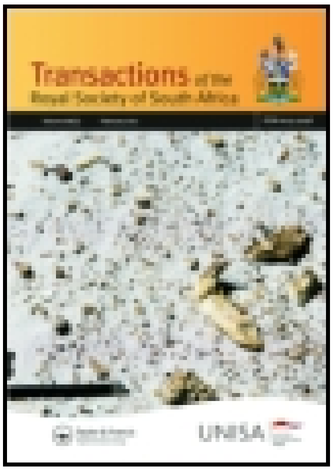

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Living with eutrophication in South Africa: a review of realities and challenges

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Review

Living with eutrophication in South Africa: a review of realities and challenges

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The socio-economic well-being of South Africa is largely dependent on reservoir lakes. Contrastingly, the country lacks reservoir management skills and training, with a generation having passed since there was limited activity in this field. This review introduces two new, independent analyses which, using in-lake total phosphorus or satellite-measured chlorophyll-a, respectively, reveal that between 41% and 76% of total storage is eutrophic or hypertrophic. This is in stark contrast to a claimed 5% made by the responsible government agency (Department of Water and Sanitation). Data and information on the incidence and toxicity of cyanobacterial blooms are sparse, yet severe problems exist. There is a concentration of focus on water quantity, with absent parallel consideration of the additional limitations posed by poor water quality. The most seriously impacted reservoirs are located in the economic heartland of South Africa, which has an extant regional water quality crisis. The reasons behind the startling lack of attention to reservoir limnology, despite clear and long-standing warnings, are examined and placed in the perspective of an acknowledged and impending water crisis. It will take considerable time to up-skill South African limnologists to meet the needs highlighted by worsening reservoir water quality, and to offset the social and economic impacts that will transpire, if not timeously ameliorated. The responsible agency urgently needs to establish a reservoir-management programme that embraces remaining individual and institutional memory, integrates all available relevant knowledge and scientific findings, prioritises needs and acquires those skills and resources necessary to meet what is likely to become a crippling legacy of inaction.

Keywords: **South Africa, eutrophication, reservoir lake management, water crisis.**

INTRODUCTION – SOUTH AFRICA'S WATER CRISIS

The period spanning 2009/2010 saw increased reporting of an imminent water crisis in South Africa (e.g. CDE, 2010). Recent concerns have focused on the water quality threat posed by acidic effluents (Acid Mine Drainage), borne by rising groundwater in disused mines in Gauteng Province (Naidoo, 2014; NWRS, 2014). While global and local water quality issues have hitherto centred on salinisation (e.g. WRI, 2000), extant concerns increasingly highlight the problem of eutrophication and the compounding problem of pharmaceuticals, endocrine disrupting compounds (EDCs), pathogens, pro-inflammatory activity, pesticides and/or heavy metals in South African reservoirs and rivers, especially where urban runoff and wastewater effluents form a substantial component of the water balance (e.g. Harding, 2010, cited in Kidd, 2011; Wose Kinge *et al.*, 2010; Nyirenda *et al.*, 2011; Siri *et al.*, 2011; WHO, 2012a-c; Adebayo *et al*, 2014; Naidoo, 2014; Barnhoorn *et al.*, 2015). High levels of nutrients in aquatic ecosystems may influence the toxicity of insecticides, complicating the understanding of invertebrate community response (Alexander *et al.*, 2013). Concomitantly, research findings point to the global impact of climate change on water quality and aquatic ecosystem function (e.g. Jeppesen *et al.*, 2003, 2010; Meerhoff *et al.*, 2007).

In South Africa, upwards of 7.6 Mm^3 (MCM) of domestic and commercial wastewater is processed daily by 850 municipal treatment plants (SAICE, 2011). Annual return flows of 6000 MCM comprise more than twice that obtained from groundwater (NWRS, 2014). Approximately 10 000 MCM is abstracted from rivers and reservoirs per annum. By contrast, groundwater provides approximately 2000 MCM per annum (NWRS, 2014) – indicating the level of importance of impoundments to overall water supply. In Gauteng Province – the country's economic heartland – 1.4% of the total land area houses 17% of the population and produces 40% of the manufacturing output. A large percentage of this wastewater is inadequately treated (e.g. DBSA, 2009; SAHRC, 2014). The Department of Water and Sanitation (DWS), responsible for water resource management, recently announced that ZAR670 billion (US$61 billion) will be needed to address problems associated with failing infrastructure (*Finweek* 4 December 2014).

Many of South Africa's rivers, reservoirs and coastal lakes no longer have the resilience to assimilate nutrients or sequestrate toxicants (Statistics South Africa, 2009). If the reservoir lakes are to fulfil the basic and multiple functions of resource provision, waste assimilation and recreation, then full attention needs to be devoted to the concept of 'integrated water resource management'. As early as 1979, it was noted that "Only by reducing pollution of this country's limited water resources, and through the multiple cycle reuse of water and ultimately the use of desalination, will a crisis be averted in the future" (Cillie & Odendaal, 1979).

The urgent need for an immediate response to the water quality problem has been laid directly at the door of government (e.g. CDE, 2010). It has recently been suggested that should current trends persist, an increase in the incidence of toxin-producing cyanobacteria may be the result (Conradie & Barnard, 2012). While there is no formal reporting system for cyanobacterial blooms in South African freshwaters, available data indicate a frequent and widespread seasonal occurrence (Downing & Van Ginkel, 2004). Data on cyanotoxins are limited (Downing & Van Ginkel, 2004). Occurrence of the controversial beta-N-methyamino-L-alanine (BMAA) was found in 97% of cyanobacterial culture collection samples isolated from local waters (Downing, 2011). South Africa has experienced animal deaths from cyanotoxins for many decades (Harding & Paxton, 2001).

The National Water Resources Strategy (NWRS, 2014) states that all aquatic ecosystems cannot be managed to the same level of protection, i.e. that an accepted level of degradation will have to be tolerated in order to sustain socio-economic development. This author argues that, with respect to South African reservoirs, the "accepted level of degradation" has long been exceeded and receives inadequate attention (e.g. Figure 1). There is a general consensus that water quality issues worldwide will progressively and significantly constrain economic development (WRI, 2000).

SOUTH AFRICA'S RESERVOIRS

South Africa has some 580 'large' reservoirs (storing 1 MCM or more) that fall within the management ambit of the DWS (see Figure 2). In addition, there are many thousands of farm dams of varying sizes. This paper addresses only the former set of 'national' reservoirs.

Of the 580 large reservoirs, 320 'major' reservoirs (reservoir lakes) store a total of 32 billion m^3 (32 000 MCM), equivalent to 66% of the country's mean annual runoff (MAR) (NWRS, 2004). South Africa is an arid country with an average rainfall of 450 mm per annum, little more than half the world average of 860 mm per annum, and with net rainfall (rainfall less evaporation) being negative (NWRS, 2004). According to the World Wildlife Foundation, South Africa is one of a group of countries having the least available freshwater per person (1131 m^3 per annum, Revenga & Cassar, 2002). The availability of sufficient water – in terms of both quality and quantity – underpins economic and cultural prosperity (Gophen, 2008).

Water consumption in South Africa is broadly divided amongst irrigation = 62% (1.5% GDP); domestic & urban = 27%; mining and power = 8%; and forestry = 3% (NWRS, 2004).

The NWRS (2004) recognised that "the deterioration of surface water resources is one of the major threats to South Africa's capability to provide sufficient water of appropriate quality to meet its needs and ensure environmental sustainability". With respect to the deliberate capture of polluted flows, the NWRS also stated "substantial volumes of water are returned to streams for re-use – provided that the quality of return flows satisfy the relevant user requirements." Herein should be implicit that the environment is the primary 'user', requiring a very high level of water quality.

RECOGNITION OF THE THREAT OF EUTROPHICATION IN SOUTH AFRICA

The NWRS (2014) provides a summary of water resource management challenges and solutions for South Africa. The document pointedly acknowledges that the resource is not receiving the attention and status that it deserves – evident, *inter alia*, in wastage, pollution and degradation. Furthermore, that the sustainability of South Africa's freshwater resources has reached a critical point – viewed against the observation that "South Africa's water security is mainly reliant on surface

Figure 1. Roodeplaat Dam (Pretoria), 28 November 2014 (source: Dr M. Silberbauer).

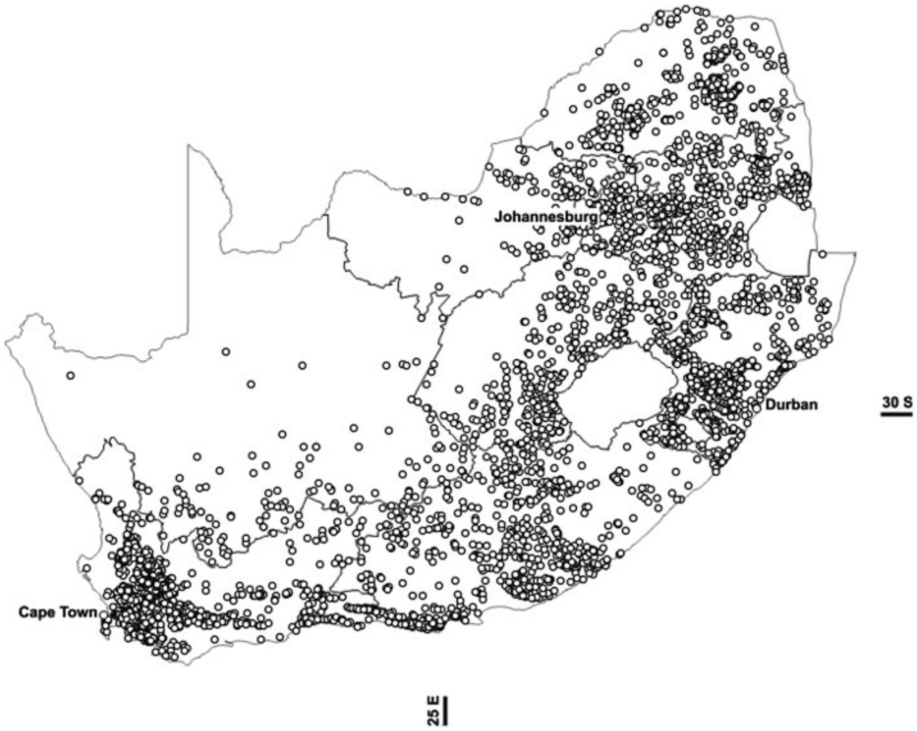

Figure 2. Map of South Africa showing the distribution of registered dams (source: DWS).

water and its development" (NWRS, 2014, Executive Summary). The risks of overexploitation were recognised some 20 years earlier (Alexander, 1985).

South Africa's limited water resources have been impaired by mineralisation (salinisation), eutrophication and acidic mine drainage (UNEP, 2008). An additional and burgeoning source of pollutants is urban runoff, coupled to the increasing movement of rural dwellers into the cities in sub-saharan Africa (e.g. Nyenje *et al.*, 2010). Urban runoff as a pollution source was identified in South Africa in 1986 (Grobler & Toerien, 1986).

The quality of South African water resources is acknowledged as a 'major' concern (NWRS, 2014). While this key document highlights the fact that 60% of South African rivers are threatened (25% critically endangered) and 65% of wetlands threatened (48% critically endangered), it oddly makes no mention of the state of the nation's reservoirs. The DWS, however, stated in its 2007/2008 Annual Report that 42% of the reservoirs subject to water quality monitoring in South Africa were eutrophic (DWAF, 2008). Curiously, this obviously serious condition was not revisited in subsequent annual reports (2009–2013) – seemingly in direct conflict with the concerns about water quality expressed in the NWRS. This aspect is discussed further hereunder. Notwithstanding the expressed concerns, a recent water resource planning model for a South African catchment long plagued by eutrophication only addresses salinity under the heading of water quality (DWAF, 2012).

In the land-locked regions of South Africa, return flows form a considerable component of water captured in reservoirs, with wastewater comprising a principal component of these effluents (Oberholster & Ashton, 2008). A recent assessment of South African wastewater treatment plants found that 80% of 852 plants were malfunctioning, due to a combination of hydraulic and/or biological overloading; underinvestment in capital infrastructure; inadequate maintenance budgets; and a lack of technical skills (Hegley, 2010). This will have undoubtedly resulted in a substantially-increased level of nutrient loading to surface waters. Inadequate wastewater treatment is frequently acknowledged as the cause of poor water quality (e.g. CSIR, 2010; Le Roux *et al.*, 2012). While pharmaceuticals are generally below thresholds of concern in potable water (e.g. WHO, 2012), EDCs have exerted a proven and negative impact on aquatic flora and fauna (e.g. Crane *et al.*, 2006; WHO, 2012a,c).

The South African Department of Environmental Affairs (DEA) has acknowledged, *inter alia,* "Despite the large amount of research that has been carried out on eutrophication in SA's water reservoirs and lakes, the collective understanding of the problem remains limited". Further, that "The impact of eutrophication on water sources ultimately results in the reduction of the quality of life of South Africans" (DEA, 2012).

The South African Institution of Civil Engineers (SAICE), an organisation presumably intimately familiar with the condition of wastewater management infrastructure, in their Infrastructure Report Card for 2011, found "persistent, serious salinization of key river systems and eutrophication in many reservoirs and rivers continues. These problems increase the cost of water treatment infrastructure and damage the environment". It also notes that "focus on water quantity, not quality, makes water services unsustainable" and that there are "Serious problems with management of many wastewater (sewage) treatment works. Wastewater leakage and spillage, especially into major rivers, is still too high" (SAICE, 2011). This clearly indicates that the message from concerned reservoir scientists is getting through, at least part of the way.

EUTROPHICATION AS A GLOBAL PROBLEM

Eutrophication, synonymous with increased biological growth resulting from increased nutrient availability, is a global threat that should no longer require qualification (e.g.

Revenga & Kura 2003; Smith & Schindler 2009; Corcoran *et al.*, 2010; UNEP, 2014). Inadequate attention to issues of water quality can result in unsustainable decisions and policy formulation, the erosion of natural capital and negative socio-economic impacts (e.g. Russi & Ten Brink, 2013). In the USA, nutrient enrichment affects approximately 20% of lakes – with 50% being eutrophic or hypertrophic), but with a clear indication that wastewater pollution control has served to slow the rate of eutrophication (USEPA, 2009). By contrast, eutrophication increasingly affects surface waters globally and directly influences the widespread increase in cyanobacterial blooms (Carvalho *et al.*, 2013; Khan *et al.*, 2014) and the control of algal biomass remains a central focus of many lake management plans (e.g. Jones et al., 2011). Countries such as Australia (e.g. Davis & Kloop 2006) and Brazil (e.g. Martinez *et al.*, 2011) have made significant strides in developing an understanding of the eutrophication problem and communicating this to a wide-range of decision-makers. While general reservoir management guidelines and protocols exist, few have been specifically-developed for individual lakes (Hein, 2006). The causes and consequences of eutrophication in African lakes are no different from those elsewhere (e.g. Thornton, 1987) and neither is the management challenge.

Where wastewater effluents provide the source of nutrients fuelling eutrophication, nutrient enrichment provides a proxy measure of the level of human pharmaceuticals and/or industrial chemicals discharged to the aquatic environment. As such, eutrophication is symptomatic of the degree to which wastewaters are treated before being disposed of, this aside from the well-known risk of noxious cyanobacterial blooms in phosphate-enriched waters (Chorus & Bartram, 1999). There is a plethora of persistent pollutants which are either not removed or which are modified by conventional wastewater treatment, so becoming potentially more noxious either in their own right or in combination with other chemicals (e.g. WHO, 2012a). As observed by the World Health Organization, the concept of eutrophication "is being used in the perspective of preserving the ecological quality of waters", further that "the term describes the qualitative conditions of an aquatic environment that has been disrupted" (WHO, 2012a,b). As in the USA, enhanced wastewater treatment has been proven to bring about a decline in the phosphorus levels of major European Union rivers (WHO, 2012b).

EXTANT LEVELS OF EUTROPHICATION IN SOUTH AFRICAN RESERVOIRS

How does eutrophication currently affect South Africa? This review introduces the findings of two independent analyses of the trophic state of South African reservoirs.

Analysis A

The first of these, undertaken expressly for this review, provides an analysis of the trophic state of all South African reservoirs for which data for total phosphorus (TP) and chlorophyll-a (Chla) were available for the period 2005–2015. The data were provided by the DWS from their National Eutrophication Monitoring Program (NEMP) database. Additionally, while sub-surface grab samples were previously the norm, contemporaneous data now include analyses of integrated 'hosepipe' water column samples spanning a depth of 5 m.

Reservoirs with more than n=20 TP samples during the indicated period were selected. During a second screening, additional reservoirs with n=10–20 samples in the period 2010–2012 were included. In cases where both grab and integrated sample data were available, the integrated data were used. For both grab- and integrated column samples, the datasets were found to be equivalent in terms of range and mean, with the exception of four where the grab sample had substantially higher TP and Chla maxima. This anomaly was deemed to be due to the inclusion of surface scums of phytoplankton, a sampling error offset by the integrated column samples.

All of the reservoirs are sampled at a single site, at a frequency of once or twice per month. It was assumed that the location of the sample site in each impoundment provides a representative indication of the overall conditions prevailing in terms of TP and Chla. Here it must be acknowledged that a single site is highly unlikely to be representative of the spatial and temporal variability in Chla. In most cases, the sampling point is understood to be located near the dam wall, i.e. closest to the point of extraction of raw potable water.

A total of 70 reservoirs were selected, with an aggregate total storage capacity equivalent to 21 000 million cubic metres (MCM) (= 65% of the 32 000 MCM total).

Analysis B

The second analysis draws on the findings of a study that measured the chlorophyll levels in the 50 largest (based on area) waterbodies in South Africa (Matthews, 2014). These data spanned 10 years of Medium Resolution Imaging Spectrometer (MERIS) data collected between 2002 and 2012, i.e. overlapping with the temporal data range of the *in situ* reservoir data (Analysis A above). The MERIS study concluded that 62% of the 50 waterbodies were hypertrophic.

Method

For this review, the aim was to determine the volumetric percentage, as opposed to the use of area as in Matthews (2014) of the bulk water storage (32 000 MCM) that is eutrophic or greater. This was undertaken in two steps: firstly the trophic state of each of the 70 reservoirs in the first dataset was determined on the basis of in-lake median total phosphorus (TP) concentration; secondly, the two datasets were combined and the trophic state determined based on median chlorophyll-a (Chla).

For the purposes of this analysis, the data were compared with the eutrophication categories as described by the Organization for Economic Cooperation and Development (OECD, 1982) (see Table 1). The levels of in-lake TP and Chla, against which trophic status is gauged in South Africa (Van Ginkel *et al.*, 2001), differ from the OECD and are provided in Table 2. Despite a belief that an incidence of noxious algal blooms occurs in South Africa at higher levels vs. the OECD ranges, the OECD values have proven to be entirely valid, indeed for Africa as a whole (Thornton & Harding, 2003). Recent work has, however, indicated that an increased frequency of noxious algal blooms occurs above a threshold value of 55 $\mu g\ l^{-1}$ TP – a level that remains to be exhaustively re-examined (Harding, 2008; Rossouw *et al.*, 2008).

The South African values in Table 2 differ substantially from those set by the OECD, particularly in terms of the TP boundary between eutrophic and hypertrophic (48 vs. 35 $\mu g\ l^{-1}$ TP, respectively) as well as for chlorophyll-a, with the ranges for oligotrophic to eutrophic being between two and four-fold higher than the OECD (see Tables 1 and 2). The derivation of the South African guidelines is unclear, as is the

Table 1. Organization for Economic Cooperation and Development (OECD) boundary values for trophic categories (OECD, 1982).

Trophic category	TP (annual median) (μg l^{-1})	Chla (annual median) (μg l^{-1})	Chla (max) (μg l^{-1})
Ultra-oligotrophic	≤ 4.0	≤ 1.0	≤ 2.5
Oligotrophic	≤ 10.0	≤ 2.5	≤ 8.0
Mesotrophic	10–35	2.5–8	8–25
Eutrophic	35–100	8–25	25–75
Hypertrophic	≥ 100	≥ 25	≥ 75

TP, total phosphorus; Chla, chlorophyll-a

use of 130 μg l^{-1} TP as the hypertrophic boundary, this being attributed to two anonymous reports produced by the then Department of Water Affairs (cited in Van Ginkel *et al*., 2001). Herein it is reported that the "target water quality aimed for to control eutrophication was set to maintain mean chlorophyll concentrations in the receiving water bodies [= reservoirs] at such levels that severe nuisance conditions would not occur for more than 20% of the time". This translated into a phosphorus management objective (PMO) of 130 μg l^{-1}. These criteria have not been reviewed since they were derived some 30 years ago.

The TP-based data were expressed as median, 75, 90 and 95 percentile and maximum values (Table 3) and then assessed per impoundment against the OECD fixed-boundary guidelines (see Table 1) as hypertrophic (H), eutrophic (E) and mesotrophic (M) in terms of median TP and median and maximum Chla values. Additionally, the period during which Chla exceeds specified levels, a criterion included in the South African guidelines (see Table 2), was included.

The capacity of the reservoirs in the set ranged between 0.17 and 5630 MCM, totalling 20 888 MCM (= 65.3% of total storage capacity). Median concentrations of TP ranged between 13 and 1320 μ g l^{-1}, Chla between 1 and 70.8 μg l^{-1} and Chla maxima between 2.7 and 28700 μg l^{-1} (Table 3). The latter high value merits further clarification. Certain South African reservoirs are notorious for chlorophyll maxima, especially Hartbeespoort Dam, from where the concept of 'hyperscums' originated. Table 4 shows the 40 highest Chla maxima for South African reservoirs, together with the dates on which the samples were collected. The set of contributing reservoirs, with Chla maxima ranging from 1600 to 28700 μg l^{-1} is quite small, with Hartbeespoort Dam being the principal contributor.

Measured against the OECD TP criteria (Table 1), 16 reservoirs (equivalent to 3% of the total storage capacity) were hypertrophic, with a further 31 (38% of total volume) being eutrophic, i.e. a total of 49 reservoirs, holding 41% of the total storage, exceeding the OECD eutrophic boundary (see Figure 3). The remaining 22 reservoirs (21% of total storage volume) were all mesotrophic. Based on median Chla, the picture is somewhat different. Here 10 reservoirs (2% of total storage) rank as hypertrophic, with a further 7 being eutrophic (15% of total storage).

Comparatively, using the SA criteria (Table 2) presents a much lower incidence of eutrophy. This yields 8 hypertrophic reservoirs (1.6% of total storage) and a single eutrophic dam (0.2% of total storage). Based on the 320 reservoirs in the dataset, this equates to 3%. All nine reservoirs would be ranked as hypertrophic using the OECD criteria.

The initial analysis was then augmented by matching the reservoirs in the TP dataset that were also considered by Matthews (2014). The resultant dataset is provided in Table 5. Non-reservoir lakes (e.g. Lake Sibaya, Barberspan, Chrissiesmeer) and reservoirs (e.g. Fairview) not owned or managed by the DWS were excluded. This yielded 43 reservoirs, equivalent in combined stored to 24 350 MCM, i.e. 76% of the total storage capacity as defined above, with 2 mesotrophic, 6 eutrophic and 35 hypertrophic (see Figure 4). Where reservoirs from both sets are matched, the chlorophyll-a values reported by Matthews (2014) are considerably higher (between one and two orders of magnitude) than those reflected by the DWS NEMP (see Table 4). As a result, the trophic state is also concomitantly higher. The data in Table 4 indicate that trophic state based on median TP, while generally lower than that determined from the MERIS work, is more accurate than that inferred from median Chla values.

A recent analysis of data from 800 European lakes indicated a marked upswing in cyanobacterial abundance from 20 μg l^{-1} TP to 100 μg l^{-1} TP, with a 40% exceedance of the WHO 'low health alert' threshold at 54 μg l^{-1} TP (Carvalho et al., 2013). King et al. (2009) have shown that the impairment of stream environments occurs from as low a level as 20 μg l^{-1} TP, indicative of the level of eutrophication that will prevail in South African rivers downstream of many large reservoirs. As South African guidelines for stream water quality are, with the exception of oligotrophy (<5 μg l^{-1}) both high and based on ortho-phosphate concentrations (Malan & Day 2005), there is little wonder that 60% of the country's rivers are considered to be seriously impaired (NWRS, 2014).

The two data analyses employed here present a picture of the overall trophic condition of South African reservoirs as being vastly different to that claimed by the Department of

Table 2. South African trophic state classification boundaries (Van Ginkel *et al*., 2001).

Trophic category	TP (annual median) (μg l^{-1})	Chla (annual median) (μg l^{-1})	Chla (max) (μg l^{-1})	% Time Chla >30 (μg l^{-1})
Ultra-oligotrophic	Not specified			
Oligotrophic	< 15	0–10	Not specified	0
Mesotrophic	15–47	11–20		<8
Eutrophic	48–130	21–30		8–50
Hypertrophic	>130	>30		>50

TP, total phosphorus; Chla, chlorophyll-a

Table 3. List of dams used to analyse trophic state based on median in-lake total phosphorus.

#	Name	Register #	WMS #	Capacity	Median TP	75% ileTP	90% ileTP	95% ileTP	Max TP	TP n	Median Chla	75% ile Chla	90% ile Chla	95% ile Chla	Max Chla	Chla *n*	Sample depth	OECD trophic state: Median TP	Median Chla	Max Chla
			MCM		mg/l						g/l									
1	Albasini*	A900/03	A9R001	28.25	0.026	0.043	0.226	0.305	0.305	19	1.3	3.83	6.92	7.7	12.7	53	0-5	M	O	M
2	Albert Falls*	U200/01	U2R003	289.12	0.023	0.036	0.044	0.051	0.051	27	1.3	1.25	1.25	3.23	3.3	32	0	M	O	O
3	Allemanskraal*	C400/02	C4R001	179.3	0.216	0.319	0.414	0.415	0.426	20	5.2	48.2	67.3	67.3	67.3	9	0-5	H	M	E
4	Bloemhof*	C900/07	C9R002	1240	0.079	0.109	0.155	0.177	0.489	60	9.6	23.4	56.5	75.6	110.0	54	0-5	E	E	H
5	Blyde River*	B600/02	B6R003	55.09	0.014	0.018	0.026	0.035	0.035	13	1.3	1.25	1.25	2.56	2.8	26	0-5	M	O	O
6	Boegoeberg	D720/01	D7R001	19.9	0.046	0.067	0.092	0.109	3.34	67	3.8	6.32	12.8	17.7	111.0	44	0	E	M	H
7	Bon Accord	A230/08	A2R002	4.38	0.138	0.252	0.409	0.606	1.33	192	70.8	224	502	651	1790.0	218	0	H	H	H
8	Boskop*	C230/04	C2R001	21.03	0.027	0.042	0.058	0.087	0.775	62	1.1	1.25	5.03	7.39	8.2	23	0	M	O	M
9	Bridle Drift	R200/05	R2R003	101.06	0.188	nd			1.06	10	7.3				19.2	4	0	H	M	M
10	Bronkhorstspruit*	B200/01	B2R001	59.73	0.101	0.129	0.16	0.2	1.93	179	42.4	67.2	95.1	115	302.0	215	0-5	H	H	H
11	Buffelskloof*	B400/01	B4R004	5.33	0.026	0.04	0.046	0.052	0.056	53	1.3	1.25	1.56	4.82	13.3	48	0-5	M	O	M
12	Buffelspoort*	A210/03	A2R005	10.25	0.028	0.036	0.093	0.173	0.173	67	7.9	12.6	23.2	24.7	117.0	79	0-5	M	M	H
13	Clanwilliam	E100/02	E1R002	123.58	0.038	0.051	0.073	0.082	0.2	59	1.3	2.44	4.84	10.4	24.2	66	0	E	O	M
14	Disaneng	D410/02	D4R003	14.82	0.044	0.065	0.088	0.152	1.43	186	1.3	4.36	10	18.8	38.1	57	0	E	O	E
15	Douglas Barrage	C900/05	C9R003	16.24	0.041	0.058	0.093	0.171	0.583	310	4.3	13	23	27	43.0	29	0-5	E	M	E
16	Driekoppies*	X100/22	X1R004	250.92	0.019	0.028	0.04	0.057	0.157	38	1.3	1.25	3.08	5.32	9.4	34	0	M	O	M
17	Flag Boshielo*	B501/11	B5R002	185	0.035	0.048	0.067	0.084	2.12	99	9.0	14.6	21.8	26.2	37.0	111	0-5	E	E	E
18	Gariep*	D350/02	D3R002	5360.23	0.041	0.062	0.088	0.116	0.537	94	1.3	4.68	10.5	15.2	69.2	73	0-5	E	O	E
19	Glen Alpine	A600/04	A6R002	19.95	0.054	0.065	0.086	0.103	0.118	49	1.3	3.39	7.02	8.33	38.2	41	0	E	O	E
20	Grootdraai	C114/02	C1R002	350	0.066	0.101	0.135	0.137	0.702	27	nd						0-5	E	O	O
21	Hartbeespoort*	A210/02	A2R001	186.44	0.306	0.373	0.458	0.6	10.8	182	38.1	79.4	162	195	12200.0	221	0-5	H	H	H
22	Hazelmere	U300/01	U3R001	17.8	0.028	0.045	0.077	0.102	0.157	28	1.3	1.25	1.25	1.25	6.3	28	0-5	M	O	O
24	Henley*	U200/09	U2R005	5.4	0.036	0.045	0.065	0.066	0.117	27	1.3	1.25	4.26	16.3	24.5	32	0-5	E	O	M
23	Inanda	U200/04	U2R004	241.71	0.036	0.057	0.073	0.097	0.189	26	1.3	1.25	5.19	10.3	17.2	27	0-5	E	O	M
25	Jericho	W530/03	W5R001	59.27	0.032	nd			0.166	12	1.3	nd			12.2	11	0	M	O	M
26	Kalkfontein	C510/04	C5R002	258	0.075	0.201	0.314	0.417	0.465	55	8.1	21.4	41	52.6	127.0	57	0	E	E	H
27	Klipfontein	L600/01	W2R001	18.09	0.073	0.136	0.213	0.219	0.333	22	nd						0	E	O	O
28	Klipvoor*	A230/2	A2R012	42.25	0.796	1.09	1.45	2.3	5.08	164	64.5	131	423	604	2590.0	207	0-5	H	H	H
30	Knellpoort	D203/39	D2R006	130.05	0.106	0.152	0.228	0.45	0.47	31	1.3	5.17	8.99	12.4	12.4	11	0	H	O	M
29	Koppies	C700/02	C7R001	42.31	0.096	0.141	0.177	0.214	0.344	85	5.9	14.6	30.3	31.6	82.3	29	0	E	M	H
31	Koster River*	A220/03	A2R011	6.7	0.042	0.051	0.084	0.102	2.76	65	9.6	15.1	20.8	23.4	55.7	72	0-5	E	E	E
32	Krugersdrift	C520/02	C5R004	73.56	0.247	0.326	0.419	0.571	1.43	51	nd	nd	nd	nd	nd	nd	0-5	H	na	
33	Laing	R200/02	R2R001	19.83	0.271	0.381	2.94	2.94	2.94	8	7.7	19	68.3	91.4	251.0	23	0	H	M	H
36	Leeukraal	A232/27	A2R016	0.54	1.320	1.5	2.31	2.35	2.75	25	17.6	32	54	57.4	80.8	41	0	H	E	H
34	Loskop*	B320/01	B3R002	361.51	0.040	0.067	0.109	0.123	0.333	90	1.3	1.25	5.94	11.2	38.2	60	0-5	E	O	E
35	Middelburg	B100/13	B1R002	48.06	0.027	0.035	0.051	0.062	0.156	105	1.3	1.25	2.78	4.28	11.2	76	0	M	O	M
37	Middle Letaba	B800/29	B8R007	171.93	0.067	0.076	0.105	0.127	0.432	23	1.3	1.25	5.56	7.39	25.6	24	0-5	E	O	E
38	Midmar*	U200/03	U2R001	235.42	0.022	0.033	0.046	0.048	0.746	27	4.1	6.21	10.1	14.1	21.5	145	0	M	M	M
39	Misverstand*	G100/06	G1R003	6.44	0.089	0.157	0.192	0.242	0.31	55	3.4	6.32	9.99	12.8	17.2	47	0-5	E	M	M

42	Modimola	D411/28	D4R004	20.72	0.173	0.267	0.649	0.795	3.59	210	10.6	38.6	105	174	213.0	65	0	H	E	H
41	Molatedi*	A300/01	A3R004	200.79	0.036	0.051	0.105	0.117	0.232	55	1.3	1.25	4.91	7.15	15.6	35	0	E	O	M
40	Mutshedzi	A802/15	A8R004	2.34	0.023	0.042	0.065	0.145	0.186	37	3.2	6.27	13.3	15.6	18.9	24	0	M	M	M
43	Mzinto*	U803/10	U8R001	0.5	0.046	0.079	0.129	0.15	1.88	31	1.3	2.72	7.96	15.7	69.8	32	0-5	E	O	E
44	Nagle*	U200/10	U2R002	23.24	0.035	0.041	0.095	0.096	0.098	25	1.3	1.25	2.59	5.82	8.0	32	0	M	O	M
45	Ntshingwayo	V300/04	V3R001	271.3	0.064	0.079	0.12	0.137	0.15	27	1.3	1.25	3.36	3.36	3.4	9	0-5	E	O	O
46	Nungwana*	U700/05	U7R002	2.18	0.028	0.037	0.059	0.072	0.187	65	1.3	1.25	1.25	5.83	17.8	27	0	M	O	M
47	Nwanedzi	A804/04	A8R003	5.25	0.024	nd			0.068	19	6.0	nd			16.9	5	0	M	M	M
49	Ohrigstad*	B600/04	B6R001	13.52	0.027	0.036	0.059	0.125	0.42	56	1.3	2.81	5.86	6.49	6.5	19	0-5	M	O	O
48	Rhenosterkop*	B310/05	B3R005	204.58	0.046	0.056	0.079	0.114	0.202	77	1.3	1.25	4.06	8.06	18.4	50	0-5	E	O	M
50	Rietvlei*	A211/58	A2R004	12.75	0.316	0.418	0.548	0.712	2.45	176	35.0	93.8	184	256	1560.0	216	0-5	H	H	H
51	Roodekopjes*	A210/01	A2R015	102.33	0.111	0.162	0.253	1.02	4.24	75	63.6	130	234	260	824.0	78	0-5	H	H	H
52	Roodeplaat*	A230/01	A2R009	42.46	0.194	0.263	0.319	0.418	0.953	181	34.5	70.9	129	179	740.0	210	0-5	H	H	H
55	Roodepoort	C700/03	C7R002	0.87	0.393	nd			1.95	13	17.3	nd			168.0	13	0	H	E	H
53	Rust de Winter*	B310/01	B3R001	29.13	0.041	0.057	0.082	0.116	0.22	64	1.7	6.6	12.9	15.1	87.4	70	0-5	E	O	H
54	Shongweni	U600/03	U6R001	4.5	0.058	0.067	0.091	0.112	0.159	30	1.3	3.71	13.9	14	25.7	29	0-5	E	O	E
57	Spitskop*	C300/01	C3R002	56.64	0.086	0.127	0.147	0.154	0.192	94	26.0	100	300	310	470.0	29	0	E	H	H
58	Sterkfontein	C801/10	C8R003	2616.9	0.016	0.025	0.041	0.054	0.372	230	1.3	1.25	1.25	3.71	3.7	54	0	M	O	O
56	Taung	C301/23	C3R006	61.37	0.042	0.092	0.2	0.292	0.513	212	3.0	8.6	17.7	45.9	28700.0	96	0	E	M	H
59	Theewaterskloof*	H600/02	H6R001	480.19	0.018	0.026	0.063	0.065	0.099	21	1.3	1.41	2.66	2.66	2.7	6	0-5	M	O	O
60	Tonteldoos*	B400/2	B4R001	0.17	0.029	0.043	0.082	0.132	0.4	93	1.0	1.25	1.25	3.29	11.2	64	0-5	M	O	M
61	Umtata*	T201/03	T2R001	248.48	0.072	0.082	0.122	0.137	0.276	46	1.0	1	2.74	2.76	31.9	26	0	E	O	E
64	Vaal*	C120/01	C1R001	2603.45	0.095	0.127	0.151	0.181	0.55	167	4.4	6.82	18.1	25.9	217.0	126	0-5	E	M	H
63	Vaalharts	C900/02	C9R001	48.92	0.073	0.102	0.158	0.224	0.438	163	2.8	8.02	26.8	31.9	147.0	66	0	E	M	H
62	Vaalkop	A220/01	A2R014	53.62	0.061	0.083	0.125	0.206	0.999	81	44.2	60.6	78.1	92.1	116.0	86	0-5	E	H	H
65	Van der Kloof	D310/01	D3R003	3171.3	0.033	0.048	0.076	0.107	0.734	90	1.3	2.37	3.36	6.54	18.1	78	0-5	M	O	M
66	Vlugkraal*	B400/04	B4R002	0.45	0.023	0.031	0.042	0.056	0.213	86	1.0	1.25	1.25	3.78	17.4	54	0-5	M	O	M
67	Voelvlei*	G100/03	G1R001	158.58	0.063	0.075	0.12	0.136	0.41	58	6.6	13.5	46.1	75.2	85.8	39	0-5	E	M	H
68	Vygeboom	X100/02	X1R003	77.84	0.013	0.023	0.044	0.606	0.638	27	1.3	1.25	7.05	7.12	33.0	29	0	M	O	E
69	Welbedacht	D200/01	D2R004	10.93	0.127	nd			0.282	18	1.0	nd			14.1	12	0	H	O	M
70	Witbank*	B100/04	B1R001	104.02	0.063	0.084	0.109	0.113	0.163	40	4.3	16.5	20.8	25.1	33.7	23	0-5	E	M	E

Key: Dams are indicated by name, Dam Register number and DWS Water Management System number. Capacities are in millions of cublic metres (MCM). Sample depths are either sub-surface grab (0 m) or 5 m integrated column. Trophic states are shown as H (hypertrophic), E (eutrophic), M (mesotrophic) or O (oligotrophic). nd = no data or insufficient data and na = not assessed.

Table 4. List of maximum chlorophyll-a values in the Department of Water and Sanitation (DWS) National Eutrophication Monitoring Program (NEMP).

Sample date	Chla μg per l	Sample depth m	Name
01/08/2010	28700	0	Taung Dam
29/07/2010	15800	0	Schmidtsdrift on Vaal River
23/04/2012	14410	0	Roodeplaat Dam
28/03/2017	12200	0–5	Hartbeespoort Dam
03/05/2016	11122	5	Hartbeespoort Dam
03/05/2016	8124	1	Hartbeespoort Dam
03/05/2016	5805	2	Hartbeespoort Dam
23/01/2018	4840	0	Hartbeespoort Dam
08/05/2012	4358	0	Hartbeespoort Dam
03/05/2016	4238	20	Hartbeespoort Dam
28/03/2017	4123	10	Hartbeespoort Dam
05/06/2011	4107	0	Roodeplaat Dam
29/03/2011	3919	0	Hartbeespoort Dam
28/03/2017	3783	5	Hartbeespoort Dam
03/05/2016	3398	10	Hartbeespoort Dam
09/05/2017	3288	0	Hartbeespoort Dam
03/05/2016	2837	15	Hartbeespoort Dam
26/04/2011	2612	0–5	Hartbeespoort Dam
15/05/2017	2586	0–5	Klipvoor Dam
27/11/2012	2529	0–5	Klipvoor Dam
15/02/2011	2438	0	Hartbeespoort Dam
19/04/2016	2427	0	Hartbeespoort Dam
20/11/2011	2344	0–5	Roodeplaat Dam
05/06/2011	2315	0–5	Roodeplaat Dam
17/05/2016	2216	0	Hartbeespoort Dam
04/12/2012	2165	0	Hartbeespoort Dam
06/05/2009	1981	0	Hartbeespoort Dam
13/02/2011	1981	0	CR Swart Dam
13/02/2011	1967	0	CR Swart Dam
17/07/2012	1839	0	Hartbeespoort Dam
11/05/2010	1825	0	Roodeplaat Dam
14/08/2011	1818	0	Roodeplaat Dam
05/05/2014	1808	0	Bospoort Dam
28/03/2012	1787	0	Hartbeespoort Dam
19/02/2012	1787	0	Bon Accord Dam
16/11/2010	1764	0	Bon Accord Dam
24/04/2011	1654	0	Roodeplaat Dam
06/11/2011	1645	0–5	Roodeplaat Dam
28/03/2017	1601	20	Hartbeespoort Dam
21/08/2017	1599	0–5	CR Swart Dam
13/02/2011	1586	0	CR Swart Dam

Water and Sanitation. Although the use of the MERIS data requires further comparative calibration, it is abundantly apparent that the South African use of median in-lake Chla, coupled with local trophic state boundaries of questionable relevance, substantially underestimates trophic state – a situation further exacerbated by the higher trophic boundaries defined by the South African guidelines for trophy (Table 2). This practice clearly generates a more favourable perception of water quality conditions. This appears to be a departure from the approach used in previous years, where it is apparent that a TP-based analysis led to the result reported in the DWS 2008 Annual Report (42% of reservoirs impaired, see above). By contrast, the DWS declared only 5% to be eutrophic in 2013, although the method of calculation was not specified (Wenger, 2013). This is a gross understatement of the apparent reality.

A HISTORY OF LAKE MANAGEMENT SCIENCE IN SOUTH AFRICA

The pinnacle of South African achievements in reservoir limnology occurred prior to 1990 with the conclusion of the Hartbeespoort Dam programme (SANSP, 1989). The latter programme encompassed a large team of specialists who, together, compiled a new vision of the ecology of hypertrophic warm temperate impoundments. Closely aligned was a comparable body of work dealing with cyanobacteria and their toxins (Harding & Paxton, 2001). This internationally recognised achievement ended suddenly and by 1989 little remained. The nexus of this situation is eloquently summarised as: "South African limnology is in disarray. It is poorly-funded, failing to address certain important environmental problems, lacks a cohesive sense of direction and its potential contributions to effective water resource management are grossly underrated".

The statement above is almost as true now in 2014 as it was in 1989 when it was made by one of the world's most eminent limnologists, the late Dr William (Bill) Williams (FRD, 1989). Williams continued: "Additionally, many of its [South Africa's] practitioners are dispirited and disillusioned, there has been significant attrition from their ranks, and few young South Africans regard limnology as a secure and attractive career. All of this might be comprehensible in a country with plentiful water of good quality; for this to be the case in a country wherein water is a basic resource and is in short supply, faced with demographic problems of the magnitude prevailing, seems incomprehensible". He went on to observe: "South African limnologists are geographically widespread and the limnological ethos spans a spectrum of attitude from mild optimism to darkest depression. However, considered as a body, South African limnologists are concerned about the continued viability of limnology in South Africa, stressed by the variety and pressure of commitments upon their time, lack job satisfaction, feel isolated from the international body of limnologists and are experiencing considerable difficulties from insufficient funding".

While the Williams Report praised many aspects of individual projects, he noted the following failures, these being:

- A clear and unequivocal failure to relate the findings of many research studies to management problems (a failure to transfer technology). Often this takes the form of non-implementation of recommendations provided by researchers;
- There has been a failure on the part of many "user" agencies to fully appreciate the nature, role and importance of limnology in water resource management;
- There has been a failure by many limnologists to understand fully the practical aspects of their work, or not fully appreciate the operations of water resource managers;
- There has been a failure to fully appreciate the fragility of the limnological manpower basis.

The Williams Report was commissioned by the then Foundation for Research Development (FRD), a unit that existed within the Council for Scientific and Industrial Research (CSIR). The report was compiled at the time when the FRD was terminating its Inland Waters Ecosystem (IWE) research programmes that encompassed a set of limnological investigations. The report was the culmination of interviews with 58 scientists – then and since forming South Africa's single

Table 5. Chlorophyll-a and total phosphorus (TP) trophic states of the impoundments (from Matthews, 2014).

#	Name	Capacity MCM	Chlorophyll-a		Chla trophy per OECD		TP trophy per OECD
			This paper	Matthews	This paper	Matthews	This paper
1	Albert Falls	289.12	1.3	8.4	O	E	M
2	Allemanskraal	179.3	5.2	248	M	H	H
3	Bloemhof	1240	9.6	142.8	E	H	E
4	Brandvlei	284.29	na	8.4	na	E	na
5	Bronkhorstspruit	59.73	42.4	105.9	M	H	H
6	Darlington	183.89	na	120.5	na	H	na
7	Erfenis	207.72	na	351.4	na	H	na
8	Flag Boshielo	185	9	42.6	E	H	E
9	Gariep	5360.23	1.3	137.2	O	H	E
10	Goedertrou	301.26	na	20.1	na	E	na
11	Grassridge	46.19	na	176.7	na	H	na
12	Grootdraai	350	nd	163.4	O	H	E
13	Hartbeespoort	186.44	38.1	92.6	H	H	H
14	Heyshope	449.8	na	23.7	na	E	na
15	Inanda	241.71	1.3	27.3	O	H	E
16	Jericho	59.5	na	18.7	na	E	na
17	Kalkfontein	258	8.1	117.3	E	H	E
18	Klipvoor	42.25	64.5	145.7	H	H	H
19	Koppies	42.31	5.9	133	M	H	E
20	Krugersdrift	73.56	nd	317.9	na	H	H
21	Loskop	361.51	1.3	58.1	O	H	E
22	Lubisi	158	na	82.8	na	H	na
23	Midmar	175.06	na	65.6	na	H	na
24	Mokolo	145.37	na	31.4	na	H	na
25	Ncora	150.05	na	380.5	na	H	na
26	Ntshingwayo	271.3	1.3	314.2	O	H	E
27	Pongolapoort	2276	na	3.8	na	M	na
28	Roodekopjes	102.33	63.6	147	H	H	H
29	Rustfontein	72.07	na	115.6	na	H	na
30	Spioenkop	271.3	na	67.5	na	H	na
31	Spitskop	56.64	26	163.4	H	H	E
32	Sterkfontein	2616.9	1.3	3.3	O	M	M
33	Theewaterskloof	480.19	1.3	43.1	O	H	M
34	Tzaneen	156.53	na	39.9	na	H	na
35	Umtata	248.48	1	478.3	O	H	E
36	Vaal	2603.45	4.4	99.6	M	H	E
37	Vaalkop	53.62	44.2	108.5	H	H	E
38	Van der Kloof	3171.3	1.3	55.3	O	H	M
39	Voelvlei	158.58	6.6	114.7	M	H	E
40	Witbank	104.02	4.3	117.5	M	H	E
41	Woodstock	373.25	na	58.1	na	H	na
42	Xonxa	125.9	na	67.5	na	H	na
43	Zaaihoek	184.7	na	14.3	na	E	na

largest collegiate group of limnologists and aquatic scientists active in this field. The period post-1990 saw the dominance of South African aquatic science by river limnologists, with the formation of niche-science groupings with environmental flow and invertebrate-based biomonitoring foci. Latterly there has been a progression from the latter grouping into wetland ecology and assessment.

As noted by Emeritus Professor Robert Hart, in a critique of the draft format of the 2014 NWRS document, "To the best of my knowledge, most raw potable water for the rapidly rising urban population is abstracted from river reservoirs or impoundments – colloquially known as 'Reservoirs'. These man-made lake ecosystems 'interrupt' or 'disturb' the natural downstream flow of rivers (vis à vis the ecological; Serial Discontinuity Hypothesis'). On this basis, it is alarming (an understatement at best) to note that the river systems that have commandeered DWA attention in the past decade or so in determinations of perceived 'national' concern – the Resource Quality Objective assessments of the River Health Programme, National Aquatic Ecosystem Health Monitoring Programme, etc., have explicitly and purposefully disregarded Reservoirs as integral components of such river systems."

Equally alarming is the apparently unsubstantiated statement made by Roux *et al.* (2014), namely, "the contribution of impoundments to the national economy had declined with widespread changes within the agricultural sector, while issues around water quality and rivers gained in scientific importance, particularly with the rise of concepts (sic) such as ecosystem services". This statement is completely at odds with the high rate of population growth in South Africa, the increased rate of urbanisation of the rural population and the

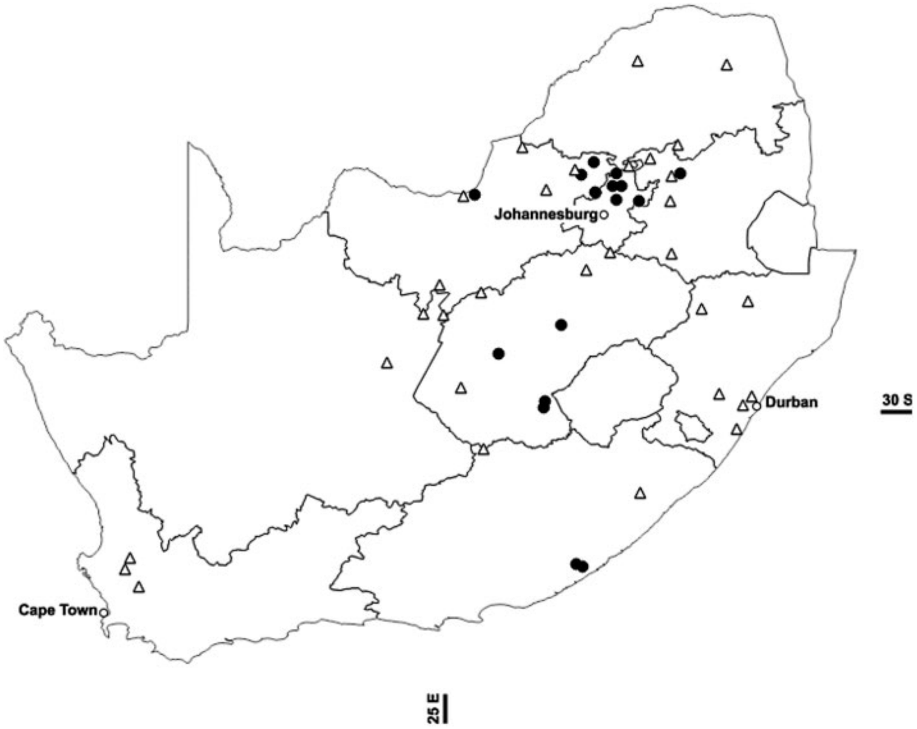

Figure 3. Map showing the total phosphorus (TP) derived hypertrophic (solid circles) and eutrophic dams (open triangles).

construction of new reservoirs, such as the De Hoop Dam – the 13th largest in South Africa, to provide a source of water for platinum mining, or the Ingula Dam pumped hydroelectric storage scheme in Kwa-Zula Natal Province.

Regrettably, the Williams report was kept secret by its initiators, although the findings were widely circulated to a wide group of organisations (DWS, CSIR, WRC) and aquatic scientists. Curiously and inexplicably, given the presumed understanding of the importance of limnology to a country such as South Africa, the FRD considered that "it would be counterproductive to enter into open debate on the issues raised by the evaluation", yet that "the future of limnology activity [is] of concern" (Arndt, 1989). Any response or interaction was left up to the individual researchers or

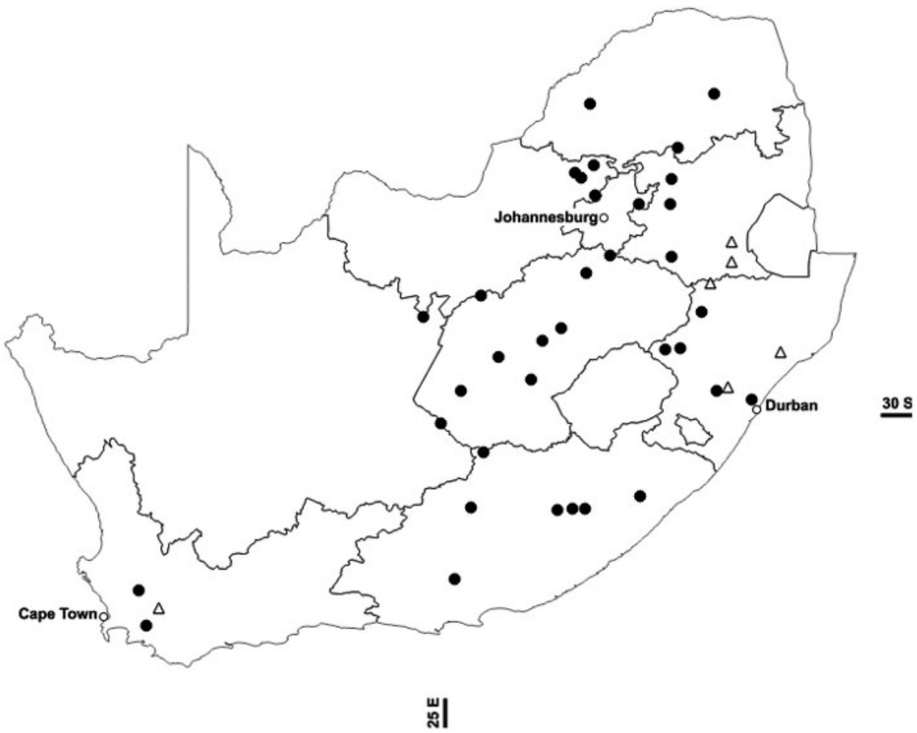

Figure 4. Map showing the Medium Resolution Imaging Spectroradiometer (MERIS) Chla-derived hypertrophic (solid circles) and eutrophic dams (open triangles)

organisations, per invitation contained in Arndt (1989) – yet on reliable authority it has been established that none approached the FRD – or anyone else for that matter – regarding their concerns for the future of South African limnology.

All of this happened at a time when urban civil unrest in South Africa was at its peak and the country's central involvement in the Namibian/Angolan conflict was placing severe strain on the fiscus. Funds became a central issue as scientific funding was slashed and all-important government funding of science was replaced by commercialisation of scientific skills (e.g. WRC, 2012). As stated in WRC 2012, "reservoir and wetland limnology is effectively terminated by an almost total shift to river research – the reasons for this abrupt change were never made clear to the researchers in these programmes", i.e. refering to the aforementioned findings of the Williams Report. This latter statement is, however, somewhat devoid of truth as many of those transitioning to river ecology were aware of Williams' findings – the circulation list of the Williams report bears this out (FRD, 1989, Appendix 1). Equally damning is that while many of these scientists associated themselves with the principles of holistic, integrated, 'source to sea' management, they have yet to speak out on the need for reservoir limnology to become an integral component of South African aquatic science and management. Early findings on the impact of reservoirs on rivers (e.g. Palmer & O'Keeffe, 1990) were not sustained in earnest, although invertebrate-focused echoes of that work have recently emerged in Mantel *et al.* (2010a, b) – work that could have enormous relevance for reservoir lake management if conducted within an integrated research programme rather than isolated as many of these studies are. Of course, it must be said that the advent of affirmative action post-1994 resulted in many state-employed scientists having to move to the private consulting sector. Additionally, several became and remain prominent in guiding the direction of aquatic science research and management in South Africa, by implication favouring certain disciplines over others.

Apart from the heyday of the Hartbeespoort Dam programme, South African lake and reservoir limnology was scant at best, startlingly so for an arid, developing country. Hart (2001) summarized the situation as "The level of limnological knowledge and understanding of South African man-made lakes belies their dominance of the country's landscape and their importance in this generally water-scarce region". Hart (2001) observed further that the general limnology of the greater portion of state reservoirs remained largely undescribed: a situation that pertains to-date. Van Ginkel (2012) remarked that "eutrophication monitoring and using modeling techniques to determine future scenario [and] implementable management techniques has not kept up with the need for real management of algal blooms and eutrophication in South Africa".

The reason for this is clearly evident, namely in an over-concentration of monitoring efforts in the near-total absence of any applied reservoir limnological science or attempts to discern the ecological associations prevailing in South African reservoirs by type, region, hydromorphic character or other criteria. As such, while South Africa benefits from an extensive database of information about its reservoirs, little has been done to convert this into useable management-knowledge. The paucity of effort applied to understand South African man-made lakes is emphasised by the summary provided in Van Ginkel (2012, Table 1). As observed nearly three decades ago "we [South African limnologists] attempt to offer management options without the sequence of cause and effect being properly researched and therefore understood" (Allanson, 1987). This lack of fundamental understanding results in knee-jerk solutions, for example installation of equipment to induce lake mixing, without any prior examination of, for instance, the wind-driven hydrodynamics of the particular waterbody. Such application of reductionism to problems in complex ecosystems is prone to fail (Walker, 1986).

The relatively-limited, yet highly productive, extent of reservoir and other limnological endeavours in South Africa pre-1990 – a generation ago – is variously summarised in CSIR (1980), SANSP (1984) and Walmsley (1992). In terms of tertiary education, South Africa benefited from a single five-year sponsored Chair of Limnology at Rhodes University in Grahamstown, held by Professor R.C. Hart, which terminated in 1987. Tertiary-level education has since been limited to elective modules in various Biological Science institutes and faculties. The latter years of the 1980s represented the apex of achievement (Jacot Guillarmod, 1988), a time when limnology was predicted to position itself as a focus of ecological theory (Reynolds, 1988).

An examination of papers published in volumes 1–14 (1977–1988) of South Africa's own *Journal of the Limnological Society of Southern Africa*, renamed as the *African Journal of Aquatic Sciences*, reveals very few papers dealing expressly with reservoir lakes – the focus rather being directed to fish or *Microcystis aeruginosa* (see Harding & Paxton, 2001). Outstanding amongst the few reservoir papers is a comprehensive assessment on Hartbeespoort Dam – which concluded that conditions were rapidly worsening and that "sound and firm remedial action is necessary" (Scott *et al*., 1977). Roodeplaat Dam, the other 'ugly sister' of enriched South African reservoirs (see Figure 1), was classified as a "highly eutrophic waterbody" by Walmsley et al. (1978). Walmsley & Bruwer (1980) published what appears to be the only dataset on water transparency in South African reservoirs, a study encompassing 92 impoundments. Forster et al. (1987) drew attention to the risks of eutrophication from declining water quality in closed catchments.

Unnecessary time and money were wasted on seeking alternatives to the OECD eutrophication modelling approach, completely unsupported by the level of in-depth understanding of load:response characteristics of individual reservoirs (e.g. Grobler, 1986a,b; Meyer & Rossouw, 1992). This occurred despite concurrent work demonstrating that the OECD applications were relevant under South African conditions (Jones & Lee, 1984a, b). All the while, isolated studies identified the need for long-term management of nutrient pollution (e.g. De Villiers & Malan, 1985). In the absence of a nationally-coordinated system of reservoir lake management, no synthesis of individual efforts was undertaken and warnings went both unnoticed and unheeded.

Thirty-year-old baseline information exists for a few reservoirs – arising from one-off examinations – with this paucity of information encompassing even the major South African reservoirs (Hart, 1999). Contemporary analyses merely seem to mimic earlier assessments and provide no impetus for an advanced understanding (e.g. Van Ginkel & Silberbauer 2007). Singular exceptions are the three-year study conducted at Rietvlei (Harding *et al*., 2012; Harding & Hart, 2013), a body of work that illustrated the fallacy of attempting top-down lake management to shape the bio-coenotic structure (see also Hart, 2006, 2011), and work undertaken in the Olifants River catchment (e.g. Oberholster *et al*., 2010; Dabrowski *et al*., 2014). A brief upswing in research into cyanobacteria and their toxins (summarised in Harding *et al*., 2010) was not paralleled by endeavours in reservoir limnology. In fact, the Water Research Commission found itself in a position where "it could not give money away for eutrophication research" (Dr S.A. Mitchell, former WRC Project Manager, personal communication 2013).

Although Williams was to acknowledge the wealth of South African limnological expertise accumulated in the years before 1989 (foreword to Allanson *et al*., 1990), Allanson himself, one of South Africa's foremost limnologists, conceded that "while river researchers and water supply managers have found a good deal of common ground, …there are other areas where the liaison is not well established, for example within the field of reservoir eutrophication, in which new research is lagging far behind" (Allanson, 2004). Allanson went on to conclude "the [South African] reservoirs and lakes… have been sadly neglected since the 1970s" (Allanson, 2004).

SOUTH AFRICA'S CURRENT EUTROPHICATION MANAGEMENT POLICY

One could reasonably assume that, in an arid country, which is largely dependent on reservoirs for its very existence – especially reservoirs as impaired as indicated above – the responsible government department would have an active directorate of reservoir-lake management. South Africa does not. Water quality, or indeed water *per se*, is also not a key focus area of the national government: these being job creation, healthcare, rural development and the fight against crime and corruption.

Confusingly, while the department responsible for water quality monitoring (DWS-NEMP) collects data in a manner similar to the Australian National Eutrophication Monitoring Programme, the data are not equivalently interrogated or routinely published – for example in the format used by the United States Environmental Protection Agency (e.g. USEPA, 2009). Even more confusing is that the National Aquatic Ecosystem Health Monitoring Programme (NAEHMP, 2008) does not contain the words 'dam, impoundment or reservoir-lake'. It is as if these components of developed rivers simply do not exist. Reports on eutrophication research (e.g. WRC, 2010a) have questionable value within a water resource management structure that appears to ignore the eutrophication concept almost entirely. Per another admission of the Minister of Water and Sanitation, reservoirs have yet to find their way into the NAEHMP as "the monitoring of reservoirs may require more resources, both human and financial, an appropriate monitoring programme for reservoirs will first have to be investigated" (Kalyan, 2010; Davidson, 2011). This acknowledgment indicates a shocking lack of high-level understanding of the relevance of reservoirs in South Africa. Arguably, waiting for reservoir management to fit into an appropriate integrated water resource management programme could be risky. As noted by Giordano and Shah (2014), there may be greater merit in getting on with "pragmatic politics and solutions to the world's many individual water challenges".

Inattention to reservoirs is not recent. In a startling and inexplicable decision, the DWAE concluded during the 1980s that eutrophication was a problem that "does not merit a high priority because of the low return for a high cost of nutrient control. As a consequence, the topic received little management attention during the 1990s, in terms of policy development, monitoring, reporting, capacity building or research" (Walmsley, 2000). This exclusion is in direct conflict with the principle of watershed-based management of lakes and reservoirs (e.g. Thornton & Rast, 2004).

The DWA website contains a document that proposes a management strategy for eutrophication (Walmsley, 2003). This document found that eutrophication was globally perceived as a long-term national priority. However, in South Africa, while newly-developed water policy requires that holistic 'source to sea' management strategies should be developed, these have not been undertaken for eutrophication. Walmsley also found that a crippling lack of understanding of lake management and eutrophication existed across all DWAE regional offices and that training was urgently required. The document continues to gather dust and the same problems persist a decade later. Of course, a reluctance to address pollution was not unique to South Africa at the time (e.g. Straškraba, 1995). During the 1980s, a survey revealed that as little as 2% of research funds applied by the Water Research Commission were directed to eutrophication studies (Walmsley & Davies, 1991).

Wastewater treatment in South Africa does not include a specific focus on the removal of phosphorus, this despite precedents set and being set elsewhere in the world. Stringent management of phosphorus in, particularly, wastewater, remains the primary global objective of choice for reducing the incidence of noxious algal blooms in surface waters. The arguments presented here do not presume that phosphorus management alone will solve all eutrophication, as considerations of nitrogen availability also play an important role (e.g. Paerl, 2014; Paerl *et al*., 2014a, b; Xu *et al*., 2014). Although control of phosphorus is extremely important, it is but one factor in a complex mixture of climatic, watershed and in-lake factors (e.g. Harris, 1994). Here it is also emphasised that nutrient-controls alone may not reverse the impacts of eutrophication and that the thermodynamics of remedying eutrophication, i.e. reducing trophy, is not the reciprocal of the pathways that caused the problem in the first place. The worst cases of eutrophication in South Africa are, however, all fuelled primarily by wastewater effluents, resulting in receiving waters with very low N:P ratios (e.g. Harding, 2008). The overall point to be made here is that, in the absence of a developed set of reservoir management skills, formulating effective solutions for individual reservoirs will remain elusive.

South African reservoirs are somewhat dubiously protected by the 1985 "1 mg l^{-1} phosphate standard" (Grobler & Silberbauer, 1985). This approach employs a concentration based 'standard' that is easy to monitor but which completely ignores the load-based trophic response of lakes to phosphorus. While some gains have been made in the few catchments where this standard has been applied, population growth and increased effluent volumes have generally negated the benefits (e.g. Oberholster & Ashton, 2008). Despite being described as "inappropriately high" (Oberholster & Ashton, 2008) it is, however, not without some merit, given that South African wastewater treatment does not focus on phosphorus removal. In catchments such as the Berg River in the Western Province, implementation thereof would effect an 86% load reduction (Harding, 2015). The Olifants River catchment would apparently also benefit from implementation of the standard as promulgated (Dabrowski, 2014).

By contrast, developments in the USA and elsewhere have clearly shown that it is both easy and cost-effective to remove phosphorus from wastewaters to a very low level, with 0.01 mg l^{-1} P, as total phosphorus, being consistently achieved (e.g. EPA, 2007). A study recently completed in South Africa indicated that approximately 20–26% of the phosphorus content of wastewaters derives from laundry detergents (WRC, 2010b). The major South African supplier of detergents removed phosphorus from all its products mid-2010, resulting in a significant reduction in wastewater effluent phosphorus at 17 out of 20 works assessed a year later (Harding, unpublished data). The prospect of beneficiating wastewater effluents through phosphorus recovery does not seem to have attracted any attention.

A further and contentious management issue is the questionable existence of the Phosphorus Management Objective (PMO) for South African reservoirs, set at 130 μg l^{-1} as TP (Van Ginkel *et al*., 2001). Not only is the origin of this value somewhat vague, it is more than two-fold higher than the level at which South African reservoirs become problematic in terms of the frequency of cyanobacterial blooms (Rossouw *et al*., 2008). Adherence to this value would simply allow oligo- and mesotrophic reservoirs to degrade to hypertrophy – accordingly, it makes no sense whatsoever, yet the Minister of Water Affairs recently referred to it as a tool in the nation's armoury against eutrophication (Sonjica, 2010). In summary, South Africa has no total mean daily load (TMDL) equivalents or other nutrient loading-based protections in place for any of its reservoirs, although the feasibility of employing the TMDL approach in South Africa is being assessed (Harding 2015).

An examination of projects funded by the Water Research Commission (WRC), South Africa's primary funder of aquatic science, reveals that during 2000–2009, a mere ZAR 4.03 million (= USD 0.56 million) was expended on 6 reservoir lake or eutrophication-related projects (WRC, 2009). This expenditure amounts to a fraction of 1% of the total WRC research budget during the period assessed. During the same period, the National Research Foundation (NRF), principally a provider of funds to tertiary organisations, did not commit any funds to this area of aquatic science (Harding, unpublished survey). In 1989, Williams remarked that "financial support for South African limnologists was 'ridiculously small'", in fact less than the budget of a single Australian institute (R.D. Williams, cited anonymously in Walmsley & Davies, 1991).

The funded projects have primarily concentrated on the development of assessment tools and a load-based assessment of key reservoirs (Harding & Paxton, 2001; Harding, 2006, 2008; Hart & Hart, 2006; Rossouw *et al*., 2008; Harding *et al*., 2010). In terms of lake science, a single project examined the efficacy of fishery-based biomanipulation in eutrophic reservoir lakes. This work confirmed that, given the absence of obligate zooplanktivores and the feeding dependence of coarse fish species on invertebrates and macrobenthos, as opposed to zooplankton, options for top-down management were negligible (Harding & Hart, 2013; Harding et al. 2012) Hart, 2006, 2011). Further work also indicates that attempts to regulate bottom-up via fish management similarly lack efficacy as lake management tools for South Africa (Hart & Harding, in press).

It must be noted that as long as the DWS does not acknowledge the need for reservoir limnologists, there will be no generation of career opportunities and nil demand or provision for funding. In this vacuum, well-intentioned, yet inexperienced managers and officials expend scarce funds on unfounded remediation efforts that often ignore the underlying causes. By contrast, a recent review of priority water research needs for South Africa noted that the "governance systems" necessary for eutrophication management need to be established (Siebrits *et al*., 2014).

From the foregoing, it is not surprising that South Africa has precious few limnologists active in the reservoir-lake arena. Prior to the SIL2010 meeting held in Cape Town, a poll conducted of the 16 South African members of SIL revealed that five (of which two are retired), responded that they had an active interest in the limnology of reservoirs. Hardly a resource base for a country dependent on impounded water.

Limnology is not seen as a 'sexy' science, unlike chemistry or microbiology where funding opportunities abound. However, a plethora of learning opportunities are possible, provided that an appropriate lake management environment is created which will underpin jobs, research, applied science and funding. Oddly, recent offers to transfer existing knowledge and skills to a new generation of reservoir limnologists and officials have met with sustained resistance.

THE FUTURE

It is clear that South Africa, with as much as 76% of its impounded water affected by eutrophication, is ill-equipped to understand and manage this burgeoning crisis. There is a near-total lack of the structures, skills and planning needed to address water quality issues that will, in effect, reduce the availability of those water resources stored in reservoir lakes. Residual skills and experience are being completely ignored. In an economic analysis of the water crisis facing South Africa, it was concluded that a 1% decrease in water quality would result in the loss of 200 000 jobs, a drop of 5.7% in per capita disposal income and an increase of 5% in government spending (PlusEconomics, 2010). This is arguably an underestimate as the full ramifications of the cumulative impacts of poor water quality may result in much higher numbers. This notwithstanding, the impact on South African socio-economic development, in addition to the crises in power generation, transport, health and education, is likely to be crippling.

The argument that low returns are attainable from the cost of eutrophication management is as incorrect and short-sighted now as it was back in the 1980s. The causes of eutrophication are as abundantly clear now as they were in the 1970s, with attention thereto now clearly much more urgent. The problem must be aggressively addressed at source, reducing nutrients in effluents and return flows to loading-based assimilable quantities. No longer can funding be directed to 'end of pipe' cosmetic 'quick fixes' and/or the symptoms of eutrophication, such as cyanobacteria and models to predict when cyanobacteria will become a problem – they already are. Remote (satellite) sensing of algal pigments would appear to provide an excellent monitoring option. Load-based assessments are already available for the key reservoirs. These should now be translated into catchment-specific permissible load allocations and enforced. It will require the best part of at least two decades before the benefits of the reversal or attenuation of eutrophication becomes evident. There is no more time to lose!

As so clearly indicated by Hart (1999), particularly needed in the [South African] limnological arena are "investigations extensive enough to incorporate and address intrinsic seasonal variability, the general predictability of which is seriously limited under the inherently variable conditions which constitute the Southern African environment." On the back of such investigations should be borne the development of reservoir management skills, a process that will require both time and the advice and skills of those few remaining limnologists possessing local experience.

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DISCLOSURE STATEMENT

The opinions expressed in this paper are those of the author.

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