2020

Water quality review of Pink Lake and Associated Lakes

- *Technical support document for the Esperance Pink Lake Feasibility Study*

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Prepared for the Shire of Esperance

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Acknowledgments

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Disclaimer

1. Introduction

The analysis of water quality data collated for Pink Lake and other associated lakes was prepared to assist the feasibility study of Pink Lake for the Shire of Esperance. This water quality analysis report forms part of a technical support document for the '*Esperance Pink Lake Feasibility Study (2020)*'.

As part of the feasibility study to determine whether it is possible to recover the pink colour of Pink Lake, several lakes were investigated for their similarities and prospective management opportunities. This includes a data review for previous research on similar subject matter and builds on work undertaken by Cater and Lizamore in 2014-2015, as well as additional data collection in 2018.

Data collected include hydrological datasets supplied by Department of Biodiversity, Conservation and Attractions, as well as other unpublished reports.

2. Background - Sites, suitability and variability

Cater and Lizamore (2014-2015) identified 11 sites (Appendix 1) for study based on specific parameters in order to determine what makes pink lakes pink. Not all lakes had the same parameters, but it was attempted to determine why certain lakes turn pink, others do not, and if there are correlations that can be identified. These parameters include:

- i. Perennial, as well as ephemeral wetting and drying
- ii. Variable salinity (from fresh to hyper saline)
- iii. Known areas of shorebird visitation, in specific that of Hooded Plover
- iv. Known colouration of surface water (i.e. goes pink or are pink)
- v. Terminal and flowthrough lakes
- vi. Location on the South Coast of Western Australia

A summary of the lakes reviewed is in Appendix 1. Although the data was never collated into a report, the datasets are available. Based on the data, four sites were identified (Figure 1) and used for the Pink Lake feasibility study, which are:

1. Pink Lake –
    - a. situated 4km west of Esperance and 3.5 km from the coast;
    - b. large lake (approximately 1040ha);
    - c. perennial lake; (Historically partially ephemeral pre catchment clearing)
    - d. varies from brackish to hyper saline;
    - e. lake used to turn pink in colour as water level drops;
    - f. terminal lake;
    - g. identified as Hooded plover habitat; and
    - h. agricultural chemical impacts, including increased phosphates.
2. Lake Warden –
    - a. situated 3km north of Esperance and the coast;
    - b. large lake (approximately 750ha);
    - c. perennial lake; (Historically partially ephemeral pre catchment clearing)
    - d. varies from brackish to hyper saline;
    - e. lake has started to turn pink in colour as water level drops in the past ten years;
    - f. terminal lake;
    - g. identified as Hooded plover habitat; and
    - h. agricultural chemical impacts, including increased phosphates.

3. Lake Benje Benjemup (Also known on web maps as Benje Benjenup Lake) –
    a. situated 17km north of Esperance and 14km from the coast;
    b. medium lake (approximately 100ha);
    c. perennial lake; (Historically partially ephemeral pre catchment clearing)
    d. varies from brackish to hyper saline;
    e. lake turns pink in colour as water level drops;
    f. terminal lake;
    g. identified as Hooded plover habitat; and
    h. agricultural chemical impacts, including increased phosphates.
4. Lake Hillier (Control Site) –
    a. situated 125km east of Esperance on Middle Island;
    b. medium lake (approximately 21ha);
    c. perennial lake;
    d. permanently hyper saline;
    e. terminal lake;
    f. almost permanently bright bubble-gum pink colour;
    g. apart from localised human impacts approximately 100 years ago, isolated and negligible chemical impact; and
    h. chosen as control site.

The main factors for the chosen sites were:

i. Chemical compatibility between sites
ii. Known pink colouration (i.e. lakes are pink as salinity increases)
iii. Proximity to Pink Lake (i.e. similar climatic variables)
iv. Similarity in land-scape placement and catchment hydrology (i.e. terminal lakes)
v. Apart from Lake Hillier, similarity in chemical threats (i.e. agricultural phosphate input)

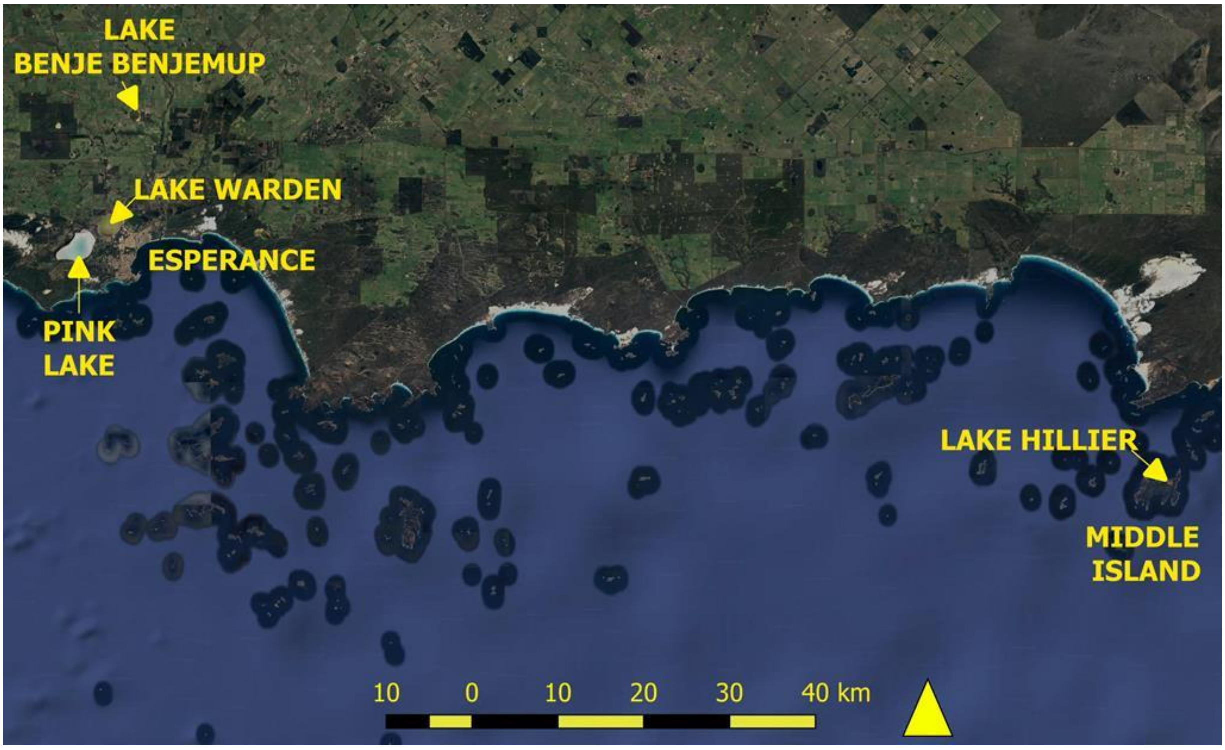


Figure 1. Lake localities used as water quality comparison analysis

3. Sampling methodology

Where possible and for consistency, water sampling followed the same method used by Cater and Lizamore (2014-2015) for collecting water samples. This include using the same methods of sampling, as well as the same laboratories for analysis (where possible).

University of Western Australia (UWA) was used for all 2019 inorganic analysis. Cater and Lizamore used a combination UWA for inorganic analysis and DBCA laboratory for anion and cation analysis in 2014-2015 (DBCA lab ceased operation in 2015).

National Measurement Institute Perth provided chlorophyll analysis.

BASF Australia laboratory (Hutt Lagoon) was used for organic analysis other than chlorophyll.

1. On site recording of:
   a. Water depth
   b. Weather conditions
   c. Fixed point photographs and photographing any aspect of interest
   d. In-situ measurement of Dissolved Oxygen
   e. Collection of 8 litres of sampling water – halfway in the water profile, but preferably at a depth no less than 40cm, without disturbing the sediments. Water to be cooled to temperature of 4°C as soon as possible and preserved for further lab processing within 24 hours
2. In the laboratory:
   a. Filter 1000ml water through 47mm glass-fibre filters for chlorophyll analysis by vacuum pump and frozen preserved.
   b. Measure pH, Electrical Conductivity and titratable alkalinity.
   c. Two 100ml bottles of water collected and frozen preserved for further chemical analysis at UWA
      i. one filtered sample (0.45µm)
      ii. one unfiltered sample
   d. 1 x 1000ml bottle of water collected unfiltered and unpreserved for BASF Australia for further analysis. Sample to be stored in the dark at 4ºC and sent for analysis within 3 days of collection.
   e. Evaporative analysis of samples to determine Total Dissolved Solids (TDS) values.
      i. Precise volumes measured off by using a 5ml pipettor
      ii. Electronic scale used for weighing, calibrated to 0, 10 and 50mg respectively. Scale accurate to 0.2mg.
      iii. Samples dried at 150ºC for a minimum of 6 hours.

All data received was entered and post-processed using Rockware AqQa software (version 1.5). Where required, data was exported to Microsoft Excel for production of relevant graphs.

4. Data and results

The source data includes datasets that goes back to the 1970's. Very little data exists to indicate methods of sampling, quality and/or accuracy of the data. Where possible, data was correlated between multiple sources. However, the inconsistency of the data available results in a potential error margin, which include, but are not limited to:

a. Salinity increases over time. This is described in more detail in Section 4.1
b. Anion and cation exchange calculations – different laboratories used different equipment and methodologies to measure inorganic components, resulting in different calculation-based elements. It is not possible to correlate this data differences as no overlapping sampling exists
c. Variability in seasonality of sampling – where historic lower-frequency data was captured, it was very much a case of hit-and-miss and upper and lower values may not include the maximum range, or necessarily accurate data trends.
d. Variability of sampling personnel – there appear to be certain trends identified where possible data errors occurred as a result of errors made by field personnel. Whereas some could be constant (e.g. tendency to under-read), often it is not possible to explain the variations in data apart from identifying more variations within one sampler's data as opposed to the next. This includes pH measurements (possibly not enough time allowed for samples to stabilise) as well quality of equipment used and relative calibration (e.g. some data that was recorded was clearly wrong and as a result of equipment defects).
e. Equipment accuracy – in the past 20 years, monitoring was mostly done with WTW®. It was found that variation between different manufacturers of reputable brands (e.g. Hach vs. WTW®) could be as much as 25%, whilst difference between two exact same manufacturer instruments could be 1-5%. There is no data to indicate what equipment was used for historic data collection to correct data.
f. Variation in major nutrient analysis – different methods was used to determine Nitrates and Phosphate derived variables over the period. Because the LWWS is a nitrate dominant system with high levels of Sodium and Chloride, testing methodology was changed over time to achieve more accurate data with less variability. It was also found that there was a high level of variability of results based on personnel changes between sample analysis. As such there may be high variability in various blocks of data.

Where possible and where identified, any abnormalities in data and trends was identified, reviewed and if it could not be verified as correct, deleted from the data-stream to improve overall accuracy.

4.1 Problems in data variability for salinity

Lizamore (2013) identified the variation in historic reported salinity compared to later data. This led to an analysis between different source data and how it was reported. It was also found that literature reported various values for the same data of up to 40% (Lizamore 2018), based on calculations (Figure 3).

In a further attempt to quantify the variability, Lizamore (2015) used various stored samples to determine and compare reported Electrical Conductivity (Ec) to measured evaporated TDS (Figure 4).

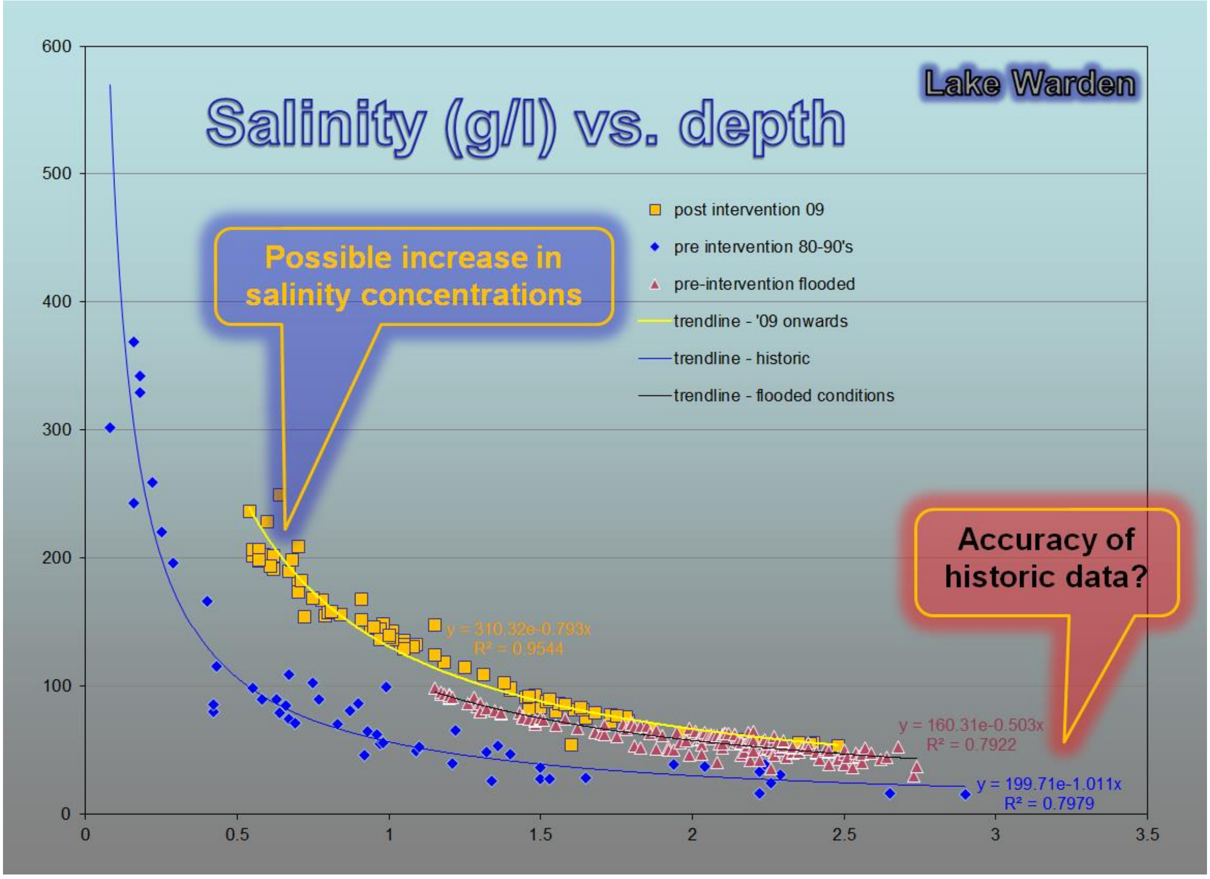


Figure 2: Salinity concentration variations at Lake Warden (Lizamore 2013)

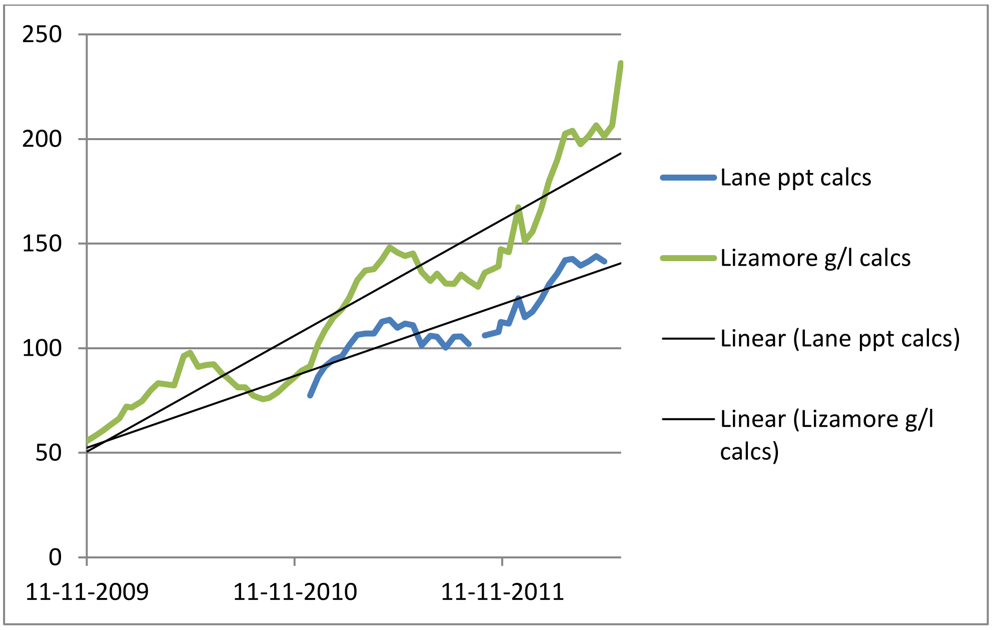


Figure 3: Salinity calculation variations for Lake Warden based on same conductivity values (Lizamore 2018)

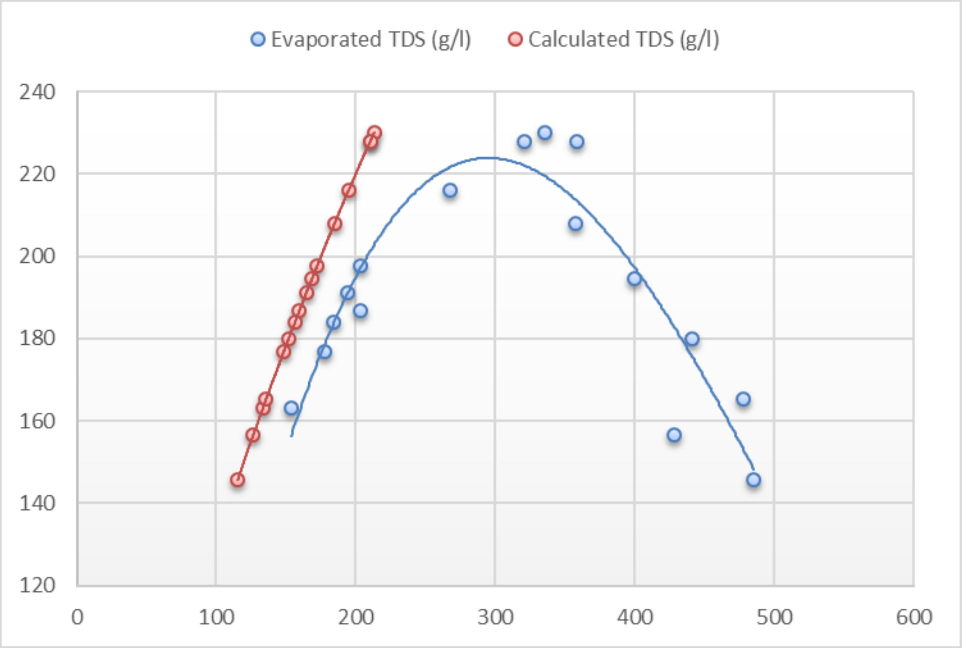


Figure 4: Salinity calculations based on Electrical Conductivity (Ec) vs. Evaporative TDS variations for Lake Warden (Lizamore 2015)

Figure 5: Suspended salts taken out of solution during field sampling (Lizamore 2015)

Other problems experienced the presence of a salt crust, as well as solid crystals contained within the water samples during measurement and storage. It was found that the standard field methodology required water samples to be frozen, or for the water to be cooled to 4°C. in practise, this resulted in rapid crystallisation of the samples with the drop in temperature. It was impossible to get the salts to dissolve back into solution again in the laboratory. As a result, reported salinity and nutrient values are lower than actual. An addition, crystallisation occurred whilst filtering the water for further analysis as well, possible resulting in a higher variation between Total Nitrates and Total Phosphates readings as opposed to Ammonia etc.

Figure 6: Salt crystallisation on paper filters during filtering (Lizamore 2015)

4.2 Quantifying error and set values

Ec:TDS values does not follow a linear regression curve, but that of a hysteresis curve similar to magnetic conductivity. Partly as a result of ion exchange, but also because salts will crystallise much faster and drop out of solution (thus lowering the Electrical Conductivity values) than they would dissolving back into solution when fresh water is added. As a result, the same Ec value could indicate different TDS values (see Figure 3).

The following formula was used for converting conductivity to salinity values (Fofonoff & Milliard; 1983):

$$S = a_0 + a_1R_t^{0.5} + a_2R_t + a_3R_t^{1.5} + a_4R_t^2 + a_5R_t^{2.5} + \Delta S$$

Where:

$$\Delta S = \frac{t-15}{1+k(t-15)} * (b_0 + b_1R_t^{0.5} + b_2R_t + b_3R_t^{1.5} + b_4R_t^2 + b_5R_t^{2.5})$$

The variation in using this formula as opposed to a straight-line conversion can be see in Figure 3. The difference between using TDS results compared to conductivity calculations can be seen in Figure 4.

Results indicate more conservative values for converting Conductivity to Salinity values can be obtained if water samples are diluted, and the results multiplied upwards rather than with a 1:1 calculation base. Lizamore (2015) recommended that all Ec readings greater than 150mS/cm should be diluted by 1:2 (50%), and all Ec readings greater than 180mS/cm should be diluted 1:4 (25%). Dilution is by using 25% and 50% of sample water, and 75% and 50% respectively deionised mineral water or distilled water (which should have an electrical conductivity reading of close to zero). The results of such dilution methods are shown in in Figures 7 and 8 for Lake Warden and Pink respectively. By using the dilution method to determine salinity concentrations, error margins for calculations can be lowered to around 5% as opposed to >50% for hyper-saline conditions.

This does not allow or facilitate for lost TDS as a result of crystallisation. Although the TDS concentration in the water may reduce, the overall salt-balance for the lake basin remain unchanged.

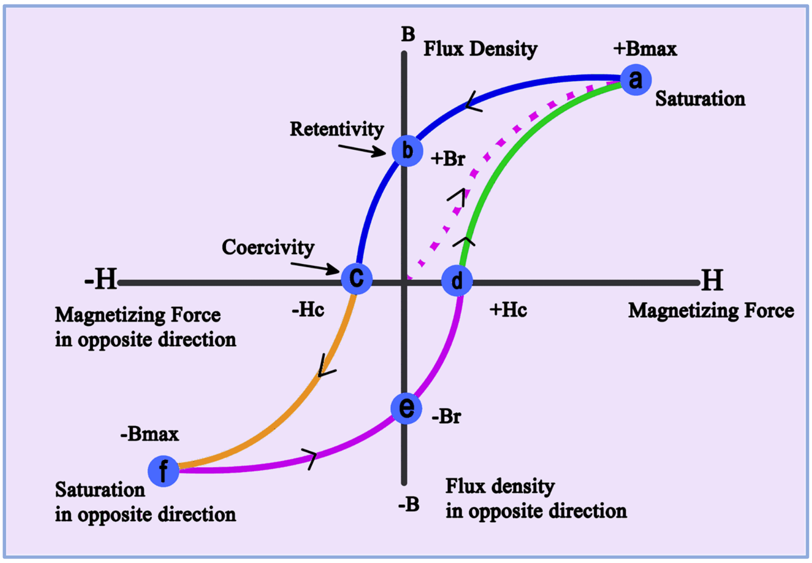


Figure 7: Visual representation of Hysteresis curve drivers

(https://electricalacademia.com/electromagnetism/hysteresis-loop-magnetization-curve/)

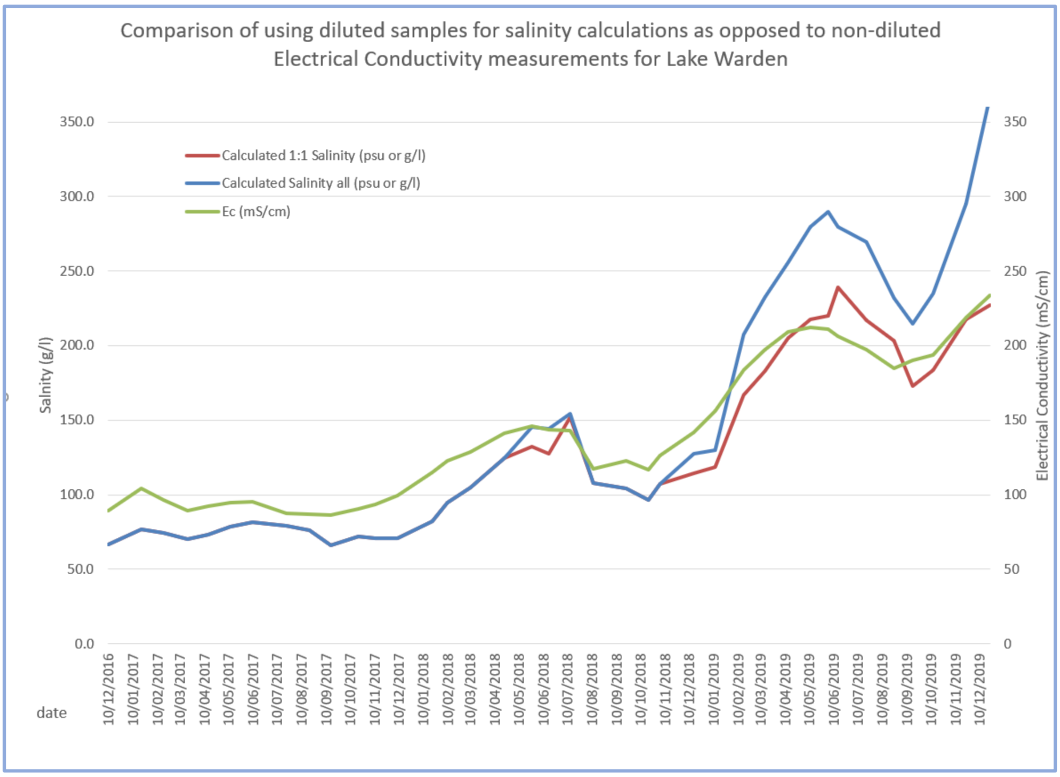


Figure 8: Comparison of using diluted samples for salinity calculations as opposed to non-diluted Electrical Conductivity (Ec) measurements for Lake Warden

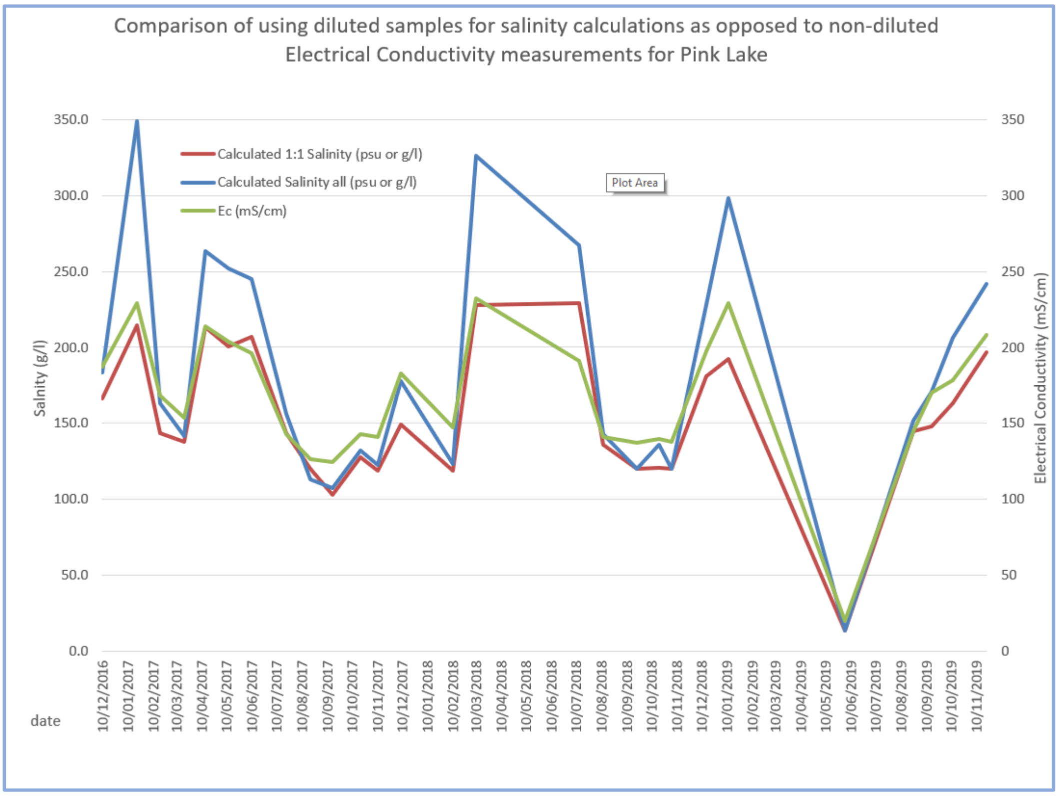


Figure 9: Comparison of using diluted samples for salinity calculations as opposed to non-diluted Electrical Conductivity (Ec) measurements for Pink Lake

4.3 Lake Benje Benjemup

Lake Benje Benjemup is a terminal, mostly perennial lake system. It has minimal overland flow entering the lake and is mostly fed by fresh to brackish groundwater. Overland flow mainly occurs during high frequency rainfall events resulting on large catchment runoff. The basin is dominated by granite on the northern shore, and limestone on the southern store. It’s an alkaline system with varying salinity concentrations. As a result of increased salt concentrations, the lake water turns pink. This normally occurs within a few weeks after salt crystallisation occurs and a salt crust forms. Exact colour varies from bright pink to a dark orange in places where Beta carotene concentrations are very high. Under these conditions, water temperature can exceed 30°C, but typically around 25-28°C during the day.

Figure 10: Typical summer photo of Lake Benje Benjemup

The system chemistry is dominated by Chlorides and Sodium. The system is chemically stable with very little changes apart from salinity concentrations (See Durov diagram in Figure 11 and major nutrients in Figure 12). Despite largescale usage of super phosphate chemicals within the catchment of the lake, the system remains phosphate limited with very low free-phosphate available. Bromine levels tend to be higher which indicates phosphates are assimilated into the system as soon as it enters.

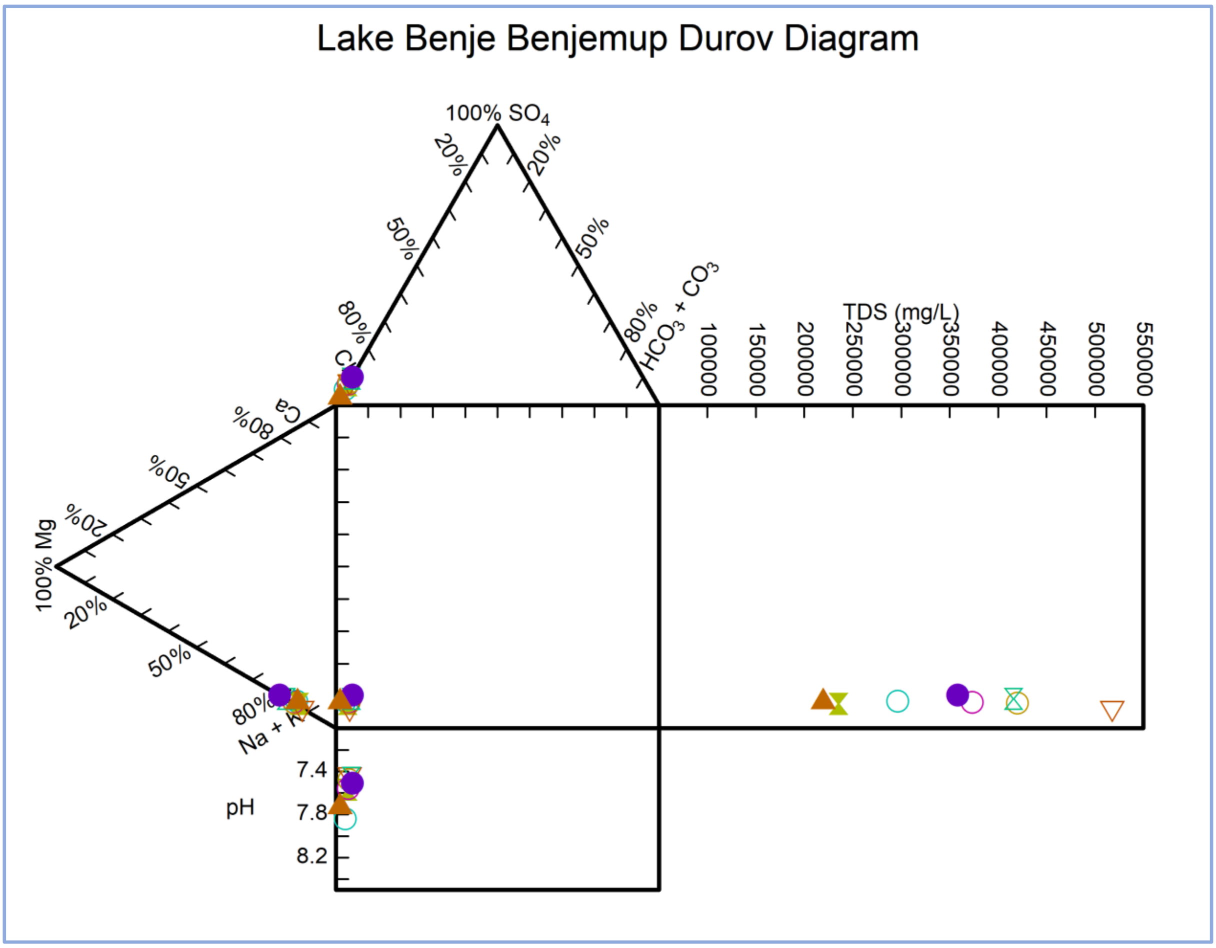


Figure 11: Durov diagram for Lake Benje Benjemup, indicating the relationship between major nutrients. (See Appendix 2 for an explanation on how to interpret Durov diagrams)

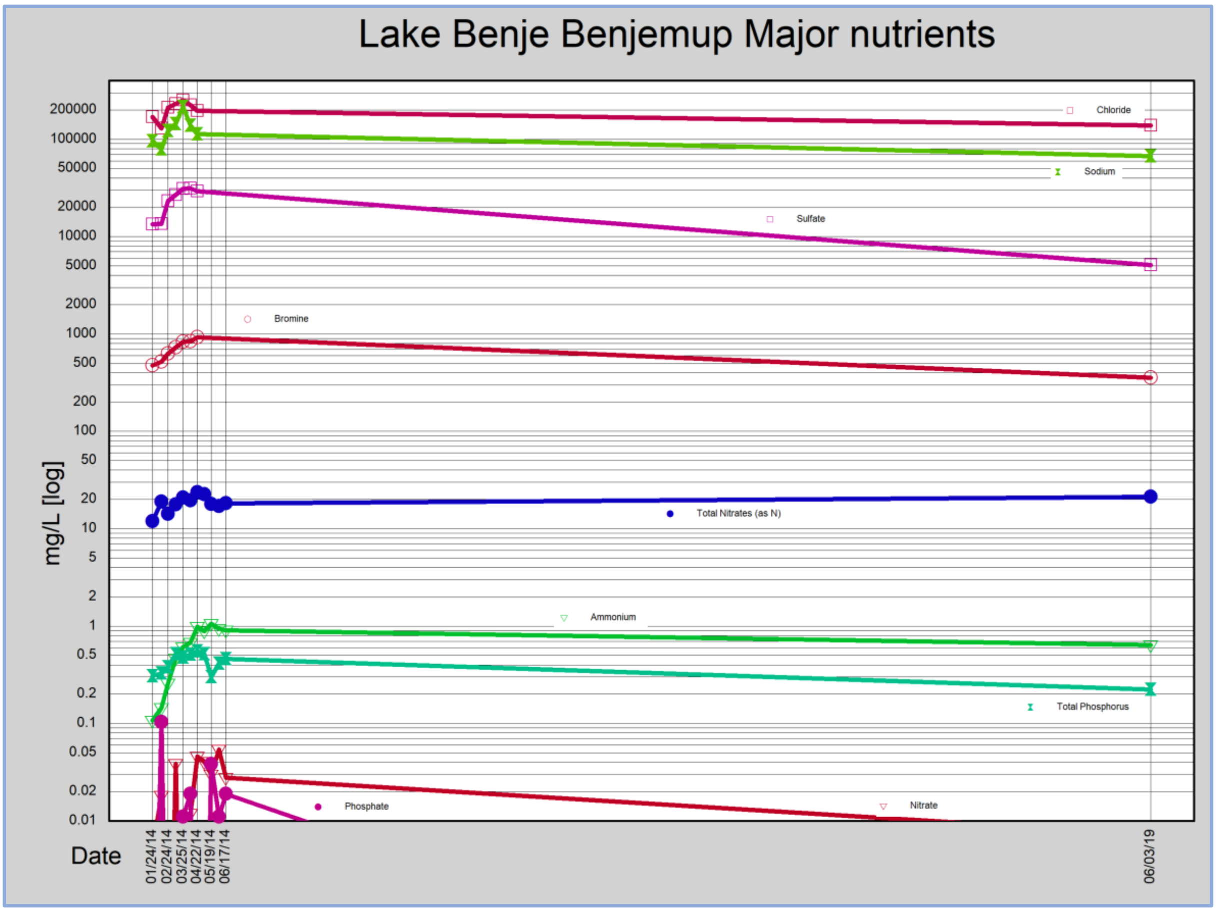


Figure 12: Timescale graph for major nutrients for Lake Benje Benjemup in logarithmic vertical scale

4.4 Lake Hillier

Lake Hillier is a terminal, perennial lake system. It has minimal overland flow entering the lake and is mostly fed by fresh to brackish groundwater. Overland flow mainly occurs during high frequency rainfall events resulting on large catchment runoff. The basin is dominated by weathered granite and some limestone. It's an alkaline system with varying salinity concentrations, but always hyper-saline. The lake water is permanently pink. A salt crust forms during summer months when lake level drops, but some salt crystallisation is almost always present. Exact colour varies but is normally bright pink. Some dark orange in areas occur on the north-west corner of the lake where Beta carotene concentrations are very high. Water temperature rarely exceeds 30°C, but typically around 25-28°C during the day in summer.

Figure 13: Typical winter photo of Lake Hillier

Figure 14: Orange colouration as a result of Beta Carotene concentrations at Lake Hillier

Figure 15: Ever present salt crystals at Lake Hillier

The system chemistry is dominated by Chlorides and Sodium. The system is chemically stable with very little changes apart from salinity concentrations (See Durov diagram in Figure 16 and major nutrients in Figure 17). The system is phosphate limited with very low free-phosphate available. Bromine levels tend to be higher which indicates phosphates are assimilated into the system as soon as it enters.

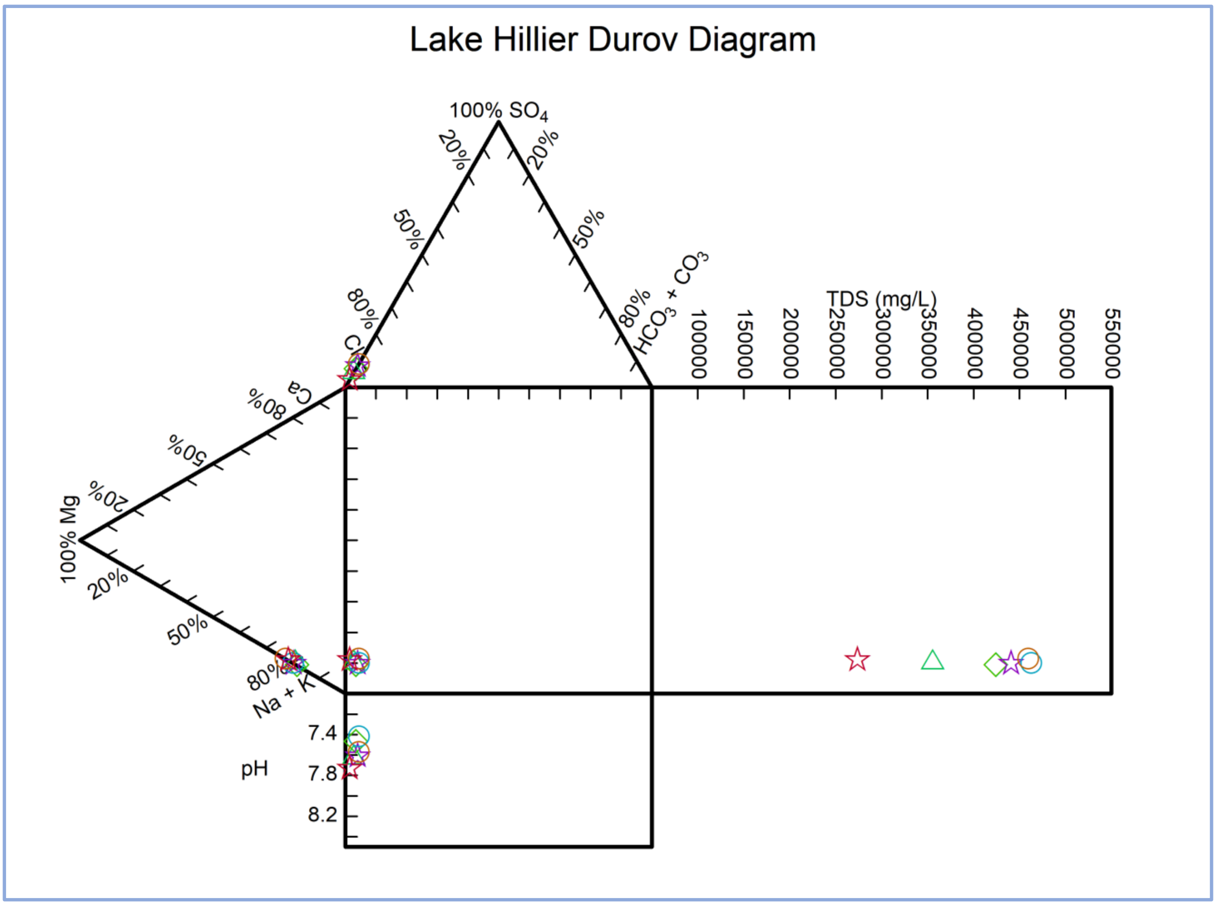


Figure 16: Durov diagram for Lake Hillier, indicating the relationship between major nutrients. (See Appendix 2 for an explanation on how to interpret Durov diagrams)

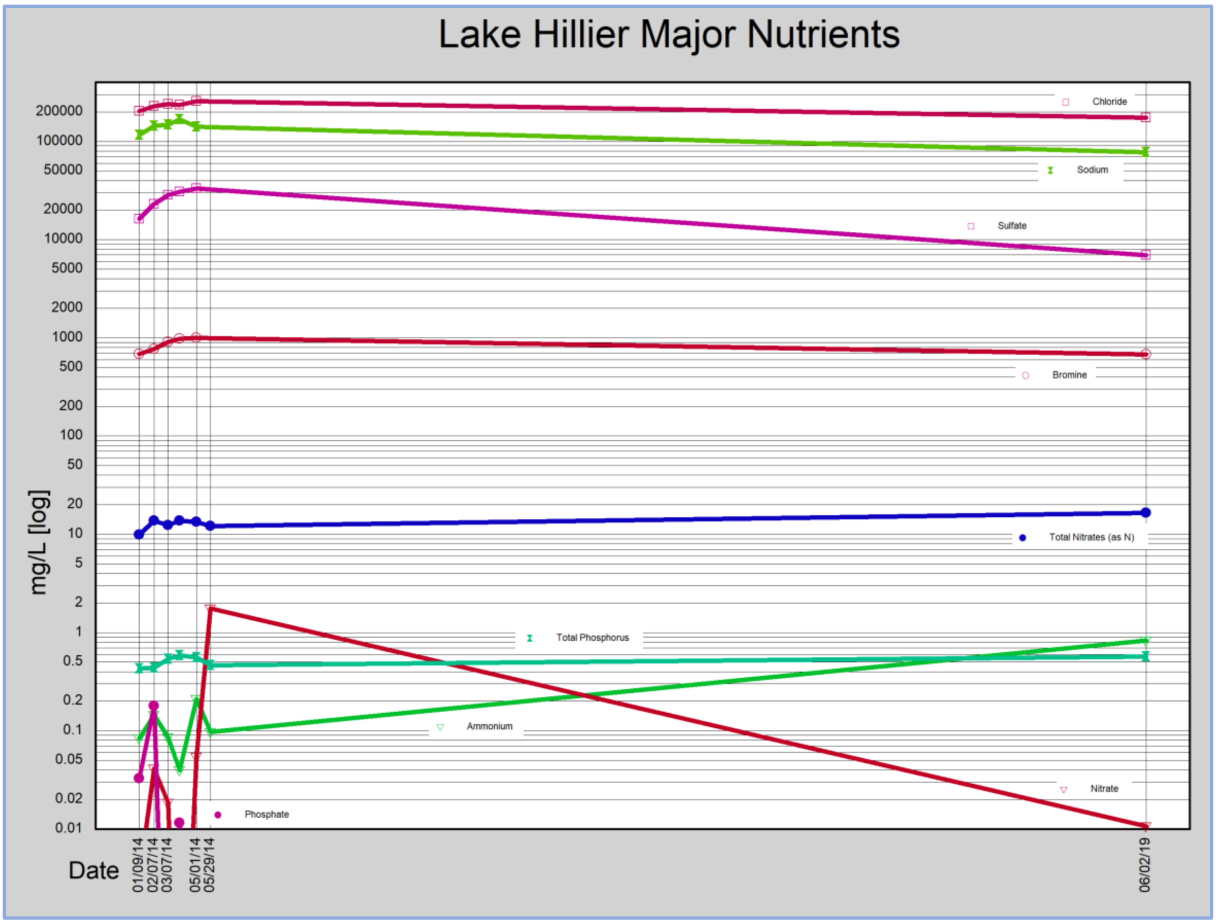


Figure 17: Timescale graph for major nutrients for Lake Hillier in logarithmic vertical scale

4.5 Lake Warden

Lizamore (2015) described the hydrology of the Lake Warden Wetland System and the hydrological link and significance between Pink Lake and Lake Warden. Lake Warden was originally a flowthrough lake, which overflowed though a series of interconnected wetlands to Pink Lake. As a result of anthropogenic impacts, the surface water link between Pink Lake and Lake Warden was severed several decades before, resulting in lake Warden becoming a terminal lake, and Pink Lake isolated from the greater Lake Warden Wetland System catchment. Historically, Lake Warden used to dry up some summers, with no recorded presence of a salt crust or pink/orange discolouration.

Currently Lake Warden is a terminal, perennial lake system. It has limited overland flow entering the lake and additionally fed by fresh to hypersaline groundwater. Surface water inflow occurs in winter from Mortinup Creek and Lake Windabout during high frequency rainfall events resulting on large catchment runoff. The basin is dominated by granite on the northern shore, and limestone on the southern store. It’s an alkaline system with varying salinity concentrations. As a result of increased salt concentrations, the lake water turns pink (1st recorded in 2012). Lizamore (2013) reported an increase in salinity concentrations at Lake Warden (Figure 2) after investigating this phenomenon.

This normally occurs within a few weeks after salt crystallisation occurs and a salt crust forms. Exact colour varies from a dirty pink to orange in places where Beta carotene concentrations are very high. Under these conditions, water temperature can exceed 30°C, but typically around 25-28°C during the day.

Although Lake Warden has a larger variation in pH compared to some other lakes, this has been identified to be as a result of algae activity and not chemical variation as such. Lizamore (2010) identified that pH increases from around 7.6 after sunrise to as high as 9.5 before sunset during a summer day.

Figure 17: Summer photo of Lake Warden

Figure 18: Orange Beta Carotene deposits on salt crusts at Lake Warden

The system chemistry is dominated by Chlorides and Sodium. The system is chemically stable with very little changes apart from salinity concentrations (See Durov diagram in Figure 19 and major nutrients in Figure 20). Despite largescale usage of super phosphate chemicals within the catchment of the lake, the system remains phosphate limited with very low free-phosphate available. Bromine levels tend to be higher which indicates phosphates are assimilated into the system as soon as it enters.

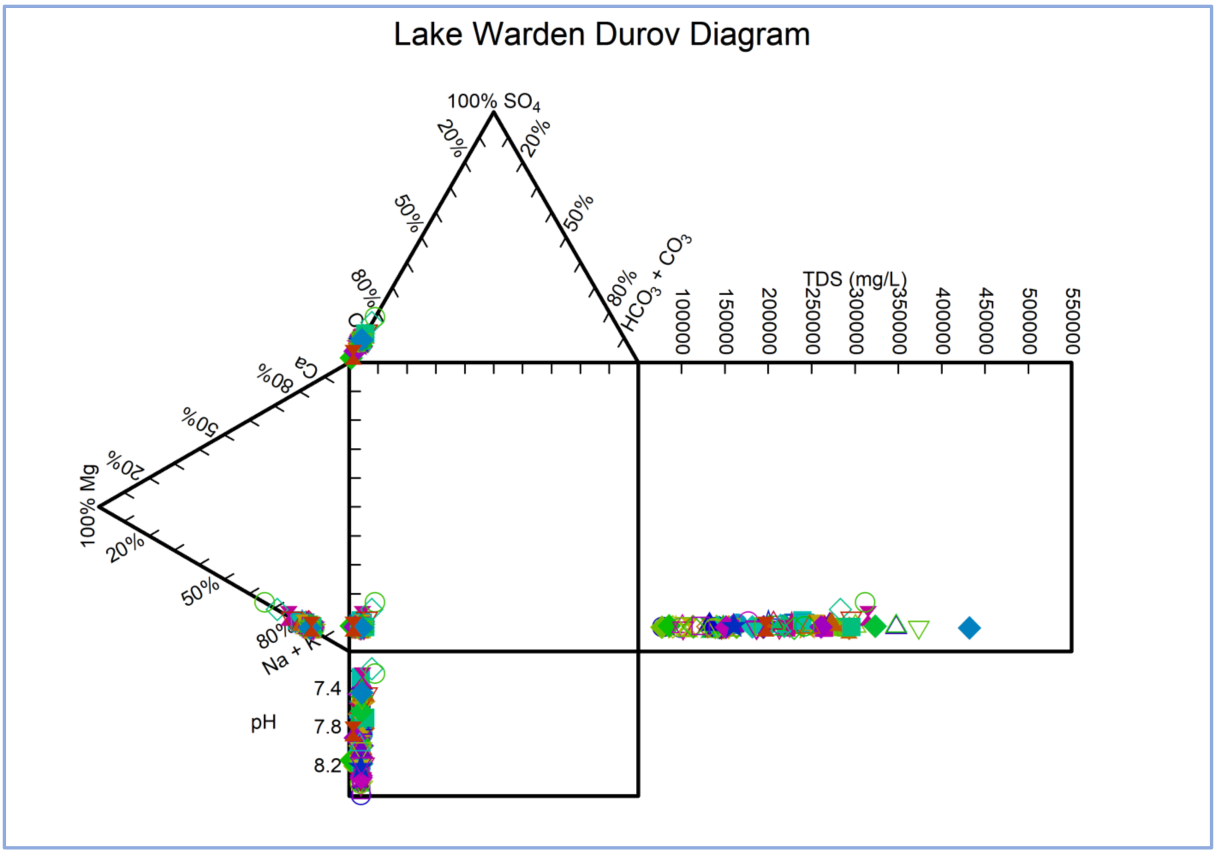


Figure 19: Durov diagram for Lake Warden, indicating the relationship between major nutrients. (See Appendix 2 for an explanation on how to interpret Durov diagrams)

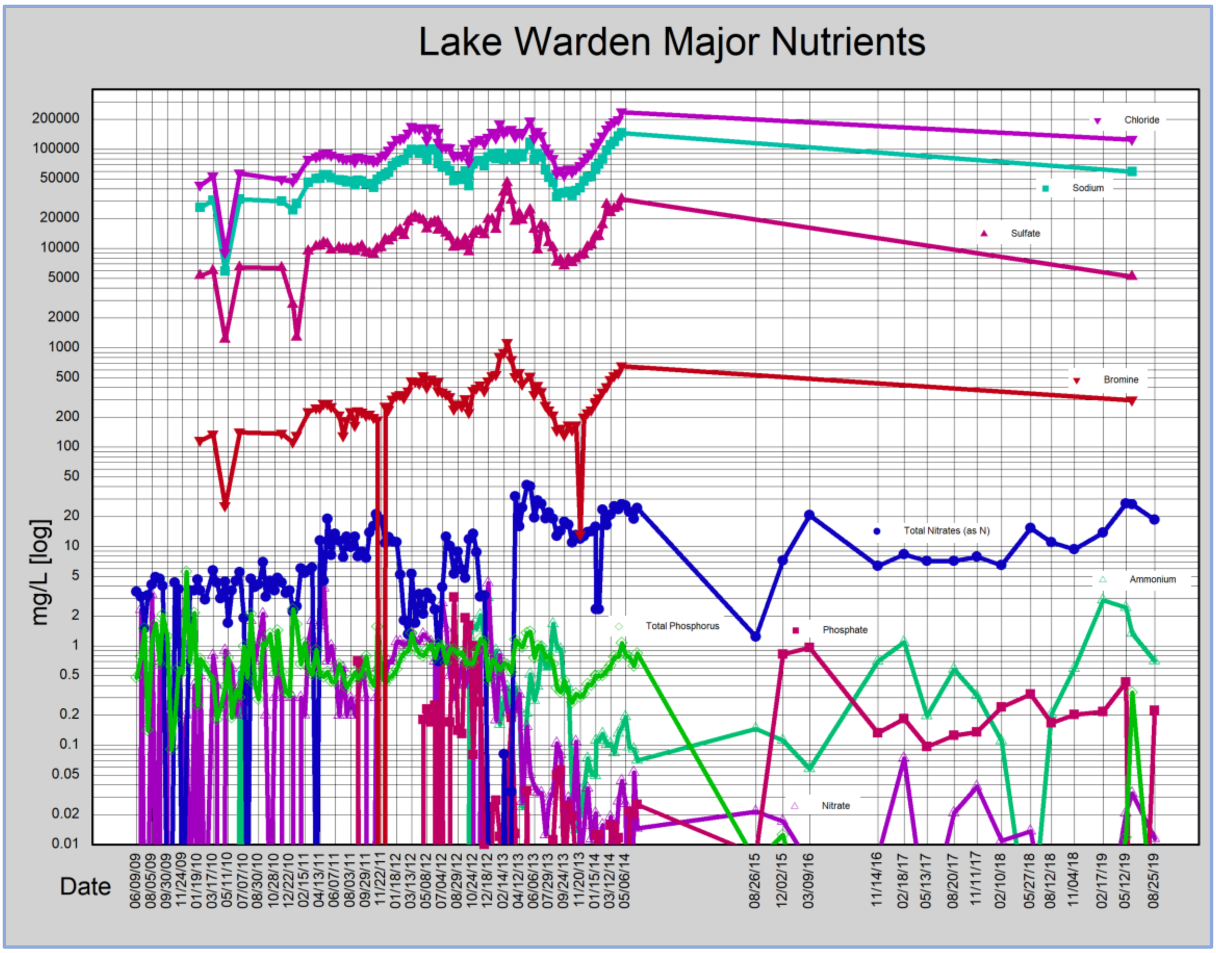


Figure 20: Timescale graph for major nutrients for Lake Warden in logarithmic vertical scale

4.6 Pink Lake

Pink Lake is a terminal, largely perennial lake system. It has minimal overland flow entering the lake and is mostly fed by fresh to brackish groundwater, with permanent seepage on the north-western side. Overland flow mainly occurs during high frequency rainfall events resulting on large catchment runoff. The basin is dominated by weathered granite and limestone. It's an alkaline system with varying salinity concentrations.

Historically, the lake water turned pink in colour some summers.

A salt crust forms during summer months when lake level drops, but some salt crystallisation may always be present on the eastern side of the lake. Water temperature can exceed 30°C, but typically around 25-28°C during the day in summer.

The salt concentration in the lake are largely affected by the prevailing wind conditions. If predominantly westerly winds are present, the lake water concentrates to the eastern side of the lake. Fresh water seepage occurs on the western side (Figure 23) of the lake with very little salt crust on the western side. During prevailing easterly winds, the water moves to the western side of the lake. The freshwater seepage is immediately absorbed into the lake water and during hot summer days, salt deposits are present.

Colour of lake varies greatly, from greenish-white colour (Figure 21) when salinity concentrations are low to a pink variation (Figure 22) when salinity concentrations exceed 250g/l.

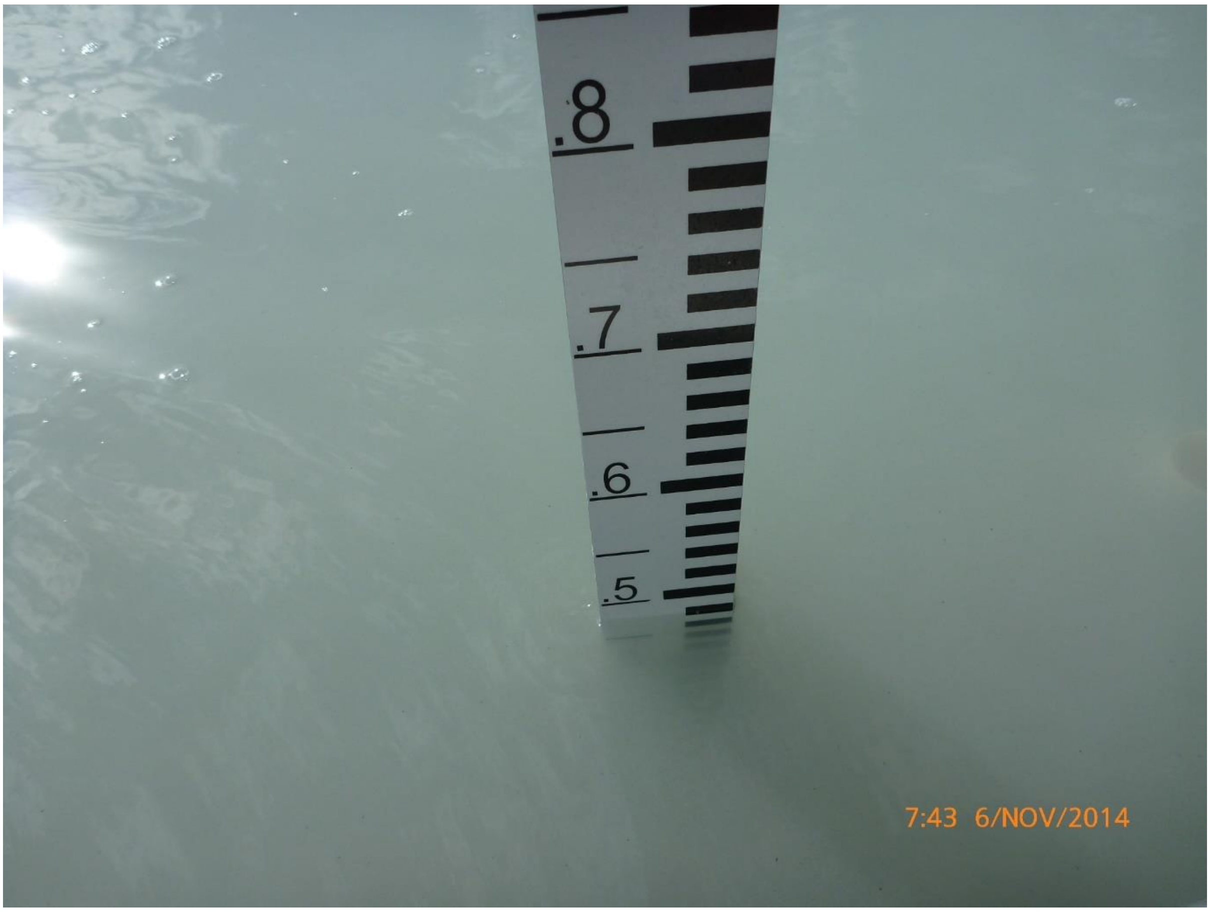


Figure 21: greenish-white water of Pink Lake during low salinity concentrations

Figure 22: Pink colouration of salt deposits at Pink Lake on western shore gauge plate

Figure 23: Fresh water seepage into western shore of Pink Lake – no salt crust and no pink colouration.

The system chemistry is dominated by Chlorides and Sodium. The system is chemically stable with very little changes apart from salinity concentrations (See Durov diagram in Figure 24 and major nutrients in Figure 25). The system is phosphate limited with very low free-phosphate available. Bromine levels tend to be higher which indicates phosphates are assimilated into the system as soon as it enters.

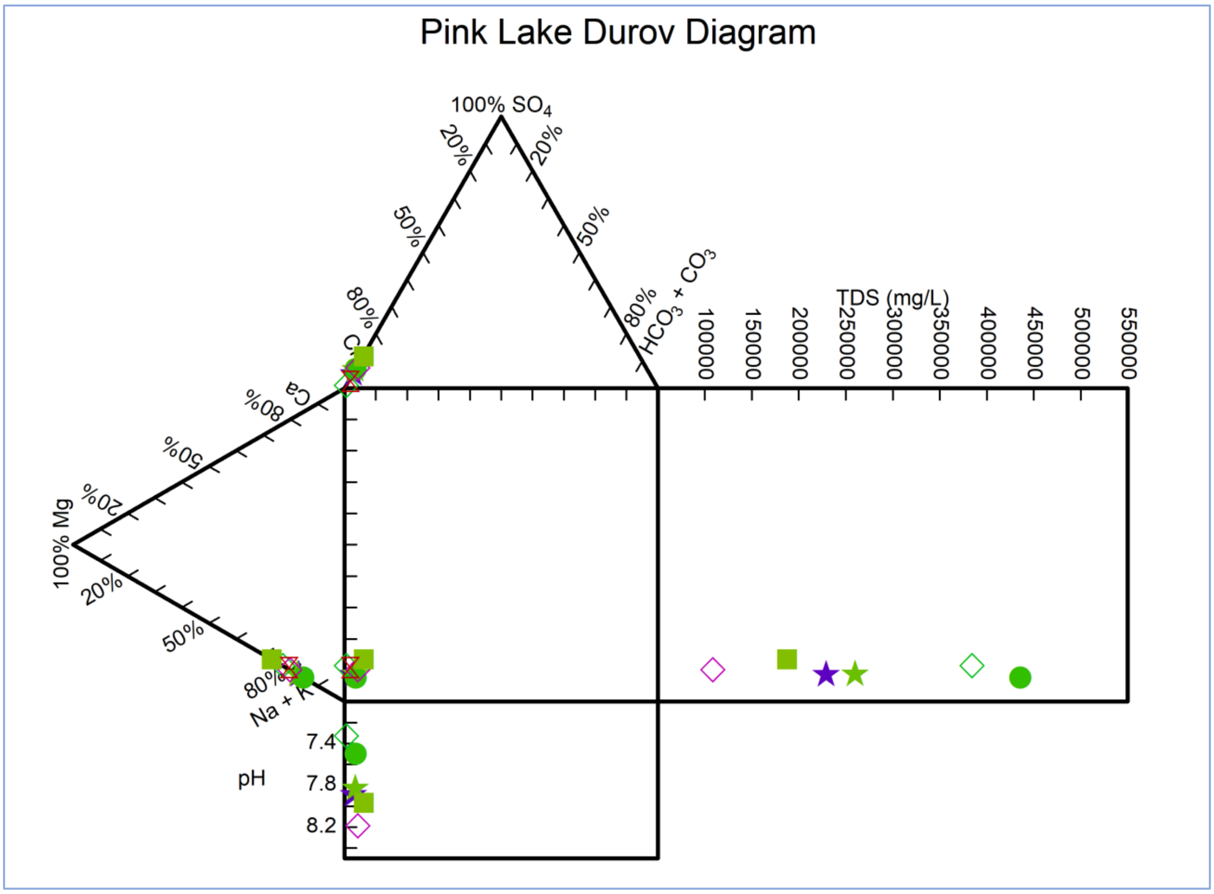


Figure 24: Durov diagram for Pink Lake, indicating the relationship between major nutrients. (See Appendix 2 for an explanation on how to interpret Durov diagrams)

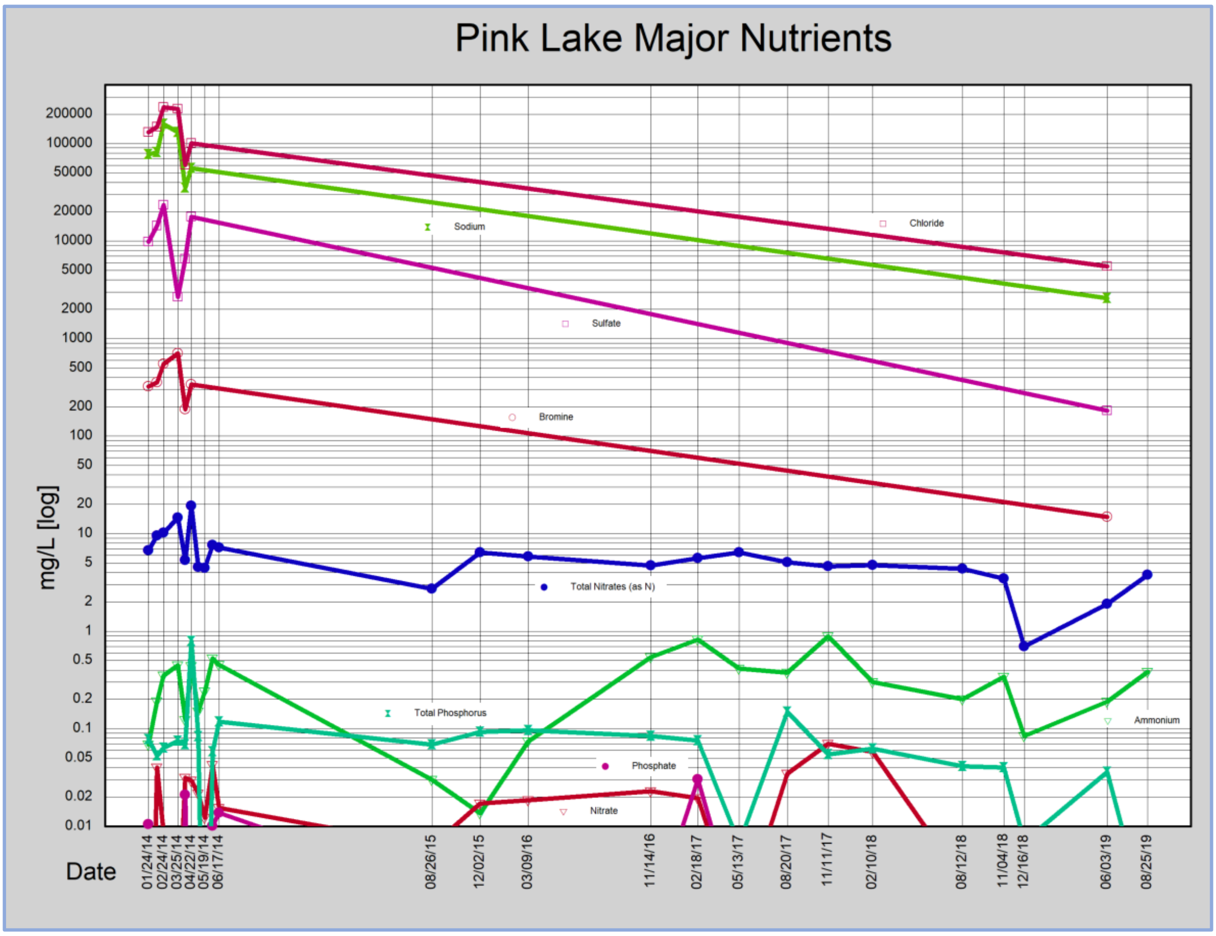


Figure 25: Timescale graph for major nutrients for Pink Lake in logarithmic vertical scale

5. Discussion

Cater and Lizamore (2014-2015) used a colour verification chart to compare lake colour. It proved to be extremely problematic photographing the lakes and getting a true colour photograph because the water tended to reflect the blue sky and gave a completely wrong indication of the colour of the water - even Lake Hillier, which was always predominantly a bubble-gum pink colour, sometimes photographed blueish. Similarly, photographs taken late in the afternoon could have a more dominant red hue as a result of longer wavelengths of light at this time.

Although these colours were not absolute (see Figure 27 for an example as taken at Lake Warden), it did provide an indication of colour variability within the lake over time, as well as an indication of colour between the various lakes. Conversely, Pink Lake never displayed more than a blueish pink colour in the water, although the salts had more of a bright pink colour (Figure 22), whilst Lake Hillier almost always displayed a bright pink colour, and Lake Warden and Benje Benjemup was more of a dirty-pink colour with more orange in the spectrum.

The presence of a salt crust and water depth was another important variable, with shallow water and a salt crust would provide brighter pink colours as opposed to deeper water with no crust present, which may explain the brighter colour of Pink Lake’s salts in Figure 22.

Taking the colour variation into account, it was identified that salinity concentration in excess of 300g/l must be sustained for periods of more than 8 weeks for pink colours to dominate, whilst brighter pink colours are present if salt crusts thicker than 3cm persist (representing salinity concentrations in excess of 350g/l).

The results of historic monitoring and research has indicated several problematic aspects when reviewing hyper-saline lakes (See section 4.2).

Based on evaporative TDS results, it is not recommended that Ec values be used unchecked as a measure of salinity concentrations. When electrical conductivity values exceed 150mS/cm, it is recommended a dilution method is utilised for measuring Ec, i.e. 1:2 dilution with distilled or deionised water for Ec values between 150 and 180ms/cm and a dilution of 1:4 where values exceed 180ms/cm. In addition, it is strongly recommended that periodic TDS by evaporation is completed to compliment the results and to calibrate salinity calculation formulae.

Chemically and physically, there is very little difference between Lake Benje Benjemup, Lake Warden, Lake Hillier and Pink Lake and each of these will act well as a control site to compare conditions at Pink Lake. The prevailing difference appears to be the lower salt concentrations and reduced hypersaline periods Pink Lake experiences. Wind action mixes the fresh water with saline brine, and unless brine conditions are experienced for periods of greater than 4 weeks, no pink colouration occurs.

Lake Warden shows the highest variation of phosphates: nitrates ratio of all the pink lakes studied. This is thought to be because the lake has the highest contribution of surface water inflow of all the lakes studied, and there appears to be a sharp increase after every largescale catchment runoff event. There is very little variation on phosphate concentrations in Pink Lake, indicating phosphates are likely entering the system through groundwater seepage and not overland flush-in events.

Chemically and physically, there is very little difference between Lake Warden and Pink Lake and Lake Warden would act well as a donor site for salts.

From a salt-harvesting perspective, the best time to harvest brine from Lake Warden would be as soon as salts start dropping out of solution and Ec values drop from >220mS/cm to <200mS/cm. This should equate of TDS values of approximately 350-400g/l (see Figures 4, 8 and 9).

If solid salts are to be harvested, the most opportune time would be to wait until all water is evaporated (unlikely in some perennial lakes like Lake Warden) or when Ec values start to rise again (indicating that salts will start to dissolve again as a result of lower salt-content water being added to the system, i.e. rain, groundwater or surface water).

During the study to determine what makes a pink lake pink, the following common parameters were identified:

i. Lake has to be hypersaline (>250g/l concentrations) for periods of 4 weeks or more
ii. Lake is alkaline with a pH>7.4
iii. Water temperature >25°C

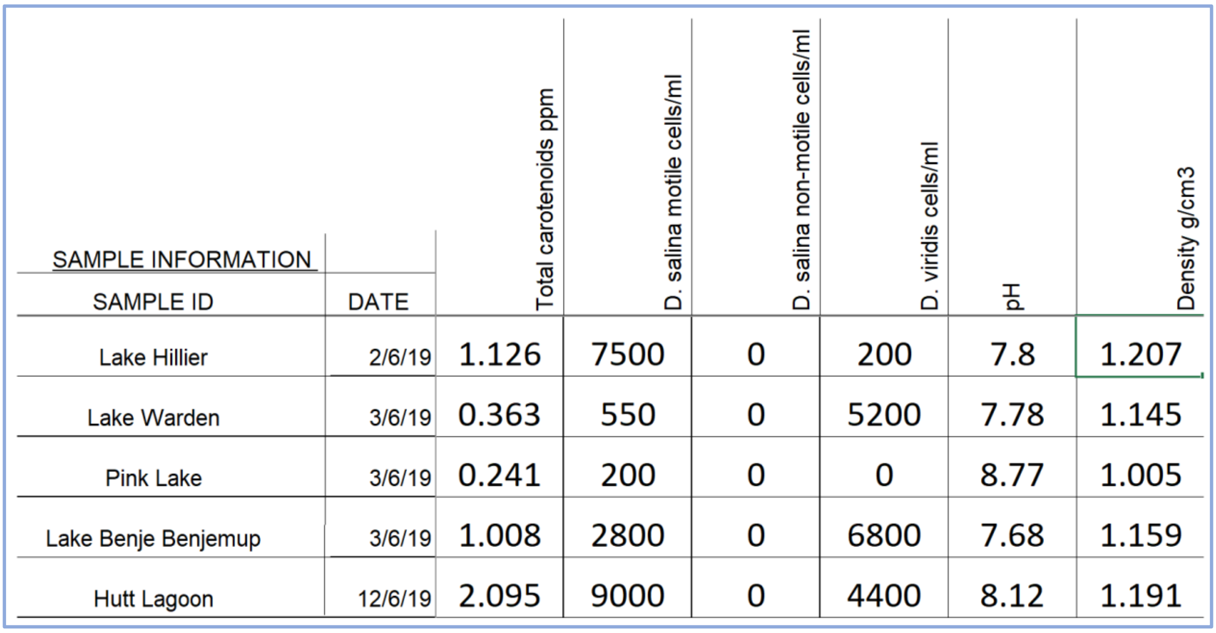
    a. During high stress situations, *Dunaliella salina* manufactures Beta Carotene to protect the cell and prevents water column light filtration to outcompete Photosynthesis reliant organisms for limited phosphates under extreme saline and temperature conditions (Coleman; 2002),

iv. Presence of a salt crust
    a. Salt crust increases solar radiation and increases water temperature – see point iii above.

v. Phosphate limited system
    a. All the systems studied were phosphate limited. It has been documented that with the presence of phosphates, blue-green algae species will outcompete *Dunaliella salina* which is responsible for the orange-pink colour of the water.

vi. Presence of *Dunaliella salina*

BASF Australia developed a method to measure cells to determine Beta 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. Furthermore, *Dunaliella salina* assimilates more green pigment, making the colouration more orange in colour. Oren (2014) found *Dunaliella viridis* grows optimally at 60–90 g/l NaCl, whilst *D. salina* prefers ~100–150g/l.



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

Figure 26: biota cell concentrations for lake water as supplied by BASF (Curnow 2019)

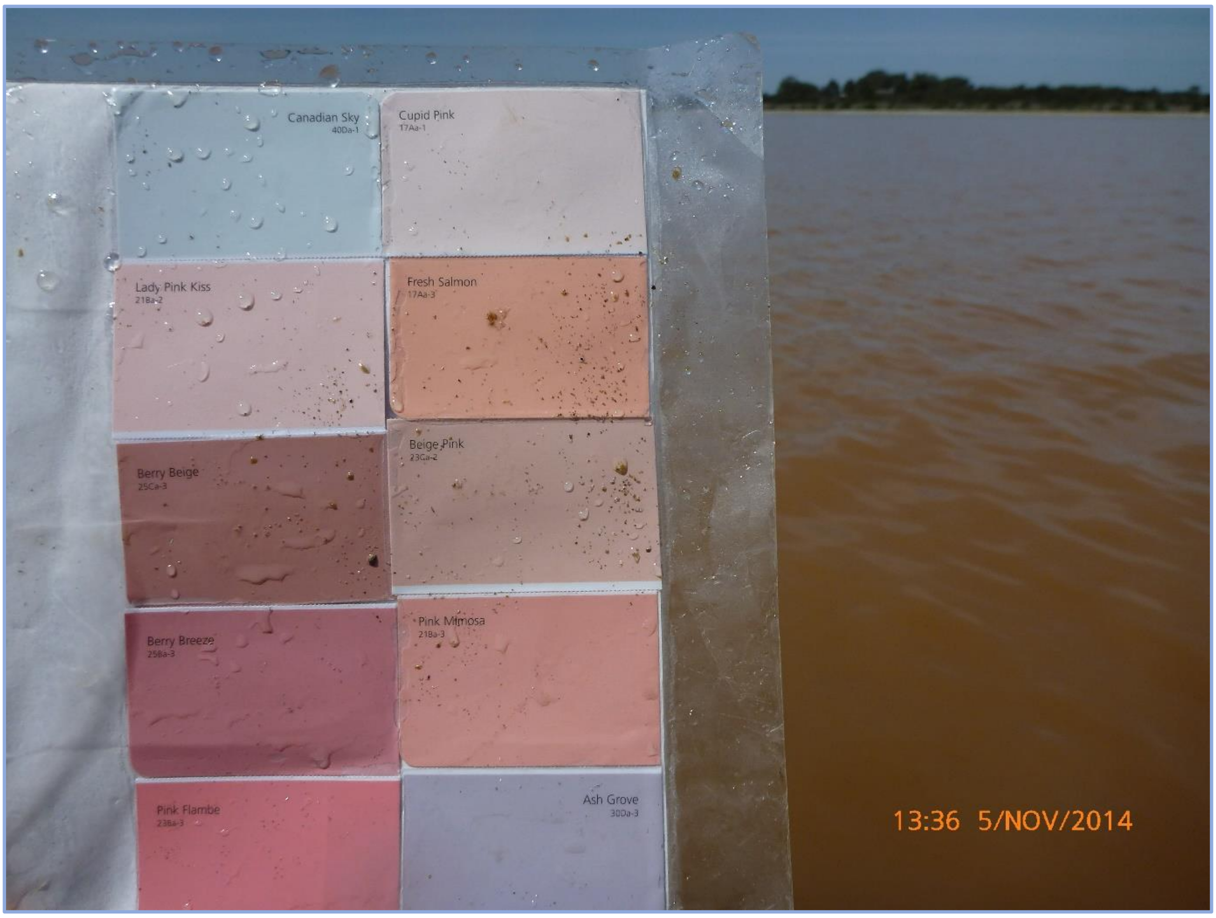


Figure 27: Colour pallet comparison at Lake Warden

In conclusion, Pink Lake can still turn pink, but lacks the salinity concentrations to sustain the colour change – either the lake water mixes with the fresh seepage which reduces the concentrations, or the water dries up before the colour occurs properly.

6. Further study

Inconsistent and insufficient resolution data makes it difficult to make accurate predictions and calibrate models to test management intervention actions and activities. The current monitoring point on the North-Western side of the lake only allows for measurements when the lake depth exceeds 40cm. As a result, there is very limited water chemistry data for the lake during low volume, hyper-saline conditions and sampling is only relevant if easterly winds were prevalent a few days prior to monthly sampling.

It is recommended that four sampling sites be developed for Pink Lake and monitored fortnightly. The sites should be placed at North, South, West and Eastern parts at positions sufficient to measure water and conditions when the lake depth drops below 40cm (i.e. sites should be located deeper than current site).

It is further recommended that all salinity measurements (as a minimum) should include a dilution regime (as described in Section 5) and quarterly evaporative TDS.

It also recommended that the Digital Elevation Model for Pink Lake be updated and the accuracy improved. This will enable more accurate salt and water balances to be created and allow better decision making for future management of the system.

7. References

Cater, D. and Lizamore, J.M. (2014-2015). *Pink Lakes Project.* Unpublished fields records and datasets. Department of Biodiversity, Conservation and Attractions. Esperance WA.

Coleman, N. (2002), *Pink Lake and it's colouration.* Internal Shire of Esperance unpublished Report prepared by actis Environmental Service.

Curnow, J. (2019). *Biotic laboratory results for pink lake samples.* Unpublished report from BASF Australia. Hutt Lagoon, WA.

Fofonoff, N.P. and Liiard, R.C. (1983). *Algorithms for computation of fundamental properties of seawater.* Unesco technical papers in Marine Science volume 44.

Lizamore , J.M. (2013). *Managing and Adapting to Secondary Salinity and Altered Hydrology in a Ramsar Listed Lake Suite: Lake Warden Wetland System Case Study (1997-2013).* WA Coastal Conference. 31 July 2013. Esperance WA.

Lizamore, J.M. (2015). *Lake Warden Wetland System: Surface Hydrology Review.* Internal report for Department of Parks and Wildlife. April 2015. Department of Biodiversity, Conservation and Attractions. Esperance, WA.

Lizamore, J.M. (2015). *Personal records and data*. Esperance, WA.

Lizamore, J.M. (2018). *Lake Warden Wetland System: Surface Water Quality and Hydrology Review.* Internal report for South Coast National Resource Management. June 2018. Esperance, WA

Lloyd, J.W. and Heathcoat, J.A. (1985) Natural Inorganic Chemistry in Relation to Groundwater. Clarendon Press, Oxford.

Massenbauer , T. (2008). *Pers comms.* Esperance WA.

Oren, A. (2014). *The ecology of* Dunaliella *in high-salt environments.* J Biol Res (Thessalon). 2014 Dec; 21(1): 23.

8. Appendix 1 - Wetland Study Sites

Cater and Lizamore (2014-2015) identified 11 sites for study based on specific parameters in order to determine what makes pink lakes pink. Not all lakes had the same parameters, but it was attempted to determine why certain lakes turn pink, others do not, and if there are any correlations that can be identified.

These lakes included:

5. Hutt Lagoon –
    a. situated 960km north-west of Esperance next to the West-Coast (i.e. not in South Coast district);
    b. large lake (>2500ha);
    c. known to be hyper saline;
    d. mostly ephemeral nature, but controlled in some areas by BASF;
    e. mostly pink;
    f. agricultural chemical impacts, including increased phosphates; and
    g. mined for beta carotene.
6. Lake Carbul –
    a. situated 37km west of Esperance and 7km from the coast;
    b. medium lake (approximately 19ha);
    c. ephemeral lake;
    d. water quality varies between brackish to hyper saline;
    e. does not turn pink;
    f. known Hooded Plover habitat;
    g. terminal lake; and
    h. agricultural chemical impacts, including increased phosphates.
7. Lake Kubitch –
    a. situated 37km west of Esperance and 6km from the coast;
    b. medium lake (approximately 37ha);
    c. mostly perennial lake;
    d. water quality varies between brackish to hyper saline;
    e. does not turn pink;
    f. known Hooded Plover habitat;
    g. terminal lake; and
    h. agricultural chemical impacts, including increased phosphates.
8. Lake Hillier –
    a. situated 125km east of Esperance on Middle Island;
    b. medium lake (approximately 21ha);
    c. perennial lake;
    d. permanently hyper saline;
    e. terminal lake;
    f. almost permanently bright bubble-gum pink colour;
    g. apart from localised human impacts approximately 100 years ago, isolated and negligible chemical impact; and
    h. chosen as control site.
9. Lake Hanson 3 –
    a. situated 36km north of Esperance and the coast;

  - b. small lake (approximately 0.7ha);
  - c. ephemeral lake;
  - d. almost permanently hyper saline except in high rainfall events;
  - e. almost permanently pink in colour;
  - f. terminal lake; and
  - g. agricultural chemical impacts, including increased phosphates.

10. Lake Hanson 1 –
    - a. situated 35km north of Esperance and the coast;
    - b. small lake (approximately 5.6ha);
    - c. ephemeral lake;
    - d. varies from brackish to hyper saline;
    - e. lake turns pink in colour as water level drops;
    - f. terminal lake;
    - g. identified as occasionally visited by higher numbers of Hooded plover and
    - h. agricultural chemical impacts, including increased phosphates.
11. Lake Benje Benjemup –
    - a. situated 17km north of Esperance and 14km from the coast;
    - b. medium lake (approximately 100ha);
    - c. perennial lake;
    - d. varies from brackish to hyper saline;
    - e. lake turns pink in colour as water level drops;
    - f. terminal lake;
    - g. identified as Hooded plover habitat; and
    - h. agricultural chemical impacts, including increased phosphates.
12. White Lake –
    - a. situated 14km north of Esperance and 12km from the coast;
    - b. small lake (approximately 2.7ha);
    - c. ephemeral lake;
    - d. varies from brackish to hyper saline;
    - e. lake turns pink in colour as water level drops;
    - f. terminal lake;
    - g. identified as Hooded plover habitat; and
    - h. agricultural chemical impacts, including increased phosphates.
13. Pink Lake –
    - a. situated 4km west of Esperance and 3.5 km from the coast;
    - b. large lake (approximately 1000ha);
    - c. perennial lake;
    - d. varies from brackish to hyper saline;
    - e. lake used to turn pink in colour as water level drops;
    - f. terminal lake;
    - g. identified as Hooded plover habitat; and
    - h. agricultural chemical impacts, including increased phosphates.
14. Lake Warden –
    - a. situated 3km north of Esperance and the coast;
    - b. large lake (approximately 750ha);
    - c. perennial lake;
    - d. varies from brackish to hyper saline;
    - e. lake has started to turn pink in colour as water level drops in the past ten years;

   - f. terminal lake;
   - g. identified as Hooded plover habitat; and
   - h. agricultural chemical impacts, including increased phosphates.

15. Station Lake –
    - a. situated 7.6km north-east of Esperance and 2.6km from the coast;
    - b. small to medium lake (approximately 7ha);
    - c. ephemeral lake;
    - d. varies from brackish to hyper saline;
    - e. lake does not turn pink;
    - f. flowthrough lake;
    - g. identified as Hooded plover habitat; and
    - h. agricultural chemical impacts, including increased phosphates.

9. Appendix 2 – Durov Diagrams explained

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 end-point 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.