**HYDROLOGY AND WATER CHEMISTRY**

* 1. **Lake Richmond**
     1. **Lake Richmond Hydrology**

Lake Richmond is a perennial, low-salinity water body, situated less than 1 km away from the Indian Ocean to the north and west (Figures 3.6 and 3.7). Originally, the lake didn’t have any connection to natural drainage and the water balance was regulated exclusively by the input and loss of water to a shallow, unconfined aquifer, direct rainfall and evaporation. Similar hydrology has been described for many other lakes along the Swan Coastal Plain where the porous nature of the sediments usually favours infiltration of meteoric water over runoff (Commander, 1984; Davidson, 1995).

In Lake Richmond, however, the basin hydrology has been significantly modified by the construction of one outlet drain, in 1968, and subsequent construction of three inlet drains on the eastern, southern and western margins of the lake (Figure 4.2; Kenneally *et al.*, 1987). The inlet drains collect rain water from the surrounding urban areas and discharge into the lake during the wet season. The outlet drain on the north, in turn, discharges lake water into the Cockburn Sound, when the water level rises above 0.58 m AHD and flows over a weir installed next to the lake (Figure 3.7; Strategen, 2012). The weir also prevents sea water inflow to the lake during storm surges. During the summer and first months of autumn, when evaporation greatly exceeds precipitation, both the inlet and outlet drains stop flowing and become disconnected from the lake.

The water level of Lake Richmond has been regularly monitored by the Western Australian Department of Water (DoW) since 1978, with more sporadic records dating back to 1945. The historical data shows the lake water level varies, on average, 0.8 m as a result of seasonality (Figure 8.1). The minimum level is usually recorded at the beginning of autumn (March or April), prior to the end of the dry season, when the lake level is around 0.25 m AHD. The maximum water level, at approximately 1.05 m AHD, occurs at the onset of spring (September) and coincides with the end of the wet season.

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| Figure 8.1 - Lake Richmond historical water level data, provided by the Western Australian Department of Water (DoW). Note the serrated pattern of the curve related to seasonal cycles. The blue line at 1.07 m AHD marks the mean high water level (HWL) and the red line at 0.26 m AHD marks the mean low water level (LWL). |

However, significant variations in water level are observed from year to year and deviations in relation to the maximum and minimum averages can reach up to 40 cm. In any case, the seasonal fluctuations are normally substantial (Figure 8.2) and consequently the shallow and relatively flat areas around the lake margins are, in great part, subjected to regular annual exposure. The flooded area is reduced by about 57% during the dry season and results in the exposure of the sedgelands and part of the microbialites for a considerable period of time (Table 8.1). This process has a profound impact on the distribution, growth rates and preservation potential of the microbial mats, altering the balance of exposed areas in favour of erosion rather than accretion.

A slight tendency for both the maximum and minimum water levels to decrease with time has been noted, which can be attributed to the installation of the artificial drains, a reduction in the amount of rainfall (Indian Ocean Climate Initiative Panel, 2002; Bureau of Meteorology & CSIRO, 2014) and groundwater abstraction associated with urban development in the region (Department of Water, 2008). Data collected prior to the installation of the drains, despite being irregularly spaced, show water levels significantly higher than currently observed, suggesting the construction of artificial drainages was a particularly important factor for the decline (Figure 8.1).

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| Figure 8.2 - Lake Richmond volume versus elevation diagram with the historical mean high water level (HWL) and low water level (LWL). The lake level oscillates about 0.8 m between the dry and wet seasons, which corresponds to approximately 16% of the total basin volume. |

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| Table 8.1 - Extension of the flooded areas during high and low water level periods. Figures show submerged areas are reduced to less than a half during the dry season, when the shallow and relatively flat margins of the lake are subjected to subaerial exposure. |

The lake water levels, salinity and temperature were monitored from March 2013 to November 2015 with a logger installed at the northern margin of the lake, away from the inlet drains (Figure 4.2). During this period, the mean water temperatures ranged from approximately 15o C during the winter to 25o C during the summer. The water levels were observed to be slightly higher than usual during 2013, when the evaporation and precipitation were close to the historical average (see section 3.2 for details on the climate). On the other hand, 2014 and 2015 were abnormally dry years and consequently the minimum water levels recorded during this period were lower than normal. The highest water level recorded during the study was 1.24 m AHD, in September 2013, and the minimum was 0.14 m AHD, in April 2014 (Table 8.2).

The water level curve recorded by the logger presents a conspicuous sinusoidal shape with strong correlation to rainfall and evaporation cycles (Figure 8.3). From May to July, the recurrence of rains associated with low evaporation rates promotes a sharp and continuous increase in water level. The lake level is observed to rise up to 20 cm during a single storm or prolonged rainfall events, providing a stepwise configuration to the rising limb. During the last part of the wet season, in August and September, the evaporation rates increase and the curve assumes a saw-like pattern, with sharp rises associated with rainfall separated by periods of gradual water level decline. The overall trend, however, is rising but at a lower rate until the lake level peaks, usually in September. In October, the rains become sparse but the evaporation rates continue to increase, a trend that is exacerbated towards the summer and causes a continuous, steady water level fall until the lake reaches its lowest level, usually in March or April.

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| Table 8.2 - Comparison between Lake Richmond historical water levels and values recorded during the period of this study. |

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| Figure 8.3 - Lake Richmond (A) water level and salinity data acquired at the northern margin of the lake from 2013 and 2015. The blue curve displays the high-frequency water level variations recorded with a logger while blue dots are manual measurements, using as reference a depth board from the Department of Water (DoW). Arrows indicate the volume of prolonged rainfall and storm events, accompanied by a rapid increase in lake water levels. The red curve represents the lake water salinity and was calculated from electric conductivity measurements performed by a logger. Pink dots are salinity values obtained through laboratory analyses of lake water samples. Results show only slight salinity variations occur between dry and wet seasons. The lower part of the figure (B) presents the monthly precipitation and evaporation in the region, recorded at the Medina Research Centre (data provided by the Australian Government Bureau of Meteorology). |

High-frequency water level oscillations, typical of tidal cycles, were not detected within the lake, suggesting the basin currently does not receive direct influence from the ocean. This is further supported by previous hydrogeological studies, which demonstrated an unconfined, low-salinity aquifer persists down to approximately -25 m AHD in boreholes adjacent to Lake Richmond (Passmore, 1970; MWH, 2011). This is considerably deeper than the lake bottom, which lies at -14 m AHD, permitting the theory of the intrusion of salty-water in the basin to be dismissed, despite the proximity to the ocean (Figure 5.2).

The interactions between Lake Richmond and the surrounding aquifer were investigated through a network of 16 shallow piezometers positioned in the sand dunes (Safety Bay Sands) adjacent to the lake (Figure 4.2; Appendix 3). Figures 8.4 and 8.5 present a comparison between lake water levels and the watertable in some representative piezometers between February 2014 and April 2015. The lake water and groundwater level curves closely resemble each other both in terms of the shape and amplitude of the variations, highlighting the good hydraulic connection between the lake and the adjoining aquifer. The groundwater rising and falling rates, however, differ slightly from site to site, controlling the distribution of groundwater recharge and outflow zones in the basin.

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| Figure 8.4 - Comparison between the lake water levels and the watertable in the surrounding dunes according to data from boreholes situated northwest, east, southeast and west of the lake. The water table remains permanently below the lake level to northwest and west of the lake. An opposite situation is observed southeast of the lake where the water table remains most of the time above the lake level, except during the apex of the flood season when the lake and aquifer level are approximately the same. East of the lake the aquifer was observed to be higher, discharging groundwater into the lake during the end of the dry season and beginning of the wet season, but remains below the lake level during other periods of the year. |

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| Figure 8. 5- (A) Logger data showing a comparison between the lake water levels (blue line) and salinity (red line) and the groundwater level (green line) and salinity (orange line) in the borehole MW-19, north of the lake (see figure 4.2 for location). Note the similarity between the lake water level and groundwater level curves. Arrows indicate the occurrence of storm events or prolonged rains and are accompanied by a rapid increase in both the lake and aquifer levels. The lower part of the figure (B) show the monthly precipitation and evaporation in the region, recorded at the Medina Research Centre (data from the Australian Government Bureau of Meteorology). |

Potentiometric maps indicate that during low water level periods, when the artificial drains become disconnected from the lake, the basin receives groundwater input from east and southeast (Figure 8.6 A). No groundwater seeps, however, were observed on exposed areas of the lake flat during this period, indicating that recharge probably occurs along submerged portions of the infralittoral platform and upper slope. Towards the north and west, groundwater levels remain slightly below the lake level and lake water slowly flows to the aquifer in these directions.

During the first months of the wet season, in May and June, the watertable rises faster than the lake water along the northern and southern margins of the lake and groundwater recharge expands to these areas. Simultaneous lake water outflow to the aquifer occurs predominantly along the northwestern margin while a nearly flat gradient develops immediately to the west of the lake (Figure 8.4). With the progress of the wet season and significant inflow of stormwater through the drains, the lake water starts to rise faster than the aquifer and, as a consequence, groundwater input areas are progressively reduced until it becomes restricted to the southeastern margin of the basin (Figure 8.6 B). At the peak of the flood season the lake behaves like a recharge zone and surface water seeps into the aquifer in most directions, with the exception of the southeastern margin, where lake water and groundwater remain approximately at the same level and the hydraulic gradient is essentially flat (Figure 8.6 C).

The opposite process happens during the dry season, when the volume of rains and water input through the drains decrease. The lake water level tends to fall faster than the aquifer and there is a gradual expansion of groundwater inflow zones, first at the southeastern margin of the lake (Figure 8.6 D) and later also along the eastern margin, as observed at the end of the dry season (Figure 8.6 A).

In summary, Lake Richmond normally loses water to the aquifer on seaward areas to the west and northwest for most of the year, accompanying the regional trend of groundwater flow in the western part of the Rockingham Plain. Groundwater input to the lake is predominantly from southeast and east, but temporarily extends to the north and southern margins of the basin during early stages of the rainy season. However, with the progress of the wet season, groundwater inflow is greatly reduced and becomes subordinate to runoff discharges originating from the artificial drains. The hydrodynamics described above is different from a previous survey carried out in 1965, before the construction of the drains, when a permanent groundwater input from the eastern, southern and western sides of the lake was identified (Passmore, 1970).

Previous studies emphasize the significance of the artificial drainages for the modern lake water balance and chemistry (Kenneally *et al.*, 1987; Ecoscape, 2012). Broad estimates suggest runoff discharges associated with the inlets are currently one order of magnitude larger than groundwater and rainfall contributions to the basin, as visualized in Table 8.3 (Bowman Bishaw Goham, 1997; Strategen, 2011). According to the basin volume, water inflow and outflow estimates the mean water residence time (RT) in Lake Richmond is predicted to be around 2.3 years according to the following relation:

RT = V x (Qi + (P-E) x A)-1,

where Qi is the annual water inflow to the basin, considering runoff and groundwater contributions, P is precipitation, E is evaporation and A is the lake area.

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| Figure 8.6 - Potentiometric maps for Lake Richmond area based on data from 16 boreholes collected during different seasons. (A) Low water level period, at the beginning of the autumn; (B) average water level, during the winter, in middle of the wet season; (C) high water level period, at the onset of the spring; (D) average water level, at the beginning of the summer, in the middle of the dry season. |

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| Table 8.3 – Water balance elements for Lake Richmond. The precipitation and evaporation volumes are based on data from Bureau of Meteorology, measured at the Medina Research Centre, 10 km NE of Lake Richmond (see section 3.2 for details). |

* + 1. **Lake Richmond Hydrochemistry**

This section presents the results of a monitoring program designed to investigate the lake water chemistry, influences on the benthic microbial communities and relationships to organomineralization processes. The physicochemical parameters and ionic composition of the water were regularly analysed from February 2013 to April 2015. The sampling sites comprised two different locations: one at the northern margin of the lake, away from the drains, and another adjacent to one of the inlets, at the southern margin of the basin. Additional samples were taken from the aquifer to the north of the lake (borehole MW19) and inside the southern inlet, aiming to characterise the water chemistry in the catchments of the basin. The sampling locations can be seen in Figure 4.2 and the analytical results are tabulated in Appendices 3 to 6.

* + - 1. **Salinity**

Lake Richmond is a subsaline water body (see Hammer, 1986, classification in Figure 1.1) subject to small salinity variations, despite the conspicuous seasonal water level fluctuations (Figure 8.3). Major ion analyses performed during this study demonstrated the lake water salinity in general ranges from about 550 mg/l, during the winter, to approximately 700 mg/l, at the beginning of the autumn (Figure 8.7 B). Lower values, during the winter, are caused by runoff discharges from the inlets, groundwater inflow and rainfall, while higher salinity values are associated with accentuated evaporation rates during the dry season.

Water samples collected at the northern and southern margins of the lake commonly presented small salinity differences linked to drainage water inflow along the southern shore (Figure 8.7 B). This was particularly evident at the outbreak of the rainy season, in May 2013, after heavy rains. On this occasion, the salinity at the southern margin of Lake Richmond was significantly below the usual range, indicating active stormwater inflow from the nearby inlet. In contrast, the salinity at the northern margin of the lake experienced a simultaneous increase associated with the inflow of more saline groundwater in that part of the basin.

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| Figure 8.7 - Physicochemical properties of the water measured at the north and south margins of Lake Richmond, inside the southern inlet and in the aquifer to the north (borehole MW19), during the 2013 to 2015 period. (A) Temperature, (B) salinity from major ion analyses, (C) pH and (D) dissolved oxygen. See figure 4.2 for sampling locations. |

Inside the southern inlet, the salinity was similar to the lake water during the dry season, but was significantly reduced during the wet season, when the stream continually receives an influx of rain water (Figure 8.7 B). In 2014, for example, the salinity fell from around 650 mg/l in May, at the end of the dry season, to approximately 400 mg/l in August, during the wet season, when the drain usually discharges freshwater into the lake.

A similar tendency to ionic concentration during dry periods and dilution during rainy months was identified in the aquifer (Figure 8.7 B). High-frequency data collected from borehole MW19, adjacent to the northern margin of the lake (Figure 4.2), demonstrated that salinity fluctuations in the aquifer are tightly coupled to rainfall (Figure 8.5). The lowest salinities were recorded immediately after the rainiest months, in July or August, a month or two before the lake and groundwater levels peak. During strong rains, the rapid infiltration of meteoric water usually causes a noticeable dilution of the groundwater. However, the salinity partially recovers after the rain ceases, providing a serrated aspect to the curve during humid periods. Interestingly, groundwater samples collected from this borehole presented higher salinities than the lake water throughout the year, ranging from 1077 mg/l in March to 782 mg/l in July 2014 (Figure 8.7 B).

The groundwater salinity, however, was observed to be variable in the area. A survey carried out in November 2015 documented a higher electrical conductivity to the north of Lake Richmond, where the groundwater measured 1.4 mS/cm. Smaller values, between 0.8 and 1.1 mS/cm were observed in the aquifer to the west, east and south of the lake, consistent with the lake water electrical conductivity on that occasion (Figure 8.8). These results are compatible with a previous study which also reported the presence of more saline groundwater, with up to 1500 mg/l total dissolved solids (TDS), to the north of Richmond whereas to the east, west and south groundwater salinity was identified to be less than 630 mg/l TDS (Passmore, 1970).

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| Figure 8.8 – Electrical conductivity data acquired in November 2015. Red circles are groundwater measurements carried out in boreholes adjacent to Lake Richmond. The electrical conductivity of lake water was measured at the elevation board, represented by the yellow circle. |

A comparison between the modern and historical data presents clear evidence of modification to the lake water quality. During the mid sixties, prior to the urbanization of the region, the lake water used to be more saline, ranging from 2000 mg/l during the winter to 3500 mg/l during the summer (Passmore, 1970). However, the salinity rapidly fell in the early seventies, after the installation of artificial drainages, transforming the lake into a low-salinity water body with minor seasonal fluctuations (Kenneally *et al*., 1987), a condition that persists nowadays.

* + - 1. **Hydrogen Ion Activity (pH)**

Lake Richmond is formed by slightly alkaline water as expected from the predominance of calcareous rocks and sediments in the catchments of the basin. During the monitoring period, the lake water pH normally ranged from 8.5 to 9.0 (Figure 8.7 C), which is similar to previous surveys carried out in the area (Bowman Bishaw Gorham, 1997; MWH, 2011; Ecoscape, 2012). In 2013, a wetter than usual year, the pH tended to be slightly lower than in 2014 and 2015, which were drier than usual, with a general tendency for the pH to increase.

Inside the southern inlet, the pH is usually lower than the lake water, despite the slightly higher carbonate alkalinity. The pH measurements carried out in the drainage oscillated between 7.3 and 8.1 with the lowest levels recorded during the summer of 2014, when the water became stagnant and disconnected from the lake (Figure 8.7 C). The accumulation and posterior degradation of organic matter presumably contributed to maintain higher carbon dioxide concentrations and a generally lower pH in the stream compared to the lake water. In addition, much of the streamflow originates from rainfall, which has an average pH of 5.9 in the Perth region (Crosbie *et al*., 2012).

Runoff discharges originating from the artificial inlet were observed to sporadically alter the lake water chemistry at the southern margin of the lake, causing a substantial pH decrease. This was particularly evident in May 2013, after heavy rains, and in November 2013, following minor precipitation (Figure 8.7 C). These events were not seen in 2014 and 2015 and the lake water quality was, in general, more homogeneous during this period, with a slightly lower pH at the southern margin than at the northern shore.

These results demonstrate that the influx of runoff can occasionally produce abrupt changes to the lake water pH. However, these events are generally short-lived and restricted to the vicinity of the inlets. Longer term pH trends, in turn, seem to reflect climactic controls, with more alkaline conditions persisting during drier periods and less alkaline waters associated with a wetter period and increased runoff inflow. These controls are potentially significant for sedimentation in the lake as carbonate and silicate minerals, the main constituents of the microbialites, are more likely to form under alkaline conditions.

In the aquifer, measurements performed during the dry season approximated to neutral conditions, with the pH normally between 7.0 and 7.2. During the recharge period, in turn, the pH gradually increased to reach a maximum of 7.6 and, after the cessation of the rains, subsequently declined until the summer conditions were restored again.

* + - 1. **Dissolved Oxygen**

A combination of wind mixing and photosynthetic activity performed by the benthic microbial communities and macrophytes usually maintains the dissolved oxygen (DO) concentrations at high levels, above 6 mg/l, in shallow near shore areas adjacent to the microbialites (Figure 8.7 D). At the northern margin of the lake, away from the inlets, DO presents a good correlation to water temperature (R2=0.42). Higher concentrations usually coincide with cold periods while hot temperatures are typically marked by a decrease in oxygen solubility and, consequently, lower DO. An exception to this trend is generally observed during the spring when DO peaks, often reaching supersaturation, despite the increasing temperatures. This behaviour probably results from the high photosynthesis rates after the end of the wet season, stimulated by the warm weather, high luminosity and abundance of nutrients in the water.

At the southern margin of the lake, near the artificial drain, DO concentrations are usually smaller and present higher variability because of the inflow of oxygen depleted runoff water. Particularly after rainy periods, when the influx of stream water increases, the oxygen levels may abruptly decline, resulting in undersaturation and concentrations as low as 4 mg/l. Consequently, a weak correlation between DO and temperature (R2=0.12) can be verified in this part of the basin as the water quality is frequently modified by runoff discharges. This behaviour is consistent with the rapid pH fluctuations detected near the inlet, described above.

Inside the southern inlet, DO concentrations are usually low compared to the lake water and remain below 4 mg/l throughout the year, maintaining the stream in a permanent state of undersaturation. The poor oxygenation is caused by the degradation of organic matter which usually accumulates inside the drain, in particular algae, whose proliferation is triggered by the high nutrient loads present in the stream (detailed in section 8.1.2.7). This oxygen depletion becomes more accentuated during the summer when a combination of high temperatures and still water prevents the effective mixing of atmospheric oxygen in the drain.

Suboxic to anoxic conditions[[1]](#footnote-1), below 0.05 mg/l DO, persisted in the aquifer to the north of Lake Richmond, except in July 2014 when the measured concentration was marginally higher (0.34 mg/l; Figure 8.7 D). These results are in agreement with a previous survey carried out by The Water Corporation of Western Australia, which demonstrated DO concentrations below 1 mg/l predominate in the aquifer near Lake Richmond, even though higher concentrations, up to 5.1 mg/l, were recorded in a few wells (ERM, 2014).

* + - 1. **Daily Water Chemistry Fluctuations**

In order to investigate the daily oscillations in water chemistry, continuous, high-frequency measurements were performed at the northern margin of the lake during a 6 day period between April and May 2014. The water level was 0.24 m AHD at the time, similar to the historical average low water level (LWL). On this occasion, the temperature, EC, pH, DO and redox potential (Eh) of the water were recorded every 15 minutes, near the substrate of the infralittoral platform, close to the microbialite structures and benthic microbial mats (Figure 8.9).

Daily variations within the lake were significant. The temperature, dissolved oxygen, redox potential and pH curves closely resemble each other and presented higher values during day time, peaking during the afternoon. Lower values occurred during the night, reaching a minimum near the sunrise or up to a couple of hours later.

Water temperature oscillated approximately 8 to 9o C between day and night, ranging from 14 to 25o C (Figure 8.9). DO was supersaturated by up to 190% from the middle of the morning to the sunset, when the photosynthetic activity of the benthic microbial communities, phytoplankton and macrophytes is most intense. During the night, when photosynthesis ceases, oxygen is rapidly consumed by aerobic respiration and leads to undersaturation. Large DO fluctuations, around 10 and 12 mg/l were observed between day and night highlighting the importance of biological processes on the lake water chemistry (Figure 8.9).

The redox potential and pH are tightly coupled to the DO concentration denoting similar controls. Consumption of carbon dioxide (CO2) by photosynthesis during the day raised the pH significantly to a maximum of approximately 9.2 just before the sunset. In contrast, an abrupt decline was observed during the night, resulting in a minimum pH between 8.7 and 8.5 near the sunrise, presumably because of an increase in CO2 partial pressure, associated with microbial and plant respiration (Figure 8.9).

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| Figure 8.9 - Continuous measurement of lake water parameters carried out at the northern margin of the lake from 30/04/2014 to 05/05/2014. The meter was installed just above the microbial mats, at approximately 20 cm water depth. Note the remarkable day-night fluctuations. The dissolved oxygen, pH and oxidation-reduction potential fall abruptly during the night until early morning and increase significantly during the day, highlighting the strong biological control from photosynthesis and respiration. |

Electrical conductivity showed an opposite behaviour to temperature, pH, dissolved oxygen and redox potential, with higher values during the night and smaller values during the day. Variations between days and nights were small, on the order of 0.040 mS/cm (circa 7 mg/l TDS), but were demonstrated to be consistent throughout the monitoring period (Figure 8.9). Causes for this behaviour, however, are difficult to determine in the absence of a more detailed investigation of the water chemistry over a diurnal cycle.

The above results demonstrate a strong link between the physicochemical properties of lake water and metabolic activity of aquatic organisms, in particular photosynthesis and respiration carried out by the microbial communities and algae. Large fluctuations, therefore, are to be expected on a diurnal basis in Lake Richmond. The pH, in particular, can potentially shift the saturation state of carbonate and silicate minerals in favour of precipitation or dissolution, producing a strong impact on the microbial sedimentation (see item 8.1.2.6).

Equally important, measurements carried out during different periods of the day may be subject to strong bias and constitute a possible source of error during the interpretation of seasonal trends. However, the water sampling program in Lake Richmond generally occurred during the late morning and afternoon periods (see Appendix 4) when conditions tend to be more stable compared to the steeper variations of early morning and after dark hours. The trends observed in the dataset, therefore, should be considered predominantly representative of longer term seasonal cycles.

* + - 1. **Water Stratification**

A stratification survey was carried out from January 2010 to October 2011 at the central part of Lake Richmond (Figure 4.2; MWH, 2011)[[2]](#footnote-2). The surface water temperatures during the survey were consistent with the temperatures observed during this project near the lake margins, suggesting horizontal temperature variations are not significant in the lake. Vertical profiles along the water column, on the other hand, revealed the lake becomes thermally stratified during the dry season when the air temperature and solar radiation increase. The temperature isopleths in Figure 8.10 A show that the stratification normally starts to develop in October and becomes well stablished during the summer when the surface water can be up to 6oC hotter than at the bottom. Profiles during the stratification period normally display a gradual temperature decrease from the top to the base of the water column, but a well-defined thermocline is occasionally observed between -9 and -12 m AHD. The stratification is attenuated in March when the temperatures start to fall and culminates with turnover in April, at the beginning of the autumn. During the following months, both the top and bottom waters become well mixed and a homogeneous temperature is observed throughout the water column, a condition that persists until October when the stratification starts to develop again. Hence, according to the circulation patterns described above, Lake Richmond can be classified as warm monomictic lake, characterized by a period of stratification from the spring to summer and turnover during the autumn and winter.

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| Figure 8.10 - Depth-time diagrams with isopleths of (A) temperature, (B) electric conductivity, (C) dissolved oxygen and (D) pH gathered at the central part of the lake. Diagrams based on data acquired by MWH (2011) and provided by Strategen. See figure 4.2 for the survey location. |

The other physicochemical parameters measured were consistent with the temperature data and confirmed the seasonal development of the stratification. This was particularly evident for the dissolved oxygen (Figure 8.10 B). Once the stratification is established, the effective circulation of water remains restricted to the shallower parts of the lake where the dissolved oxygen concentrations remain close to saturation. In contrast, replenishment of oxygenated waters to deeper, poorly-mixed parts of the basin becomes greatly reduced. Under such conditions, the degradation of organic matter settling into the hypolimnion rapidly consumes the available oxygen and, in the absence of renewal mechanisms, leads to depletion. Consequently, dysoxic to suboxic conditions prevail in the depocentre, below -7 to -10 m AHD, in the period from October to February/March.

Interestingly, the dissolved oxygen concentrations slightly increase near the interface with bottom sediments, despite the generally low levels verified in the hypolimnion. This feature is here attributed to the presence of flocculent microbial mats in the central portions of the lake and suggests these benthic microbial communities are able to sustain photosynthetic activity despite their relatively deep location (Figure 5.5). During turnover periods, however, this characteristic often disappears, either because of the increased water circulation or because of reduced photosynthesis rates, typical of the autumn and winter periods.

From April to September, when the stratification is broken, the water circulation increases the supply of dissolved oxygen to deeper parts of the lake and oxic conditions normally persist across the basin. In these periods, similar DO concentrations tend to occur throughout the water column or a slight and gradual reduction is observed with depth, depending on the intensity of mixing processes. A more accentuated depletion is only occasionally verified near the interface with bottom sediments, where organic matter decomposition tends to be more intense, but never reaches the same intensity of the stratification periods.

Besides affecting the distribution and behaviour of the aquatic organisms (Goodale & Goodale, 1999), the recurrence of stratification periods and poor oxygenation of deeper portions of the lake tends to reduce the efficiency of organic matter degradation and enhance its preservation in the sediments. This mechanism explains the high organic content identified in carbonate muds from the central part of the basin, as evidenced by the analysis of a sample containing 14.5 % total organic carbon.

The pH logs, similarly to dissolved oxygen, presented strong correlation to circulation patterns and biochemical processes operating in Lake Richmond. Near the surface, carbonate alkalinity and the photosynthetic uptake of carbon dioxide (CO2) contributed to maintain the pH between 8.7 and 9.1 throughout the year (Figure 8.10 C). Near the bottom, in contrast, the pH was significantly lower and in general ranged from 6.7 to 8.0. Vertical gradients are particularly accentuated during the stratification periods when the surface pH is normally more than one unit higher than in deeper parts of the basin. The lower pH values, usually verified below -10 m AHD, coincide with an accentuated oxygen depletion and therefore can be attributed to the oxidation of organic matter and accumulation of the resultant CO2 in the hypolimnion. During the winter and autumn, when water circulation increases, the pH variations tend to be smaller, but an abrupt decrease is often noted near the interface with bottom sediments as a result of organic matter decomposition. Homogeneous pH values are observed only occasionally, in periods of vigorous mixing, when deeper portions of the lake are effectively involved in circulation, such as in May and June 2011.

The saturation state of the water in relation to carbonates and magnesium silicates tend to decrease under lower pH conditions, therefore a lower precipitation potential is expected in deeper portions of the basin. This might at least in part explain the abundance of microbialites around the lake margins and the absence of calcified structures in association with the flocculent microbial mats at the central parts of the lake. However, a more detailed study of these microbial mats, including their structure, diversity and metabolism are still necessary to elucidate their role in the immediate environment and capacity to mediate the mineralization process.

The electrical conductivity (EC) profiles presented slightly higher values in the hypolimnion during the summer months, when the stratification is well developed (Figure 8.10 D). In these periods the EC measurements above -8 m AHD ranged from 0.9 to 1.2 mS/cm but gradually increased below this depth to reach values around 1.4-1.5 mS/cm in the lower part of the water column. This vertical gradient was attenuated or completely disappeared during the autumn and winter when the lake water becomes well mixed, akin to the DO and pH profiles.

Exact causes for the higher hypolimnetic EC, however, are difficult to determine in the absence of a more detailed analysis of the water chemistry in deeper portions of the lake. A probable mechanism may be linked to organic matter decomposition processes, which usually occurs through a number of different chemical reactions, commonly associated with microbial metabolism. End products of the degradation such as carbon dioxide or hydrogen sulphides often accumulate as dissolved compounds in the hypolimnion, contributing to increase the salinity and EC of the bottom waters during periods of stratification (Boehrer & Schultze, 2008).

The above results, therefore, demonstrate the circulation patterns identified in Lake Richmond can be ascribed to a climactic control, with stratification and mixing periods determined predominantly by the water temperatures. The dissolved oxygen and pH, in turn, are tightly coupled to the circulation patterns, and are subject to a strong biological influence resulting from the activity of microbial organisms and macrophytes. On the other hand, only slight vertical EC variations are detected within the lake implying a predominantly external control from the basin hydrology and chemistry of the catchments.

* + - 1. **Chemical Composition of the Water**

Rain, groundwater and runoff from artificial drains constitute the main water sources to Lake Richmond. A comprehensive study of rain water across Australia demonstrated the rain in the Perth region normally has sodium and chlorideas dominant ions, a compositional pattern typical of a marine origin (Crosbie *et al*., 2012). The proportion of calcium and bicarbonate, however, is slightly enriched in the rain compared to standard seawater.

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| Figure 8.11 - Piper diagram displaying the water compositions at the north and south margins of the basin, the chemical compositions of the aquifer and the southern inlet. The standard seawater and the average Perth rain compositions are also plotted as reference. Rain data is from Crosbie *et al*. (2012). See figure 4.2 for sampling locations. |

The aquifer and water samples collected from the southern inlet, in turn, were proportionally enriched in calcium, magnesium and bicarbonate ions compared to rainwater, which is expected due to the predominance of carbonate sediments in the region (Figure 8.11). Therefore, the origin of these ions can be explained by carbonate dissolution in the catchments of Lake Richmond, as groundwater and streams flow across the coastal plain. Once discharged into the lake, water sources from the drains, the aquifer and, to a smaller amount, rain mix and become subject to processes of a physical, chemical and biological nature operating in the water column and at the interface with bottom sediments.

Bicarbonate is the most abundant anion in the lake water followed by chloride, sulphate and small concentrations of carbonate (HCO3- > Cl- > SO42- >> CO32-). In relation to cations, sodium is the most abundant species, followed by magnesium, calcium and only minor amounts of potassium (Na+ > Mg2+ > Ca2+ >> K+), as shown in Figure 8.12. However, the calcium concentration is observed to be occasionally higher than magnesium near the southern drain, in particular during the wet season when the inlet discharges a significant volume of calcium-rich water into the lake. As a result, the magnesium-calcium ratio in the lake water changes from approximately 0.8 at the end of the wet season to 1.8 at the end of the dry season.

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| Figure 8.12 - Average composition of the lake water at the north and south margins, artificial drain south of the lake and aquifer based on water samples collected from 2013 to 2015. See figure 4.2 for sampling locations. |

Sodium, potassium and chloride are conservative in Lake Richmond and do not participate in the precipitation of mineral phases or biochemical processes. Therefore, their relative concentrations inside the lake tend to be maintained in relation to the main water sources, namely the artificial drains and groundwater. The behaviour of these ions can be simply explained by evaporative concentration during the dry season and dilution by inflowing waters during wet periods (Figure 8.13). Sulphate, despite its importance for the metabolism of sulphate reducing bacteria, presented similar behaviour to conservative ions in the lake water, either because of low consumption rates or because of the rapid cycling between sulphur species (sulphate reduction and sulphide oxidation) near the lake margins, where oxidizing conditions are dominant. On the other hand, calcium and bicarbonate ions are permanently depleted inside the lake compared to the concentrations observed in the drain and aquifer. To a smaller degree, the same applies to magnesium, which is usually characterised by a slight depletion (Figure 8.13).

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| Figure 8.13 – Cross plots of major ions against chloride for Lake Richmond water, aquifer and the artificial drain south of the lake. The displayed regression is from aquifer and drainage samples, which constitute the main water sources to the lake. Chloride is conservative and follows seasonal concentration-dilution cycles. The same applies to (A) sodium, (B) potassium (note the scale) and (F) sulphate. In turn, (C) Calcium, (D) magnesium and (F) bicarbonate, are permanently depleted in relation to inflowing waters because these ions are removed by carbonate and magnesium silicate precipitation inside the lake. |

The abstraction of calcium, bicarbonate and magnesium ions from the water can be attributed to the precipitation of carbonates resulting in the formation of widespread microbialites along the lake margins and micritic deposits in deeper, central portions of the basin. Likewise, authigenic magnesium silicates were identified as a coexisting mineral phase in microbialite fabrics and may also account for a portion of the magnesium depletion. Modern evidence of precipitation, in particular, was confirmed to occur in association with the microbial mats, despite the recent alterations to the lake hydrology and water chemistry resulting from the installation of the artificial drains.

The hydrochemical analysis of the lake water demonstrated the seasonal fluctuations in calcium diverge from the behaviour of other major ions. Calcium concentrations are higher in the runoff and groundwater and, as a result, tend to increase during the wet season, when a significant volume of water is discharged into the lake. Other ions, in contrast, experience dilution along the rainy periods (Figure 8.14). During the dry season, when the influx of runoff decreases, the calcium content falls while other ions experience evaporative concentration. The lowest levels of calcium are normally observed during the summer, which coincides with the preferential timing of carbonate mineralization identified during the monitoring of the microbial mats (see section 7.1.8). These observations are comparable to descriptions from Passmore (1970) who also noted “an increase in dissolved calcium in winter and depletion in late summer, when algae and lime-secreting organisms were most active”.

Geochemical modelling demonstrated the lake water remains supersaturated in relation to carbonate minerals for most of the time (Figure 8.15). The saturation indices for aragonite (SIar) ranged from 0.58 to 1.0 and the saturation indices for calcite (SIcc) from 0.72 to 1.15 at the northern margin of the lake, away from the drains. A strong supersaturation in relation to dolomite (SIdol) was similarly detected, occasionally reaching over 600 times the equilibrium condition. Lower saturation values were detected during the 2013 wet season, followed by a gradual increase during 2014 and 2015, which were drier than average years. In general, similar conditions were observed at the southern margin of the lake but in this area runoff occasionally produces a sharp decrease in the saturation state of the water with respect to carbonate minerals. This effect was particularly evident in May and November 2013 and resulted in a marked undersaturation during the first occasion.

The pH (R2=0.81 to 0.87) and concentration of carbonate ions (R2=0.59 to 0.65) were identified as the main controls on the degree of calcium carbonate saturation, with a negligible influence from the calcium (R2=0.04 to 0.12) concentrations. However, the pH was demonstrated to be quite variable over diurnal cycles potentially affecting the saturation state of the water. To simulate these conditions a 0.6 pH fluctuation (as shown in Figure 8.9) was modelled, utilizing as reference the measured values in the lake water. The results demonstrated the lake water probably remains supersaturated in relation to aragonite and calcite even during night time conditions, when the pH abruptly falls. Hence, the dissolution of carbonates is presumably unlikely to occur under typical conditions in the water column (Figure 8.15). During the afternoon, when the pH peaks, calcite and aragonite saturations indices normally remain above 1.0, according to the modelled conditions.

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| Figure 8.14 – Concentrations of chloride (blue), calcium (red) and calcium to chloride ratios (orange) measured at the northern margin of the lake from 2013 to 2015. Note the calcium concentration increases during the wet season and falls during the dry season, approximately opposite to chloride and other major ions. Calcium depletion during the dry season, when the lake water is subject to evaporative concentration, is explained by the precipitation of calcium carbonates. |

In a comparison of diverse microbialite-forming environments Kempe & Kazmierczac (1990) concluded that a calcium carbonate saturation index above 0.8 is required for cyanobacteria calcification. Arp *et al*. (2001) similarly concluded that a saturation index of 0.86 would be necessary for biofilm mineralization by aragonite and 1.0 for the precipitation of calcite. These values, therefore, are comparable to Lake Richmond and suggest favourable conditions for calcium carbonate precipitation persist in the water throughout the year, despite the slightly higher saturation indices and evidence of preferential microbial mat mineralization observed during the dry season.

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| Figure 8.15 - Saturation indices for (A) aragonite and (B) calcite at the northern and southern margins of Lake Richmond. Most of the water measurements and sampling was carried out during the morning. The yellow shaded area was modelled to simulate diurnal variations resulting from a 0.6 pH unit fluctuation (see figure 8.9). Graphs show the lake water is, in general, highly supersaturated in relation to aragonite and calcite, but runoff discharges through the artificial drain at the southern margin of the lake can temporarily reduce the saturation state of lake water in nearby areas and eventually causes undersaturation, as observed in May 2013. |

1. Tyson & Pearson (1991) propose the following terminology for dissolved oxygen (DO) regimes: oxic = 8.0 to 2.0 ml/1 DO; dysoxic = 2.0 to 0.2 ml/l DO; suboxic = 0.2 to 0.0 ml/l DO and anoxic = 0.0 ml/l. [↑](#footnote-ref-1)
2. The survey was performed by MWH and the acquired temperature, dissolved oxygen, pH and electric conductivity profiles were previously presented in an unpublished report (MWH, 2011). This section includes isopleth diagrams and interpretations based on the same data set. The data was provided by Strategen, the contractor of the survey. [↑](#footnote-ref-2)