2020

Esperance Pink Lake Feasibility Study

Technical report of major findings

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Prepared for the Shire of Esperance

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Photo courtesy of Dan Paris, March 2020 – Esperance, Lake Warden D. salina bloom

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Contents

Figures

Tables

Plates

Executive Summary

The iconic named Pink Lake is located near the Town of Esperance, approximately 600 km south east of Perth Western Australia. The Shire of Esperance (SoE) is concerned about Pink Lake's prolonged diminished 'pink colour' amenity since the mid 1990's impacting on tourism and local community values and commissioned a feasibility study to assess whether it could be part or fully recovered.

The cause of Pink Lake's historic pink colour is a result of an algae known as *Dunaliella salina (D. salina)*. The organism produces red carotenoid pigment at high concentrations when stressed as a survival response to outcompete other organisms for limited nutrients. The stress factors include salinities greater than 10 times seawater, warm water, extremely low phosphates and high light intensity. Under these optimum stress conditions, the red coloured *D. salina* stained water fades to pink when there is the presence of a salt crust at lake depth, and fine white to light grey suspended carbonate particles to diffuse light intensity. All these factors sustained for more than a four-week period likely result in a pink bloom.

Pink Lake is likely no longer pink due to the removal of too much salt based on annual salt harvest quotas being set by incorrect hydrological investigations undertaken in 1986. Of the estimated 923,500 tonnes of salt present in Pink Lake as of 1900, about 50 per cent had been harvested up until 2007. The removal of salt has resulted in *D. salina* bloom salinity thresholds not being sustained for periods longer than four weeks and diminished salt crust formation at very shallow depths when the lake dries out before *D. salina* can bloom. Because of the low salinities in Pink Lake under current conditions, adding more *D. salina* to the lake will not result in a bloom. Land development, road infrastructure adjacent Pink Lake and climate change flood events add to the current dilution problem but could be a benefit during a drying climate.

A 30 per cent and 50 per cent increase in salinity scenarios would likely return Pink Lake's salinity to 1991 and 1983 concentrations respectively and associated historic pink blooms. Adding 164,000 tonnes of salt would result in 1991 salinities and 273,000 tonnes of salt would result in 1983 salinities. Adding 466,000 tonnes of salt would recover Pink Lake to pre-1900 salt levels. The groundwater under Pink Lake is not suitable to meet Pink Lake's salt needs. A do-nothing scenario would take about 787 years to naturally accumulate enough salt to meet the 1991 target and 1,319 years to meet the 1983 target.

The adjacent Lake Warden has a salt accumulation problem resulting from catchment salinity with an estimated stored excess of 530,000 tonnes of salt. The salt chemistry is similar to Pink Lake. Sustainably harvesting salt from Lake Warden for Pink Lake would likely benefit both wetlands. Pumping salt brine and harvesting salt crust from Lake Warden can meet Pink Lake's 1991, 1983 and 1900 salinity targets. The strategies meet modelled annual pink bloom thresholds for longer periods under all scenario salinity targets using observed data from 2014 to 2020. To access target quantities of salt at Lake Warden, the Lake Wheatfield pipeline is integral to maintaining Lake Warden's depths at levels optimal for salt crust and/or brine harvesting. Brine pumping would cause higher nutrient loads deposited into Pink Lake which would likely be naturally assimilated over time, with the pink lake colour returning. The brine nutrient issue, salt quantities and methods can be trialed using the existing evaporation ponds on Pink Lake.

The internationally recognised Ramsar listed Lake Warden site's water bird values would greatly benefit from a large reduction in salinity resulting in more foraging biomass availability due to better water quality at optimal wading habitat depths. Based on the findings of this study, recovering Pink Lake's pink amenity to benefit the Esperance, State, National and International community is environmentally and technically feasible.

Introduction

The iconic named Pink Lake is located near the Town of Esperance (Figure 1), is approximately 600 km south east of Perth Western Australia. The Shire of Esperance (SoE) is concerned about Pink Lake's prolonged diminished 'pink colour' amenity impacting on tourism and local community values. These concerns have resulted in the SoE funding a preliminary study to:

1) Technically assess and define the likely causes as to why Pink Lake is no longer pink? and
2) Assess the technical feasibility of recovering fully or part there of the Lake's pink amenity value through intervention options.

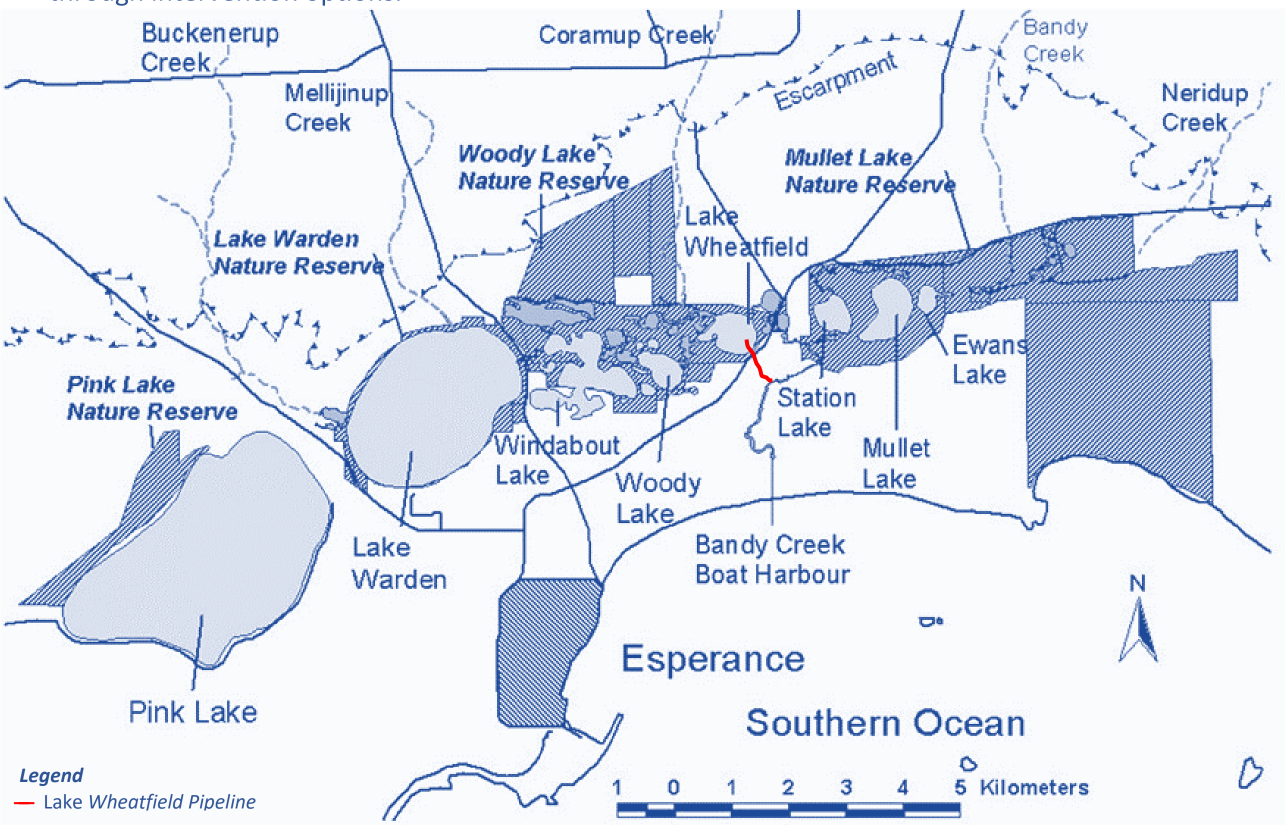

Figure 1 The Lake Warden Wetland System and Lake Wheatfield pipeline route in red

Document Scope

This Pink Lake feasibility study is presented in three documents to manage the complexity of the findings. This main document outlines background, methods, major findings for biology, salt balance, scenarios, and broad scope engineering analysis. The two technical support documents outline water balance and water quality review components of the study. The three documents comprising the Pink Lake Feasibility study are:

1. Esperance Pink Lake Feasibility Study – Technical report of major findings (Massenbauer 2020)
2. Water balance for Pink Lake and Lake Warden Esperance – technical support document for the Esperance Pink Lake Feasibility Study (Marimuthu 2020)
3. Water quality review of Pink Lake and Associated Lakes - technical support document for the Esperance Pink Lake Feasibility Study (Lizamore 2020)

Background

Pink Lake is about 1,040 hectares in area located approximately five kilometres west of the town of Esperance on the South Coast of Western Australia. It is a terminal, predominately rainfall and groundwater lake located on the Esperance coastal plain at the western end of the Lake Warden Wetland System (Figure 1).

The climate is Mediterranean, with cool, wet winters and warm to hot, dry summers. The average monthly temperatures for the study area range from 16 ℃ to 26 ℃ during summer (December-February) and 4 ℃ to 17 ℃ during winter months (June-August). The average annual rainfall is 616 mm, and mainly occurs during winter (BOM 2019).

Pink Lake historically had many uses by the Local Community. These human use values have included amenity aesthetic tourist attraction for its seasonal pink colour (Plate 1), (Beta) ß-Carotene and salt harvesting, horse racing, speed way car racing, land sailing, bird watching, and aboriginal cultural and spiritual significance. There are other biodiversity values associated with Pink Lake such as the WA State listed Priority 1 Ecological microbialite community, Migratory water birds listed under the Commonwealth EPBC Act and the Class C Nature reserve located on the western edge of the lake.

Plate 1 Pink Lake in 1985 (Photo provided by Patricia Birch)

The following background information, in part, is used to prepare a methodology to address the above aims. Some of this information has been collated from the Esperance Museum Archives (EMA) (Appendix 1 and 2) and State Library of Western Australia (SLWA) with reference archive numbers which are used as a method of documentation referencing in this report.

The Esperance area has been occupied by aboriginal people for thousands of years prior to European settlement. The first European to visit Pink Lake was Monsieur Riche as part of the French La Recherche expedition on the 16th of December 1792 (EMA 1783). Monsieur Riche's experience is described as, "*Through a petrified forest of leafless white branches and calcined roots he climbs the dunes to a crest and disappears. A glittering lake is a happy surprise, a waterless lake of bright pink sand, rosé* (EMA 7049)." In 1848 explorer John Septimus Roe named the now Pink Lake, Lake Spencer after Sir Richard Spencer. The Lake has displayed a distinct pink hue in the past and was colloquially referred to as Pink Lake until 1966 when the Shire of Esperance submitted a successful request to rename Lake Spencer officially to Pink Lake (Voigt 1996).

Salt was harvested from Pink Lake from 1896 to 1911 by Esperance Land Co. McCarthys, which was continued by the Synnot Brothers in 1937 (Voigt 1996). Salt harvesting continued intermittently in unknown quantities up until the 1960's when the Lister Family took over the salt lease. Frank Lister commented that salt crust was harvested by hand shovels up until the 1960's (EMA 1802) (Plates 2 and 3). The company, WA Salt Supply increased the scale of salt harvesting after the establishment of 13 hectares of evaporation ponds on the north eastern end of the lake (EMA 1168) and pumped lake water from 1977 to 2007 (Plate 4) into these ponds. Salt harvesting from Pink Lake ceased in 2007. In 1986 a salt harvest cap of 14,000 tonnes per annum using Pink lake surface water was placed upon WA Salt Supplies as a result of the Hurle (1986) hydrological study.

Plate 2 Premier Scaddan at Pink Lake salt pile 1915 and Pink Lake Salt pile 1939, crust extracted by shovel (SLWA)

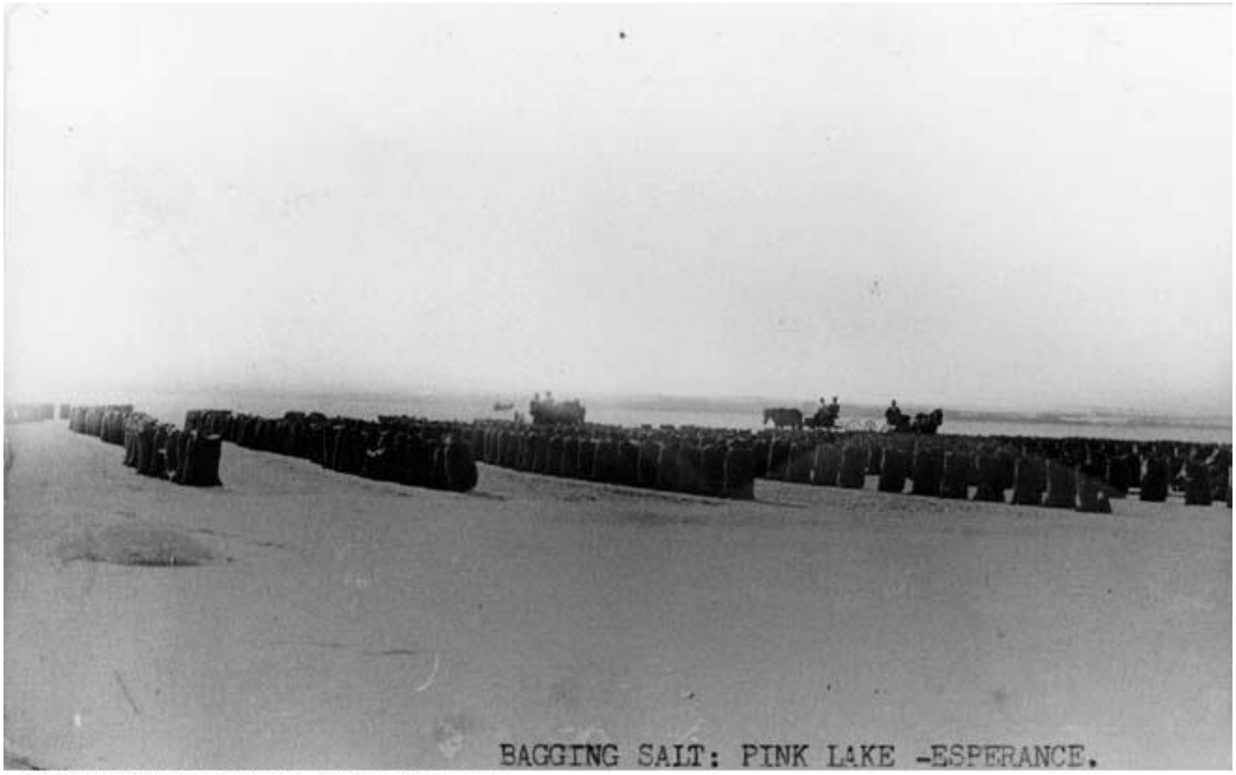

Plate 3 Bagging salt on Pink Lake around 1900 (SLWA 0000658d)

Plate 4 Pink Lake 2008, Pink salt evaporation ponds after salt harvesting permanently closed (State Library WA b3024487_2, Photo taken by Daryl Jones)

In 1980 water samples of Pink Lake taken during a pink bloom were collected by Thelma Danniells and analysed by the University of Western Australia identifying a species of Dunaliella and Coccomonas by their reddish precipitates in their cell walls (EMA 1158). This is the first definitive evidence that the pink colour of the lake resulted from an organism. The burgeoning ß-Carotene Vitamin industry also identified the species *Dunaliella salina (D. salina)* as the primary cause for Pink Lake's pink colour (EMA 1787).

In 1986, the first formal hydrological study of Pink Lake by Hurle and Associates was conducted to help sustainably manage salt and beta carotene harvesting operations. Hurle also summarised existing biological information collated for Pink Lake as one of several sites sampled by Geddes (et.al 1981). Borowitzka (1981) reviewed conditions conducive to grow *D. salina* in salt lakes, including Esperance, with specific reference to Hutt Lagoon north of Perth.

In 2002, the Shire of Esperance engaged a consultant, Coleman, to prepare a report on Pink Lake and its colouration. Coleman analysed and compared water samples taken from Pink Lake and the salt harvesting evaporation ponds. The report links colouration of *D. salina* species to salinity, temperature and nutrients.

In 1977 the now DBCA began a South West Wetlands Monitoring Program (SWWMP). Pink Lake was not included as part of the program but the adjacent Lake Warden (Figure 1) was routinely monitored for lake depth and salinity (Lane et.al 2017). In 1997, the Lake Warden Wetlands were recognised under the State Salinity Action Plan and included as a State Natural Diversity Recovery Catchment until 2012, which involved detailed wetland studies. Additional research programs and monitoring were implemented over this period with focus being on the wetlands Ramsar values, and not Pink Lake.

During the mid-2000's separate water balance models were prepared for each individual major lake within the Lake Warden Wetland system (Marimuthu and Reynolds, 2005), except for Pink Lake, to assist in understanding the likely response of the system to proposed engineering solutions. During the modelling process, some data was lacking and resulted in uncertainties within the water balance model for Lake Warden. During April 2009, a gravity pipeline was established at Lake Wheatfield (Figure 1) and began operation depositing water into Bandy Creek to manage lake levels between Lake Warden and Lake Wheatfield (Plate 5).

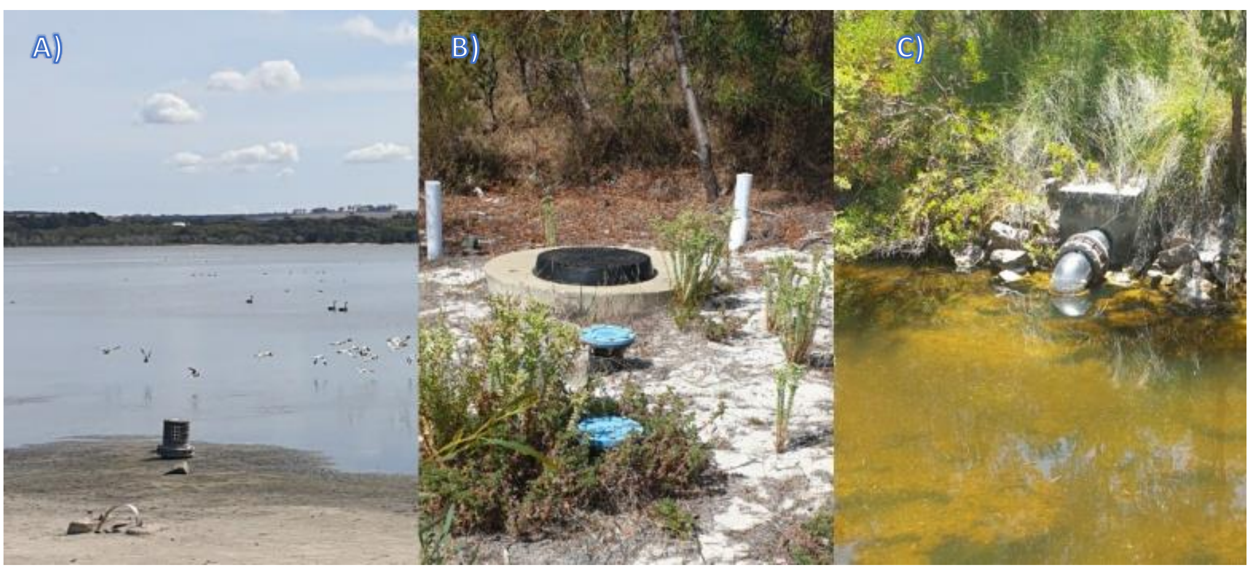

Plate 5 Lake Wheatfield Pipeline A) Lake Inflow, B) Pipe junction, C) Bandy Creek outflow (Photo T. Massenbauer)

During 2014 and 2015, DBCA conducted specific research about Pink Lake's pinkness. The water quality data collated for the Pink Lake project and Recovery Catchment Program have been summarised by Lizamore (2020) into a technical support document for this report. No formal periodic sampling and monitoring of Pink Lake's colour had been conducted up to 2014, only anecdotal evidence through photographs and historical descriptions.

The Esperance to Coolgardie railway was opened in 1927 (Voigt 1996), which is significant as the railway separating Pink Lake and Lake Warden possibly inhibits flood flows preventing additional transport of dissolved salt during rare overland flows from Lake Warden to Pink Lake (Hurle 1986). It is likely unfeasible to address the South Coast Highway and Railway hydrological barrier issue, and whether this would address the problem noting that Pink Lake remained seasonally regularly pink up until the late 1980's and intermittently through the 1990's.

Methodology

The methods utilised for this project involve collating, integrating, summarising, extrapolating and interpreting existing information sources of varying quality, completeness and currency. The information used range from technical nutrient, salinity, temperature and biological water quality sampling data, lake depth, climate, and groundwater data, surface terrain models, comparing data from similar lakes with desirable pink attributes, historical media sources from museum and library archives, information provided by WA salt supply, dated photographic evidence, anecdotal accounts, and expert opinion. Based on the prementioned background information, this proposal involves the following technical aspects:

1) Determining optimum threshold targets/ranges for Pink Lake by defining:
   a) The minimum biological threshold or range required for Pink Lake to appear pink. This included determining a species-specific *D. salina* measure of ß-Carotene cell content and biomass concentration to lake volume, and or a surrogate such as calibrated visual pigment stained filter paper based on water sampling or drone photography.
   b) The minimum habitat hydro-chemical condition thresholds required to attain and sustain target concentrations of *D. salina* likely to result in a pink bloom. This involved setting targets for total salt storage of Pink Lake (surface salt crust and total dissolved salt (TDS)), and nutrients.

      Lizamore (2020) selected several variables to identify likely combinations of physical, chemical and biotic attributes which affect a pink lake's colouration. Measurable parameters were compared over time within the same sample site and between samples sites (refer to 1c) to identify trends or thresholds when lakes(s) are changing colour. Piper and Durov diagrams (Appendix 4) were used to display patterns between geochemical factors which may cause colouration changes. Below are variables that will be measured:

      - Salinity and TDS
      - Irradiance/UV level
      - Dissolved Nutrients
      - Nitrogen levels
      - Phosphorus levels
      - Ammonium
      - Phosphate
      - Nitrates
      - Nitrites
      - Chlorophyll a, Phenophytin a by florescence
      - Chlorophyll a, b, c by absorption
      - Dissolved Oxygen
      - pH

   c) Set targets 1a, b by reviewing historic Pink Lake data and anecdotal evidence prior to loss of pink colouration. The Lizamore (2020) water quality report was used to compare results for Pink Lake, Lake Warden, Lake Hillier and Lake Benje Benjemup. Lake Hillier located on Middle Island is relatively pristine, with extremely stable hydrology, has unique stable biological assemblages that result in its unique all year-round deep natural pink colouration. Pink Lake is a different system to Lake Hillier and it is important to recognise that it is unlikely that Pink Lake has in the past or will in the future present such vivid pink values due to land use disturbance and climate change flooding. Separate to the Lizamore (2020) support document is the use of Hutt Lagoon north of Perth as a comparison wetland being a similar coastal wetland type to Pink Lake.

2) Determining the current status of *D. salina* and salt storage for Pink Lake:

   a) Water samples of Pink Lake and comparison lakes, Lake Warden, Lake Hillier and Lake Benje Benjemup were collected and analysed for the presence and quantity of *D. salina* according to the defined Target biomass measures (1a).

   b) Estimates of current total salt loads, solute and precipitated available in Pink Lake were calculated (1b). This was achieved by reviewing historic information to calculate an estimate of how much salt has been harvested annually from Pink Lake since 1896 (Appendix1). Pink Lake salt crust and lake water salt volumes for the early 1900's was estimated by extrapolating from historic records.

3) Identifying the likely causes driving the current state of Pink Lake.

   a) Marimuthu (2020) water balance and Lizamore (2020) water quality (salinity and nutrients) analysis was linked to salt harvesting, catchment land use and climate information. This involved reviewing surrounding land use areas and proximity to Pink Lake and climate analysis.

4) The quantity of additional salt required to provide optimum habitat conditions for an increase in *D. salina* and/or ß-Carotene concentration needed to result in Pink Lake looking pink again was calculated.

   a) A Pink Lake Volume depth model was used to convert observed lake depth and salinity data to calculated TDS loads at varying lake depths.

   b) The modelling of a proportional percentage increase in TDS salinity against observed lake depth and TDS data (2014-2019) was conducted until the results showed *D. salina* TDS salt levels, duration of salinity, and lake depth could be achieved.

   c) The threshold Pink Lake modelled TDS salt increase was converted to a total salt load.

   d) The modelled salt load target threshold was linked to a historic salt load year based on the cumulative amount of Pink Lake salt harvested at that time. i.e. Pink Lake salt loads recovered to 1985 and 1991 salt loads.

5) Defining an asset objective/s for Pink Lake based on steps 1 to 5 to determine:

   a) Applying the area extent, duration, intensity of colour and hue of pinkness desired for Pink Lake based on historic dated photographs, modelling and salt harvest calculations.

6) Identifying potential sources of salt that could be introduced to Pink Lake to meet defined targets which involved:

   a) Determining how much salt is available, in what form the salt is available (I.e. brine solution, precipitated/crystallised crust), and over what period is the resource available.

   b) Determining if the identified resource addresses all or part of the short fall in salt required to make Pink Lake pink again?

   c) Determining how long it would take to expect to see Pink Lake, or their part of, turn pink again (4b).

7) Estimating duration of Pink Lake being pink again using current climate and extreme event scenarios (4b).

8) Scoping three preliminary conceptual engineering scenarios were tested against the modelling as how to potentially recover part, all and for how long (temporal) Pink lakes pinkness.

   a) A basic proof of concept trial methodology to test the engineering options was developed.

9) Assessing the likelihood of engineering scenarios meeting key pink colouration thresholds was conducted.

The outlined project logic steps were implemented by:

- Reviewing literature of existing pink lake ecology (not just Esperance) used to define biological and hydro chemical threshold targets. (1)
- Collating and analysing available hydrological, hydrogeological, climate, and land use information relevant to Pink Lake and Lake Warden. (5)
- Conducting a present-day one-off water quality/quantity testing of lake water to show what the Pink and Warden Lakes are doing relating to pink colouration (2).
- Building a Pink Lake depth/volume model as part of a lake hydrology water balance model (2, 3, 4, 5)
- Building lake water balance hydrology models for both Pink Lake and Lake Warden based on data collation steps (Marimuthu 2020).

  Marimuthu (2020) collated and evaluated available geological and hydrological information to assess the surface water and groundwater interaction details of Pink Lake and Lake Warden. The assessment of site hydrogeology was based on following information:

  - Locations of existing monitoring bores within the Lake Warden and Pink Lake area were determined to allow an assessment of reduced groundwater levels within the area. The groundwater flow and surface water-groundwater interactions are complex.
  - Depth of Surficial sediments.
  - Nature and depths of underlying aquitards and aquifers and detailed lithology of the Surficial sediments and underlying strata.
  - The area of fresh groundwater discharge to Pink Lake.
  - Comprehensive sampling and assessment of groundwater quality across the site.

  The above information assisted in determining geological sections across the site and assess hydraulic connection between shallow and deep aquifers and assisted in the development of a site hydrogeological conceptual model.

  The water balance of the Pink Lake and Lake Warden were analysed by constructing a daily water budget that includes inflow, outflow and a storage change term. The daily inflows are the overland flow, groundwater inflow and precipitation on the lake surface. The outflow terms are evaporation and groundwater. The change in storage of the lakes was calculated from the measured lake levels and bathymetry. Evaporation, humidity and precipitation data were obtained from the Bureau of Meteorology Esperance site located 2 km away from the study area and Australian Climate Data (SILO 2019).

- Building a salt balance for both Pink Lake and Lake Warden based on observation data and the bucket model results.

- Identifying and transparently outlining underlying uncertainties, assumptions and extrapolations applied in the absence of adequate information which provides an informal method of information gap analysis.
- Providing evidence to support hypothesis as to why Pink Lake is no longer pink based on available data, uncertainties, and threshold research. This included assessing land use such as salt harvesting, surrounding urban rural subdivision, road and utility infrastructure, and climate change effects on Pink Lake.
- Defining three objective scenarios according to findings based on a 'do nothing' approach and recovering Pink Lake conditions for two set historic periods.
- In association with the water balance information and observed hydrological data, an assessment of the availability and suitability of salt for Pink Lake from under the lake itself, and from the adjacent Lake Warden was completed and:
    - Broad engineering options based on this information were developed and.
    - A scoped proof of concept trial utilising the existing salt harvesting ponds at the northern end of the lake was outlined to further assess feasibility.

Biology - colouration

The cause of historic pink blooms occurring at Pink Lake (Plate 6 a), b), c), and d)) were first confirmed in the early 1980's by the University of Western Australia (UWA) (EMA 1158) as high concentrations of an algae, *Dunaliella sp*.

b) 1964

c) 1970’s

Plate 6 Pink Lake colouration community photos of a) 1963, b) 1964, c) 1970's, d) 1985

Note: Photos by a) by Graham Cooper, b) by Stanley Cook, c) C. Green, d) Patricia Birch

In 1981 Pink Lake was sampled as part of a Salt Lake ecology study conducted by Geddes (et.al 1981) and Borowitzka (1981) for the ß-Carotene Vitamin industry confirming the presence of *Dunaliella salina* as the cause of Pink Lakes pink colour (Figure 2). *D. salina* produce more ß-Carotene in cell structures when under stress (Ramos 2011), which in part provided Pink Lake its colouration.

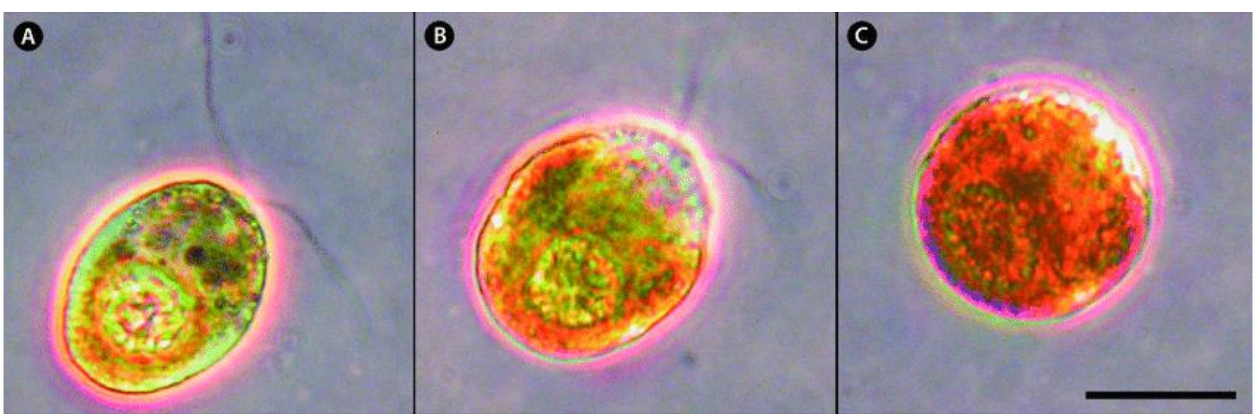

Figure 2 Dunaliella salina cells in different culture conditions. (A) Green cell from a non-stressed culture. (B) Stressed cell turning orange. (C) (Ramos et.al 2011)

In 2002 a study conducted by Coleman involved sampling water from Pink Lake and the lakes salt evaporation ponds (Plate 4). Coleman postulates the pink colour of Pink Lake is due to biological activity. The two main species contributing to the lakes colour is *D. salina* and a bacteria *Halobacterium halobium*. It is important to note that *Halobacterium* was not recorded in Coleman's samples, or has never been recorded in previous sampling of Pink Lake so it is unlikely that it is a cause of its historic pink colour in the absence of more definitive evidence.

Colman states *D. salina* imparts a brick red, dark red to orange colour to the lake brine and the *Halobacterium* bacteria a pinker to crimson colour. The unconfirmed bacteria live off by-products from *D. salina* and often occur in association with one another. Coleman also postulates the colour maybe influenced by the amount of inorganic matter suspended in the water such as clay and gypsum, which is present in Pink Lake surface sediments.

Coleman surmises *D. salina* is outcompeted by other species such as *D. viridis* in salinities less than 75 g/L. This is supported by Moulton (1987) and *D. salina* survive better at salinities greater than 175 g/L. *D. salina* are autotrophic and use sunlight to provide energy for the uptake of nutrients and carbon to produce organic material and grow. Nutrients must be available in the correct form and suitable quantities. *D. salina* does not grow well with nitrogen as ammonia or urea (prefers Nitrogen as nitrate) and prefers phosphate only. When phosphate nutrient concentrations are low and excess strong sunlight is available, *D. salina* produce ß-carotene that shades chloroplast. This process reduces photosynthesis in highly saline environments and out competes other algae relying on chloroplast photosynthesis.

Water quality nutrient analysis of DBCA data undertaken by Lizamore (2020) highlights Lake Warden shows the highest variation of phosphates to nitrates ratio when compared to Pink Lake. This is likely due to Lake Warden experiencing higher contribution of surface water inflow, and there being a sharp nutrient increase after large scale catchment runoff events. There is little phosphate concentration variation in Pink Lake, indicating phosphates are likely entering the system through groundwater seepage and not overland run-off (Lizamore 2020). When Lake Warden levels no longer connect with Lake Windabout and no inflows occur over an extended period, nutrient concentrations reduce under aquatic biological processes as lake depth levels reduce. During these lower lake levels, especially when Lake Warden is below 0.6 m deep, chemically and physically, there is little difference between Lake Warden and Pink Lake except for salt concentration (Appendix 4).

In 2002 Coleman collected two samples, one from Pink Lake and the other from a salt extraction pond (Refer to Plate 4) located on north east end of the Lake. The Lake water contained high concentrations of *D. salina,* other algae species, 3 blue-green bacteria and a diatom (Table 1).

Table 1 Water sample results as 1000 cells per mL taken from Pink Lake and pink pond water in 2002 (Coleman 2002)

	Blue-green bacteria			**Diatom**	**Algae**	
Genus	**Synchococcus**	**Synechocystis**	**Oscillatoria**	**Navicula**	***Dunaliella salina***	***Dunaliella viridis***
Lake Water	0.111	0.222	0.111	0.111	4.667	1.333
Pink pond water					1.222	

The pond water was mainly populated by *D. salina* at lower cell concentrations than the lake water. The pond had redder colouration than the lake, though *D. salina* lake concentrations were higher. The key to the pond redness was *D. salina* which had larger more heavily pigmented cells with carotenoid (Coleman 2002) than the lake water cells (Plates 4 and 6, and Figure 2). This demonstrates the *D. salina* in the ponds were under more stress (Ramos 2011) than those sampled from the Lake water.

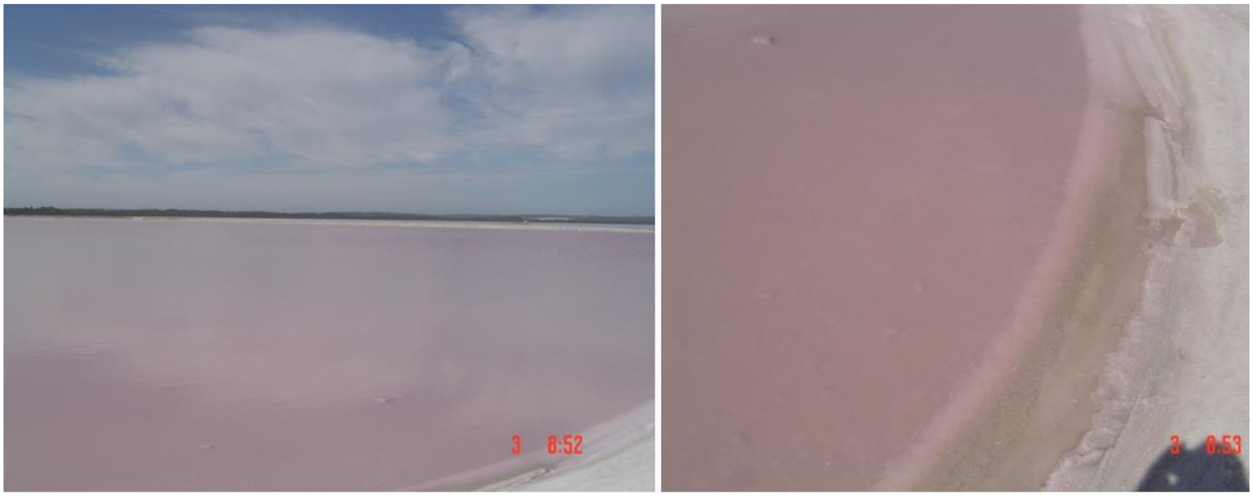

Plate 7 Pink Lake evaporation pond water in December of 2008 (Photo provided by Steven Ellen)

Though there are no salinity samples recorded as part of the Coleman report, it is likely the salinity of the pond water was much greater than that of Pink Lake as WA Salt Supplies were still using the ponds for salt harvesting in 2002. This involved pumping diluted salt bring from the lake and concentrating it in evaporation ponds over the summer months (Appendix 1 Salt harvest). The high salinity levels of the ponds were the likely stressor resulting in fewer, but more heavily pigmented *D. salina* cells.

The following biology summary compares research at Hutt Lagoon located north of Perth to Lake Warden's *D. salina* blooms hydrological cycles, and lack of colouration for Pink Lake observed since 2012. *D. salina* remains active in the water column at salinities up to 310 g/L, the saturation point for sodium chloride in Hutt Lagoon. Salinity at Hutt Lagoon also does not drop below 200 g/L during the winter months (Moulton et.al 1987). The lagoon is filled to a depth of 50–75 cm by rainfall during the winter months and is desiccated to 5 cm or more thick salt crust during the summer (Post et.al 1983).

Present day Lake Warden and Pink Lake colouration

Similar conditions to Hutt Lagoon occur episodically since 2012 at Lake Warden during a *D. salina* bloom when Lake depth drops below 60 cm down to 15 cm and salinities are consistently well above 300 g/L. The winter salinities for Lake Warden leading to the 2015 and 2020 *D. salina* blooms were above 200 g/L and exceeded 310 g/L for the summer periods (As interpreted from Figure 16 on page 36, Pink Lake *D. salina* salt requirements document section). Lake Warden depths have resulted primarily from the effects of the Lake Wheatfield pipeline and salts concentrated to greater than 310 g/L. Salt crust formation at Lake Warden begins at depths shallower than 0.65m to 0.6m. The source of the increased salt loads at Lake Warden have been the result of increased catchment secondary salinity and surface water run-off post extensive catchment clearing for agriculture since the late 1960's (Short et.al 2000, Kusumastuti 2006, Janicke 2004).

The Lake Warden conditions resulting in periodic *D. salina* blooms since 2012 (Plate 8), only partially occurred on one occasion at Pink Lake which started to bloom for a very short period but dried out quickly and faded (Plate 9).

Plate 8 Lake Warden D. salina orange bloom 2nd of February 2012, Lake Depth 0.7 m (Photos by John Lizamore)

Plate 9 Pink Lake early stages of a D. salina bloom 2nd of February 2012 (Photos by John Lizamore)

Observed data for Pink Lake's depth range is between 80 cm to dry, and salinity range is predominately between 100 and 175 g/L and rarely exceeds 310 g/L, which is only for a short period of time (As interpreted from Figure 16 on page 36, Pink Lake *D. salina* salt requirements document section). When Pink Lake reaches 310 g/L salinity at a depth of about less than 0.4m, the lake either dries out too quickly during summer or is diluted to below 200 g/L in the event of a moderate rainfall event and mixing of freshwater seeps at the margins of the lake. The decreased salinity and fast drying lake mean a salt crust only forms when the lake is too shallow and over a smaller area than in the past, resulting in not enough time for *D. salina* to bloom. Plate 10 shows the comparison of difference in area extent of salt crust formation at Pink Lake for March 2020 and 1985.

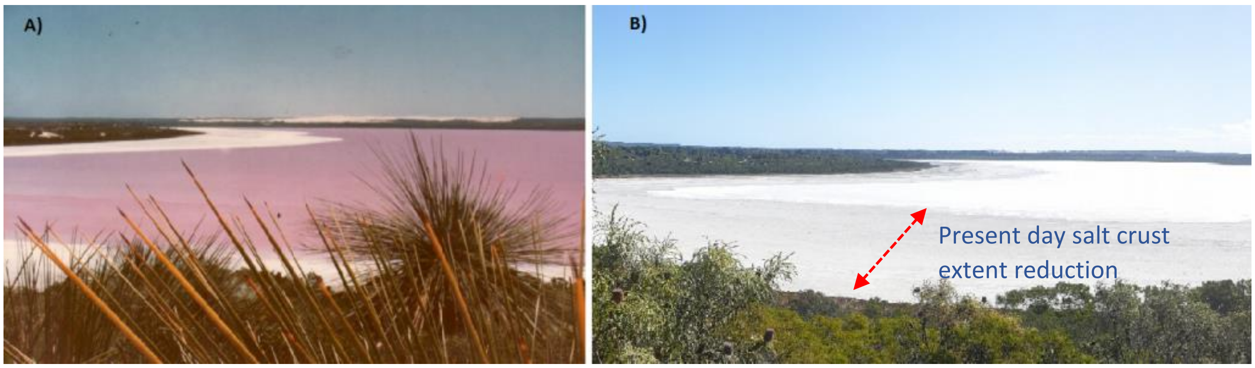

Plate 10 Pink Lake bloom and salt crust formation near edge of Lake 1985 (Photo P. Birch), and March 2020 dry lake and decrease in salt crust area by hundreds of meters (Photo T. Massenbauer).

The periods post the Lake Wheatfield pipeline dewatering intervention has resulted in an increase in *D. salina* bloom events for Lake Warden. There is little data relating Lake Warden colour to lake depth and salinity for all three parameters. Anecdotally, date referenced photographs of a Lake Warden *D. salina* blooms have been linked to Lake depth information and some salinity data (Plates 11 to 14). The photos used to show colour bloom events have been post processed rectified using only a digital polarizing filter with no other alterations. Photos by Kylie Ryan had been pre-enhanced resulting in likely exaggeration of Lake Wardens pink hue at the time (Plates 13 and 14).

Plate 11 Lake Warden 18th of March 2020, pink/orange bloom, 0.28 m depth, salinity 540 g/L (Photo Wayne Foote)

Plate 12 Lake Warden 9th of February 2020, orange bloom, 0.4 m depth, salinity 510 g/L (Photo Tilo Massenbauer)

Plate 13 Lake Warden 27th of December 2015, pink bloom, 0.61 m depth, no salinity reading (Photo Kylie Ryan)

Plate 14 Lake Warden 7th of December 2014, pink bloom, 0.615 m depth, salinity 304.5 g/L (Photo Kylie Ryan)

Additionally, there is Lake Warden salinity data (>300 g/L) with corresponding Lake depth data, but no corresponding date referenced photograph of a *D. salina* colour blooms (Table2). In the absence of photographic evidence during these key periods, local knowledge was applied to confirm Lake Warden displayed *D. salina* colour blooms during these times (Table 2).

Table 2 Lake Warden observed lake depth and salinity data > 300 g/L (Data collected by John Lizamore, Source DBCA) result in verified expert opinion occurrence of colouration blooms ranging from pink to orange

Date	Depth (m)	Corrected dissolved salt g/L
15-03-20	0.28	540
16-02-20	0.40	510
23-12-19	0.540	366.6
22-04-15	0.29	540
10-04-15	0.20	428
26-03-15	0.15	485.5
10-03-15	0.15	478
26-02-15	0.25	441.5
19-02-15	0.31	399.5
28-01-15	0.35	357.5
15-01-15	0.44	358.5
05-12-14	0.615	304.5
20-05-14	0.52	335.5
07-05-14	0.50	320.5

Lake colouration resulting from a *D. salina* bloom can appear different even though lake depth, water chemistry (salinity, nutrients, ph) and biology (cell and carotenoid concentration) may not change. This can be a result of complex spectroscopy physics in the way sunlight interacts with other particles. Visible and near visible light interact differently under varying parameters such as solar radiant heat intensity, azimuth, atmospheric conditions, water column particles and temperature, and lakebed substrate. Changes in hue, light infiltration, absorption and reflectance during a *D. salina* bloom can appear as different colouration depending whether the sky is overcast or sunny and clear at similar times of day. These differences may result in subtle or major changes in colour appearance. Plate 15 shows a comparison of two sets of drone photos of Lake Warden taken by Dan Paris less than one week apart at similar times of day, lake depth, salinity and light winds, but one being overcast and the other being sunny (Appendix 5).

The intensity of solar radiation is also expected to influence the competitive interaction between *D. salina* and *D. viridis*, because the accumulation of ß-carotene by *D. salina* appears both to protect the algae from intense radiation and to increase the point of compensation between photosynthesis and respiration (Borowitzka et al., 1984). The behaviour of the two species reflects this, *D. salina* migrating towards intense light and *D. viridis* seeking lower light intensities. *D. viridis* have an adverse effect on *D. salina* at low salinities but less effect at high salinity (Moulton et.al1987). DBCA have collated raw data for measured light concentrations as part of their Pink Lake Study but the data has not yet been analysed and was not used as part of this project (Pers. Comm. Lizamore 2020a))., which relies on simple photographic evidence associated with water quality data and literature reviewed cause and effect relationships

Sunny 26/03/2020 Overcast 02/04/2020

Plate 15 Light intensity and atmospheric conditions such as cloud cover affecting colour perception of D. salina bloom at Lake Warden using same settings with drone photography, March 2020 (Photos Dan Paris). Depth 0.28m salinity 540g/L

Moulton et.al (1987) speculate the major factor involved in competition between *D. salina* and *D. viridis* in ponds at Hutt Lagoon is the behaviour of the two species. *D. viridis* tend to occur in bottom sediments at all salinities and migrate to the bottom with increasing salinity. This behaviour leads to an apparent absence of *D. viridis* in the water column at higher salinities and, importantly, gives *D. viridis* the advantage of a larger inoculum size when ponds are pumped dry and refilled. *D. viridis* tend not to be pumped from the pond because it persists within the sediments, and it is available as inoculum when the pond is refilled, especially if the salinity is set relatively low (Moulton et.al 1987).

Another interspecific interaction relevant to Pink Lake occurs at Lake Hillier on Middle Island which contains both *D. salina*, and a halophilic bacterium *Salinibacter ruber*, but it is the latter making the lake pink, not *D. salina* (Scott Tighe *pers comms* 2019). This is not the case for Pink Lake as *D. salina* is the driving organism behind the lakes historic pink colour, but it is not clear whether Pink Lake's sediments have been sampled and tested for the presence, absence or historic evidence of *Solenogaster ruber*.

Lizamore (2020) has collated biological water sampling of wetlands relating to the Esperance Pink Lakes project (Table 3) which shows Pink Lake still contains *D. salina,* all be it at low densities when sampled during a dry 2019 winter. The samples were analysed by the chemical company BASF Australia, who have developed a method measuring cells to determine ß-Carotene production for commercial purposes. Based on results received from Curnow (2019), Pink Lake has the necessary biota present, but in too low concentrations for colouration to appear, or at too low salinity to stress the cells into increase carotenoid production. Furthermore, *D. salina* assimilates more green pigment, making the colouration more orange in colour. Oren (2014) found *D. viridis* grows optimally at 60–90 g/l NaCl, whilst *D. salina* prefers ~100–150g/l. These results specific to Pink Lake are complimented by the Coleman (2002) and Moulton et.al (1987) studies.

Table 3 Biota cell concentrations for lake water as supplied by BASF (Curnow 2019)

SAMPLE INFORMATION							
SAMPLE ID	DATE	Total carotenoids ppm	D. salina motile cells/ml	D. salina non-motile cells/ml	D. viridis cells/ml	pH	Density g/cm3
Lake Hillier	2/6/19	1.126	7500	0	200	7.8	1.207
Lake Warden	3/6/19	0.363	550	0	5200	7.78	1.145
Pink Lake	3/6/19	0.241	200	0	0	8.77	1.005
Lake Benje Benjemup	3/6/19	1.008	2800	0	6800	7.68	1.159
Hutt Lagoon	12/6/19	2.095	9000	0	4400	8.12	1.191

Additional evidence relating to the presence of *D. salina* at Pink Lake are the remains of faded ß-carotene deposits on the dry lakebed amongst fossil remains of microbialite structures photographed during winter 2019 (Plate 16).

Plate 16 Pink Lake faded ß-carotene deposits 24/07/2019 (Photo. Tilo Massenbauer)

Pink Lake versus Lake Warden – Pink versus Orange

The present day colour blooms at Lake Warden are generally orange/brown (Plate 15), and historical blooms at Pink Lake were variations of pink (Plate 6). The colour is primarily caused by *D. salina* responding to differing types of environmental stress. Secondary causes of Lake colour derive from natural geochemical and climatic processes and human induced catchment impacts.

D. salina can range in colour from green to yellow to orange to red (Figure 2a, b, c). This colour range is the algae's trophic processes responding to stress within the cell structure (Ramos 2011). High concentrations of carotenoid pigment are produced under extreme salinity and very low phosphate nutrient availability when light intensity is high and water temperature is warm.

Pink Lake is relatively closed to surface water run-off and has low levels of nutrients entering via surficial groundwater discharge on the Lakes outer margins (Lizamore 2020). Historically at Pink Lake, the *D. salina* dark red pigment concentration was softened to a pink colour by mixing with suspended fine white to light grey clay, silica gypsum and salt particles in the water column at salinity saturation, with strong winds driving the mixing process. Light absorption and reflectance from the Lake beds white to light grey colour also adds pink hue colour variation, diluting the effect of dark red *D. salina* cells.

The high gypsum content in the Lake sediment (Mernagh 2013) is because of several factors:

- Up until the late 1980's long term stable extreme salinity,
- high carbonate content from marine sediment deposits,
- high carbonate from adjacent deep sand dune surficial groundwater discharge,
- wind deposited fine sediments of high silica and carbonate from surrounding dunes, and
- the system being closed to catchment surface water run-off.

Lake Warden's colour under extreme salinity is from *D. salina* responding to higher nutrient levels. Within a *D. salina* cell, extreme salinity results in red carotenoid production, but high nutrients result in yellow/green chlorophyll production under photosynthesis. The red and yellow/green pigments inside the *D. salina* cell appear as a secondary to tertiary orange/brown colour (Figure 2b). The darker sediments at Lake Warden caused by the accumulation of catchment eroded silt (Wilson 2004) and buildup of organic material results in less light reflectance and darker Lake colour.

Lake Warden has higher nutrients due to catchment surface water inflow from farms (Lizamore 2020, Janicke 2004, Neville 2009) (Appendix 6). The nutrients are stored and cycled between lake water and sediment. Prior to the construction and usage of the Lake Wheatfield pipeline, Lake Warden was much deeper with lower salinity. From 1989 to 2009 annual aquatic rupiah grass meadows would bloom during winter and spring and blue green micro and macro algae during summer. Anaerobic bacteria drive nutrient cycles in the dark coloured lake sediment.

The unusual pink colour of Lake Warden during December 2014 and 2015 (Plates 13 and 14) were likely due to low nutrients from consecutive dry winters and a prolonged stable white salt crust forming on the lakebed.

D. salina pink bloom threshold summary

Based on previous studies and summary by Lizamore (2020), key determining parameters as to what makes a pink lake pink, specifically Esperance's Pink Lake are the following:

i. Presence of *D. salina*
ii. Lake must be hypersaline (>300 g/L concentrations) for periods of 4 weeks or more
iii. Lake is alkaline with a pH>7.4
iv. Water temperature is greater than 25°C
    a. During high stress situations, *D. salina* manufactures ß-Carotene to protect the cell (Ramos 2011) and prevents water column light filtration to outcompete Photosynthesis reliant organisms for limited phosphates under extreme saline and temperature conditions (Coleman; 2002). Mouton et.al (1987) also postulates that the increased production of ß-Carotene darker colour under hypersaline conditions results in increased water temperature, like that of a green-house effect. This process benefits *D. salina* especially when seasonal air temperatures begin to cool and rainfall increases during Autumn, Winter and Spring, prolonging increased water temperature through biological processes.
v. Presence of a salt crust at depth and over expansive lake areas
    a. Salt crust increases solar radiation, increases water temperature, and heat storage of the water column and surrounding sediments – see point iv above.
vi. Phosphate limited system
    a. All systems studies were phosphate limited. Coleman (2002) documents the presence of phosphates, blue-green algae species will outcompete *D. salina* which is responsible for the orange pink colour of lake water.
vii. Suspended fine white/grey silica, gypsum carbonate, salt particles in the water at salinity saturation to diffuse light. I.e. Suspended dark red pigmented *D. salina* mixed with white/grey suspended particles results in a pink hue.

Pink Lake and climate change

Evidence of climate change is supported by an increase in occurrence and severity of extreme episodic rainfall events resulting in large quantities of fresh water adding to an already diluted Pink Lake. Recent historic rainfall events for the Esperance area during 1989, 1992, 1999, 2000, 2005, 2007, 2013, and 2017 ranged over a 72-hour period between 224mm and 100mm (BOM 2019) (Figure 3).

Alternatively, Esperance has experienced increases in regular extreme dry periods such as 1983, 1991, 1994, 2002, 2006, and 2019. Esperance mean annual average rainfall has reduced from 640mm during 1957-1987 to 612mm as of 1989-2019 (BOM 2019) (BOM 2019). The observed extreme climatic events align with regional climate change modelling.

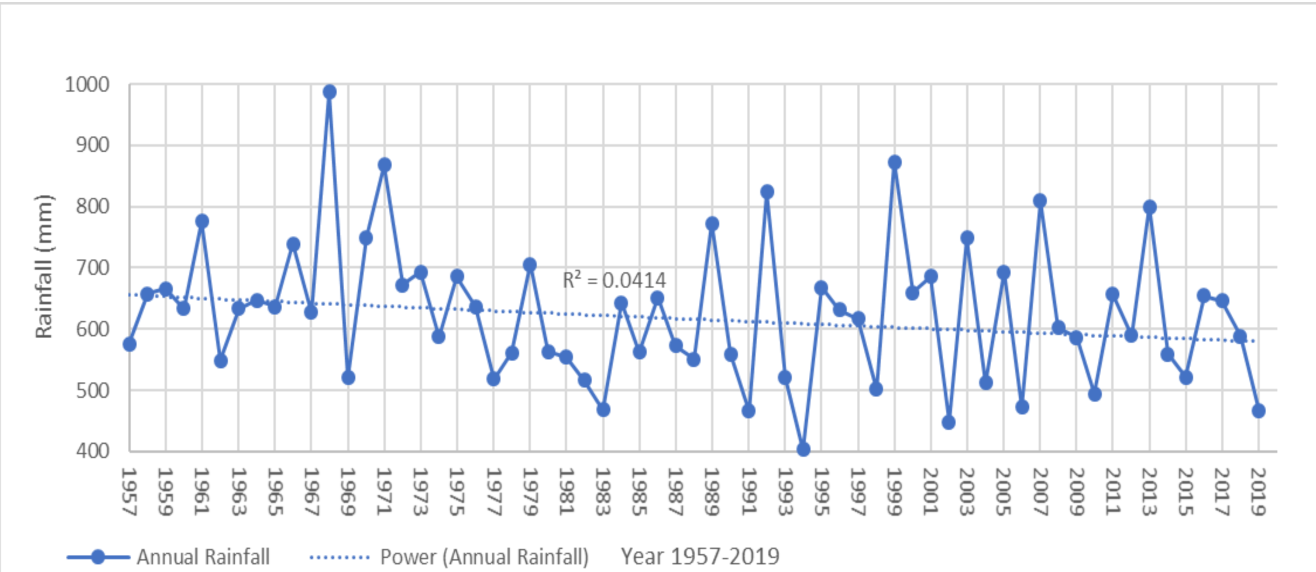

Figure 3 Esperance annual rainfall totals from 1957 to 2019 and Power trendline line. (Raw data sources BOM SILO)

Water balance scenario modelling for Pink Lake (Marimuthu 2020) include the duration and extent of dilution effects (Marimuthu 2020) and rapid lake drying of such extreme events between 2014 and 2019 (Figure 4). Increased freshwater inputs to Pink Lake resulting from land clearing for urban rural allotments and hard surfaced road infrastructure may buffer the lake during drought events but exacerbate current salt dilution issues associated with flood events.

The observed lake monitoring data for Pink Lake used in this study was collected between 2014 and 2019. Climatically this period observed data includes an average rainfall 2016 year, very wet 2017 summer, wet 2014 and 2018 winter, a very dry 2014 summer, very dry 2015 and 2019 years (Figure 4). The rainfall trend during this period indicate more extreme dry and wet periods with less occurrence of average wet winters.

Pink Lake depth has slightly increased from 2014 to 2019 (figure 5), and annual rainfall trend has been relatively steady (Figure 4), though erratic. It is important to note that monthly climatic extremes of high and low rainfall were common over this period and there are also lake depth gauge and bathymetry uncertainties that may affect the slight linear trend increase in lake depth.

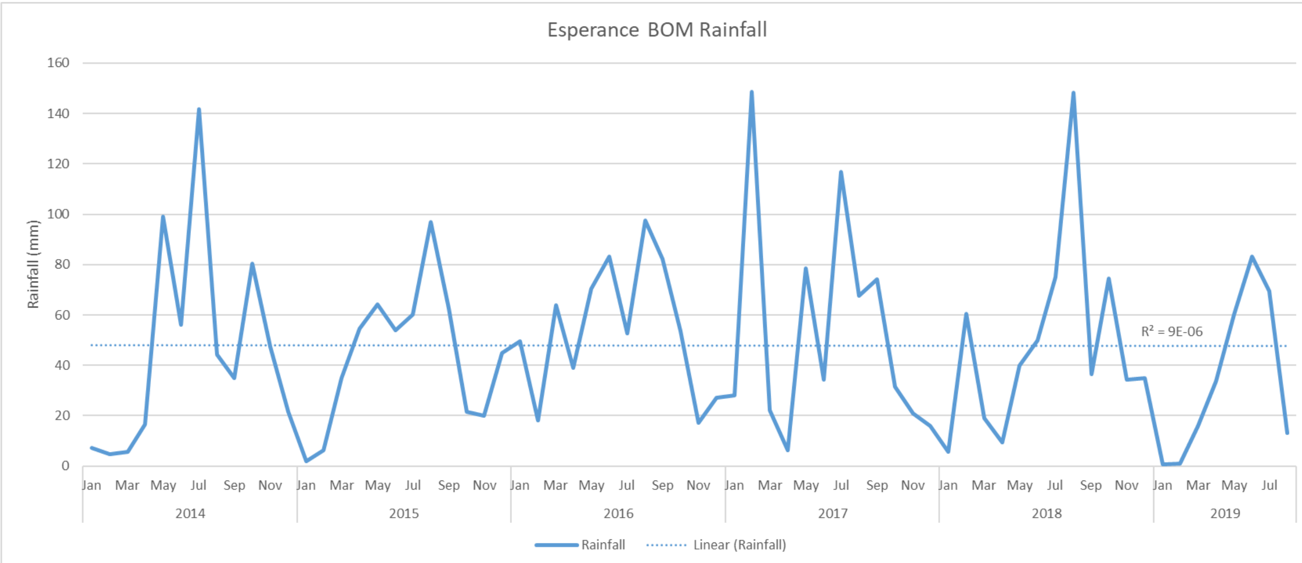

Figure 4 Esperance monthly rainfall totals from 2014 to 2019 for lake water quality sampling period post Wheatfield Pipeline (Raw data sources BOM SILO)

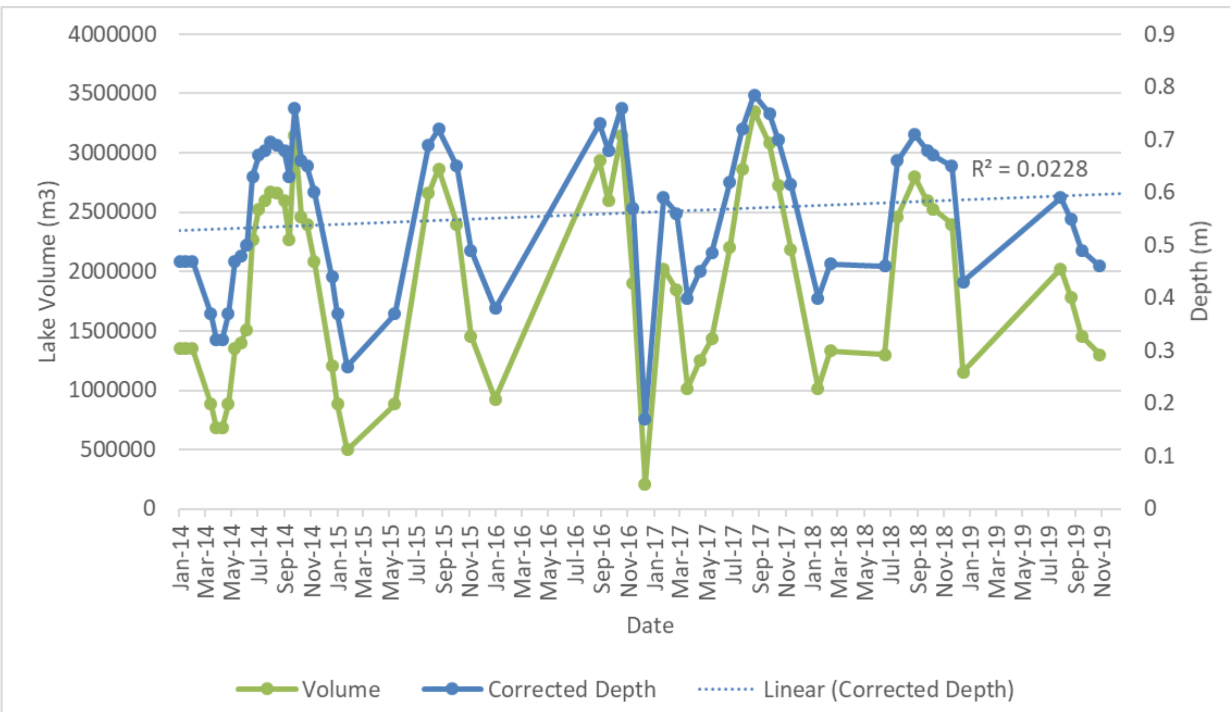

Figure 5 Pink Lake depth observed data (Raw data source DBCA) and calculated volume from 2014 to 2019

Pink Lake bathymetry volume model

Understanding how much water Pink Lake contains at varying depths is critical to understanding parameters required for the lake to be pink at certain periods throughout a year. A model of the lake's bathymetry has been prepared to calculate lake depth volumes as a foundation for water and salt balance analysis.

An old contour map of Pink Lake published in Hurle (1986) was scanned as an image and QGIS used to spatially georeferenced (align) the map to an existing digital orthophoto (Figure 6). QGIS was used to convert the 1986 Pink Lake contours to a Triangular Irregular Network (TIN), and then to a lake depth Digital Elevation Model (DEM) (Figure 7). SAGA GIS software was used to build a Lake Depth Volume model from the resulting DEM and summarised using Microsoft Excel. (Figure 8) (Appendix 3)

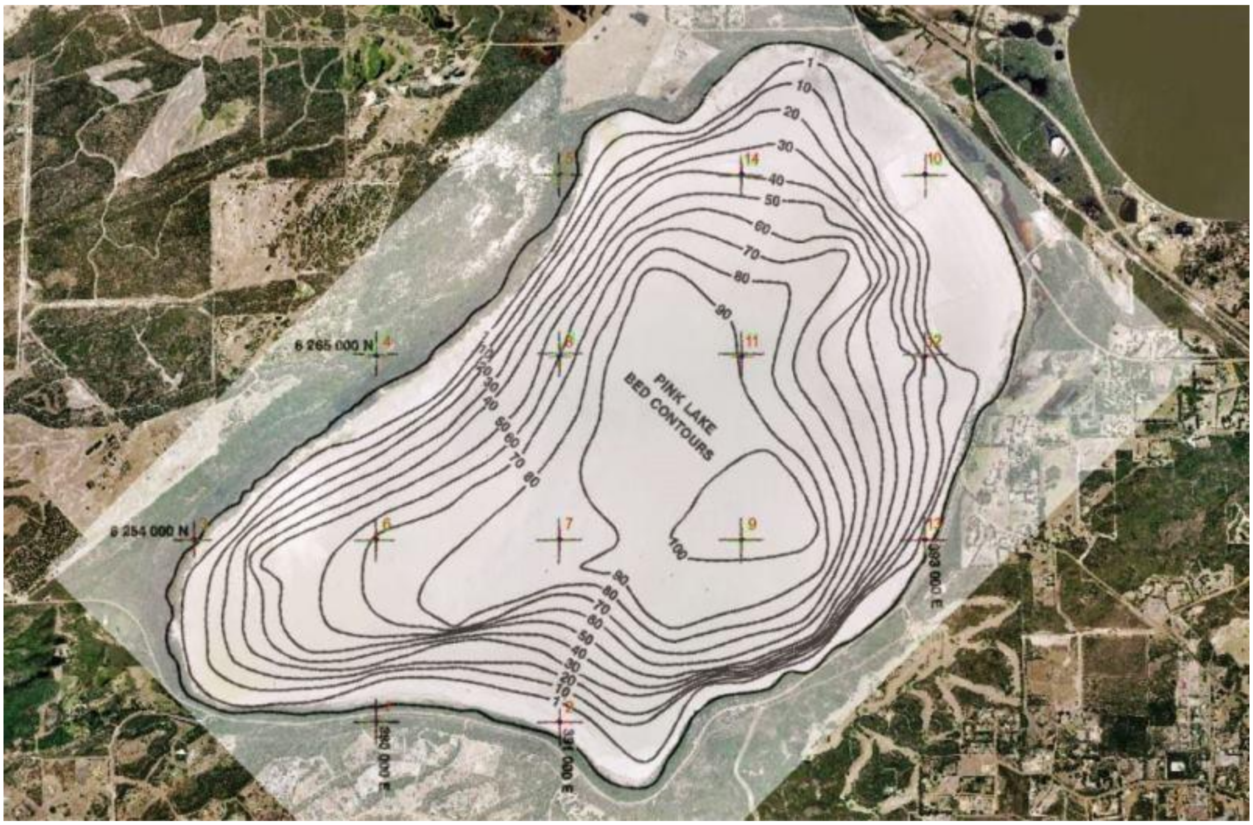

Figure 6 Georeferenced 1986 contour map (Raw data source Hurle 1986)

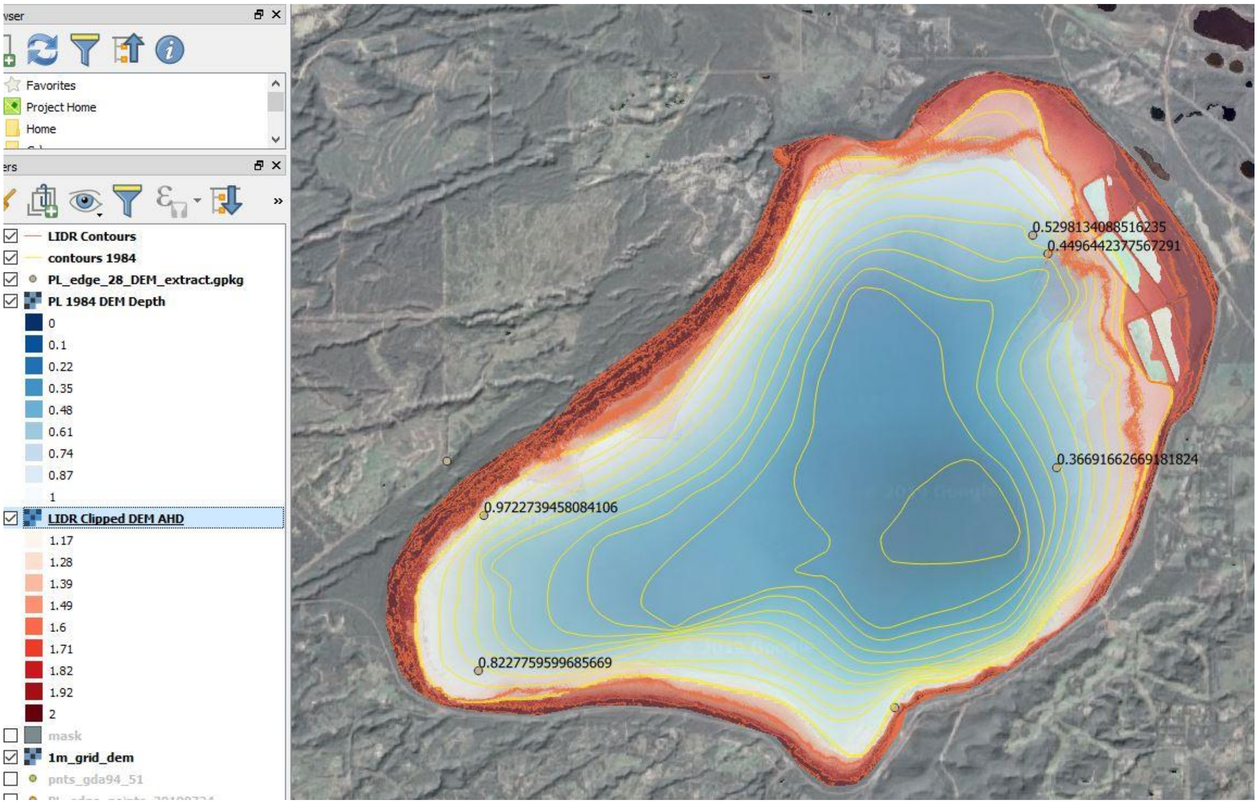

Figure 7 Pink Lake depth GIS DEM derived from 1986 contour information (Raw data source Hurle 1986)

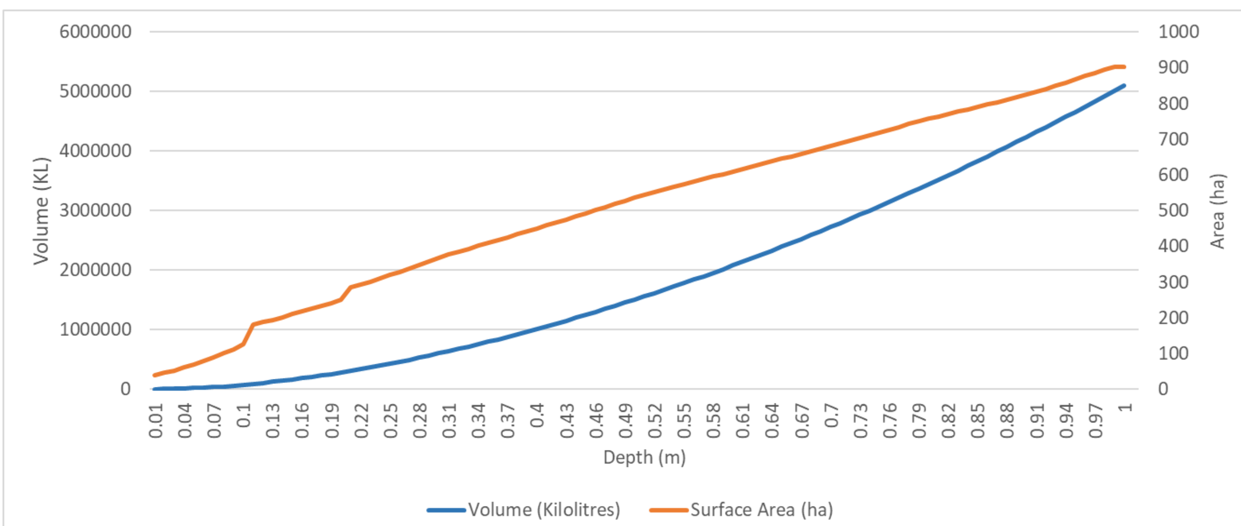

Figure 8 Pink Lake volume and area model (Raw contour data source Hurle 1986)

A partial manual bathymetry survey was conducted when surveying the existing Pink Lake depth gauge, so recalibrating lake depth observation was applied to fit the DEM bathymetry model based on the 1986 survey. This was conducted by taking a lake depth reading for Pink Lake on the 24th of July 2019 during calm wind conditions (Plate 17 and Figure 8). A GPS point was taken at the water's edge at six different locations around the lake (Figure 7). The GPS points were plotted onto the DEM using QGIS to determine a modelled lake depth. The observed lake depth of 0.27m and plotted lake edge points mean variance were calculated against the DEM model to be approximately 0.44m, an additional 0.17m. The additional 0.17m correction was added to all observed Pink Lake depth data used in the water and salt balance modelling components of this project.

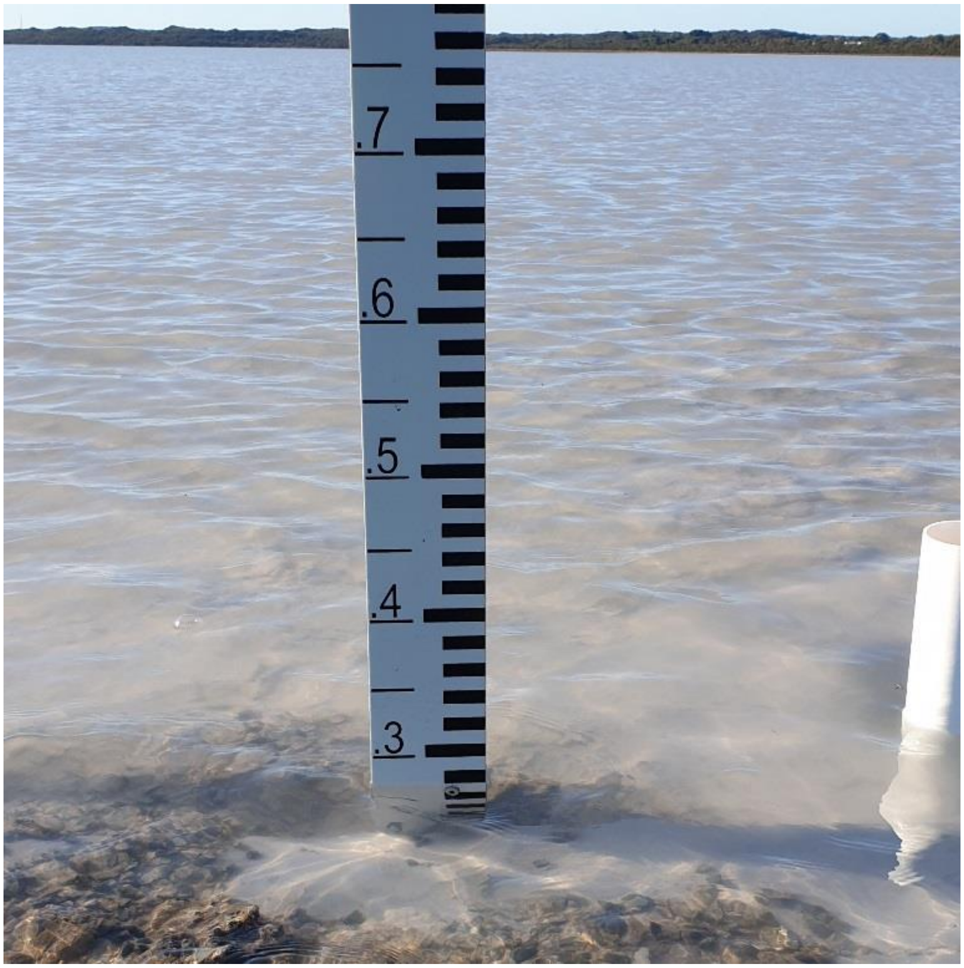

Plate 17 Pink Lake depth gauge reading on the 24th of June 2019

Measuring salinity correction

Understanding lake water salinity is critical to defining current threshold deficiencies in the likelihood of a *D. salina* pink bloom event in Pink Lake and how much salt may be available at an alternative source. As outlined in the background section of this report there have been various programs collecting water quality data across the Lake Warden Wetland System since 1979 through to the present day.

Salinity has been recorded as Parts Per Thousands (PPT) by Lane et.al (2017) for the South West Wetlands Monitoring Program (SWWMP), as electrical conductivity (Ec) mS/cm throughout the DBCA Natural Diversity Program, and more recently as evaporated TDS.

Lizamore (2020) highlighted the variation in historic versus present day reported data determining that there is up to 40 per cent lower PPT derived salinity values above 100 g/L when compared to measured evaporated TDS over the same sample period between 2009 to 2011 (Figure 9).

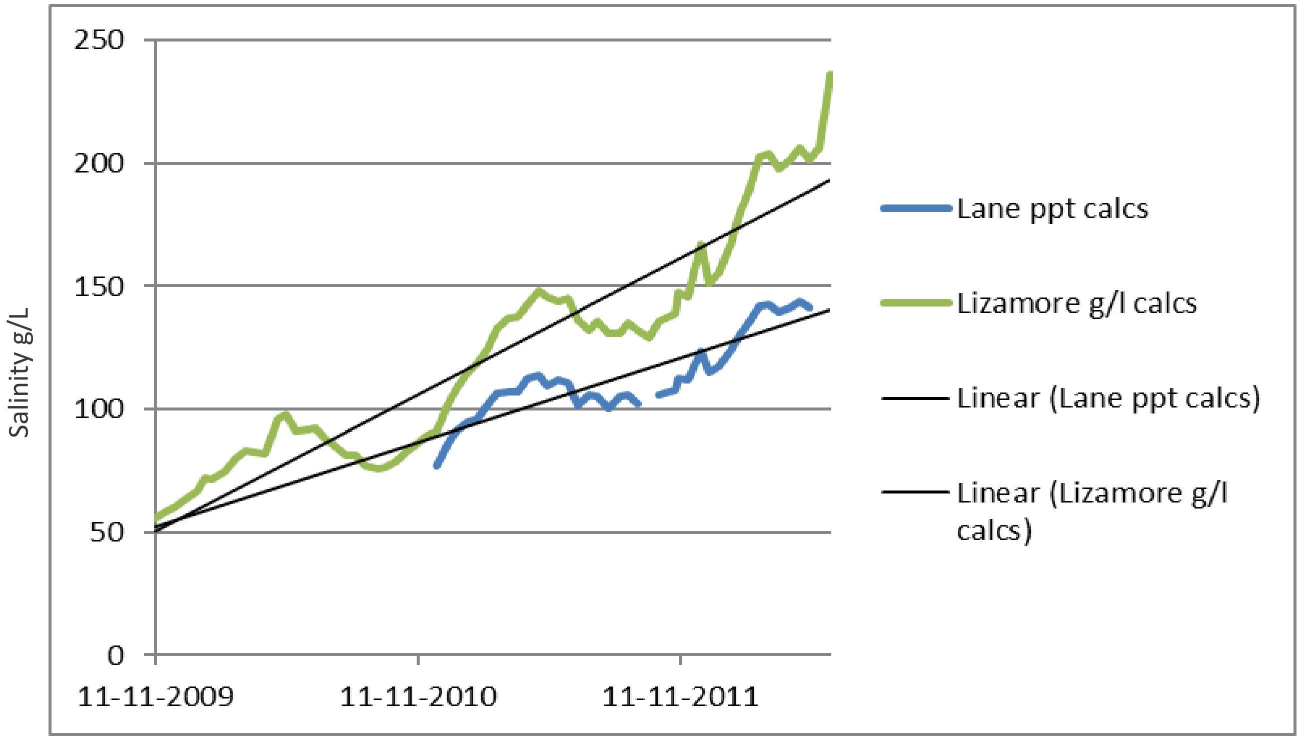

Figure 9 Salinity calculation variations for Lake Warden based on the same sampling period (Lizamore 2020)

Lake Warden is an important study comparison to Pink Lake and since the implementation of the Lake Wheatfield dewatering pipeline, salinity levels have exceeded Ec measuring equipment capability as a 1:1 ratio sample. Lizamore (2020) recommends all Ec readings greater than 150 mS/cm be diluted by 1:2 (50%), and Ec readings greater than 180 mS/cm be diluted 1:4 (25%) (Figures 10, and 11). To address accuracy issues when measuring hypersaline water close to or at saturation point, Lizamore applied a formula by Fofonoff and Liiard (1983) to convert conductivity to salinity for Lake Warden and Pink Lake data (Figures 10 and 11). Lizamore generated a Microsoft excel formula based on Fofonoff and Liiard equation to apply to Lane (2017) data (Figure 9) and other Ec DBCA Recovery Catchment data as follows:

=IF(CELL>120000,(1.0233*((((CELL-120000)^2)/CELL)+CELL)),CELL).

If the salinity value is greater than 120,000 mg/L, then a correction value will be applied. To provide further context, 120,000 mg/L is about 3.4 times more than seawater salinity. For the purposes of this feasibility study analysing primarily hypersaline lake conditions, salinity will be expressed as grams per litre (g/L), collated as evaporated TDS or corrected calculated salinity.

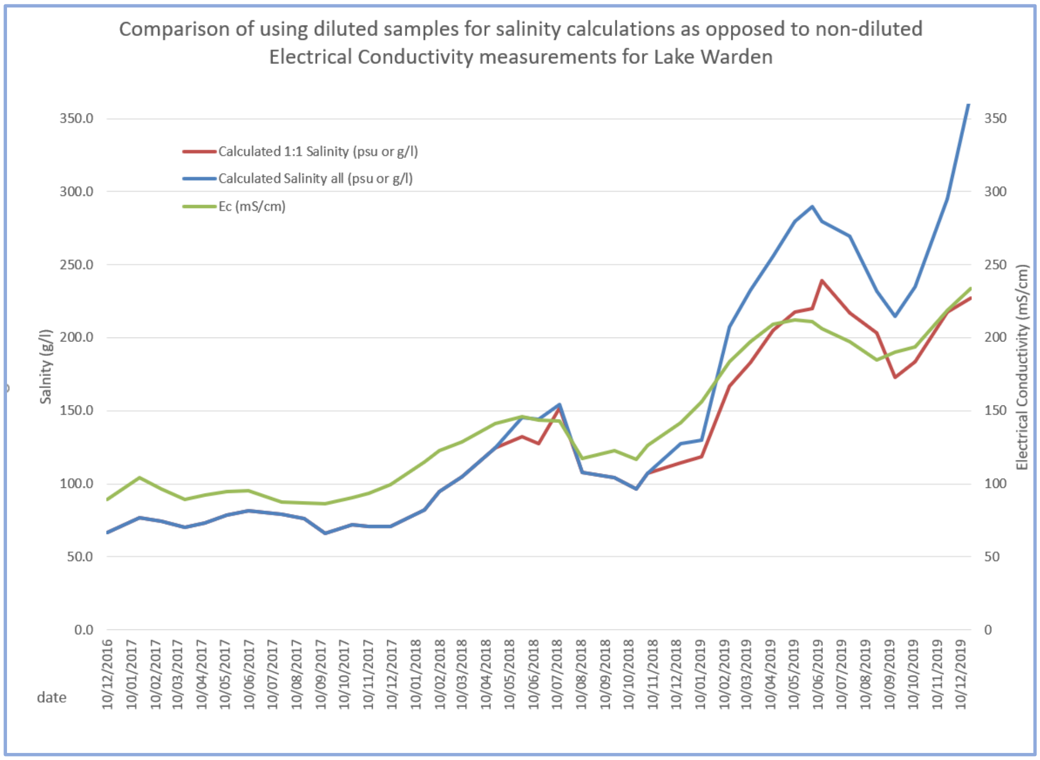

Figure 10 Comparison of using diluted samples for salinity calculations as opposed to non-diluted Electrical Conductivity (Ec) measurements for Lake Warden (Lizamore 2020)

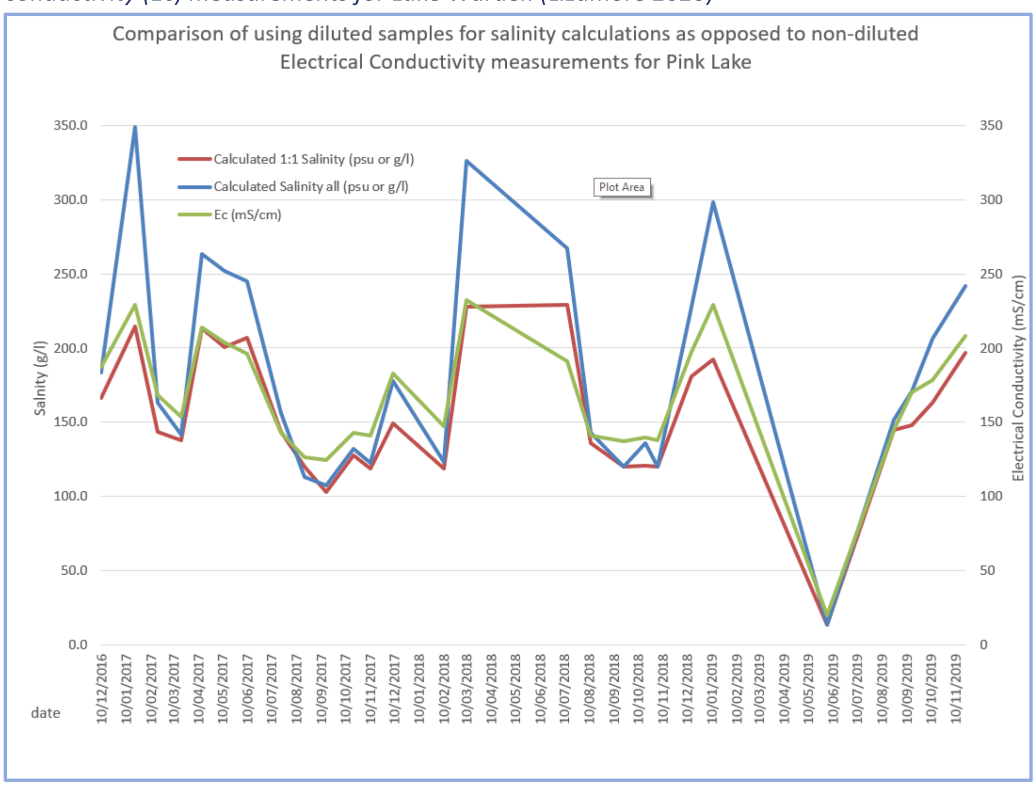

Figure 11 Comparison of using diluted samples for salinity calculations as opposed to non-diluted Electrical Conductivity (Ec) measurements for Pink Lake (Lizamore 2020)

Pink Lake salt modelling

The following section outlines a critique of the Hurle 1986 Pink Lake hydrological modelling and provides salt harvest calculations, and extrapolated salt modelling results for Pink Lake.

Critique of historic Pink Lake hydrology modelling

The first major hydrological study undertaken for Pink Lake was in 1986 by Hurle and Associates. The report's findings were used to set a maximum annual salt harvest level of 14,000 tonnes per annum using lake water pumped into evaporation ponds. If salt harvest was to exceed this quantity, then groundwater was to be used from beneath the lake to pump into evaporation ponds (Hurle and Associates 1986) as part of the license agreement (EMA 1789). WA Salt Supply never extracted groundwater for salt harvesting operations on Pink Lake (Lister Pers. Comms 2020).

Mernagh (2013) summarised findings from the 1986 Pink Lake Hydrology study. Hurle estimated surface water salt inflow at 800 tonnes per year, ground water salt inflow at 5,500 tonnes per year, and an estimated 1.1 million tonnes of salt on the Lake Surface. Drilling results estimated up to 18 million tonnes of salt stored in subsurface sediments (Galloway et al 1986).

A review of the Hurle (1986) report findings using Marimuthu (2020) water balance modelling for Pink Lake and salt balance modelling in this document show that Hurle significantly over estimated surface water, groundwater salt inputs and lake surface salt storage processes.

Based on Marimuthu (2020) and Marimuthu et.al (2005b) hydrological studies, there is no evidence that the estimated 18 million tonnes of salt in subsurface sediments under Pink Lake as identified by Hurle (1986) discharges into Pink Lake from the underlying saline Pallinup aquifer. Nested groundwater monitoring piezometer sites between Pink Lake and Lake Warden demonstrate overlying sand dune surficial aquifers recharge into the underlying Pallinup aquifer, and not vice versa. This observation is based on extremely low transmissivity in the Pallinup aquifer measured during past studies using pump tests on Pink Lake and Lake Warden nested piezometer sites and lake-bed mini-piezometer monitoring during the early to mid-2000's (Marimuthu et.al 2005a and 2005b).

The underlying Pallinup aquifer gradient is very flat and slightly slopes towards the Esperance bay adding further evidence to non-discharging into Pink Lake. Also, the 10-17 meters of sandy calcareous sediments identified beneath Pink Lake by Hurle during three exploration drill holes in 1986, near the evaporation ponds indicate the sediment porosity is too porous to result in atmospheric up-wicking of salts from the Pallinup aquifer into that particular area of Pink Lake.

Hydrogeologically there is also a groundwater flow barrier of shallow to exposed basement granite on the north western lakebed of Pink Lake that runs approximately south west to north east under the northern portion of the lakebed (Street and Abbott 2004). The granite basement ridge further prevents saline discharge into Pink Lake on the north western lake surface by impeding already low transmissive and groundwater gradients from the Pallinup aquifer which is recharged by the cleared Lake Warden western sub catchments (Bukenerup creek and Lake Monjingup areas) (Figure12). The Department of Water (2016) geophysics interpretation report further provides evidence to the location of the shallow granite basement areas identified by Street and Abbott (2004). Marimuthu (2020) has modelled the contribution of the intermediate scale Pallinup siltstone sediments and flat gradient saline aquifer to Pink Lake surface discharge as negligible to zero.

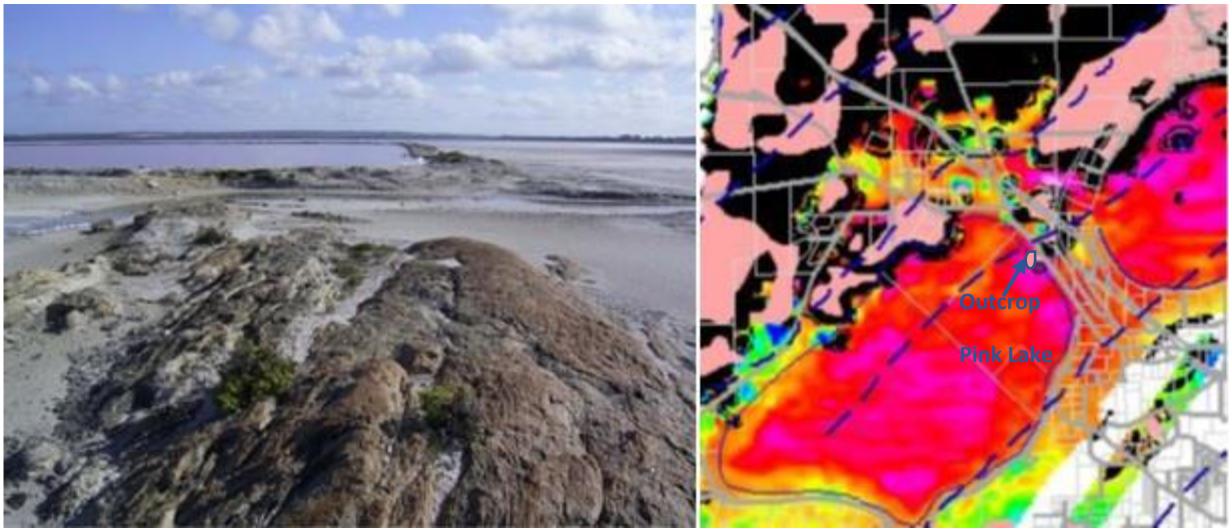

Figure 12 Exposed banded gneissic rock in Pink Lake northern edge. Geophysics uncertainty masked in black and interpreted shallow basement overlaid in 'skin colour pink'. Dashed lines are metamorphic fabric from regional magnetic data (Street and Abbott 2004).

The large discrepancies in Hurle's estimates in part is likely due to the application of available broad scale regional data to local Lake scale models, and non-availability of current technology used in this study. The Hurle salt input over estimation is addressed by developing a salt balance using observed water quality data, a water balance model, and extrapolating historic archive information in the absence of formal data. Understanding the salt balance of the system is critical to understanding how to make Pink Lake pink again as high levels of dissolved salt is a key stressor for *D. salina* to produce large quantities of required ß-Carotene.

Pink Lake pre 1980 surface salt loads.

Pink Lake was regularly pink during the 1980's (Plate 6) in late spring/early summer, whilst salt harvest operations increased markedly around 1980. Estimating Pink Lake's surface salt load prior to 1980 required extrapolated calculations using archive information in the absence of scientific data. The 1980 Esperance Express Newspaper article (EMA 1797) quoted salt quantities were used to calculate lake water salinity as g/L for early summer, and Esperance Express 1987 Newspaper article content (EMA 1778), to determine when water was pumped into evaporation ponds during October/early November. This information was used to compare current day October/November water salinity observations with extrapolated pre 1980's salinity estimates to demonstrate how long-term salinity trends have changed.

The EMA 1797, 1980 Newspaper article references 1 gallon of water containing 2.5 pounds of salt as of October/November when water was pumped from Pink Lake to evaporation ponds (Appendix 1). This salt quantity converts to being about 300 g/L of dissolved salt. The lake depth for this period would be an approximated minimum 0.4 - 0.5 m to pump the quoted 60,000 gallons (227,125 L) per hour rates. The approximated pre 1980 late spring lake depth, when converted to a volume using the bathymetry model, is calculated at approximately 304,493 tonnes of salt with salinity at 300 g/L.

This 1980 estimated quantity of late spring dissolved salt stored in the lake water would likely have been similar to 1914 levels, due to low rates of manual shovel extraction in the past. This assumption is based on the intact salt crust precipitation cycle occurring on Pink Lake up until the late 1980's, even though the bulk of salt crust had been harvested by shovel by 1960. This cycle involves salt precipitating and crystallising in and out of solution at the point of saturation (about 310 g/L) in the water column and is driven by evaporation and wind. The important salt crust precipitation cycle historically would begin during late spring when lake depths were about 0.5-0.6m and salinity equal to or greater than 300 g/L for periods longer than four weeks. The salt precipitation cycle became shorter in duration and over less area during the 1990's, resulting in the lake becoming too shallow to support a *D. salina* pink bloom. This greatly diminished hydro chemical process results in an anecdotal decrease in *D. salina* pink blooms on Pink Lake. One of the last major pink bloom periods for Pink Lake was noted in the Esperance Express Newspaper in May of 1994 which quotes "*the pink colour only lasted 8 weeks due to a dry year*" (EMA 1168).

The EMA West Australian Newspaper article (12/03/1914) was used to estimate salt crust quantities on Pink Lake (Appendix 1). The article references the presence of a 3-inch-thick salt crust which is calculated to be about 317.5 tonnes of salt per acre. This estimate is supported by EMA 1797 reference newspaper article in 1980 that states an inch of salt crust at Pink Lake equates to about 100 tonnes of salt per acre. The salt thickness at Pink Lake estimated for 1914 at 3 inches thick is about 784.60 tonnes per hectare. This calculation does not account for a decrease in crust thickness towards the lake's outer margins. The current changes in salt thickness across Lake Warden were used to estimate a varying salt crust thickness from the outer lake edged to the centre for Pink Lake based on its area of 1000 ha as shown in Table 3. The total estimated summer salt crust load for Pink Lake in 1914 is about 619,000 tonnes.

Table 4 Estimate of Pink Lake Salt Crust as of 1914

Crust Thickness	Area (Ha)	Salt load (Tonnes)
8.00	600	470,757
5.00	200	98,842
2.50	200	49,421
Total	**1,000**	**619,020**

Based on the above estimates, the accessible total salt load for Pink Lakes surface crust and lake water prior to salt harvesting beginning in the late 1800's was about 923,500 tonnes. An estimated 156,000 tonnes of salt crust and lake brine salt were harvested from Pink Lakes surface up to 1980 prior the salt evaporation ponds becoming fully operational (Appendix 1). Taking this quantity into account, about 767,500 tonnes of surface salt was present in Pink Lake around 1980. Hurle (1986) estimated 330,000 tonnes more than this calculation, their total being 1,100,000 tonnes of surface salt as of 1986 for Pink Lake. An estimated 465,800 tonnes of salt have been harvested from Pink Lake between 1897 to 2007 which is about 50 per cent of the lakes estimated total available salt (Appendix 1). Up until 1980, about 156,000 tonnes of salt had been harvested over 83 years, and a further 310,000 tonnes between 1980 to 2007 over 27 years.

Pink Lake salt inputs

The supporting hydrological water balance technical report prepared by Marimuthu (2020), and BOM SILO (2019) rainfall data for Esperance were used to calculate an annual salt contribution estimate for Pink Lake. Pink Lake is a terminal, primarily surficial groundwater discharge and in-situ rainfall driven lake, with limited local adjacent surface inflow from surrounding roads. Rainfall containing minute quantities of marine salt resulting from ocean evaporation precipitates onto the lake and accumulates over millennia. Other salt transport mechanisms include sea mist, and super fine salt dust particles from surrounding bare sand dune systems. In 1976 Esperance was one of several sites used to determine the geographic variation of salt precipitated across Western Australia by Hingston and Gailitis (1976).

The study calculated 178 kg of TDS per hectare based on 664 mm of annual rain during 1972 at the Esperance BOM site located adjacent Lake Warden. This TDS measure was used to extrapolate for all Esperance annual rainfall records. The 178 kg/ha value equates to 0.26807 kg/mm of TDS per hectare and then multiplied by the total annual rainfall value recorded by BOM for each year from 1957 to 2019. This method provides an annual total kilograms of TDS per hectare for each actual year of rainfall recorded at the Esperance BOM site. Each annual salt value was then multiplied by 1040 ha, being the surface area of Pink Lake and converted to Tonnes per annum of salt contribution to Pink Lake for each year of rainfall recorded. Between 1957 and 2019 (62 years) approximately 11,000 tonnes of TDS have been deposited into Pink Lake via rainfall and other climatic processes. Considering annual total rainfall variability for the 62-year period of rainfall records, the annual mean (average) rainfall deposited salt into Pink Lake is about 174.5 tonnes per annum.

The other main mechanism for salt to enter Pink Lake is via surficial groundwater discharge. The main groundwater contribution to Pink Lake is via fresh to brackish groundwater discharge onto the lake's margins where quaternary Holocene deep sand dunes, created under aeolian processes, intersect with the underlying tertiary Pallinup siltstone sediments that from part of the lakebed surface (Plate 18).

Plate 18 Fresh to brackish surficial groundwater discharge onto northern and southern margins of Pink Lake, 24th June 2019.

Prior to extensive land clearing in 1962, anecdotal historical evidence in the EMA (ref:1801) newspaper article describes, "*Mrs J. Gordon noticed freshwater streams fed by springs and soaks entering Pink Lake but noted it did not seem to affect the lakes colour*" (Appendix 2). These local surficial aquifers discharging onto the margins of Pink Lake can still be seen in current day Google map imagery on the lakes north western boundary (Figure 13), as tannin stained surface water (Plate 18) and brackish tolerant sedge land plant communities.

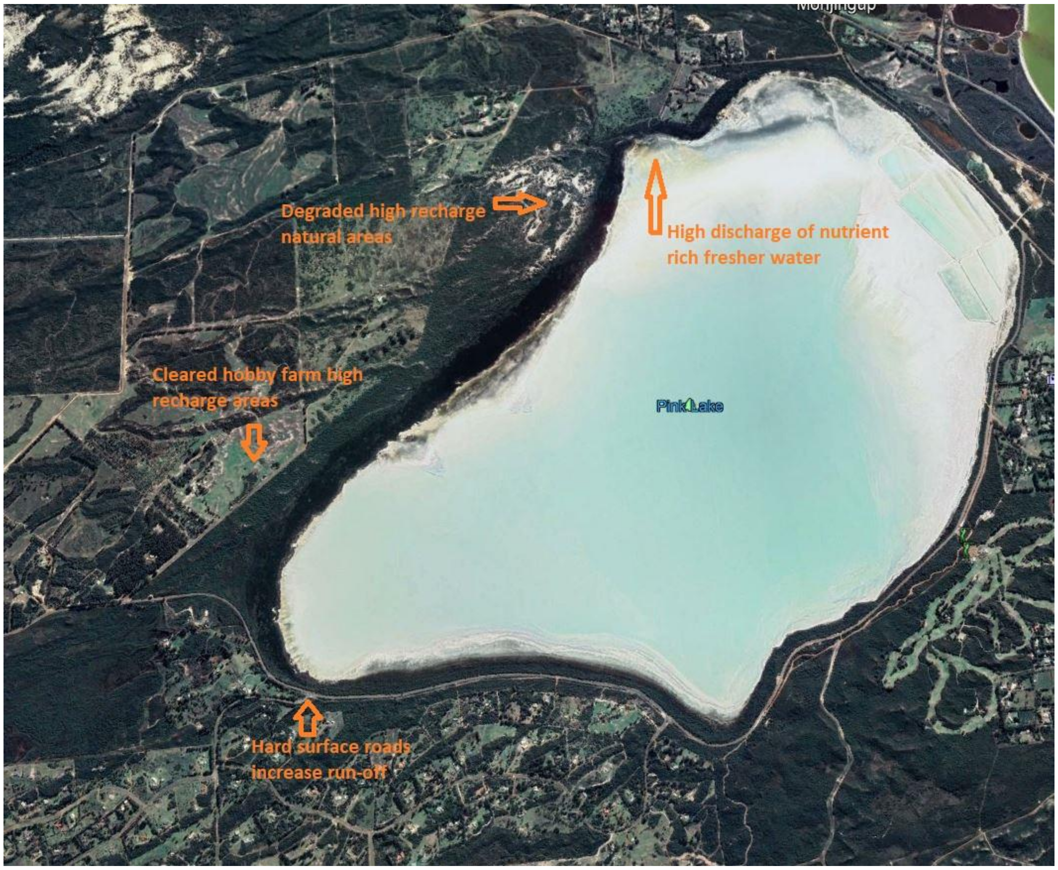

Figure 13 Pink Lake freshwater discharge from stream fed soaks and springs and surficial aquifer contributing recharge areas (Image from Google Earth 2020)

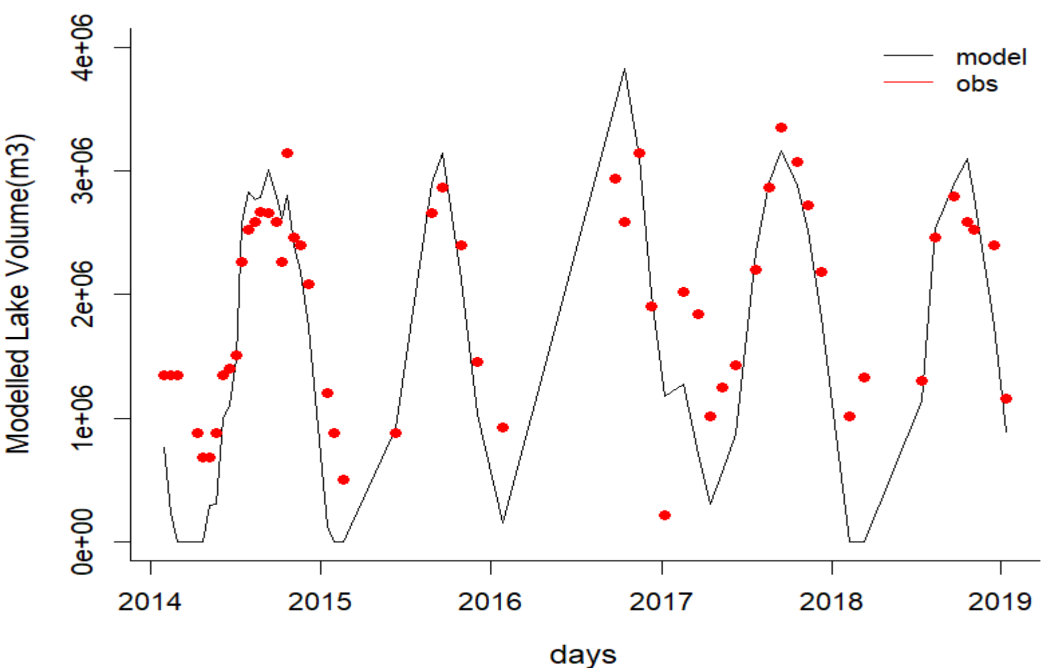

Figure 14 Modelled vs Observed Pink Lake Volume (Source of Observed data DBCA)

The volume of Pink Lake discharge from the surficial aquifers have been modelled by Marimuthu (2020) for a 7.5-year period from 2012 to 2019 using limited observation bore and lake depth data (Figure 14).

The surficial groundwater input component of the Pink Lake volume water balance model (Figure 15) was used to calculate salt contribution. The modelled surficial groundwater daily discharge quantities were converted to an estimated salt load using sample results of discharge water measured by Lizamore (2020) at a TDS of about 9.5 mg/L (Plat 9, Figure 15). The sampled TDS value was multiplied against each daily modelled discharge value and summed to show a total salt contribution of about 241 tonnes to Pink Lake between 2012 to 2019. The mean annual amount of surficial groundwater salt inflow to Pink Lake over the 7.5 years of modelled data is about 32 tonnes per annum. These inputs take into account increased recharge of surrounding current day land clearing for urban rural development (Figure 13).

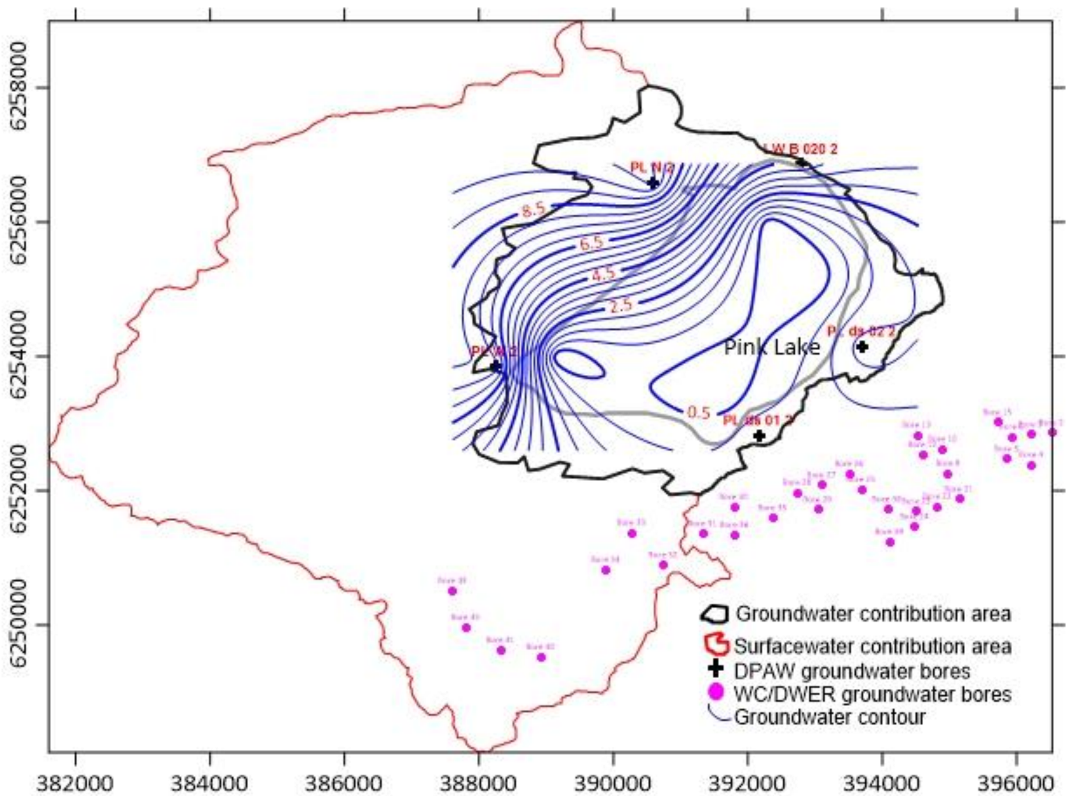

Figure 15 Estimation of surficial groundwater flow to Pink Lake (Marimuthu 2020)

Note: Groundwater contour has been blanked out on the south-eastern site due to insufficient data.

Marimuthu (2020) surficial groundwater model parameters include: K=hydraulic conductivity (m/d) – 32.0 m/d; I= average hydraulic gradient (m/m) – $8.33X10^{-4}$ to $6.22X10^{-3}$ m/m; D= average aquifer flow depth (m) – 10 to15 m; P length of flow section (m) – 1500 to 4250 m

The total average annual estimate of salt contribution to Pink Lake via rainfall and surficial groundwater discharge is about 207 tonnes per annum. The total estimated salt harvested from Pink Lake between 1896 – 2008 is about 465,798 tonnes (Appendix 1) in the form of salt crust and evaporated lake brine. This is the estimated equivalent of removing about 2,254 years of naturally accrued salt from the lake surface over a 112-year period, with 75 per cent of the total salt removed in the last 30 years of salt harvesting operations up until 2008.

Pink Lake *D. salina* salt requirements

The likelihood of a present *D. salina* pink bloom occurring at Pink Lake is extremely low to nil. Observed salinity and lake depth data from 2014 to 2019 (6-year period) (Lizamore 2020) demonstrates key thresholds for current lake depth to salt concentration of greater than 300 g/L maintained for longer than a four week period are not being achieved under existing hydrological, and climatic conditions (Figure 15). The management option of adding more *D. salina* to the lake would not be sustained or result in a pink bloom under existing lake conditions.

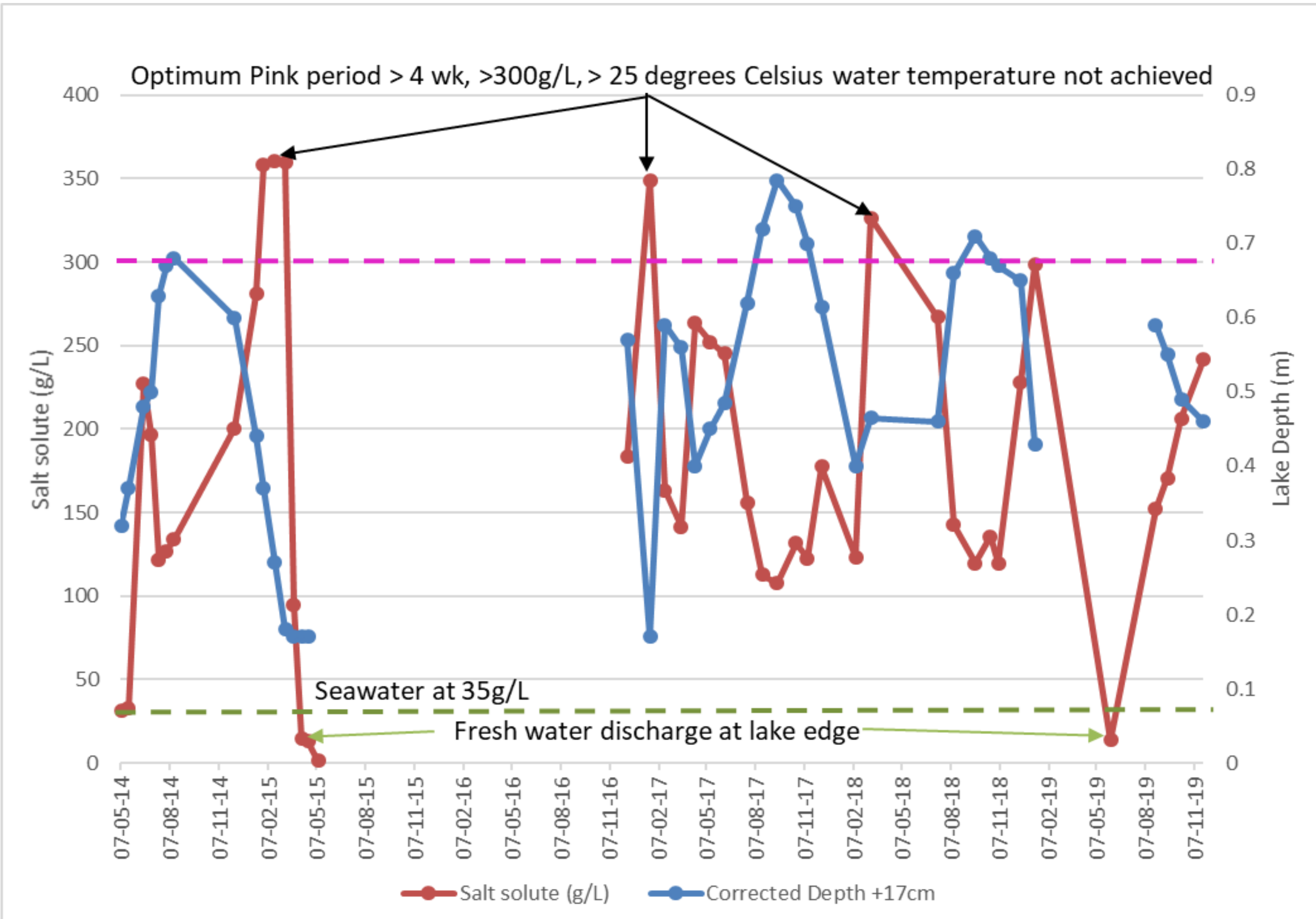

Figure 16 Pink Lake salinity to lake depth and D. salina pink bloom salinity threshold as a pink dashed line (Raw Data Source DBCA)

Salinity, salt quantity, lake depth, time of year and duration of variables are key to defining the current day response of *D. salina* biological processes in Pink Lake. To estimate quantities of surface salt currently in Pink Lake, observed salinity and lake depths were converted to tonnes of salt using the lake volume depth bathymetry model. The salinity sampling data was multiplied by its associated lake depth volume, measured in litres, and converted to a salt load value as tonnes (Figure 17). The highly variable results are due to water mixing processes from strong winds and the location of the water sampling and depth gauge site at the south western edge of Pink Lake where there is fresher surficial aquifer discharge occurring.

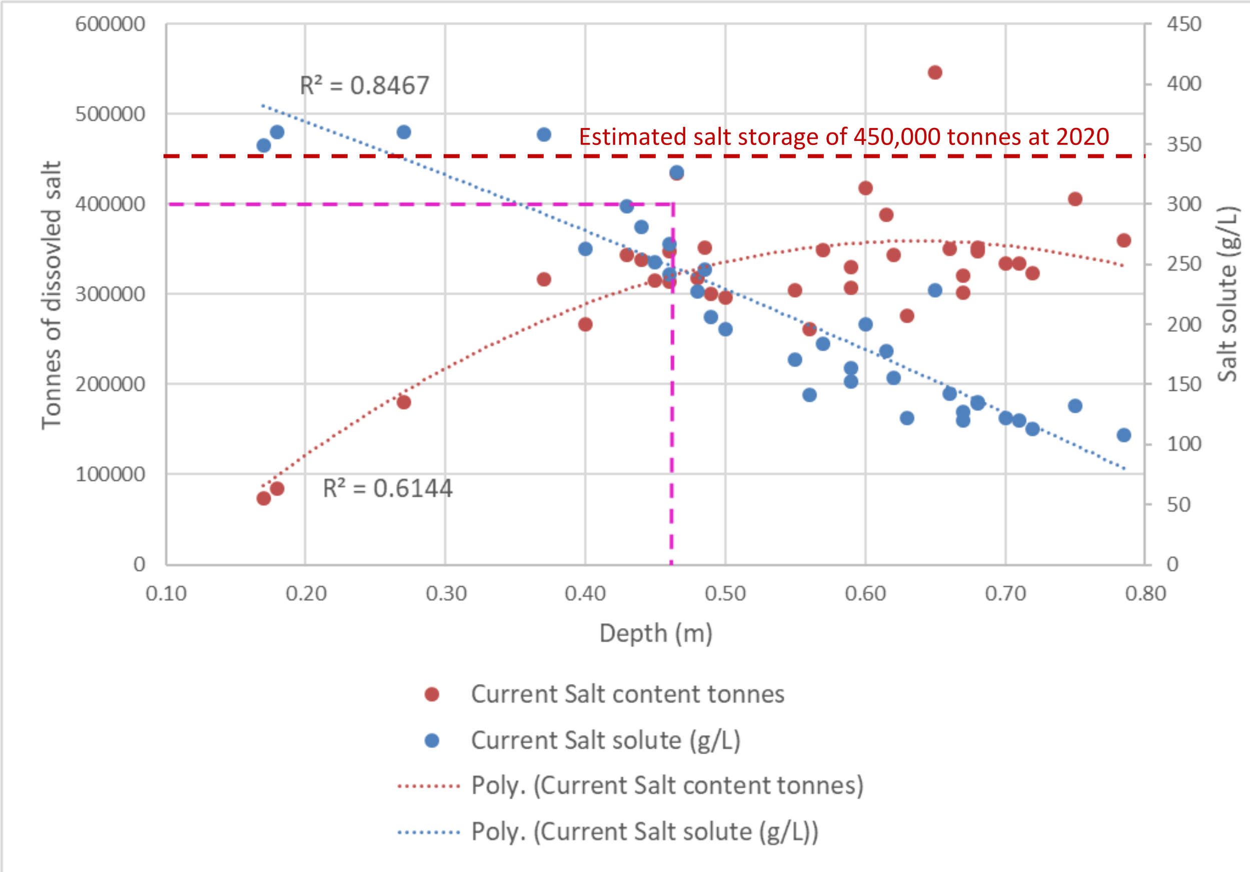

Figure 17 Pink Lake water salt load and salinity at depth, with lake edge freshwater seep data removed. Pink dotted line represents D. salina salinity of >300 g/L and estimated lake depth thresholds (Raw data source DBCA).

The pink dotted line represents the minimum salt concentration (>300g/L) and Lake depth (<0.47m) require for the possibility of Pink Lake to turn pink under current conditions (Figure 17), which need to start around October and November. The fresher surficial discharge sample records were removed from the analysis to gain a better representation of the main water body and lake surface salt components. The salinity range is between about 100 g/L to 360 g/L. Most of these values range between 100 g/L to 250 g/L at depths of 0.8 m to 0.4m, respectively. Maximum intermittent salinity is about 360 g/L ranging between depths of dry/pooling (0.17m) to 0.38m. Current dissolved salt loads in Pink Lake range between 80,000 to 450,000 tonnes of salt. As lake salinity reaches saturation at depths of less than 0.38m, between 100,000 to 350,000 tonnes of salt precipitates to form a crust on the lake surface (Figure 17) (Plate 10b).

How much additional salt would be needed to increase Pink Lake's salinity at depths required to maintain a minimum four-week period conducive for existing *D. salina* to produce a pink bloom? Two scenarios have been modelled hypothetically increasing observed salinity records by 30 per cent (Figure 18) and 50 per cent (Figure 20). The increased salinities of the observed data are converted to salt volume to show new dissolved salt loads at observed lake depth. Changes in modelled temporal response of Pink Lake salinity scenarios are used to demonstrate the likelihood of the *D. salina* pink bloom salinity duration and depth thresholds being achieved (Figures 19 and 21). The calculated maximum salt quantity for each scenario is then linked to the quantity of salt present at a year of salt harvest operations for reference to historic pink bloom evidence (Appendix 1).

Pink Lake 30 per cent salinity increase scenario

Modelling Pink Lake with a 30 per cent increase to current salinity (g/L) requires about 164,000 tonnes of additional salt (Figure 18). This increases the chance of exceeding *D. salina* pink threshold targets of salinity >300 g/L for periods longer than 4-week using observed data between 2014-2020. The following modelled threshold duration periods are estimated from Figure 19 for duration periods 1, 2, 3 and 4.

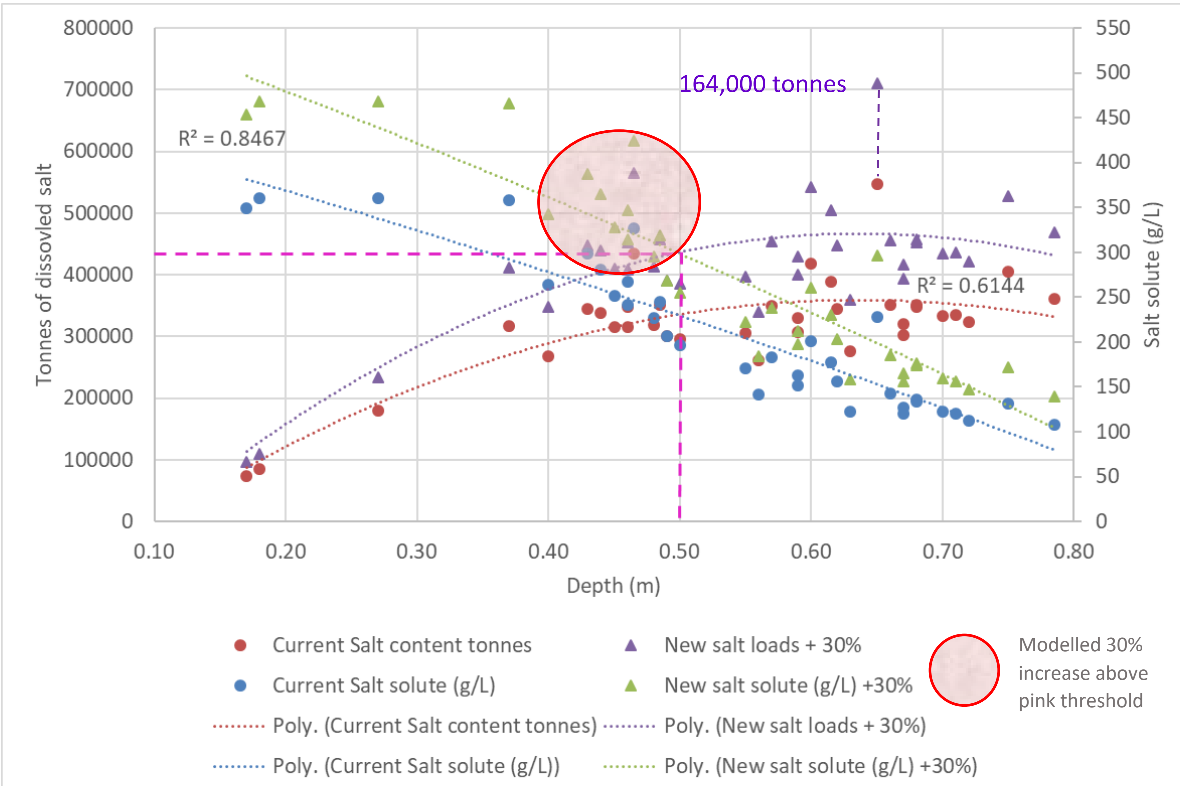

Figure 18 Pink Lake modelled 30% salinity scenario changes to observed data and calculated salt volumes at depths. Pink dashed line is salinity threshold for D. salina bloom (Raw Data Source DBCA)

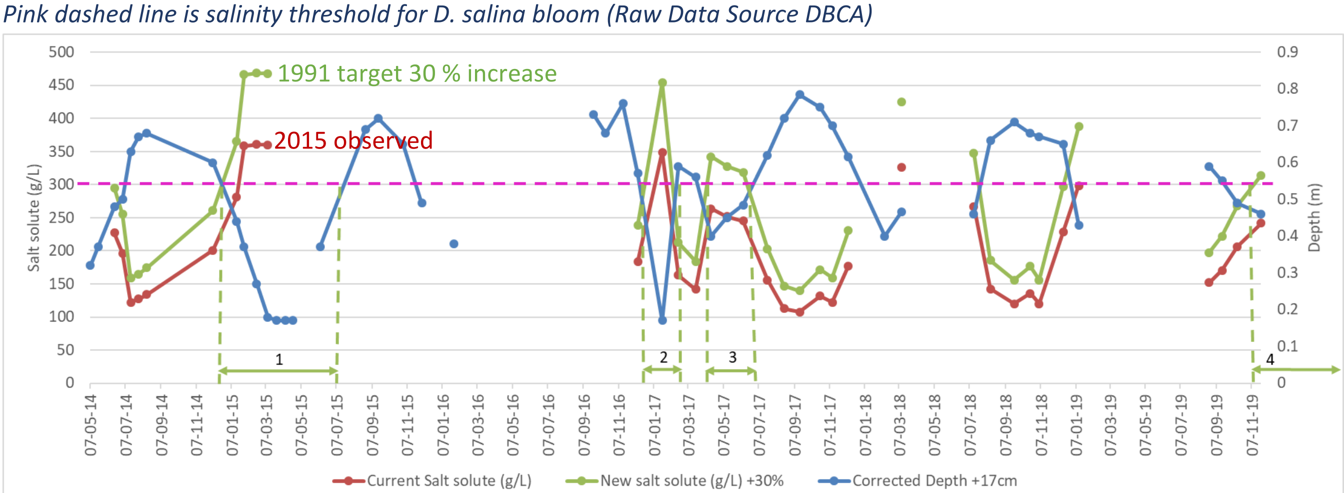

Figure 19 Pink Lake modelled 30% salinity increase scenario (additional 164,000 tonnes of salt) to observed data at depth over time. Pink dashed line is salinity threshold for D. salina bloom (Raw Data Source DBCA)

Both salinity duration and lake depth thresholds are required to meet the likelihood of a pink bloom (Table 5). Based on limited discontinuous observed lake depth and salinity data a modelled additional 164,000 tonnes of salt would likely result in at least four pink bloom events between 2014 and 2020. It is also likely that the bloom events would occur multiple times within a threshold period as the lake dries in summer and then increases in depth during autumn for 2014 and 2015, 2016 and 2017, and 2019 and 2020 (Table 5). The summer of 2018-2019 would also likely have met both pink bloom thresholds.

Table 5 Pink Lake observed data and modelled 30% salinity increase scenario comparison to D. salina pink bloom condition thresholds for salinity, duration, and lake depth.

Period	Scenario	Salt Threshold Start date	Salt Threshold finish date	Duration Weeks	Salt duration >4 weeks	Depth range	Depth threshold 0.45m
1	Observed	5-01-15	4-05-15	15wk, 5d	Yes	0.30-pooling	No
	Modelled	22-12-14	6-07-15	28wk, 1d	Yes	0.55-pooling	Yes
2	Observed	10-01-17	30-01-17	3wk	No	0.25-pooling	No
	Modelled	14-12-16	10-02-17	8wk, 3d	Yes	0.50-pooling	Yes
3	Observed	Not reached	N/A	0	No	0.44-0.47	Yes
	Modelled	8-04-17	25-06-17	11wk, 2d	Yes	0.50-0.40	Yes
4	Observed	Not reached	N/A	0	No	0.45-pooling	Yes
	Modelled	10-11-19	Ongoing as of 29-02-20	16wks ongoing	Yes	0.48-pooling	Yes

An additional 164,000 tonnes of salt would increase the 300 g/L salt threshold duration for 2014 to 2019 observed data by approximately 5-15 weeks and salt solute levels from 250-350 g/L to 300-450 g/L. The 300 g/L threshold would also be reached at lake depths of about 0.5m resulting in a long period for the *D. salina* to build up in concentration and produce greater amounts of ß-carotene pigment. Temperature and light intensity during warmer months would be important increasing likelihood of a pink bloom during these periods of high salinity.

The additional 164,000 tonnes of salt would recover Pink Lake approximately to 1991 salt levels (Appendix 1). Though land clearing and development in the Lakes catchment area has resulted in increased local run-off and surficial groundwater discharge into the lake, these impacts may help buffer climate change extreme dry periods and help Pink Lake meet a minimum early summer lake depth threshold of >0.45 m. Extreme episodic flood events greater than 100mm within 24 hours would likely dilute the lake and delay the occurrence of an algal bloom by up to three years depending on how dry the following years are.

Pink Lake 50 per cent salinity increase scenario

Increasing salt by 273,000 tonnes would further buffer the likelihood of pink blooms post flood events resulting in an estimated 50 per cent increase in lake salt concentrations (Figures 20, 21) and depth thresholds increasing to 0.5 -0.6 m. These salinities would likely be representative of 1983 concentrations (Appendix 1) and indicative of a pink bloom as shown in Plate 1. Salt crust formation would likely expand and thicken out to margins of the lake.

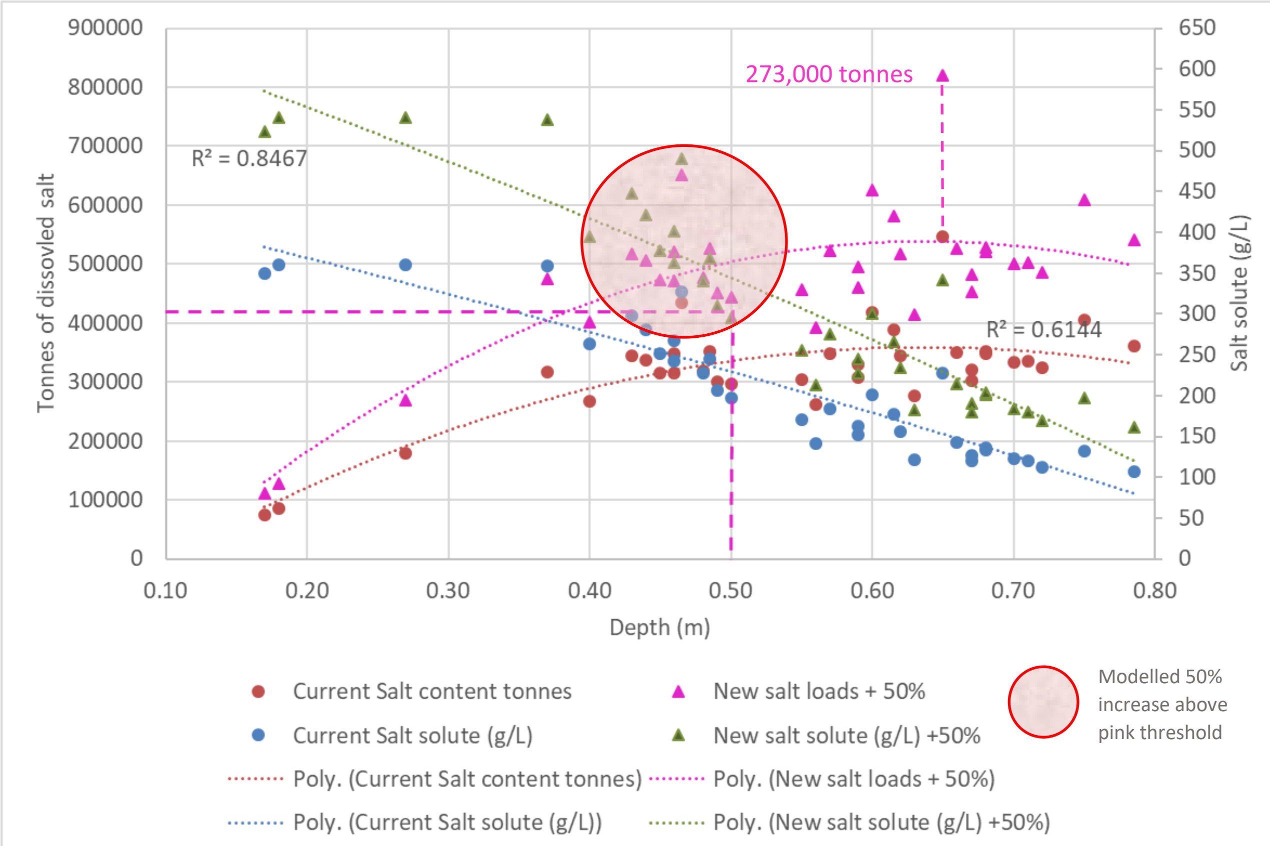

Figure 20 Pink Lake modelled 50% salinity scenario changes to observed data and calculated salt volumes at depths. Pink dashed line is salinity threshold for D. salina bloom (Raw Data Source DBCA)

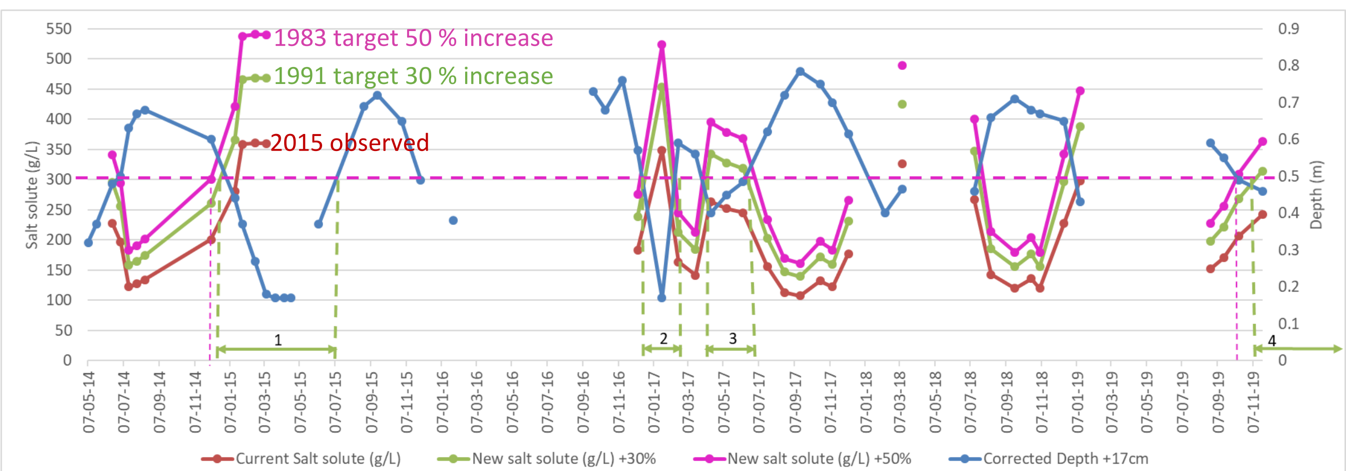

Figure 21 Pink Lake modelled 50 % and 30% salinity increase scenario to observed data at depth over time. Pink dashed line is salinity threshold for D. salina bloom (Raw Data Source DBCA)

Pink Lake salt summary

The following points summarise major findings from the Pink Lake salt modelling and extrapolated calculations using historic information:

- The 1900 total surface salt, including crust and brine, is estimated at 923,500 tonnes
- The 1980 total salt crust and solute loads are estimated at 767,500 tonnes
- Between 1897 to 2007, an estimate 465,800 tonnes salt was harvested from Pink Lake.
- Up until 1977, 111,000 tonnes of salt crust were harvested from the lake by hand shovel.
- Between 1977 – 2007, 353,800 tonnes of brine salt were removed by pumping lake water to evaporation ponds
- The Hurle (1986) salt modelling and harvest quotas of 14,000 tonnes overestimate salt inputs and surface salt availability for Pink Lake.
- The late springtime average lake salinity estimates up to the early 1990's was about 300 g/L at a depth of about 0.4-0.5 m
- Current springtime lake depth salinity observations range from 120 g/L at 0.5 m and 240 g/L at 0.45 m.
- As the lake has become more diluted in salinity, the salt crust precipitation cycle is now shorter in period, over a smaller lake area, forms at shallower Lake depths later in the year, and salinity saturation occurs just before the lake dries out resulting in no longer sustaining *D. salina* pink bloom events.
- Pink Lakes current salt storage estimate is about 450,000 tonnes of salt
- Salt naturally accumulates in Pink Lake via rainfall and surficial aquifer discharge at estimated rates of about 207 tonnes per year.
- Adding the estimated total salt harvested from Pink Lake (465,800) to the current estimated salt total (450,000) equals 915,800 tonnes of salt, which can be tested against the 1900 salt estimate. This is 7,700 tonnes less than the 1900 estimate of 923,500 tonnes, with a one per cent variation between the two estimate methods.
- Increasing Pink Lakes salinity by 30 per cent would require an additional 164,000 tonnes of salt. The additional salt would return the lake to approximately 1991 salinities and have resulted in likely *D. salina* pink blooms over a minimum eight-week period for every year from 2014 to 2020.
- Increasing Pink Lakes salinity by 50 per cent would require an additional 273,000 tonnes of salt. The additional salt would return the lake to approximately 1983 salinities and have resulted in likely *D. salina* pink blooms over a minimum eleven-week period for every year from 2014 to 2020, at an increased bloom depth of 0.5 to 0.6 m.
- Accessing salt from groundwater under the lake to meet the current short fall is not feasible due to salinity, hydraulic head and transmissivity being too low in the Pallinup aquifer. Another alternate salt source is required such as Lake Warden.

Salt source – Lake Warden

The estimated feasibility of time required to extract the target 164,000 (1991) or 273,000 tonnes (1983) of salt for Pink Lake from an alternate salt source such as Lake Warden has been assessed based on analysing observed data between 2012 to February 2020.

The surrounding Esperance Sandplain to the north of the Lake Warden Wetland System was developed for Agriculture in the mid-1950s. The development phase finished in the 1970's with new land releases in the eastern and western Mallee. Prior to clearing native vegetation, groundwater was generally deeper than two meters. Since clearing, groundwater recharge has increased causing water tables to rise. Dryland salinity occurs when the groundwater level rises and intersects the land surface (Simons and Alderman 2004).

The extensive clearing of native vegetation within the Lake Warden Catchments resulted in increased groundwater discharge and surface water runoff entering the Esperance coastal plain, into the Lake Warden Wetland System. The Lake Warden System, during the dry summer months acts as a window to the water table. A new hydrological equilibrium became apparent for Lake Warden by the late 1980's resulting in an increased minimum and maximum lake depth for Lake Warden (Figure 22) (Robertson and Massenbauer 2005).

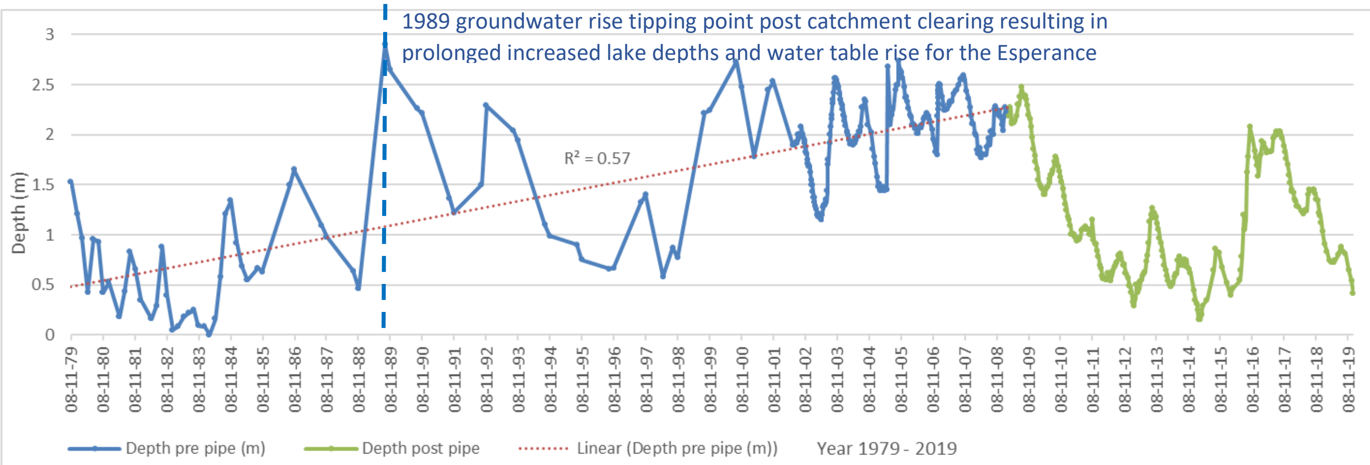

Figure 22 Lake Warden depth records pre and post Lake Wheatfield engineering (Raw Data Source DBCA)

Since 2009, a gravity pipe installed at Lake Wheatfield intercepts catchment inflows and disposes excess water into Bandy Creek flowing to the Southern Ocean (Figure 1). This pipe is manually opened and closed to manage lake levels for waterbird habitat requirements (Plate 5). The gravity pipe has resulted in recovery of lake levels for Lakes Wheatfield, Woody, Windabout and Warden (Figure 22).

A consequence of the lower water levels in Lake Warden, as a terminal lake, is the concentration of accumulated catchment transported salt (Figure 23) increasing to a level where *D. salina* result in orange to pink hue blooms (Plate 8 and 11 to 14) during extended dry periods over summer. Lizamore (2020) clearly demonstrates the differences in Lake Warden's salinity versus lake depth pre and post intervention with the Lake Wheatfield pipeline (Figure 23 and 24). The partial benefits of the Lake Wheatfield gravity pipe have not extended to groundwater and lake level reduction for Pink Lake.

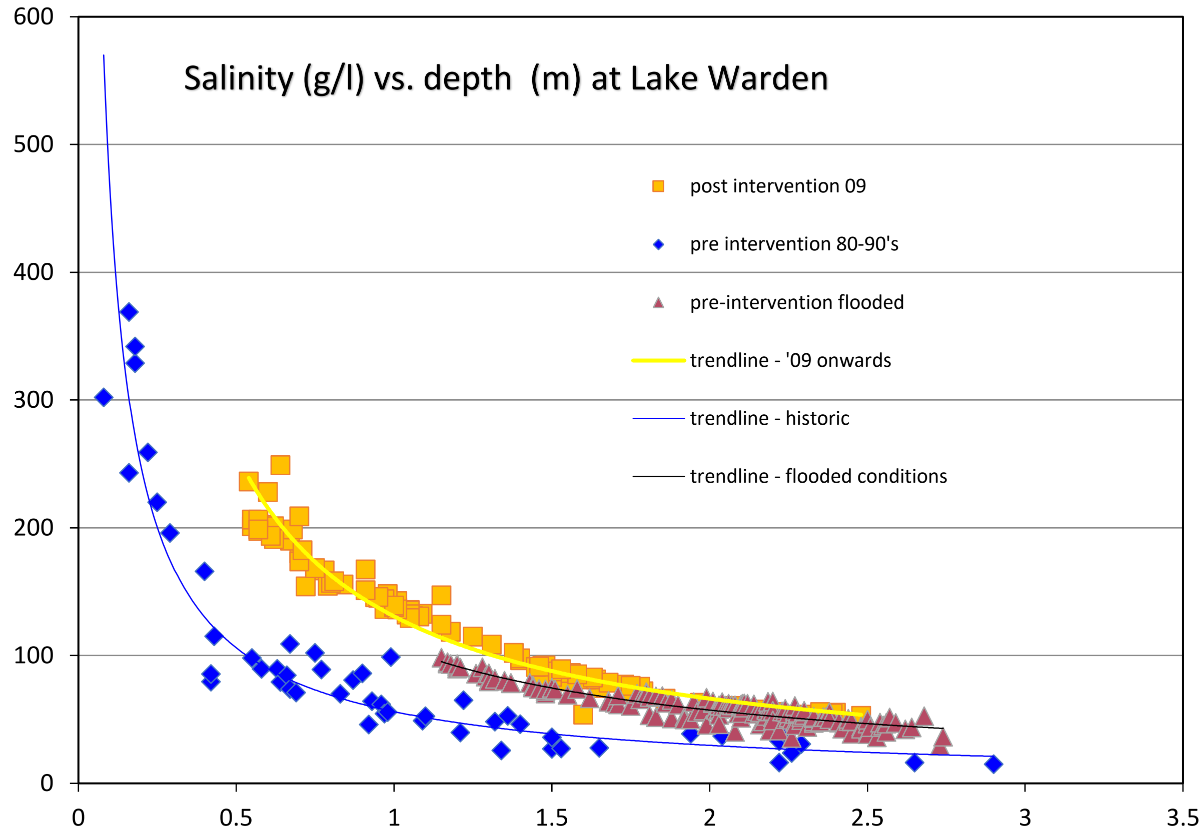

Figure 23 Lake Warden salinity versus depth pre and post engineering invention, graph generated by John Lizamore (Raw Data Source DBCA)

How much excess salt is potentially available in Lake Warden? Salt monitoring data collated by Lane (2017) as part of the SWWMP for Lake Warden was recalibrated using the Fofonoff and Liiard (1983) formula as recommended by Lizamore (2020). This recalibrated data was added to the Lizamore (2020) salt monitoring data and linked to an associated lake depth reading.

DBCA lake depth volume tables for Lake Warden were used to convert the lake depth salinity data to a salt load measure to demonstrate the increase in lake depth and salt loads post catchment clearing, then decrease in lake depth and increase in salt concentration post Lake Wheatfield pipeline intervention (Figure 24).

Further analysis of the Lake Warden monitoring data to identify and quantify a potential Pink Lake salt source focusses on data collated post Lake Wheatfield pipe intervention from 2012 to January 2020 (Figure 26, Page 46).

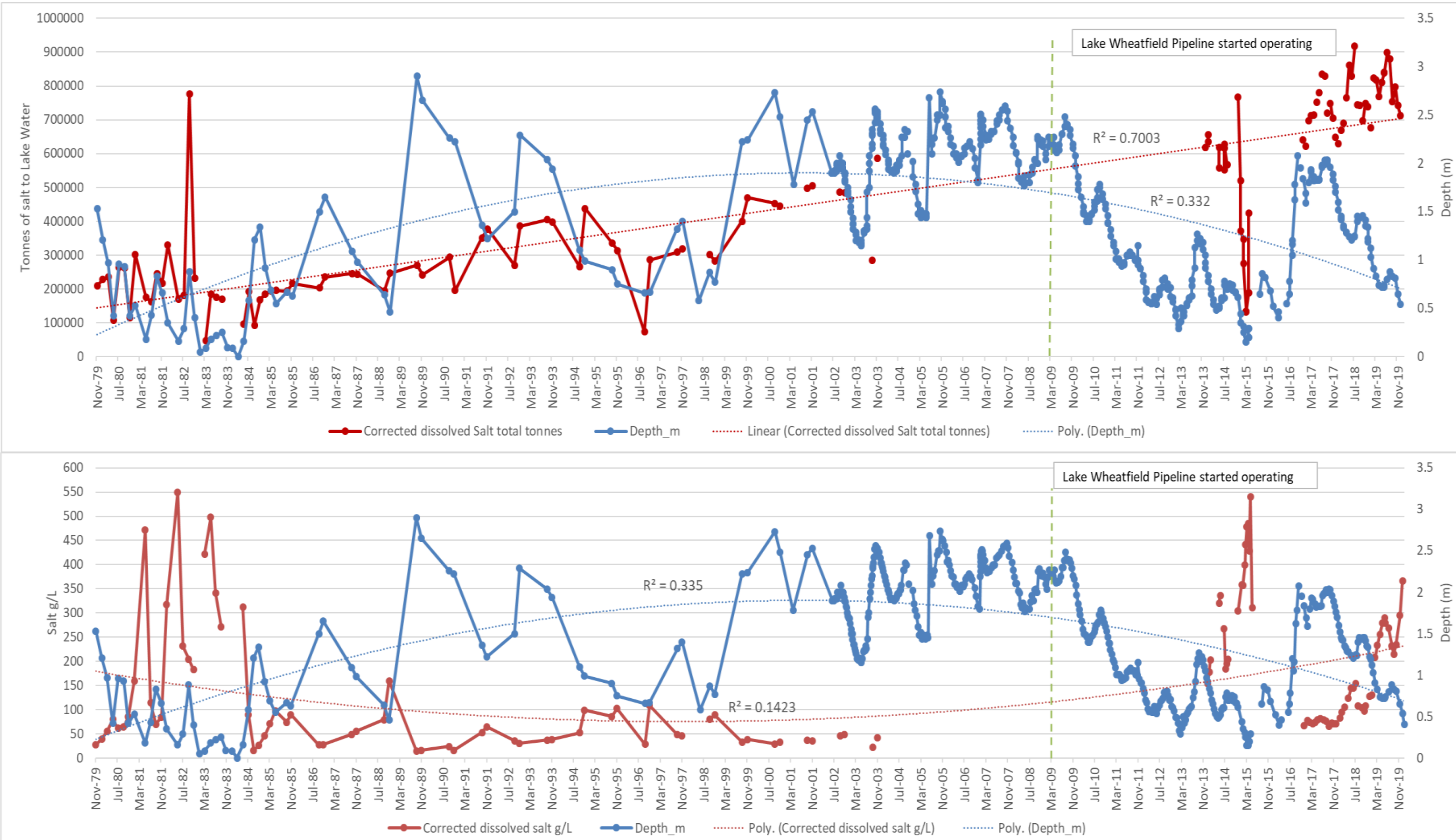

Figure 24 Effect of Lake Wheatfield Pipeline on Lake Warden water levels, salinity and salt load (Raw Data Source DBCA)

The current Lake Warden salt loads, as of January 2020, have increased by about 530,000 tonnes since the early 1980's (Figure 24). This estimated increase is likely due to increased surface water run off (Kusumastuti 2006) washing over expanding primary and secondary saline areas (Short et.al 2000) in the catchment since land clearing for agriculture and washing salts into the lake via Bukenerup, Melijinup, and Coramup Creeks (Janicke 2004) (Plate 19). Salt mapping data from Land Monitor satellite project (Meston 2001) and DBCA Recovery Catchment 2004 land holder survey show about 1900 ha of saline areas are linked to Lake Warden via the above creeks.

Plate 19 Upper Coramup Creek primary and secondary saline areas flowing towards Lake Wheatfield and Lake Warden (Photo Tilo Massenbauer)

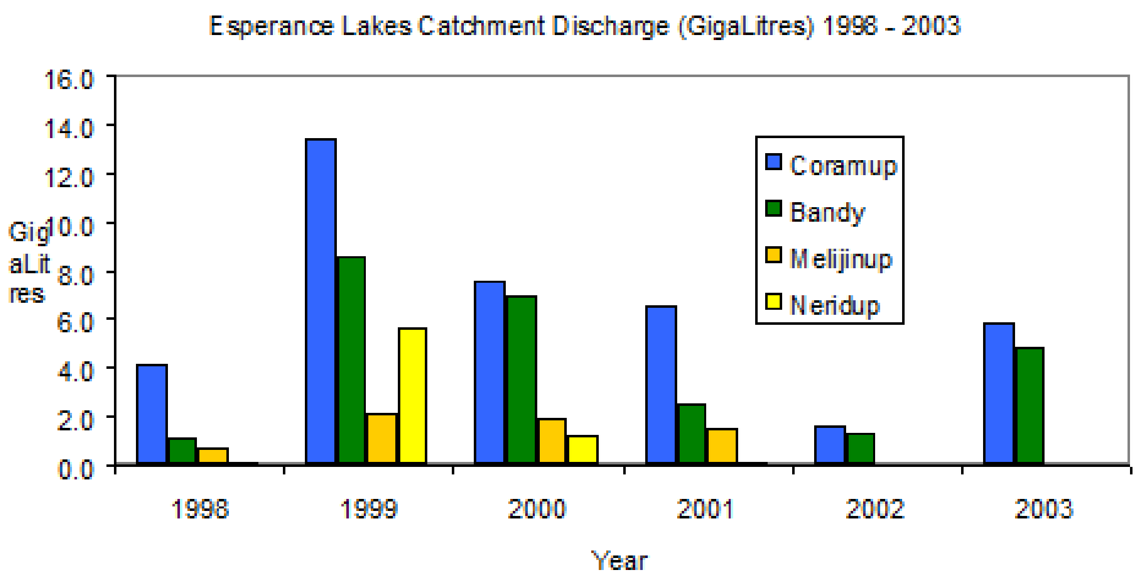

Figure 25 Lake Warden Catchment Stream flow volumes from 1998 - 2003 (Janicke 2004)

Janicke (2004) states the short duration of Water and Rivers Commission data collected between 1998 to 2003 was insufficient to determine salinity trends within the Lake Warden catchment waterways. The salt loads carried by the various streams are flow related. A significant part of the total annual discharge volume from Coramup creek (Figure 25), and hence total salt load occurs as base flow, but flood events in 1999 and 2000 showing a lower average salt concentration would contain a substantial total salt load (Janicke 2004). Stream salinity increases in winter and spring as upper saline catchment flow thresholds are triggered. Flushing of the increased catchment transported salt out of Lake Warden is likely to have decreased due to changes in surface water connectivity between adjoining Lakes and the Ocean. These flow barriers may include road, rail, harbour weir infrastructure and silting of lake flow through pathways.

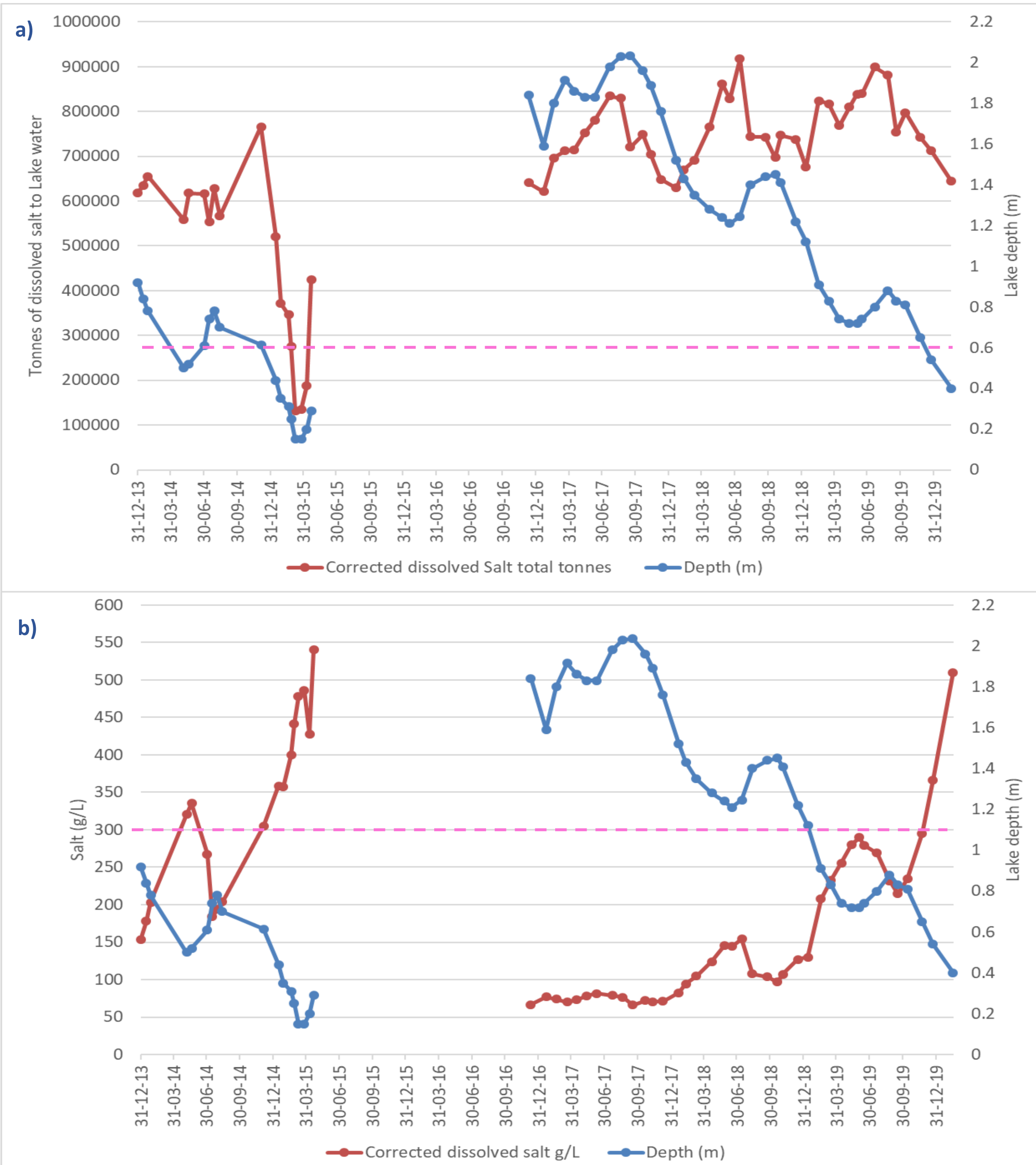

Figure 26 Lake Warden water salinity and salt loads to lake water for sample periods post the 2009 Lake Wheatfield pipeline. (Raw Data Source DBCA) Pink line denotes D. salina a) lake depth threshold and b) salt concentration threshold.

Lake Warden presented *D. salina* orange and pink bloom periods in 2012, 2014, 2015 and 2019 (Plates 8, 11 to 14) when lake levels reached a depth of about 0.63 m, salinity > 300 g/L and lake water salt loads at about 650,000 tonnes (Figure 24, 26.). There are no known recorded *D. salina* bloom events at Lake Warden prior 2012.

Salt brine harvesting

A strategy for harvesting salt from Lake Warden for Pink Lake is via naturally concentrated salt brine transportation. Methods of brine extraction would need to be further developed separate to this project. Methods can include using a pipeline to transport brine via a pump primed siphon, continuous mechanical pumping at various rates, and less likely option of trucking brine in water tankers. An artificial surface water drain would be unlikely due to existing transport corridor infrastructure barriers and major environmental impacts from disturbing natural wetlands and native vegetation.

The maximum salt brine pumping lake depth and salinity from Lake Warden is less than 0.6m and 300 g/L salinity (Green dotted line Figure 27). The optimum brine pumping depths and salinity is between 0.4m to 0.15m at respective salinities of 350 – 500 g/L (Pink shaded area Figure 27).

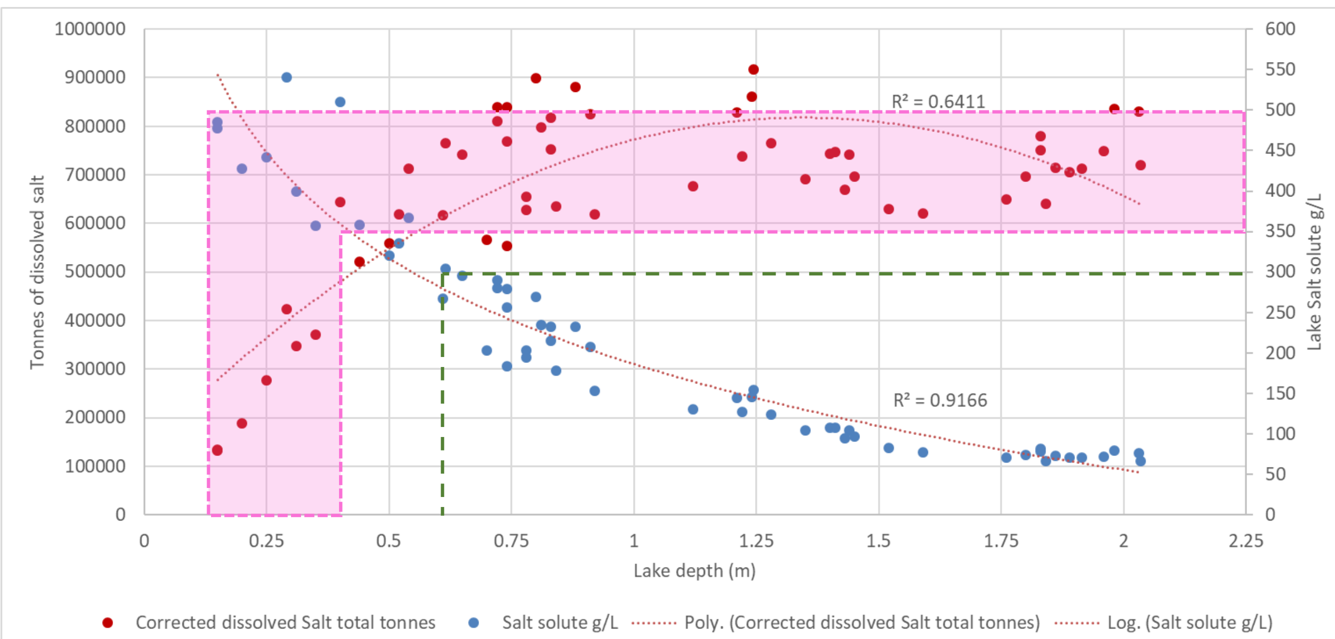

Figure 27 Lake Warden post Wheatfield pipeline 2015- 2020 lake water dissolved tonnes of salt and salinity. (Raw Data Source DBCA), maximum brine pumping depth green dotted line and optimum brine pumping depths pink shaded area.

The estimated salt loads available from brine were calculated based on observed data measuring varying lake depth, and salinity. Lake Warden salinity measured as g/L was multiplied by the volumetric litres of water at an associated sampled lake depth below 0.6 m and converted to tonnes of salt (Table 6).

Table 6 Lake Warden estimated salt brine availability at lake depths less than 0.6 m depth

Lake Depth (m)	Salt solute range (g/L)	Available brine (KL)	Available Salt (Tonnes)
0.15	480	276,737	**132,280**
0.20	430	440,438	**188,507**
0.25	440	625,449	**276,135**
0.29-0.31	390-540	784,876-867,525	**423,833-346,576**
0.44	350	1,451,277	**520,282**
0.5-0.52	330	1,742,521-1,842,064	**558,478-618,012**
0.6-0.61	260-300	2,304,024-2,516,052	**616,326-766,137**

Pumping scenarios for two different pumping rates (100,000 L/hour and 20,000 L/hour) starting at two different depths, (0.6m and 0.3m) and finishing at three different lake depths (0.38m, 0.2m and 0.15m) were tested to estimate how much available salt could be accessed over a calculated period (Table 7). The scenarios help further define optimum pumping rates, lake depth and salinity required to meet the Pink Lake salt targets.

Table 7 Lake Warden brine extraction scenarios for lake depths starting at 0.6 m and 0.3 m depths.

Scenario	Starting Depth (m)	Depth remaining (m)	Salt solute (g/L)	Brine removed (KL)	Salt content (Tonnes)	Days to pump @ 100,000 l/hr	Days to pumping at 20,000 l/hr
1	0.6	0.38	300	1,152,012	345,603	960	4,800
2a	0.3	0.2	450	412,969	185,836	344	1,720
2b	0.3	0.15	450	549,201	247,140	457	2,288

Note: Pumping at 50% of the time i.e. 12 hours per day

The brine salt availability and pumping scenarios were analysed against observed Lake Warden depth data from 2012 to 2020 to determine if the duration of brine harvesting depth thresholds are suitable to extract enough salt to meet the Pink Lake targets of 164,000 and 273,000 tonnes. Since the instalment of the Lake Wheatfield pipeline Lake Warden has reached a brine depth pumping threshold of less than 0.6 cm on six occasions (Figure 28 and table7).

Pumping brine from Lake Warden when depths reach 0.6 m or lower, at salt concentrations of about 350 g/L for the scenario of 100,000 L/hr at 12 hours per day, would meet the Pink Lake modelled 1991 target of 164,000 tonnes of salt within: (Table 8):

- three years between 2012 to 2014 or
- two years between 2014 and 2015, and 2015 and 2016.

The Pink Lake 50 per cent salt concentration scenario of 1983 levels, being an additional 273,000 tonnes of salt could be met within 3 years when at pumping rates of 100,000 L/hr and 83 per cent of a full salt recovery target to pre-1900 of 466,000 tonnes could be achieved (Table 8).

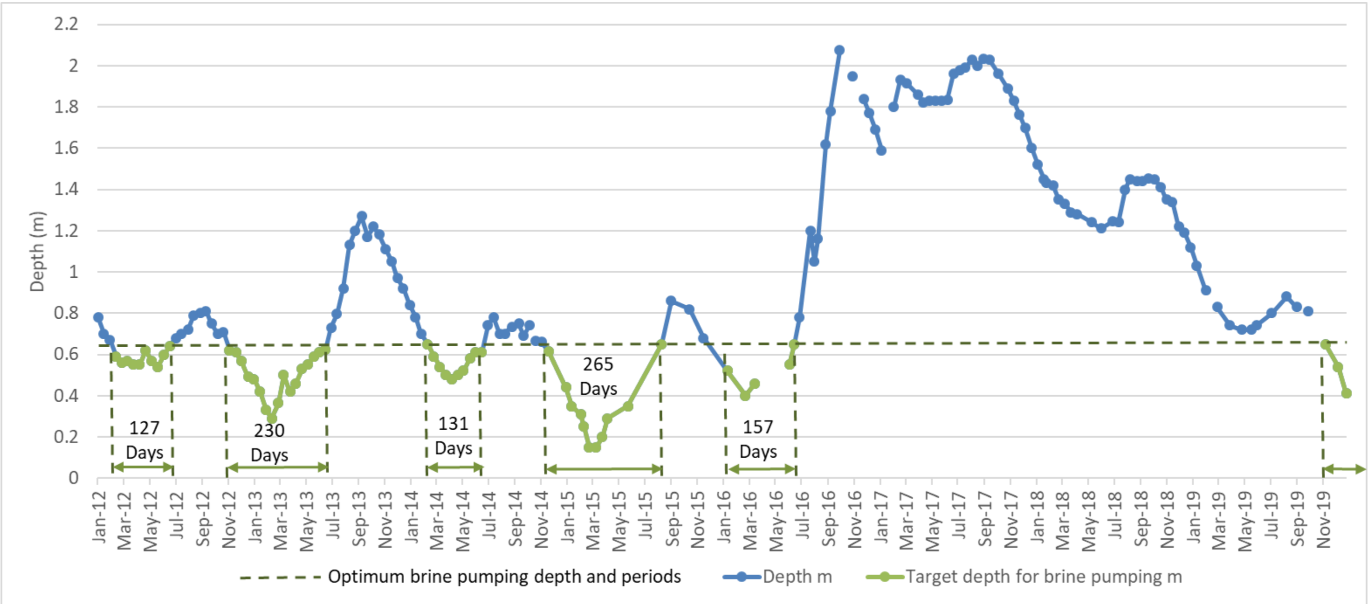

Figure 28 Lake Warden optimum brine extraction periods below 0.6 m depth related to observed data from 2012-2020 (Raw Data Source DBCA)

Table 8 Lake Warden optimum brine extraction depth and duration scenarios at depths less than 0.6 m for 2012 – 2020 observed data

Year	Duration Days	Minimum salt solute extraction g/L	Pumping rate 100,000 L/hr (KL)	Salt load @ 100,000 L/hr (Tonnes)	Pumping Rate 20,000 L/hr (KL)	Salt load @ 20,000 L/hr (Tonnes)
2012	127	350	152,400	**53,340.00**	30,480,000.00	**10,668.00**
2013	230	350	276,000	**96,600.00**	55,200,000.00	**19,320.00**
2014	131	350	157,200	**55,020.00**	31,440,000.00	**11,004.00**
2015	265	350	318,000	**111,300.00**	63,600,000.00	**22,260.00**
2016	157	350	188,400	**65,940.00**	37,680,000.00	**13,188.00**
Totals	**910**		1,092,000	**382,200.00**	218,400,000.00	**76,440.00**

Pumping at 50% of the time i.e. 12 hours per day

Pumping brine at a more modest scenario of 350 g/L at 20,000 L/hr would require the full 5-year period between 2012 to 2016 to meet about 46 per cent of the Pink Lake 164,000 tonne target 17 per cent of a pre-1900, 45,600 tonne full salt recovery target (Table 8). It is important to note that brine salinity would naturally increase as Lake Warden became shallower under natural evaporation during long period pumping scenarios, hence the estimated salt loads are likely underestimated.

Salt crust harvesting

The strategy of brine pumping from Lake Warden can be complimented by the strategy of harvesting salt crust from the lakebed as water levels recede due to evaporation as an alternate form of salt. Salt crust harvesting methods are well developed throughout Western Australia's salt mining industry. Harvesting methods include scarifying, scalping, and crushing salt crust into wind rows for ease of collection (Plate 11). This report does not investigate the methods, logistics and costs of harvesting salt crust.

Plate 20 Examples of salt crust harvesting machinery and methods

Salt crust begins to appear on the lakebed and exposed shoreline at Lake Warden when depths reach about 0.6m and salt concentrations exceed 300 g/L. As lake levels recede via evaporation, salt concentrations increase and precipitation of salt out of solution settle onto the lakebed as crystals which accumulate into a thicker and denser salt crust. The longer salt crust is exposed to sun and wind the drier it becomes. The salt crust will compact in the event of small rainfall events less than five millimetres and movement of shallow lake water blown across the lake via wind. Larger rainfall events or intense down pores tend to dissolve the crust and wash the salt into different parts of the lake until dry conditions re-establish the crust. John Lizamore observed this process on the 15th of March 2020 after rain, where the salt crust extent decreased as it was temporarily dissolved and concentrated to lower parts of the lake, and as the lake dried out again the salt crust was thicker over a less extensive area. Lizamore's March observation was at a lake depth of 0.28m and water salinity of 540 g/L. Plate 21 photos show extensive salt crust formation in Lake Warden at a depth of 0.44m during January 2020.

Salt crust harvesting calculations are based on accessing up to 75 per cent of available salt on Lake Warden at optimum periods and anticipating the need for harvesting machinery not to break through the lake sediments and become bogged or damage the lake.

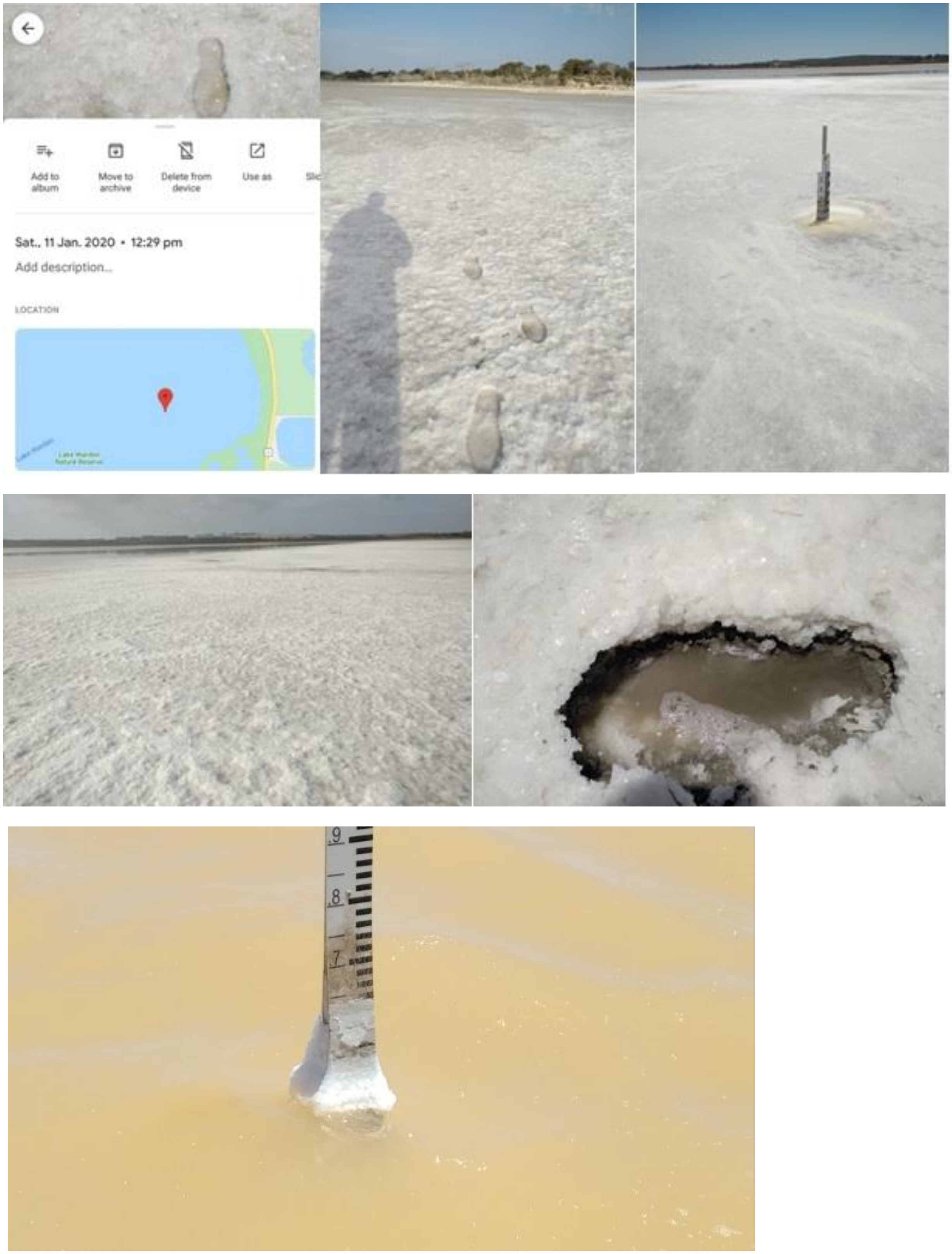

Plate 21 Lake Warden salt crust formation at a lake depth of 0.44m, January 2020 (Photos by John Lizamore)

Salt crust availability is estimated on 75 per cent of the exposed shore/beach being accessible to potential vehicle extraction and restricted by lake bathymetry and morphology i.e. deep soft sediment areas at the Bukenerup and Melijinup Creek inflows, and shallow exposed granite areas on the northern lake edged. The DBCA Lake Warden depth volume and area model was used to calculate the area of exposed beach for 1 cm lake depth increments below 0.6m. Salt crust depth and mass was calculated by applying:

- the Esperance Express Newspaper article (1980) (EMA 1797) quoted Pink Lake salt harvest crust estimates of 10 cm at evaporation ponds producing about 97 tonnes per hectare per centimetre (Appendix 1), and
- Salt crust observations at Lake Warden at a depth of 40 cm where salt crust formation was about 7 cm thick (Plate 21).

The information was used to develop a sliding scale estimate of salt crust availability for Lake Warden based on decreasing thickness to the outer margins of the lake (Table 8). The sliding scale salt crust thickness for areas of exposed shore at lake depths less than 0.64m was calculated as a "lake depth to tonnes of crust available" model (Figure 29).

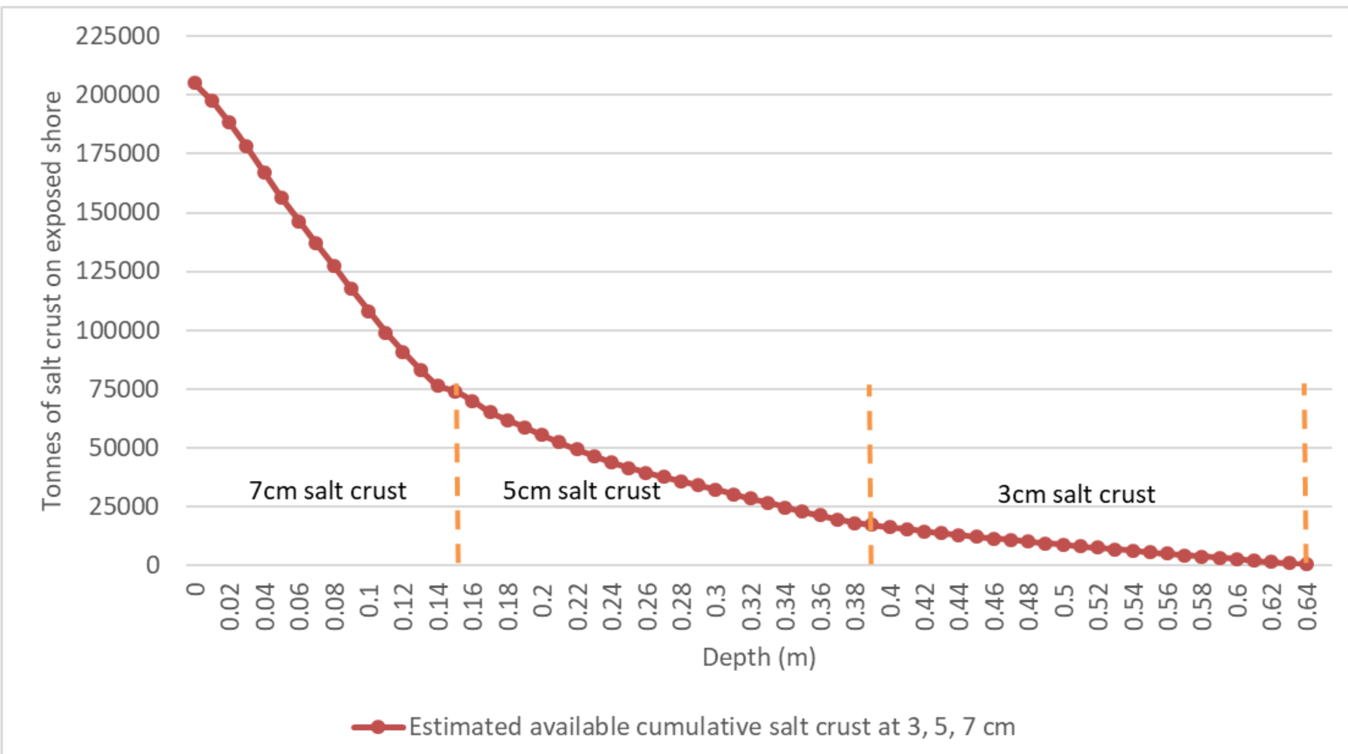

Figure 29 Lake Warden estimated salt availability as crust thickness on exposed shore at varying lake depths below 0.65 m. (Raw Data Source DBCA)

Figure 28 (Page 49) was used link duration of observed harvestable depth range to salt crust yield estimates (Figure 29). The available salt crust quantities estimated for potential extraction from Lake Warden for Pink Lake are outlined in Table 9.

Table 9 Lake Warden exposed shoreline salt crust estimate quantities at lake depth scenarios of 0.64 m, 0.4 m, and 0.15 m

Minimum depth range to expose shore (cm)	Estimated total crust (cm)	Estimated available salt crust (cm)	Salt solute range (g/L)	Lake water area range remaining (ha)	Estimate of accessible Salt crust area range. (ha)	Estimated salt crust yield range (Tonnes)
0.14-0	10	7	430-540	290-38	183-372	**76,315-205,045**
0.39-0.15	7	5	370-430	456-303	59-174	**17,156-73,948**
0.64-0.40	5	3	300-370	532-460	2-56	**493-16,269**

Harvesting salt crust to a depth of about 75 per cent of the total thickness in 2015 at a lake depth of about 0.15 m deep from 75 per cent of the available exposed lakebed would result in an approximate total yield of about 75,000 tonnes. Harvesting operations would need to have been undertaken between the 26-02-2015 to 10-04-2015, being a total of 44 days or 6 weeks and 2 days. An additional 50,000 tonnes of salt crust would have been available during 2013 and 2020 totalling about 100,000 tonnes of salt available to be harvested from the lake surface. The three major salt crust harvest periods being during 2013, 2015 and 2020 could potentially yield approximately 175,000 tonnes of salt in the form of salt crust. This meets the Pink Lake 1991 target harvest requirement of 164,000 tonnes or 64 per cent of the 1983 (273,000 tonnes) target (Table 10).

Pink Lake salt target feasibility summary

Lake Warden has excess salt at available quantities, concentrations, quality, and likely accessible duration of optimum harvest lake depths to meet Pink Lakes 1991 and 1983 targets when modelled against observed data from 2012 to 2020. The total available salt quantities would also likely meet pre-European salt harvesting levels for the early 1900's resulting in full salt recovery of Pink Lake. A combination of salt crust, and brine pumping at two different rates of 100,000 L/hr and 20,000 L/hr salt harvest methods would meet Pink Lake 1991 salt targets, all, or part of the 1983 target (Table 10).

Table 10 Pink Lake 1991, 1983 and 1900 salt target engineering scenario feasibility estimate summary

Lake Warden harvest method scenario	a) Pink Lake proportion of 1991 Target met (%)	b) Pink Lake proportion of 1983 Target met (%)	c) Pink Lake proportion of 1900 Target met (%)	Time period (Years)
Brine Pump 100,000 L/hr	100%	100%	82%	a) 1991 = 2 yrs, b) 1983 = 3 yrs
Brine Pump 20,000 L/hr	46%	38%	16%	8
Salt crust harvesting	100%	64%	44%	8
Salt crust and brine 20,000L/hr	100%	91%	62%	8
Salt crust and brine 100,000L/hr	100%	100%	100%	a) and b) = 2 yrs c) = 8 yrs

In the event of a large summer flood episodic event, the ongoing operation of Lake Wheatfield pipeline is critical to returning Lake Warden back to regular optimum salt harvest lake depths within a three-year period (Figure 28, Page 49)).

Salt target scenarios – 1991, and 1983

The brine pumping scenario of 100,000 L/hr (12 hours per day) would meet Pink Lakes 1991 target within two years and 1983 target within three years based on optimum Lake Warden depths and salinity occurrence observed between 2012 and 2020.

Pumping brine at 20,000 L/hr scenario would take the full five years of Lake Warden optimum lake depth pumping periods reached between 2012 and 2020 to meet only 46 per cent of Pink Lakes 1991 target and 38 per cent of the 1983 target.

Brine pumping from Lake Warden would result in higher nutrients being deposited into Pink Lake. The additional short-term nutrient input would likely be assimilated and exhausted over time by existing trophic cycles, with *D. salina* cells returning to dark red concentrations. The *D. salina* red colour would be diffused back to a pink colour by Pink Lakes suspended gypsum content and white lakebed sediment.

Periodic salt crust harvesting alone at optimal lake depths over an eight-year period would meet pink lakes 1991 target and 64 per cent of the 1983 target.

Combining salt crust harvesting with brine pumping at the 20,000 L/hr scenario would meet 91 per cent of the 1983 Pink Lake salt target. By relying primarily on salt crust harvesting to meet 64 per cent of the 1983 target, an additional possible 76,440 tonnes from pumping brine would address a large component of the shortfall. The estimated maximum amount of salt harvested using a combination of the two methods totals about 249,000 tonnes which would meet 1985 Pink Lake salt targets based on past salt harvesting records (Appendix 1).

No nothing or pre-1900 full salt recovery

A do-nothing approach relying on natural salt accumulation processes at 207 tonnes per annual would take about 787 years to meet the 1991 target and 1,319 years to meet the 1983 target. A full salt recovery target for Pink Lake to pre-1900 levels of 466,000 tonnes from lake Warden is feasible between 2012-2016. Pumping brine at 100,00 L/hour at 50 per cent of the time during the available 910 day harvest period between 2012-2016 could potential yield 382,000 tonnes of salt (Table 8), and salt crust harvesting at a lake depth of 0.14 m and salt concentration of 540 g/L could yield a maximum of 205,000 tonnes of salt (Table 9). These calculated estimates do not account for salt dilution depreciation over time.

Pink Lake salt trial

Prior to investing resources required to recover the pink amenity of Pink Lake, a proof of concept environmental engineering trial would reduce the risk of failure. Currently located on Pink Lake is a series of eight disused evaporation ponds (Figure 30, Plate 4, page 5 and plate 7, page 14) remaining from the previous WA Salt supply operations that finished in 2008. The condition of these ponds is unknown and may require additional maintenance as part of a trial.

All ponds used in the trial should contain Pink Lake surface water at a baseline salinity of about 200 g/L and filled to a depth of about 0.5m. This water will contain *D. salina* (Table 3, page 20). Ponds are then used to test the response of observed *D. salina* colouration when salinity is increased by 30 per cent (1991 Pink Lake target) and 50 per cent (1983 Pink Lake Target) stress scenarios. These two salinity target scenarios can be further divided into observed *D. salina* response to brine salt, salt crust and a combination of brine and salt crust harvested from Lake Warden. The Lake Warden brine will also contain *D. salina* as shown in table 3 (Page20). A further description of Pond salinity management trial scenarios are as follows:

1. Establish a baseline standard pond using preferably only Pink Lake water (Compare differences in current pond water and Pink Lake salinities). Water may need to be pumped from the lake into the ponds.

2. Add salt brine from Lake Warden to a pond until existing water salinity reach 275 g/L (30% salinity increase). Remove brine from Lake Warden at an optimal depth of < 0.4m deep and > 400 g/L salinity or a minimum depth of < 0.6m, salinity > 300g/L (Figure 27, page 47, Table 6, page 48). Use a water tanker truck to pump and transport brine.

3. Harvest a target amount of salt crust from Lake Warden when depths are < 0.4m, and crust thickness is > 50mm and add to a pond until salinity reaches 275 g/L (Figure 29, page 52, Table 9, page 53). The salt crust may need to be harvested and stored at a separate location, then added to a trial pond when baseline water conditions are established.

4. A combination of scenario 2 and 3, being add 64 per cent of the required target salt as salt crust and the remainder as brine to the test pond to simulate a 1983 target scenario and brine pumping rate of 20,000 L/hr.

The parameters to be monitored across all trial ponds should reflect those outlined by Lizamore (2020) and section "*D. salina* biological pink bloom threshold summary" of this report.

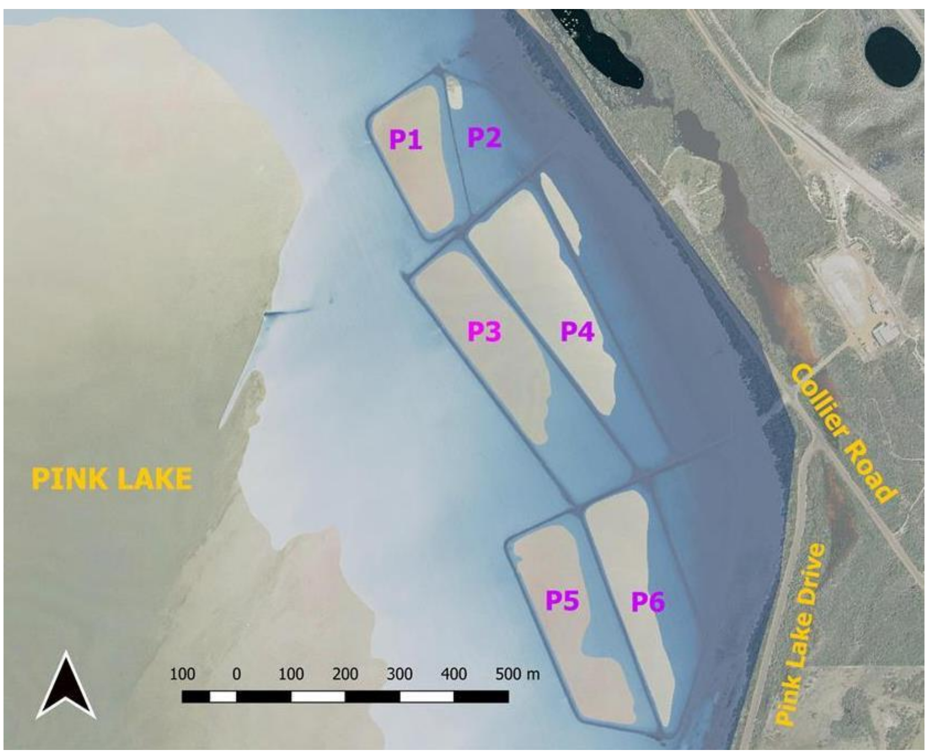

Figure 30 Layout of existing disused evaporation ponds with blue shaded areas being extent of Department of Water hillshade DEM (2013)

Esperance district coloured lakes tourist drive

The Esperance district is interspersed with hundreds of groundwater dominated salt lakes spread across Sandplain and Mallee agricultural landscapes to the north of the Lake Warden Wetland system. These lakes contain unusual biological assemblages of halophile bacteria, algae (*D. salina*) and brine shrimp under extreme salinities of greater than ten times seawater. A combination of extreme salinity, hydrochemistry, climate, and organisms can result in ephemeral blooms of different colouration ranging from pink, to orange, to yellow to luminous green (Appendix 7). Such variable blooms tend to occur during spring to early summer as lakes dry out, post a wet summer rainfall event and autumn break of season. These lakes tend be much smaller in area than Pink Lake but are strikingly colourful when conducive bloom conditions align.

In some instances, these smaller lakes can be viewed adjacent roads on road reserves or in neighbouring farm paddocks. The roadside seasonal colourful lakes represent a potential accompanying tourist value to Pink Lake or as a standalone alternative. Additional feasibility planning of a colourful lake tourist drive (Esperance Rainbow Lakes Drive) option would need be further developed separate to this report.

Study Uncertainties

As previously mentioned in the methodology of this report there are numerous uncertainties underlying the calculations presented in this report based on data sources, methods, quality, currency, accuracy, and completeness. Non-traditional forms of information such as museum archives, newspaper articles, local knowledge have been integrated with expert opinion and observed research data to calculate and extrapolate information. Marimuthu (2020) and Lizamore (2020) summarise uncertainties within the technical support documents to this report. Some of the major underlying uncertainties are:

- There are inconsistencies in methods and results for measuring salinity at Lake Warden. Only corrected and verified TDS measure data in g/L or mg/L have been used in this report as recommended by Lizamore 2020. The problem associated with using this accurate data is that it is not continuous or extensive containing gaps requiring interpolation and extrapolation of salinity from lake depths post 2012 in the absence of salinity data. Date referenced lake depth records with a corresponding dated *D. salina* bloom photograph have been correlated to lake depth salinity readings from different years. Lizamore recommends a standard method for measuring salinity for future reference.
- Past colour images of Pink Lake and Lake Warden filter samples and photographs do not align with salinity TDS and lake depth monitoring data (Lizamore 2020). In future at minimum lake depth, salinity and photograph of Pink Lake and Lake Warden should align when salinities are measured at > 300 g/L. Drone photography using a polarized filter, recorded time of day, cloud cover, wind speed and direction, air temperature, altitude and GPS location meta data should be collated to monitor lake colour in accordance with corresponding lake depth and salinity readings.
- There is little evidence in the Coleman (2002) report that pink *Halobacterium halobium* and UWA 1981 identified *Coccomonas* species (EMA 1158) are present at Pink Lake. There is also an issue of taxonomic identification accuracy. Additional biological sampling for bacteria, algae, and micro invertebrate identification at varying lake water salinities, lake depths, lake sediment and differing parts of the lake (margins versus middle) would provide a better understanding if other organisms attribute to the lakes pink colour.

- Detailed interspecific competition and possible predation on *D. salina* by other organisms are unknown within Pink Lake and would require either targeted species-specific sampling or full biological sample to identify as many species of potential predator bacteria, algae or diatom.
- Biology uncertainty regarding unknown impacts and sensitivity of very low-level measured nitrate nutrients in the form of ammonia and urea (Coleman 2002) may affect *D. salina*. The nutrient data is also non continuous with associated uncertainties outlined by Lizamore 2020. Nutrient transport in Lake Warden brine to Pink Lake may affect short term colour and can be tested in trial ponds proposal.
- Pan evaporation coefficient – varying water salinity and temperature over time will affect evaporation inputs for Pink Lake and Lake Warden. Unknown complexity in evaporation rates affected by not only water salinity, but water temperature, salt crust formation and presence of *D. salina* colour blooms likely differ markedly from current coefficients. Conceptually low evaporation is modelled when salinity is high. But based on the theory of increased heat stored in dissolved salt, salt crust and an "aquatic greenhouse effect" during *D. salina* pink/orange blooms, lake evaporation has been observed to be high at Lake Warden under extreme salinity (> 300g/L). Pink Lake also has varying salinities with freshwater seeps, and when hypersalinity occurs in lake surface waters it does not always mix so the fresher lake water evaporates more quickly than the modelled coefficient.
- The south eastern edge of Pink Lake shows physical and biological evidence of substantial freshwater seepage from surficial aquifers. As there are no observation bores close to the south edge of the lake, Marimuthu (2020) removed modelled groundwater contour and gradient information from this area as part of the water balance. The water balance model underestimated this areas lake discharge contribution because Water Corporation bores used in the model were too far from the lake and biased surficial flow direction towards the town of Esperance bi-passing Pink Lake.
- Pink Lake Bathymetry uncertainty. There are likely errors using old unknown survey quality data (Hurle 1986) which will compound and cascade through the water balance, salt balance, and engineering calculations. An up to date detailed bathymetric field survey needs to be completed and added to the current gaps in the Department of Water high resolution LIDR DEM. Lake Depth volume models would need to be updated along with all relevant salt volume calculations and modelled increases in salinity.
- The location of Pink Lakes gauging and sample site result in problems with wind affecting depth reading accuracy, and water sampling fresh discharge area under low pooling lake levels or strong wind blowing water to the eastern side of lake exposing fresh seep water (Lizamore 2020). Data presented in this report demonstrates this process but also has been removed when analysing the total salt content of Pink Lake. The existing surveyed depth gauge site is based on an incomplete survey of the lake due to logistical accessibility issues. The lake depth gauge estimated +17cm correction value aligned to a likely inaccurate 1984 generated bathymetry model compounds further uncertainty. Additional lake depth gauges north, south, east, and deepest lake point should be surveyed and calibrated to an updated bathymetry DEM survey
- Lake Warden salt crust estimates are based on opportunistic observations from lake sampling visits during early 2020, photographic evidence, and archive newspaper quotes, but with no formal monitoring procedure. Salt crust thickness at various lake depths <0.6m over time during a dry period should be sampled using a GPS referenced transect core method to proof estimates used in salt calculations.
- Salt harvest estimates from Lake Warden to meet Pink Lake scenarios do not account for depreciated salt concentrations over time.

Conclusions

The cause of Pink Lake's historic pink colour is a result of *D. salina* algae. The organism produces ß-Carotene at high concentrations when stressed as a survival response to outcompete other organisms for limited nutrients. D. salina still survives in Pink Lake in lower densities and does not currently produce high concentrations of carotenoid pigment.

The stress factors driving this response correspond directly with salinities greater than 300g/L, water temperature greater than 25 degrees, and extremely low nutrients as preferred phosphates. Lake water with dark red ß-Carotene *D. salina* produced under optimum conditions fades to variations of pink colour when there is the presence of a salt crust precipitation cycle at lake depths around 40 to 60cm deep, and fine white to light grey suspended alkaline silica, clay carbonate, salt particles and lakebed diffuse light intensity. All these factors sustained for more than a four-week period likely result in a pink bloom. Once the bloom begins, the *D. salina* biologically helps maintain these conditions by producing its own aquatic "greenhouse" effect until the lake dries out, is diluted below 300 g/L from rainfall, winter water temperatures drop below 25 degrees Celsius or low phosphate nutrients are depleted.

Pink Lake is likely no longer pink due to the removal of too much salt based on annual salt harvest quotas set by incorrect hydrological investigations undertaken in 1986. Of the estimated 923,500 tonnes of salt present in Pink Lake as of about 1900, about 50 per cent has been harvested up until 2007. During the final 30 years of salt harvesting, about 353,800 tonnes was removed from the lake as brine. The excessive removal of salt has resulted in *D. salina* bloom thresholds dropping below 300 g/L and not being sustained for periods longer than four weeks. The salt reduction has also resulted in a diminished salt crust precipitation cycle to only a small portion of the lake when depths are very shallow, and the lake dries out before *D. salina* can bloom. Because of the low salinities in Pink Lake under current conditions, adding more *D. salina* to the lake will not result in a bloom.

An increasingly variable climate with more extreme episodic dry and wet periods, extensive clearing of native vegetation for urban rural development and associated hard surfaced roads near the lake has exacerbated the dilution of Pink Lake from increased freshwater runoff and groundwater discharge onto the lake. This process may be beneficial during a drying climate, but types and quantity of nutrient inputs need to be carefully monitored and managed.

A 30 per cent and 50 per cent increase in salinity scenarios would likely return Pink Lake's salinity to 1991 and 1983 concentrations, respectively. During the early 1990's pink blooms would occur annually but for only about an 8-week period. During the early to mid-1980's Pink blooms would occur multiple times per year and for periods up to 12 to 16 weeks. Adding 164,000 tonnes of salt would result in 1991 salinities and likely *D. salina* pink blooms over a minimum eight-week period for every year from 2014 to 2020. Adding 273,000 tonnes of salt would result in 1983 salinities and likely multiple annual *D. salina* pink blooms over a minimum eleven-week period for every year from 2014 to 2020, at an increased depth of 0.5 to 0.6 m. A 1983 target would likely respond in increased *D. salina* bloom resilience to episodic flood events with an approximate two-year recovery rather than a possible three to five years depending on the size of rain event.

The groundwater under Pink Lake is not conducive for Pink Lake's salt needs because of its salinity. In addition, the aquifer beneath is low transmissive and yielding. A do-nothing scenario would take about

787 years to naturally accumulate enough salt to meet the 1991 target and 1,319 years to meet the 1983 target.

The adjacent Lake Warden has identical salt chemistry characteristics as Pink Lake and at depths less than 0.6m starts to display reduced concentrations of nutrients through biological metabolism. Nutrient concentrations at these shallower depth in Lake Warden are still higher than that of Pink Lake.

Lake Warden has an excess salt problem accumulating over years of catchment salinity increased run-off into the Lake. The estimated excess 530,000 tonnes of salt could hypothetically replace all the estimated 466,000 tonnes of salt removed from Pink Lake back to pre-European settlement. Sustainably harvesting salt from Lake Warden for Pink Lake would likely benefit both wetlands. The issue is cost effectively accessing quantities of salt to meet either 1991, 1983 and 1900 Pink Lake salt targets which result in a high probability of annual pink *D. salina* colour blooms.

To access target quantities of salt, the Lake Wheatfield pipeline is integral to maintaining Lake Warden's depths at levels optimal for salt crust and/or brine harvesting. Enough salt could be removed from Lake Warden to meet Pink Lakes 1991 and 1983 targets, over a two to three-year period respectively, and 82 per cent of the 1900 target over an eight year period by brine pumping at a rate of 100,000 L/hr. Salt crust harvesting alone over an 8-year period from 2012 to 2020 would meet the 1991 target. A combination of salt crust harvesting and top-up brine pumping at 20,000 L/hr over an 8-year period from 2012 to 2020 would meet 62 per cent of the 1900 target, 91 per cent of the 1983 targets or 100 per cent of a revised 1985 target. The 1983 and 1985 target would likely result in multiple annual pink *D. salina* blooms for periods up to 12 weeks. Full salt recovery of a pre-1900 target could be met over an 8-year period by a combination of brine pumping at 100,000 L/hr and salt crust at a lake depth of 0.15m.

Brine pumping from Lake Warden would result in higher nutrient loads being deposited into Pink Lake. The additional short-term nutrient input would likely be assimilated and exhausted over time by existing trophic cycles, with *D. salina* cells returning to dark red concentrations. The *D. salina* red colour would be diffused back to a pink lake colour by suspended gypsum content and white lakebed sediment. The brine nutrient issue can be trialed using the existing evaporation ponds on Pink Lake. The internationally recognised Ramsar listed Lake Warden site's water bird values would also greatly benefit from a large reduction in salinity resulting in more foraging biomass at optimal wading habitat depths.

The next stages would be to investigate in greater detail:

- The implementation of the evaporation salt pond trial recommendations and
- Engineering options, design, logistics, environmental approval processes and costs required to implement salt harvesting operations at Lake Warden to meet

As previously mentioned in this report there are numerous uncertainties underlying the calculations presented in this report based on data sources, methods, quality, currency, accuracy, and completeness. These uncertainties have been transparently communicated and where possible, their effect on results minimised. Based on the findings of this study, recovering Pink Lake's pink amenity to benefit the Esperance, State, National and International community is environmentally and technically feasible. There is also potential to further explore the option of developing an Esperance district rainbow lakes tourist drive as an economic benefit to the town which would complement colourful Lake values such as Lake Hillier, Lake Warden and Pink Lake if recovered.

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Appendix1 Esperance Pink Lake historic salt harvesting research summary

Note: EMA refers to Esperance Museum Archive. Additional research summary continues after the salt harvest table section.

Harvest year	Salt harvest Tonnes	Notes	Source Date	Source	Reference	Format	Calculated estimate reference
1896	181.437						Estimate ref EMA 1138
1897	181.437						Estimate ref EMA 1138
1898	181.437						Estimate ref EMA 1138
1899	181.437						Estimate ref EMA 1138
1900	181.437						Estimate ref EMA 1138
1901	181.437						Estimate ref EMA 1138
1902	181.437						Estimate ref EMA 1138
1903	181.437						Estimate ref EMA 1138
1904	181.437						Estimate ref EMA 1138
1905	181.437						Estimate ref EMA 1138
1906	178.715			EMA	No number	Transcript	
1907	181.437						Estimate ref EMA 1138
1908	181.437						Estimate ref EMA 1138
1909	181.437						Estimate ref EMA 1138
1910	181.437						Estimate ref EMA 1138
1911	6350.295	Salt Co Started, 135 tons loaded. Wanted to load another 5 tons. Crushed 40-45 tons/day. Truck did 6 trips per day with over 4-ton loads.	28-12-79	EMA	1125	Newspaper	Estimate ref EMA 1125
1912	4535.925						Estimate ref EMA 1125
1913	4535.925						Estimate ref EMA 1125
1914	7257.48		1914				Estimate ref EMA 1125, West Australian paper 1914 article
1915	4535.925						Estimate ref EMA 1125
1916	680.389	Great war		EMA	1125		Recorded ref EMA 1138
1917	0	Great war					Recorded ref EMA 1138
1918	0	Great war					Recorded ref EMA 1138
1919	907.185						Estimate
1920	907.185						Estimate
1921	907.185						Estimate
1922	907.185						Estimate
1923	272.1555	1922-1923		EMA	1125		Recorded

Harvest year	Salt harvest Tonnes	Notes	Source Date	Source	Reference	Format	Calculated estimate reference
1924	4535.925						Estimate based on shed used to 1937, ref EMA 1125
1925	4535.925						Estimate based on shed used to 1937, ref EMA 1125
1926	4535.925						Estimate based on shed used to 1937, ref EMA 1125
1927	4535.925						Estimate based on shed used to 1937, ref EMA 1125
1928	4535.925						Estimate based on shed used to 1937, ref EMA 1125
1929	4535.925						Estimate based on shed used to 1937, ref EMA 1125
1930	4535.925						Estimate based on shed used to 1937, ref EMA 1125
1931	4535.925						Estimate based on shed used to 1937, ref EMA 1125
1932	4535.925						Estimate based on shed used to 1937, ref EMA 1125
1933	4535.925						Estimate based on shed used to 1937, ref EMA 1125
1934	4535.925						Estimate based on shed used to 1937, ref EMA 1125
1935	4535.925						Estimate based on shed used to 1937, ref EMA 1125
1936	4535.925						Estimate based on shed used to 1937, ref EMA 1125
1937	4535.925						Estimate based on shed used to 1937, ref EMA 1125
1938	4535.925						Estimate based on WA State Government 1939 Photo from WA Library 816B/B/6394
1939	4535.925						Estimate based on WA State Government 1939 Photo from WA Library 816B/B/6395
1940-1968	0						No information or reference for this period
1969	907.185	Late 1960's? States Middle Islands Pink Lake is a finer (better) example than Esperance PL		EMA	1160	Newspaper	Also a flood year

Harvest year	Salt harvest Tonnes	Notes	Source Date	Source	Reference	Format	Calculated estimate reference
1970	1000		31-12-19	Peter Lister		Email	P. Lister email estimated 1000 tonnes/year
1971	1000		31-12-19	Peter Lister		Email	P. Lister email estimated 1000 tonnes/year
1972	1000		31-12-19	Peter Lister		Email	P. Lister email estimated 1000 tonnes/year
1973	1000		31-12-19	Peter Lister		Email	P. Lister email estimated 1000 tonnes/year
1974	0		31-12-19	Peter Lister		Email	P. Lister email, washed out due to Cyclone Alby, no production for 3 years
1975	0		31-12-19	Peter Lister		Email	P. Lister email, washed out due to Cyclone Alby, no production for 3 years
1976	0		31-12-19	Peter Lister		Email	P. Lister email, washed out due to Cyclone Alby, no production for 3 years
1977	14000						
1978	20000	Peter Lister Age 19 Date reference? Listers had lease for about 30 years when article was written. Date reference? Article 1980 About 200 tonnes of PL salt is transported from Esperance per week. 1978 harvest was 24,000 tonnes, 1979 was 18,000 tonnes and 1980 was 10,000 tonnes. Mr Lister is certain salt comes from beneath the Lake, but they have not drilled the Lake. Vital statistics for salt production are for every 1 gallon of water there is 2.5 lbs of salt. 1 inch of salt per acre will yield 100 tonnes.	09-01-20	Peter Lister		Email	Logbook records provided in email by Peter Lister WA Salt. This logbook reference is considered more accurate than the referenced newspaper salt quantities.
1979	10000		09-01-20	Peter Lister		Email	Logbook records provided in email by Peter Lister WA Salt
1980	13500		09-01-20	Peter Lister		Email	Logbook records provided in email by Peter Lister WA Salt
1981	15000		09-01-20	Peter Lister		Email	Logbook records provided in email by Peter Lister WA Salt
1982	13000		17-12-19	Peter Lister		Email	Excellent - Provided by Peter Lister WA Salt Supplies
1983	12000		17-12-19	Peter Lister		Email	Excellent - Provided by Peter Lister WA Salt Supplies

Harvest year	Salt harvest Tonnes	Notes	Source Date	Source	Reference	Format	Calculated estimate reference
1984	11000		17-12-19	Peter Lister		Email	Excellent - Provided by Peter Lister WA Salt Supplies
1985	13000		17-12-19	Peter Lister		Email	Excellent - Provided by Peter Lister WA Salt Supplies
1986	14000		17-12-19	Peter Lister		Email	Excellent - Provided by Peter Lister WA Salt Supplies
1987	11000		17-12-19	Peter Lister		Email	Excellent - Provided by Peter Lister WA Salt Supplies
1988	12000		17-12-19	Peter Lister		Email	Excellent - Provided by Peter Lister WA Salt Supplies
1989	13000		17-12-19	Peter Lister		Email	Excellent - Provided by Peter Lister WA Salt Supplies - Wet year
1990	14000		17-12-19	Peter Lister		Email	Excellent - Provided by Peter Lister WA Salt Supplies
1991	6000		17-12-19	Peter Lister		Email	Excellent - Provided by Peter Lister WA Salt Supplies
1992	18000		17-12-19	Peter Lister		Email	Excellent - Provided by Peter Lister WA Salt Supplies
1993	10000		17-12-19	Peter Lister		Email	Excellent - Provided by Peter Lister WA Salt Supplies
1994	3000		17-12-19	Peter Lister		Email	Excellent - Provided by Peter Lister WA Salt Supplies
1995	15000		17-12-19	Peter Lister		Email	Excellent - Provided by Peter Lister WA Salt Supplies
1996	12000		17-12-19	Peter Lister		Email	Excellent - Provided by Peter Lister WA Salt Supplies
1997	14000		17-12-19	Peter Lister		Email	Excellent - Provided by Peter Lister WA Salt Supplies
1998	16000		17-12-19	Peter Lister		Email	Excellent - Provided by Peter Lister WA Salt Supplies
1999	2500		17-12-19	Peter Lister		Email	Excellent - Provided by Peter Lister WA Salt Supplies - Wet year
2000	3500		17-12-19	Peter Lister		Email	Excellent - Provided by Peter Lister WA Salt Supplies - Wet year
2001	16000		17-12-19	Peter Lister		Email	Excellent - Provided by Peter Lister WA Salt Supplies
2002	12200		17-12-19	Peter Lister		Email	Excellent - Provided by Peter Lister WA Salt Supplies

Harvest year	Salt harvest Tonnes	Notes	Source Date	Source	Reference	Format	Calculated estimate reference
2003	14500		17-12-19	Peter Lister		Email	Excellent - Provided by Peter Lister WA Salt Supplies
2004	5500		17-12-19	Peter Lister		Email	Excellent - Provided by Peter Lister WA Salt Supplies
2005	14500		17-12-19	Peter Lister		Email	Excellent - Provided by Peter Lister WA Salt Supplies
2006	3400		17-12-19	Peter Lister		Email	Excellent - Provided by Peter Lister WA Salt Supplies
2007	2200		17-12-19	Peter Lister		Email	Excellent - Provided by Peter Lister WA Salt Supplies - Wet year
2008	0	No more salt harvesting post 2007 summer	17-12-19	Peter Lister		Email	Excellent - Provided by Peter Lister WA Salt Supplies - Wet year
Total	**465798**						

Additional salt harvesting notes on the following page.

Additional historic Pink Lake Salt Harvest Information

Source Date	Source	Reference	Format	Harvest year	QTY	Measure	Notes
2013	www.ga.gov.au	Mernagh, T.P. (ed), (2013), A review of Australian salt lakes and assessment of their potential for strategic resources. Record 2013/39. Geoscience Australia: Canberra					Summary of 1986 PL hydro study. Salt surface inflow estimated at 800 tonnes per year, 5500 tonnes per year ground water inflow, estimated 1.1 million tonnes of salt on the Lake Surface. Drilling estimates up to 18 million tonnes of salt in subsurface sediments (Galloway et al 1986)
??	EMA	1802	Newspaper				WA Salt Owner Frank Lister said PL had been worked for 60 years using shovels. Listers farming family in 1950's
28-12-79	EMA	1125	Newspaper	1911	1000	Tons	Salt Co Started, 135 tons loaded. Wanted to load another 5 tons. Crushed 40-45 tons/day. Truck did 6 trips per day with over 4-ton loads.
	EMA	1125					Great war
	EMA	1125		1916	750	Tons	Great war
	EMA	1125					Great war
	EMA	1125		1923	300	Tons	1922-1923
	EMA	1125		1937			Shed used up to 1937
	EMA	1129			12000	Tonnes	Finished on March 9?? Dry year meant a short season. 1988???
	EMA	1138	RJ McCarthy transcript	1896			E J Mcarthy 1896-1907 maybe 1000 tons per year. Around 1911 a shed was built. 8 bags to the ton and 12 bags to the ton. 40-45 tons per day were usual, 6 days a week. Season was December to March. 120 days @ 40-45 tons = 5,400 ton/year. Started 1911. SS Perth took 2,000tons, The Chillagoe came 3 x, heaviest load 1,750 tons. The great war interrupted salt business. Standard salt co from 1907 and stops after 1924
	EMA	1155	RJ McCarthy transcript				Salt finished in May 1916, started again in 1919 after the war.

Source Date	Source	Reference	Format	Harvest year	QTY	Measure	Notes
	EMA	1160	Newspaper		1000	Tons	Late 1960's? States Middle Islands Pink Lake is a finer (better) example than Esperance PL
1969	EMA	1161	Newspaper				Salt loader for the Esperance Port. Can load 1000 ton per hour
Late 1960's??	EMA	1162	Newspaper				CSIRO finds breakthrough in use of D. salina beta-carotene in food products.
Mid 1980's?	EMA	1167	transcript		10000	tonnes	
26-05-94	EMA	1168	Newspaper				Salt harvested once a year. Saltwater is pumped into a crystallising pond and flows through low ponds which are shut off as they fill. Water evaporates and remaining water is drained away. Remaining salt is graded into windrows and harvested onto trucks taken to the stockpile. Weather could be an issue. Harvest on average 10,000 tonne/yr, had 3000 tonnes during a poor year (1989 wet year??). Company budgets on 10000 tonnes a year as it's the believed harvest threshold for the lake. In 1938 the Listers (Jack) set up salt works in Esperance. Tony Lister came to Esperance in 1970, and set up evaporation ponds. In 1994 the pink colour only lasted about 8 weeks due to the dry year.
late 1980's??	EMA	1169	Pamphlet?		20000	tonnes	At present 20000 tonnes a year are harvested. This may have been confused with the Koolyanobbing harvest (refer to ref 1778)
07-10-87	EMA	1778	Newspaper	1987	10000-12000	tonnes	Listers took the lease in the 1960's, started production in the 1970's. Jack started in Esperance in 1942. Talk about the 1986 hydro report. They quote the estimated 30 million tonnes of salt. Weather important to harvest. Water pumped to ponds in October/early November. When about 10 cm of salt has formed the water is drained off and harvest begins

Source Date	Source	Reference	Format	Harvest year	QTY	Measure	Notes
1983	EMA	1786	Newspaper	1983	14000	tonnes	WA salt supply, About 14000 tonnes/year. Pre vitamin company. In pencil there is written 83. They discuss issues with the lake drying which happened during the early 80's drought.
29-08-86	EMA	1789	Newspaper	1986	14000	tonnes	New lease stated salt production be limited to 14000 tonnes/yr using surface lake water. If this is to be exceeded, then a study of the lake regolith volume be estimated and brine from below the lakes (groundwater) be used to replenish the evaporation ponds and not the lake water.
??	EMA	1790	Newspaper		500,000	Tons	Good season, approximately. Very low confidence
1980	EMA	1797	Newspaper	1978	24000	tonnes	Peter Lister Age 19 Date reference? Listers had lease for about 30 years when article was written. Date reference? Article 1980 About 200 tonnes of PL salt is transported from Esperance per week. 1978 harvest was 24,000 tonnes, 1979 was 18,000 tonnes and 1980 was 10,000 tonnes. Mr Lister is certain salt comes from beneath the Lake, but they have not drilled the Lake. Vital statistics for salt production is every 1 gallon of water there is 2.5 lbs of salt. 1 inch of salt per acre will yield 100 tonnes.
1980	EMA	1797	Newspaper	1979	18000	tonnes	
1980	EMA	1797	Newspaper	1980	10000	tonnes	
?	EMA	EMA folder - No number	Summary transcript in EMA folder	1906	197	tons	

Source Date	Source	Reference	Format	Harvest year	QTY	Measure	Notes
early 1980s	EMA	1798	Newspaper				Pre 1986 hydro study, waiting on study results, early-mid 1980s??. Talk of driest year on record, concerns by Vitamins Australia of over extraction of salt impacting on D. salina. < 20% of the Lake was under water during this period. Western Salt increased extraction from 1800 tonnes to 10000 tonnes.
	EMA	1809	Newspaper				5000 tonnes/yr of table salt to provided. Additional salt will still be harvested for abattoirs. This amount does not include quantity of salt harvested for other uses. Pump distributes 60,000 gallons of water an hour which is 60 tonnes of salt an hour.
?	EMA	No number	Museum printout				PL evaporation ponds. 8 ponds totalling 13 ha
12-03-14	EMA	The West Australian 12/3/1914	Newspaper				PL Deepest point was 3ft 9inches (1143 cm) summer level, Salt is inches thick crystallized on lake surface estimated at 350 tons (317.515 tonnes) per acre (0.405 ha). Target was 8000 ton for year 1914

Appendix 2 Pink Lake historic biological pink colour research summary

Source	Reference	Date	Format	Description	Target/Issue
EMA	1172	20-10-94	Newspaper	1984 report Hurle and Associates High salt, light intensity and temperature catalytic factors for colouration	red colour @ 250 gm/l, green <12.5gm/l, all 3 forms of algae at >200gm/l, including common blue green. Pink at salt concern 200-250gm/l
EMA	1773	Jun-83	Newspaper	PL nearly drying out during 1983 at the end of the 1979 - 1983 climatic drought. Concerns re over extraction of salt leading to increased drying of PL. Possible due to increased evaporation rates of less saline water.	Drying out problem
EMA	1775	18-08-81	Newspaper	Concerns over plans to harvest D. salina. And increased fresh water impacting PL. Biologist Jill Kessell took about 50 lake samples and said unlikely that fresh water would affect the overall lake but did not put a number value on water quantity.	Flooding, freshwater problem
EMA	1782	02-04-86	Newspaper	Concerns over the Mr Helm proposed development for rural residential lots and a golf course. Planning officer Howard Wright raised concerns about chemical fertiliser resulting from the development impacting the water table.	Water quality threat
EMA	1783	29-04-??	Newspaper	First European person to see PL was Déntrecasteaux Monsier Riche in December 16, 1792. Mrs Daniells took PL water samples to Perth.	PL samples found the Lakes colour produced by *D. salina* with some help from Coccomonas algae
EMA	1787	??	Newspaper	PL algae extraction for Vitamins. Murdoch Uni running trials. Team led by Sydney based microbiologist Lesley Borowitska provided comments.	Algae grows in salt concentrations 10 x seawater
EMA	1790	??	Newspaper	Letter by Jean Gordon. Talks about theory of natural bromine dye making PL pink. (Not the case Refer to ref: 1801) Discussed the need to us a polarised filter to capture a representative photo of Pink Lakes colour. Fine salt crystal formation on the lakebed and coarse crystal in the water.	

Source	Reference	Date	Format	Description	Target/Issue
EMA	132	??	Newspaper	Concerns over freshwater contamination effecting PL by Mrs J Gordon. Post 1969 floods PL colour changed for some time. In 1962 she noticed freshwater streams coming from springs/soaks entering PL but noted it didn't affect the Lake.	Flooding, freshwater problem
EMA	1801	??	Newspaper	The beta carotene project was supposed to be monitoring the D. salina and pink colour of PL. Concerns over predators impacting D. salina, especially bacterial predators. John Fogden operations manager. University study of Thelma Daniells samples override the bromide theory and confirm D. salina	
	1805	??	Newspaper	SoE address road flooding problem for P Paxton and J Hanks increasing surface flows to PL from Keenans Road	Flooding, freshwater problem
EMA	1807	??	Newspaper	Council concerned over fresh flooding water into PL. Keenan's and Collier Rd area. Cr Beilken said the water was in the opposite direction draining into L Warden.	Flooding, freshwater problem. Cr Stearne raised concerns that flooding causing PL to take 2 to 3 years to recover to get back to its Pinkness
EMA	7049	01-01-58	Walkabout	Pink Lake and Monsieur Riche. Quote "*Through a petrified forest of leafless white branches and calcined roots he climbs the dunes to a crest and disappears. A glittering lake is a happy surprise, a waterless lake of bright pink sand, rosé.*"	Prior to catchment clearing and development it is likely that PL was ephemeral under pristine hydrological conditions with its water and salt balance in perfect equilibrium.
EMA	8437	18-12-89	Newspaper	1989 floods result in increased surface inflows and PL losing its pink colour to deep large expanse of blue-green water.	Flooding, freshwater problem

Source	Reference	Date	Format	Description	Target/Issue
EMA	8881	?-07-2002	Coleman M (2002), Pink Lake and its Colouration, actis Environmental Services	Report outlines two species D. salina and *Halobacterium halobium*. Can't find evidence of samples proving the presence of both species, also no reference for the assumption. Does state bacteria feeds off *D salina* by-products.	*D. salina* is outcompeted by other species in salinities < 2 x seawater salt concentration. *D. salina* survive better at > 5 x seawater. Nutrients must be available in the correct form and in suitable quantities. D. salina does not grow well with nitrogen as ammonia or urea (prefers N as nitrate), and prefers phosphate only. When nutrients concentrations are low and there is excess strong sunlight available, *D. salina* produces beta-carotene that shades chloroplast. This reduces photosynthesis in highly saline environments out competing other algae relying on chloroplast photosynthesis. Two samples taken from PL, one from the lake and other from a salt extraction pond. The Lake water contained high concentration of D. salina and several other algae species. This included 3 blue-green bacteria and a diatom. The pond water mainly populated by *D. salina* at lower concentrations than the lake. The pond was redder than the lake, thought D. salina lake concentrations were higher. The key to the pond redness was *D. salina* had larger cells more heavily pigmented with carotenoid.
EMA	1158	25-03-80	handwritten letter	UWA results of the Thelma Danniells samples	*D sp* and *Coccomonas sp* recognised by reddish precipitates in the cell walls.
EMA	1168	26-05-94	Newspaper	In 1994 the pink colour only lasted about 8 weeks due to the dry year.	

Appendix 3 Pink Lake Depth Volume tables

Depth (m)	Surface Area (ha)	Volume (KL)	Giga litres	Olympic pools
0.01	39	3589	0.00	1.4
0.02	46	7843	0.01	3.1
0.03	53	12801	0.01	5.1
0.04	61	18533	0.02	7.4
0.05	70	25106	0.03	10.0
0.06	80	32594	0.03	13.0
0.07	90	41074	0.04	16.4
0.08	101	50613	0.05	20.2
0.09	113	61277	0.06	24.5
0.1	126	73159	0.07	29.3
0.11	180	90753	0.09	36.3
0.12	188	109140	0.11	43.7
0.13	195	128281	0.13	51.3
0.14	203	148167	0.15	59.3
0.15	210	168812	0.17	67.5
0.16	218	190224	0.19	76.1
0.17	226	212428	0.21	85.0
0.18	234	235421	0.24	94.2
0.19	242	259232	0.26	103.7
0.2	251	283860	0.28	113.5
0.21	285	311921	0.31	124.8
0.22	294	340847	0.34	136.3
0.23	302	370628	0.37	148.3
0.24	311	401276	0.40	160.5
0.25	320	432804	0.43	173.1
0.26	329	465257	0.47	186.1
0.27	339	498649	0.50	199.5
0.28	348	532993	0.53	213.2

Depth (m)	Surface Area (ha)	Volume (KL)	Giga litres	Olympic pools
0.29	358	568326	0.57	227.3
0.3	368	604646	0.60	241.9
0.31	378	642053	0.64	256.8
0.32	386	680287	0.68	272.1
0.33	394	719277	0.72	287.7
0.34	402	759083	0.76	303.6
0.35	410	799675	0.80	319.9
0.36	418	841089	0.84	336.4
0.37	426	883317	0.88	353.3
0.38	435	926366	0.93	370.5
0.39	443	970260	0.97	388.1
0.4	451	1014977	1.01	406.0
0.41	460	1060537	1.06	424.2
0.42	468	1106907	1.11	442.8
0.43	476	1154105	1.15	461.6
0.44	485	1202144	1.20	480.9
0.45	493	1251018	1.25	500.4
0.46	502	1300761	1.30	520.3
0.47	510	1351352	1.35	540.5
0.48	519	1402832	1.40	561.1
0.49	528	1455184	1.46	582.1
0.5	538	1508433	1.51	603.4
0.51	545	1562561	1.56	625.0
0.52	553	1617459	1.62	647.0
0.53	560	1673071	1.67	669.2
0.54	567	1729418	1.73	691.8
0.55	574	1786484	1.79	714.6
0.56	582	1844265	1.84	737.7

Depth (m)	Surface Area (ha)	Volume (KL)	Giga litres	Olympic pools
0.57	589	1902782	1.90	761.1
0.58	596	1961995	1.96	784.8
0.59	603	2021970	2.02	808.8
0.6	610	2082613	2.08	833.0
0.61	617	2143987	2.14	857.6
0.62	624	2206060	2.21	882.4
0.63	631	2268821	2.27	907.5
0.64	638	2332316	2.33	932.9
0.65	646	2396488	2.40	958.6
0.66	653	2461387	2.46	984.6
0.67	660	2527007	2.53	1010.8
0.68	667	2593348	2.59	1037.3
0.69	674	2660414	2.66	1064.2
0.7	682	2728237	2.73	1091.3
0.71	689	2796792	2.80	1118.7
0.72	697	2866114	2.87	1146.4
0.73	704	2936171	2.94	1174.5
0.74	712	3006985	3.01	1202.8
0.75	720	3078555	3.08	1231.4
0.76	727	3150897	3.15	1260.4
0.77	735	3224001	3.22	1289.6
0.78	743	3297885	3.30	1319.2
0.79	750	3372541	3.37	1349.0
0.8	758	3447958	3.45	1379.2
0.81	765	3524044	3.52	1409.6
0.82	771	3600809	3.60	1440.3
0.83	778	3678243	3.68	1471.3
0.84	784	3756344	3.76	1502.5
0.85	791	3835113	3.84	1534.0
0.86	798	3914545	3.91	1565.8

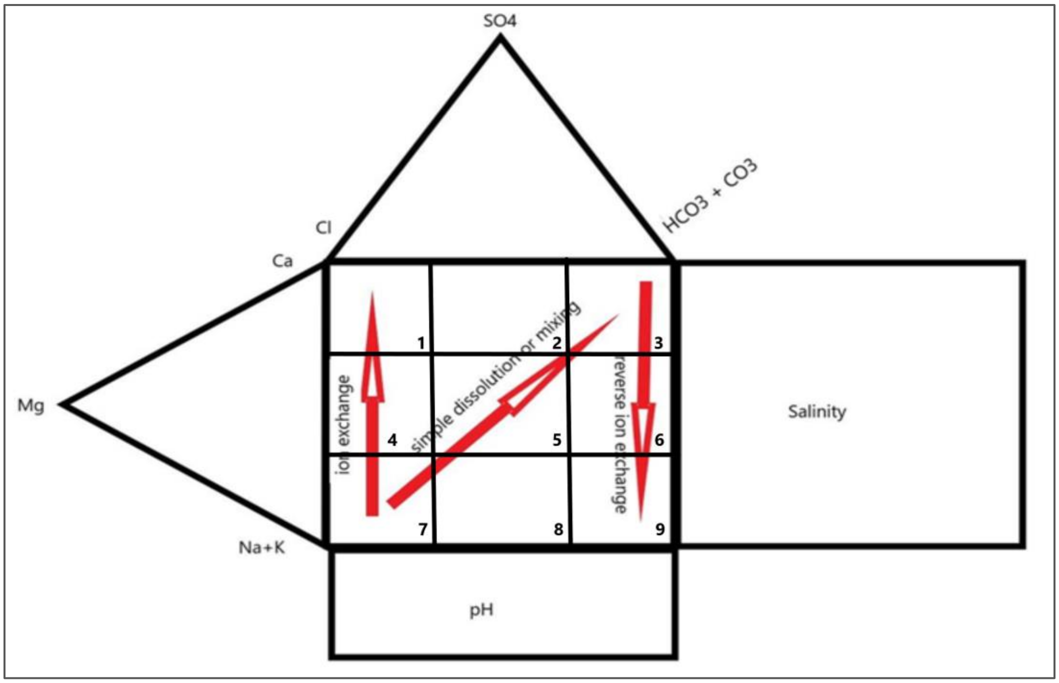
Depth (m)	Surface Area (ha)	Volume (KL)	Giga litres	Olympic pools
0.87	805	3994658	3.99	1597.9
0.88	812	4075490	4.08	1630.2
0.89	819	4156983	4.16	1662.8
0.9	826	4239201	4.24	1695.7
0.91	834	4322198	4.32	1728.9
0.92	842	4405995	4.41	1762.4
0.93	851	4490622	4.49	1796.2
0.94	859	4576124	4.58	1830.4
0.95	868	4662498	4.66	1865.0
0.96	877	4749760	4.75	1899.9
0.97	886	4837942	4.84	1935.2
0.98	895	4927027	4.93	1970.8
0.99	902	5017009	5.02	2006.8
1	904	5107718	5.11	2043.1

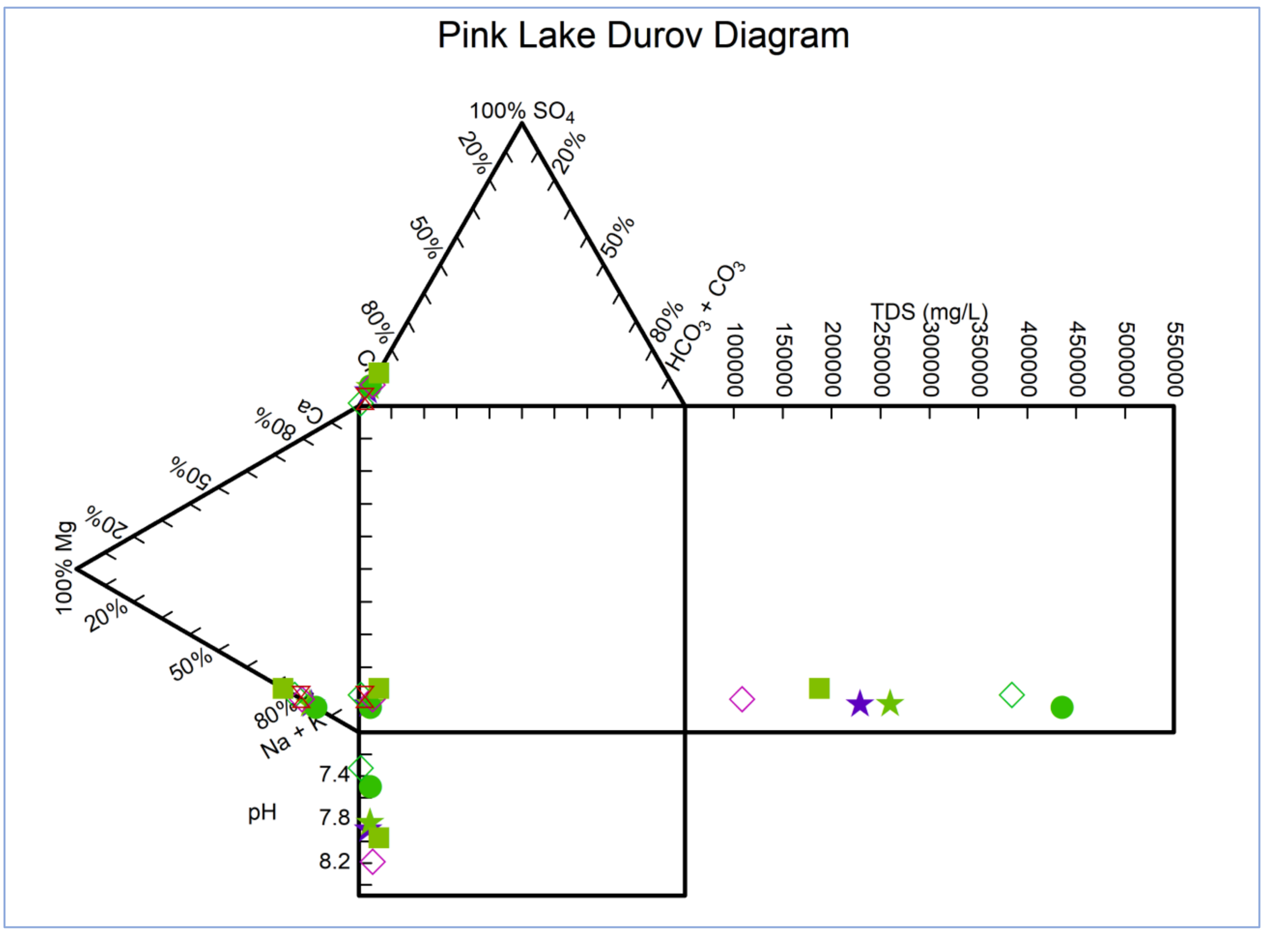
Appendix 4 Pink Lake and Lake Warden Water quality Durov Diagrams explained (Lizamore 2020)

Lloyd and Heathcoat (1985) offer a detailed discussion of Durov graphs. Expanded Durov graphs are similar to Piper diagrams in that analyses are plotted on separate anion and cation triangles 90° apart. The result is a square plot divided into nine areas, each characteristic of a different water type. These nine types are:

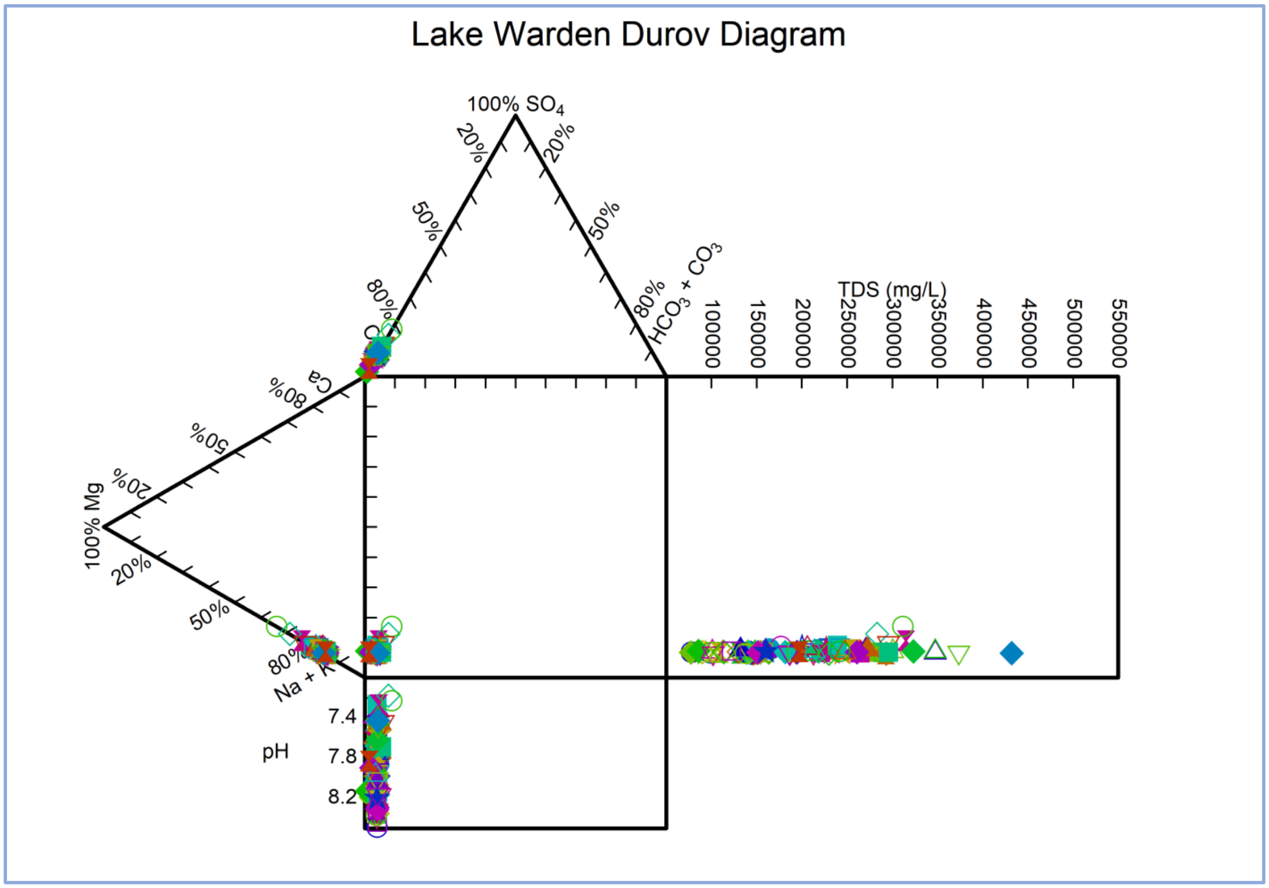
1. HCO3 and Ca dominant, frequently indicates recharging waters in limestone, sandstone, and many other aquifers.
2. This water type is dominated by Ca and HCO3 ions. Association with dolomite is presumed if Mg is significant. However, those samples in which Na is significant, an important ion exchange is presumed.
3. HCO3 and Na are dominant, normally indicates ion exchanged water, although the generation of CO2 at depth can produce HCO3 where Na is dominant under certain circumstances.
4. SO4 dominates, or anion discriminant and Ca dominant, Ca and SO4 dominant, frequently indicates recharge water in lava and gypsiferous deposits, otherwise mixed water or water exhibiting simple dissolution may be indicated.
5. No dominant anion or cation indicates water exhibiting simple dissolution or mixing.
6. SO4 dominant or anion discriminate and Na dominant; is a water type that is not frequently encountered and indicates probable mixing or uncommon dissolution influences.
7. Cl and Na dominant are frequently encountered unless cement pollution is present. Otherwise the water may result from reverse ion exchange of Na-Cl waters.
8. Cl dominant anion and Na dominant cation, indicate that the water be related to reverse ion exchange of Na-Cl waters.
9. Cl and Na dominant frequently indicate endpoint down gradient waters through dissolution.

The graphic below serves as reference. All samples analysed within the LWWS fall within block 7, indicating that the system is dominated by both Chloride and Sodium, with limited ion exchange during high runoff periods when phosphates enter the system, and chemical compositional and changes are mostly limited to salinity changes.





Appendix figure 1. Durov diagram for Pink Lake, indicating the relationship between major nutrients. (See above explanation how to interpret Durov diagrams)



Appendix figure 1. Durov diagram for Lake Warden, indicating the relationship between major nutrients. (See above explanation how to interpret Durov diagrams)

Appendix 5. Examples of *D. salina* light intensity and colour variation

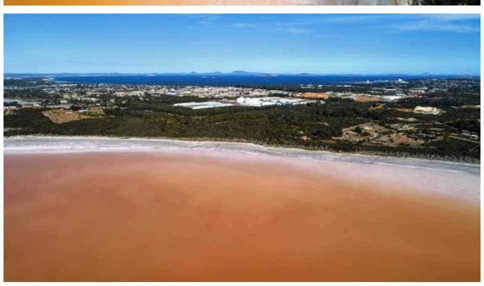
Lake Warden photos provided by Dan Paris, Bauhaus films, late March 2020. A lake depth of 0.28m and salinity at 540 g/L. Lake surface sediments are darker than Pink Lake due to catchment sedimentation and higher nutrient levels under extreme hypersaline conditions resulting in *D. salina* ß-Carotene mix of green and red carotenoid production. This mix results in an orange colour rather than Pink.

Sunny 26/03/2020 Overcast 02/04/2020





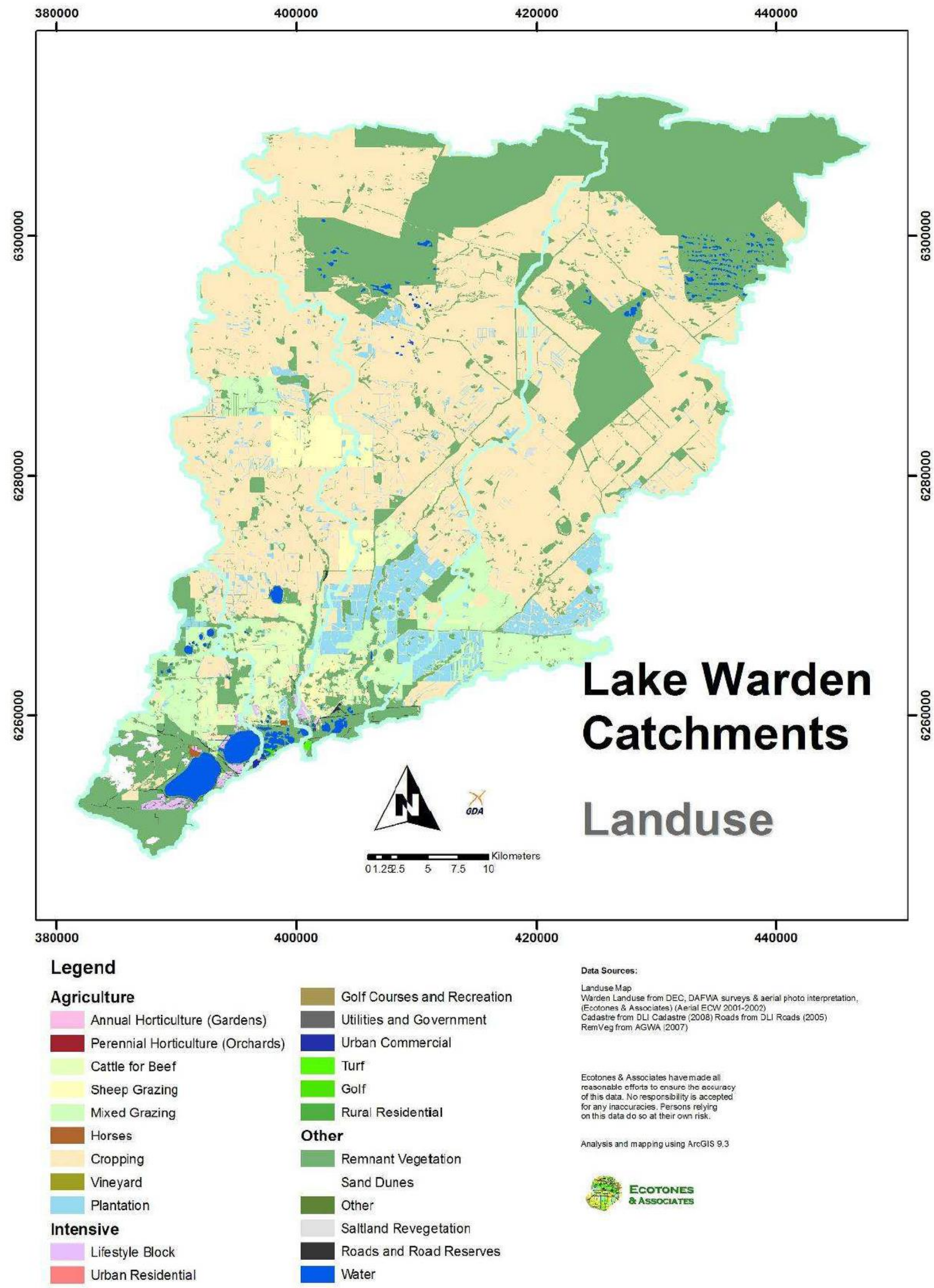


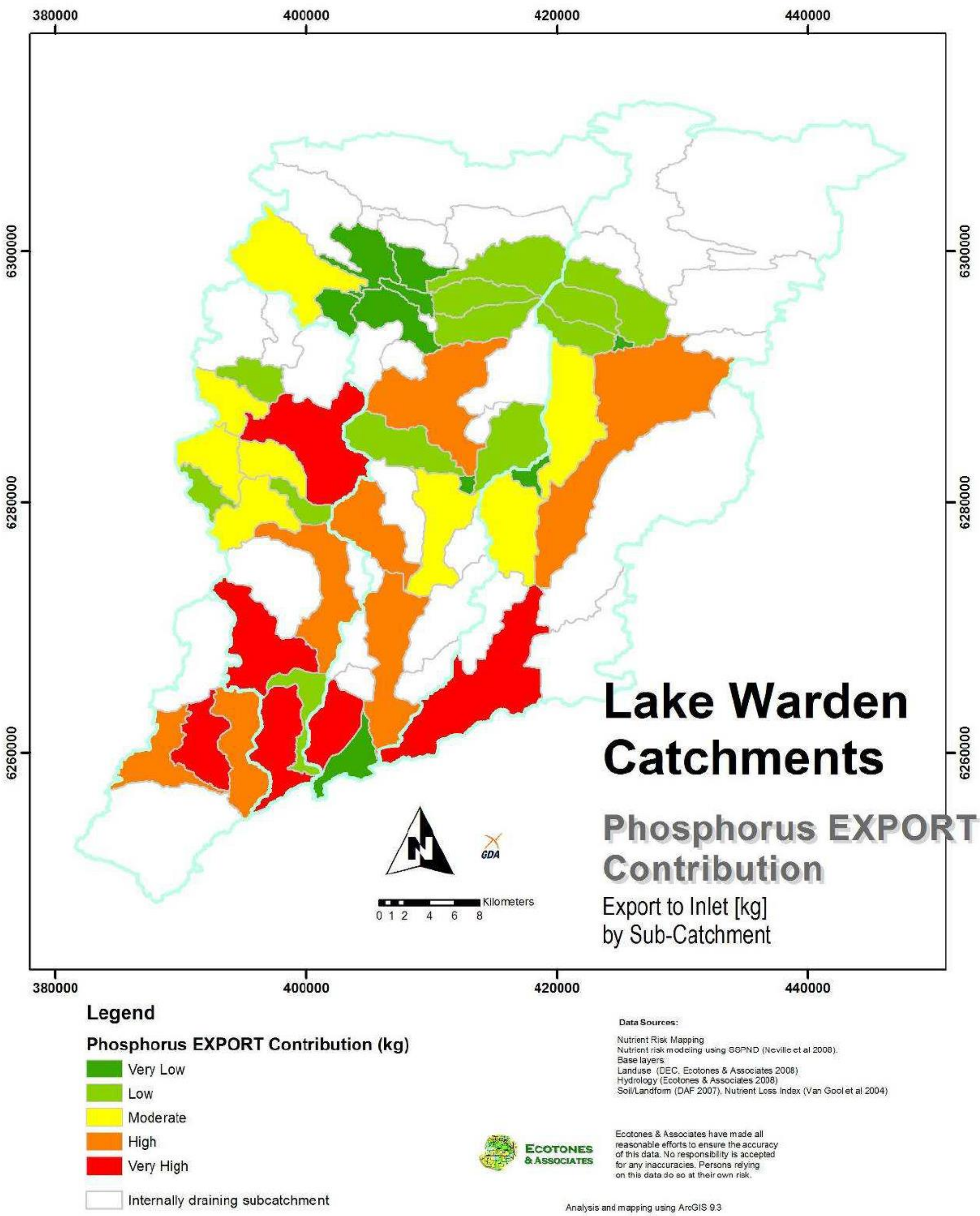



Appendix 6 Lake Warden Catchments nutrient export maps

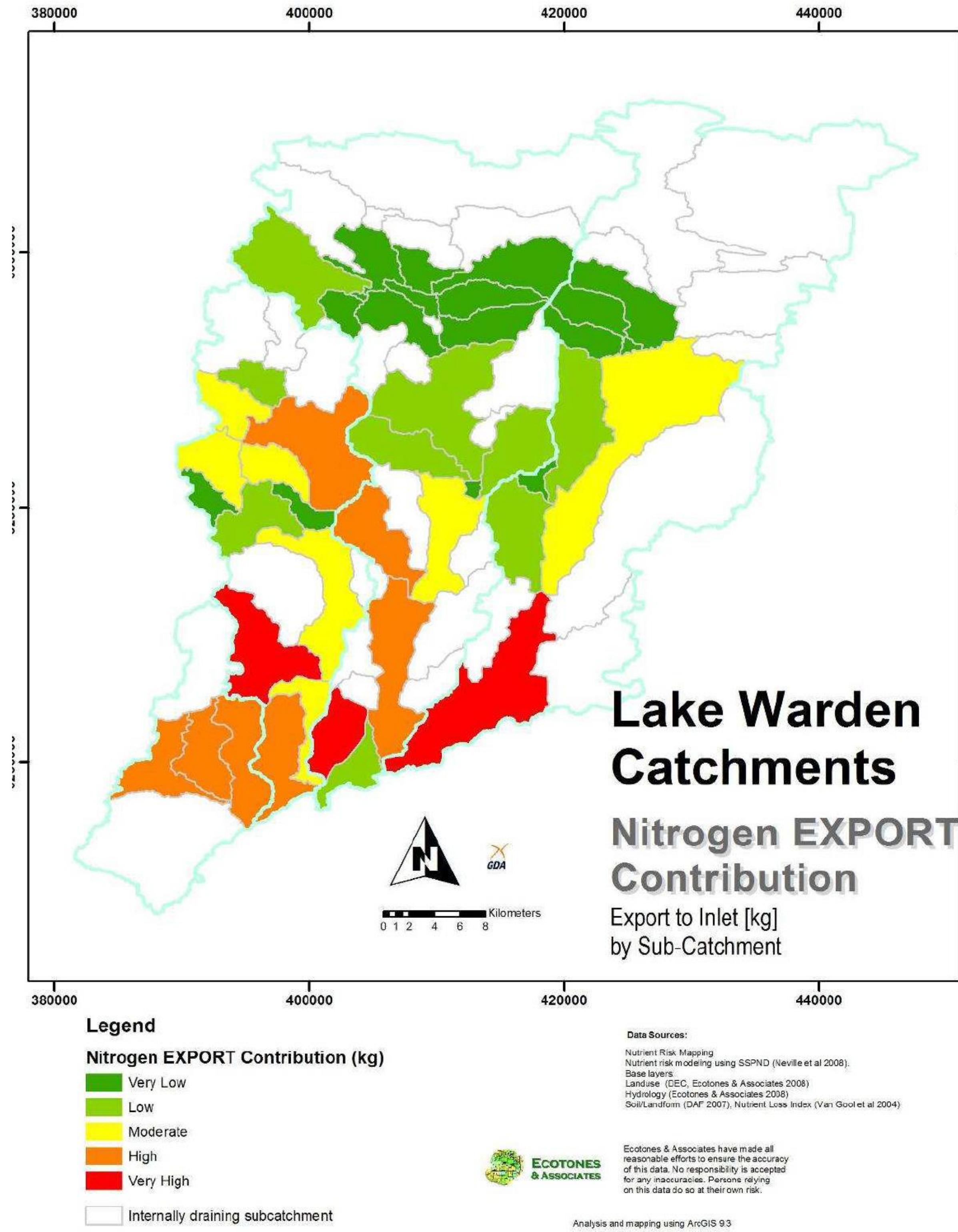
The following nutrient export maps were prepared by Simon Neville for the Department of Agriculture as part of a nutrient modelling project. (Nitrogen – N, Phosphorus – P)

The export contribution maps are significant from a catchment outlet perspective into Lake Warden. They indicate the key subcatchments for loads: for N all bar the Western Lakes catchment have a single very high contributing subcatchment. For P, a larger number of subcatchments contribute large loads, and these exist in each of the four main catchments. There is a large amount of overlap for N and P loads, and we have nominally identified four subcatchments with highest-band loads for both P and N as 'Target" subcatchments.





It should be noted that the subcatchments are dissimilar in size, so a larger subcatchment will tend to indicate a larger export simply because of size. Hence where smaller subcatchments indicate large relative loads, this indicates a combination of large load and higher intensity.



380000
400000
420000
440000
6300000
6280000
6260000
Lake Warden Catchments
Nitrogen EXPORT Contribution
Export to Inlet [kg] by Sub-Catchment
GDA
0 1 2 4 6 8 Kilometers
Legend
Nitrogen EXPORT Contribution (kg)
Very Low
Low
Moderate
High
Very High
Internally draining subcatchment
Data Sources:
Nutrient Risk Mapping
Nutrient risk modeling using SSPND (Neville et al 2008).
Base layers
Landuse (DEC, Ecotones & Associates 2008)
Hydrology (Ecotones & Associates 2008)
Soil/Landform (DAF 2007), Nutrient Loss Index (Van Gool et al 2004)
ECOTONES & ASSOCIATES
Ecotones & Associates have made all reasonable efforts to ensure the accuracy of this data. No responsibility is accepted for any inaccuracies. Persons relying on this data do so at their own risk.
Analysis and mapping using ArcGIS 9.3

Appendix 7. Esperance district coloured Salt Lake tourist drive

The following images are examples of seasonal colourful salt lakes located throughout the Esperance district.

Scaddan east area salt lakes (Google Earth 2020)

Cascade Road pink Lake, October 2019 (Photo Tilo Massenbauer)

Scaddan Pink Lake October 2015 (Photo Tilo Massenbauer)

Scaddan February 2007 (Photo Tilo Massenbauer)