al.* 2011). The Centre for Ecohydrology also installed soil moisture probes as part of an evaluation of the SALTWATCH program completed by the Department of Agriculture and Food (DAFWA) (Ovens *et al.* 2010).

A manual sampling program to verify salinity data acquired from continuous monitoring stations was carried out in July 2007, with results showing they were comparable and in agreement with observations made by Cattlin *et al.* (2004). Results from both datasets confirmed that water quality sampled from ephemeral streams at higher elevations had lower salinities. In contrast, valley floor streams were characterised by higher but variable salinities, possibly due to groundwater baseflow from seasonal aquifers (Callow *et al.* 2008). Callow and others (2008) discussed other trends including the gradual rise in salinity in the upper catchment and potential for episodic salt movement in the lower landscape producing cumulative salt load step trends. However, caveats were put on these conclusions given the limited temporal data, missing data parameters to convert salinities to salt loads and concerns about the quality of the available datasets (mainly due to limited adherence to best practice measurement techniques).

Callow (2008) put forward recommendations that relate to management targets from the 1994 Toolibin Lake NDRC Recovery Plan in addition to Ramsar monitoring commitments. These are;

- Continued monitoring of the stream gauging network to capture sufficient data (at least five to seven years) to quantify water and salt movement using standard methods and protocols complemented with event observations and sampling,
- Determine the environmental water requirements of Toolibin Lake including:
    - quantity of water required to inundate Toolibin Lake;
    - optimal hydroperiod of a lake-fill event for the biodiversity;
    - water quality range and removal threshold during a lake-fill event; and
    - required frequency of lake-fill events.
- The new drainage channel at Dulbining (Figure 10) should be monitored, using several gauging stations, to assess the movement of water through the valley-floor landscapes; and
- A research project should be developed to determine how spatially distributed recharge affects groundwater trends.

The Dulbinning channel was commissioned in 2008/09 in response to concerns raised by Cattlin *et al.* (2004) that the east drain was delivering high volumes of poor quality water into the Dulbinning Reserve. The channel construction was supported financially by the South West Catchments Council (SWCC). A 2009 hydrology review reported that although the channel was well designed and constructed, monitoring and assessment of the channel performance was necessary as the construction work was undertaken “in the absence of an overall surface water model from which to base the initial design and establish an indication of its impact” (URS Pty Ltd 2009).

The final UWA Centre of Ecohydrology report was produced in 2011 and reported on data collected in the expanded surface water program (Callow *et al.* 2011). The interpretation of data collected suggested the spatial patterns of water volumes and quality were complex and that disconnected flows were common. They reported that during the period of data collection, up gradient low salinity surface water flows didn’t reach Toolibin Lake. Interpretation of limited data from the Dulbinning channel suggested that the mean streamflow salinity had been reduced by approximately 20% and stream flow had increased. However Callow and others (2011) stated that further event monitoring of Dulbinning Channel was required to develop robust conclusions. In December 2011 surface water grab samples from the Dulbinning waterway showed high salinities (~6000 to 10000 mg/L) and concerns were raised that the waterway was moving low quality water from the Dulbinning Reserve into Dulbinning and potentially Toolibin Lakes (Farmer 2012). The waterway had changed the hydroperiod of Dulbinning Lake as the lake was now likely to fill under lower rainfall and surface water flow conditions, encouraging groundwater recharge and evaporation within the lake. Concern was raised that this may reduce the likelihood of fresh water inflows for Toolibin Lake and options to extend the waterway and bypass Dulbinning Lake should be explored.

DEC undertook a surface water monitoring review in 2014 to assess surface water data collected across the length of the program; 1977 to 2013 (Muirden and Coleman 2014). The main conclusion was that due to a lack of quality control procedures many of the time series data collected were not fit for purpose and couldn't be used to develop a robust understanding of sub catchment water and salt yields. Where there was confidence in data collected these were used to produce rainfall – salinity relationships (e.g. DoW station 609009) and discharge rating curves, both produced with limited data and requiring the collection of further robust data for validation. The report reviewed catchment boundaries using high resolution topographic data acquired using LiDAR and put forward a set of alternative surface water management areas. The LiDAR data were also used to produce bathymetry data for Toolibin and Dulbinning Lakes. Other conclusions generally concurred with Callow and others (2011). Recommendations include the need to undertake regular data audits, improve event monitoring and focus data collection and interpretation of flows into the following surface water bodies to assess the efficiency of engineering work (Figures 9 and 10);

- Toolibin Lake,
- Toolibin inflow channel,
- East drain,
- West drain and
- Dulbining Channel.

3.4 Surface Water Infrastructure

Toolibin Lake NDRC surface water monitoring sites and infrastructure programs are summarised in Table 3 Summary of surface water engineering infrastructure and monitoring station programs in the Toolibin Lake NDRC (shaded cells indicates information available)

3.

Table 3 Summary of surface water engineering infrastructure and monitoring station programs in the Toolibin Lake NDRC (shaded cells indicates information available)

Surface water program manager	Year	Engineering structures	Gauging Stations/ Gauge Board	Report/Reference	No. Sites	Site / Infrastructure Name/ID	See Figure No in this report
PWD	1977			(Froend and Storey 1996)	6	Gauging stations 609010, 609009, 609013; Depth gauges installed at Dulbining, Walbyring and Taarblin Lakes	8
CALM	1985			(Stokes and Sheridan 1985)	5	Monitoring sites for manual sampling: 6091024, 6091025, 6091026, 6091027, 6091028	
Alcoa	1990			(McIntosh 1991)	19	Monitoring sites for manual sampling: LT01-LT19	9
CALM	1995			(Jim Davies and Associates 1995)	0	Construction of the diversion channel, bund, spillway and separator gates at Toolibin Lake	
CALM	1995			(Jim Davies and Associates 1994a&b)	0	Construction of the east and west drains	
WRC	1999			No report located	3	DoW gauges 609037 (east drain) and 609038 (west drain), 609029	
DAFWA	2004-2005			(Callow, Pope *et al.* 2008)	23	Gauging Stations:10WDR 1 & 2, 11DOR001, 11WOG001, 11EDR 2 & 3, 03TIN 1 & 2, 05TIN001, 05WED001, 13DUL001, 2, 3, 3A, 4, 5, 6A, 7, 7A, 14TOT001, 03BRO002, 05TON1 & 2	10
DAFWA	2004-2006			(Callow, Pope *et al.* 2008)	19	EC loggers installed and/or gauging stations upgraded on previously established sites:(10HAL 1 & 2, 11TAB001, 11EDR 1 & 2, 03TON 1-5, 03BAK001, 05HAR 1, 2 & 3, 13DUL 6 & 8, 09WDR001, 11EDR001	
DEC	2007-2009			(URS Pty Ltd 2009, Ovens, Coles *et al.* 2010)	0	Construction of Dulbining channel	
DEC	2010			(Davies, Martens *et al.* 1999) (Jim Davies and Associates 1999, BG&E Consulting 2005)	0	Construction of sump and outflow at Toolibin Lake to pump saline water out of the lake	

4 Climate

Rainfall and evaporation are the major input and output water balance parameters in catchment scale semi-arid climate hydrological studies. Stream inflow is generally a more important water balance parameter for wetlands and lakes. However, under ephemeral conditions this is dependent on streams being able to deliver sufficient water to produce frequent and longer lived surface water bodies.

Hydrological reporting in the TLNDRC have included a basic discussion of likely average rainfall and evaporation values but frequently don't supply or reference information sources. It is likely that most studies have sourced reference data from Bureau of Meteorology (BoM) weather stations. BoM have 25 weather stations within 50km of the Toolibin Lake NDRC and the majority of these stations record rainfall only and not pan evaporation. Where reports reference climate data, the data tend to have been provided from the BoM Wickepin (010654) (rainfall only) and Corrigin (010536) (rainfall and pan evaporation) stations due to their proximity to the TLNDRC and their length of data collection record.

4.1 Rainfall

In Toolibin local rainfall data, within a 50km radius of Toolibin Lake, have been collected using pluviometers to assist in the calibration of streamflow measurements from data loggers. Of the 13 pluviometers installed, five were installed by DAFWA and eight by DoW (including pluviometer No. 510254 to assist in the calibration of DoW gauging station Northern Arthur River (609010)). Data from these stations are not often used in hydrological studies undertaken due to their reliability and relatively short data collection record.

Reports referenced as using climate data obtained from Bureau of Meteorology (BoM) Wickepin Station include groundwater assessment work undertaken by Martin (1990) and Sinclair Knight Merz Pty Ltd (2000). Data from the Corrigin BoM station were used by Noorduijn (2008) to determine the relative effects of reduced rainfall and revegetation on the water balance. Limited data collected from the DAFWA pluviometer network were interpreted in 2004 and 2006 and results reported a 50mm (around 10%) variation in annual rainfall across the TLNDRC (Cattlin et al 2004; Cattlin 2006).

4.2 Evaporation

Modelling results for Toolibin Lake estimated evaporation to account for almost 80% of the water balance outputs (Dogramaci *et al.* 2003). However, this is a modelled estimate and local measurements of pan evaporation or open water body evaporation (when Toolibin Lake has been inundated) have not been carried out. Where evaporation has been used in assessments, it has been taken from weather stations (e.g. Jones *et al.*, 2009). Data from the Lake Grace BoM station were used in the Lake Taarblin water and salt balance study undertaken by Actis Environmental Services (2001), while Noorduijn (2008) sourced pan evaporation data from DAFWA (Davenports weather station) and data from the Corrigin BoM station.

5 Water quality

5.1 Salinity

In the 1970's land salinsation was identified as a problem that needed to be managed in the TLNDRC. Work undertaken by Watson (1978) concluded that to manage salinity you needed to understand the different contributions of salt provided by both surface water and groundwater. In this report, Section 2.1 discusses groundwater quality work that followed Watson (1978), while Section 2.2 covers the surface water quality investigations. Results presented for both groundwater and surface water in these sections indicate the spatial patterns are complex and processes that underpin the fate and transport of salt are poorly understood.

Salinity monitoring for groundwater and surface water in the TLNDRC has generally been undertaken using electrical conductivity (EC) measurements as a surrogate and deriving a relationship between electrical conductivity and laboratory measurements of total soluble salts.

In the TLNDRC accurate groundwater EC measures can be obtained by airlifting groundwater at the time of drilling and completing bores. The aquifers in the TLNDRC are generally low yielding and difficult to sample and therefore require significant time to collect a sample that is representative of the target aquifer. Without a detailed standard operating procedure (SOP) data collected can be inaccurate and misleading. Due to these considerations the TLNDRC groundwater monitoring program doesn't include regular water quality data monitoring (Coleman and Wroe 2011). A groundwater audit of the TLNDRC bores by Mudgway *et al.* (2008) included groundwater EC and these data demonstrated a strong correlation with airborne electromagnetic data collected in 2007 to map aquifer water quality (George 1998, Rutherford *et al.* 2013). This is discussed in more detail in Section 9.

Monitoring surface water quality in semi-arid areas where the streams are ephemeral is difficult. In the TLNDRC there are few annual rainfall events that generate sufficient flow to warrant sampling (Muirden and Coleman 2014). Many investigations (see Section 2.2) have focused on the manual sampling from streams during higher rainfall events to assist in the calibration of continuous data collection at fixed sites, many of which have been operational for a few years. Cattlin *et al.* (2004), reported that the salinity of surface water flows varies according to the location in the catchment, with surface water in the upper catchment recording salinities of <700mg/L TDS, while in the valley flats it ranges from 3,000mg/L to 12,000mg/L TDS. Callow and others (2008) suggested that surface water salinities could be increasing in the valley floor due to seasonal groundwater baseflow (Callow *et al.* 2008). Other work has shown that high intensity summer rainfall events are more likely to produce lower salinity flows compared to winter (Callow *et al.* 2008; Muirden and Coleman 2014). Limited data indicate that salinity of the surface water in Toolibin Lake has increased from 900mg/L TDS when measurements first began, and now ranges from 1,800mg/L TDS (lake fill phase) to >10,000mg/L TDS (lake evaporation phase) (Dogramaci *et al.* 2003).

Due to the problems in collecting water quality data from representative aquifers and controlled surface water sites, there has been limited progress in understanding where salt has moved. As a result default generic conceptual models on salt mobility, available in numerical modelling packages, have been to simulate behaviour. This is discussed further in Section 9.

5.2 Nutrients

Froend and Storey (1996), reported that although there are no official reports there are historical anecdotes of algal blooms occurring in Toolibin Lake. A brief nutrient monitoring program reported the majority of phosphorous was organic rather than from anthropogenic sources (e.g. farming practices - fertiliser, animal waste) and was therefore not considered a threat to the biodiversity values (Froend and Storey 1996).

The likelihood of nutrient fluxes being a future problem in Toolibin Lake is low due to the ephemeral nature of surface water flows, the likely volume of surface water losses along drainage lines and the lack of intensive agriculture. Analysis of nutrients in groundwater is infrequent due to issues discussed in Section 5.

6 Vegetation Transpiration

Transpiration is potentially the largest water balance output parameter (user of water) but the success of vegetation in this role is dependent on the species, and the volume and quality of water available for use.

Vegetation water use in the Wheatbelt has been researched extensively over the past thirty years and results have demonstrated that native species that rely on fresh seasonal water have been less successful in surviving and adapting in waterlogged and salinity-prone low relief landscapes (e.g. Sharma 1984 & Cordon and Leytey 1992). Major remnant vegetation in the Wheatbelt generally occupy low lying valley floors and these landforms are susceptible to waterlogging and salinisation. Increases in water levels and waterlogging since the 1970s has reduced vegetation coverages in these areas and as a consequence the ability of vegetation to transpire available excess water has decreased.

Transpiration research in semi-arid areas tends to now be focused on mapping and measuring change in remaining native vegetation coverages, as well identifying suitable high water use salt tolerant species for revegetation efforts. In the TLNDRC the main aim was to increase vegetation coverage and transpiration rates through managing vegetation, groundwater, surface water, grazing and fire. To quantify the success of these actions, regular vegetation monitoring programs were established.

Transpiration in the TLNDRC has been based upon the collection of two independent measurements, the first is an implied quantity produced from the presence and condition of vegetation and the second is produced by a direct measurement.

The first baseline vegetation survey and map was completed for the Northern Arthur River Wetlands Rehabilitation Committee in 1977 (Mattiske 1978). This work established over twenty vegetation monitoring plots, mainly within Toolibin Lake, and mapped the condition of different plant communities. Over time more plots were established to the north of the lake to assess the impact of clearing and burning activities. Follow up terrestrial and lake vegetation surveys were completed by Mattiske Consulting in 1980, 1982, 1986, 1992, and 1999. Results confirmed that trees were still dying, with the majority of tree deaths occurring in flat, low-lying areas.

In 1983, Edith Cowan University undertook additional vegetation surveys and established four vegetation plots at Toolibin Lake to investigate the causes of lake bed tree mortality. These plots were re-surveyed in 1988 and results reported in Froend and Storey (1996) and Froend and others (1997). These plots are also monitored as part of the Salinity Action Plan Wetland Monitoring (Ecoscapes 2005). Broad scale mapping of vegetation is discussed in Section 5.

Transpiration studies were undertaken as part of the (2008-2014) Future Farms CRC BioRisk Project. In this study Drake *et al.* (2013) measured sap fluxes to determine transpiration during a local scale flooding simulation on Toolibin Lake. Measurements were made for two species *C. obesa* and *M. strobophylla* before, during and after the flood simulation. The investigation collected important data on quantitative water use for the two main species of vegetation on Toolibin Lake. Suggestions were put forward following the experiment, that the more rapid uptake of water by *C. obesa,* may mean the species has a shallower rooting depth compared to *M. strobophylla* and that this may have assisted its survival as water levels increased in the lake.

7 Land Surveying – landscapes and engineering

Western Australian Wheatbelt landscapes are characterised by low relief and a variable thickness of shallow sediment cover that is mobilised by gravity, wind and water. Variation in relief also influences soil development and as a consequence the vertical and lateral movement of surface water and groundwater, as well as the distribution of vegetation complexes (e.g. McFarlane et al 1989 & 2004). In the Wheatbelt erosion has slowed compared to millions of years ago when sedimentation of the valley floor was most active (e.g. George el al. 2008). This hiatus means that land surveying of most locations remains current for significant periods of time, and once a reliable high resolution dataset is acquired it can be used to undertake surface water and groundwater gradient assessments, site surface water and groundwater measurement infrastructure and undertake planning for engineering works to remove excess water.

7.1 Topographic Surfaces - Digital Elevation Models (DEMs) & Digital Terrain Models (DTMs)

In the TLNDRC a number of different airborne mapping technologies have been used to acquire broad scale high resolution topographic data, which has been used to produce digital elevation (land surface) and terrain (mixed land, vegetation and anthropogenic) models. In the TLNDRC the variation in the ground surface relief is low and vegetation and anthropogenic features are sparse and all three features are of interest for environmental management. This has created many challenges and questions on how to produce surfaces that accurately resolve ground, vegetation and anthropogenic features at optimal resolutions for mapping and modelling.

In 1997 aircraft altimeter data acquired during airborne geophysical investigations across the TLNDRC were used to produce a DTM. The data were required for the processing and interpretation of other geophysical data collected (see Section 6). The resultant DTM was produced at a 25m spatial resolution, however it was noted by Pracilio *et al.* (1998) that the surface lacked vertical accuracy, particularly in the western sub catchment.

One of the first DEMs produced for the south west of Western Australia was the Land Monitor DEM (colloquially known as the Wheatbelt DEM), which was produced at a 10 and 25 metre spatial resolution in the late 1980s (http://www.landmonitor.wa.gov.au/default.aspx?id=3). A major aim of the Land Monitor project was to produce a DEM with a vertical accuracy of 1-2m that could be used in vegetation and land salinisation assessments (McFarlane *et al.* 2004). It is likely that an up-scaled (lower spatial resolution) version of the Land Monitor DEM was used in TLNDRC numerical groundwater and surface water models developed in the late 1990's and 2000's, however the modelling reports don't disclose topographic information (e.g. Sinclair Knight Merz Pty Ltd 2000; Dogramaci *et al.* 2003).

Cattlin and others (2004) and Cattlin (2006) used the Land Monitor DEM to assess low slope areas that may cause waterlogging in relation to the location and efficiency of drains and natural surface water flow paths. Results using this approach were compared with information in soil-landscape maps produced using the same DEM (Schoknecht et al 2004). Fine scale ephemeral flow paths were noted to be difficult to resolve in the Land Monitor DEM and recommendations were made to acquire high resolution data.

A contract to acquire topographic data for the Toolibin Catchment, using Light detection and ranging data (LiDAR), was awarded to DiMAP in 2010 (Figure 11). The outputs from this contract were the delivery of raw point data (LiDAR cloud data) and a 10 metre gridded DEM produced from contours with an accuracy of ±0.25 metres. Artefacts were identified in the LiDAR data in 2011 so to provide confidence in using the outputs Farmer (2014) was contracted to complete an accuracy assessment. Results from this assessment reported the LiDAR dataset met a basic mapping standard (0.2-0.3m spot heights and 0.5m contours) but strip join issues and vertical inaccuracy prohibited its use in the resolution of subtle topographic features in the low relief valley floor. These problems were noted in a TLNDRC project involving two dimensional surface water flow modelling of the valley floor (Zanella-Coletti *et al.* 2015). For this project the LiDAR were not fit for purpose and were replaced by the Wheatbelt DEM, with the approximate 30 metre gridded Shuttle Radar Topography Mission (SRTM) 1 second DEM (http://www2.jpl.nasa.gov/srtm/) also trialled. Recently LiDAR data have been cleaned and edited to create bathymetric contours and 1 metre gridded surfaces for Toolibin Lake and the Dulbining Lakes (Muirden and Coleman 2014). However, these datasets need to be quality assured prior to use as a methodology or metadata that details how the LiDAR data were cleaned isn't available (Farmer 2014).

7.2 Ground Surveying

In the TLNDRC ground surveying work has been undertaken to provide quality control for digital elevation models (DEMs) and site water measurement infrastructure and engineering works. Monitoring bore standpipes and land surface elevations have also been surveyed for many bores to provide confidence in groundwater level measurements and produce accurate fine scale groundwater gradient maps (e.g. Martin 1990 and De Silva 1999).

Reports that detail only land survey data are rare and metadata and copies of the original data supplied is absent for many or most or archived datasets. Some land survey data are reported in surface water engineering reports, such as the design and performance of engineering structures in Toolibin Lake and the TLNDRC valley floor. In 2002, the DoW completed a survey of the diversion channel, separator, inlet, outlet and lake floor of Toolibin Lake (Table 4 Summary of ground surveying undertaken for engineering works in the Toolibin Lake NDRC

4**)**. Surveying of the Dulbining Channel occurred in 2006 and gauging stations installed and upgraded by the Centre of Ecohydrology were surveyed on installation (Callow *et al.* 2008). In 2010 ground surveys were carried out for the Toolibin Lake diversion structure and associated control points (Table 4).

A ground surveying project was commissioned by the DPaW in 2013 and included surveys of Toolibin Lake, Toolibin Sump, Toolibin Main Drain and Secondary drain, the invert-gate structure, diversion drain, North-West Channel, North-East Channel, South-East Creek, West Overflow, Booloo Creek (West Drain), Dulbinning Channel, Dulbinning Lake, Dulbinning Outlet, Dulbinning Inlet, East Drain, East Tributary, Millers north saline swamp in addition to a number of key roads and gauge boards (Table 4 Summary of ground surveying undertaken for engineering works in the Toolibin Lake NDRC

) (Figure 11). Details of these surveys are reported in Muirden and Coleman 2014.

Table 4 Summary of ground surveying undertaken for engineering works in the Toolibin Lake NDRC

Survey Program Custodian	Year	Contractor and report	Area surveyed	Report Figure No.
DoW	2002	DoW; no report located	Toolibin Lake inlet, outlet, separator diversion channel and data logger sites	
DEC	2006	DEC; no report located	Toolibin Diversion, Dulbinning Drain and Millers Block	
DEC	2007	UWA Centre for Ecohydrology: (Callow, *et al.* 2008)	Gauging station installation and upgrades	
DEC	2009	DEC; (Mudgway 2009a)	Dulbining Drain	**11**
DEC	2009	John Kinnear & Associates; (Mudgway 2009b&c)	Surveyed main waterway, North Toolibin Road culvert and East drain connections	
DEC	2010	P.H. and K.E. Gow; no report located	Toolibin lake bed, separator and control points	
DPaW	2013	P.H. and K.E. Gow; (Muirden and Coleman 2014)	Road cross sections , culverts and flood marks	

8 Remote Sensing – vegetation coverage and transpiration

The term remote sensing generally refers to using an electromagnetic method that employs high flying aircraft and satellites with various sensors to map features on the earth's surface, atmosphere and oceans. In hydrology, remote sensing data from satellites is commonly used to assess vegetation cover and condition and resolve the extent of surface water bodies in relation to their position in the landscape (e.g. McFarlane *et al.* 2004, Farmer 2014). For vegetation coverage an index of plant "greenness" or photosynthetic activity can be produced by using the data to calculate a normalised difference vegetation index (NDVI). This is a popular technique to detect live green plant canopies and calculate transpiration for input to numerical hydrological models (e.g.. Silberstein *et al.* 2009, Richardson *et al.* 2011 and Barnett 2012).

8.1 Aerial photography (panchromatic sensors)

In 2002 the Department of Agriculture acquired historical aerial photography for the TLNDRC to complete a catchment 'rapid assessment' that included assessing changes in vegetation coverage over the past forty years (Beeston and Metternicht 2002). Results were interrogated within a GIS framework, and unverified coarse scale statistics were reported and compared with the presence of different broadscale landscape features. Follow up work was undertaken using selected aerial photograph time sequences to examine both coarse and fine scale changes in vegetation related to landscape and anthropogenic associations (Cattlin *et al.* 2004) and (Cattlin 2006). This work included the spatial verification of current vegetation and anthropogenic features. Suggestions were put forward that areas of declining vegetation were due to surface water induced waterlogging.

8.2 Satellite (multispectral sensors)

Vegetation coverage and condition are routinely mapped for Department of Parks and Wildlife Estate using Landsat satellite data (e.g. Karfs *et al.* 2004). An in-house NDVI approach has been developed, termed "Veg Machine", and resultant vegetation maps are verified with follow up 'on-ground' observations at an appropriate scale (e.g. 30 metres for Landsat TM data).

Zdunic (2010) used Veg Machine to assess vegetation change in the TLNDRC and reported a general positive trend in normalised, relative vegetation cover between 1996 and 2009. Vogwill and others (2010) incorporated this spatial information to map vegetation decline and regeneration and assess links between hydrological management and vegetation condition.

8.3 Hyperspectral Surveys (hyperspectral sensors)

Hyperspectral sensors are frequently fixed to aircraft and map fine scale spectral characteristics due to having tens to hundreds of bands compared to more traditional satellite fixed multispectral sensors such as Landsat MSS or TM (Cocks *et al.* 1998).

In the 1990s CSIRO developed the hyperspectral HyMap™ system and in November 1998 it was used to acquire hyperspectral data over the Toolibin Lake and Toolibin Flats areas to assess the feasibility of routinely using this technology to monitoring vegetation. In 2000 World Geoscience Corporation Ltd. (WGC) tested a hyperspectral system Optical Airborne Research Spectrometer (OARS) over the Toolibin Lake and Toolibin Flats areas and results on soil mapping are reported in Street and Pracilio (2000). A repeat HyMap™ survey was flown in December 2006 and following an on-ground verification program Lau (2007) reported that different vegetation communities were mappable due to their different spectral properties, however the 3 metre spatial resolution did contain a mixture of vegetation, soil and cellulose. Features that were difficult to map and resolve change included narrow trial plots and trees with sparse canopy leaf structures (e.g. casuarinas).

In 2010 a contract was awarded to DiMap to acquire raw high resolution (0.75 metre) NEO-HySpex and LiDAR data. Following data acquisition CSIRO were contracted to assess the quality and information in the NEO-HySpex data and compare with data acquired by HyMap in 2006. CSIRO reported that their assessment was limited due to a high noise to signal ratio, an absence of metadata covering data acquisition and processing, and lack of on-ground data verification (Ong and Lau 2013).

9 Geophysical Investigations

Geophysical data are frequently acquired in hydrogeological studies to assess the physical properties of materials below the earth's surface and to map in three dimensions the different geological formations and their water storage, water quality and transmission properties. Geophysical method (e.g. seismic, radiometric, electrical, magnetic, electromagnetic or gravitational) and scale (borehole, ground and airborne) selection both need to be considered in planning a geophysical investigation.

Information on the likely physical properties of the underlying geology and how these properties vary spatially is critical in designing a successful geophysical study.

9.1 1980 - 1999

Geology in the TLNDRC has been mapped at 1:250 000 scale (Chin & GSWA 1986) and includes findings from a ground seismic refraction survey across Toolibin Lake (Kevi 1980). This work was undertaken to map the thickness of sediments and weathered basement beneath the lake, which was estimated to vary between 27-48m below ground level. Martin (1990) recommended that further geophysical data be acquired to gain a better understanding of the distribution of sediments (aquifers) to help target the location of production bores for dewatering the lake. This was followed in 1994 when Tesla10 were contracted to acquire both shallow ground electromagnetic data across Toolibin Lake and airborne magnetic data across the lake and nearby reserves (survey area ~25km^2). The latter survey to map low magnetite bearing regolith that was likely to represent higher aquifer yields (George and Bennett 1995). A geological fault was resolved on the western margin of the lake and targeted for the installation of pumping and monitoring bores; 95/01 – 95/11 (Tables 1 & 2 and Figure 4). High magnetite hosting mafic dykes were also resolved to the northeast and it was hypothesised that these features may slow groundwater movement towards the lake.

In 1997 the TLNDRC was selected as one of five Western Australia dryland salinity areas to trial recently developed airborne geophysical (electromagnetic) systems (George 1998). The airborne electromagnetic (AEM) data were part of a suite of geophysical data (electromagnetic, magnetic, gamma-ray spectrometric and topographic) being acquired to assist in dryland salinity management. This work was funded by the Commonwealth Department of Primary Industry and Energy (DPIE) as part of the National Dryland Salinity Program (NDSP). Contracts were awarded through the National Airborne Geophysics Program (NAGP) and World Geoscience Corporation Ltd. (WGC) was contracted to acquire geophysical data over the TLNDRC valley floor and eastern sub catchment. The Department of Agriculture funded a separate contract for WGC to collect magnetic, gamma-ray spectrometric and topography data across the TLNDRC western sub catchment. Pracilio and others (1998) reported on data collected under both contracts and discuss the development of the main interpretation products, TLNDRC water resource and salinity hazard maps.

Scientists from universities and state and commonwealth agencies were include in the assessment of information in the geophysical data acquired in the TLNDRC. The WRC and AgWA developed independent drilling and borehole geophysical logging programs to assess the performance of the SALTMAP AEM system to reliably map groundwater salinity and salt stored in the unsaturated zone (see Table 1). The programs included the sampling and analysis of drill core/chips for soil-water electrical conductivity and pH using the EC1:5 method (George 1998, De Silva 1999). Following drilling, monitoring bores were constructed and geophysical borehole logging carried out using gamma-ray spectrometric and induction conductivity tools. AgWA and WRC produced separate reports commenting on correlations between geophysical data and regolith EC1:5 measurements, using data from each agency as well as combined results (George 1998, De Silva 1999).

AgWA results reported by George (1998) summarised that SALTMAP data did not resolve electrical conductivity variation in near the surface (< 5 metres below ground level) but was successful in explaining the variance of salt-stored at 5-15 metres below ground level (~50 to 70%) and 15 metres below ground level to bedrock (~80 to 95%). Good correlations were produced with later-time (deeper) SALTMAP AEM data and groundwater electrical conductivity and it was noted that the data provided useful spatial information including mapping the presence of a palaeochannel in the Toolibin Flats and a series of small tributary alluvial systems in the eastern sub catchment. George (1998) commented that the airborne magnetic data collected and subsequent interpretations improved the geological understanding of the catchment but the airborne radiometric classifications required further work for use at a local scale. In addition, both the water resource target maps and salt hazard maps presented in Pracilio and others (1998) required verification using additional hydrogeological information, eg groundwater depth, rates of groundwater rise and aquifer type and yield.

De Silva (1999) reported WRC found that borehole electromagnetic data showed a good correlation (R^2 67%) with EC1:5 data confirming electromagnetics was a robust geophysical method to use to resolve salt stored in regolith materials. However these relationships didn't always translate to the SALTMAP data with correlations of WRC EC1:5 data with unsaturated and saturated zone conductivities producing correlations of 38% and 77% respectively. As the SALTMAP system produced satisfactory results for saturated materials it was deemed a useful tool to provide regional scale groundwater salinity estimates. Poor relationships were found to exist between depth to bedrock (data obtained from drilling) and SALTMAP regolith thickness models. This confirmed SALTMAP data would have limited application in the development of catchment salt balances, particularly as total salt storage and salt storage in the unsaturated zone were inaccurate.

9.2 2000 - 2013

In 2000 WGC tested a newly developed TEMPEST AEM system across Toolibin Lake and valley. The TEMPEST system improvements were designed to address the problems with the SALTMAP system documented by George (1998). In particular the greater bandwidth (25-37500 Hz) of the TEMPEST system provided better correlations with deeper (>20 meters below ground level) salt storage. This also allowed for the better definition of the palaeochannel on the eastern margin of the lake (Street and Pracilio 2000).

Although AEM systems had improved in their ability to resolve deeper electrical conductivity, the ability to resolve and quantify near surface electrical conductivity (<5 metres below ground level) remained a challenge. Based on this CALM engaged Geoforce in 2003 to acquire ground Geonics EM31 and Geonics EM38 data across Toolibin Lake to map ground electrical conductivity to depths of 4 metres below ground level (Campbell and Turner 2004). The aim of the work was to resolve changes in near surface salt storage by comparing these data with those collected in 1998 by Tesla10 (Tesla10 1998). Near surface conductivity increases were hypothesised to occur where capillary rise was active, whereas decreases were likely where groundwater pumping was effective.

Unfortunately due to a lack of supporting information for the Tesla10 ground survey (e.g. located data, processing notes, other metadata and reports) results could only be reported qualitatively. Possible decreases in salt storage were noted, but causation was unclear due to there being no correlation with groundwater pumping bores. Near surface salt (possibly due to capillary rise) was observed in open to lightly forested areas in the southern half of the lakebed. Recommendations from the survey were to manage data and information from these surveys to allow comparisons to be made in the future, undertake a comprehensive soil sampling program to understand the vertical and lateral changes in salt storage, and acquire borehole geophysical data (gamma-ray and induction conductivity) to derive associations between salt storage and low permeability regolith materials.

In 2007 GroundProbe (previously Geoforce) working with CSIRO, flew a test survey across Toolibin Lake and Toolibin Flats with SkyTEM a newly developed Danish AEM system. Modelled inverted data resolved the palaeochannel (Reid *et al.* 2007).

In 2007, to address the perceived short fall in borehole gamma-ray logging recommended by Campbell and Turner (2004), a logging program was carried out as part of a TLNDRC bore audit (Mudgway *et al.* 2008).

Rutherford and others (2013) undertook a further geophysical borehole logging program to compare with data collected in the TLNDRC in the late 1990s (George 1998). Induction conductivity (Geonics EM39) data were collected for Toolibin Lake and catchment bores, while borehole Nuclear Magnetic Resonance (NMR) were also acquired for suitable bores on Toolibin Lake using the Vista Clara Javelin tool (Walsh et al 2013). The NMR technology was used to directly measure total water content including total porosity in the saturated zone and moisture content in the unsaturated zone. The NMR data also provided estimates of relative pore-size distribution (bound versus mobile water content) and the hydraulic conductivity of the materials being logged outside the diameter of the bore.

Data from the different borehole induction conductivity surveys were compared with downhole gamma-ray logs and change identified and quantified to resolve zones where salt had moved within the time period 1997 to 2012. Where NMR borehole data were also available these zones were examined in relation to their hydraulic properties, such as vertical changes in bound and mobile water content as well as vertical hydraulic conductivity measurements. Changes were then assessed spatially, against a new inversion of SkyTEM AEM data (Viezzoli *et al.* 2013), to identify areas where lithological formations have preferentially held or released water and salts over the past 15 years.

The main findings of this study were that bedrock topography map derived from the newly inverted SkyTEM AEM data modelled an accurate basement-regolith boundary, which when interpreted with the NMR data provides a more accurate estimate of total aquifer water and salt storage. Lithologies identified as effective dewatering targets in the 1990s, such as the palaeochannel sands beneath Toolibin Lake, have higher yields but their ability to remove salt from shallow aquifers requires further assessment (Rutherford *et al.* 2013). Alternative dewatering targets at shallower depths were identified in the combined SkyTEM and borehole geophysics interpretation and recommendations put forward to develop a three dimensional conceptual model and then test a number of pumping scenarios within a numerical saturated flow model.

10 Hydrological water and salt balance assessments - Numerical Modelling

Numerical modelling is a useful tool to simulate physical processes and test data interpretations presented in conceptual models. Over the past 15 years numerous water and salt balance models have been developed for the TLNDRC. Many have been constructed with limited data and trialled to understand which water balance parameters might be managed to produce better outcomes for the biodiversity and Toolibin Lakes Ramsar status. Most models have been developed and used to understand the success of managing groundwater (dewatering Toolibin Lake and revegetation) or surface water (natural and anthropogenic structures). Some models have attempted to examine the dynamics of salt and link/cover the behaviour of both water and salt, with limited success.

10.1 Toolibin Lake Groundwater flow model (1998 – 2000)

A contract was awarded to Sinclair Knight Merz (SKM) in 1998 to develop a three dimensional, three layer numerical groundwater flow model for Toolibin Lake using the model platform MODFLOW(Sinclair Knight Merz Pty Ltd, 1998). In 2000 SKM were contracted to update the model with new hydrogeological data and information from the WRC and AgWA 1990s drilling programs and geophysical investigations. This included the geometry and parameterisation of the Tertiary palaeochannel sediments beneath Toolibin Lake, where aquifer parameters were provided by unpublished drilling notes compiled by AgWA and WRC (Sinclair Knight Merz Pty Ltd, 2000). Airwell pumps had been installed on the western margin of the lake since around 1996 and were operating at a combined well yield of around 200kL/day, while pumps in the eastern palaeochannel bores were installed in 1999 and were expected to provide higher yields. The 2000 numerical modelling study was undertaken to assess the drawdown for the combined west and east borefields under different hydrological conditions.

A number of modelling scenarios were undertaken to assess the veracity and sensitivity of the model. The calibration was reported as reasonable and the sensitivity analysis results indicated the model to be most sensitive to broad scale changes in pumping rates and hydraulic conductivity (both horizontal and vertical) and relatively insensitive to fine scale changes in hydraulic conductivity (Sinclair Knight Merz Pty Ltd, 2000). Results suggest that without pumping, groundwater would remain within 2 metres of the lake surface allowing saline groundwater to discharge via capillary action. An assessment of head response to pumping, with continuous and non-continuous pumping schemes (e.g. pumps off while the lake is full), were found to be similar. Following a lake-fill event water levels could be reduced to greater than 2m below ground level across 80% of the lake after pumping for 1000 days, non- continuous pumping inducing a time lag in the drawdown.

10.2 Lake Taarblin Salt and Water Balance Model (2001)

In 2001 Actis Environmental Services was contracted to assess using Lake Taarblin, a termination lake located downgradient from Toolibin Lake, as a groundwater disposal site for discharge water from Toolibin Lake (Actis Environmental Services, 2001). This assessment was required for submission to the Commissioner of Soil and Land Conservation and the Department of Environmental Protection Western Australia.

Lake Taarblin is a sink for water and salt moving from up-gradient areas and believed to only overflow infrequently (around every thirty years). Actis Environmental Services (2001) employed a generic discharge basin analytical model to assess the impacts of disposal. The model incorporated runoff estimates as well as all existing data compiled on Toolibin Lake discharge water volumes and salinities, evaporation (Lake Grace BoM station) and rainfall (Narrogin BoM station).

Results from the model indicate the volume of discharge water is unlikely to change the hydroperiod of Lake Taarblin, however there would be significant increases in the salinity and salt loads, with annual fluxes prior and post disposal of around 3,000 and 12,500 tonnes respectively. Before disposal Lake Taarblin had a high static salt store with the upper 2cm estimated at 10,000 tonnes. Disposal was planned for a localised area of less than 50ha, with the increases in salt load concentrated in the topographically lower lying area, judged to be an existing bare playa in the south margin of Lake Taarblin. Risk to significant plant species was also noted to be low as a vegetation survey found no significant plant species in the disposal area, and the species that were represented were noted to be found in other nearby localities.

An argument was proposed that without groundwater and surface water disposal from Toolibin Lake, the Lake would continue to increase in salinity, with salt moving through the intermediate wetlands to Lake Taarblin and rising groundwater and salt scalds possibly affecting surrounding farmland and reserves. Therefore it was recommended that discharge of saline groundwater from Toolibin Lake to Lake Taarblin be capped at a rate of 12,000 tonnes of salt and 350,000 KL per year and this would be permitted providing regular vegetation and water quality monitoring was undertaken at Lake Taarblin and alternative disposal strategies investigated. The pumping and disposal of groundwater in Lake Taarblin was proposed as a temporary solution. Pumping would continue until the vegetation became established and transpired sufficient groundwater to halt the groundwater level rising trends.

10.3 Toolibin Catchment – Flowtube modelling (2001)

George *et al.* (2001) examined a number of Wheatbelt catchments to assess changes in the catchment water balance that could be achieved by managing vegetation, in particular reductions in groundwater recharge through targeting revegetation with respect to species, landscapes and areal extent. The flow tube model is a two-dimensional cross sectional transient groundwater model which is constructed along groundwater flow lines from topographically high to low areas (e.g. catchment divide to valley floor). Flow tube modelling results for Toolibin Catchment indicated that the long term salinity risk could only be mitigated through significant reductions in recharge that could be obtained by large scale planting of deep-rooted perennial plants. It was noted that smaller areal extent plantings of tree belts (oil mallee) in non-saline areas could delay the expansion of shallow groundwater in lower landscape areas.

10.4 Toolibin Catchment Water Balance and Salinity Trend (2003)

In 2003 WRC and AgWA collaborated in analysing existing Toolibin Lake and catchment groundwater and surface water data and the writing of a joint report (Dogramaci *et al.* 2003). Data interpretation and reporting carried out can be grouped into three main sections of work, catchment hydrogeology and groundwater flow, Toolibin lake hydrology and catchment water balance.

The catchment hydrogeology section used regression analysis to assess groundwater trends for fourteen catchment bores located in different landscape and aquifer settings. This analysis was undertaken to assess variation in groundwater recharge, throughflow and anthropogenic effects such as groundwater pumping and the technique chosen was noted to be limited in interpreting shallow aquifer trends. Results indicated rates of groundwater rise are highest in the upper parts of the catchments (0.5m per year) and are similar in magnitude to lateral groundwater flow rates (0.1m to 1m per year). In these settings the thickness of the unsaturated zone (>20 metres thick) delays the visibility of the rising groundwater trends, with throughflow estimates also delaying discharge from the catchment divide to the valley floor for hundreds to thousands of years. Vertical flow dominates the lower landscape discharge areas, but as evaporation keeps pace with rates of rise there is generally little or no net change in groundwater levels. Evapotranspiration concentrates salts in the uppermost few metres in these areas creating a higher salt store in the root zone, which if mobilised could create large episodic salt flows. Watertable drawdown from pumping ranges from 5m below ground level where groundwater abstraction is from the confined palaeochannel aquifer, to 2m on the western side of the lake where the aquifer is unconfined.

The Toolibin hydrology discussion drew on limited available data to determine a relationship between stream flow and water quality (salinity and salt load) at station 609010, up gradient of Toolibin Lake. Descriptive statistics showed a large variation in flow rate and inflow salinity, with only the 10^{th} percentile of flow and salt loads suitable for inflow (<1000 mg/L TDS) into Toolibin Lake. Despite this the catchment was exporting lower salinity water than other headwater sub-catchments of the Blackwood Catchment, and as a result was classified by Bowman and Ruprecht (1999) as a relatively static catchment. Dogramaci and others (2003) suggested this was due to TLNDRC landscapes and soils encouraging salt mobilisation, detention and remobilisation processes as opposed to classical headwater catchments where uniformly ‘thin’ regolith and aquifers promote salt export through groundwater baseflow. This led to the hypothesis that catchment land salinization in response to early land clearing hasn’t yet been realised and salt storage in the valley flats is increasing as will salt loads in streamflow.

An analytical salt and water balance model was constructed for Toolibin Lake for the period Jan 1980 to Dec 2000 using manual lake level observations to verify the model (Peck, 2000). A good qualitative relationship was observed between graphed observations and modelled data for many inflow events, but problems were noted replicating lake recession with causation linked to characteristics of the outflow channel. A partial suite of modelling results were reported in Dogramaci *et al.* (2004), showing streamflow and rainfall to be the major inputs at around 84% and 16% respectively and the outputs represented by evaporation (65%) and outflow (lake outlet) at approximately 35%. Streamflow dominated the salt balance input at close to 100% and represented approximately 40% of the output, with evaporation being the greatest contributor to the salt balance at close to 60%. Loss of water to the lake floor and precipitation of salt due to evaporation of groundwater moving upwards through capillary action was considered negligible (less than 1% of the water or salt balance). Other important considerations for the water balance raised included the infrequency of stream flow, with events creating outflow in the lake only occurring in 10 percent of months during the 21 year simulation.

For the catchment water balance Mauger’s (1996) MAGIC model was used to simulate the distribution and increase of shallow aquifers under different land management conditions. This was carried out by modelling changes in groundwater recharge. Physical datasets to model rainfall-runoff (precipitation, surface water flow and landscape topography), evapotranspiration (pan and potential evaporation and vegetation leaf area index (LAI)) and change in both surface water and groundwater stores (surface water evaporation and groundwater recharge and regolith and soil moisture and hydraulic data) were incorporated into the MAGIC model. The model was verified by assessing its ability to simulate changes in seasonal soil moisture. Where model input data weren’t available for the TLNDRC, theoretical values or values from other studies in south Western Australia were used. Results from a number of management scenarios were compared with the major outcome reported to be similar to that reported by George *et al.* (2001) in that most of the catchment would need to be revegetated with perennial plants to effectively lower shallow water levels.

10.5 Toolibin Lake – water and salt balance (2004)

Bari (2004) employed the analytical lake spreadsheet model developed by Peck (2000) to remodel the hydrology of Toolibin Lake, this time incorporating a long term (1910-2000) data time-series of daily streamflow and salinity produced by the catchment numerical model LUCICAT (Bari and Smettem, 2003). The LUCICAT model has three main components, two-layer unsaturated zone module (upper and sub-surface unsaturated zone stores), a saturated subsurface groundwater module and a transient stream zone module. The LUCICAT model has terms to account for vegetation transpiration and modelled runoff, interflow and baseflow by considering soil and regolith moisture content and hydraulic parameters. Water losses to groundwater due to seepage in the lake were scrutinised within the lake model water balance by incorporating aquifer head and the lake-bed conductance. It is unclear if any local data were collected for model inputs to transpiration or soil and regolith moisture, storage or specific yields.

Partial results reported in Bari (2004) model lower stream inflows and salt loads into the lake compared to those reported in Dogramaci *et al.* (2003), with inflows over the same period reduced by approximately 8% and salt loads by 45%. It is unclear if the salt load reduction is an artefact of the model, due to salinity being capped at 30000 mg/L TDS to produce model numerical stability, or if the model is indicating natural inflow events to Toolibin Lake occurred under conditions that produce low salt load flows. Monthly lake salinity observations for two inflow events roughly follow modelled trends, with starting concentrations being similar. Other model observations include modelled streamflow for the 1950s- 1970s, which is high due to higher average rainfall, suggesting that the lake may have filled and overflowed more frequently during this period.

A partial suite of results for the lake water and salt balance were reported in Bari (2004) and they show similar input results to those reported in Dogramaci *et al.* (2003) with streamflow and rainfall the major inputs at around 83% and 17% respectively. Graphed outputs of lake observations and modelled lake levels also look similar, again showing difficulties in modelling the recession of the lake water body. The outputs represented by evaporation and outflow (lake outlet) at approximately 58% and 23%, with the remaining 20% attributed to lake seepage. Similar to Peck (2000) streamflow dominated the salt balance input at close to 100% but was modelled as representing only around 28% of the output, with evaporation the lowest contributor to the salt balance at around 11%. Major loss of salt, at approximately 61% was provided through deep drainage and export via groundwater flow. Bari (2004) tested the importance of lake seepage by excluding this term over the 90 year model run time and concluded that without leakage to groundwater the salinity of the lake would be 3-5 times higher than reported observations, thereby supporting the need for considerable leakage. This hypothesis contradicts the findings of Sinclair Knight Merz (2000) who modelled and reported a net contribution of groundwater and salt to the lake. To address these conflicting ideas Bari (2004) recommended that a modelling study of Toolibin Lake groundwater and surface water interactions be undertaken.

10.6 Toolibin Lake – statistical simulation Model (2009)

Jones and others (2009) developed a statistical water and salt balance model to assess the benefits and threats of changing the inflow salinity threshold at Toolibin Lake. The 1994 TLNDRC threshold of 1000 mg/L TDS for inflow was compromising bird breeding as it was limiting the frequency and extent of lake inundation. The hypothesis stated as being tested in this work was raising the inflow water quality limit to 5000 mg/L TDS would pose minimal risk to the lakebed vegetation.

A dynamic Monte Carlo simulation model based on a water and salt mass balance was developed to model the lake system and run for a maximum period of around 2yrs. The first order analyses included major parameter water and salt balance variables streamflow (water and salt), pan evaporation and rainfall. Parameter sensitivity analyses suggest the availability of habitat is most sensitive to pan evaporation, lower inflow volumes and higher than expected inflow salt concentrations. The second order analyses covered uncertainty and included a caveat to consider the results as relative rather than absolute, the magnitude of improvement being uncertain and requiring to be weighed against possible risks to the condition of the lakebed vegetation. Uncertainty depicted as a shaded zone on graphed results. Results indicated that the relaxation of the threshold to 5000 mg/L TDS would improve prospects for bird habitat, but this was based on limited local stream flow, pan evaporation and rainfall data. Further monitoring would be required to calibrate and validate the model and therefore provide confidence in model results. Given these modelling limitations the proposed hypothesis was unable to be satisfactorily tested.

The model wasn't designed to provide a quantitative water or salt balance as it was run for a short length of time and didn't attempt to model parameters assessed as important in Bari (2004) or acknowledge and discuss water and salt balance results in Dogramaci *et al.* (2003) or Bari (2004). The lack of consensus on the major salinity mechanisms contributing to salt stores within the lake was raised. It was noted that Dogramaci et al (2003) argue groundwater discharge within the lake as the major current and future cause while Cattlin *et al.* (2004) suggested saline inflows sourced from upgradient evaporated surface water was the main problem. The former process was not modelled in this study, indicating the authors had chosen Cattlin *et al.* (2004) as the preferred model. Further modelling was recommended to assist in identifying the major salinisation processes and the authors noted that success of this exercise would be contingent on the model set up explicitly to determine the key salt delivery systems.

10.7 Toolibin Lake unsaturated zone – Hydrus 1D modelling (2010 & 2012)

To improve understanding of groundwater recharge and discharge in Toolibin Lake two University of Western Australia (UWA) student projects were undertaken in 2010 (Taplin 2010 BSc Hons) and 2012 (Bartlett 2012 MSc – part dissertation) to determine the physical properties of the lake sediments and model the hydrodynamics and biological interaction. These projects used physical and chemical properties of drill chips collected by Noorduijn (2009) to derive hydraulic parameters and model unsaturated zone processes including rates of groundwater recharge and capillary rise. Vegetation data were provided by ancillary studies undertaken by Drake *et al.* (2013).

Taplin (2010) investigated unsaturated zone processes by analysing physical properties of regolith materials sampled from four, three metre deep cores extracted from two lake shoreline sites. Physical parameters derived from laboratory analyses were then used as inputs to a one-dimensional model (HYDRUS-1D) to model groundwater recharge. Model input parameters included existing groundwater level, rainfall and pan evaporation data. Model data derived from laboratory analyses and field measurements in this study include soil texture, porosity and moisture retention and vertical hydraulic conductivity.

Textural data from particle size analyses were variable. ROSETTA was used to estimate hydraulic conductivity values although it was noted this method was likely to provide an overestimate the parameter. To account for transpiration of the main species on the lake (*Casuarina obesa* and *Melaleuca strobophylla*) a relationship was developed between laboratory soil matric potential and optimum species matric potentials. HYDRUS-1D model boundary conditions were developed to best represent conditions on the western margin of the lake and this included limited lateral or vertical movement of groundwater into deeper aquifers (greater than 9 metres below ground level).

Modelling scenarios considered the current climate as well as drier and wetter conditions, with driest conditions obtained from 1944 records, which represented a dryer than average summer with no significant lake inflow events. Modelling included annual time steps for periods of 100, 500 and 1 000 years. Solute behaviour was not modelled independently to the soil water.

For a wetter climate incident rainfall was examined separately to lake inflows. Results show that an increase in average annual rainfall of between 350 and 550mm will produce some salt mobilisation in sediments one metre from the ground surface due to their higher vertical hydraulic conductivities. Water and salt movement slows in the lower permeability underlying clays. A 40 day lake inflow simulation was carried out to assess lake seepage and groundwater recharge. The results of the modelling indicated that 34 days (at greater than 10cm lake water depth) was the optimal hydroperiod for surface water to remain in the lake prior to aquifers filling and groundwater intersecting the land surface. Salt leaching was relatively insensitive to changes in the height of the water body (lake level).

Modelling current conditions showed that the optimal soil water-groundwater storage recovery time between a winter and summer inflow event was around six months, the lengthy period a reflection of the higher pre-inundation groundwater levels as well as the high water retention and low vertical hydraulic conductivity of the clay sediments. Finally a scenario to test salt flushing was carried out, with the lower groundwater model boundary changed to allow free drainage. Results showed that salts could move vertically to depths greater than one metre in a 100-350 day lake inundation, provided an average infiltration velocity of 0.48 cm per day could be maintained and groundwater levels remain below the root zone. Lags in rates of water and salt movement were noted to occur in sediments with high percentages of clay-sized material. Modelling results for vegetation show a greater gain in groundwater level reductions for deeper rooting species, the limiting factor being the need to flush stored salts to improve water quality for the vegetation to establish and survive. The flushing process was noted as needing to outpace the reestablishment of salt stores due to continued transpiration.

Results indicate the current system is characterised by low soil moisture and salt leaching, both of which are detrimental for vegetation health. Managed flushing is suggested as necessary to move the stored salts deeper into the profile, but the success of this action would be dependent on minimising both the evaporation of surface water and groundwater level rises during and after inundation.

Limitations of the model selection focus mainly on the fact that HYDRUS 1D is not a spatially distributed model and therefore processes that require spatial discretisation to accurately simulate their behaviour are not considered.

Bartlett (2012) undertook a theoretic study of using HYDRUS 1D to model the movement in salt in four different soil types that might exist on Toolibin Lake, including a clay soil where data were sourced from Taplin (2010). The four scenarios undertaken were, root zone salt accumulation, salt flushing, salt rebound (flushing versus continued transpiration) and salt diffusion. All scenarios, apart from salt diffusion, were carried out by Taplin (2010) and outcomes reported were similar. For salt diffusion the results indicate that the upwards movement of salt by diffusion is negligible compared to salt storage increases through transpiration. Similar to Taplin (2010), evaporation and transpiration data used as inputs to the model (Table 2 Bartlett 2012) exceed the commonly accepted values of 70 to 120% of rainfall, instead evaporation for averaging at 50% of rainfall and transpiration at over 400% of rainfall (a total of 450% of rainfall). Drake *et al.* (2013) reports low pre flooding transpiration values of around 35% of rainfall (0.15 to 0.5mm per day) using sap flow data collected from three vegetation plots. Transpiration was noted to increase by 3-4 fold during inundation, however these transpiration rates can't be sustained by *Melaleuca strobophylla* when the root zone becomes saturated. Without clarification on the origin and validity of the transpiration and evaporation data used in this study the results and conclusions should be treated with caution. Limitations with the approach and model suitability are the same as discussed above for Taplin (2010).

10.8 Toolibin Lake – pump condition assessment (2012)

In 2011 URS were contracted to undertake a condition assessment of the Toolibin Lake pumping infrastructure. URS updated the Sinclair Knight Merz (2000) model into the latest MODFLOWsoftware, Visual MODFLOW(2009), and simulated a number of pumping scenarios to estimate pumping rates and location of additional bores required to achieve a water level drawdown of around eight meters beneath the lake. No changes were made to the aquifer geometries or parameterisation.

The scenarios undertaken in the modelling all included continuous pumping for 3.5 years without surface water inundation. Results showed that if pumped to capacity (approximately 666 kL/d) the existing system can achieve two metres drawdown across 50% of the lake in 3.5 years. To increase the existing pumping capacity it was assumed that additional dewatering bores could be drilled into the paleochannel and produce yields close to those of Pump11 at 250 kL/d. In the southwestern area of the lake the assumption was made that aquifers could support lower yielding bores at 25 kL/d, similar to the average yields of the existing Airwell pumps. Based on these assumptions installing an additional nine bores, with five located in the palaeochannel, would increase capacity to around 2000 kL/d, which may reduce water levels across 87% of the lake to at least eight metres below the ground surface.

10.9 Biorisk Decision Support System (DSS) - 2015

This work was undertaken by the University of Western Australia as part of the CRC Future Farm Industry BioRisk Program. The main aim was to develop hydrological numerical models to assist in the management of wetlands. For Toolibin Lake this included optimising hydrological conditions for wetland vegetation health, operating the surface water diversion and groundwater pumping systems as well as identifying suitable revegetation sites and species.

The work included a high level discussion on the conceptualisation of the catchment and Toolibin Lake hydrology to support the numerical model selection. The numerical model framework included a wetland water and energy balance 'bucket style' model with streamflow and salinity fluxes produced by quasi three dimensional valley floor and uplands models. Models were not directly coupled and the approach was described as parsimonious, although the combined models have around 100 parameters that needed to be measured or estimated in order to construct and run the models. Report appendices describe most of the empiricism underpinning the main models and the content of the report tabulates the derivation of the main parameters of interest.

Rainfall-runoff modelling was undertaken using LASCAM (LArge Scale Catchment Model) (Sivapalan el al. 2002). Three sub-models were developed to model water movement in the main zones, LASCAM-S models the "shedding" landscape in the upland region and was divided into 31 sub-catchment model domains. LASCAM-R the "receiving" landscape represented by the valley floor region was divided into three modelling domains and LASCAM-Q, which is included to convey surface water between sub-catchments and account for in transit spatio-temporal gains and losses of water. Two dimensional valley floor surface water flow simulations using TUFLOW were used to parameterise LASCAM-Q. Toolibin Lake was modelled using WET0D, a lumped parameter radial flow model, which provides an average response of the lake.

The WET-0D model was developed to model both inundated and ephemeral conditions in Toolibin Lake and included numerical constraints for modelling both conditions. Parameterisation was mainly sourced from Taplin (2010), Drake *et al.* (2013) as well as theoretical values and results from other research to extend the previous work to include a detailed quantitative energy/carbon balance. The maximum vertical hydraulic conductivity calculated by Taplin (2010) was used as WET-0D became numerically unstable with less water moving through the lake substrate (R. Vogwill pers comm). This had a consequential effect to the parameterisation of horizontal hydraulic conductivities, which were also elevated.

The WET-0D modelled lake inflows appear to show an improved correlation against lake water depth observations, when compared with modelling presented in Dogramaci *et al.* (2003) and Bari (2004). However, the WET-0D modelling didn't extend past 2005, before the effects of drier climate; lower rainfall-runoff, became apparent. Similarly the carbon growth model reports a decline in the biomass in the late 1980s early 1990s and a recovery into the 2000s but as the modelling ceased in 2005 the predicted biomass under the last ten years of a drying climate has not been simulated.

It was noted the calibration of the models was complicated by the lack of robust data to verify the model results. For surface water flows and lake water levels this was partly due to the transition to a drier climate characterised by lower frequency and duration of surface water flows and lake inundation events.

A water and salt balance wasn't developed. The authors suggest the models could be used to investigate other questions relating to the influence of the catchment water balance on Toolibin

Lake ecohydrology. Although questions posed would need to be cognisant of the reported limitations of the Biorisk DSS model which are an inability to:

- resolve and simulate local scale water and salt balances,
- assess absolute changes,
- model evapotranspiration as an independent parameter,
- simulate a pressure response from semi-confined aquifers,
- model individual pumping bores installed on Toolibin Lake,
- model known lateral and vertical Toolibin Lake substrate heterogeneity (e.g. porosity, specific yield and hydraulic conductivity),
- model the unsaturated zone and
- model discrete or anisotropy in aquifer drawdown.

Concluding comments advise caution when applying the results absolutely and recommend the following work is undertaken;

1. Develop a fully distributed groundwater model to understand hydrodynamics in the deeper aquifer system, assess the effectiveness of groundwater abstraction and develop a groundwater level criteria to operating the diversion gate. A caveat to this modelling approach is that it will not simulate near surface unsaturated and ecohydrological processes at the fine scale time steps required and therefore may not provide useful water, salt and energy/carbon balances,
2. Develop a suite of hydrological management actions to increase plant available water in Toolibin Lake. Under a dry climate the current hydrological management of the lake doesn't provide surplus water to support broadscale revegetation efforts. It is likely that the system will not support morevegetation than that which will naturally co-evolve,
3. Study of the hydraulics of Toolibin Lake gate and lake entrance, using a two dimensional surface water flow model,
4. Continue research into the development of suitable models to simulate WA Wheatbelt surface water – groundwater – ecophysiology interactions and
5. Develop smaller local scale models to assess the water and salt balance benefits of 'paddock-scale' revegetation trials.

11 Discussion

Research into groundwater and surface water hydrology in the Toolibin Lake NDRC has broadened the understanding of the how and when ephemeral wetlands in the Western Australian Wheatbelt adapt to changes in the water and salt balance. Research over the past forty years was aimed at understanding changes and threats at both fine and coarse scales, with results being transferrable to similar hydrological settings. Projects were developed using a whole of government approach, with the development of multidisciplinary teams drawing on expertise in hydrology sub-disciplines available within State and Commonwealth Agencies.

Difficult research challenges have included the management and integration of data, combining data and results from previous hydrology projects, adapting monitoring programs to compliment climate trends, designing appropriate scaled (spatial and temporal) investigations and modelling programs, assessing when and where new technologies should be employed and understanding the level of complexity to research and report.

The studies undertaken to date are of national and international importance being recognised and awarded (e.g. Institute of Engineers (Australia) 2002 National Salinity Prize in recognition of the integrated approach to salinity management and strong community support).

11.1 Research highlights – 1977 to 2003

Research within the period 1977 to 2003 spanned both the wet and dry climate cycles. The threat of salinisation due to rising groundwater and saline surface water inflows into Toolibin Lake were the major focus. This required knowledge of the degree of saturation of different aquifers and how quickly this water and entrained salt would move to the ground surface and to the root zones of plants. The water and salt delivered by seasonal surface water flows was also critical, as average rainfall and stream flow frequencies during this period were high, resulting in more surface water reaching the lake.

Main research topics investigated at this time were;

1. The vegetation water use and lag times associated with a response to water and solute stress,
2. The mobilisation and redistribution of water and salt from the uplands to the valley floor,
3. The origin of salt stores and contemporary processes contributing to the storage of salt in unsaturated and saturated materials in the lake and catchment, and
4. The variability of aquifer specific yields and water and salt storages in the catchment and beneath the lake.

During 1977 to 2003 progress was made on research topics 2 through to 4, with advancement in quantifying water and salt balance parameters for Toolibin Lake and the catchment. Work to improve understanding on these included the calculation of Toolibin Lake aquifer yields, storages and hydraulic conductivity. Catchment groundwater fluxes were estimated and the majority of surface water and evapotranspiration data were obtained from theoretical values sourced from published literature. Data acquired to map the three dimensional geometry of the aquifers and their variable water quality storages were found to fall short in providing information for the full profile. Assessments tended to use partial datasets and discuss trends separately rather than integrate information from different hydrology sub-disciplines (e.g. groundwater and surface water).

Despite these limitations there remained sufficient data and information to develop a simple numerical groundwater flow model for Toolibin Lake that could test the effectiveness of groundwater abstraction. This numerical model was iterated to simulate more complex hydrogeology (e.g. the presence of a palaeochannel aquifer) when new data were acquired. However, a quantitative conceptual model was not developed during this period. Groundwater and surface water infrastructure was emplaced for the acquisition of data suitable to progress the main research topics and develop a quantitative conceptual model at a future date.

Concern was raised on the effects of a reduction in average annual rainfall, which had become more apparent in the mid-2000s with waterlogging and the precipitation of salts at the land surface being less prevalent. Reporting in 2003 had forecast that a drier climate would change stream flow regimes and observed that rates of groundwater level rises were likely to decrease. Although these changes occurred, groundwater levels in low lying areas remained high and the precipitation and accumulation of salt continued at shallow depths rather than at the ground surface. As a result threats to vegetation health and salinity levels in Toolibin Lake have not abated under the lower average rainfall conditions.

11.2 Research highlights – 2004 to 2015

Research from 2004 moved away from groundwater research. Efforts were directed to the first two research topics in Section 11.1; the roles of surface water, vegetation and the unsaturated zone in storing and moving water and salt. This work was essential in assessing if salt could be flushing in the lake.

Progress on understanding surface water fluxes in this period were hampered by reductions in average rainfall producing fewer measureable seasonal flows. Event flows from summer storms remained a credible threat and infrastructure and resources were invested to capture this information. Due to these challenges the quality of data collected is variable, which resulted in numerical models remaining reliant on theoretical values based upon estimates and published literature.

A drier climate combined with engineering structures regulating surface water inflows had reduced the frequency and duration of surface water within Toolibin Lake. To understand if this was influencing changes in near surface processes (e.g how vegetation and the unsaturated zone stores water and salt) a controlled flood event experiment in Toolibin Lake was undertaken, with responses measured and numerically modelled. Transpiration rates were calculated for the major species on the lake under flood and dry conditions. Prior to flooding, shallow lake substrate cores were extracted and regolith materials analysed to understand the variability in their physico-chemical properties. Numerical models were employed to analyse the soil and vegetation data but were challenged by the heterogeneity of the regolith analyses.

Some existing hydrological data were interpreted and a qualitative, rather than quantitative, conceptual hydrological model was produced. A suite of numerical models were then developed to assist in making water and salt balance management decisions (e.g.. pumping groundwater, revegetation strategies and operating the Toolibin Lake surface water diversion gate and sump pump). Lumped parameter models were chosen for the numerical modelling to remove problems with heterogeneity in the physical system. Most models had a surface water-unsaturated zone focus and limited data for calibration or verification. Uncertainty in modelling results was reported as high, but as a quantitative conceptual model was not developed prior to modelling it is unclear if this is the result of poor data, using part datasets and/or poor numerical model selection.

11.3 Knowledge gaps

Knowledge gaps that hamper progress on verifying criteria put forward for the 1994 recovery plan criteria (see Section 1) include:

- A lack of understanding what groundwater level beneath Toolibin Lake represents an appropriate depth measure to protect the lake bed from threats of rising groundwater and long lived lake inundation events,
- Identifying a maximum, or range, of lake water salinity to satisfy lake vegetation tolerances, composition and structure, as well as the lake salt balance,
- Measuring and mapping catchment surface and groundwater processes responsible for changing surface water and salt fluxes into Toolibin Lake and
- Determining an optimal hydroperiod for Toolibin Lake, under wet and dry climate regimes, to sustain vegetation composition, structure and biomass.

The knowledge gaps reflect the absence of a reliable quantitative hydrological conceptual model (e.g. questions remain on how water and salt is stored and how it moves under different seasonal and longer term climatic conditions).

The broad nature of the TLNDRC hydrological research questions, or topics, has allowed researchers to develop projects and collect hydrological data to understand different water and salt balance parameters. Sufficient hydrological data and information has been collected over the past forty years to address these outstanding knowledge gaps.

To realise the value in these datasets they need to be quality assured and managed with the Department of Parks and Wildlife having put considerable effort into this work over the past five years. Following this work the next step is to interpret and integrate all available data to produce a quantitative hydrological conceptual model. This will achieve two things – recognition of the full value of the work done in the TLNDRC over the past few decades, and the development of a functional generic model that can used to manage Toolibin Lake and its catchment, as well as similar hydrological settings in the WA Wheatbelt.

12 References

Actis Environmental Services (2001). Evaluation of Saline Discharge to Lake Taarblin within the Context of Toolibin Lake Recovery Plan, Groundwater Pumping and Drainage Proposals Mundijong, Western Australia.

Agriculture Western Australia, Department of Conservation and Land Management, Department of Environmental Protection and Water and Rivers Commission (1996). Western Australian Salinity Action Plan. Westen Australia.

Anonymous Toolibin Lake Technical Note, Lake Outflow Control Structure. Unpublished, Department of Environment and Conservation.

Bari, M. A. (2004). Surface water modelling and salt balance of Toolibin Lake, Western Australia. National Salinity Engineering Conference W. A. Dogramaci S. S. Burswood International Resort, Perth, Western Australia, Institution of Engineers, Australia.

Bari, M. A. and Smettem A. J. (2003). Development of a salt and water balance model for a partially cleared catchment, Australian Journal of Water Resources, Institution of Engineers, Australia, 93-99.

Barnett et al, 2012, Australian groundwater modelling guidelines, Waterlines report, NationalWater Commission, Canberra.

Barrett-Lennard, A. (2008). Surface Water Ponding on Low-Lying Valley Floors in South-West Western Australia: Interactions with Groundwater and its Role in Secondary Dryland Salinity, Dissertation thesis, 83 pp, The University of Western Australia, Crawley, Australia

Bartlett, M. (2012). Water and Salt Dynamics in Arid Zone soils Using HYDRUS-1D, 34 pp, The University of Western Australia, Perth, Australia.

Beeston, G R, and Metternicht, G. (2002), Assessing chronological changes in remnant native forest at catchment level : a case study on the Toolibin catchment area. *Dep*artment of Agriculture and Food, Western Australia. Report 248.

BG & E Consulting (2005). Toolibin Lake Separator Gates Repair/Replacement Options. Perth, Western Australia.

Bowman, S., and Ruprecht, J.K., (1999). Blackwood River catchment flood risk study, Surface water hydrology report series, SWH 29, Water and Rivers Commission.

Brown, A. and Air Well Pumps Pty Ltd (2000). Salinity Control Using Air Displacement Pumps at Toolibin Lake. Malaga, Western Australia.

Callow, N., T. Pope and N. Coles (2008). Surface Water Flow Redistribution Process: Toolibin Lake Natural Diversity Recovery Catchment, ARWA Centre for Ecohydrology.

Callow, N., T. Pope and N. Coles (2011). Toolibin Lake Natural Diversity Recovery Catchment, Surface Water Flow Monitoring 2007-2010 FINAL REPORT, Centre for Excellence in Ecohydrology, Department of Environment and Conservation.

Campbell, T. and G. Turner (2004). Electromagnetic Ground Survey of Toolibin Lake. Malaga, Western Australia, Geoforce.

Cardon, G.E. and Letey, J. (1992). Soil-based irrigation and salinity management model:I. Plant water uptake calculations. Soil Science Society of America Journal 56:1881-1887

Casson, N. and K. Atkins (1989). Toolibin Lake and reserves: interim management guidelines. Narrogin, Western Australia, Department of Conservation and Land Management.

Cattlin, T. (2006). The Impact of Redistirbuted Surface Water and Spatially Distributed Recharge on Water Quality decline in the Toolibin Lake Catchment: a modelled approach to process management. Masters of Science Masters, University of Technology, Sydney.

Cattlin, T., D. Farmer, N. Coles and D. Stanton (2004). Surface Water Assessment for the Toolibin Lake Recovery Catchment, Engineering Water Management Group, Department of Agriculture Western Australia.

Chin, R. J.& Geological Survey of Western Australia. (1986). *Corrigin, Western Australia : sheet SI 50-3 International index*. Perth, W.A : Geological Survey of Western Australia

CCA Industrial Pty. Ltd. (2011). Asset Condition Assessment of: Groundwater Pumping System at Toolibin Lake Natural Diversity Recovery Catchment (TLNDRC). Subiaco, Western Australia.

Cocks, T., Jenssen, R., Stewart, A., Wilson I. & Shields T. (1998). The HyMap™ airborne hyperspectral sensor the system, calibration and performance. Presented at 1st EARSEL Workshop on Imaging Spectroscopy, Zurich, October 1998

Coleman, B. and R. Wroe (2011). Groundwater Data Review Toolibin Lake Natural Diversity Recovery Catchment, Department of Environment and Conservation, Natural Resources Branch.

Davies, J., Martens S. and Panasiewicz R. (1999). Toolibin Lake Evaluation and Design of Outflow Control Works. Subiaco, Western Australia.

De Silva, J. (1999). Evaluation of Airborne Geophysics for Investigation Land and Water Salinisation in the Toolibin Catchment. Perth, Western Australia, Water and Rivers Commisions.

De Silva, J. (1999). Toolibin Catchment Airborne Geophysics Bore Completion Report, Water and Rivers Commission.

Department of Conservation and Land Management and K. McIntosh (1990). Toolibin Lake catchment stream monitoring programme 1990 winter. Booragoon, Alcoa.

Department of Parks and Wildlife (2014). Information Sheet on Ramsar Wetlands (RIS) - 2009-2012 version, Lake Toolibin (also known as Toolibin Lake), Western Australia.

Dogramaci, S. (1999). Toolibin Lake Drilling Program - Bore Completion Report and Pumping Test Data. Hydrogeology Report 139. Perth, Water and Rivers Commission.

Dogramaci, S. (2000). Toolibin Lake Bore Completion Report. Perth, Western Australia, Water and Rivers Commission.

Dogramaci, S., R. George, G. Mauger and J. K. Ruprecht (2003). Water balance and salinity trend, Toolibin catchment, Western Australia, Department of Conservation and Land Management**:** 60.

Drake, P., B. Coleman and R. Vogwill (2013). The response of semi-arid ephemeral wetland plants to flooding: linking water use to hydrological processes Ecohydrology 6: 852–862

Ecoscapes 2005 Vegetation Monitoring of Toolibin Lake and Reserves*Rep.*, 126 pp, North Fremantle, Australia

Farmer, D. (2012) Toolibin Recovery Catchment File Note

Farmer, D. (2014). Toolibin Recovery Catchment DiMap LiDAR Review, unpublished draft report.

Froend, R. H., S. A. Halse and A. W. Storey (1997). Planning for the recovery of Toolibin Lake, Western Australia. Wetlands Ecology and Management 5: 73-85.

Froend, R. H. and A. W. Storey (1996). Monitoring Design and Data Analysis Toolibin Lake and Catchment Part 1: Review and Analysis of Monitoring Data. Perth, Western Australia.

Furness, L. J. (1977). Preliminary Report on the Hydrogeology of Toolibin Lake, Hydrology Report No. 1625. Western Australia, Northern Arthur River Rehabilitation Committee.

George, R.J. (1992). Hydraulic properties of groundwater systems in the saprolite and sediments in the wheatbelt, Western Australia. Journal of Hydrology 130:251-78

George, R. (1998). Evaluation of Airborne Geophysics for Catchment Management. for Agriculture, Fisheries and Forestry - Australia and the National Dryland Salinity Program.

George, R. and Bennett D. (1995). Toolibin Groundwater Management Program, Drilling Results, Explanatory Notes and Drill Logs, Completion Report to CALM. Bunbury, Western Australia.

George, R., D. Bennett, K. Wallace and D. Cochrane (1996). Hydrologic systems to manage salinity at Toolibin and Towerrinning Lakes. in Proc. 4th National Workshop on the Production Use and Rehabilitation of Saline Lands, Albany, Western Australia.

George, R., Clarke, C.J., Hatton, T. (2001). Computer-Modelled Groundwater Response to Recharge Management for Dryland Salinity Control in Western Australia. Advance in Environmental Monitoring and Modelling 2(1): 3-35

George, R., S. Dogramaci and J. Wyland (2004). Can groundwater pumps and surface water engineering protect Toolibin Lake? 1st National Salinity Engineering Conference - "Engineering Salinity Solutions", 9-12 November 2004, Perth Western Australia, Institution of Engineers, Australia.

Greenbase Consulting (1991). Salt and water yield estimates for Toolibin Lake, Greenbase Consulting for the Department of Conservation and Land Management**:** 20

Gutteridge Haskins and Davey Pty Ltd (GHD) (1992). Toolibin Lake Hydrological Studies

Harris, A. and McIntosh, K. (1990). Land waterlogging north of Toolibin Lake. Booraboon, Western Australia, Department of Conservation and Land Management

Jim Davies and Associates (1994a). Toolibin Lake, Toolibin Flats Drainage Options. Subiaco, Western Australia

Jim Davies and Associates (1994b). Toolibin Lake: West Toolibin Flats Drainage., Jim Davies and Associates Pty Ltd for the Department of Conseravtion and Land Management**:** 28

Jim Davies and Associates (1995). Toolibin Lake Control Works, Jim Davies and Associates Pty Ltd for the Department of Conseravtion and Land Management

Jim Davies and Associates (1999). Toolibin Lake evaluation and design of outflow control works: feasibility report. Subiaco, Western Australia

Jones, S., P. Lacey and T. Walshe (2009). "A dynamic hydrological Monte Carlo simulation model to inform decision-making at Toolibin Lake, Western Australia. Journal of Environmental Management 90: 1761-1769

Karfs, R.A., Daly, C., Beutel, T.S., Peel, L., Wallace, J.F., 2004. VegMachine–Delivering monitoring information to northern Australia's pastoral industry. Presented at the Proceedings 12th Australasian Remote Sensing and Photogrammetry Conference, Fremantle Western Australia.

Kevi, L. (1980). Toolibin Lake Seismic Refraction Survey. Geological Survey of Western Australia Geophysics file note 4/80.

Lau, I. (2007). Lake Toolibin Hyperspectral Airborne Study Vegetation Mapping and Change Detection. Australia, CSIRO Australia.

Martin, M.W. (1987). Hydrogeology of Lake Toolibin. Geological Survey of Western Australia, Record 1986/13, Department of Mines, Western Australia.

Martin, M.W. (1990). Salinity Control by Groundwater Pumping at Lake Toolibin, Geological Survey of Western Australia. Record 1990/30. Department of Mines, West Australian.

Mattiske, E. M. (1978). Vegetation Studies of Toolibin Lake and Surroundings.

Mauger, G. (1996) Modelling dryland salinity with the MAGIC system. Water and Rivers Commission, Water Resources Technical Series no. 7.

McFarlane, D.J., Engel, R., & Ryder, A.T., (1989) The Location of Recharge areas responsible For valley salinity in The Lake Toolibin Catchment, Western Australia. In Groundwater Recharge (ed.) Sharma, M.L. Proceedings of the Symposium on Groundwater recharge, 255-269.

McFarlane, D. J., George, R. J. & Caccetta, P.A. (2004). The extent and potential area of salt-affected land in Western Australia estimated using remote sensing and digital terrain models, 1st National Salinity Engineering Conference - "Engineering Salinity Solutions", 9-12 November 2004, Perth Western Australia, Institution of Engineers, Australia

McIntosh, K. (1991). Study of stream water quality in Toolibin Lake Catchment. Land and Water Research News. Issue No. 8: 10-11.

Mudgway, L. (2009a). Dulbining Nature Reserve Surface Water Conveyance Final Construction Notes.

Mudgway, L. (2009b). Toolibin Lake Natural Diversity Recovery Catchment Dulbining Nature Reserve Surface Water Conveyance Final Construction Notes.

Mudgway, L. (2009c). Toolibin Lake outlet sump and collector channels - request for works DEC407W0152009. Narrogin, Western Australia, Department of Environment and Conservation.

Mudgway, L., P. Lacey and R. Vogwill (2008). Know what you are measuring - a detailed review of groundwater monitoring at Toolibin Lake and Lake Bryde. 2nd International Salinity Forum: "Salinity , Water and Society – Global issues, local action", 31 March - 3rd April 2008, . Adelaide, South Australia.

Muirden, P. and S. Coleman (2014). The Toolibin Natural Diversity Recovery Catchment, Review of Surface Water Monitoring. Department of Parks and Wildlife, Western Australia. Unpublished report NRB-HR-2013_010.

Negus, T. (1991). Toolibin Flats surface drainage network preliminary design proposals: draft. Narrogin, Western Australia, Western Australian Department of Agriculture.

Noorduijn, S. (2008). Temporal and Spatial Effects of a Long Term Large Scale Alley Farming Experiment on Water Table Dynamics: implications for effective agroforestry design. Masters of Engineering Science Masters Thesis, University of Western Australia.

Noorduijn, S. (2009). Toolibin Lake Ecohydrology Project Bore Completion Report. Department of Environment and Conservation, Western Australia, Unpublished Report

Northern Arthur River Wetlands Rehabilitation Committee (1978). Northern Arthur Rivers Wetland Rehabilitation Committee Progress Report, Northern Arthur Rivers Wetland Rehabilitation Committee.

Northern Arthur River Wetlands Rehabilitation Committee (1987). The Status and Future of Toolibin Lake as a Wildlife Reserve. Leederville, Western Australia, Water Authority of Western Australia.

Ong, C. and Lau, I. (2013). An investigation of the feasibility of retrieving vegetation and soil characteristics from remotely sensed hyderspectral imagery and other complimentary remotely sensed data for two different catchments within the wheatbelt region of Western Australia. Australia, CSIRO Australia.

Ovens, R., N. Coles, N. Callow, T. Pope and B. Cohen (2010). Toolibin Lake: Surface Water Runoff and Water Quality Monitoring Project - Preliminary Report. Perth, Western Australia, Centre for Excellence in Ecohydrology for the Department of Environment and Conservation.

Peck, A.J., (2000) Salt lake hydrology: Potential impact of drainage schemes, International Hydrology and Water Resources Symposium, The Institution of Engineers, Australia, 391-394.

Pracilio, G., G. J. Street, P. Nallan Chakravartula, J. R. Angeloni, D. Sattel, M. Owers and R. Lane (1998). Toolibin Lake SALTMAP Survey, Interpretation Report - August 1998. Floreat, Western Australia, World Geoscience Corporation Limited.

Reid, J. E., T. Munday and A. Fitzpatrick (2007). High-resolution airborne eletromagnetic surveying for dryland salinity management. The Toolibin Lake SkyTEM Case Study. ASEG. Perth, Western Australia**:** 1-5.

Richardson S, et al 2011 Australian groundwater-dependent ecosystems toolbox part 2: assessment tools,Waterlines report, National Water Commission, Canberra

Rutherford J, Viezzoli A, Grunewald E, Vogwill R, Munday T, Coleman B and Drake P (2013). Integrating borehole NMR and EM data - developing a new conceptual hydrogeological model to manage Toolibin Lake SW Australia. 26th Annual Symposium on the Application of Geophysics for Engineering and Environmental Problems (SAGEEP). March 17-21, 2013, Denver, Colorado USA**.**

Schaap, M.G., Leij, F.J. and van Genuchten, M.T. (2001) Journal of Hydrology, v251, 163-176p.

Schoknecht N., Tille, P., and Purdie, B. (2004). Soil-landscapes in south western Australia Overview of methodology and outputs, Technical Report 280, Department of Agriculture and Food, Western Australia.

Sharma, M. (1984). Evapotranspiration from a Eucalyptus community. Agricultural Water Management.8:41-56

Silberstein, R, Barr, A, Hodgson, G, Pollock, D, Salama, R, Hatton, T 2009, A vertical flux model for the Perth groundwater region, Hydrogeological record series no. HG33, Department of Water, Perth, Western Australia.

Sivapalan, M., N. R. Viney, and C. Zammit (2002), LASCAM: Large Scale Catchment Model, in *Mathematical models of large watershed hydrology*, edited, Water Resources Publications, Colorado, USA.

SKM Sinclair Knight Merz (1998) Project report groundwater model the effects of pumping on Lake Toolibin – Unpublished report submitted to CALM October 1998.

SKM Sinclair Knight Merz (2000). Lake Toolibin Numerical Groundwater Model Project Report. Unpublished report submitted to CALM October 2000.

Smith, A. and K. Wallace (1998). Major Project Review, Toolibin Lake Recovery Plan. Narrogin, Western Australia, Department of Conservation and Land Management.

Smith, M. and M. Lee (in prep). Miller's Block groundwater investigation program: Bore completion report 2012. Department of Parks and Wildlife, Western Australia. Unpublished report NRB-HR-2013-002.

Stokes, R. A. and M. W. Martin (1986). The hydrology of an ephemeral lake in the Wheatbelt of South Western Australia. Hydrology and Water Resources Symposium, The Institution if Engineers Australia.

Stokes, R. A. and R. J. Sheridan (1985). Hydrology of Toolibin Lake. Leederville, Western Australia.

Street, G. J. and G. Pracilio (2000). Toolibin Lake, Upgrading Catchment Interpretation, Department of Conservation and Land Management Project. **1**.

Taplin, R. (2010), Time scales of a wetland regime: impacts of climate and management on Lake Toolibin, WA, Dissertation thesis, 76 pp, The University of Western Australia, Perth, Australia.

Tesla 10 Pty Ltd, 1998: Suit of EM31 and EM38 data collected from the environs of Lake Toolibin.

Water and Salinity Management Toolibin Lake, Groundwater Pumping and Drainage Proposals: Submission to the Commissioner of Soil and Land Conservation and the Department of Environmental Protection, Western Australia. Narrogin, Western Australia.

Toolibin Lake Recovery Team and Toolibin Lake Technical Advisory Group (1994). Toolibin Lake Recovery Plan. Perth, Australia.

URS Pty Ltd (2009). ME03 Evaluation of Toolibin Lake Perth, Western Australia.

URS Pty Ltd (2011). Asset Condition Assessment of Ground Water Pumping System at Toolibin Lake Natural Diversity Recovery Catchment. Perth, Western Australia, URS Australia Pty Ltd.

van Genuchten, M.T., Simunek, J., Leij, F.J., and Senja, M., 1991, The RETC Code for Quantifying the Hydraulic Functions of Unsaturated Soils, Version 6.02., EPA Report 600/2-91/065: U.S., Salinity Laboratory, USDA, ARS, Riverside, California.

Viezzoli A., Rutherford J., Munday T. and Vogwill R (2013). Updated inversion of SkyTEM data using downhole a-priori for new conceptual model and groundwater management targets at Toolibin Lake. ASEG-PESA: The Eureka Moment, 23rd International Geophysical Conference and Exhibition, Melbourne Vic. 11th to 14th August 2013. ASEG Extended Abstracts 2013(1) 1 - 4p.

Vogwill, R., Drake, P., Coleman B. & Noorduijn S. (2010). Toolibin Lake 2010, combining hydrogeology, remote sensing and plant ecophsyiology to explain the response to management interventions. Groundwater 2010: The Challenges of Sustainable Management, Canberra ACT 31st October to 4th November 2010, International Association of Hydrogeologists

Wallace, K. J. and Toolibin Lake Recovery Team (1996). Toolibin Lake Recovery Team: annual report 1995. Narrogin, Western Australia. 13p

Walsh, D., Turner, P., Grunewald, E., Zhang, H., Butler, J. J., Reboulet, E., Knobbe, S., Christy, T., Lane, J. W., Johnson, C. D., Munday, T. and Fitzpatrick, A. (2013), A Small-Diameter NMR Logging Tool for Groundwater Investigations. Ground Water. doi: 10.1111/gwat.12024

Watson, A.N. (1978). The clearing history of the Toolibin area and some of its effects. In. The Northern Arthur River Wetlands Rehabilitation Committee Progress Report. Unpublished report to the State Minister of Fisheries and Wildlife, Perth, Western Australia

Zanella-Coletti, J., Vogwill, R., Busch, B., Callow, N. & Hipsey, M.R. (2015). A decision support system for assessing the ecohydrological response of Toolibin Lake. AED Report R27, The University of Western Australia, Perth, Australia. 143pp

Xu, C., Canci, M., Martin, M., Donnelly M. & Stokes, R. (2008). Perth regional aquifer modelling system (PRAMS) model development: Application of the vertical flux model, Department of Water, Western Australia, Hydrogeological record series HG 27

Zdunic, K. (2010), Lake Toolibin Vegetation and Landsat TM Analysis Report 6pp DEC Perth Western Australia

Figure 1: Site Location

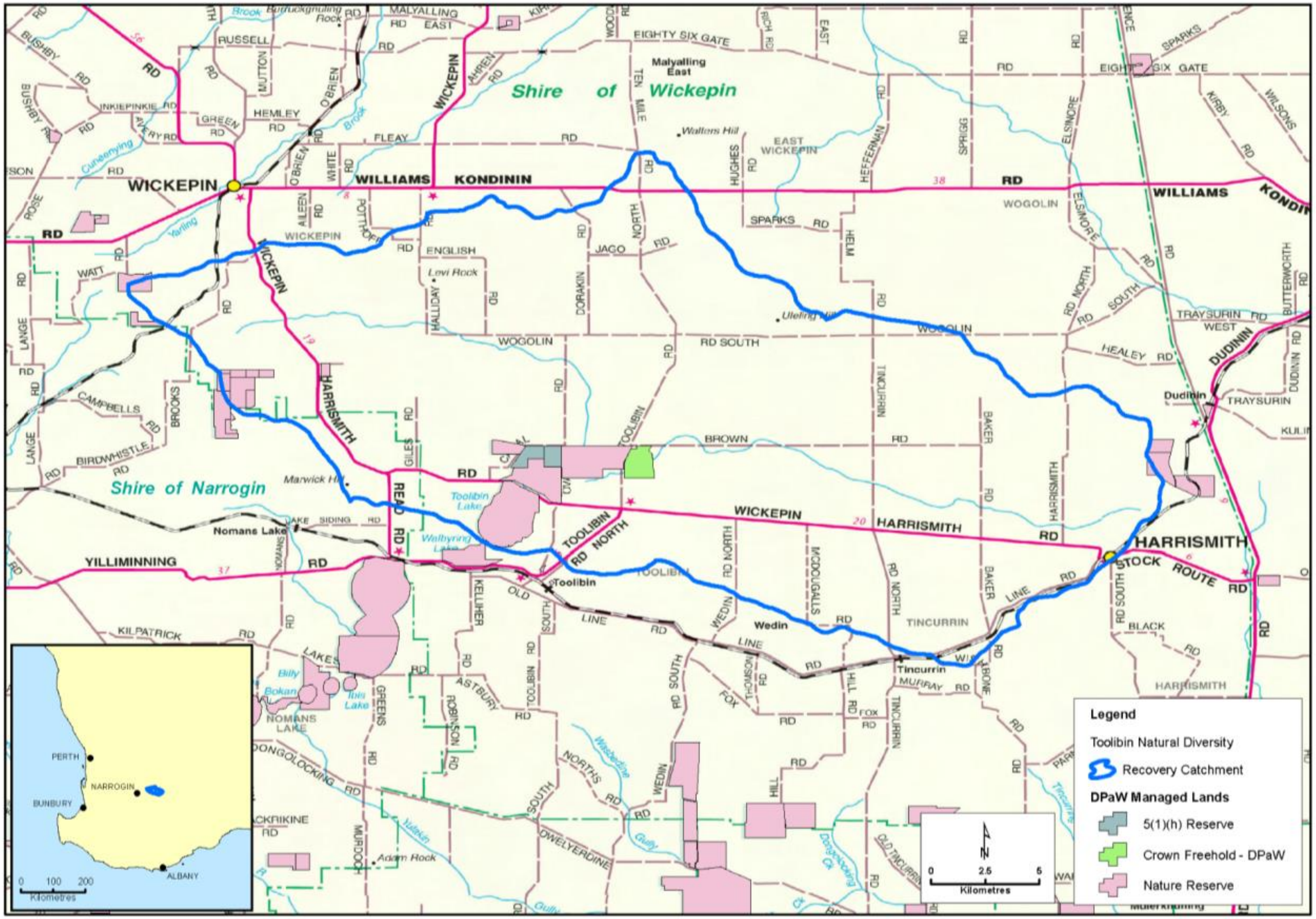

Figure 2: Bores installed in the Toolibin Lake NDRC 1977-1989

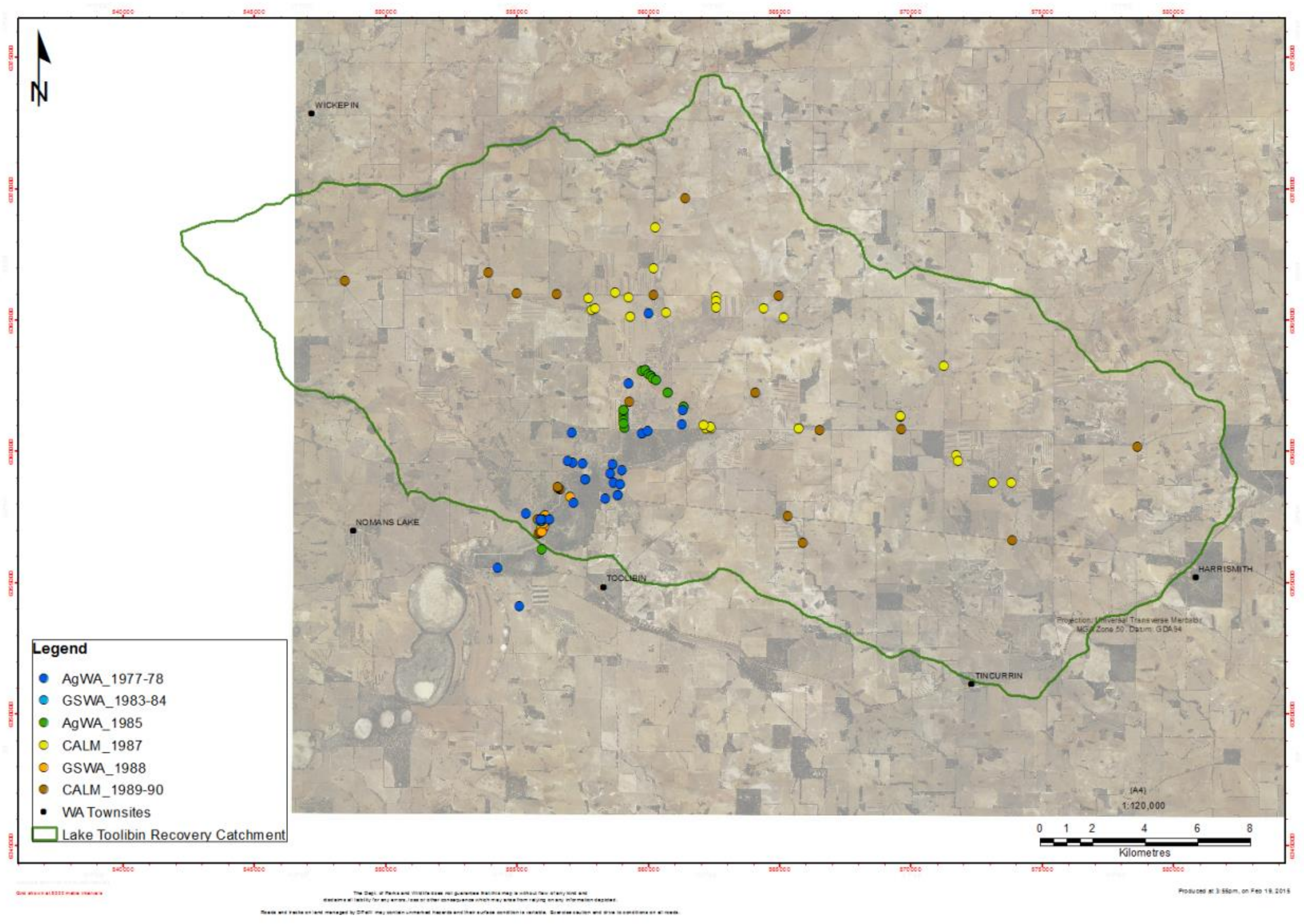

Figure 3: Pumping bores installed in the Toolibin Lake NDRC 1984-88

Figure 4: Bores installed in the Toolibin Lake NDRC 1990-1999

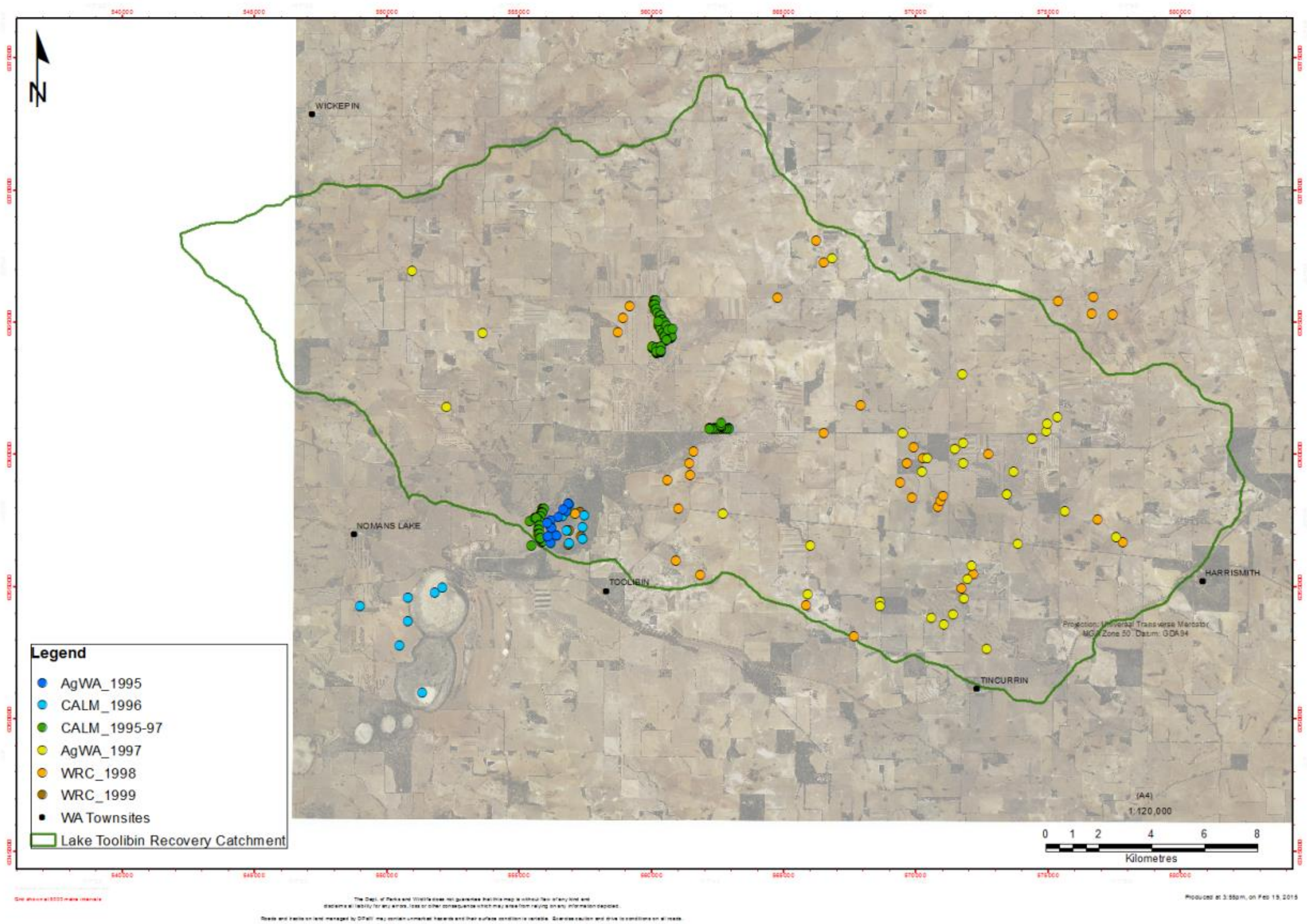

Figure 5: Pumping bores installed in the Toolibin Lake NDRC 1995

Figure 6: Pumping bores installed in the Toolibin Lake NDRC 1999

Figure 7: Bores installed in the Toolibin Lake NDRC 2000-2012

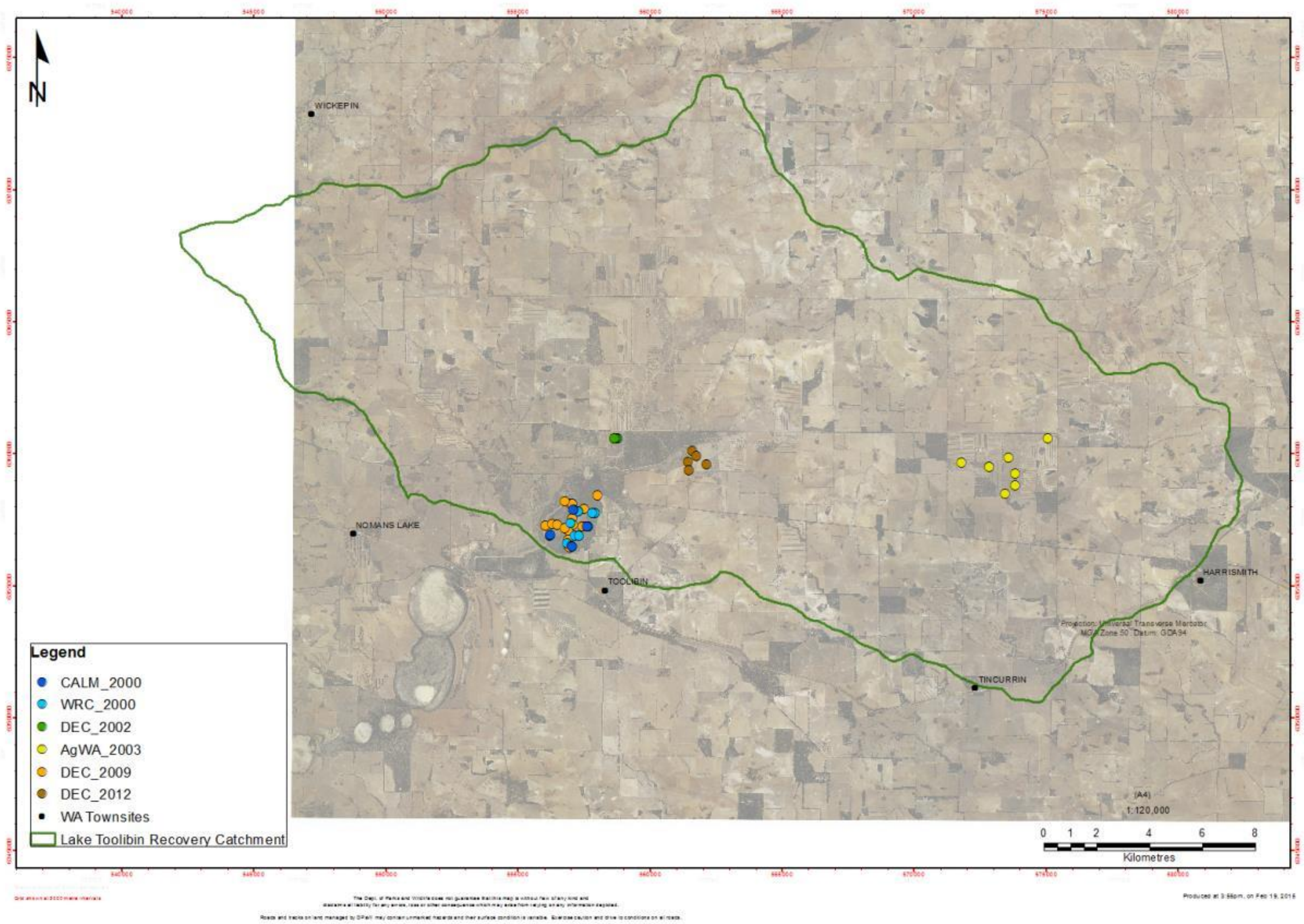

Figure 8: Surface water monitoring stations installed in the Toolibin Lake NDRC 1977-1989

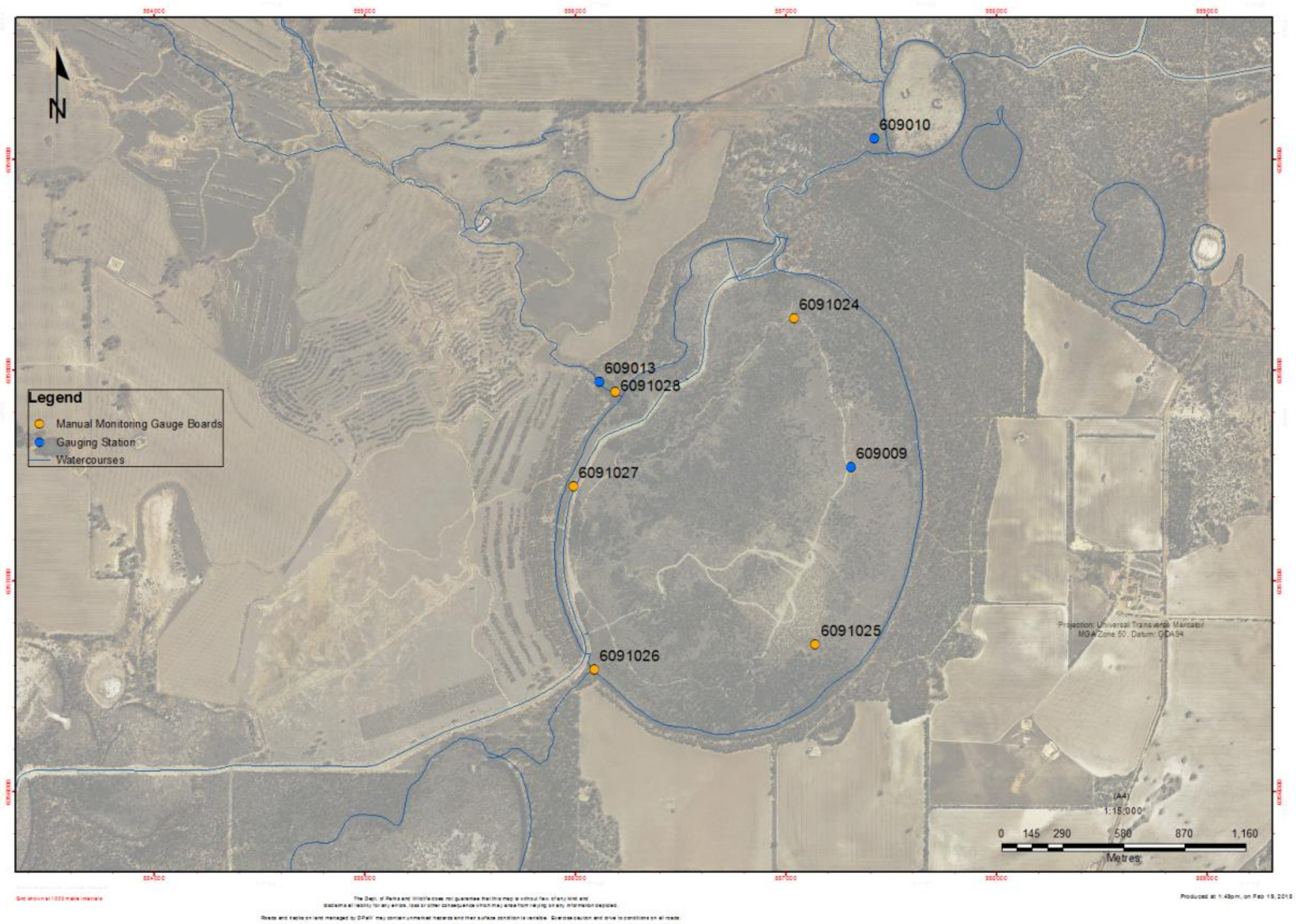

Figure 9: Surface water infrastructure and monitoring stations installed in the Toolibin Lake NDRC 1990-1999

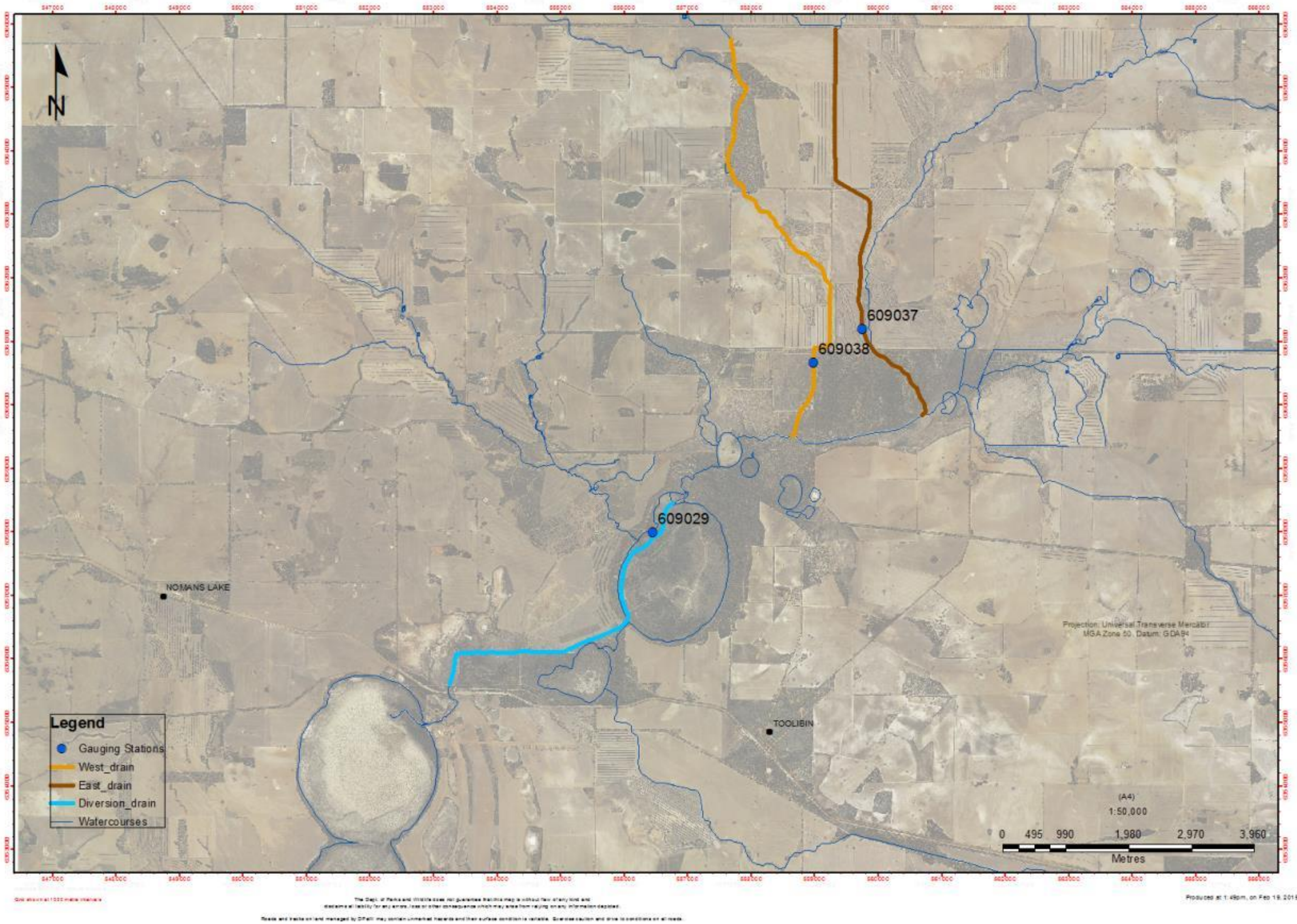

Figure 10: Surface water infrastructure and monitoring stations installed in the Toolibin Lake NDRC 2000-2013

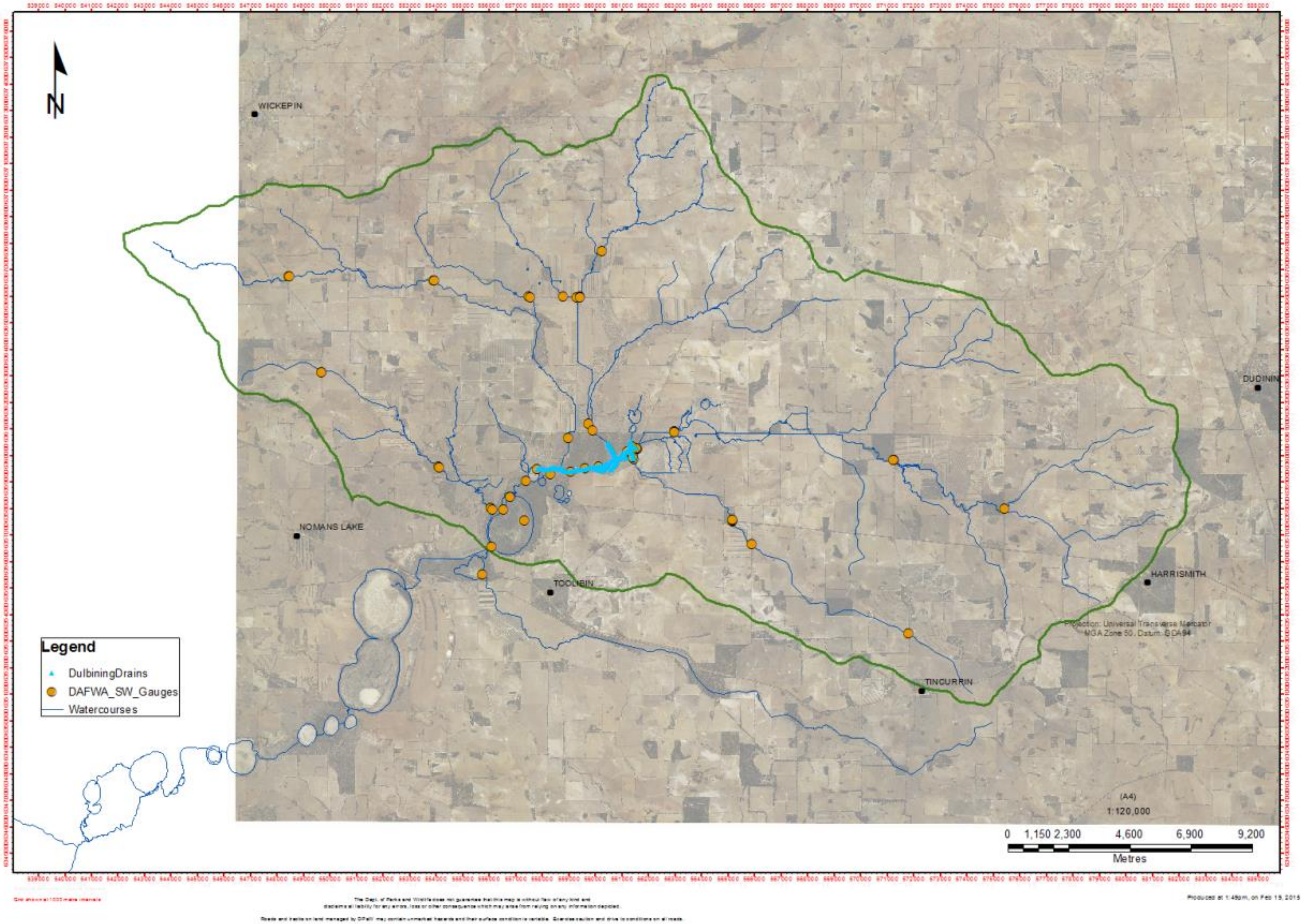

Figure 11: Ground surveying undertaken in the Toolibin Lake NDRC