Comparison of phytoplankton control measures in reducing cyanobacteria assemblage of reservoirs found in the arid region of Southern Africa

Johannes Sirunda [1,2,*], Paul Oberholster [3], Gideon Wolfaardt [2], Marelize Botes [2], Christoff Truter [4]

[1] Namibia Water Corporation, 176 Iscor Street, Northern Industrial Area, Windhoek, Namibia
[2] Stellenbosch University Water Institute, Faculty of Science, Stellenbosch University, Matieland 7600, South Africa
[3] Centre for Environmental Management, Faculty of Natural and Agricultural Sciences, University of the Free State, Bloemfontein 9300, Republic of South Africa
[4] University of Pretoria, Department of Paraclinical Sciences, Faculty of Veterinary Science, University of Pretoria, Pretoria 0110, South Africa

*Corresponding author at Namibia Water Corporation, 176 Iscor Street, Northern Industrial Area, Windhoek, Namibia
Email address: Johannes.sirunda@gmail.com

Abstract

Ecological restorations of reservoirs are implemented worldwide, however, minimal successes are reported and understood for warmer African lakes like Swakoppoort Dam, Namibia. The objectives of the study were (a), to establish the effectiveness of the two control measures in reducing cyanobacteria growths in comparison to untreated control areas, (b) to compare the results generated before and after control measures with the reference Von Bach Dam. During Phoslock® treatment, the average cyanobacteria cells and total phosphate (TP) were 90 521cells/ml and 0.3mg/l in the treated area and 55 338cells/ml and 0.1mg/l in the control area. During Solar Powered Circulation (SPC) treatment, the average cyanobacteria cells were on average 906 420 cells/ml in the treated areas and 121 891cells/ml in the control area. The TP on average was 0.3mg/l during SPC treatment. While during the combined treatment the average cyanobacteria cells, TP, and total nitrogen (TN) were 18 387 226cells/ml, 0.27mg/l and 2.41mg/l before and 22 836 511cells/ml, 0.42mg/l and 1.50mg/l after treatment. This was higher compared to the reference site. PCA triplot indicates no grouping pattern and the repeated measures mixed model analyses indicate that

treatment had no significant effect on cyanobacteria cells. It was evident that, the two control measures were ineffective in reducing cyanobacterial cells.

Practitioner points

Key findings of the article:

- Two phytoplankton control measures were found ineffective to reduce the cyanobacterial cell numbers.
- High cell numbers of cyanobacteria were recorded at the treatment areas compared to untreated control areas during both treatments.
- The combined effect of the two control measures was ineffective as more cyanobacterial cells were recorded during the treatment.
- During control measure treatment, the Swakoppoort Dam was hypertrophic, which could be due to a malfunctioned WWTP upstream.
- The inefficiency of the control measures could be due to small treatment area, higher nutrients, or treatment period.
- The implications of the results to water/wastewater practice:
- The selection of appropriate mitigation measures considering treatment area for dams with high nutrient situated in warmer arid environments.
- There is a need to understand the trophic relationships, climatic conditions, and the sources of the internal and external nutrients to manage water quality.
- Focus on point and non-point sources of nutrients as the root causes of the degradation of Swakoppoort Dam water.

Keywords: Anabaena, biomanipulation, chlorophyll-a, Microcystis, nutrients, PhoslockR, restoration, Solar Powered Circulation, Swakoppoort Dam, trophic status

1. Introduction

Freshwater ecosystems such as man-made dams are constructed to provide a wide range of ecosystem services to human beings. However, since most of man-made dams are constructed adjacent to populated cities or towns, they can become eutrophic due to poor environmental protection structures upstream (Bozelli, 2019). The eutrophication state, is causing the formation of toxic phytoplankton blooms, which are limiting the ecosystem services from man-made dams. Although ecological restoration remains a great challenge with more failure than success, some measures such as phytoplankton control is an alternative to face the degradation of man-made dams (Beklİoğlu, 1999; Gulati *et al*., 2008; Bozelli, 2019).

Over the last four decades, different phytoplankton control measures have been implemented globally mainly in the developed world, to improve water quality by effective manipulation of nuisance phytoplankton blooms (Jeppesen *et al*., 2017; Bozelli, 2019). However, very little is known and reported about phytoplankton control measures in man-made dams situated in the warmer arid environment of Southern Africa. It is widely known that it is very difficult to control phytoplankton blooms in warmer arid environments as warmer drought conditions in itself create symptoms similar to eutrophication (Jeppesen & Meerhoff, 2011; Jeppesen *et al*.,2017). Bozelli, (2019) states that, unlike in the developed world, restoration is limited in the developing world due to costs and knowledge. Although restoration measures are implemented in the developed world, they are not simple and directly transferable due to differences in climatic conditions despite similar problems (Bozelli, 2019), thus the need for modifications of existing and alternative methods for warmer reservoirs (Jeppesen *et al*., 2017).

The main purpose of phytoplankton control is to ensure the prevention of the proliferation of nuisance bloom forming phytoplankton species (Pęczuła, 2012; Visser *et al*., 2016; Lürling *et al*., 2016; Burford *et al*., 2019; Lürling & Mucci, 2020). According to Pęczuła, (2012) phytoplankton control measures includes the following: (1) physical (aeration, hydrologic manipulations, circulation, reservoir drawdown, ultrasound, etc.) (2) biological (biomanipulation, bacteria, natural predators, etc.) and (3) chemical controls (algaecides, coagulation, nutrient-binding clay, etc.). Pęczuła, (2012) stated that the success of any phytoplankton control measure is dependent on external nutrient control. The latter was verified in a study on Lake Washington, Washington, USA where external nutrient reduction resulted in the reduction of toxic cyanobacterial blooms (Edmondson & Lehman, 1981). However, due to internal nutrient loading, the reduction of external nutrients alone did not lead to long term water quality improvement, as observed in Alderfen Broad in Great Britain (Pęczuła, 2012). External nutrients reduction has proven to be the most sustained effective approach for control of cyanobacterial blooms, even before considering any control methods or products (Lürling *et al*., 2016; Burford *et al*., 2019).

According to Søndergaard *et al*. (2007) the results from the various cyanobacterial control studies were not similar. For examples capping of phosphorus through the application of gypsum in Paldang Reservoir (Korea), Phoslock® in Swan-Canning River and Vasse estuaries (Australia) (Robb *et al*.,2003), aluminum sulphate in Green Lake, Seattle (USA), and iron (III) chloride in Lake Groot Vogelenzang (Netherlands) resulted in only a short term water quality improvements mainly in water transparency and chlorophyll-*a* (Pęczuła, 2012). Phoslock® is a modified clay designed to bind phosphorus in the water as it descends and traps it in the bottom sediment by forming a cap that prevents its release from the sediment into the water column (Robb *et al*., 2003; Burford *et al*., 2019).

To suppress cyanobacterial blooms in the epilimnion Solar Powered Circulation (SPC) technology has been used in some reservoirs (Kirke, 2000; Lürling & Mucci, 2020). Installation in Crystal Lake, Des Moines, Illinois, (2 SPCs), East Gravel Lake, Thornton, Colorado (3 SPCs), and Lake Palmdale, Califonia (6 SPCs), USA, were found to suppress cyanobacteria within the treatment zones, which resulted in the increase in density of green algae and diatoms following SPC initiation (Hudnell *et al*., 2010). These are however shallow reservoirs of <10m, with surface area of >1km^2 (Hudnell *et al*., 2010). SPCs suppress cyanobacteria by creating mixing that inhibits the growth of the inedible cyanobacterial cells and thus improves the water quality (Hudnell *et al.*, 2010). While inhibiting cyanobacteria growth, it creates an environment that allows edible algae to grow and get consumed by zooplankton (Visser *et al*., 2016). The method is based on the principles of bio-manipulation and it only treats symptoms of eutrophication but not the cause of eutrophication (Hudnell *et al*., 2010). The habitat disturbance of the cyanobacterial colonies are within the epilimnion zone of the dam, where the SPCs intake hose is set above the thermocline zone of the water column. One unit of SPC is capable of circulating 40 000 liters of water per minute.

The current study compares the effectiveness of two phytoplankton control measures employed in the Swakoppoort Dam, in Namibia. The objectives of the study were (a), to establish the effectiveness of the two control measures in reducing cyanobacteria growths in comparison to untreated control areas in the Swakoppoort Dam, (b) to compare the results generated before and after phytoplankton control measures with the nearby reference Von Bach Dam.

It should be noted that the Swakoppoort and Von Bach dams are important water sources to central Namibia. They are found in the subtropical desert climate characterised with large differences in day and night-time temperature, low rainfall, low humidity, and high evapotranspiration. The two dams were constructed on an ephemeral river, which only flows during the rainy season. The Swakoppoort and Von Bach dams are warm, monomictic man-made dams that stratify throughout the year, with only overturn or mixing during the winter season (Sirunda & Mazvimavi, 2014). The Swakoppoort Dam is reported with frequent cyanobacteria blooms (Lehmann, 2010; Sirunda & Mazvimavi, 2014; Garus-oas, 2017). Total phosphorus concentration in the Swakoppoort Dam is reported to be higher in magnitude in comparison to that of the Von Bach Dam (Sirunda & Mazvimavi, 2014). The poor water quality of the Swakoppoort Dam is reported to be linked to the changes in land use activities in the catchment area (Cashman *et al*., 2014; Sirunda & Mazvimavi, 2014; Garus-oas, 2017). To the authors' knowledge, this is the first study on phytoplankton control measures on a selected dam in the desert region in Southern Africa.

2. Material and methods

2.1. Study area

2.1.1. Characteristics of the study area

The Von Bach (21° 59'59.27'' S 16° 58'54.76" E) and Swakoppoort dams (22° 12'44.31" S 16° 31'44.97" E) are situated in central Namibia with a desert climate (Figure 1). The latter dams are used to supply water to the city of Windhoek, Okahandja Town, Karibib Town, Otjimbingwe Village, and Navahacb Mine (Slabbert & Grobbelaar, 2007; Scott et al., 2018). The application of the phytoplankton control measures was done in the Swakoppoort Dam, which is designed to hold water for two rainy seasons with no flow into the environment, except during periods of water overflow due excessive rainfall runoff (Figure 1). Although control sites were set out in the Swakoppoort Dam where treatment was applied, the nearby untreated Von Bach Dam was also used as a reference Dam (Figure 1). The Von Bach Dam was selected as a reference site because it is on the same river as the Swakoppoort Dam (Figure 1; Table 1) and experience the same environmental conditions. Furthermore, the phytoplankton assemblage of the Von Bach Dam is dominated by the same cyanobacterial species of *Microcystis* followed by *Anabaena* as in the case of the Swakoppoort Dam. Nevertheless, any environmental conditions e.g. climate that may have changed during the employment of the two phytoplankton control measure period in the Swakoppoort Dam will also have the same effect on the environmental conditions and cyanobacterial assemblage in the Von Bach Dam.

Table 1: The main morphometric features of the Swakoppoort, and Von Bach Dams situated on the Swakop River

Features	Von Bach Dam	Swakoppoort Dam
Capacity (Mm^3)	48.56	63.48
Max. Depth (m)	29	30
Evapo. Losses (mm/a)	2254	2275
Ann. Rainfall (mm/a)	370	350
Surface area (FSC) (km^2)	4.89	7.81
Catchment area size (km^2)	2 920	5 480
Geology of the areas	Schist and granite	Schists and granite
Year completed	1970	1977

FSC: full supply capacity

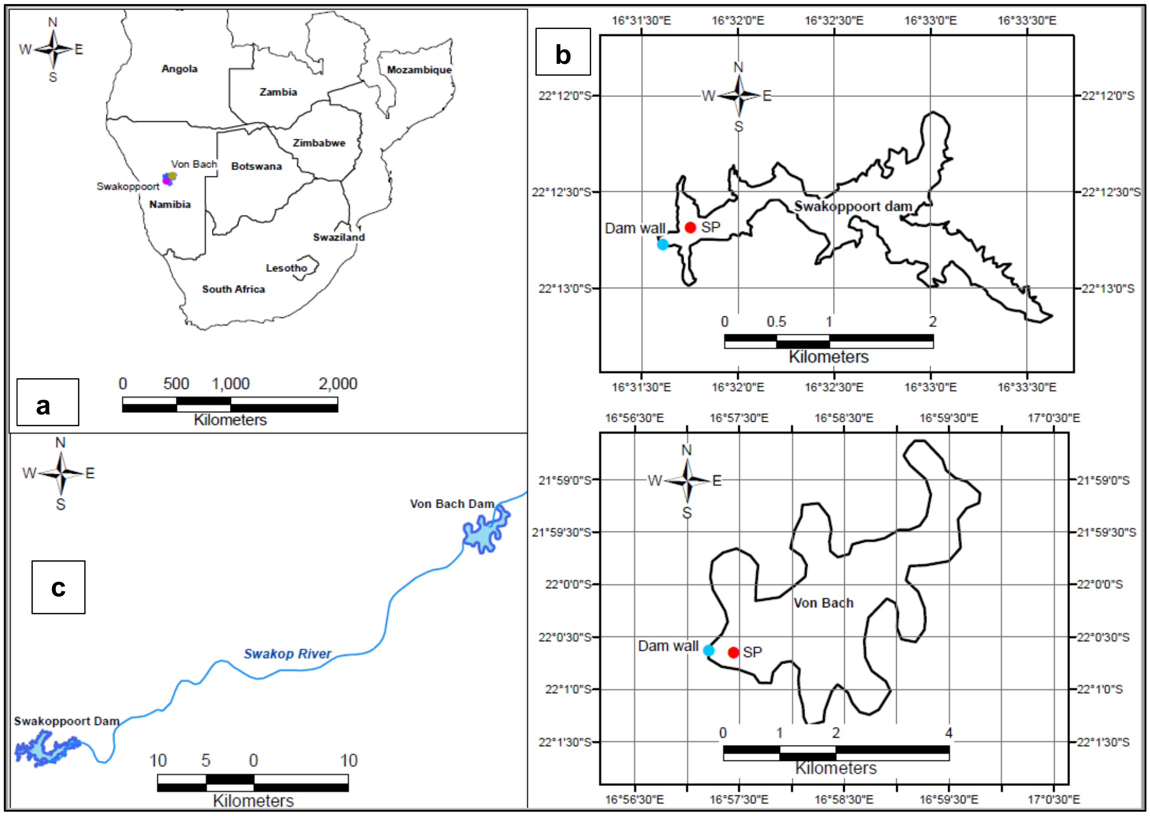

Figure 1*:* Maps created with QGIS v 3.14 pi (Open Source Geospatial Foundation Project) using the Namibia Water Corporation dataset, indicating a) location of Namibia within Africa; b) the study site, treated Swakoppoort and the reference Von Bach dams located in the central of Namibia, with a sampling point, and c) the location of the study areas on the Swakop River.

2.2. Application of phytoplankton control measures in the Swakoppoort Dam

To reduce the cyanobacterial blooms in the Swakoppoort Dam, two types of phytoplankton control measures namely Phoslock® and Solar Powered Circulation (SPCs) were implemented. The first control measure was with Phoslock® which was applied in a 0.245 hectare bay of the Swakoppoort Dam on the 14th of November 2012 and monitored until April 2013 (Figure 2). The bay was boomed off with floating curtains which spanned the length of the entire water column and from the surface to the bottom to ensure that the Phoslock® slurry does not move out of the bay (Figure 2). The floating curtains length for the treated area was 24.5m and with a depth of 2.5m. To compare the effectiveness of the Phoslock® treatment, another bay

(Phoslock® Control Area) of a size of 0.162 hectare was selected as a control site with no treatment and boomed off with floating curtains which spanned the length of the entire water column and from the surface to the bottom to ensure similar conditions as the latter treated area (Figure 2). The floating curtains length for the control area was 27.0m and with a depth of 2.5m The distance between the treated (SP1) and the control (SP2) areas was 1.2km (Figure 4).

Figure 2: Pictures of the application of Phoslock as a phytoplankton control measure in the Swakoppoort Dam from 14 November 2012 to 16 November 2012 for a period of 3 days.

In general Phoslock® dosages are calculated for each water body using the quantity of phosphorus in the water column, and the quantity of releasable phosphorous in the sediment (Finsterle, 2014; Pallí, 2015; Epe *et al*., 2017). However, in an event that the quantity of phosphorus in the water column and sediment is not known, the manufacturer's recommends a Phoslock® dosage of 2 tonnes per hectare (Finsterle, 2014). For the selected treatment area size of 0.245 hectare, around 0.6125 tonnes of Phoslock® was applied. The applied dosage of Phoslock® (0.6125 tonnes) was increased by 25% over the theoretical requirement of (0.4900 tonnes) to compensate for changes in surface area and increases in phosphorus concentration due to water inflow, since the field experiment was done during the rainy season. To prepare a dosage of 2 tonnes per hectare, two 25kg of Phoslock® were mixed in a 400l water tank and the mixed slurry was sprayed onto the water surface using a water pump and a hosepipe (Figures 2). The dissolved phosphorus was on average 8.3mg/kg in the sediment and 0.9mg/kg in the water column of the treated area before application of Phoslock®. The water column pH was on average 8.9, which was within the effective range of Phoslock® pH 4 to 11.

Biochemical and phytoplankton cell number analyses indicated that the Phosclock in comparison to the control site in the Swakoppoort Dam was not effective. Therefore it was decided to install Solar Powered Circulation (SPCs) in April 2013 to cover 0.78 km^2 (10%) surface area of the Swakoppoort Dam. The area was then monitored until June 2015 (Figure 3). The covered area was toward the water abstraction area near the dam wall, where water is abstracted for treatment for human consumption and also for limnological sampling (Figure 5). The SPCs were deployed at densities of approximately 0.16km^2/unit (Figures 5). The SPCs were installed 400m apart, as their sphere of influencing the cyanobacteria growths is within the 200m from the SPC machine as per the manufacturer specifications (Figure 5). The cyanobacterial cells in the treated area were compared with that of the control site (Ctrl) which was established further away from the SPCs in the Swakoppoort Dam (Figure 5).

Figure 3*:* Pictures of Solar Powered Circulation installation as a phytoplankton control measure in the Swakoppoort Dam from 23 to 25 April 2013 for a period of 3 days.

2.3. Selection of sampling points and data collection

Phoslock® treatment

During the Phoslock® treatment, one sampling point was established inside the boomed areas of the treated and untreated control area (Figure 4). At both the treated and control area, seventeen (17) water samples for biochemical and phytoplankton cell collection were taken at a depth of 30cm below the water surface in the photic zone with a total of thirty-four (34) samples from November 2012 to April 2013. Water samples for biochemical and phytoplankton cell numbers were collected on an hourly basis for two days during the application, weekly after application, and monthly for a period of six (6) months at the treated and untreated control sites in the Swakoppoort Dam.

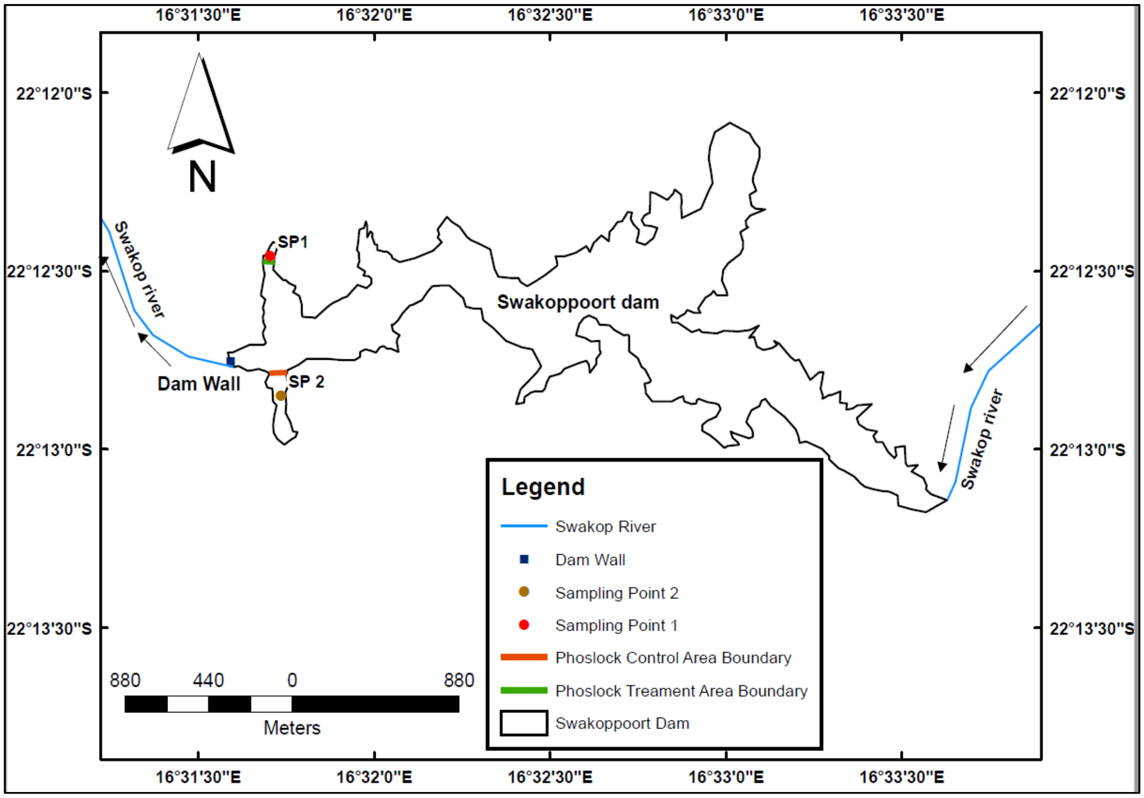

Figure 4: Maps created with QGIS v 3.14 pi (Open Source Geospatial Foundation Project) using the Namibia Water Corporation dataset, indicating Phoslock treatment, with treated area SP1 and control area SP2.

Solar Powered Circulation treatment

During the SPCs treatment as part of the experimental design, firstly, six (6) sampling points were established at the SPC machines, and eight (8) water samples were collected at each SPC at a depth of 30cm with a total of forty-eight (48) samples from May 2013 to July 2013, without the untreated control sampling point (Ctrl) (Figure 5). This was done to establish the exact effect of the SPCs machine on cyanobacteria not further away from the machine. Secondly, after three months, in August 2013, seven (7) sampling points were established at 200m away from the SPCs machine where the water samples were collected at a depth of 30cm (Figure 5). One of the seven sampling points (Ctrl) was an untreated control sampling point located at 800m away from SPC 5 (Figure 5). Around forty-five (45) water samples were collected from these

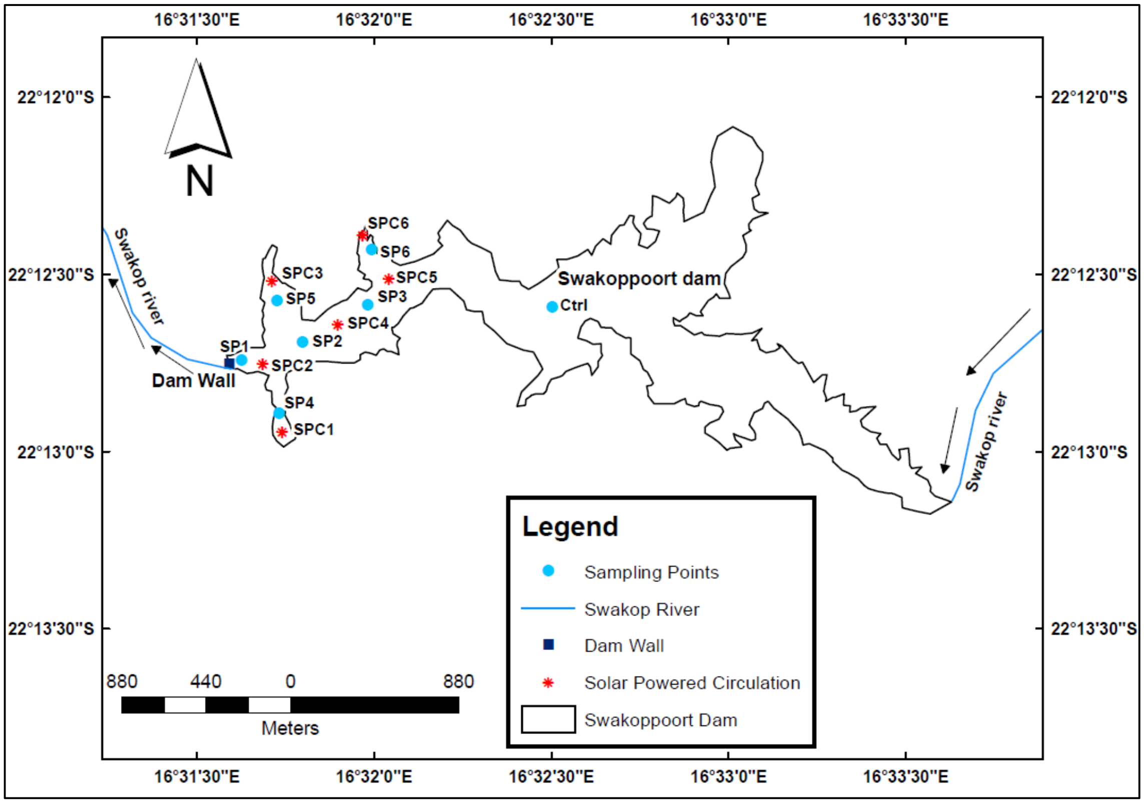

Figure 5: Maps created with QGIS v 3.14 pi (Open Source Geospatial Foundation Project) using the Namibia Water Corporation dataset, indicating Solar Powered Circulation treatment, with the locations of the SPC machine in the dam, sampling points (SP) in the treated area (SP1-6) and control sampling point (Ctrl).

sampling points with a total of 315 samples from August 2013 to June 2015. This was done to establish the effect of the SPCs on cyanobacteria cells at a distance of 200m from the machine. Lastly, as part of the experimental design, ten (10) water samples were also collected at an interval of 50m, 100m, 150m, and 200m from SPC 2 at a depth of 30cm with a total of forty (40) water samples from July 2014 to February 2015 to establish changes in phytoplankton at spatial scale caused by the machine. During the SPC treatment, the intake hose of the installed SPCs were set and adjusted to be above the thermocline at all times as per the manufacturer requirement when targeting the treatment/control of cyanobacteria growths. Water samples for phytoplankton cell numbers were collected twice a month after installation for a period of 24 months, at all the selected sampling points and an untreated control site in the Swakoppoort Dam.

During this period, biochemical water samples (chemistry, turbidity, suspended chl-*a*) were collected at one sampling point nearby the dam wall.

The combined effect of phytoplankton control measures

For the combined effect of the phytoplankton control measures water samples for biochemical and phytoplankton cells were collected on monthly basis. Water samples were collected at the different depths ranging from the surface to the bottom at the sampling point located at the dam wall, in both Swakoppoort Dam and the reference Von Bach Dam (Figure 1). The collected data at the different depths on a monthly basis in both dams from 2003 to 2019 were used to determine the combined effect of the phytoplankton control measures in reducing phytoplankton growths in the Swakoppoort Dam, in comparison to untreated reference Von Bach Dam.

For the current study, the set of data collected from 2003 to 2019 for the two phytoplankton control measures used, and the frequency of sampling method was sufficient as it provided more insight on the effectiveness of the combined control measures employed for phytoplankton growths.

To collect a representative sample at selected sampling points, a dip sampling method was employed. A dip sampling method involves the dipping of the *Von Dorn* 5L water sampler from a boat into the water to retrieve the water sample which was transferred to the appropriate sample container (Burns *et al*., 2000). The collected water samples were transferred into labelled acid wash plastic and glass containers, which were preserved in cooler boxes. The cooler boxes were transported to the laboratory where the algae and suspended chl-*a* were analysed within 24 hours.

2.4. Field and laboratory water samples analyses

In the laboratory, water samples were analysed in replicates for phytoplankton assemblage. To identify phytoplankton, samples were sedimented in a Sedgewich-Rafter counting chamber and analysed under an inverted microscope at 400 × magnification using the strip-count method (APHA 1992). All algae were identified according to Truter, 1987, Wehr *et al*., (2015), Van Vuuren *et al*., (2006) and Taylor *et al*., (2007). The total phosphate and nitrogen of the water samples were also measured in the laboratory. The ortho and total phosphate of the water samples was measured using the Ascorbic Acid method as described in APHA (1998: part 4500 P E). A spectrophotometer with infrared phototubes was used as colorimetric equipment. The total nitrogen of the water samples was measured using the Cadmium Reduction method as described in APHA (1998: part 4500 NO3-E). In the analysis of total nitrogen, the reduction column was used as an apparatus together with the spectrophotometer. The total phosphate and nitrogen of the water samples were reported in mg/l. The turbidity of the water samples was measured using the turbidity meter and the nephelometric method (APHA, 1998: part 2130 B) in the laboratory. Furthermore, the value for turbidity was reported in Nephelometric Turbidity Units (NTU). Suspended chlorophyll-*a* contained in the water samples was measured using the spectrophotometric determination method as described in APHA (1998: part 10200 H). A blank sample without the analyte was used for quality control of the analytical processes for each analysed phytoplankton. Calibration standards were checked to make sure that there were made up correctly. Laboratory generated data were recorded on a spreadsheet. The data were arranged in chronological order and sorted according to sampling points, treatment type, date, and depths.

2.5. Data analysis

The period during which Swakoppoort Dam was treated with Phoslock® was in November 2012, and the possible water quality changes were monitored until April 2013. Treatment with Solar Powered Circulation commenced in May 2013 and water quality improvement was monitored until June 2015. In this study, the effectiveness of each control measure in reducing the cyanobacteria cell numbers in the treated area of the Swakoppoort Dam was compared to the untreated control sites. The combined effect of the phytoplankton control measures was determined using the monthly data collected at the water abstraction tower near the dam wall before and after treatment periods from 2003-2019, while the nearby Von Bach Dam was used as a reference untreated control site where water samples were also collected at the intake at different depths similar to that Swakoppoort Dam.

Descriptive statistics such as mean and standard deviation were estimated for each phytoplankton parameter measured in the two dams during Phoslock®, SPC and combined treatment before and after. Spearman correlation was used to assess the relationship between the dominant phytoplankton in the two dams and scatterplots were generated for the significant positive correlation variables using SPSS 26.0 statistical package software and the level of significance used was $p < 0.05$ for all tests. The limiting nutrients of the two dams were established using the molar mass Redfield ratio of Total Nitrogen: Total Phosphate (TN:TP) of 16:1, which implies that, TN:TP >16 is designated as phosphate limiting and TN:TP <16 is designated as nitrogen limiting (Redfield, 1958; Guildford & Hecky, 2000). The TN:TP ratio was used for classification of the trophic status of the two dams before and after phytoplankton control measures using the nutrients index criteria (Jones et al., 2003; Dodds, 2006; Dodds & Smith, 2016).

A Principal Component Analysis (PCA) triplot was constructed using annual average phytoplankton cell count data representing the 0–5m depth range in combination with water quality parameters for the same period before and after treatment in the Swakoppoort Dam. The phytoplankton data forms the focal plot of the PCA triplot, whereas, water quality parameters were treated as supplementary variables. Phytoplankton data were centred and standardised prior to use in the PCA (Ter Braak and Smilauer 2002). Canoco v5 (Microcomputer Power, USA) was used for Multivariate statistical analyses.

Variation in phytoplankton abundance between periods before and after phytoplankton control measures in the Swakoppoort Dam was assessed using repeated measures mixed models (Variance Estimation and Precision Module, Statistica v13, Tibco Software, USA). The mixed models featured seasonal means of abundance estimates representing 2003 to 2019. “Season” and “Year” were applied as repeated measures and depth range of the intake tower in the Swakoppoort Dam and treatment as fixed effect. In addition, short term variation of phytoplankton abundance in response to SPC treatment was assessed using repeated measures mixed models with “sampling event” specified as repeated measure. Normality of the datasets applied in for mixed models was evaluated using normal probability plots. Data that were not normally distributed were rank transformed before analysis.

3. Results

3.1. Effectiveness of the phytoplankton control measures in reducing cyanobacteria growths in the Swakoppoort Dam

3.1.1. Phoslock® treatment

During Phoslock® treatment the cyanobacteria cells at the treated area at SP1 were higher compare to the cyanobacterial cells recorded at the untreated control area at SP2 (Figure 6). In the treated area at SP1, the average cyanobacteria cell numbers were 90 521cells/ml, and 55 338cells/ml at the control area at SP2 for the duration of the treatment period (Figure 6). At all the sampling points *Microcystis* was the dominating species followed by *Anabaena*, and *Merismopedia* during the treatment period. Suspended chlorophyll-*a* was fluctuating but was reported to be higher at the untreated control area at SP2 with an average of 69.9ug/l compared to the treated area at SP1 with an average of 46.7ug/l (Table 2a &b). The turbidity of the water was higher at the treated area at SP1 (18.2NTU) compared to the untreated control area at SP2 (17.4NTU) during the Phoslock® application dates, thereafter, similar conditions were observed at both treated and the control areas (Table 2a &b). The average total phosphate concentration in the treated area at SP1 was 0.3mg/l in comparison to 0.1mg/l at the untreated control area (SP2) (Table 2a &b). The average Ortho-P at the treated area (SP1) was 0.1mg/l and the untreated control area (SP2) was 0.1mg/l (Table 2a &b). It was evident from the data that the suspended chlorophyll-a and turbidity of the treated area was affected by Phoslock® (Table 2a &b).

Table 2: a, Water quality parameters of the Phoslock® treated area (November 2012-April 2013); **b**, Water quality parameters of the Phoslock® untreated control area (November 2012-April 2013)

a

Treated area	14-Nov-12	14-Nov-12	15-Nov-12	15-Nov-12	16-Nov-12	20-Nov-12	27-Nov-12	04-Dec-12	11-Dec-12	04-Feb-13	05-Mar-13	30-Apr-13	Avg	Std
Turbidity (NTU)	15,9	36,3	12,8	28,7	19,5	22,8	22,7	17,1	14,9	8,44	8,69	10,2	18,2	8,4
Total Nitrogen (mg/l)	1,1	1,3	0,9	1	0,7	0,7	0,6	1,3	1,5	0,9	0,4	0,6	0,9	0,3
Total Phosphate (mg/l)	0,14	0,06	2,21	0,13	0,09	0,25	0,12	0,1	0,25	0,43	0,07	0,07	0,3	0,6
Ortho-Phosphate (mg/l)	0,08	0,04	0,1	0,06	0,07	0,04	0,03	0,07	0,06	0,02	0,03	0,02	0,1	0,0
Chlorophyll *a* (µg/l)	35,5	63,1	28,2	28,2	46,2	26,5	35,4	55,6	46,3	25,6	63,5	106,0	46,7	23,2
Cyanobacteria (cells/ml)	93 337	92 277	35 638	38 042	75 943	116 813	132 016	69 296	76 791	32 244	88 105	235 752	90521	55 215

b

Control area	14-Nov-12	14-Nov-12	15-Nov-12	15-Nov-12	16-Nov-12	20-Nov-12	27-Nov-12	04-Dec-12	11-Dec-12	04-Feb-13	05-Mar-13	30-Apr-13	Avg	Std
Turbidity (NTU)	16,5	16,1	16,4	16,4	17,6	24,6	28	19,1	17,5	11,1	14	11,5	17,4	4,8
Total Nitrogen (mg/l)	1,4	1	1,1	0,9	0,9	0,5	0,5	1,1	0,8	0,7	1,1	0,8	0,9	0,3
Total Phosphate (mg/l)	0,13	0,1	0,26	0,12	0,09	0,15	0,15	0,13	0,15	0,13	0,07	0,08	0,1	0,0
Ortho-Phosphate (mg/l)	0,06	0,04	0,08	0,06	0,05	0,06	0,03	0,08	0,07	0,03	0,02	0,03	0,1	0,0
Chlorophyll *a* (µg/l)	63,5	70,5	41,6	41,6	55,9	37,3	51,7	66,7	62,3	31,9	136,0	180,0	69,9	43,9
Cyanobacteria (cells/ml)	31 820	62 154	23 617	38 537	43 487	91 074	82 589	69 013	53 810	23 971	105 641	38 340	55338	27 037

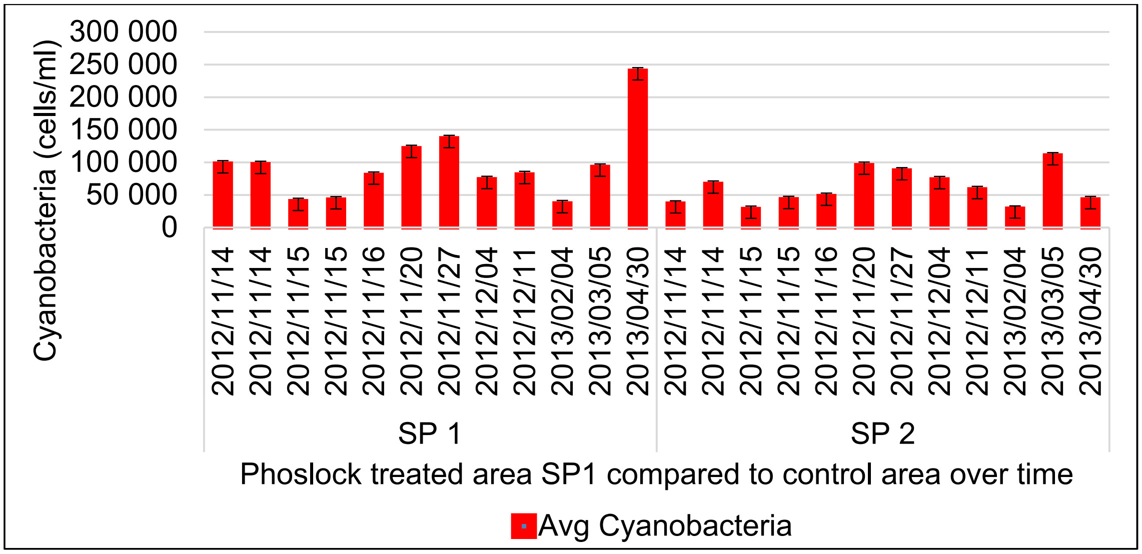

Figure 6: Cyanobacterial cell number during the Phoslock application, a comparison of the treatment area (SP1) and the control area (SP2). Error bars indicate standard error.

3.1.2. Solar Powered Circulation treatment

During the SPC treatment, cyanobacteria abundance at sampling points in the proximity of the treated area (SP1, 2, 3, 4, 5, & 6) did not vary significantly from the untreated control area ($F_{6,300}$ = 1.32, P = 0.25) (Figure 7c). At all the sampling points, *Microcystis* was the dominating species followed by *Anabaena* during the treatment period (Figure 8). Furthermore, 50m interval collections away from SPC2 (i.e. 50m, 100m, 150m and 200m) revealed no significant spatial difference in cyanobacteria abundance due to the effect of the machine ($F_{3,9}$ = 1.04, P = 0.42) (Figure 7b). In addition, cyanobacteria cells collected at SPC machines did not vary among the different SPCs ($F_{5,35}$ = 1.91, P = 0.12) and also revealed no temporal significant change due to the treatment process ($F_{2,33}$ = 1.60, P = 0.22) (Figure 7a). During the SPC treatment period from May 2013 to June 2015, on average the total phosphate was 0.3mg/l, ortho-phosphate was 0.1mg/l, total nitrogen was 1.2mg/l, suspended chlorophyll-*a* was 92.6µg/l.

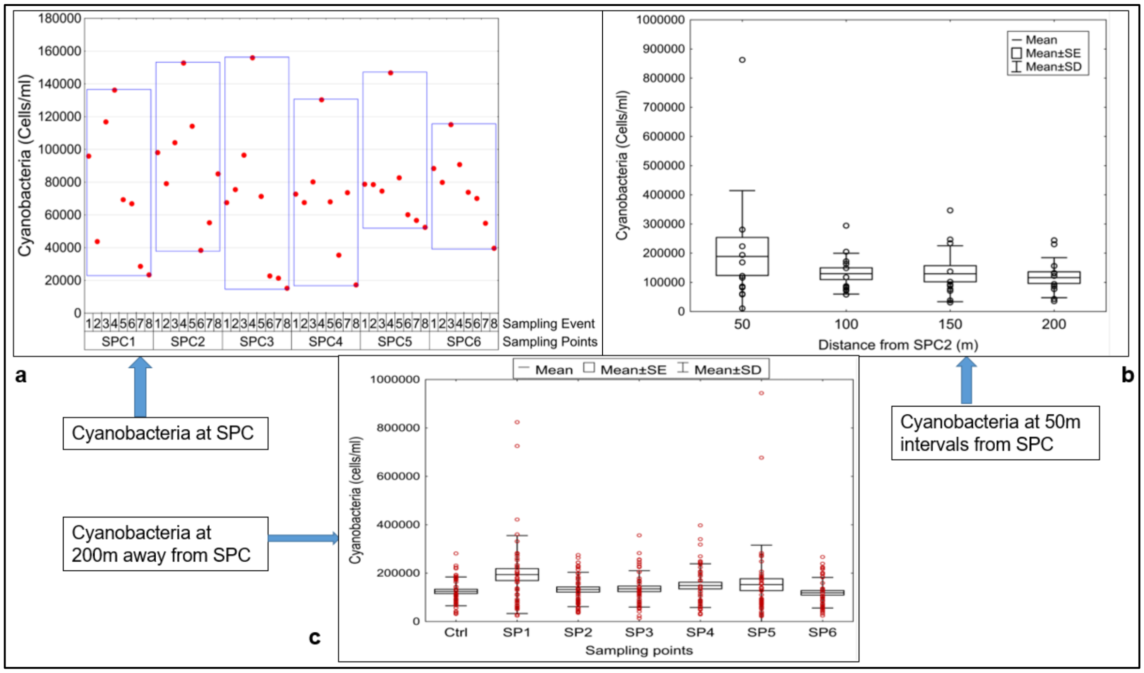

Figure 7: The figure depicts the result of the Solar Powered Circulation (SPC) treatment, indicating a) the average cyanobacteria cells monitored at the SPC machine from May 2013 to July 2013, b) the average cyanobacteria cell number monitored at 50m intervals from the Solar Powered Circulation from July 2014 to February 2015, and c) the average cyanobacteria cells monitored at a 200m away from the Solar Powered Circulation (in the treated area (Sampling Point 1-6) compared to the control area (Control Sampling Point Ctrl) from August 2013 to June 2015. Error bars indicate standard error.

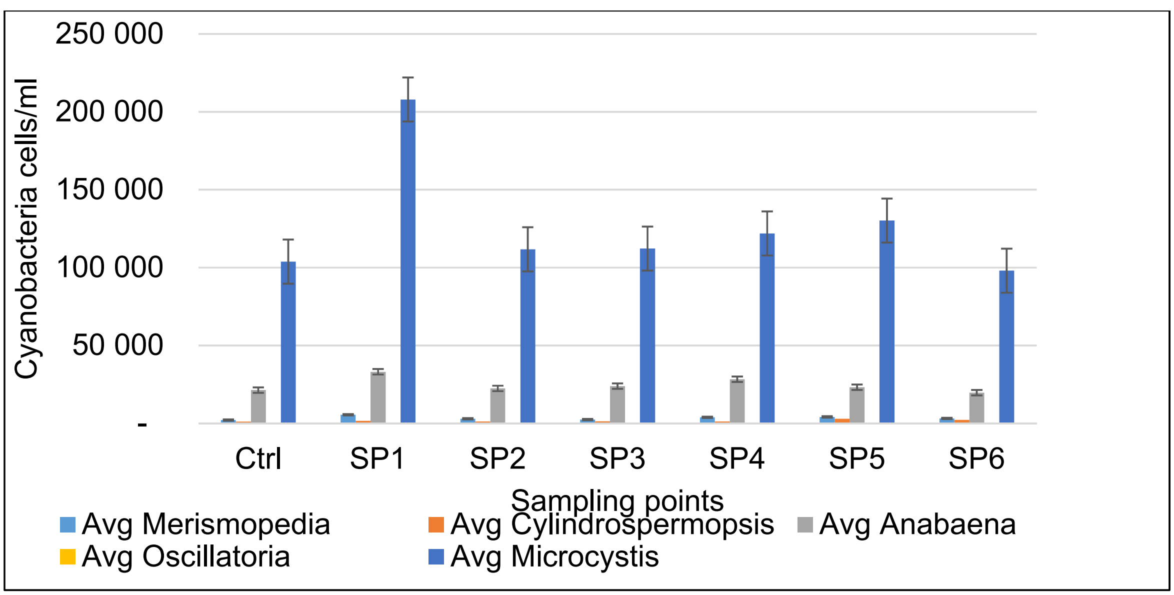

Figure 8: The dominant cyanobacterial species during the Solar Powered Circulation (SPC) treatment at 200 m away from a SPC monitored in the treated area (sampling point 1–6) compared to the control area (control sampling point Ctrl) from August 2013 to June 2015. Error bars indicate standard error.

3.2. The combined effect of the phytoplankton control measures

The combined effect of the control measures in the Swakoppoort Dam resulted in cyanobacteria which dominated the phytoplankton community by 85% of the total cell counts, before and after control measures. While in the untreated reference Von Bach Dam, the cyanobacteria dominated the phytoplankton community by 79% of the total cell counts. The treated Swakoppoort Dam recorded more cyanobacterial cells compared to the untreated Von Bach Dam during the study period (Figure 9c). In the Swakoppoort Dam, on average the cyanobacterial cell numbers before control measures were 18 387 226 cells/ml and after treatment, it increased to 22 836 511 cells/ml (Figure 9a). The average cyanobacterial count in the Von Bach Dam (untreated reference) was reduced from an average of 14 020 cells/ml to 8 026 cells/ml after treatment. Among the cyanobacteria species, *Microcystis* and *Anabaena* dominated in the Swakoppoort Dam over the 17 years before and after control measures (Figure 9b), which was similar to the untreated control area. It was evident that there was a 58% increase in *Microcystis* and a 49% decrease in *Anabaena* after control measures in Swakoppoort Dam.

During the study period from 2003 to 2019, the average TP and TN was 0.27mg/l and 2.41mg/l before phytoplankton control measures and 0.42mg/l and 1.46mg/l after control measures in the Swakoppoort Dam. While in the untreated reference Von Bach Dam, TP and TN were 0.19mg/l and 1.52mg/l during the study period. The average suspended chlorophyll–*a* was 41.8μg/l before control measures and 82.3μg/l after control measures in the Swakoppoort Dam. In the untreated reference Von Bach Dam, on the other hand, the average chlorophyll-*a* was 22.3μg/l during the whole study period respectively. Before treatment, using the mean TN: TP ratio, the Swakoppoort

Dam was eutrophic with a ratio of 20.0, however after treatment, the dam become hypertrophic with a ratio of 12.0. The reference Von Bach Dam on the other hand was mesotrophic with a ratio of 32.0 before control measures and eutrophic with a ratio of 16.0 after control measures.

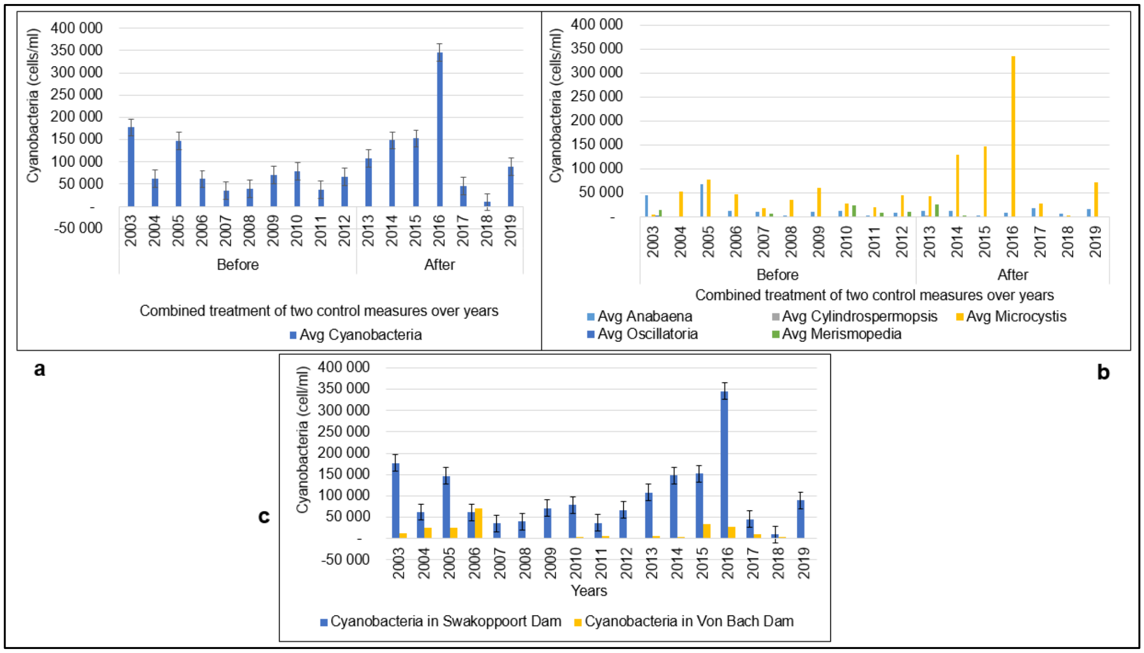

Figure 9: The figure depicts the results of the combined effect of the two phytoplankton control measures applied in the Swakoppoort Dam, before and after treatment, indicating, a) the effect of the two control measures on the cyanobacteria before and after treatment 2003-2019, b) the effect of the control measures on the dominance of the cyanobacteria species 2003 to 2019, and c) comparison of cyanobacterial cells in the treated Swakoppoort Dam to the reference Von Bach Dam. Error bars indicate standard error.

Before control measures in the Swakoppoort Dam a significant positive correlation was observed between cyanobacteria and *Microcystis* (r=*0.57*; R^2=0.411*)*, between cyanobacteria and *Anabaena* (r=*0.47*; R^2=0.496), and cyanobacteria and total phytoplankton (r=*0.97* ; R^2=0.993). After control measures, a significant positive correlation *0.926* (r = *0.926*; R^2=0.936) existed between cyanobacteria and *Microcystis*, (r= *0.989*; R^2=0.999) as was the case between total algae cells and cyanobacteria in Swakoppoort Dam. In the Von Bach Dam, a significant positive correlation of (r= *0.718*; R^2=0.979) was observed between cyanobacteria and

Microcystis, (r= *0.705*; R^2=0.014) and between cyanobacteria and *Anabaena,* as well as (r= *0.878;* R^2=0.997*)* a between cyanobacteria and total phytoplankton.

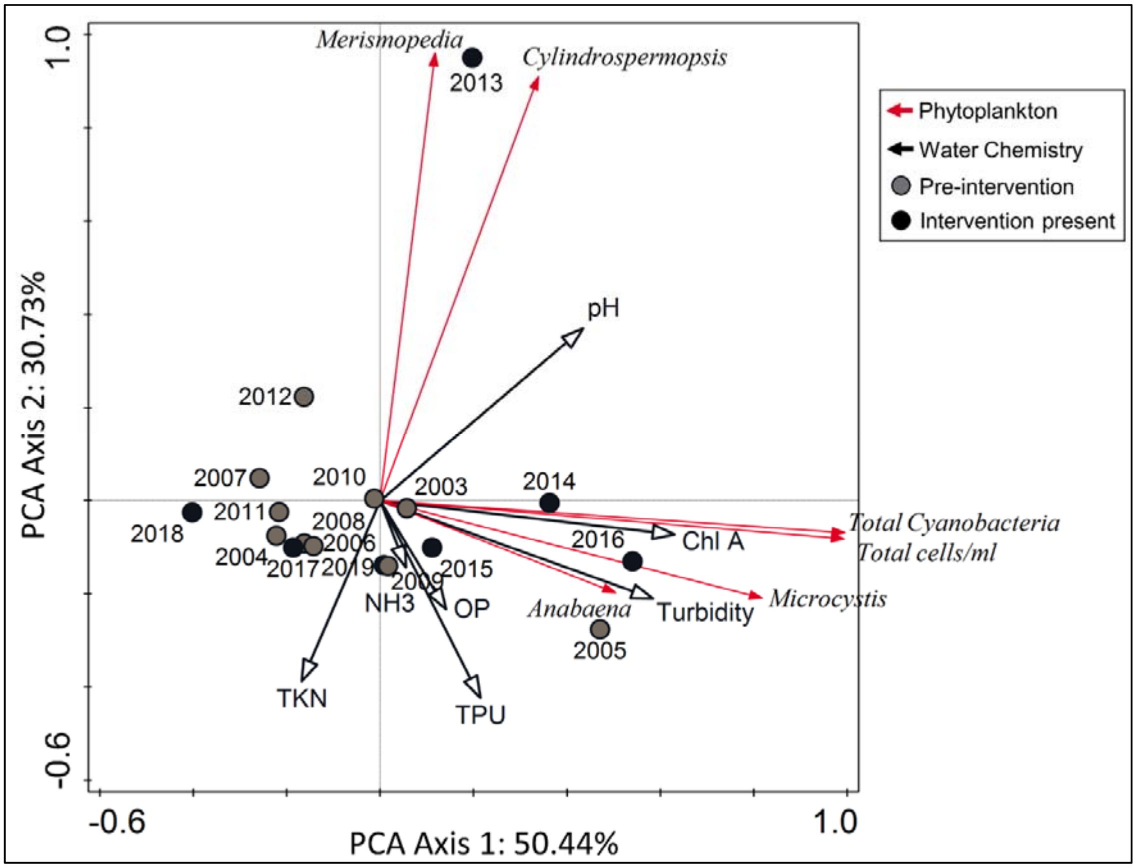

Figure 10: Principal component analysis (PCA) triplot indicating the associations between selected cyanobacteria genera, total phytoplankton cell number, and selected water quality parameters over time in the Swakoppoort Dam. Grey and black circles indicate the periods prior to intervention and during intervention respectively. Chl A: Chlorophyll A; NH3: Ammonia; TKN: Total Nitrogen; OP: Orthophospate; TPU: Total Phosphate - Unfiltered.

A Principal Component Analysis triplot indicates no grouping pattern in ordinal space of the years before and after phytoplankton control in the Swakoppoort Dam (Figure 10). Suspended chlorophyll-*a*, turbidity, pH, and TP were positively correlated with total phytoplankton cells, total cyanobacteria, *Microcystis,* and *Anabaena* (Figure 10). Increased abundance of the cyanobacteria *Cylindrospermosis* and *Merismopedia* occurred in 2013 relative to the other years studied as indicated by the close association in ordinal space (Figure 10).

Cyanobacteria cells was not significantly altered in the Swakoppoort Dam when preventative measures were in place. In particular, treatment had no significant effect on cell counts for the cyanobacterial genera *Anabaena* and *Microcystis*, total cyanobacteria, or total phytoplankton (Table 3). Depth ranges however had a significant effect on the aforementioned cyanobacterial genera, total cyanobacteria, and total phytoplankton (Table 3).

Table 3: Repeated measures mixed model analyses indicating the influence of treatment, depth ranges, and the interaction between treatment and depth ranges on the abundance of (a) *Anabaena*, (b) *Microcystis*, (c) total cyanobacteria, and (d) total phytoplankton

	(a) *Anabaena*				(b) *Microcystis*		
Effect	*Df*	*F*	*P*		*df*	*F*	*P*
Treatment	1.126	0.07	0.79		1,126	3.69	0.06
Depth ranges	2.126	28.29	<0.001*		2,126	11.73	<0.001*
Treatm*Depth ranges	2.126	0.01	0.99		2,126	1.01	0.37
	(c) Total Cyanobacteria				(d) Total Phytoplankton		
Effect	*Df*	*F*	*P*		*df*	*F*	*P*
Treatment	1.126	2.51	0.12		1,126	2.23	0.14
Depth ranges	2.126	13.49	<0.001*		2,126	14.68	<0.001*
Treatm*Depth ranges	2.126	0.57	0.56		2,126	0.57	0.57

4. Discussion

4.1. Effectiveness of the phytoplankton control measures in reducing cyanobacteria growths in the Swakoppoort Dam

The Phoslock® treatment in the Swakoppoort Dam was found not to reduce TP as higher concentrations were recorded at the treatment area compared to the untreated control area. The lack of TP reduction seemed to indicate that the Phoslock active ingredient Lanthanum (La^{3+}) likely bound to compounds other than TP. It could be important to do jar tests in a laboratory setting before field treatment is planned to prevent high costs of such treatments. The higher TP concentration at the treated area could have led to the growth of more cyanobacterial cells in that area as compared to the untreated control area. The average cyanobacteria cell numbers were higher at the treated area (90 521cells/ml), compared to the untreated control area (55 338 cells/ml). Although there was a fluctuation in the concentration, TP and Orth-P on hourly sampling collected during treatment was still higher, and not different from what was recorded in the untreated control area (Table 2a &b).

The shortcoming of the Phoslock® treatment could have been due to the occurrence of higher concentrations of nutrients in the Swakoppoort Dam as a result of the malfunctioned WWTP upstream during this time, which was only fixed in 2014 after the treatment. However, the long-term effects of most restoration measures of this nature are also questionable as some reservoirs tend to return to normal states after trial periods (Søndergaard *et al*., 2007; Jeppesen *et al*., 2017). Materials such as zeolite, calcium compound, and clay are used to form a barrier that inactivates phosphorus (Pęczuła, 2012). For example, the application of bentonite clay (Phoslock®) in river Canning in Australia resulted in the reduction of phosphate concentration for a short-term. The decrease in phosphate due to Phoslock® treatment was also observed in the Swan-Canning River and Vesse in Australia (Robb et al., 2003). Phoslock® leads to short-term improvement in water quality immediately after treatment. This product is more useful in aquatic systems where phosphorus loads originates from the bottom sediment, rather than from external point sources or non-point such as catchment runoff (Burford *et al*., 2019).

The SPC treatment was also found not to reduce cyanobacterial cell numbers at the treatment area compared to the untreated control area. Surprisingly, even samples taken at the location of the SPC and those taken at the 50m distance interval from the machine reveal no temporal and spatial difference in cyanobacterial cell numbers. The poor performance of the SPCs in the Swakoppoort Dam could be related to the nature of the treatment (partial), which covered only 10% of the surface area, and the location of the SPCs toward the dam wall, which receives more cyanobacteria cell sometimes due to wind movement.

Successful mixing requires a high rate of movement in a large part of the lake and that light available to cyanobacteria is limited (Visser *et al*., 2016; Lürling & Mucci, 2020). Burford *et al*., (2019) further mentioned that the effectiveness to prevent buoyant cyanobacteria from accumulating at the surface and to form blooms, is dependent on the severity and rate of mixing. They further mentioned that, mixing of surface water causes accumulation immediately outside the mixing zone (Burford *et al*., 2019). These preconditions could explain the increase in the cyanobacterial cell counts at the sampling points within the treatment area compared to the control area of the Swakoppoort Dam.

The successful treatment of SPCs as observed by Hudnell *et al*., (2010) could be related to trials that were carried out in smaller and shallow reservoirs compared to the Swakoppoort Dam. Installation of SPCs in small shallow reservoirs with a surface area <1km^2 were observed to suppress cyanobacterial growths within the treatment area, which also showed an increase in diatoms (Hudnell *et al*., 2010). The findings from the two control measures revealed that, both treatments were not effective in reducing cyanobacterial cells, which was dominated mainly by *Microcystis* and *Anabaena*.

4.2. The combined effect of the phytoplankton control measures

The combined effect of the two control measures was observed with an increase in cyanobacterial cell numbers from 18 387 226 cells/ml before treatment to 22 836 511 cells/ml after treatment. The opposite was observed in the untreated reference Von Bach Dam that could be due to low TP concentration, as this dam catchment area contains no towns and cities with potential activities to generate nutrients unlike the Swakoppoort Dam although on the same river. There was less TN available and more TP, which may have, promoted *Microcystis* dominance during the treatment period in the Swakoppoort Dam. The Swakoppoort Dam was found to be hypertrophic during the treatment period, while the Von Bach Dam was eutrophic.

Nutrients coupled with other climatic factors such as temperature and sunlight play a critical role in the proliferation of cyanobacteria in many reservoirs. Over the past seventeen years, the concentration of nutrients in Swakoppoort Dam was sufficient in relationship with climate conditions for the nuisance cyanobacterial growth (United States Environmental Protection Agency, 2000) even before and after control measures. The nutrient concentrations in both the studied dams were found to be higher than that of Australian and Brazilian standard guideline for freshwater quality (Sharip & Suratman, 2012).

The high concentration of nutrients in the Swakoppoort Dam was reflected by the high concentration in suspended chlorophyll-*a* before and after control measures as compared to the nearby reference Von Bach Dam. The concentration of the total phosphorus was lower before control measures in comparison to after control measures in the Swakoppoort Dam. While total nitrogen was high before treatment and decreased during the treatment period in the Swakoppoort Dam. The high concentration of total phosphorus compared to total nitrogen could be due to the change in the types of land use activities in the catchment of the Swakoppoort Dam during the study period. Lehmann, (2010) states that wastewater overflow from Gorengab Dam, Ujam ponds, Chicken Farm, Okapuka Tannery, Okahandja Sewage Ponds are reported to be the root cause of cyanobacteria blooms in the Swakoppoort Dam.

The high concentration of TP during treatment compared to before treatment could also be due to the accumulation in the sediment of the dam over time because of the increase in effluent discharge due to changes in land use activities in the Swakoppoort Dam catchment area. During the implementation of the phytoplankton control measures period, the Old Ujams Wastewater Treatment Plant (UWWTP), which treats industrial effluent, was malfunctioning due to overloads as result of the expansion of industries such as tannery, brewery, and abattoir effluent discharges. The UWWTP was replaced with a Membrane Bioreactor Plant in 2014. During the period of malfunction, the effluent was discharged in the Klein Windhoek River, which empties into the Swakop River. Besides, the overflowing of the Goreangab Dam, which holds domestic wastewater, could have also contributed to the increase in TP concentrations in the Swakoppoort Dam. The Goreangab Dam which is used to store domestic wastewater was overflowing during this period when the ammonia concentration was very high (i.e. max 2.3mg/l) and as a result, the water was not abstracted for treatment at the at the Windhoek Goreangab Operating Company (Pty) Ltd (WINGOC) Wingoc

Wastewater Treatment Plant. The overflow was release into the Otjiseva River, which drains into the Swakop River.

A study conducted by Cashman *et al*., (2014) showed that wastewater infrastructure in the city of Windhoek lacks maintenance and monitoring. As a result, numerous blockages are experienced, which cause wastewater to spill into nearby tributaries ending up in the Swakoppoort Dam, located downstream. Industries located in the city of Windhoek face financial challenges to maintain their wastewater treatment facilities (Cashman *et al*., 2014). Despite the above, lack of awareness of the effect of pollution on surface water quality was found to be the root cause of lack of compliance to discharge untreated effluent in tributaries (Kgabi & Joseph, 2012). Kgabi and Joseph, (2012), reported pollution from domestic waste, open defecation, and municipal sewer on the water quality of the Gamammas River situated in the western part of Windhoek. Nutrients emanating from the Windhoek area are resulting in an eruption of cyanobacteria blooms in the Swakoppoort Dam, affecting the quality of water to be subjected to treatment at the Von Bach Treatment Plant. These studies support that, nutrient-rich effluent was emanating from the catchment area of the Swakoppoort Dam during the period of phytoplankton control measures.

Control of external nutrients minimise cyanobacterial growths of shallow and rapidly flushed reservoirs (Pęczuła, 2012; Burford et al., 2019). For example, in Denmark, the quality of shallow reservoirs have improved due to countermeasures such as modernization of sewage treatment plants, usage of phosphate-free detergents, increase in storage capacity of animal manure, 2m cultivation free riparian buffer zone, and increase afforestation (Pęczuła, 2012). With the implementation of the above measures, about 75% reduction in phosphorus has been achieved in Denmark shallow reservoirs. These measures could also be suitable for the Swakoppoort Dam catchment areas, although the reduction of 75% might not be achieved due to the difference in dam structure and climatic conditions (Jeppesen *et al*., 2017;Bozelli, 2019). For deeper dams of this type internal phosphorus in the sediments plays a critical role and this delays the reservoir recovery due to the reduction in external phosphorus by 10-15 years (Klapper, 2003; Pęczuła, 2012).

The period before the implementation of control measures and the period when control measures were in place in the Swakoppoort Dam did not segregate or group in ordinal space on a PCA triplot, providing evidence suggesting control measures did not affect cyanobacterial assemblages and the water quality parameters investigated.

In view of the ineffective control measures tested, it is proposed to improve the water quality of the Swakoppoort Dam, by repairing/renovating the failed WWTP to reduce the external nutrients from the watershed. Subsequently, internal nutrients reduction methods, such as sediment removal by dredging, could be implemented. Although dredging method is associated with environmental costs (Beklİoğlu, 1999; Ã et al., 2008) this was applied in Cockshoot Broad in Great Britain, and the Braband reservoir in Denmark (Pęczuła, 2012). A positive response such as a decline in chlorophyll-*a* and phosphorus were noted (Pęczuła, 2012). However, these are all shallow reservoirs of less than 1m deep compared to Swakoppoort and Von Bach dams, which are 30m deep. Bozelli, (2019), advocates for the focus on urgent restoration, which implies focusing on environmental protection and management of the catchment area, because the traditional restoration measures yield less convincing results and are very costly. This could be a solution to restore Swakoppoort Dam, although this might take longer to implement and yield results, it is more sustainable compare to the other costly and complex traditional restoration measures.

5. Conclusions and recommendations

In conclusion, the two phytoplankton control measures (Phoslock® and Solar Powered Circulation) were found ineffective to reduce the cyanobacterial cell numbers over the study period as high cell counts of cyanobacteria were recorded at the treatment areas compared to untreated control areas. The combined effect of the two control measures was also found ineffective as more cyanobacterial cell numbers were recorded during the treatment period. The concentration of the nutrients was found suitable to support cyanobacteria growths during both individual and combined assessment. During the application of the control measures, the Swakoppoort Dam was hypertrophic, with an increase in TP and OP, which could be related to changes in land-use activities. A Principal Component Analysis triplot indicates no grouping pattern in the ordinal space of the years prior to and during the implementation of phytoplankton control measures. Repeated measures mixed model analyses indicate that treatment had no significant effect on cyanobacteria cell counts. It was evident that, the two phytoplankton control measures were ineffective in reducing cyanobacterial cells during the individual and combined assessment, which could be due to the small treatment area or treatment period and higher TP and OP concentrations during the treatment period from the malfunctioned WWTP upstream. The outcome of the current study could assist water managers in the future on the selection of appropriate restoration measures related to the treatment area and for dams with high nutrient enrichment situated in warmer arid environments.

As a result, the following recommendations are proposed when considering restoration of the Swakoppoort Dam: Firstly, there is a need to understand the trophic relationships, climatic conditions, the concentration of the internal nutrients, and sources of external nutrients of the Swakoppoort Dam. Secondly, water managers need to focus on point and non-point sources of nutrient pollution in the upper catchment of the Swakoppoort Dam since these are the root causes of the degradation of the Swakoppoort Dam water.

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