A long term analysis of
stratification and anoxic development in
hypertrophic impoundments in South Africa.

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Abstract
The study provides insight into the temperature and oxygen characteristics of six selected hypertrophic impoundments in three different climatic areas, altitudes, latitude and longitude all of which is downstream of the most populated area of South Africa. The results show that the development of anoxic zones are temperature and seasonally driven, with the anoxic upper border (< 1 mg/l O₂) following an annual temperature cycle irrespective of the depth of this upper anoxic border, when excess nutrients are available. The six impoundments have water column temperatures primarily > 10 °C throughout the year, which have implications for the fast development of the anoxic zones during the spring period, irrespective of the stability of the thermocline. The anoxic zone breaks through the thermocline or temperature barrier annually and all of these systems show occasional 100 % anoxia during the turnover period. The results give insight into the recycling of nutrients within these hypertrophic systems, which may contribute to the extreme primary production bloom conditions that are regularly found.

Keywords: South Africa, hypertrophic, freshwater, impoundments, anoxic, hypolimnion, eutrophication, nutrient recycling, stratification characteristics

Background
South Africa, as a dry to very dry country, has relied primarily on impounded water for sustainable development in all parts of the country. Within these impoundments, there has been an increasing incidence of eutrophication over many years (Grobler and Silberbauer, 1984; Van Ginkel, 2011 & 2012). Matthews (2014) with the latest developed monitoring technology stated that 62% of the South African impoundments are eutrophic. Rigorous monitoring lead to more expensive treatment of affected waters and increased the level of awareness of the causes and effects of cyanobacterial growth within the water sources (Harding 2006). The eutrophic water poses a health threat to direct users due to the potential cyanobacterial toxicity (Chorus and Bartram, 1999; Watson et al., 2016). In addition, the contribution of internal re-cycling (Dzialowski et al., 2007) and hypoxia (Watson et al., 2016) in hypertrophic impoundments can hamper the effect of management measures.

The classification of lakes, impoundments and pans are based on the temperature regime within the water column. The literature describes a clear distinction between the epilimnion, metalimnion (thermocline) and the hypolimnion (Horne and Goldman, 1994; Moss, 2000; Wetzel, 2001) and its use in
classifying fresh water systems and their mixing characteristics, which is based on the thermal characteristics of the water column through seasonal cycles. The development and knowledge on freshwater characteristics and the development of anoxic hypolimnias are primarily based on information of northern hemisphere systems (e.g. Watson et al., 2016), although a large amount of work has now been done in temperate, tropical and sub-tropical areas (e.g. Ashton, 1985; Moss, 2000; Wetzel, 2001; Müller et al., 2012).

According to Grobler and Silberbauer (1984) the use of oxygen depletion rate as quality variable for measuring the impact of eutrophication was queried by Walmsley and Toerien (1977). Wetzel (2001) warned that hypolimnietic oxygen deficits should be used with caution and with careful consideration of differences in hypolimnetic temperature and thickness. Yet, the use of the relative areal hypolimnion oxygen deficit method (RAHOD) to determine changes in trophic status (Charlton, 1980; Lind and Dávalos-Lind, 2009; Watson et al., 2016) is used internationally to determine the rate of oxygen loss within the hypolimnion. This method focusses specifically on hypolimnion depth and is based on the assumption that anoxic conditions are confined to the hypolimnion and that a large quantity of oxygen is still present in the upper hypolimnion at the onset of stratification.

Müller et al. (2012) and Watson et al. (2016) indicated a gap in the understanding and hence initiated new interest in the anoxia/hypoxia. The oxygen in the water of thermally stratified lakes is controlled by a combination of solubility conditions, hydrodynamics, photosynthesis, and losses to chemical and metabolic oxidations. Müller et al. (2012) notes that according to Cornett and Rigler (1979, 1980) the mean depth of the hypolimnion (zₘ) was more important in the aerial hypolimnion oxygen demand (AHOD) determination than the benthic O₂ consumption. Ashton (1985) had also identified a shortcoming in the interpretation of the biotic and abiotic interactions that regulate the increase and decline of individual phytoplankton species. This still seems to be the case to a large extent, as expressed by Oliver and Ganf (2000).

Per definition, anoxia refers to a total depletion in the level of oxygen, an extreme form of hypoxia or ‘low oxygen’. Within the fresh water context, the term anoxic waters are used (WWW 1, 2018). A review considering the importance and effect of hypoxia (O₂ < 2 mg/ℓ) on the formation of harmful algal blooms in Lake Erie (Watson et al., 2016) came to the conclusion that in addition to phosphorous control, the effects of climate, nitrate and other factors should also be considered in the context of adaptive management.

South African freshwater is often classified as warm, monomictic, temperate systems (Ashton 1985). Wetzel (2001) classified these systems as those having temperatures which do not drop below 4 °C, circulate freely in the winter, and stratify stably during the summer period. In addition, warm, monomictic lakes are common to warm regions of the temperate zones. Hutchinson (1975) and Moss (2000) (after Hutchinson and Loffler, 1956) already showed that the stratification types are based on latitude and altitude of the systems due to the orientation of water bodies towards the sun.

Within the context of this study, the extent of anoxic conditions, defined as oxygen concentrations of less than 1 mg/ℓ, of the South African impounded waters are investigated. This was done to determine the characteristics of freshwater system anoxic areas for the southern hemisphere, specifically focussing on whether anoxic areas are limited to the ‘hypolimnion’ as per the international accepted definitions (Wetzel, 2001; Whitton and Potts, 2000). However, it is mentioned that hypolimnion entrainment of nutrients does occur in many systems (Horne and Goldman, 1994). The study compares impoundments
with varying depth, morphology and thermal stratification scenarios and although the sites were within relatively close proximity of each other, they represented different altitudes and climatic zones of South Africa.

Temperature (isotherms) and oxygen (isopleths) are regularly measured by the Department of Water and Sanitation in selected hypertrophic South African impoundments. However, little research focussed on the nature, characteristics and development of anoxic extents for southern African freshwater systems, as the classification of Wetzel (2001) was accepted as a sufficient method to classify South African freshwater systems.

It is well known that most chemical gas constituents can be predicted by the temperature of the water column (Moss, 2000), which includes oxygen. Temperature and oxygen tables have been produced in the early development of limnology, and were based on pure H₂O and oxygen relationships (Hutchinson, 1975). However, much research has been done on the intricate movement of water and the effect of wind action on the epilimnion (Horne and Goldman, 1994), which cause eddies that pare portions of hypolimnion water (Moss, 2000). Strong winds may result in the deepening of the epilimnion by erosion of the hypolimnion in medium to shallow lakes. This contributes to the final overturn within freshwater systems according to Horne and Goldman (1994) and Moss (2000), together with the cooling of surface water during the late summer to autumn period.

Most oxygen regime work has been done within lakes, and within the interface of the hypolimnion with the bottom sediments (Wetzel, 2001; Whiton and Potts, 2000). Within the literature, anoxic conditions are thus primarily limited to the developed hypolimnion during the stratification period. However, there are a number of other mixing scenarios and one question that arises is whether many of the South African systems that have been classified as warm, monomictic impoundments are in fact neither dimictic nor polymictic and could be classified separately, intermediate to some of these classifications, as suggested by Ashton (1985).

This study investigates the extent of the anoxic conditions, as the re-cycling of sediment-bound phosphorous within anoxic conditions can contribute significantly to eutrophication related symptoms (Dzialowski et al., 2007; Watson et al., 2016). Donnelly at al. (1997) noted that there is a number of mechanisms by which hypolimnion water can move into the epilimnion, which included a) natural seasonal overturn, b) increase in wind action causing internal currents, and c) small diurnal changes in the water body that lead to leakages of the bottom water to the surface. In addition, Ashton (1985) noted that differences in northern and southern hemisphere phytoplankton habitats are primarily due to variability and seasonality of the southern hemisphere rainfall patterns. According to Steinberg and Hartmann (1988) and Oliver and Ganf (2000), the occurrence of cyanobacteria is dependent primarily on physical factors, particularly the degree of water column stability within water bodies, with a threshold of total phosphorous concentrations of > 10 mg/m³ (10 µg/ℓ).

As early as 1978 it was mentioned that Roodeplaat Dam can be up to 58 % anaerobic during the summer period (Walmsley et al., 1978). No further research has been done to determine if the anaerobic conditions within the systems are limited to the developed hypolimnion, as well as the potential contribution of the extensive anoxic areas due to eutrophication towards symptomatic development within the hypertrophic systems.
Methodology

Data Collection

The Department of Water and Sanitation (DWS) of South Africa has been monitoring a number of large and smaller impoundments in the Crocodile West Catchment and Olifants River Catchments. These impoundments are downstream of the largest portion of the population of South Africa (Gauteng), and have experienced increasing eutrophication to the extent of serious hypertrophic conditions.

All available physical, nutrient and chlorophyll-a data were collected by the DWS, RQIS Directorate, and are available on the national database (WMS). The data is readily available and include data from as early as 1968. The temperature and oxygen data for six selected impoundments was extracted from the WMS by Resource Quality Services personnel.

Study sites

The six impoundments that were selected for the study was Bronkhorstspruit Dam, Hartbeespoort Dam, Klipvoor Dam, Roodekopjes Dam, Roodeplaat Dam and Rietvlei Dam (Fig. 1). Limnological characteristics of the selected impoundments are shown in Table 1.

Table 1.  Limnological characteristics of the six selected impoundments. BHP = Bronkhorstspruit Dam, HBP = Hartbeespoort Dam, KV = Klipvoor Dam, RDK = Roodekopjes Dam, RDP = Roodeplaat Dam and RV = Rietvlei Dam. The data indicates median values, showing minimum, median and maximum values in brackets (DWAF, 1980; Van Ginkel, 2008; Van Vuuren, 2012; This study).

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>BHP</th>
<th>RV</th>
<th>KV</th>
<th>RDK</th>
<th>HBP</th>
<th>RDP</th>
</tr>
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<tbody>
<tr>
<td>Year of Construction (Raised)</td>
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<td>1934</td>
<td>1970</td>
<td>1985</td>
<td>1925</td>
<td>1959</td>
</tr>
<tr>
<td>Catchment</td>
<td>Olifants</td>
<td>Crocodile</td>
<td>Crocodile</td>
<td>Crocodile</td>
<td>Crocodile</td>
<td>Crocodile</td>
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<tr>
<td>Longitude</td>
<td>28.721389</td>
<td>28.373</td>
<td>27.811111</td>
<td>27.5772</td>
<td>27.85</td>
<td>28.265278</td>
</tr>
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<td>Climatic area</td>
<td>Mpumalanga Highveld Cold Temperate</td>
<td>Gauteng Highveld Cold Temperate</td>
<td>North West Warm Temperate</td>
<td>North West Warm Temperate</td>
<td>Gauteng Highveld Warm Temperate</td>
<td></td>
</tr>
<tr>
<td>Volume (fsl) (10^3 m³)</td>
<td>57.9</td>
<td>12.88</td>
<td>43.8</td>
<td>192.6</td>
<td>195</td>
<td>41.9</td>
</tr>
<tr>
<td>Altitude (asl) (m)</td>
<td>1429.42</td>
<td>1476</td>
<td>989</td>
<td>1006.5</td>
<td>1162</td>
<td>1314</td>
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<tr>
<td>Max depth (Zm) (m)</td>
<td>14.32</td>
<td>19</td>
<td>20.9</td>
<td>21.5</td>
<td>32.5</td>
<td>43</td>
</tr>
<tr>
<td>Mean depth (zm) (m)</td>
<td>6.73</td>
<td>6.2</td>
<td>5.78</td>
<td>6.53</td>
<td>3.6</td>
<td>10.6</td>
</tr>
<tr>
<td>Surface area (km²)</td>
<td>8.609</td>
<td>2.06</td>
<td>7.58</td>
<td>15.71</td>
<td>20</td>
<td>3.97</td>
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<td>Relative Depth (%)</td>
<td>0.24</td>
<td>2.08</td>
<td>1.19</td>
<td>0.85</td>
<td>1.14</td>
<td>3.39</td>
</tr>
<tr>
<td>Catchment size (km²)</td>
<td>1263</td>
<td>492</td>
<td>6138</td>
<td>6120</td>
<td>4112</td>
<td>690</td>
</tr>
<tr>
<td>Morphology</td>
<td>Dendritic with large open area</td>
<td>Small open area</td>
<td>Long linear with large open area</td>
<td>Dendritic with large open area between mountain ranges</td>
<td>Dendritic in steep narrow valley</td>
<td></td>
</tr>
<tr>
<td>Residence time (annum)</td>
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<td>NA</td>
<td>0.32</td>
<td>NA</td>
<td>0.51</td>
<td>0.69</td>
</tr>
<tr>
<td>Circulation type</td>
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<td>Warm monomonic</td>
<td>Warm monomonic</td>
<td>Warm monomonic</td>
<td>Warm monomonic</td>
<td>Warm monomonic</td>
</tr>
<tr>
<td>Mean minimum &amp; maximum air temperature (°C)1980-2016</td>
<td>4.4/27.2</td>
<td>-3.4/28.7</td>
<td>-1.6/36.5</td>
<td>Unknown</td>
<td>-3.5/33.8</td>
<td>1.8/36.2</td>
</tr>
<tr>
<td>WST °C (min/max)</td>
<td>10.0/28.8</td>
<td>9.3/30.7</td>
<td>12.2/36.3</td>
<td>13.0/30.2</td>
<td>9.0/32.4</td>
<td>11.1/30.5</td>
</tr>
<tr>
<td>WT 5m °C (min/max)</td>
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<td>8.7/24.8</td>
<td>11.8/27.7</td>
<td>12.6/27.2</td>
<td>6.6/27.6</td>
<td>10.9/26.1</td>
</tr>
<tr>
<td>WT 10m °C (min/max)</td>
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<td>8.5/24.2</td>
<td>11.3/26.7</td>
<td>12.4/26.5</td>
<td>6.6/26.5</td>
<td>10.8/24.4</td>
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<tr>
<td>Median Anoxic Period (months &amp; range)</td>
<td>5</td>
<td>6</td>
<td>6</td>
<td>5</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>Anoxic depth (m)</td>
<td>0/Bottom</td>
<td>1/Bottom</td>
<td>0/Bottom</td>
<td>0/Bottom</td>
<td>0/Bottom</td>
<td>0/Bottom</td>
</tr>
<tr>
<td>All Data (Min/Max)</td>
<td>6/Bottom</td>
<td>6/Bottom</td>
<td>6/Bottom</td>
<td>6/Bottom</td>
<td>0/Bottom</td>
<td>0/Bottom</td>
</tr>
<tr>
<td>Median Annual (min/max)</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>H</td>
</tr>
<tr>
<td>Trophic Status</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>H</td>
</tr>
</tbody>
</table>
The study sites are located within northern Gauteng, North West and Mpumalanga, South Africa (Fig. 1). All six systems are hypertrophic, situated in varying climatic and altitude zones and have different morphological compositions (Table 1). Of the six impoundments, only Hartbeespoort and Roodeplaat have waste water treatment works that discharge directly into the impoundment.

**Temperature and oxygen**

The > 15 year datasets were used to produce median annual isotherms, as well as the median extent of the anoxic areas each year. The isotherms were compiled for each growth period, starting in winter (July) of one year and ending at the start of winter (June) the following year, so as to ensure that the development of stratification can be captured within the growing season. Therefore, the data used for each graph included the summer periods and also the extent of the rainy season in the northern parts of South Africa, and cross-over between years. For each impoundment, median annual stratification was determined. Although stratification was created for each year (unpublished data), it is acknowledged that there is annual differences in stratification patterns from year to year, which will be discussed briefly below.

Additionally, the temperature of the upper border of the anoxic zone irrespective of depth (taken as the area where the dissolved oxygen was < 1 mg/ℓ) was determined. This was done to investigate the potential impact of temperature on the development of anoxic areas within the impoundments, as well the depth at which the upper anoxic border occurs. This data was annotated on each day of the year, as measured, over the spectrum of available data and years. Annual temperature changes of the upper anoxic border were plotted showing variability per month, through minimum, mean and maximum values found per month.

Isopleths were not created for each year, but the upper limit depth of the anoxic zone (< 1 mg/ℓ) and temperature were determined from the DWS data. A seasonal anoxic cycle was determined for each impoundment to investigate if there was a repeatable pattern that could potentially be used in future predictive studies to classify sites or improve our understanding of the phenomenon of cyanobacterial bloom development within these impoundments.

**Morphology & Locality**

The morphology, catchment area, catchment composition and locality (altitude as well as latitude and longitude) of each impoundment are shown in Table 1.

Bronkhorstspruit and Rietvlei are situated in the cold temperate Highveld above 1400m above sea level and are located in two different catchments, namely the Olfants and the Crocodile, respectively. Rietvlei is the smallest of the impoundments, with a surface area of 2.06 km² and lies within the borders of the highly populated Pretoria and downstream of Johannesburg suburbs. The system has been classified as hypertrophic since the 1970’s. Although Bronkhorstspruit is larger than Rietvlei, they are both subjected to colder winter temperatures compared to the other systems. Bronkhorstspruit has become hypertrophic fairly recently (Van Ginkel et al., 2001). Both these systems have mean depths < 10 m and are located in open savannah. Relative depth measurements (Table 1) indicate that Rietvlei Dam is a deeper system than the Bronkhorstspruit Dam. Rietvlei is surrounded by a nature reserve. Recently the Bronkhorstspruit Dam has been increasingly exploited as a recreational site due to its close proximity to the main centres of Pretoria and Johannesburg, and also since the water quality of the impoundment
used to be higher than that of the other impoundments close to the Gauteng Metropole (Hartbeespoort and Roodeplaat).

Hartbeespoort and Roodeplaat are situated in the temperate Highveld, downstream of the main population centre of South Africa, but on the border of the warmer Bushveld region, so both air and water temperatures are higher than for the Bronkhorstspruit and Rietvlei localities (Table 1). The Hartbeespoort altitude is more comparable to the warmer Bushveld sites. The relative depth of the Hartbeespoort Dam indicates that it is also a shallow impoundment, even though the maximum depth is over 32.5 m. Roodeplaat Dam, with an altitude closer to the Highveld region, borders on the description of a deep water body, with a relative depth of 3.39 and a maximum depth of 43 m.

Roodekopjes and Klipvoor are situated in the warm temperate Bushveld area of the Crocodile West catchment. The Bushveld are subject to warm summers and mild winters and ranges within an altitude range of 750 m – 1400 m above sea level. The annual rainfall ranges between 350 mm and 600 mm. The Roodekopjes Dam is dendritic and is used to supplement Vaalkop Dam for domestic purposes. The impoundment is situated downstream of the hypertrophic Hartbeespoort Dam. Klipvoor is an elongated system and situated within the Borakalalo Nature Reserve, although the catchment consists of some densely populated areas. The impoundment is the most northern of the six selected sites and downstream of the Roodeplaat Dam. Of these two impoundments, Klipvoor is the deeper system with a relative depth of 1.19. Roodekopjes has a relative depth of 0.85. Both impoundments have similar maximum depths of 20.9 m (Klipvoor) and 21.5 m (Roodekopjes), indicating that Roodekopjes is a much larger system than Klipvoor.

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Figure 1. Map of South Africa indicating the locality of the six impoundments studied. GP = Gauteng, NW = North West, MP = Mpumalanga, LP = Limpopo, FS = Free State, KZN = KwaZulu Natal, EC = Eastern Cape, WC = Western Cape and NC = Northern Cape.
Results

In a previous investigation into the temperature regime of the anoxic zones of the Hartbeespoort Dam, it was found that the upper anoxic border temperature over a period of 27 years had a distinct seasonal cycle in temperature, irrespective of the depth at which the upper anoxic border is situated (Figure 2) and irrespective of influxes into the impoundment which temporarily disrupts the anoxic zone (unpublished data). These temperatures varied between ± 11 °C and 26 °C in the Hartbeespoort Dam. The only anomaly in the data was found during the 2008/2009 growth season.

![Figure 2. The daily changes of the upper anoxic border temperature of the Hartbeespoort Dam. Data for twenty seven years of available data from 1980 to 2017 are shown. The growth season are from 1 July to 30 June, and are shown as month/day. The broken line indicates an anomaly during the 2008/2009 growth season.](image)

This led to the further investigation of the anoxic zone formation of the other five impoundments, which are within similar latitude and longitude, as well as of similar trophic status. The other selected impoundments showed similar phenomena, although some of the impoundments do not develop anoxic zones throughout the year (Figure 4-6), even though a relatively large dataset was available for all the impoundments.

The impoundments differ in terms of climatic zones, mean depths the extent of eutrophication, and are discussed with this in mind. It is apparent from Figure 3 that the temperature differences in the six impoundments, due to the different climatic zones did show variability. The nutrient concentrations and establishment of primary productivity, as measured through chlorophyll-a, did not necessarily coincide. For instance, Bronkhorstspruit and Roodekopjes nutrient concentrations were considerably lower than the other systems, yet the primary production was not in accordance with the nutrient availability. Of the six impoundments Klipvoor and Hartbeespoort showed the highest maxima in phytoplankton production, while Roodeplaat had the lowest minimum in chlorophyll-a concentration.
Figure 3. Comparison of maximum, 75th percentile, 25th percentile and minimum values of a) the surface water temperature, b) the total phosphorous concentrations (0-5m), c) the ortho-phosphate concentrations (0-5m) and d) the chlorophyll-a concentrations (0-5m) in the selected impoundments. BHS = Bronkhorstspruit, RV = Rietvlei, KV = Klipvoor, RDK = Roodekopjes, HBP = Hartbeespoort and RDP = Roodeplaat.
Additionally, the thermocline and hypolimnion formation during the summer, as well as the extent of complete mixing, was investigated (Figure 4, 5 and 6). The impoundments were separated because of their mean depth and climatic position. Impoundments with a mean depth < 10 m were considered a shallow impoundment (Figure 4 & 5) and impoundments with a mean depth > 10 m were considered a deep impoundment (Figure 6). Hartbeespoort Dam’s mean depth was close to 10 m and were therefore considered a deep impoundment and comparable to the Roodeplaat Dam’s mean depth of just > 10 m. However, according to the relative depths of these impoundments, Hartbeespoort Dam can be considered a shallow impoundment and its characteristics may be more comparable to those for Klipvoor and Roodekopjes.

The median temperature values per depth used to determine the temperature regimes in each impoundment indicate warm, monomictic characteristics. However, it must be noted that the systems did show polymictic characteristic scenarios, depending on weather fluctuations over consecutive years (unpublished data not shown here).

Figure 4. Shallow impoundments in the Highveld area, with a mean depth < 10 m, indicating a) the median monthly stratification pattern, median anoxic zone formation, and median biomass productivity, as chlorophyll-a, for the time periods as indicated on the graphs; b) The mean monthly anoxic upper border temperature showing variability as minimum and maximum.

The Bronkhorstspruit and Rietvlei dams, which are situated in the colder Highveld area, showed median surface temperatures not exceeding 24 °C. It is important to note that the bottom temperatures seldom reached temperatures below 10 °C during the winter period. During summer, the bottom waters often, and for prolonged periods, reach temperatures in the vicinity of 20 °C or higher. These two shallow impoundments show weak thermocline development with median anoxic zones forming during October (Rietvlei Dam) and December (Bronkhorstspruit Dam) and lasting until March. The mixed periods are long due to early set-in of complete mixing in March, when temperatures start to decline, and because
of the late start of stratification. The upper-border of the anoxic zone reaches in general an upper depth of around 6 m, although minima of 0 m and 1 m were measured in these impoundments during turnover events (Table 1). This indicates that there are periods of 100 % anoxic conditions within the water column. These events are associated with the turnover period of late summer to autumn.

The variability in mean anoxic upper zone border temperature is relatively small in the Bronkhorstspruit and Rietvlei impoundments when compared to some of the other impoundments. Bronkhorstspruit never started stratification before August (Fig. 4 b). This is probably due to the fact that the system is within the colder Highveld area above 1400 m above sea level, and the temperatures favouring bacterioplankton growth start late in the season.

Figure 5. Shallow impoundments in the temperate Bushveld area, with a mean depth < 10 m, indicating a) the median monthly stratification pattern, anoxic zone formation, and biomass productivity for the time periods as indicated on the graphs; b) The mean monthly anoxic upper border temperature showing variability as minimum and maximum. Take note that Roodekopjes Dam did not show any anoxic conditions during June to August for the period of available data.

The Klipvoor and Roodekopjes impoundments are situated in much warmer Bushveld areas, and temperatures increase to 27 °C at the surface. During the summer growth period, temperatures of up to 25 °C were found in the bottom waters of the systems. Again, the coldest winter temperatures seldom fell below 10 °C. These two shallow impoundments show weak thermocline development with anoxic zones forming during September and lasting until March (Roodekopjes Dam) and April (Klipvoor Dam). The median anoxic upper border zone in the Klipvoor Dam reached 6 m with occasional minima of 0 m during turnover. The Roodekopjes median anoxic upper border zone reached only up to 10 m with occasional minima of 0 m during turnover events.
The variability in mean anoxic upper zone border temperature was relatively small in the Klipvoor and Roodekopjes impoundments when compared to the Hartbeespoort and Roodeplaat impoundments. Roodekopjes never started stratification before September and no anoxic zones were found during June (Fig. 5 b), even though the system is situated within the warm Bushveld area. This is probably due to the fact that the catchment and the catchment impact are small as compared to the upstream Hartbeespoort Dam, which may act as a nutrient trap (Van Ginkel et al., 2001). The fact that Roodekopjes is the youngest of the impoundments (thus, the build-up of eutrophication causing factors not having developed to the extent of the other systems) may be another potential explanation.

Figure 6. Deep impoundments with a mean depth of ± 10 m, indicating a) the median monthly stratification pattern, anoxic zone formation, and biomass productivity for the time periods as indicated on the graphs; b) The mean monthly anoxic upper border temperature showing variability as min and max.

The Hartbeespoort showed weak thermocline formation, while Roodeplaat indicated a strong thermocline through most of the year. Both impoundments had extended periods of anoxia, indicating a median occurrence of anoxia from August to May in the Hartbeespoort, and August to June in Roodeplaat. The mixed periods were much shorter than in the other impoundments. The surface temperatures were (for short periods) as high as 26 °C. During the summer period, temperatures at 30 m could be 20 °C in the Hartbeespoort Dam, while the Roodeplaat hypolimnion temperature seldom fell below 14 °C. The winter temperatures during complete mixing periods were seldom below 10 °C in both systems. The mixing period in the Roodeplaat Dam was extremely short and lasted for about a month. The median anoxic zone in the Hartbeespoort Dam reached 9 m with occasional minima of 0 m during turnover. The Roodeplaat median anoxic zone reached up to 7.5 m with occasional minima of 0 m during turnover events.

The variability in mean anoxic upper zone border temperature was much larger in the Hartbeespoort and Roodeplaat impoundments when compared to the shallower impoundments. Stratification in both
systems was found throughout the year (Fig. 6 b). This is probably due to the fact that the catchments of these systems are severely impacted by urbanisation and both these systems have waste water treatment works that discharge directly into the impoundments with limited secondary nutrient removal. The Roodeplaat Dam showed the highest variability in the anoxic upper border temperature and the main difference of Roodeplaat, namely the strong thermocline formation, may be the cause of this variability.

Discussion

Previous studies in South Africa classified the systems as warm monomictic (Stofberg, 1983; Ashton, 1985; Van Ginkel et al., 2000, Van Ginkel, 2008), according to the Wetzel (2001) classification. However, some studies mention weak thermocline formation (Tow, 1981) in other South African systems and Ashton (1985) note that summer stratification are often disrupted by the erratic storm and flood events characteristic of southern Africa. The northern parts of South Africa, where these impoundments are situated, are particularly prone to irregular afternoon thunderstorms (Van Ginkel, 2008), especially during the summer period. It is generally accepted that the hydrological cycles start in October. The results of this study showed that all the shallow impoundments developed a weak thermocline during the spring stratification and warming period, including the Hartbeespoort Dam. The only impoundment that showed a strong and distinct thermocline for most of the year was the Roodeplaat Dam. Anoxia developed rapidly at the onset of the growing season (Figures 4a, 5a & 6a) and the extent of the anoxic zones in all instances pushed through the initial thermocline, even in the strong, dense thermocline that formed in the Roodeplaat Dam.

Ashton (1985) noted that Southern Hemisphere lakes and impoundments tend to occupy a position intermediate between tropical equatorial and northern temperate lakes. The hypolimnion oxygen deficit method measures the change in oxygen in the hypolimnion. As the hypolimnion’s oxygen concentration decrease to 1 mg/ℓ, the rate of oxidation slows so as to determine the oxygen change caused by input of organic matter. The measured rates must be corrected to a standard temperature of 4 °C, a temperature that does not occur in South African waters. Four important factors in determination of rate of hypolimnion oxygen deficit are: 1) the quantity of organic matter present; 2) temperature; 3) the depth of the hypolimnion; and 4) the oxygen concentration of the hypolimnion. Considering the results presented here, the method to determine hypolimnion oxygen deficit and mineralization (Müller et al., 2012), become irrelevant in the southern African context, as the formation of a stable hypolimnion is not readily found throughout the summer period, and even when developed, the anoxic zone annually push through the temperature barriers of the thermocline or metalimnion.

According to Wetzel (2001), bacterioplankton abundance and biomass were markedly greater in anoxic hypolimnion than in oxic epilimnia. It is well known that at temperatures < 15 °C, bacterioplankton growth correlates positively with temperature. Yet, at higher temperatures (as is the case for South African freshwater) other variables such as nutrient availability can become more important in the growth of bacterioplankton. Lind and Dávalos-Lind (2009) stressed that the rate of biochemical processes, such as bacterial oxidation of organic matter, is temperature dependent and that it follows the Van’t Hoff principle with a Q10 of approximately 2. This means that the rate of oxygen depletion due to exponential bacterial growth will double with each 10 °C temperature increase. Phosphorous is often the limiting nutrient for bacterioplankton, yet Wetzel (2001) did not mention the minimum requirement of phosphorous for bacterioplankton growth. Toolan et al. (1991) found bacterioplankton to increase at
DIP concentrations of \( \sim 1.5 \, \mu g/\ell \) as it is sufficient to stimulate bacterial production. This is an extremely low concentration which is below the detection limit of the DWS laboratory capacity.

Wetzel (2001) mentions that bacterioplankton productivity, as a percentage of all decomposition in lakes, increases in deeper lakes that have a longer residence time for degradation of sedimenting particulate organic matter, relatively small allochthonous loading of dissolved organic matter and large pelagic areas in comparison to those of the littoral areas. In Roodeplaat Dam the residence time and large pelagic areas are applicable, however it is subject to high allochthonous matter due to the effluent from two Waste Water Treatment works, as well as runoff from agriculture and dense settlements. The Roodekopjes and Bronkhorstspruit dams, which have relatively small catchment developments and activities, as compared to the other impoundments (Bronkhorstspruit, Hartbeespoort, Klipvoor and Rietvlei dams) in the study, show the shortest median period of anoxic development. All these systems are situated within an area with irregular rainfall events.

After brief re-oxygenation by turbulence or respiratory and feeding activities of benthic animals, community respiration rates and oxygen consumption rates of highly organic sediments quickly (within hours to a few days) return to values similar to those of undisturbed sediments with comparable organic content and composition in shallow lakes (Hargrave, 1975 and Viner, 1975: according to Wetzel 2001). Additionally, respiratory oxygen consumption is primarily and directly related to temperature (Wetzel, 2001).

The greatest heterotrophic activity of benthic microorganisms in shallow water sediments occurred in the summer months when the water temperatures exceeded 10 °C as found by Hall et al. (1972), Toerien and Cavari (1982): in Wetzel (2001). However, under South African conditions, winter temperatures seldom fall below 10 °C. Therefore, heterotrophic activity seldom ceases to occur during the winter months. According to Soares et al. (2017), carbon is the most likely limiting nutrient for bacterioplankton in DOM-rich systems. This is because carbon is less available when total concentrations are considered in comparison to N and P availability, where DIP is more readily available within the TP fraction. This study did not consider the carbon content of the systems per se.

The six impoundments investigated here seldom reached temperatures below 10 °C, even in the winter periods. This is the growth initiating temperature for bacteria, as mesophilic bacteria grow optimally between 20°C and 40°C, but can multiply between 10 °C and 50 °C (WWW3 2018). This is the bacterial group found within the South African freshwater context as bacterioplankton. Ratowsky et al. (1982) established a regression coefficient for the relationship between bacterial growth and temperature and White et al. (1991) found a direct relationship between temperature and bacterioplankton specific growth rate, with enhanced effects when chlorophyll-a is considered. This also supports the findings of Pearl (2000). This illustrates the possibility that all these systems (perhaps with Bronkhorstspruit and Rietvlei as exceptions) have a certain degree of restricted bacterioplankton growth during the winter period. The slight increases in temperature during the spring periods may lead to exponential growth of bacterioplankton, resulting in fast development of anoxic zones.

According to Oliver and Ganf (2000), cyanobacterial blooms is reliant on a complex interplay of environmental stimuli, including physical, chemical and cyanobacterial characteristics. Pearl (2000) noted that there are cyanobacterial-microbial interactions that characterize periods of bloom development and proliferation, since there may be mutually beneficial metabolite exchanges between these groups and also potential detoxifying roles of microbial bacteria. These interactions may not be
indicative of cyanobacterial senescence but rather be the result of parallel optimization of growth and bloom potential among the cyanobacterial host and the associated bacteria. Adams (2000) noted that cyanobacteria are unique in their capacity to form symbiotic associations, where they provide nitrogen and occasionally carbon. However, the benefit to the cyanobacteria is less clear. When Cyanophages are considered, Suttle (2000) concluded that environmental factors and the physiological state of cyanobacteria clearly affect cyanophage-cyanobacterial interactions, but still remain poorly understood. According to Aufinger et al. (1991) increases in bacteria do coincide with the germination of the cyanobacterial akinetes.

Nitrogenase, responsible for N\textsubscript{2} fixation, is suppressed by the presence of oxygen. This problem is countered by the development of heterocysts that create an anoxic environment within which N\textsubscript{2} fixation can occur. This is a typical characteristic of the heterocystous, filamentous Anabaena species. Therefore, these species are often found in bloom conditions where nitrogen is limiting and the system is well oxygenated (Oliver and Ganf, 2000; Pearl, 2000). Anabaena species occur for very short periods within the Hartbeespoort and Roodeplaat impoundments (Van Ginkel, 2008), and specifically in the spring period, when anoxic zones are largely not developed yet. This may be due to the advantage that these species have because of the presence of heterocysts and their ability to bind N\textsubscript{2} in the presence of oxygenated conditions. As soon as bacterioplankton growth are initiated due to temperature increases and the development of anoxic zones, it is proposed that the contribution of the bacterioplankton to the development of the anoxic zone, may favour the development of Microcystis development, due to the establishment of an ideal environment where Microcystis can access the available re-cycled nutrients.

It is proposed that the large anoxic areas within the water column in South African impoundments create ideal conditions for Microcystis species, which do not have heterocysts. These species are able to perform N\textsubscript{2} fixation in these large anoxic zones, and also form mutual beneficial metabolite interchange with associated bacteria (and probably cyanophages), which proliferate and respire to contribute to the extremely fast anoxic development under increased temperature changes from early spring to late summer. The high temperatures throughout the water column during the summer periods create ideal conditions for optimum bacterioplankton and cyanobacterial growth, and during turnover, the influx of the recycled nutrients leads to anoxic zones. This occasionally reaches the surface water (unpublished data) and is associated with phytoplankton flare-ups, as shown in the Roodekopjes Dam (Fig. 5a).

Conclusions

Hypertrophic impoundments have nutrients available in excess, and potential limitations to the exponential growth of phytoplankton become irrelevant, especially during the turnover period. The temperatures in South African impoundments are exceptionally high, which may then lead to exponential bacterioplankton growth during the spring to early summer period, and contribute to anoxic zone formation throughout the warm summer periods. Anoxic zones are not limited to the ‘hypolimnion’ in these hypertrophic systems in South Africa. The climatic zone, altitude, latitude and longitude and extent of nutrient enrichment do impact on the extent of primary productivity in the shallow impoundments. The stability of the thermocline in the deeper Roodeplaat Dam does seem to limit the extent of primary productivity, yet the anoxic zone is not confined to the hypolimnion. These fluctuations of anoxic zones outside the thermoclines provide a means by which additional nutrients can be added in already hypertrophic systems. The low nutrient concentration in the summer to autumn period is an indication that the nutrients are consumed by plant growth, including the macrophyte and phytoplankton populations present, that then become noxious.
The cyclic anoxic upper border temperature results indicated clearly that the anoxia in the hypertrophic systems is driven primarily by seasonal changes in temperature. This may lead to extreme increases in bacterioplankton growth in these systems, which seldom reach temperatures below the optimal growth conditions for mesophilic bacteria. The rapid formation of anoxia and the conditions within these hypertrophic systems implicate that nutrients and temperature are not limiting and that it supports bacterioplankton, cyanophage and *Microcystis* mutualistic development, as soon as anoxic zones are initiated by the bacterioplankton respiration needs.

Questions that arise, and may lead to further research, are:

1. What are the implications of these results for eutrophication management?
2. Is anoxia partly driven by bacterioplankton and cyanophage activity, which are in turn determined by the cyclic seasonal temperature characteristics of the hypertrophic systems?
3. Does the heat energy created by bacterioplankton activity contribute to the temperature increases and breakthrough of anoxia through the metalimnion/thermocline, in addition to the influx and nature of inflowing waters after rainfall events?
4. Are the cyanophages, which contribute no more than 3% to cell lysis of cyanobacteria, just one step in the mutualistic association with the bacterioplankton, to provide the nutrients required in the hothouse conditions of the hypertrophic South African impoundments during summer?

References


