The deteriorating nutrient status of the Berg River, South Africa

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Abstract

The upper catchment area of the Berg River in the Western Cape, South Africa, supplies most of Cape Town and its suburbs with freshwater, in addition to providing water for irrigation purposes along the middle and lower reaches of the river. This study investigates the nutrient status of the Berg River and long-term trends therein. It is shown that inorganic nitrogen and phosphorus levels increase downstream by a factor of more than 10, in response to anthropogenic inputs. Similarly, nutrient levels fluctuate seasonally by more than an order of magnitude, in response to input from diffuse and point sources of pollution. These changes of more than 1 000% far exceed the 15% maximum change stipulated by the South African water quality guidelines for aquatic ecosystems. Total phosphorus levels indicate that hypertrophic conditions prevail at least episodically at all of the Berg River monitoring stations and most of the time at some of them. Additionally, river water phosphate levels show a dramatic increase over the past 20 years. There is also strong evidence that the trophic status of the Berg River is very sensitive to reduced river runoff. The implication is that the construction of the new Berg River Dam in the upper catchment area of the Berg River will exacerbate the existing situation, threatening ecosystem services, human health and lucrative agricultural activities.

Keywords: Berg River, eutrophication, nutrients, nitrate, phosphate

Introduction

Eutrophication, excessive plant growth in response to nutrient enrichment, is considered to be one of the most serious problems facing freshwater ecosystems, globally (Vitousek et al., 1997; Carpenter et al., 1998; Galloway and Cowling, 2002; Camargo and Alonso, 2006; Mainstone and Parr, 2002). The major nutrients that contribute to eutrophication are phosphorus as phosphate ions (PO$_4^{3-}$) and nitrogen as nitrate (NO$_3^-$), nitrite (NO$_2^-$) and ammonium (NH$_4^+$) ions. Nutrient levels of many freshwater ecosystems have increased dramatically, by a factor of 4 at least, over the last couple of decades in response to widespread agricultural intensification and increased discharge of domestic wastes (Vitousek et al., 1997; Galloway and Cowling, 2002). A particular problem facing developing countries such as South Africa is the significant increase in urban runoff and increasingly so from overloaded or dysfunctional municipal water treatment plants and un-served human settlements (Barnes, 2003; Bere, 2007; Mietwa and Schutte, 2003; Luger and Brown, 2003; Van Vuuren, 2005). All of these are potentially significant sources of nutrients and other pollutants to river and groundwater reservoirs.

The South African water quality guidelines (DWAF, 1996a) stipulate Target Water Quality Range (TWQR) values for 7 different water-use sectors: domestic, recreational, industrial, irrigation, stock watering, aquaculture and aquatic ecosystems. TWQR is defined as ‘the range of concentrations or levels at which the presence of the constituent would have no known adverse or anticipated effect on the fitness of the water assuming long-term continuous use, and for safeguarding the health of aquatic ecosystems.’ Aquatic ecosystems are unique amongst the different types of water users, in that aquatic plant and animal species have very different water quality requirements and tolerances, depending on locality. As a result, there are no stipulated TWQR nutrient values for aquatic ecosystems, but rather a recommendation that ‘a TWQR should be derived only after case- and site-specific studies’ (DWAF, 1996b). Additionally, ‘inorganic nitrogen (and phosphorus) concentrations should not be changed by more than 15% from that of the water body under local unimpacted conditions at any time of the year.’ There is no documented evidence, however, that such ‘case- and site-specific studies’ have been carried out for any of South Africa’s freshwater ecosystems. It is also not clear that the development of such site-specific TWQR values for nutrients is one of the objectives of the relatively new National Eutrophication Monitoring Programme, NEMP (DWAF, 2002). As a result, classification of the trophic status of South Africa’s aquatic ecosystems is presently restricted to the use of 4 broad categories: oligotrophic, mesotrophic, eutrophic and hypertrophic (Table 1), with no allowances made for diverse ecosystem requirements.

This study provides a detailed investigation of the nutrient status of the Berg River, located in the Western Cape Province in South Africa (Fig. 1). The Berg River provides the bulk of the water for household and industrial use in the Cape Town metropole and greater Cape Peninsula area, in addition to irrigation water for extensive cultivation along the length of the river. A combination of recent dry spells, population growth and a fast growing local economy has put severe pressure on water resources within this system. The construction of an additional dam in the Groot Drakenstein Mountains near Franschhoek (Berg River Dam) will provide some relief for Cape Town’s water supply problems, but has also raised serious concerns about the implications for water quality along the lower reaches of the river.
TABLE 1

| Parameter | Oligotrophic | Mesotrophic | Eutrophic | Hypertrophic |
|-----------|--------------|-------------|-----------|-------------|
| Inorganic Nitrogen (µg N/l) – SAWQ guidelines for Aquatic Ecosystems | < 500 | 500 - 2 500 | 2 500 - 10 000 | > 10 000 |
| Inorganic Phosphorus (µg P/l) – SAWQ guidelines for Aquatic Ecosystems | < 5 | 5 - 25 | 25 - 250 | > 250 |
| Mean annual total phosphorus (µg P/l) – NEMP | < 15 | 15 - 47 | 47 - 130 | > 130 |
| Mean annual chlorophyll a (µg/l) – NEMP | < 10 | 10 - 20 | 20 - 30 | > 30 |

Study area and database

The Berg River (300 km long) rises in the Groot Drakenstein Mountains near the town of Franschhoek, drains a catchment area of about 9 000 km², and enters the sea on the west coast at Velddrif (Fig. 1). The geology of the catchment area is dominated by sandstone and quartzites of the Cape Supergroup in the upper reaches, Cape granites in the middle reaches and recent sediments near the coast. The catchment is therefore characterised by nutrient-poor lithologies. Almost 50% of the catchment area is cultivated agricultural land, mainly vineyards, fruit trees and wheat fields. River flow peaks during the winter rainy season, from June to August. Although evaporation exceeds precipitation throughout the catchment, the river water budget is dominated by runoff.

DWAF water quality monitoring data is available at 9 sites along the Berg River: LB1, LB2 and B1 to B7 (Fig. 1, Table 2), from as early as 1967 at one of the stations and from the 1970s at most of the stations. With due consideration of differences in length and completeness of time series data between stations, only data from 1985 onwards were considered in this study. Sampling frequency also varies between sites, from almost weekly to monthly. Where more than one water quality data point was available in a given month, an average monthly value was calculated to provide time-series data at a monthly resolution. This also provides compatibility with DWAF’s total monthly water flow records.

The DWAF database contains data for the dissolved inorganic nitrogen species [NO₂⁻ + NO₃⁻] and [NH₄⁺] (all expressed as µg N/l, with 20 to 40 µg N/l detection limits) and dissolved total phosphorus (TP) and soluble reactive phosphate (SRP) measured as PO₄³⁻, expressed as µg P/l, with reported 3 to 5 µg P/l detection limits. Data for [NH₄⁺] and total dissolved phosphorus (TP) were available at only some of the stations or sections of the record. As a result median, mean and maximum TP and [NH₄⁺] values reported (Table 2) represent shorter data periods.

For data evaluation purposes nutrient levels in the Berg River are compared to both South African trophic status guidelines (Table 1) and more detailed international water quality guidelines. The latter, for the protection of aquatic animals, are 2 000 to 3 600 µg NO₃⁻-N/l for the NO₃⁻-NO₂⁻ forms of inorganic nitrogen (Camargo et al., 2005; CCME, 2003) and between 20 and 100 µg P/l for soluble reactive phosphorus (Mainstone and Parr, 2002). Un-ionised ammonia (NH₃) is the most toxic form of inorganic nitrogen to aquatic animals and water quality criteria ranging from 50 to 350 µg NH₃-N/l for short-term exposures and 10 to 20 µg NH₃-N/l for long-term exposures have been recommended (Camargo and Alonso, 2006; Constable et al.,
TABLE 2
Berg River water quality monitoring station detail, time-series data median, mean and maximum dissolved [NO$_3^-$ + NO$_2^-$], [NH$_4^+$], [TP] and [PO$_4^{3-}$] values. NA denotes stations for which no TP data is available

| Sample – DWAF ID – Location | Lat (°S) | Long (°E) | Data period | [NO$_3^-$] µg N/ℓ | [NH$_4^+$] µg N/ℓ | [TP] µg P/ℓ | [PO$_4^{3-}$] µg P/ℓ |
|-----------------------------|----------|------------|-------------|-----------------|----------------|--------------|------------------|
| LB1 – G1H021 – Mountainview | 33.185   | 19.155     | 1976-2004   | 65 65 450       | 5 22 120      | NA NA NA     | 10 16 304       |
| LB2 – G1H008 – Niewkloof   | 33.311   | 19.075     | 1977-2004   | 130 241 1216    | 23 32 235     | 57 63 210    | 15 19 572       |
| B1 – G1H004 – Bergrieviershoek | 33.927   | 19.061     | 1985-2004   | 110 137 1410    | 68 80 405     | 62 70 182    | 19 25 244       |
| B2 – G1H020 – Dal Josafat  | 33.708   | 18.911     | 1967-2004   | 564 598 2070    | 47 54 945     | NA NA NA     | 18 24 110       |
| B3 – G1H36 – Hermon        | 33.435   | 18.957     | 1982-2004   | 791 829 4334    | 47 58 307     | 255 271 740  | 72 91 785       |
| B4 – G1H013 – Drieheuvels  | 33.133   | 18.862     | 1970-2004   | 328 472 1937    | 31 40 157     | 96 106 276   | 23 31 415       |
| B5 – G1H31 – Misverstand  | 32.997   | 18.779     | 1974-2005   | 378 490 2434    | 40 50 570     | 98 111 487   | 24 29 487       |
| B6 – G1H023 – Jantjiesfontein | 32.925  | 18.329     | 1972-2004   | 150 440 6346    | 45 45 357     | NA NA NA     | 20 30 495       |
| B7 – G1H024 – Kliphoek     | 32.817   | 18.194     | 1983-2004   | 135 341 2172    | 76 92 717     | NA NA NA     | 29 38 323       |

2003; Environment Canada, 2001; USPA, 1986). NH$_4^+$ concentrations are not directly measured in the Berg River, but measured levels of NH$_4^+$ combined with pH values of 6 to 8 predict very low to negligible levels of NH$_4^+$. Recommended dissolved inorganic nitrogen and phosphorus levels for the prevention of eutrophication are lower than those for aquatic animals. Levels higher than 30 µg TP/ℓ are generally considered conducive to eutrophication, provided that inorganic nitrogen or other nutrients are not limiting (Camargo and Alonso, 2006; Swedish EPA, 2000). Plants require nitrogen and phosphorus in a ratio of between 7 and 8 (weight/weight) and concomitant dissolved values of > 400 µg total N/ℓ and > 30 µg total P/ℓ are generally considered favourable for eutrophication in freshwater systems.

Annual nutrient fluxes at each of the monitoring stations were calculated for 2 time periods (1985-1994 and 1995-2004) as follows: for each 10-year period, monthly averaged river flow, [NO$_3^-$] and [PO$_4^{3-}$] values were calculated, an average monthly nutrient flux was then calculated from the product of the average flow and [NO$_3^-$] or [PO$_4^{3-}$] values for that month. The annual nutrient flux for each 10-year period was then calculated from the sum of the monthly average flux values.

Results

Downstream trends in river water nutrient levels

Long-term monthly median, mean and maximum Berg River nutrient values are listed in Table 2 and time-series data for monthly values are illustrated in Figs. 2 and 3. The long-term median values indicate an almost 10-fold downstream increase in [NO$_3^-$ + NO$_2^-$] and [TP] levels, with these parameters as well as [PO$_4^{3-}$] peaking along the middle section of the river at B3, where values are 791, 255 and 72 µg/ℓ respectively. The long-term mean values for [NO$_3^-$ + NO$_2^-$], [TP] and [PO$_4^{3-}$] levels at B3 are 829, 271 and 91 µg/ℓ respectively (Table 2). Towards the coast nutrient levels decrease again, to values approximating those observed in the upper reaches of the catchment, possibly indicating the consumption of nutrients by algal and macrophyte productivity within the river system. Ammonium levels are relatively constant downstream and represent a minor fraction of the total inorganic nitrogen pool, indicative of a well-aerated system (Table 2).

According to the NEMP trophic status classification scheme (DWAF, 2002), based on long-term mean [TP] levels, all of the stations for which TP monitoring data are available are eutrophic with the exception of B3, which is hypertrophic. Along almost the entire length of the Berg River, from B2 to B6 (Dal Josafat in Paarl to Hermon; Fig. 1) long-term mean [NO$_3^-$ + NO$_2^-$] values exceed the 400 µg/ℓ recommended international guideline for aquatic plant life. Additionally, at all the stations where TP data are available, the long-term mean value exceeds the 30 µg TP/ℓ recommended international guideline for aquatic plant life, by a factor of 2 to almost 10 (Table 2). It is instructive to note that nutrient levels at the Misverstand Dam (B5), earmarked as the NEMP monitoring site on the Berg River, are more than a factor of 2 to almost 10 (Table 2). It is instructive to note that nutrient levels at the Misverstand Dam (B5), earmarked as the NEMP monitoring site on the Berg River, are more than a factor of 2 to almost 10 (Table 2). It is instructive to note that nutrient levels at the Misverstand Dam (B5), earmarked as the NEMP monitoring site on the Berg River, are more than a factor of 2 to almost 10 (Table 2). It is instructive to note that nutrient levels at the Misverstand Dam (B5), earmarked as the NEMP monitoring site on the Berg River, are more than a factor of 2 to almost 10 (Table 2). It is instructive to note that nutrient levels at the Misverstand Dam (B5), earmarked as the NEMP monitoring site on the Berg River, are more than a factor of 2 to almost 10 (Table 2). It is instructive to note that nutrient levels at the Misverstand Dam (B5), earmarked as the NEMP monitoring site on the Berg River, are more than a factor of 2 to almost 10 (Table 2). It is instructive to note that nutrient levels at the Misverstand Dam (B5), earmarked as the NEMP monitoring site on the Berg River, are more than a factor of 2 to almost 10 (Table 2). It is instructive to note that nutrient levels at the Misverstand Dam (B5), earmarked as the NEMP monitoring site on the Berg River, are more than a factor of 2 to almost 10 (Table 2). It is instructive to note that nutrient levels at the Misverstand Dam (B5), earmarked as the NEMP monitoring site on the Berg River, are more than a factor of 2 to almost 10 (Table 2). It is instructive to note that nutrient levels at the Misverstand Dam (B5), earmarked as the NEMP monitoring site on the Berg River, are
Seasonal fluctuations and long-term trends in river water nutrient levels and fluxes

Evaluation of long-term nutrient levels (Figs. 2 and 3) demonstrates well-defined seasonal changes in \([\text{NO}_3^- + \text{NO}_2^-]\) and that the amplitude of this seasonal cycle has remained fairly constant since the 1980s at all stations except B3, where it has increased by a factor of ~ 2, and B4, where it has increased by ~ 50% (Fig. 2c). Even at the stations where the seasonal amplitude of change in \([\text{NO}_3^- + \text{NO}_2^-]\) levels has remained fairly constant, however, the magnitude of seasonal variability is at least an order of magnitude (Fig. 2). This translates into a seasonal change resulting from anthropogenic factors of at least 1 000%, compared to the less than 15% change stipulated by the South African water quality guidelines for aquatic ecosystems (DWAF, 1996b). The long-term \([\text{PO}_4^{3-}]\) records demonstrate less well-defined seasonal cycles compared to \([\text{NO}_3^-]\), but a dramatic increase in levels and the magnitude of intra-annual variability over time (Fig. 3). During the 1985-1994 period \([\text{PO}_4^{3-}]\) levels were relatively constant throughout the year at all stations in the catchment area. During the past 10 years, however, concentration levels have almost doubled throughout the year at all stations and a more pronounced seasonal cycle has emerged.

Representative seasonal runoff and nutrient concentration profiles were constructed for the periods 1985-1994 and 1995-2004, to yield insight into changing nutrient dynamics and the relative roles of diffuse and point sources of nutrients. Typical Berg River seasonal profiles are illustrated for B3 (Fig. 4) and the total annual fluxes derived from the combined run-
off and concentration profiles tabulated for all the stations (Table 3). Runoff (Fig. 4a) peaks during the winter, consistent with the winter rainfall location of the Berg River catchment area. An important observation is that the 1995-2005 period was drier than 1985-1994, with average runoff for the month of June reduced by as much as 60% at Station B3 (Table 4).

Seasonal [NO\textsubscript{3}] profiles peak during high runoff conditions, consistent with a diffuse source such as agricultural runoff (Fig. 4b). The 1995-2004 [NO\textsubscript{3}] profile also indicates increased levels compared to 1985-1994, throughout the year (Table 4). Increased values during drier conditions are indicative of a concentration effect, i.e. reduced dilution of anthropogenic inputs. The most pronounced impact of this concentration effect during reduced runoff conditions is an increase of almost 400% in NO\textsubscript{3} levels at monitoring station B3 (Table 4).

Seasonal [PO\textsubscript{4}] profiles demonstrate a dramatic change in seasonality over time (Fig. 4c), in addition to 67 to 373% increases in average monthly concentrations over time (Table 4). An absence of seasonality in [PO\textsubscript{4}] during the 1985-1994 period has been replaced by a seasonal profile that exhibits a peak in [PO\textsubscript{4}] values coinciding with the onset of increased river flow during late spring/early winter (Fig. 4c).

Evaluation of the average annual NO\textsubscript{3} flux during 1995-2004 compared to the 1985-1994 period reveals a flux reduction of only 13%, compared to an almost 40% reduction in runoff (Table 3). PO\textsubscript{4}\textsuperscript{3-} fluxes, in contrast to NO\textsubscript{3}, have increased during the 1995-2004 period by as much as 50%, despite the reduced runoff (Fig. 4c). NO\textsubscript{3} fluxes/catchment area values peak in the middle section of the Berg River at station B2, coincident with peak concentration levels (Table 3). PO\textsubscript{4}\textsuperscript{3-} fluxes/catchment area values however, peak in the upper Berg River catchment at station B1 (Table 3).

A reduction in the annual NO\textsubscript{3} flux between B4 and B5 and in the annual PO\textsubscript{4}\textsuperscript{3-} flux between B3 and B5 suggests in situ consumption of nutrients, most probably assimilation by plants and algae and adsorption by sediments (Table 3). There is a reduction in runoff at B5 compared to B4, however, attributable to water extraction just upstream of the B3 monitoring station, that contribute to the nutrient flux reductions observed between B4 and B5 (Table 3).

Discussion

The two most likely anthropogenic sources of nutrients along the Berg River are agricultural runoff and effluent from overloaded municipal sewage works and un-sewered communities. Both sources are expected to peak in magnitude along the middle section of the Berg River, between Paarl and Hermon (B3 to B4), the most heavily cultivated and most populated area along the river. This includes informal human settlements that have developed along the banks of the river.

Diffuse nutrient sources, such as agricultural runoff, produce seasonal concentration profiles coincident with river runoff, i.e. concentrations that peak during high runoff conditions. In contrast, point sources such as sewage effluent from municipal water treatment plants generally result in seasonal concentration profiles that have no relation to runoff, i.e. relatively constant input throughout the year, or an inverse relation to river runoff.

The positive relationship between NO\textsubscript{3} levels and fluxes with runoff, i.e. peaks during the rainy winter season, is consistent with a diffuse source such as agricultural runoff being the most likely source of NO\textsubscript{3} enrichment (Fig. 4b). Additionally, the smaller NO\textsubscript{3} flux reduction during the past 10 years, compared to the 40% reduction in runoff, implies one of two scenarios or a combination thereof:

- Increased fertiliser application during the latter 10 years
- An increase in a different source, such as sewage effluent

Evidence for increased NO\textsubscript{3} levels during low runoff conditions supports an increased point-source scenario. It is also suggested that overloading of water treatment plants during high runoff conditions or flooding of informal human settlements during winter storm events may result in nutrient enrichment during

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**TABLE 3**

Runoff and nutrient fluxes at the Berg River monitoring stations, calculated as described in the text.

| ID  | Location                  | Area    | Average runoff 10\(^6\) m\(^3\)/a | Average NO\textsubscript{3} flux kg N/a | Average PO\textsubscript{4}\textsuperscript{3-} flux kg P/a | NO\textsubscript{3} flux kg N/a/km\(^2\) | PO\textsubscript{4}\textsuperscript{3-} flux kg P/a/km\(^2\) |
|-----|---------------------------|---------|-----------------------------------|----------------------------------------|-----------------------------------------|-----------------------------------------|-------------------------------------------|
| LB1 | Little Berg @ MountainView| 30      | 17                                 | 14                                     | 1319                                    | 284                                     | 36                                       | 9                                        |
| LB2 | Little Berg @ Niewkloof   | 383     | 84                                 | 58                                     | 43321                                   | 1189                                    | 60                                       | 4                                        |
| B1  | Berg @ Bergriviershoek    | 75      | 169                                | 133                                    | 20668                                   | 2765                                    | 250                                      | 56                                       |
| B2  | Berg @ Dal Josafat        | 592     | 396                                | 304                                    | 308373                                  | 9194                                    | 425                                      | 24                                       |
| B3  | Berg @ Hermon             | 1444    | 500                                | 304                                    | 480510                                  | 24508                                   | 291                                      | 29                                       |
| B4  | Berg @ Drieheuvels        | 3554    | 717                                | 492                                    | 584880                                  | 22113                                   | 128                                      | 8                                        |
| B5  | Berg @ Misverstand        | 4772    | 523                                | 379                                    | 452949                                  | 15127                                   | 71                                       | 4                                        |

**TABLE 4**

Long-term percentage change in average monthly flow, [NO\textsubscript{3}] and [PO\textsubscript{4}\textsuperscript{3-}] levels at monitoring station B3, calculated as follows: 100*([monthly average\(_{1995-2005}\) - [monthly average\(_{1985-1994}\)]/[monthly average\(_{1985-1994}\)]

| Month | Flow % | Average NO\textsubscript{3} % | Average PO\textsubscript{4}\textsuperscript{3-} % |
|-------|--------|------------------------------|-----------------------------------------------|
| January | 72     | 380                          | 67                                           |
| February | 5     | 251                          | 119                                          |
| March    | -40    | 223                          | 146                                          |
| April    | -69    | 182                          | 373                                          |
| May      | -45    | 133                          | 293                                          |
| June     | -60    | 54                           | 177                                          |
| July     | -51    | 60                           | 253                                          |
| August   | -21    | 14                           | 169                                          |
| September | -12   | 35                           | 120                                          |
| October  | -32    | 15                           | 99                                           |
| November | 15     | 47                           | 140                                          |
| December | -3     | 84                           | 98                                           |

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high runoff, related to these ‘point sources’.
Seasonal [PO₄³⁻] and TP flux profiles suggest that the P budget of the river is dominated by point sources, most likely domestic waste and sewage effluent. It is not clear at this stage whether the late summer/early winter PO₄³⁻ concentration peak originates from agricultural runoff during early winter rains, i.e. increased P-fertiliser application, or whether it is related to increased loads associated with sewage and/or wastewater effluent.
A worst-case future scenario for the nutrient status of the Berg River would be a combination of increasing agricultural loading and point source pollution, and decreased streamflow in response to damming in the upper catchment or increased extraction. This is the scenario that the Berg River is faced with in the light of the almost completed construction of the Berg River Dam in the upper catchment. If the downstream flushing effect of runoff originating in the upper catchment is reduced, it can be confidently predicted that nutrient levels in the Berg River will significantly increase above their already unacceptably high levels. Reduced flow conditions in combination with higher nutrient levels will produce conditions even more favourable for the development of eutrophic and hypervertical conditions than is already the case. There is, therefore, an urgent need for the implementation of the NEMP in the Berg River water management area, including monitoring strategies that incorporate measurement of algal biomass (i.e. chlorophyll a). There is also a strong argument to be made for NEMP activities on the Berg River to be carried out further upstream from the Misverstand Dam, closer to monitoring Station B3. Urgent remedies, such as the identification of point sources and source reduction, coupled with immediate intervention strategies such as the construction of artificial wetlands (Morse et al., 1998; Reed et al., 1988; Kovacic et al., 2000; Hammer, 1992; Comin et al., 1997; Fink and Mitch, 2004), need to be put in place.

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