

**ENVIRONMENTAL WATER QUALITY MONITORING
FOR RICHARDS BAY MINERALS:
SMELTER SITE AREA**



Report for 2011/2012

AK Gordon, NJ Griffin
Unilever Centre for Environmental Water Quality
Institute for Water Research, Rhodes University
Grahamstown, 6140

July 2012

Executive summary

This document reports on a programme monitoring environmental water quality of surface waters in the vicinity of the Smelter Site of Richards Bay Minerals. All 7 identified sites were sampled in winter (August) 2011 and late summer / early autumn (April) of 2012 (scheduled summer sampling was postponed from March until April due to flooding caused by tropical storm Irina). Aquatic ecological health indices were calculated for each site based on water quality data, habitat quality, macroinvertebrate and diatom taxa sampled.

Indices for each site are presented in Table 1. A provisional overall aquatic ecological health assessment for each of the sites assessed is included. (Note: there is no health index for the habitat score (IHAS) as it was designed to interpret the South African Scoring System (SASS) results and it is included here for that reason). It must be noted that the methods used to provide the subsequent categories are largely based on expert opinion and assessment of the available data. In addition, the boundary values for the categories are based on the default values provided by the ecological Reserve method and require site-specific refinement.

Table 1. A summary of main index score results to provide an overall assessment for each of the sites.

Site	ASPT	IHAS	Water Quality	Diatoms	Overall ecological health assessment
1	Poor	56	Good	Good	Good/ Fair
7	Poor	58	Fair/Good	Fair	Fair
10	Poor	54	Fair/Good	Fair	Fair
11	Fair	43	Good/ Fair	Good	Good/ Fair
12	Fair	50	Good	Good	Good
13	Fair	50	Good/ Fair	Fair	Fair/Good
14	Good	47	Fair/Good	Fair	Fair/Good

The upper reaches of the Mpisini River (Site1) are in a Good/Fair state. The macroinvertebrate index (ASPT) is classed as Poor, but this is mostly attributable to low river flows and consequent lack of habitat for invertebrates. The diatoms, which are less affected by habitat availability, are in a Good class. In past assessments diatoms have always been classed Natural suggesting a possible slight decline in ecological health at this site. This may be correlated to the sudden appearance of a red floc covering the benthos. The reason for the appearance of the red floc is unknown, but may be related to increased contribution of ground water to the flow at this site. As a consequence, the macroinvertebrate community is becoming more similar to that present at Site 10. The diatom communities of Site 1 and 10 are still very different however.

The results from the diatom community assessment suggest a decline in water quality between Sites 1 and 7 on the Mpisini River. The smelter complex is situated immediately upstream of site 7, and as there appears to be limited impact from human settlements, it is possible that this water quality impairment may be related to the vicinity of the smelter.

The overall ecological health of the Mdibi River declines from Good at Site 12 to Fair/Good at Sites 13 and 14. Along this course it flows from an area of low anthropogenic impact at Site 12 through settlements in the vicinity of Sites 13 and 14. The input of water from the Mpisini and Manzamnyana Rivers to the Mdibi River between Sites 13 and 14 appears to have no additional detrimental effect to the overall ecological health.

The total number of invertebrate taxa collected at Site 11 was determined from data collected during the comprehensive sampling of all sites undertaken in winter 2011 and late summer 2012, and also during a specific survey of this site in spring 2011 . The average number of taxa collected during the assessment year 2011/2012 was 11 and the overall total number of taxa per year was 23. The numbers of taxa are lower than the previous assessment year (2010/2011) in which the average number of taxa sampled was 15.5 and the total number 25. This decline is likely due to the effects of tropical storm Irina causing low numbers of taxa to be collected in late summer 2012. A list of species collected at Site 11 during four sampling trips in different seasons is supplied in Appendix 6.

Table 2. Total taxa per season and average taxa per year collected at Site 11.

Year Month Season	2011 August winter	2011 November spring	2012 April late summer
Total taxa per season	12	16	5
Average taxa per year	11		
Total taxa per year	23		

Table of contents

1	Introduction.....	5
2	Methods and materials	6
2.1	Sampling sites.....	6
2.2	Water quality assessment.....	6
2.3	Biomonitoring.....	7
3	Results and discussion of comprehensive biomonitoring.....	10
3.1	Water quality assessment.....	10
3.2	Habitat assessment.....	15
3.3	Macro-invertebrate assessment	15
3.3.1	SASS assessment	15
3.3.2	Macroinvertebrate community assessment	17
3.4	Diatom assessment.....	17
3.4.1	Diatom indices.....	17
3.4.2	Description of diatoms sampled at each site.....	20
3.4.3	Diatom community analysis.....	23
3.4.4	Overall diatom assessment.....	25
4	Results and discussion of limited biomonitoring.....	34
4.1	Water quality assessment.....	34
4.2	SASS and habitat assessment.....	34
5	Conclusion	36
6	References.....	38
7	Appendices	40

1 Introduction

The Unilever Centre for Environmental Water Quality, based within the Institute for Water Research at Rhodes University, was appointed by Richards Bay Minerals (RBM) to undertake environmental water quality monitoring of the surface waters in the vicinity of the RBM Smelter Site during winter 2011 and summer 2012.

Richards Bay Minerals is situated in northern KwaZulu-Natal, producing titania slag, pig iron, rutile and zircon through processes of dune mining, mineral separation, smelting and beneficiation. The RBM Smelter Site is adjacent to the KwaBonambi State Forest and is situated within a larger afforested area. The area around the Smelter Site and the Tisand Mineral Lease area is drained by several small streams which flow into the Mdibi River and ultimately into Lake Mzingazi (Figure 1).

There is concern that RBM activities at the Smelter Site may impact the ecological health of the surrounding rivers. Contaminants from the RBM Smelter premises can reach the rivers either directly, via surface water run-off to the rivers (e.g. from pollution incidents, via effluent pipes or rainfall run-off), or indirectly, via groundwater contamination. The natural drainage from the RBM Smelter Site is towards the Mpisini and Manzamnyana Rivers, which drain into the Mdibi River, which subsequently flows into Lake Mzingazi.

For comprehensive biomonitoring in winter 2011 and late summer 2012 the following tasks were identified:

1. Undertake aquatic macroinvertebrate biomonitoring at the 7 identified sites.
2. Undertake diatom biomonitoring at the 7 identified sites.
3. Undertake a habitat assessment (IHAS) at the 7 identified sites.
4. Undertake water quality monitoring of the following parameters: nutrients (specifically, Total Inorganic Nitrogen (TIN) and Soluble Reactive Phosphorus (SRP)) and chlorophyll-*a* analysis (of phytoplankton and periphyton), turbidity, electrical conductivity, dissolved oxygen (DO), biological oxygen demand (BOD), water temperature and pH at each of the 7 identified sampling sites.

In addition to the comprehensive biomonitoring at 7 identified sites, limited biomonitoring (SASS only) and basic on-site water quality analysis at Site 11 (confluence of the Mpisini and Manzamnyana Rivers) was undertaken during spring 2011.

The specific tasks identified were:

1. Undertake on-site SASS biomonitoring at Site 11
2. Undertake a habitat assessment (IHAS) at Site 11
3. Measure turbidity, electrical conductivity/TDS, dissolved oxygen, water temperature and pH at Site 11

2 Methods and materials

2.1 Sampling sites

Comprehensive biomonitoring and water quality sampling was undertaken at seven sites: 1, 7, 10, 11, 12, 13, 14 (Figure 1) and consisted of macroinvertebrate and diatom biomonitoring, IHAS assessments and an extended water quality analysing programme including field measured parameters (such as pH and EC) and laboratory analysed parameters (such as SRP and BOD). This was undertaken during winter (August 2011) and late summer (April 2012) (scheduled summer sampling was postponed from March until April due to flooding caused by tropical storm Irina). Additionally, limited biomonitoring was undertaken at Site 11 during spring (November 2011), and consisted of SASS biomonitoring only. The biotopes sampled at each site are depicted in the individual site summaries section, along with a description of each site (Tables 6-12).

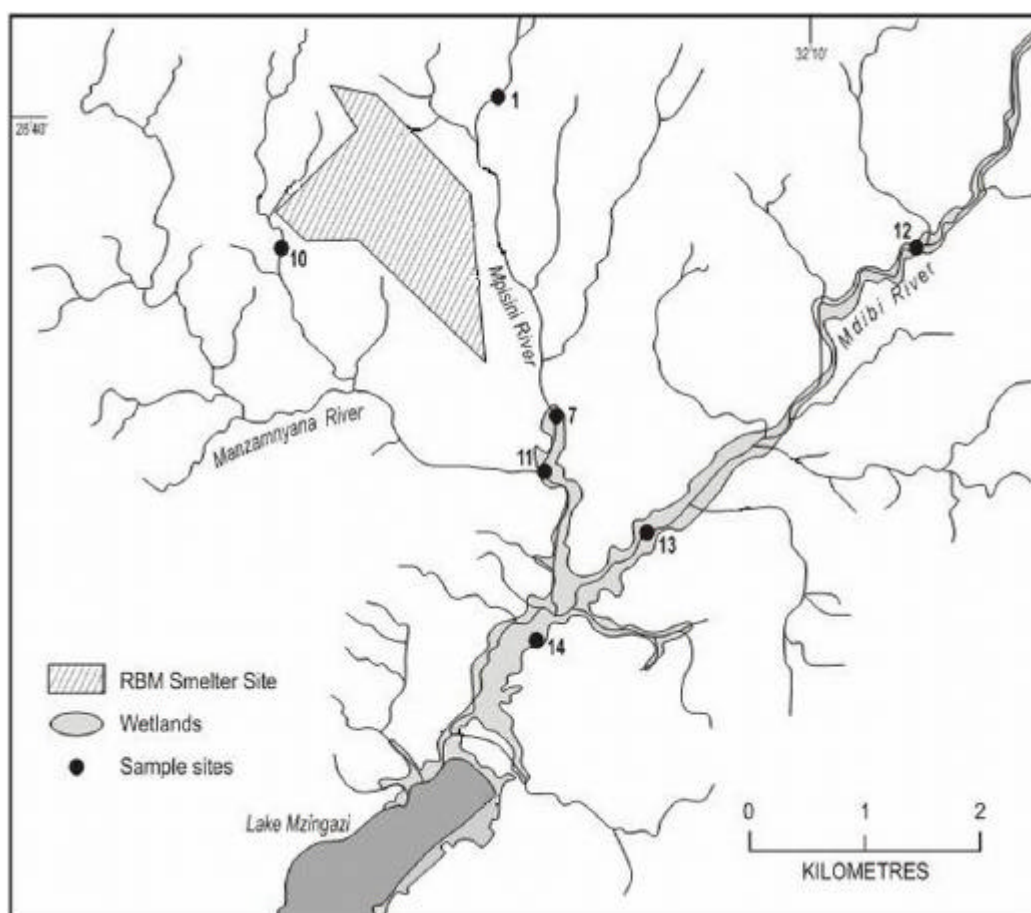


Figure 1. Monitoring points sampled in the Smelter Site area.

2.2 Water quality assessment

Water samples were collected during the winter (August 2011) and late summer autumn (April 2012) surveys at each of the biomonitoring sites and kept at 4°C for analysis at the Institute for Water Research, Rhodes University, Grahamstown. The following parameters were measured: NO₂-N, NO₃-N, NH₄-N and PO₄-P (soluble reactive phosphorus - SRP). The nitrogen data were combined to obtain Total Inorganic Nitrogen (TIN) concentrations.

Assessing only dissolved nutrient status (TIN and SRP) can lead to an incorrect conclusion regarding the nutrient enrichment of the water body. Dissolved nutrients are directly available for uptake by plants, consequently during active plant growth periods the concentrations of these nutrients will be a poor indicator of nutrient enrichment. The measurement of algal biomass (periphyton and phytoplankton) using chlorophyll-a concentration provides additional information when assessing the level of nutrient enrichment (Palmer et al. 2004). Periphyton and phytoplankton samples were collected following methods described by Holm-Hansen and Riemann (1978). Additional water samples were collected to assess biochemical oxygen demand (BOD). This test determines the amount of dissolved oxygen used by the aerobic microorganisms that decompose organic waste matter in the water. It is therefore used as a measurement of the presence of certain types of organic pollutants in water. In addition, the greater the BOD the smaller the amount of dissolved oxygen available in the river to other organisms. The standard method for a 5-day test (BOD₅) was used (APHA 1992). In addition to the parameters described above, on-site measures of dissolved oxygen (DO), electrical conductivity (EC), temperature and pH (using appropriate hand-held meters) were recorded during all biomonitoring occasions.

Where appropriate, water quality data were interpreted using the default benchmark boundary values for ecological health as provided for in Palmer et al. (2004). Electrical conductivity default benchmark boundary values were determined from DWA (2008).

2.3 Biomonitoring

Habitat assessment

A habitat assessment was undertaken at each site, using the Integrated Habitat Assessment System (IHAS; McMillan 1998). IHAS was initially developed for use with SASS4 (i.e. to interpret the SASS4 score). It provides a useful assessment of the habitat available at a site as the diversity of macroinvertebrates can be influenced by availability of biotopes and physical characteristics of the river, and surrounding land-use impacts.

Macroinvertebrate sampling

At each of the sites, SASS5 samples were taken from available biotopes and scored according to Dickens and Graham (2002). During the comprehensive biomonitoring a further two samples from each of the biotopes were collected using the SASS sampling method (replicate samples) with all samples preserved in 80% ethanol. In the laboratory, all samples were enumerated providing accurate counts for each of the taxa for further data analysis (macroinvertebrate community assessment). For each site the SASS score was divided by the total number of families sampled in order to obtain the Average Score per Taxon (ASPT) (Dickens and Graham 2002). ASPT scores were classified according to default boundary values for ecological Reserve categories as an estimation of ecological health (DWA 2008).

Diatom assessment

Diatom data reported on here are from samples collected from sample sites during August 2011 (winter) and April 2012 (late summer). Diatom samples were collected from hard substrates (vegetation, wood, brick or rock) on site and fixed in 20% ethanol for transport. Samples were prepared for examination using the potassium permanganate and hot hydrochloric acid method recommended by Taylor *et al.* (2007a). Cleaned frustules were

mounted in Pleurax on microscope slides and examined at 1000× magnification using bright field and phase contrast optics. Only whole frustules in valve view were used for identification. One hundred frustules per slide were identified.

Where possible, diatoms were identified to species level or below. Morphospecies were assigned where identification to species level was not possible and these were maintained throughout the analysis. All diatom counts were converted to proportional abundance before analysis. Abundances were used to calculate IPS (Coste in Cemagref 1982), a diatom-based index of general water quality that has been tested for use in South Africa (Taylor *et al.* 2007b, 2007c) and has been successfully applied in KwaZulu-Natal (Taylor, pers. comm.). The new Biological Diatom Index (BDI-2006, Coste *et al.* 2009), a general pollution index, was also calculated. The older BDI index on which the new version is based has also been tested and used in South Africa (Taylor *et al.* 2007b, 2007c). Both indices use a large number of taxa in inferring water quality. IPS and BDI-2006 scores were rescaled to give a maximum of 20 as per common convention. Water quality classes were assigned to IPS index data after Eloranta and Soininen (2002) and to BDI-2006 index data after Prygiel and Coste (2000) (Table 3).

Table 3. Water quality classes for the IPS index (Eloranta and Soininen 2002) and the BDI-2006 index (Prygiel and Coste 2000).

Class	IPS value	BDI-2006 value
High	>17	BDI=17
Good	15-17	17>BDI=13
Moderate	12-15	13>BDI=9
Poor	9-12	9>BDI=5
Bad	<9	BDI<5

Previous reports (Muller *et al.* 2007, Gordon *et al.* 2008) used an index based on expert opinion as doubt existed as to the applicability of indices derived in Europe in a region where tropical taxa might be encountered. However, as the IPS index has been successfully applied in the region (Taylor, pers. comm.) and the BDI-2006 index contains a number of tropical taxa (Coste *et al.* 2009), and as the majority of taxa encountered in previous surveys are included in the two diatom indices, these indices will be used for sample classification in this report. For continuity with previous reports, sample classifications based on expert opinion are also derived for each sample. The sample classifications based on the expert opinion approach are derived by using environmental preferences of common taxa as presented by Taylor *et al.* (2007d) and Van Dam *et al.* (1994) to infer the ecological health of the site. Using this information, samples are scored according to the scheme presented in Table 4. Sites are ranked according to scores assigned according to the above scheme. Where sites fall between classes, intermediate scores are assigned e.g. 4 represents a classification of Good, and 2 represents a classification of Poor.

Only taxa that were well represented in each sample were used to infer water quality class, as these will best indicate the prevailing and recent water quality. For the purposes of this analysis, dominant taxa are the one taxon with the greatest abundance in the sample. Where other taxa have abundances not less than 10% less than the dominant taxon, they are classed as co-dominant. Other taxa that are less common than the dominant taxa and that make up 10% or more of the sample are classed as subdominant and are used to infer water quality. Taxa present in lower quantities are only used in this analysis where information from dominant and subdominant taxa is insufficient for site classification.

Table 4. Classification system for expert opinion-based diatom index

Class	Environmental preferences of common taxa	Score
High	Samples where all or most taxa found are characteristic of unpolluted oligotrophic to mesotrophic water with low to moderate levels of electrolytes. Dominant taxa must be typical of these conditions.	5
Good		4
Moderate	Dominant taxa not consistently indicative of clean conditions, and the sample has taxa typical of clean and stressed condition.	3
Poor		2
Bad	Most taxa present are tolerant of at least moderate levels of pollution, or typical of eutrophic or osmotically stressed conditions.	1

For the overall diatom classification of sites, the expert opinion-based classification described above was combined with IPS and BDI-2006 using weight of evidence to derive an overall sample classification. This overall diatom classification was adjusted to the ecological reserve categories in order to provide an overall assessment of aquatic ecological health (Table 5).

Table 5. Alignment of diatom classification system and ecological Reserve categories

Diatom classification	Ecological Reserve categories
High	Natural
Good	Good
Moderate	Fair
Poor	Poor
Bad	

Statistical analysis

Statistical analyses of macroinvertebrate community structure was undertaken using non-metric multi-dimensional scaling (NMDS) provided for in the PRIMER V5 programme (Clark and Warwick 2001). The NMDS ordination plot represents the similarity of abundances of family level taxa between samples. Statistical analysis was conducted using the analysis-of-similarity test (also provided for by the PRIMER v5 programme). In addition to the significance value, the Global R value indicates the degree to which the samples are similar or dissimilar. An R value of 1 indicates complete separation of groups, whereas an R value near 0 implies little or no segregation.

Analysis of variance and post-hoc testing of diatom scores was undertaken using R 2.11.0 with base and stats packages (R Development Core Team 2010). Calculation of alpha diversities and ordination using non-metric multidimensional scaling were undertaken using the package vegan 1.17-2 (Oksanen et al., 2010). Hypotheses relating to the differences in diatom community structure between sites and seasons were explored using the function adonis, which undertakes non-parametric multivariate analyses of variance (after Anderson 2001).

3 Results and discussion of comprehensive biomonitoring

In the sections below, the water quality, habitat and biological monitoring data collected are reported and discussed. Individual site summaries detailing specific site information observed by the samplers, water quality parameters measured and biological monitoring results are presented in Tables 6-12. Raw data are presented in Appendices 1-6.

3.1 Water quality assessment

Water temperatures recorded showed little variation between sites (the temperature at Site 12 represents the winter sample only) (Figure 2A). Warmer temperatures were recorded during late summer (Figure 2B).

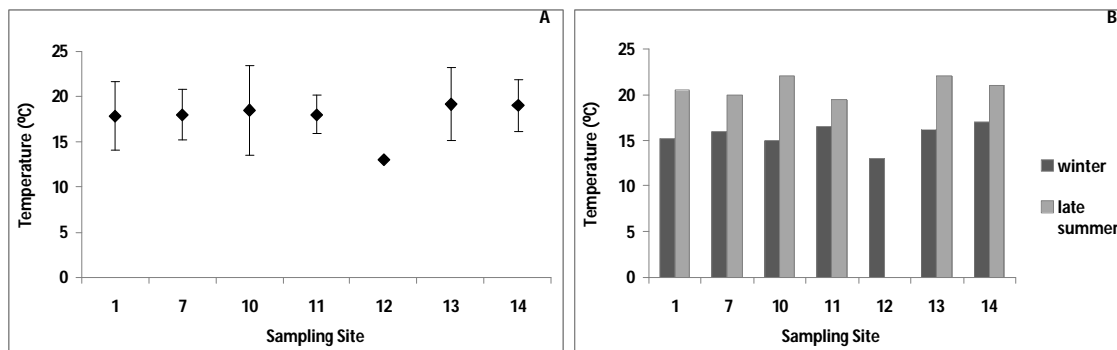


Figure 2A-B. A: Mean (with standard deviation) temperature values measured at sampling sites over two seasons. B: Seasonal temperatures measured at each site.

Differences in measured pH were small, with the uppermost sites on each river being slightly more acidic (Figure 3A). All sites were classed as either Natural or Good. Electrical conductivity at all upstream sites were classed as Good, with average EC values at remaining sites being classed as Fair (Figure 3B). Generally, EC values increased with distance downstream and were lower in late summer (Figure 3D). Increased EC levels at Site 7 appear to be related to the proximity of the Smelter Site as no other cause for the increase could be identified. Remaining sites downstream of the smelter are surrounded by human settlements and thus it is difficult to determine relative contributions of these two land uses to increased EC.

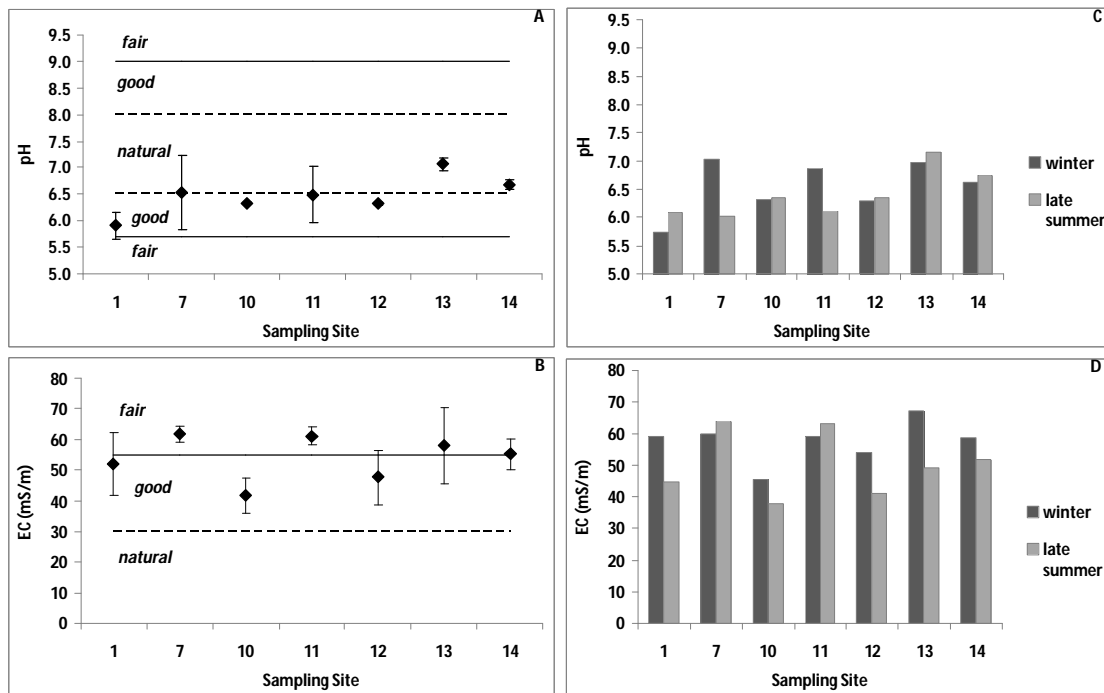


Figure 3A-D. A-B: Mean (with standard deviation) pH and electrical conductivity (EC) values measured at sampling sites over two seasons. Default ecological categories based on ecological Reserve determination methodologies are superimposed on the graphs. C-D: Seasonal values measured at each site.

Average DO was considerably lower at Site 10, falling within the Poor ecological category (Figure 4A), remaining sites were classified as Good (except Site 14 which was classed as Fair). DO levels were generally lower in late summer (Figure 4C). The low DO measured at Site 10 could possibly be attributed to the large proportion of ground water feeding the wetland lake immediately upstream and limited surface flow. The average values for the 5-day biological oxygen demand (BOD) test ranged between 1.5 – 2mg/L (Figure 4B) with higher concentrations in late summer (Figure 4D).

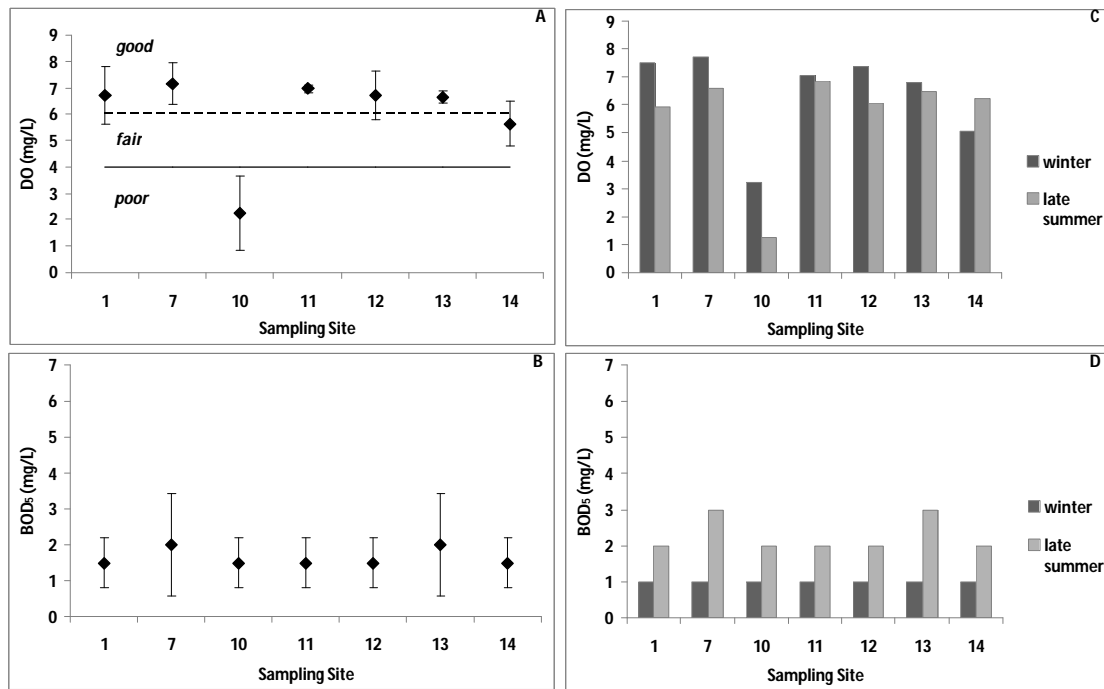


Figure 4A-D. A-B: Mean (with standard deviation) DO (dissolved oxygen) and BOD₅ (biological oxygen demand over 5 days) measured at sampling sites over two seasons. Default ecological categories for DO based on ecological Reserve determination methodologies are superimposed on graph A. C-D: Present seasonal values measured at each site.

Due to a fault with the laboratory reagents utilised for processing the summer 2012 samples, total inorganic nitrogen (TIN) was only determined for the winter 2011 sample, with all sites classified as Good (Figure 5A and C). Soluble reactive phosphorus (SRP) concentrations were mostly classed as Fair, except Sites 1 and 14 which were classed as Poor (Figure 5B). The Poor category for Sites 1 and 14 is attributable to the higher SRP concentrations measured during the winter 2011. In summer 2012, SRP at all sites was below the detection limit (Figure 5D).

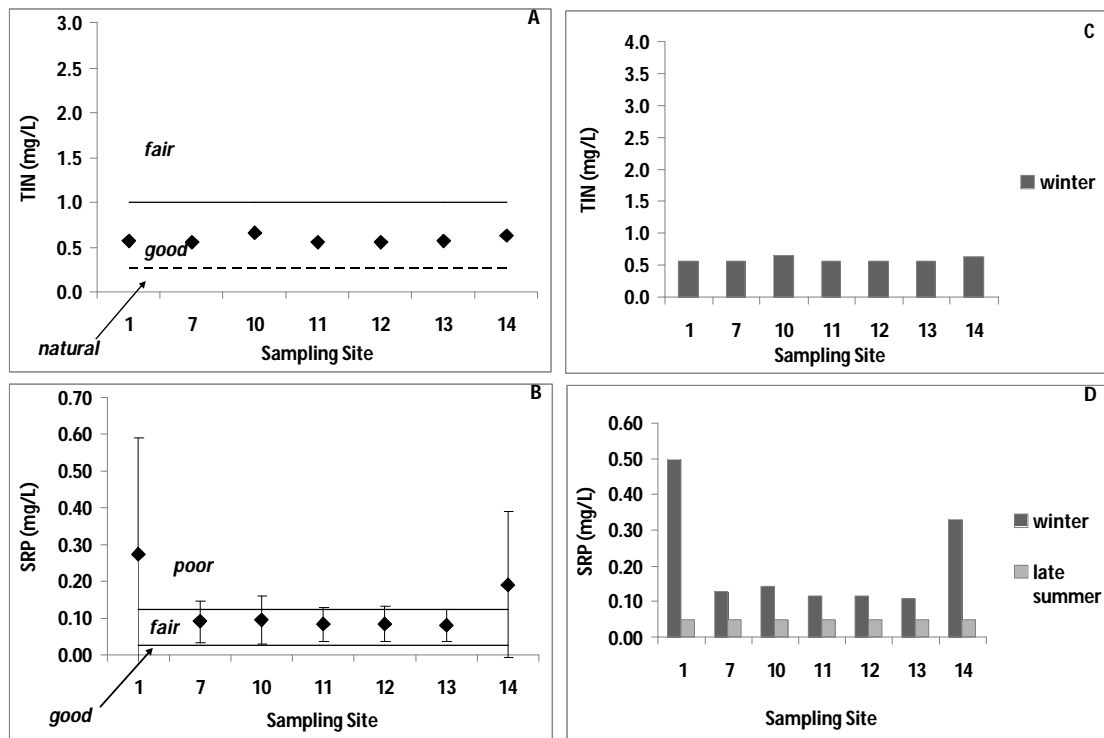


Figure 5A-D. A-B: Mean (with standard deviation) TIN (total inorganic nitrogen) and SRP (soluble reactive phosphorus) values measured at sampling sites over two seasons. Default ecological categories based on ecological Reserve determination methodologies are superimposed on the graphs. C-D: Seasonal values measured at each site.

Phytoplankton chlorophyll-*a* concentrations at all sites were classed as Natural (Figure 6A), with no significant seasonal variations (Figure 6C). Periphyton chlorophyll-*a* concentrations ranged from Good to Poor (Figure 6B). Sites 7, 10 and 13 (all classified as Poor) are not affected by shade from overhanging vegetation and thus algal growth is more likely at these sites. The higher periphyton chlorophyll-*a* at Site 10 may also be attributable to the impact of cow faecal matter present at the site. Large seasonal variations were observed at Sites 7 and 13 (Figure 6D).

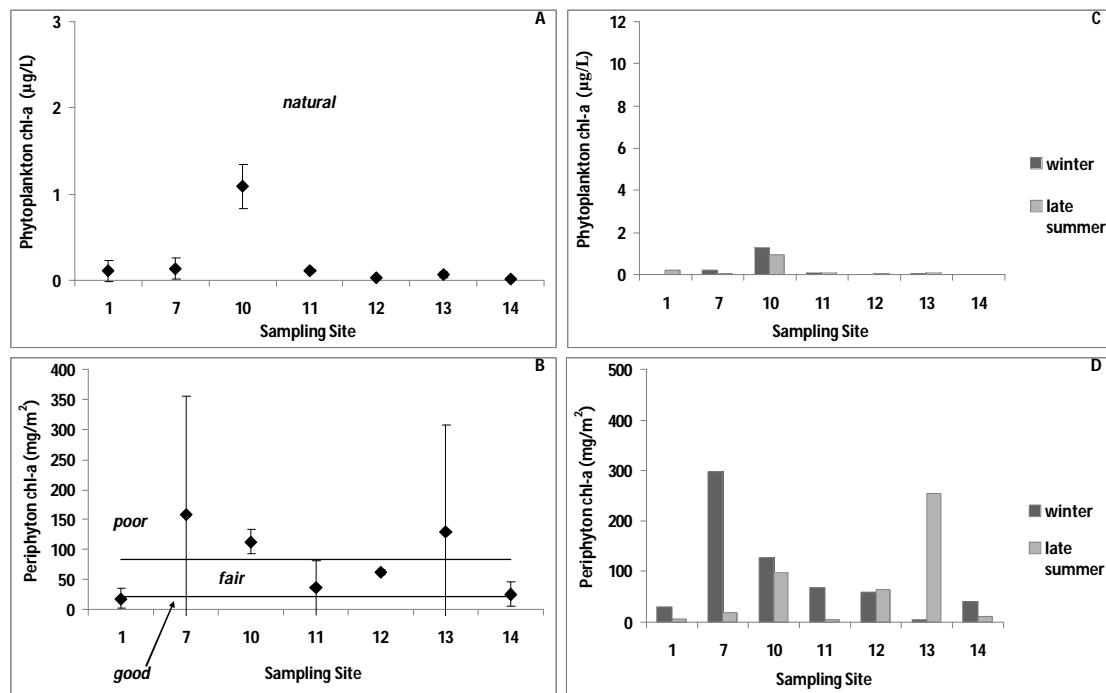


Figure 6A-D. A-B: Mean (with standard deviation) TIN (total inorganic nitrogen) and SRP (soluble reactive phosphorus) values measured at sampling sites over two seasons. Default ecological categories based on ecological Reserve determination methodologies are superimposed on the graphs. C-D: Seasonal values measured at each site.

3.2 Habitat assessment

Generally, IHAS scores were low at all sampling sites (Figure 7A). The higher IHAS score at Site 7 is due to the presence of stones habitat which is absent at other sites. Seasonal variability was negligible (Figure 7B). Further reasons for low IHAS scores include: Site 10 being characterized by a pool with slow moving water which is regularly disturbed by cattle; Sites 1, 11 and 12 being affected by low flows which reduced available vegetation sampling habitat; and Site 13 having reduced GSM biotope.

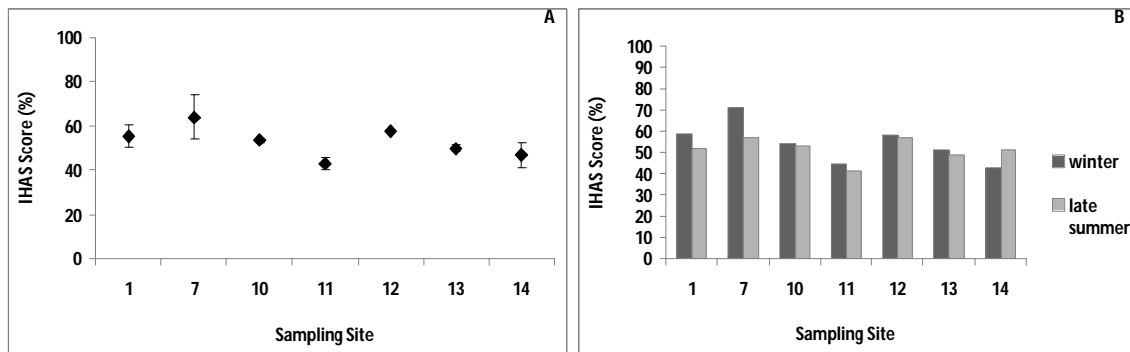


Figure 7A-B. A: Mean Integrated Habitat Assessment System (IHAS) score (with standard deviation) per sampling site. B: Seasonal differences in IHAS recorded at each site.

3.3 Macro-invertebrate assessment

3.3.1 SASS assessment

At each site, results from vegetation and GSM biotopes were combined to provide overall SASS scores, number of families and ASPT values (Figure 8A-C). SASS scores, number of taxa and ASPT values were generally lower at upstream sites compared to downstream sites (Figure 8A-C) possibly caused by reduced habitat availability as a result of limited and slow river flows at these sites. SASS scores and number of taxa were considerably lower in late summer 2012 at Sites 7, 10, 11, 12 and 14, probably a consequence of the flooding caused by tropical storm Irina six weeks earlier (Figure 8D).

ASPT values were, however, more consistent seasonally (Figure 8F). The ASPT score is generally considered to be the least variable of the SASS assessment scores and thus preferred when assessing river health. ASPT scores were classed as Poor at Sites 1, 7 and 10 (uppermost sites), Fair at Sites 11, 12, and 13, and on the Good/Fair boundary at Site 14 (Figure 8C).

Poor habitat due to low water levels might be the cause for the low SASS and ASPT scores at Sites 1 and 10. Site 10 has in addition very low DO values, which impact on organisms at this site. Along the length of the Mdibi ASPT values increased from Fair at Site 12 and 13 to Good at Site 14.

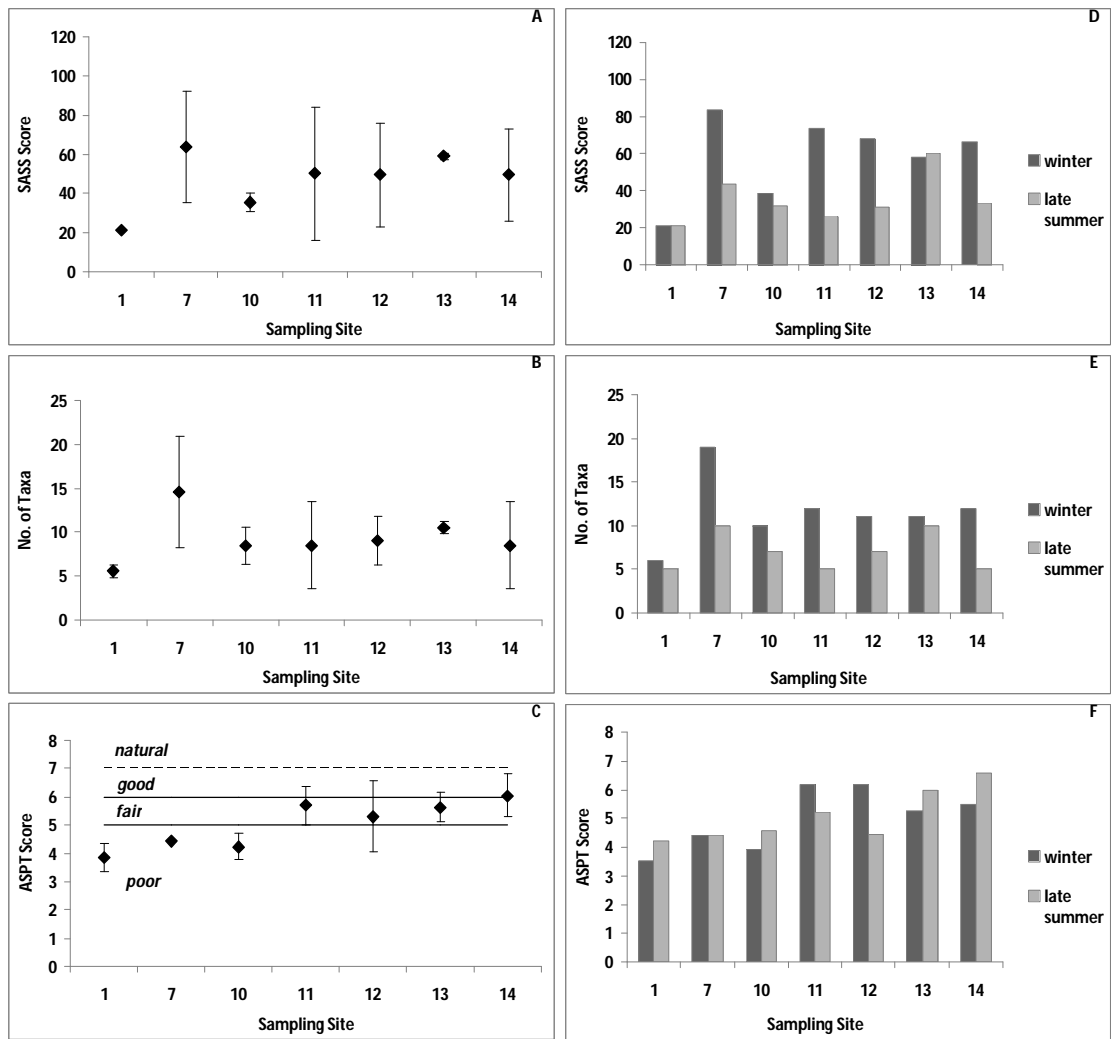


Figure 8A-F. A-C: Mean (with standard deviation) South African Scoring System (SASS) scores, number of families/taxa sampled and Average Score Per Taxon (ASPT) values determined for sites over two seasons. Default ecological categories for ASPT scores based on ecological Reserve determination methodologies are superimposed on graph C. D-F: Seasonal variation in SASS, number of taxa and ASPT values at each site.

3.3.2 Macroinvertebrate community assessment

An analysis of similarity of enumerated family-level macroinvertebrate data collected during winter 2011 and late summer 2012 showed that all sites were significantly different from one another. However, the NMDS plot showed that Sites 1 and 10 were considerably different from the remaining sites (Figure 9). Since biomonitoring began in 2007, Site 1 has always been more similar to the remaining sites than to Site 10. However, there appears to be a shift occurring in the macroinvertebrate community at Site 1. The cause of this shift is not known, however increased amounts of red floc excreted by iron bacteria have concurrently appeared at this site, a situation similar to Site 10. This suggests that iron bearing ground water is increasingly contributing to the flow at Site 1.

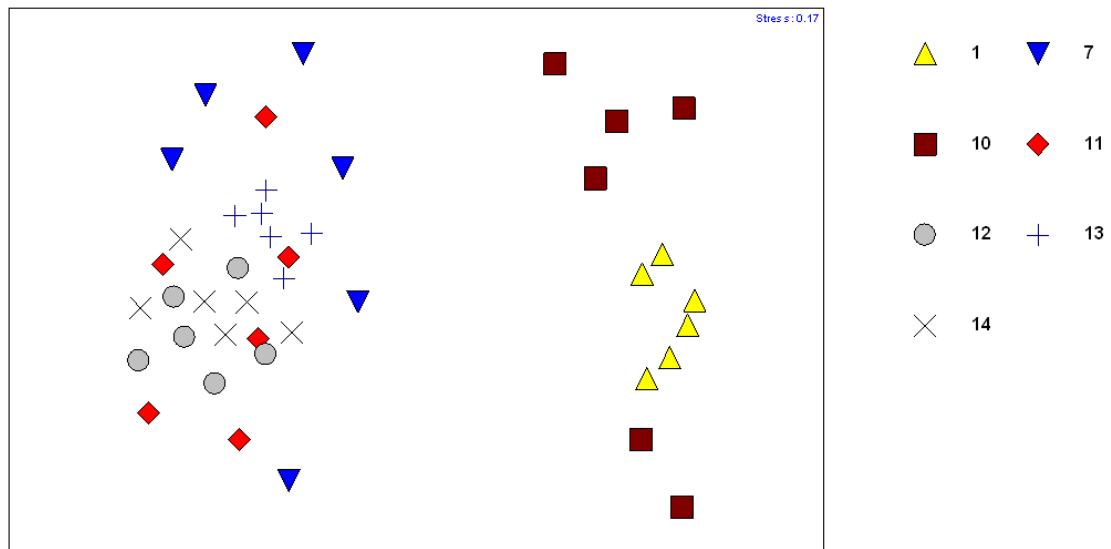


Figure 9. Non-metric multi-dimensional scaling plot of enumerated macro-invertebrate data, analysed according to location sampled.

3.4 Diatom assessment

Diatom indices

Mean index values for each site are presented in Figure 10. Raw data underlying these plots are presented in Appendix 1. General trends between sites are broadly the same across all indices, although inter-site variation and the range across scores are greater for the score based on expert opinion. Differences between indices are largely a function of whether taxa in samples, and in particular dominant taxa, contribute to the indices in question.

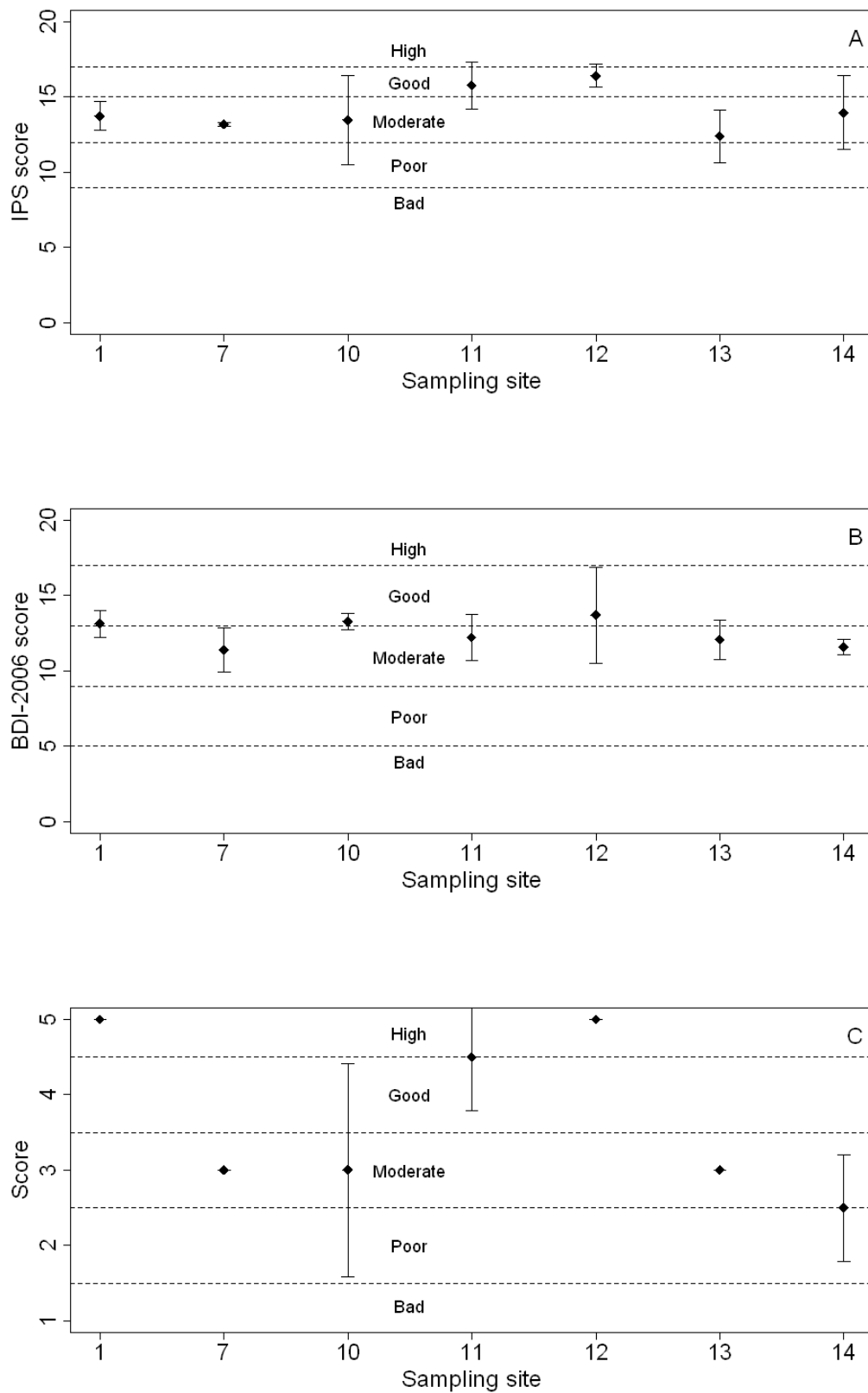


Figure 10A-C. Mean scores (\pm standard deviation) of the three diatom indices used in this study. A: IPS index; B: BDI-2006 index; C: Score based on expert opinion.

Sites 1, 11 and 12 have the highest weight-of-evidence scores overall, and all are classed as being of good quality. In previous reports (Gordon *et al.* 2008, 2010, Holland *et al.* 2011), sites 1 and 12 have generally been of high quality, and it appears that the water quality at these sites may have degraded. While the impact of tropical storm Irina in early March 2012 may be expected to modify results of surveys undertaken, no clear pattern of response to this event is evidenced, and the decrease in water quality according to diatom biomonitoring results appears not to be caused by the storm. Over the period August 2010 to February 2011, samples from sites 1 and 12 were classed as good to high quality according to the IPS and BDI-2006 indices; in the most recent samples, however, these indices indicate that samples were of moderate to good quality. The index based on expert opinion did not change over this period. In all cases, diatom communities at these sites were dominated, often heavily, by one or a few taxa drawn from a range that comprises *Achnanthes oblongella*, *A. pulviscula*, and two undescribed species of *Brachysira*. The IPS index uses information on *A. oblongella* in index derivation, but the BDI-2006 index does not. Neither index uses information on *A. pulviscula* or the *Brachysira* species. This means that indices derived for these sites are largely based on taxa that are present in very low numbers. If the remaining, rarer taxa include members typical of clean water, index scores rise. On the other hand, the presence of a small minority of taxa typical of unclean water will depress scores (with the exception if the IPS index where *A. oblongella* is dominant). The index based on expert opinion uses the information that the dominant taxa listed above are typical at reference sites, and is therefore less affected by the lack of ecological information on these taxa. For this reason, the apparent drop in water quality at sites 1 and 12, based on indices using information from diatom communities, may be a function of the unusual taxa found at these sites and not necessarily a reflection of changing water quality over the past year.

High variation in index values with time at site 11 is similarly driven by the extreme dominance of *Achnanthes oblongella* in samples from August 2011.

Site 10 index values show considerable change with time, increasing from August 2011 to April 2012. This may be a function of substrates sampled. Samples are usually collected from a submerged log on the downstream side of the site. This location may be impacted by vehicle and livestock passage (signs of both are present). In April 2012, no diatoms were present in the sample collected from the wooden substrate, and an alternate sample from *Nymphaea* collected upstream was used. Index values for all increased along with the change in sampling location.

The indices show decreasing water quality with distance downstream along the Mpisini (sites 1 and 7, Figure 10) and Mdibi (sites 12, 13 and 14, Figure 10). Site 10 is the only sample site on the Manzamnyama, as site 11 is the confluence of the Mpisini and Manzamnyama rivers. Inferred water quality improves on average over the year reported on from Site 10 to Site 11.

Consistent changes across sites are not supported by statistical analysis of the IPS and BDI-2006 indices (IPS $p=0.352$; BDI-2006 $p=0.763$). Detection of further statistical significance of changes was confounded by inflated error variance owing to changes in index values with time at particular sites. Changes across sites are significant with the index based on expert opinion is assessed ($p=0.014$), with notable differences between upstream sites 1 and 12 compared to downstream site 14 ($p=0.036$ for both). At a lower level of significance, site 1 had better inferred water quality than sites 7, 10 and 13, and site 12 had better inferred water quality than sites 7, 10, 11 and 13 ($p=0.091$ for all). This illustrates the decrease in inferred water quality with overall distance downstream, and also that upstream sites 1 and 12 had better inferred water quality than upstream site 10.

The decrease in inferred water quality noted in previous years between sites 1 and 7 on the Mpisini river is less pronounced in these results. This is largely a result of lowered index values from site 1, and not to an improvement at site 7.

No consistent seasonal pattern in index change across all sites for any index was noted (IPS $p=0.286$; BDI-2006 $p=0.737$; expert opinion $p=0.103$).

Description of diatoms sampled at each site

Site 1 (Upper Mpisini)

August 2011

This sample contained 14 taxa and had a Shannon diversity of 1.79. *Achnanthes pulviscula* and an unidentified species of *Brachysira* were co-dominant in this sample. No knowledge on the specific ecological requirements of these taxa is available. However, these taxa have been found to be associated with good quality water in the Smelter region (Gordon *et al.* 2008, 2010, Holland *et al.* 2011) and are commonly dominant in upstream reference sites. In addition, *Brachysira* species typically are found in oligotrophic, electrolyte-poor water, and many prefer a somewhat acid pH. *Achnanthes oblongella*, a taxon typical of small, circumneutral, oligotrophic, electrolyte poor streams, was subdominant. Of the remaining taxa that make up more than 1% of the sample, some are typical of oligotrophic conditions, though some are pollution tolerant.

April 2012

This sample contained 16 taxa and had a Shannon diversity of 1.88. *Achnanthes pulviscula* was again dominant in this sample, and another unidentified *Brachysira* species was subdominant. As in the August 2011 sample, both taxa are associated with good quality water. The remaining taxa consist of a mix of taxa typical of clean, often acidic water, and several that are pollution tolerant.

Site 7 (Lower Mpisini)

August 2011

This sample contained 22 taxa and had a Shannon diversity of 2.57. *Gomphonema parvulum* and *Achnanthidium minutissimum* were codominant in this sample. The former is a cosmopolitan taxon that can be found in polluted conditions, and the latter is more typical of well-oxygenated and clean water. Remaining taxa include those typical of oligotrophic, electrolyte-poor conditions, as well as taxa more typical of high electrolyte levels, and often of polluted conditions.

April 2012

This sample contained 15 taxa and had a Shannon diversity of 2.06. An unidentified species of *Gomphonema* and *Achnanthes oblongella* were codominant in this sample. The former has never been seen before in samples from this region, and nothing is known of its ecological preferences. The latter is typical of oligotrophic, electrolyte-poor, and circumneutral conditions, and is not typically associated with pollution. Of the remaining taxa making up more than 1% of the population and with known ecologies, all are electrolyte-tolerant, and some are common in eutrophic conditions.

Site 10 (Upper Manzamnyana)

August 2011

This sample contained 26 taxa and had a Shannon diversity of 2.80. The sample was dominated by *Navicula gregaria*, a cosmopolitan taxon common in eutrophic conditions and tolerant of moderate to high electrolyte levels. It been identified as a good indicator of pollution. *Brachysira brebissonii* was subdominant. This taxon in turn is typical of oligotrophic, acidic and electrolyte poor waters, and it has been recommended as an indicator of a lack of anthropogenic impact. Of the remaining taxa that make up more than 1% of the population, all are tolerant of elevated levels of electrolytes.

April 2012

This sample contained 23 taxa and had a Shannon diversity of 2.51. The sample was dominated by *Stauroneis heinii*, a cosmopolitan taxon with a relatively wide ecological niche. *Nitzschia paleaeformis* was subdominant. The latter is typical of acidic, relatively non-saline and oligotrophic water with fairly high oxygen levels. Of the remaining taxa that made up more than 1% of the sample, many are typical of acidic waters, while several others are more typical of electrolyte-rich water.

Site 11 (Confluence)

August 2011

This sample contained only 9 taxa and had a Shannon diversity of 0.74. The sample was heavily dominated by *Achnanthes oblongella*, a taxon found in oligotrophic, electrolyte-poor, circumneutral streams. The remaining taxa with an abundance of more than 1% were all typical of polluted or heavily polluted conditions.

April 2012

Insufficient diatoms were present on the hard substrates sampled on this occasion, and as a result a sample collected from organic sediment was processed. The use of samples collected from sediment is non-standard and may results may indicate a lowered water quality compared to samples collected from a hard substrate.

This sample contained 30 taxa and had a Shannon diversity of 2.68. The dominant taxon is this sample was *Diademsis contenta*, a taxon typical of oligotrophic, acidic water (also common in sites with low light levels, which is the case at Site 11). No other taxa had abundances of more than 10%. Of the wide range of taxa present in abundances of more than 1%, the more common ones were all typical of clean and often acidic water. The remainder include taxa typical of clean water as well as those found in polluted conditions

Site 12 (Upper Mdibi)

August 2011

This sample contained 13 taxa and had a Shannon diversity of 1.93. *Achnanthes oblongella*, typical of oligotrophic, electrolyte-poor, circumneutral streams is dominant. An unidentified species of *Brachysira*, and *Eunotia minor* are subdominant. This species of *Brachysira* has been associated with clean water around the smelter, and the genus in general is associated with oligotrophic, electrolyte-poor water, and often acidic, water. *Eunotia minor* is typical of circumneutral water. The majority of remaining taxa present with an abundance of greater than 1% are characteristic of clean water.

April 2012

This sample contained 15 taxa and had a Shannon diversity of 1.32. The site was heavily dominated by *Achnanthes oblongella*. No other diatom made up more than 10% of the population, but the majority of taxa present at more than 1% abundance are indicative of clean, unimpacted water.

Site 13 (Middle Mdibi)

August 2011

This sample contained 33 taxa and had a Shannon diversity of 3.04. *Gomphonema pumilum* var. *rigidum*, *Gomphonema angustatum* and *Navicula veneta* were codominant in this sample, with no subdominant taxa. *Gomphonema pumilum* var. *rigidum* is typical of meso- to eutrophic water with moderate electrolyte levels. *Gomphonema angustatum* is a cosmopolitan taxon, but one that is only common in oligotrophic conditions. *Navicula veneta* is also cosmopolitan, but in contrast is common in highly eutrophied, electrolyte-rich water. Remaining taxa with an abundance of 1% or higher include those typical of both clean and impacted conditions.

April 2012

This sample contained 26 taxa and had a Shannon diversity of 2.64. The sample was dominated by Achnanthidium species, with Achnanthidium saprophilum dominant, and Achnanthidium minutissimum subdominant. Achnanthidium saprophilum is typical of organically enriched and eutrophic waters, while Achnanthidium minutissimum is found in oxygen-rich clean water. The remaining taxa with more than 1% abundance cover a range from a few typical of oligotrophic, electrolyte-poor water to several characteristic of eutrophic, electrolyte rich water.

Site 14 (Lower Mdibi)

August 2011

This sample contained 31 taxa and had a Shannon diversity of 3.04. This sample was co-dominated by *Navicula longicephala* and an unidentified species of *Navicula*. *Navicula longicephala* is described as being typical of eutrophic, electrolyte-rich water, and as being tolerant of critical levels of pollution. The remaining taxa with an abundance of greater than 1% are for the most part associated with elevated electrolyte levels, and to a less extent with eutrophic conditions. A few taxa are associated with clean water.

April 2012

This sample contained 18 taxa and had a Shannon diversity of 2.20. The sample was dominated by *Achnanthes oblongella*, with *Gomphonema parvulum* and *Cocconeis placentula* var. *euglypta* subdominant. As noted elsewhere, *Achnanthes oblongella* is associated with circumneutral, oligotrophic, electrolyte-poor conditions. *Gomphonema parvulum* is a cosmopolitan taxon and thus found in a wide range conditions, and it is reported to be extremely pollution tolerant. *Cocconeis placentula* var. *euglypta* is common in meso- to eutrophic waters. Of the remaining taxa present with an abundance of more than 1%, many are typical of unpolluted water, with a few taxa more typical of higher levels of electrolytes or nutrients also present.

Diatom community analysis

The ordination of samples based on diatom abundance is presented in Figure 11. The effects of site on diatom community structure were significant ($p=0.022$). However, there was no significant change with time ($p=0.200$). In general samples with better inferred water quality are found at the bottom right of Figure 11. Samples from sites 1 and 12 are clustered together. These are considerably spaced away from the summer sample from site 10, which also had fairly good quality water, but a distinctly different diatom community structure. Location of a sample near the bottom right of the figure does not indicate good water quality, however. The summer sample from site 7, for example, has considerably worse inferred water quality than the winter sample from site 11, despite being placed near it on the plot. This contradiction can be explained by the site 7 summer sample having an unknown *Gomphonema* species and *Achnanthes oblongella* codominant. The *Gomphonema* species is only found in one other sample from the reported period, and then in low quantities, and so contributes little to the placement of the site in the ordination. However, the presence of significant numbers of *A. oblongella* causes the sample to be placed near other samples with this taxon, namely those from cleaner sites where this taxon is common.

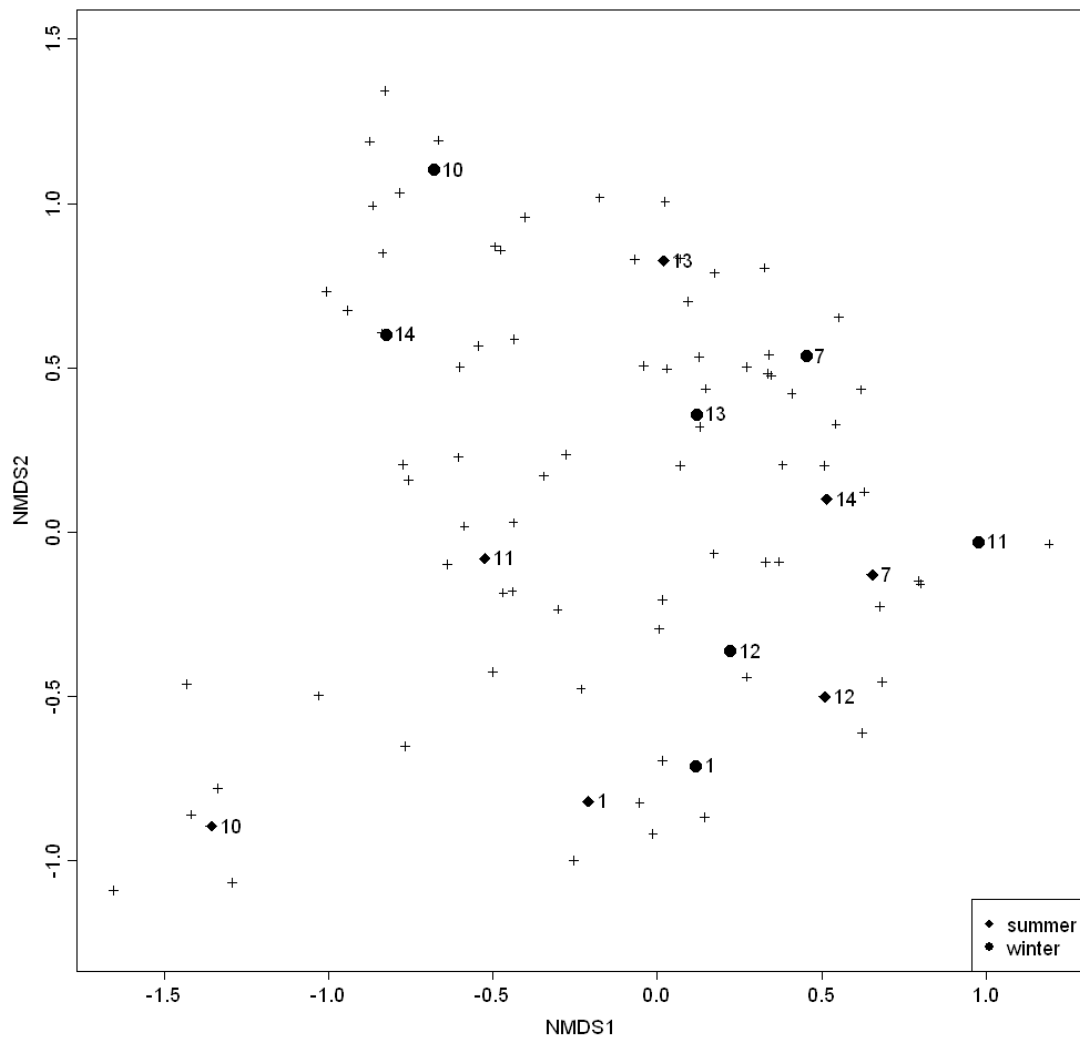


Figure 11 NMDS ordination plot of Bray-Curtis distances between all samples assessed, based on untransformed diatom abundances (stress: 13.8). Sites are labeled and species indicated by +.

The plot also highlights that there is relatively little change over time in diatom communities from reference sites 1 and 12, and that these closely resemble one another. The similarity of diatom communities from these sites, and their distinctness to those communities from upstream site 10 has been noted before (Holland *et al.* 2011).

The relative lack of change in community structure over time observed at sites 1 and 12 is not noted in all sites, however. In Figure 11, large changes in community structure between the two sampling occasions can be seen for samples from sites 10, 11 and 14. The cause of these changes is not known. Some change may be due to the use of samples collected from different substrates (at sites 10 and 11, insufficient diatoms were present in the initial samples processed, and backup samples from alternate substrates were used). However, with the exception of site 11, where the backup sample was collected from sediment, a substrate not normally used in biomonitoring but collected owing to the lack of other appropriate substrates at the site, all samples were collected from standard substrates used for biomonitoring. In addition, samples from site 13, which shows relatively little change over time, samples were collected from different substrates and this had little impact. At

site 10, the alternate sample was collected from a site less exposed to impact from livestock, and this may partially account for the shift. The impact of tropical storm Irina, one month before summer samples were collected, might also contribute to changes; however, statistical analysis found no significant overall change in diatom community structure between the two periods sampled. According to one or more of the diatom indices used, the changes in community structure are accompanied by a significant change in inferred water quality. The increased dispersion of sites, particularly in comparison with site 1, has been noted in previous reports (Gordon *et al.* 2010, Holland *et al.* 2011).

Overall diatom assessment

According to the weight-of-evidence score that combines the three metrics used to classify sites on the basis of diatom communities, the inferred water quality at sites 1 and 12 over the sampled period was classed as good. This is a decrease from the classification of high quality noted in reports from the previous two years (Gordon *et al.* 2010, Holland *et al.* 2011). In contrast, site 11 showed a distinct improvement in inferred water quality in moving from a moderate to a good class. Otherwise, in comparison with results from the previous year (Holland *et al.* 2011), site classifications did not change significantly. However, the previous report noted that site classifications for sites 10, 13 and 14 had decreased from good to moderate compared to results from the previous year. The outcome of this is an overall decrease in inferred water quality over a three year period (previous reports did not use the same combination of scoring systems and so results are not directly comparable). This is particularly evident at sites that had been classed as good to high by Gordon *et al.* (2010).

Difficulties with the application of indices that do not use some of the taxa that are dominant particularly at upstream sites 1 and 12 are discussed above. The consequence of this is that BDI-2006 index, and, to a slightly less extent, the IPS index, score these sites based on taxa that are less common in a sample (the index based on expert opinion is not affected in this way). Changes in these indices over time may therefore be a function of changes in rarer taxa and not in dominant taxa. Nevertheless, the apparent decrease in water quality with time warrants further investigation.

Several samples reported on here had unusual dominants that had seldom, if ever, been encountered before in these streams. Examples include *Stauroneis heinii* in the summer sample from Site 10, which was found for the first time. *Stauroneis phoenicenteron* has been recorded from this site before in low numbers in 2008 only. The two are similar and the possibility of misidentification cannot be ruled out; however, even if this is the case, the dominance of this taxon on this occasion is unusual. The dominance of an unidentified species of *Gomphonema* at Site 7 in summer, and its appearance in very low numbers at Site 14 in summer, marks the first observation of this taxon in the area.

The similarity in results between sites and over time in samples from Sites 1 and 12, in comparison to those from Site 10, are discussed above. Water quality changes that are associated with this include lower electrical conductivity, and very low oxygen levels at Site 10, with no obvious changes in pH or nutrient levels (see below for a consideration of phosphate levels). Electrical conductivity is a measure of the concentrations of all ions in solution (and their charge), and therefore a fairly crude measure of the ions that are present. It is possible that changes in electrical conductivity include changes in the relative levels of a number of ions, and these may be further responsible for the differences in results between Site 10 and Sites 1 and 12.

It is of interest to note that the high levels of phosphate encountered particularly at Site 1 in winter appeared to have little effect on the diatom index response when compared with results from Site 1 in summer and all samples from Site 12. Phosphate is commonly identified as a limiting nutrient in freshwater systems, and, if so, an increase would be expected to lead to a response by algae. However, neither chlorophyll-a levels nor diatom communities reflect this. It is possible that nitrogen (TIN), or another compound, may be limiting growth of algae in the systems reported on here.

The drop in inferred water quality between site 1 and site 7 has been noted in previous reports (Gordon *et al.* 2008, 2010, Holland *et al.* 2011), as has the change in diatom community structure between these sites. Attention was drawn to this as this change occurs along a relatively short stretch of river, and the possibility that stormwater drainage from the RBM Smelter site may account for the change has been noted. In the data presented here, the decrease in water quality between the two sites is present, but reduced compared to previous years. This is largely a function of the decrease in overall inferred water quality at site 1, although a slight increase in inferred water quality at site 7 also contributes to lowered difference between the sites. Increases in pH and electrical conductivity have been associated with the change in diatom communities along this stretch in the past, and this trend is observed in the current dataset as well.

Inferred water quality degrades with distance downstream such that sites lower on the rivers surveyed are all classed as moderate. This change in inferred water quality is accompanied by increases in pH and electrical conductivity. Particularly along the Mdibi River, the decrease in inferred water quality occurs where rivers pass through or adjacent to settled areas and it is likely that this has some impact.

Table 6. Summary of Site 1 on the Mpisini River.


							
<p>Site description: This site is upstream of the Smelter Site and chosen as a possible reference site. During winter 2011 red floc covering the benthos first appeared and was present in late summer 2012 too. Consequently there was poor GSM habitat available. There is extensive aquatic vegetation but limited marginal vegetation due to low water levels.</p>							
<p>Water quality parameters: (T: temperature; DO: dissolved oxygen; EC: electrical conductivity; TIN: total inorganic nitrogen; SRP: soluble reactive phosphorous; (water quality categories based on the ecological Reserve methodologies for water quality are provided below the values where relevant).</p>							
T (°C)	pH	DO (mg/L)	EC (mS/m)	TIN (mg/L)	SRP (mg/L)	Chlorophyll-a	
						Phytoplankton (µg/L)	Periphyton (mg/m ²)
17.9	5.9	6.7	51.9	0.6	0.3	0.1	18.3
	Good	Good	Good	Good	Poor	Natural	Good
<p>Biological and water quality indices: summary of the main index scores (ASPT: average score per taxon; IHAS: integrated habitat assessment system; diatoms; and water quality) (ecological health categories are largely based on those used for ecological Reserve determinations).</p>							
ASPT		IHAS		Diatoms		Water quality	
3.9		56		3.9		Good	
Poor				Good			
<p>Overall ecological assessment: Good/Fair</p>							

Table 7. Summary of Site 7 on the Mpisini River.



Site description: This site is immediately downstream of the Smelter Site. The surrounding land use is forestry (there is no impact from human settlements). Vegetation and GSM biotopes provide good sampling opportunities. This is the only site which contains gravel and limited stones (sampling of these areas is included in the GSM biotope). This is a cattle drinking site.

Water quality parameters: (T: temperature; DO: dissolved oxygen; EC: electrical conductivity; TIN: total inorganic nitrogen; SRP: soluble reactive phosphorous; (water quality categories based on the ecological Reserve methodologies for water quality are provided below the values where relevant).

T (°C)	pH	DO (mg/L)	EC (mS/m)	TIN (mg/L)	SRP (mg/L)	Chlorophyll- <i>a</i>	
						Phytoplankton (µg/L)	Periphyton (mg/m ²)
18	6.5	7.1	61.9	0.6	0.1	0.1	158.5
	Natural	Good	Fair	Good	Fair	Natural	Poor

Biological and water quality indices: summary of the main index scores (ASPT: average score per taxon; IHAS: integrated habitat assessment system; diatoms; and water quality) (ecological health categories are largely based on those used for ecological Reserve determinations).

ASPT	IHAS	Diatoms	Water quality
4.4	58	3.0	Fair/Good
Poor		Fair	

Overall ecological assessment: Fair

Table 8. Summary of Site 10 on the Manzamnyana River.



Site description: This site consists of a deep wetland lake (upstream of picture) which gradually becomes shallower (pictured above) before flowing very slowly into a wetland. Surrounding land use is forestry with the Smelter Site in close proximity. There are no impacts from human settlements. Vegetation biotope is sampled in the wetland lake, consisting of marginal vegetation (reeds and grass) and aquatic vegetation. GSM biotope is sampled in the shallower part of the lake and consists of sand, anoxic mud and red floc. The GSM is regularly disturbed by cattle passing through and drinking.

Water quality parameters: (T: temperature; DO: dissolved oxygen; EC: electrical conductivity; TIN: total inorganic nitrogen; SRP: soluble reactive phosphorous; (water quality categories based on the ecological Reserve methodologies for water quality are provided below the values where relevant).

T (°C)	pH	DO (mg/L)	EC (mS/m)	TIN (mg/L)	SRP (mg/L)	Chlorophyll-a	
						Phytoplankton (µg/L)	Periphyton (mg/m ²)
18.5	6.3	2.2	41.7	0.7	0.1	1.1	113.0
	Good	Poor	Good	Good	Fair	Natural	Poor

Biological and water quality indices: summary of the main index scores (ASPT: average score per taxon; IHAS: integrated habitat assessment system; diatoms; and water quality) (ecological health categories are largely based on those used for ecological Reserve determinations).

ASPT	IHAS	Diatoms	Water quality
4.2	54	3.2	Fair/Good
Poor		Fair	

Overall ecological assessment: Fair

Table 9. Summary of Site 11 at confluence of the Mpisini and Manzamnyana Rivers.


							
<p>Site description: The site is within a forest at the confluence of the Mpisini and Manzamnyana Rivers, downstream of the Smelter Site. Surrounding land use is forestry with no effects from human settlements. There is very limited vegetation biotope available for sampling, particularly during the lower flows. Vegetation sampled usually consists of marginal vegetation leaves that dip into the water, root wads and twig snarls. GSM biotope consists of sand and mud.</p>							
<p>Water quality parameters: (T: temperature; DO: dissolved oxygen; EC: electrical conductivity; TIN: total inorganic nitrogen; SRP: soluble reactive phosphorous; (water quality categories based on the ecological Reserve methodologies for water quality are provided below the values where relevant).</p>							
T (°C)	pH	DO (mg/L)	EC (mS/m)	TIN (mg/L)	SRP (mg/L)	Chlorophyll- <i>a</i>	
						Phytoplankton (µg/L)	Periphyton (mg/m ²)
18	6.5	7.0	61.2	0.6	0.1	0.1	36.0
	Good	Good	Fair	Good	Fair	Natural	Fair
<p>Biological and water quality indices: summary of the main index scores (ASPT: average score per taxon; IHAS: integrated habitat assessment system; diatoms; and water quality) (ecological health categories are largely based on those used for ecological Reserve determinations).</p>							
ASPT		IHAS		Diatoms		Water quality	
5.7		43		3.8		Good/Fair	
Fair				Good			
<p>Overall ecological assessment: Good/Fair</p>							

Table 10. Summary of Site 12 on the Mdibi River



Site description: This is the uppermost site on the Mdibi River and tentatively proposed as a reference site for this river. Surrounding land use is forestry and some limited human settlement. The GSM biotope consists of sand, some mud and limited leaf litter. Vegetation habitat consists of aquatic plants and marginal grasses.

Water quality parameters: (T: temperature; DO: dissolved oxygen; EC: electrical conductivity; TIN: total inorganic nitrogen; SRP: soluble reactive phosphorous; (water quality categories based on the ecological Reserve methodologies for water quality are provided below the values where relevant).

T (°C)	pH	DO (mg/L)	EC (mS/m)	TIN (mg/L)	SRP (mg/L)	Chlorophyll-a	
						Phytoplankton (µg/L)	Periphyton (mg/m ²)
13 (winter only)	6.3	6.7	47.6	0.6	0.1	0.03	62.0
	Good	Good	Good	Good	Fair	Natural	Fair

Biological and water quality indices: summary of the main index scores (ASPT: average score per taxon; IHAS: integrated habitat assessment system; diatoms; and water quality) (ecological health categories are largely based on those used for ecological Reserve determinations).

ASPT	IHAS	Diatoms	Water quality
5.3	50	4.2	Good
Fair		Good	

Overall ecological assessment: Good

Table 11. Summary of Site 13 on the Mdibi River.


							
<p>Site description: The site is located downstream of a bridge culvert. Surrounding land use includes forestry and settlements. Vegetation biotope is dominated by reed stalks and leaves, although there are some aquatic plants available. GSM biotope is limited, usually consisting of some mud and sand which is covered by thick shredded leaf litter.</p>							
<p>Water quality parameters: (T: temperature; DO: dissolved oxygen; EC: electrical conductivity; TIN: total inorganic nitrogen; SRP: soluble reactive phosphorous; (water quality categories based on the ecological Reserve methodologies for water quality are provided below the values where relevant).</p>							
T (°C)	pH	DO (mg/L)	EC (mS/m)	TIN (mg/L)	SRP (mg/L)	Chlorophyll-a	
						Phytoplankton (µg/L)	Periphyton (mg/m ²)
19.2	7.1	6.6	58.1	0.6	0.1	0.06	128.9
	Natural	Good	Fair	Good	Fair	Natural	Poor
<p>Biological and water quality indices: summary of the main index scores (ASPT: average score per taxon; IHAS: integrated habitat assessment system; diatoms; and water quality) (ecological health categories are largely based on those used for ecological Reserve determinations).</p>							
ASPT		IHAS		Diatoms		Water quality	
5.6		50		3.0		Good/Fair	
Fair				Fair			
<p>Overall ecological assessment: Fair/Good</p>							

Table 12. Summary of Site 14 on the Mdibi River.



Site description: This is the lowermost site on the Mdibi River, situated upstream from Lake Mzingazi. Surrounding land use is subsistence forestry and human settlements. Vegetation biotope usually consists of marginal reeds, grasses and aquatic plants. GSM consists of good sand and mud sampling biotope. Irregular disturbance by cows has been noted.

Water quality parameters: (T: temperature; DO: dissolved oxygen; EC: electrical conductivity; TIN: total inorganic nitrogen; SRP: soluble reactive phosphorous; (water quality categories based on the ecological Reserve methodologies for water quality are provided below the values where relevant).

T (°C)	pH	DO (mg/L)	EC (mS/m)	TIN (mg/L)	SRP (mg/L)	Chlorophyll-a	
						Phytoplankton (µg/L)	Periphyton (mg/m ²)
19.0	6.7	5.6	55.2	0.6	0.2	0.02	26.0
	Natural	Fair	Fair	Good	Poor	Natural	Fair

Biological and water quality indices: summary of the main index scores (ASPT: average score per taxon; IHAS: integrated habitat assessment system; diatoms; and water quality) (ecological health categories are largely based on those used for ecological Reserve determinations).

ASPT	IHAS	Diatoms	Water quality
6.1	47	3.0	Fair/Good
Good		Fair	

Overall ecological assessment: Fair/Good

4 Results and discussion of limited biomonitoring

In the sections below, water quality, habitat and biological monitoring data collected at Site 11 during limited sampling undertaken in spring (November) 2011 are presented. Data from the comprehensive sampling undertaken during winter 2011 and late summer 2012 are included for comparative purposes.

4.1 Water quality assessment

Water temperatures recorded at Site 11 ranged between 16 °C and 20°C (Figure 12A). Measurements of pH were classified as Natural to Good (Figure 12B). Electrical conductivity was classified as Fair during all seasons (Figure 12C). Dissolved oxygen concentrations ranged from Fair to Good (Figure 12D).

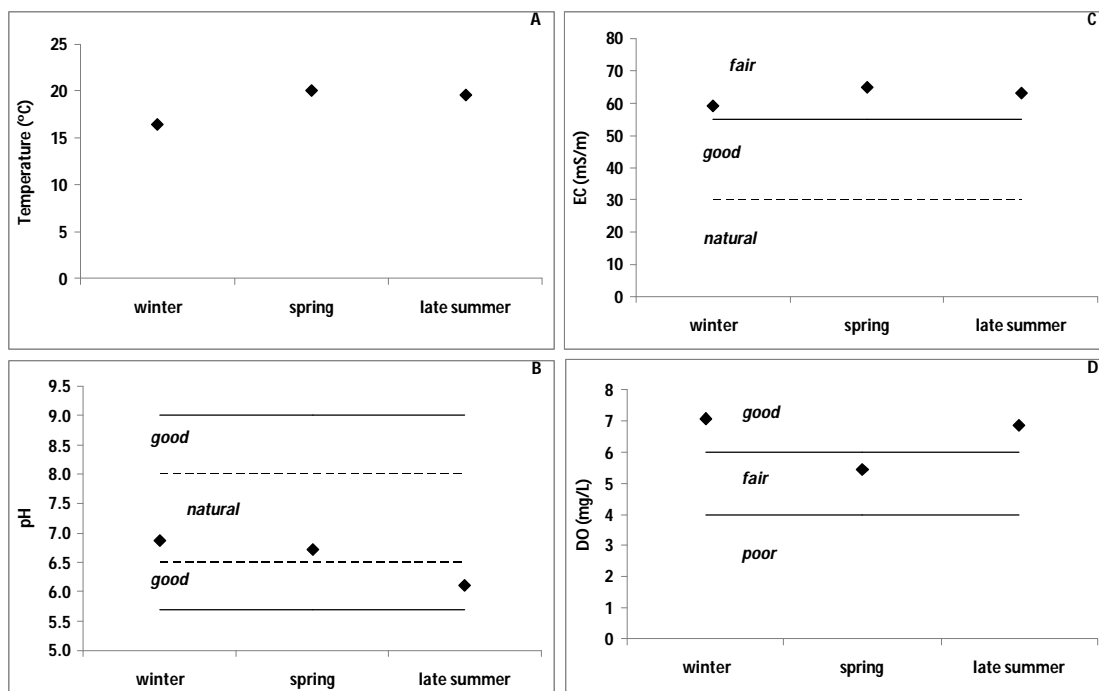


Figure 12A-D. Temperature, pH, electrical conductivity (EC), and dissolved oxygen (DO) values measured at sampling Site 11 over four seasons. Default ecological categories based on ecological Reserve determination methodologies are superimposed on the graphs.

4.2 SASS and habitat assessment

SASS scores, number of families and ASPT values were lower in late summer 2012, likely due to the effects of tropical storm Irina (Figure 13A-C). The ASPT score in winter 2011 bordered on the Good/Fair boundary, while in spring and late summer ASPT was classified as Fair (Figure 13C). IHAS scores were low due to the absence of a stones biotope with little seasonal variation (Figure 13D). Site 11 was badly affected by low flows in winter 2011 which reduced available vegetation sampling habitat, adding to the low IHAS score. All raw data for the water quality and SASS assessments are supplied in Appendix 5.

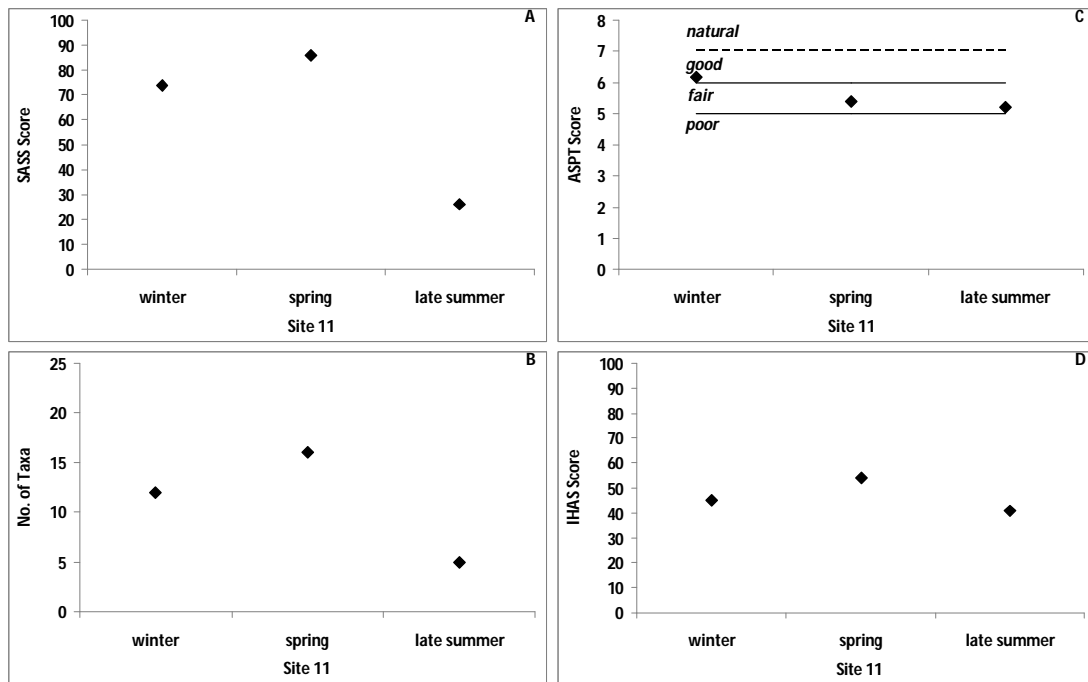


Figure 13A-D South African Scoring System (SASS) score (A), number of families/taxa sampled (B) and Average Score Per Taxon (ASPT) values (C) determined for Site 11 over four seasons. Default ecological categories for ASPT based on ecological Reserve determination methodologies are superimposed on graph C.

Total taxa collected at Site 11 per season ranged between 5 and 16, with spring 2011 being the taxa richest season and late summer 2012 the taxa poorest (Table 13). The average number of taxa collected during the assessment year 2011/2012 was 11 and the overall total number of taxa per year was 23. The numbers of taxa are lower than the previous assessment year (2010/2011) in which the average number of taxa sampled was 15.5 and the total number 25. This decline is likely due to the effects of tropical storm Irina causing low numbers of taxa to be collected in late summer 2012. A list of taxa collected at Site 11 during four sampling trips in different seasons is supplied in Appendix 6.

Table 13. Total taxa per season and average taxa per year collected at Site 11.

Year Month Season	2011 August winter	2011 November spring	2012 April late summer
Total taxa per season	12	16	5
Average taxa per year	11		
Total taxa per year	23		

5 Conclusion

A summary of the indices measured is provided in Table 1. A provisional overall aquatic ecological health assessment for each of the sites assessed is provided. It must be noted that the methods used to provide the subsequent categories are largely based on expert opinion and assessment of the available data. In addition, the boundary values for the categories are based on the default values provided by the ecological Reserve method and require site-specific refinement.

Upstream sites on the Mpisini and Mdibi Rivers (Sites 1 and 12) possessed the best water quality in terms of the water chemistry data measured. Although the water at these sites was relatively acidic, there were low dissolved salt levels and Good levels of DO. There was some evidence of increased SRP at Site 1, but only during the one season sampled. The diatom community indices confirm the Good water quality status of these sites. However the macroinvertebrate community data and indices were Poor, particularly at Site 1. This result is probably a consequence of poorer macroinvertebrate habitat. The recent occurrence of red floc at this site has further reduced the number of taxa associated with the GSM biotope.

Site 10, upstream on the Manzamnyama River, had poorer water quality as inferred from diatom and macroinvertebrate indices and from the water quality parameters measured. This site is driven by groundwater, and the resultant DO values measured there are considerably lower than at all other sites. In addition, there is poor sampling habitat for macroinvertebrates at this site.

The diatom indices suggest a water quality impact may be occurring between Sites 1 and 7. Measured EC, pH and BOD show increases between the two sites. In contrast, macroinvertebrate indices improve between the two sites, although this is probably due to improved macroinvertebrate habitat at Site 7. The smelter complex is situated immediately upstream of Site 7, and as there appears to be limited impact from human settlements, it is possible that this water quality impairment may be related to the activities of the smelter. Further monitoring of changes in water quality between these sites is recommended to identify the cause of the change.

As in the past, water quality as inferred from diatom indices was found to improve from Site 7 on the Mpisini to Site 11, at the confluence of the Mpisini and Manzamnyama Rivers (Gordon et al. 2008, 2010). This can be attributed either to recovery along the Mpisini, or dilution of Mpisini water by Manzamnyama water at Site 11, or both. The input of water from the Mpisini and Manzamnyama rivers to the Mdibi River between Sites 13 and 14 appears to have no detrimental effect in terms of the diatom and macroinvertebrate indices and water quality parameters measured.

Overall water quality as inferred from diatom indices shows a decreasing trend with time over the last three years. While the patterns between sites have remained largely the same, the inferred water quality at all sites has decreased to some extent, and most sites are in lower classes in more recent samples.

In the current study, additional limited biomonitoring was undertaken at Site 11 in autumn (November 2011). There was little change in the water quality parameters at this site over the different seasons. SASS score, number of taxa and ASPT were particularly affected by tropical storm Irina as reflected in the late summer sampling results. An overview of total

taxa per season and average taxa per year collected at Site 11 is provided in Table 2 in the summary and Table 13 in the results section.

The biological data collected so far will go towards establishing better site-specific reference conditions, and may be useful in assessing the validity of recalibrating the benchmark boundary values for water quality parameters to yield site specific boundary values.

6 References

- Anderson MJ (2001). A new method for non-parametric multivariate analysis of variance. *Austral Ecology* 26: 32-46.
- APHA (1992) *Standard methods for the examination of water and wastewater*. 18th ed. American Public Health Association, Washington, DC.
- Clarke KR and Warwick RM (2001) *Change in marine communities: an approach to statistical analysis and interpretation*. 2nd edition. PRIMER-E: Plymouth.
- Cemagref (1982) *Etude des méthodes biologiques quantitatives d'appréciation de la qualité des eaux*. Rapport Division Qualité des Eaux Lyon. Agence financiè de Bassin Rhone-Méditerranée. Corse, Pierre-Bénite. 28 pp.
- Coste M, Boutry S, Tison-Rosebery J and Delmas F (2009) Improvements of the Biological Diatom Index (BDI): Description and efficiency of the new version (BDI-2006). *Ecological Indicators* 9: 621-650.
- Dallas HF (2007) *River Health Programme: South African Scoring System (SASS) Data Interpretation Guidelines*. The Freshwater Consulting Group / Freshwater Research Unit, University of Cape Town, South Africa.
- Dickens CWS and Graham PM (2002) The South African Scoring System (SASS) Version 5 rapid bioassessment method for rivers. *African Journal of Aquatic Science* 27: 1-10
- DWA (2008) *Methods for determining the Water Quality component of the Ecological Reserve*. Department of Water Affairs, South Africa. Second Draft. Prepared by P-A Scherman of Scherman Consulting.
- Eloranta P and Soininen J (2002) Ecological status of some Finnish rivers evaluated using benthic diatom communities. *Journal of Applied Phycology* 14: 1-7.
- Gordon AK, Griffin NJ and Muller WJ (2008) *Environmental water quality monitoring for Richards Bay Minerals: Smelter Site area*. Unpublished report submitted to RBM by Institute for Water Research.
- Gordon AK, Griffin NJ and Holland AJ (2010) *Environmental water quality monitoring for Richards Bay Minerals: Smelter Site area*. Unpublished report submitted to RBM by Institute for Water Research.
- Holland AJ, Griffin NJ and Gordon AK (2011) *Environmental water quality monitoring for Richards Bay Minerals: Smelter site area*. Unpublished report submitted to RBM by Institute for Water Research.
- Holm-Hansen O and Riemann B (1978) Chlorophyll *a* determination: improvements in methodology. *Oikos* 30: 438-447.
- McMillan PH (1998) *An integrated habitat assessment system (IHAS V2), for the rapid biological assessment of rivers and streams*. CSIR Research Project Number ENVP- I 98132

for the Water Resources Management Programme, Council for Scientific and Industrial Research, Pretoria

Muller WJ, Gordon AK and Griffin NJ (2007) *Environmental water quality monitoring for Richards Bay Minerals: Smelter Site*. Unpublished report submitted to RBM by Institute for Water Research.

Oksanen J, Blanchet FG, Kindt R, Legendre P, O'Hara RB, Simpson GL, Solymos P, Stevens MHM and Wagner H (2010) *vegan: Community Ecology Package*. R package version 1.17-2. URL <http://CRAN.R-project.org/package=vegan>.

Palmer CG, Muller WJ and Hughes DA (2004) Chapter 6: Water quality in the ecological reserve. IN: *SPATSIM, An Integrating Framework For Ecological Reserve Determination and Implementation*. Hughes DA (Ed.). WRC Report No. 1160/1/04, Water Research Commission, Pretoria, South Africa.

Prygiel J and Coste M (2000) *Guide méthodologique pour la mise en oeuvre de l'Indice Biologique Diatomées NF T 90–354*. Agences de l'Eau – Cemagref-Groupement de Bordeaux. Agences de l'Eau, mars 2000, 134 pp + clés de détermination (90 planches couleurs) + cédérom bilingue français-anglais(Tax'IBD).

R Development Core Team (2010) *R: A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL <http://www.R-project.org>.

Spaulding SA, Lubinski DJ and Potapova M (2010). *Diatoms of the United States*. URL <http://westerndiatoms.colorado.edu>. Accessed on 06 July, 2012.

Taylor JC, Harding WR and Archibald CGM (2007a) *A methods manual for the collection, preparation and analysis of diatom samples*. Water Research Commission Report TT 281/07.

Taylor JC, Janse van Vuuren MS and Pieterse AJH (2007b) The application and testing of diatom-based indices in the Vaal and Wilge Rivers, South Africa. *Water SA* 33: 51-59.

Taylor JC, Prygiel J, Vosloo A, de la Rey PA and van Rensburg L (2007c) Can diatom-based pollution indices be used for biomonitoring in South Africa? A case study of the Crocodile West and Marico water management area. *Hydrobiologia* 592:455–464

Taylor JC, Harding WR and Archibald CGM (2007d) *An illustrated guide to some common diatom species from South Africa*. Water Research Commission Report TT 282/07.

Van Dam H, Mertens A, Sinkeldam J (1994) A coded checklist and ecological indicator values of freshwater diatoms from the Netherlands. *Netherlands Journal of Aquatic Ecology* 28: 117-133.

7 Appendices

Appendix 1. Diatom index scores from sample sites in the Smelter area August 2011-April 2012 are presented below. Scores range from 0-20 for IPS and BDI-2006 indices, and from 1-5 for the index based on expert opinion. Site classifications based on the indices are also presented.

Site	Date	IPS		BDI-2006		Expert opinion	
		Index	Class	Index	Class	Index	Class
1	Aug 2011	14.4	Moderate	13.8	Good	5	High
1	Apr 2012	13.1	Moderate	12.5	Moderate	5	High
10	Aug 2011	11.4	Poor	12.9	Moderate	2	Poor
10	Apr 2012	15.6	Good	13.7	Good	4	Good
11	Aug 2011	16.9	Good	11.1	Moderate	4	Good
11	Apr 2012	14.7	Moderate	13.4	Good	5	High
12	Aug 2011	15.9	Good	15.9	Good	5	High
12	Apr 2012	17.0	Good	11.5	Moderate	5	High
13	Aug 2011	11.1	Poor	11.1	Moderate	3	Moderate
13	Apr 2012	13.6	Moderate	13.0	Moderate	3	Moderate
14	Aug 2011	12.2	Moderate	11.2	Moderate	2	Poor
14	Apr 2012	15.7	Good	11.9	Moderate	3	Moderate
7	Aug 2011	13.3	Moderate	12.4	Moderate	3	Moderate
7	Apr 2012	13.1	Moderate	10.3	Moderate	3	Moderate

Appendix 2. Summary of water chemistry and nutrient analyses undertaken. Detection limits were as follows: Ammonium (NH₄⁺): 0.05mg/L; Nitrites (NO₂⁻): 0.01mg/L; Nitrates (NO₃⁻): 0.5mg/L; Soluble Reactive Phosphorus (SRP): 0.05mg/L. Total Inorganic Nitrogen (TIN) were calculated by adding NH₄⁺, NO₂⁻ and NO₃⁻. Values below detection limit are shown as half the detection limit (NH₄⁺= 0.025mg/L; NO₂⁻=0.005mg/L; NO₃⁻=0.25mg/L; SRP=0.025mg/L). TIN=0.280mg/L indicates that all added parameters were below the detection limit.

Site Code	River	Month	Season	Year	Sass Score	No. of Taxa	ASPT Score	IHAS Score [%]	Temp [°C]	DO [mg/L]	pH	EC [mS/m]	NH4 [mg/L]	NO3 [mg/L]	NO2 [mg/L]	TIN [mg/L]	SRP [mg/L]	Phyto-plankton chl-a [µg/L]	Periphyton chl-a [ug/cm2]	Turbidity [ntu]	BOD5 [mg/L]
1	Mpisini	August	winter	2011	21	6	3.5	59	15.2	7.5	5.7	59.2	0.05	0.50	0.01	0.56	0.50	0.02	29.27	4.3	1.0
7	Mpisini	August	winter	2011	84	19	4.4	71	16.0	7.7	7.0	60.0	0.05	0.50	0.01	0.56	0.13	0.22	297.94	4.6	1.0
10	Manzamnyama	August	winter	2011	39	10	3.9	54	15.0	3.2	6.3	45.6	0.13	0.50	0.02	0.65	0.14	1.27	127.57	18.1	1.0
11	Confluence	August	winter	2011	74	12	6.2	45	16.5	7.1	6.9	59.2	0.05	0.50	0.01	0.56	0.12	0.10	68.12	17.0	1.0
12	Mdibi	August	winter	2011	68	11	6.2	58	13.0	7.4	6.3	54.0	0.05	0.50	0.01	0.56	0.12	0.02	59.45	1.2	1.0
13	Mdibi	August	winter	2011	58	11	5.3	51	16.3	6.8	7.0	67.0	0.05	0.50	0.02	0.57	0.11	0.04	3.47	3.4	1.0
14	Mdibi	August	winter	2011	66	12	5.5	43	17.0	5.0	6.6	58.8	0.12	0.50	0.01	0.63	0.33	0.02	40.94	4.0	1.0
11	Confluence	November	spring	2011	86	16	5.4	54	20.0	5.4	6.7	65.0								8.6	
1	Mpisini	April	late summer	2012	21	5	4.2	52	20.5	5.9	6.1	44.6	0.05				0.05	0.19	7.33	4.2	2.0
7	Mpisini	April	late summer	2012	44	10	4.4	45	20.0	6.6	6.0	63.7	0.05				0.05	0.05	19.06	7.4	3.0
10	Manzamnyama	April	late summer	2012	32	7	4.6	53	22.0	1.2	6.4	37.8	0.05				0.05	0.91	98.52	27.4	2.0
11	Confluence	April	late summer	2012	26	5	5.2	41	19.5	6.9	6.1	63.2	0.05				0.05	0.12	3.73	12.3	2.0
12	Mdibi	April	late summer	2012	31	7	4.4	57		6.1	6.4	41.2	0.05				0.05	0.03	64.56	6.0	2.0
13	Mdibi	April	late summer	2012	60	10	6.0	49	22.0	6.5	7.2	49.2	0.05				0.05	0.09	254.34	6.9	3.0
14	Mdibi	April	late summer	2012	33	5	6.6	51	21.0	6.2	6.8	51.7	0.05				0.05	0.01	11.15	7.5	2.0

Appendix 3. Summary of number of macroinvertebrate taxa found at each sampling site in both seasons (August = winter, April = late summer).

Site	1	7	10	11	12	13	14	1	7	10	11	12	13	14
Month	Aug	Aug	Aug	Aug	Aug	Aug	Aug	Apr	Apr	Apr	Apr	Apr	Apr	Apr
Season	winter	winter	winter	winter	winter	winter	winter	summer	summer	summer	summer	summer	summer	summer
Year	2011	2011	2011	2011	2011	2011	2011	2012	2012	2012	2012	2012	2012	2012
Oligochaeta	0	6	0	0	0	1	1	2	2	57	7	0	26	4
Leeches	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Amphipoda	0	0	0	3	0	0	1	0	0	0	0	0	27	0
Potamonautidae	6	7	0	2	0	2	1	3	9	0	2	1	1	0
Atyidae	0	48	0	99	224	115	237	0	58	0	86	117	79	188
Hydracarina	0	0	2	0	0	0	0	0	0	3	0	0	0	0
Baetidae	0	177	6	41	30	52	2	0	1	4	4	9	83	6
Caenidae	0	21	0	3	0	28	21	0	4	0	0	1	9	3
Tricorythidae	0	1	0	4	0	5	3	0	2	0	2	1	1	3
Chlorocyphidae	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Coenagrionidae	5	12	4	2	7	11	3	2	3	6	1	0	3	7
Aeshnidae	0	0	0	0	4	0	0	0	0	0	0	0	0	0
Gomphidae	2	2	0	0	0	2	1	11	0	11	0	3	1	6
Libellulidae	0	0	0	1	0	1	0	1	1	7	0	0	0	0
Gerridae	0	0	2	0	2	0	0	0	0	0	11	7	1	0
Hydrometridae	0	0	0	1	1	0	0	0	0	0	0	0	0	0
Nepidae	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Notonectidae	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Pleidae	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Veliidae	0	1	0	1	0	0	0	0	0	2	0	0	0	0
Ecnomidae	2	3	0	0	0	0	0	1	1	0	0	0	0	1
Hydropsychidae	0	4	0	0	0	0	0	0	9	0	0	2	1	0
Hydroptilidae	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Lepidostomatidae	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Leptoceridae	1	0	0	0	9	5	12	0	0	0	0	0	2	1
Dytiscidae	0	0	5	0	2	0	0	0	1	5	0	0	0	0
Elmidae/Dryopidae	0	2	0	0	0	0	0	0	1	0	0	0	1	0
Gyrinidae	1	4	0	2	0	0	0	1	0	0	6	0	1	0
Helodidae	0	0	0	0	0	0	3	0	1	1	0	0	0	0
Hydraenidae	0	0	0	0	0	0	0	0	4	0	2	0	0	0
Hydrophilidae	0	0	0	0	0	0	0	0	0	2	0	0	0	0
Athericidae	0	0	0	2	0	0	0	0	1	0	0	0	0	0
Ceratopogonidae	0	4	13	1	0	1	0	1	3	15	0	0	0	0
Chironomidae	43	2	22	13	2	8	5	21	9	27	3	4	10	1
Culicidae	4	4	1	0	1	0	1	1	1	3	0	1	0	0
Muscidae	0	1	0	0	0	1	1	0	0	0	0	0	0	0
Psychodidae	0	2	0	4	0	0	1	0	0	0	0	0	0	0
Simuliidae	0	60	0	13	0	1	3	0	0	0	0	2	0	0
Tipulidae	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Ancylidae	0	1	0	2	1	0	0	0	0	0	0	0	0	0
Lymnaeidae	0	0	0	0	0	0	0	0	0	1	0	3	0	0
Physidae	0	1	0	0	0	1	0	0	1	0	0	0	0	0
Planorbinae	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Thiaridae	0	2	0	0	0	0	0	0	12	0	0	0	0	0
Corbiculidae	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Isopoda	0	19	0	0	0	0	0	0	0	0	0	0	0	0
Pyralidae	0	0	1	0	0	0	0	0	0	0	0	0	0	0

Appendix 4. Diatoms present at sample sites in the Smelter area August 2011–April 2012 follow. Where diatoms could not be identified, morphospecies were assigned and used in all analyses.

Site	1		10		11		12		13		14		7	
	2011	2012	2011	2012	2011	2012	2011	2012	2011	2012	2011	2012	2011	2012
	Aug	Apr	Aug	Apr	Aug	Apr	Aug	Apr	Aug	Apr	Aug	Apr	Aug	Apr
<i>Achnanthes divergens</i>							X							
<i>Achnanthes oblongella</i>	X	X			X	X	X	X	X	X		X	X	X
<i>Achnanthes pulviscula</i>	X	X				X	X	X			X	X		X
<i>Achnantheidium affine</i>									X		X			
<i>Achnantheidium biasolettianum</i>			X											
<i>Achnantheidium deflexum</i>								X						
<i>Achnantheidium eutrophilum</i>										X				
<i>Achnantheidium exiguum</i>			X			X		X						
<i>Achnantheidium minutissimum</i>	X		X		X	X			X	X	X	X	X	X
<i>Achnantheidium rivulare</i>	X													
<i>Achnantheidium saprophilum</i>						X			X	X	X			
<i>Adlafia bryophila</i>		X												
<i>Brachysira aff. steindorfiana</i>	X	X		X		X	X	X	X					
<i>Brachysira brebissonii</i>			X											
<i>Brachysira sp2</i>		X	X	X		X	X	X		X	X	X	X	
<i>Brachysira styriaca</i>				X										
<i>Caloneis bacillum</i>				X										
<i>Caloneis hyalina</i>			X			X		X			X			

Site	1		10		11		12		13		14		7	
	2011	2012	2011	2012	2011	2012	2011	2012	2011	2012	2011	2012	2011	2012
	Aug	Apr	Aug	Apr	Aug	Apr	Aug	Apr	Aug	Apr	Aug	Apr	Aug	Apr
<i>Capartogramma crucicula</i>						X				X		X		
<i>Cocconeis placentula</i>					X									
<i>Cocconeis placentula</i> var. <i>euglypta</i>				X		X						X		
<i>Craticula accomoda</i>									X					
<i>Craticula buderi</i>		X												
<i>Cyclostephanos dubius</i>						X								
<i>Cyclotella meneghiniana</i>				X										
<i>Cymbella leptoceros</i>										X				
<i>Denticula subtilis</i>						X								
<i>Diadесmis confervacea</i>			X										X	
<i>Diadесmis contenta</i>						X			X	X	X		X	
<i>Diploneis</i> sp1														X
<i>Diploneis subovalis</i>										X				
<i>Discostella pseudostelligera</i>				X		X								
<i>Discostella stelligera</i>			X											
<i>Encyonema mesianum</i>				X										
<i>Encyonopsis subminuta</i>						X								
<i>Eolimna subminuscula</i>						X		X						
<i>Eunotia bilunaris</i>				X							X			
<i>Eunotia minor</i>						X	X		X					
<i>Eunotia similis</i>								X						

Site	1		10		11		12		13		14		7	
	2011	2012	2011	2012	2011	2012	2011	2012	2011	2012	2011	2012	2011	2012
	Aug	Apr	Aug	Apr	Aug	Apr	Aug	Apr	Aug	Apr	Aug	Apr	Aug	Apr
<i>Eunotia</i> sp1					X									
<i>Eunotia</i> sp2	X	X						X	X		X	X		X
<i>Eunotia</i> sp4		X				X								
<i>Fragilaria capucina</i> var. <i>vaucheriae</i>				X										X
<i>Fragilaria ulna</i> var. <i>acus</i>														X
<i>Frustulia crassinerva</i>		X									X			
<i>Frustulia</i> sp1														X
<i>Gomphonema</i> aff. <i>gracile</i>			X	X	X									
<i>Gomphonema</i> aff. <i>lagenula</i>							X							
<i>Gomphonema affine</i>												X		
<i>Gomphonema angustatum</i>	X						X		X			X	X	X
<i>Gomphonema clavatum</i>										X		X		
<i>Gomphonema gracile</i>		X		X									X	X
<i>Gomphonema insigne</i>									X				X	
<i>Gomphonema lagenula</i>									X	X				
<i>Gomphonema parvulum</i>			X		X	X	X		X	X		X	X	X
<i>Gomphonema parvulum</i> f. <i>saprophilum</i>									X					
<i>Gomphonema procerum</i>											X			
<i>Gomphonema pseudoaugur</i>									X			X		
<i>Gomphonema pumilum</i> var.									X	X		X	X	X

Site	1		10		11		12		13		14		7	
	2011	2012	2011	2012	2011	2012	2011	2012	2011	2012	2011	2012	2011	2012
	Aug	Apr	Aug	Apr	Aug	Apr	Aug	Apr	Aug	Apr	Aug	Apr	Aug	Apr
<i>rigidum</i>														
<i>Gomphonema</i> sp10				X										
<i>Gomphonema</i> sp9												X		X
<i>Gomphonema venusta</i>														
<i>Gomphosphenia</i> aff. <i>oahuensis</i>													X	X
<i>Hantzschia amphioxys</i>												X		
<i>Luticola goeppertiana</i>						X						X		
<i>Luticola kotschyi</i>			X	X								X		
<i>Luticola mutica</i>												X		
<i>Luticola</i> sp1										X				
<i>Mayamaea atomus</i>		X								X		X		
<i>Mayamaea atomus</i> var. <i>permitis</i>											X			
<i>Navicula arvensis</i> var. <i>maior</i>	X		X									X		
<i>Navicula caterva</i>			X											
<i>Navicula cryptocephala</i>										X				
<i>Navicula cryptotenelloides</i>						X								
<i>Navicula erifuga</i>			X								X		X	
<i>Navicula gregaria</i>			X		X	X			X	X	X		X	
<i>Navicula libonensis</i>					X									
<i>Navicula longicephala</i>							X				X			

Site	1		10		11		12		13		14		7	
	2011	2012	2011	2012	2011	2012	2011	2012	2011	2012	2011	2012	2011	2012
	Aug	Apr	Aug	Apr	Aug	Apr	Aug	Apr	Aug	Apr	Aug	Apr	Aug	Apr
<i>Navicula microcari</i>			X						X					
<i>Navicula namibica</i>												X		
<i>Navicula notha</i>										X				
<i>Navicula recens</i>									X				X	
<i>Navicula riediana</i>									X					
<i>Navicula rostellata</i>											X			
<i>Navicula schroeteri</i>	X				X				X	X			X	X
<i>Navicula seibigiana</i>						X								
<i>Navicula sp1</i>			X				X	X	X		X			
<i>Navicula sp8</i>									X					
<i>Navicula tenelloides</i>							X	X	X				X	
<i>Navicula vandamii</i>									X	X	X	X		
<i>Navicula veneta</i>						X		X	X					
<i>Navicymbula pusilla</i>			X											
<i>Neidium bisulcatum</i>											X			
<i>Nitzschia acidoclinata</i>	X													
<i>Nitzschia capitellata</i>		X	X								X			
<i>Nitzschia clausii</i>	X	X				X				X	X			
<i>Nitzschia communis</i>			X											
<i>Nitzschia desertorum</i>				X										
<i>Nitzschia filiformis</i>										X			X	

Site	1		10		11		12		13		14		7	
	2011	2012	2011	2012	2011	2012	2011	2012	2011	2012	2011	2012	2011	2012
	Aug	Apr	Aug	Apr	Aug	Apr	Aug	Apr	Aug	Apr	Aug	Apr	Aug	Apr
<i>Nitzschia fonticola</i>	X	X												
<i>Nitzschia frustulum</i>				X		X			X		X			X
<i>Nitzschia inconspicua</i>								X						X
<i>Nitzschia liebetruthii</i>											X			X
<i>Nitzschia linearis</i>			X											
<i>Nitzschia microcephala</i>			X							X	X			
<i>Nitzschia nana</i>				X										
<i>Nitzschia palea</i>			X						X		X			
<i>Nitzschia paleaeformis</i>				X										
<i>Nitzschia perminuta</i>						X							X	
<i>Nitzschia pusilla</i>	X													
<i>Nitzschia sp1</i>														X
<i>Nitzschia sp9</i>										X				
<i>Nitzschia sublinearis</i>			X											
<i>Nitzschia supralitorea</i>		X												
<i>Nitzschia valdecostata</i>							X				X			
<i>Pinnularia biceps</i>									X					
<i>Pinnularia sinistra</i>									X					
<i>Pinnularia sp6</i>				X										
<i>Pinnularia subcapitata</i>				X		X								
<i>Placoneis dicephala</i>			X								X			

Site	1		10		11		12		13		14		7	
	2011	2012	2011	2012	2011	2012	2011	2012	2011	2012	2011	2012	2011	2012
	Aug	Apr	Aug	Apr	Aug	Apr	Aug	Apr	Aug	Apr	Aug	Apr	Aug	Apr
<i>Planothidium frequentissimum</i>				X										
<i>Planothidium rostratum</i>						X								
<i>Pleurosigma salinarum</i>										X				
<i>Sellaphora pupula</i>	X		X								X			
<i>Stauroneis heinii</i>				X										
<i>Stauroneis obtusa</i>												X		
<i>Stauroneis pachycephala</i>		X		X										
<i>Tabularia fasciculata</i>														X
<i>Tryblionella</i> sp1						X								

Appendix 5. Summary of biomonitoring and water chemistry at Site 11 during three seasons.

Month	Season	Year	Sass Score	No. of Taxa	ASPT Score	IHAS Score (%)	Temp (°C)	DO (mg/L)	pH	EC (mS/m)
August	winter	2011	74	12	6.2	45	16.5	7.1	6.9	59.2
November	spring	2011	86	16	5.4	54	20.0	5.3	6.7	65.1
April	late summer	2012	26	5	5.2	41	19.5	6.9	6.1	63.2

Appendix 6. List of macroinvertebrate taxa collected at Site 11 during three seasons using the SASS5 method.

Abundances are estimated as follows: 1 = 1, A = 2-10, B = 10-100.

Month	Aug	Nov	Apr
Year	2011	2011	2012
Oligochaeta		1	
Amphipoda	A		
Potamonautidae	1		
Atyidae	B	B	A
Hydracarina		A	
Baetidae	B	A	1
Caenidae		1	
Tricorythidae	A	A	
Chlorocyphidae		1	
Coenagrionidae		B	1
Gomphidae		A	
Libellulidae		A	
Gerridae		B	A
Hydrometridae	1		
Notonectidae		A	
Veliidae	1	A	
Leptoceridae		B	
Gyrinidae	1		A
Ceratopogonidae	1		
Chironomidae	A	A	
Psychodidae	1		
Simuliidae	B		
Thiaridae		B	
Total taxa per season	12	16	5
Average taxa per year	11		
Total taxa per year	23		