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

Report for 2009/2010

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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. Data reported were collected during winter of 2009 and summer of 2010. 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	Fair	56	Good	Natural	Good
7	Fair	73	Good/Fair	Fair	Fair
10	Poor	42	Fair	Good	Fair
11	Fair	42	Good	Fair	Fair/Good
12	Fair	48	Good	Natural	Good
13	Good	53	Good	Good	Good
14	Fair	53	Good	Good	Good/Fair

Overall, the scores indicate that the rivers assessed were in good condition at the top of their reaches, and that ecological health decreased as one moved downstream. It is not possible to determine whether the decrease in ecological health class from Good at site 13 to Good/Fair at site 14 is due to the input of water from the Mpisini and Manzamnyna rivers which drain the smelter complex or from impacts of human habitation occurring between site 13 and 14. This decrease is quite small in either case.

The low macroinvertebrate ASPT values recorded at upstream “reference” sites (1 and 12) are related to poor availability of sampling habitat. Low water levels reduced the marginal vegetation available, gravel/sand/mud has always been limited at these sites and stones-in-current biotope (with which more sensitive macroinvertebrates are usually associated) is absent. High diatom index scores and good water quality results suggest that these sites are indeed in good condition.

As diatoms are less affected by habitat availability they probably provide a better indication of the water quality impacts at sampled sites. The results from the diatom community assessment indicate a clear degradation of water quality between sites 1 and 7 on the Mpisini River. This is not reflected in the scores based on macro-invertebrates or the physicochemical parameters that were used in this assessment. 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.

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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 2009 and summer 2010.

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.

The specific tasks for winter 2009 and summer 2010 were to:

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.

2 Methods and materials

2.1 Sampling sites

Biomonitoring and water quality sampling was undertaken at seven sites: 1, 7, 10, 11, 12, 13, 14 (Figure 1). The biotopes sampled at each site are depicted in the Individual Site Summaries section, along with a description of each site (Tables 5-11). Fieldtrips took place during winter (September) 2009 and summer (February) 2010.

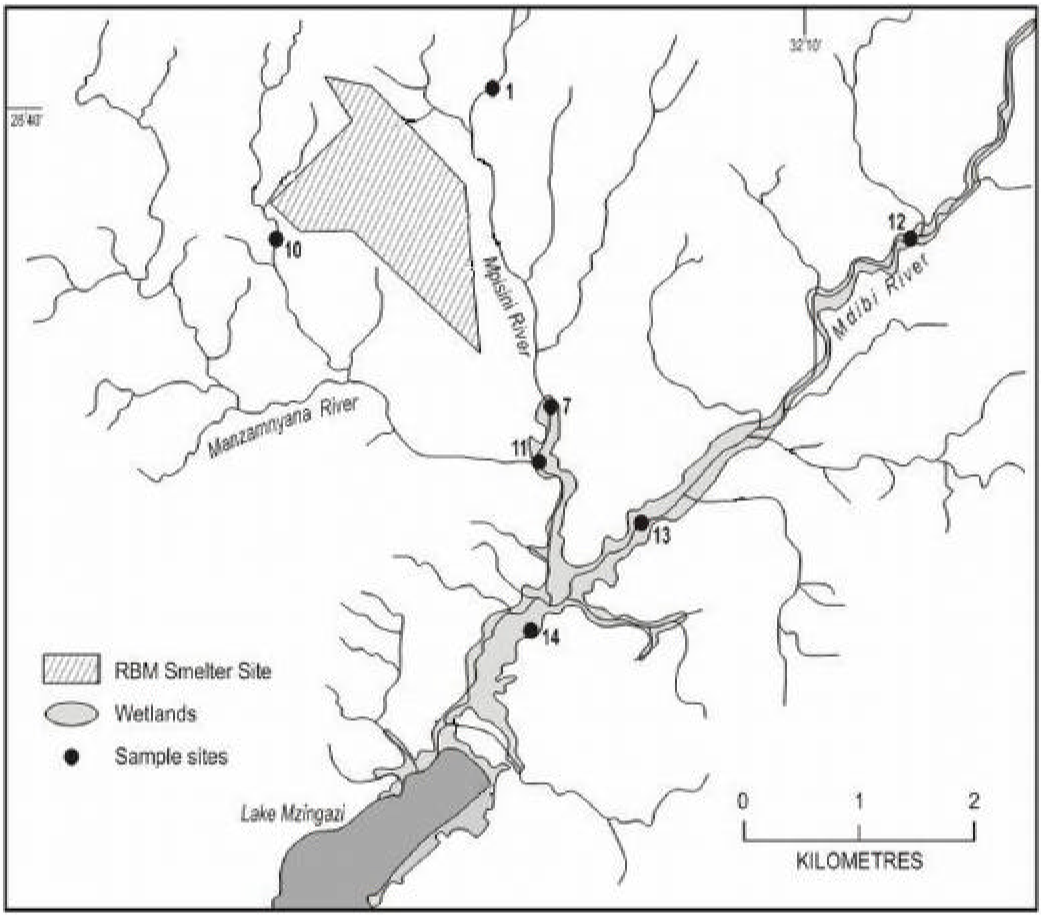

Figure 1. Monitoring points sampled in the Smelter Site area.

2.2 Water quality assessment

Water samples were collected 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: NO_2-N, NO_3-N, NH_4-N and PO_4-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 as algae cause most of the problems associated with nutrient enrichment (Palmer et al. 2004). Periphyton and phytoplankton samples were collected following methods described by Holm-Hansen and Riemann (1978) and analysed for chlorophyll-*a* concentrations, as an additional indication of nutrient status of the surface waters. 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 (BOD_5) was used (APHA 1992). Analysis of BOD_5 during the 2009/2010 sampling programme forms part of a method refinement exercise for full application in future monitoring at RBM. 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 the biomonitoring exercise.

Where appropriate, water quality data were interpreted using the default benchmark boundary values for ecological health as provided for in the ecological Reserve methodology for water quality assessments (Palmer et al. 2004).

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 adjust 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 accordingly (Dickens and Graham 2002). Once the SASS evaluation was complete, a further two samples from each of the biotopes were collected (replicate samples) and all samples were preserved in 80% ethanol. The standard SASS protocol (described in Dickens and Graham (2002) as well as the standard data sheet) was utilised to collect the SASS samples as well as replicate samples. All samples were further enumerated at the UCEWQ-IWR laboratories, providing accurate counts for each of the taxa for 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 (Palmer et al. 2004).

Diatom assessment

Diatom samples were collected from hard substrates (vegetation, wood, brick or rock) on site and fixed in 20% ethanol for transport. If no suitable hard substrate was present, diatoms were sampled from the sediment surface. 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. 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 2).

Table 2. 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 3. 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.

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 4).

Table 3. 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

Table 4. 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). Function betadisper and associated function anova was used to calculate an index of multivariate dispersion after Anderson (2006) and test for the significance of changes with season.

3 Results and discussion

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 5-11. Raw data presented in Appendices 1-4.

3.1 Water quality assessment

Water temperatures recorded at sampling sites were not significantly different from one another (Figure 2A), with summer being the warmer season at all sites (Figure 2D). There were, significant differences in measured pH, with the uppermost sites on each river being more acidic (Figure 2B). All sites, however, were classed either Natural or Good and seasonal variations were negligible (Figure 2E). Electrical conductivity at the uppermost sites on the Mpisini (site 1) and Mdibi (site 12) were classified as being on the Natural/Good boundary, with average EC values at remaining sites being categorized as Good (Figure 2C). Generally, river water at downstream sites had higher EC compared with upstream sites. The higher EC at site 7 appears to be related to the proximity of the smelter site as no other cause for the increase could be identified. Remaining sites downstream the smelter are all surrounded by human settlements and thus it is difficult to determine relative contributions of these two land uses to increased EC.

Average DO was considerably lower at site 10, falling within the Poor ecological category (Figure 3A), whereas all other sites are classified as Fair or Good. 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. Water at site 11 and 12 emerges from a mangrove swamp forest and could explain the low DO concentrations. The BOD results should be interpreted with caution. The high variability observed in winter 2009 may be a consequence of the method development. More consistent recorded values among sites in summer 2010 suggest analytical methods had improved in reliability.

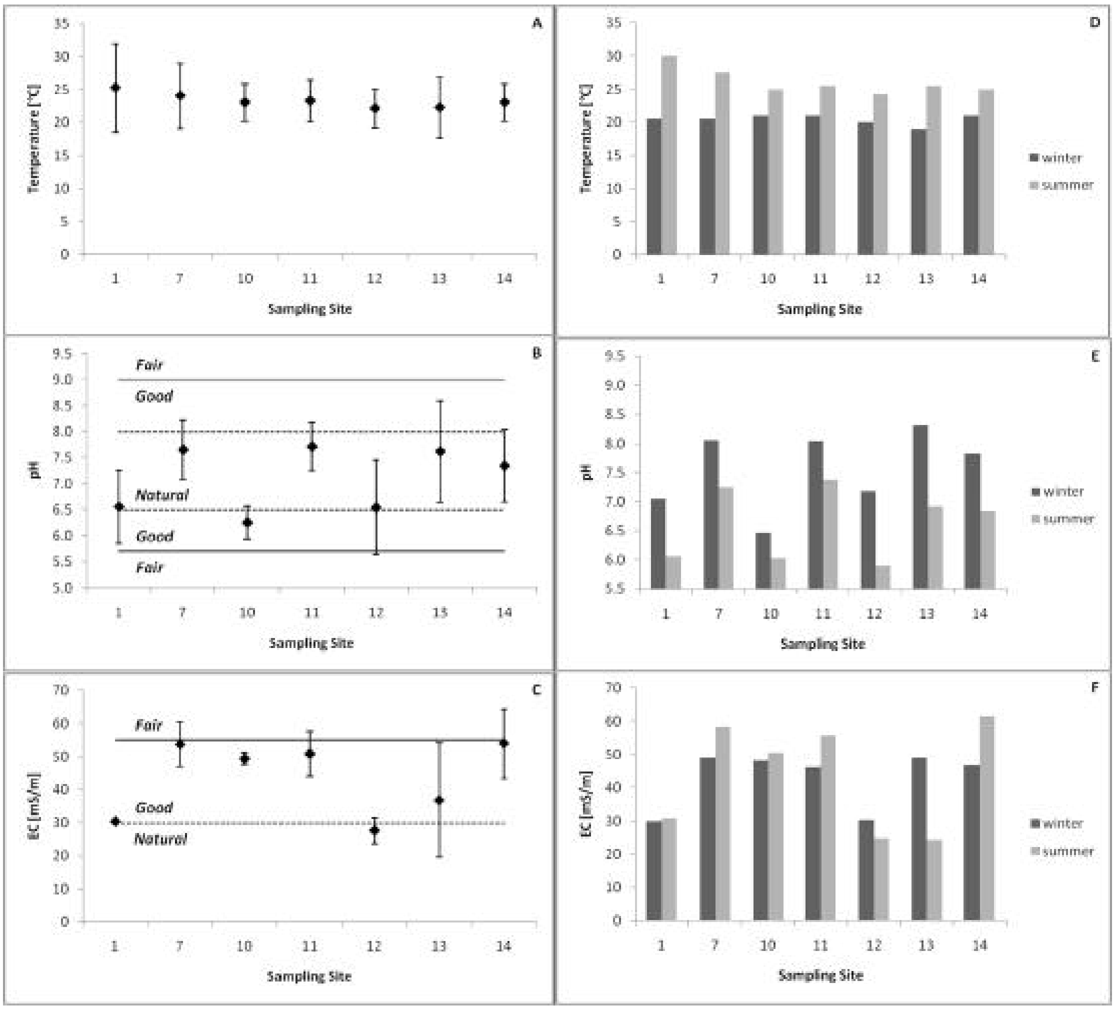

Figure 2A-C. Mean (with standard deviation) temperature, pH and electrical conductivity (EC) values measured at sampling sites over two seasons. Default ecological categories based on ecological Reserve determination methodologies are superimposed on the graphs. Figures 2D-F present seasonal values measured at each site.

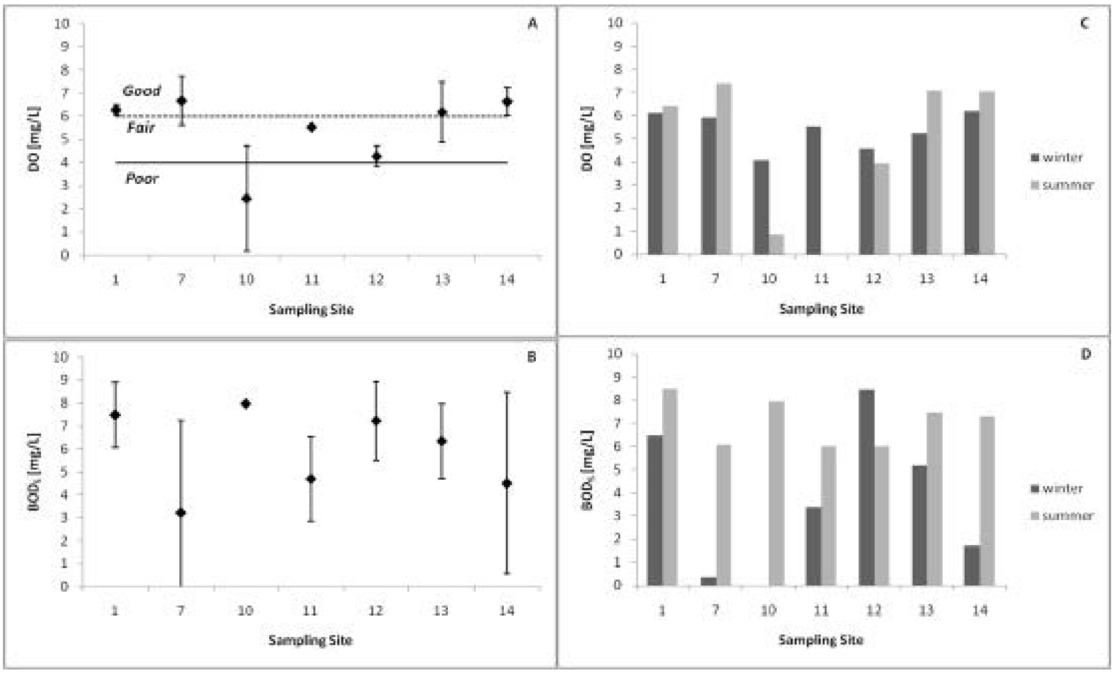

Figure 3A-B. Mean (with standard deviation) DO (dissolved oxygen) and BOD5 (biochemical oxygen demand) values measured at sampling sites over two seasons. Default ecological categories based on ecological Reserve determination methodologies are superimposed on DO graph. Figures 3C-D present seasonal values measured at each site.

Total inorganic nitrogen (TIN) was highest at the uppermost site on the Manzamnyana River (site 10) (Figure 4A), which was classified as Poor. TIN levels were highly variable over different seasons, with concentrations in summer being considerably higher than in winter (Figure 4E). Soluble reactive phosphorus (SRP) concentrations were mostly classed as Fair except site 14 (Good category) (Figure 4B). There were large seasonal variations in SRP, with significantly higher concentrations in winter compared to summer (Figure 4F). Phytoplankton chlorophyll-*a* concentrations at all sites were classed as Natural (Figure 4C), with no significant seasonal variations (Figure 4G). Periphyton chlorophyll-*a* concentrations at sites sampled were either classed as Good or Fair (Figure 4D), with large seasonal variations at most sites (Figure 4H).

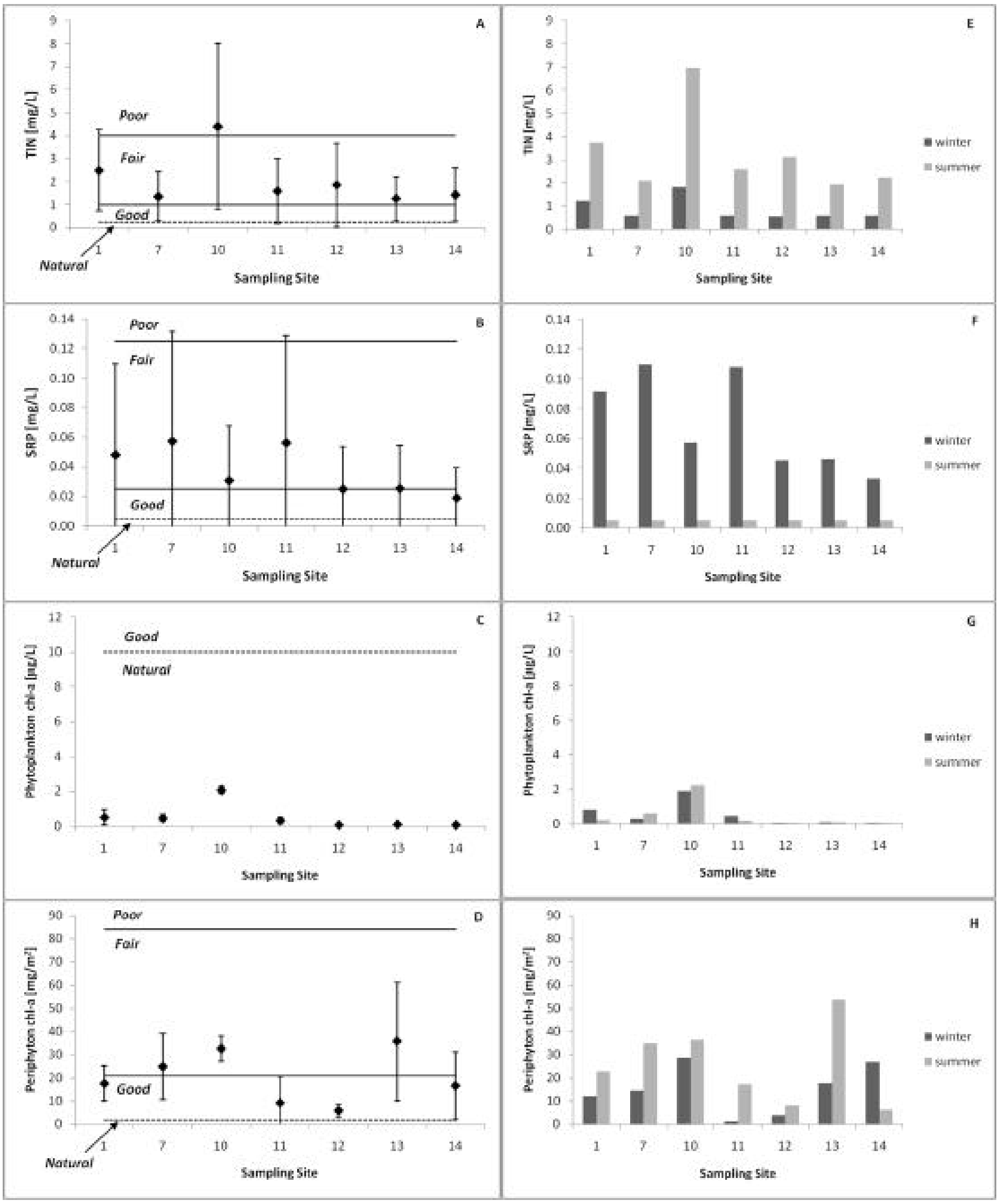

Figure 4A-D. Mean (with standard deviation) TIN (total inorganic nitrogen), SRP (soluble reactive phosphorus), periphyton chlorophyll-*a* and mean phytoplankton chlorophyll-*a* measured at sampling sites over two seasons. Default ecological categories based on ecological Reserve determination methodologies are superimposed on the graphs. Figures 3F-H present seasonal values measured at each site.

3.2 Habitat assessment

Overall, IHAS scores are low due to the absence of a stones biotope at all sampling sites, except at site 7 which is reflected in the significantly higher IHAS score (Figure 5A). Seasonal variability was negligible (Figure 5B). Further reasons for low IHAS scores include site 10 being characterized by a pool with slow moving water which is regularly disturbed by cattle, site 11 and 12 being badly affected by low flows which reduce available vegetation sampling habitat and site 13 havingreduced GSM biotope.

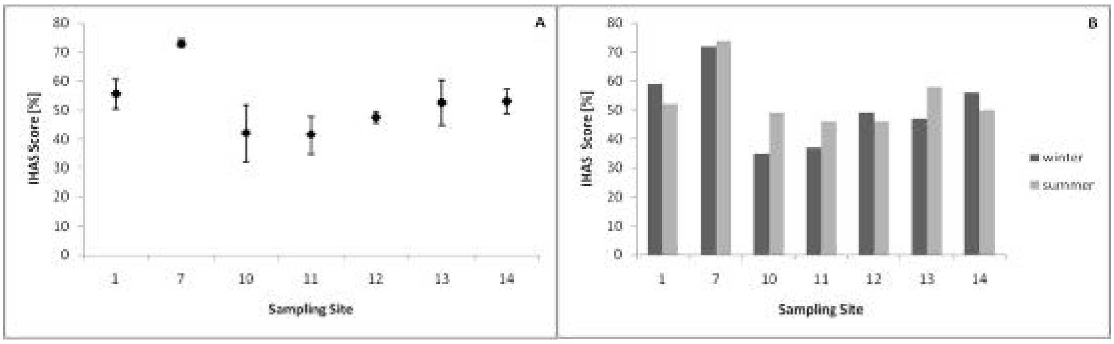

Figure 5A. Mean Integrated Habitat Assessment System (IHAS) score (with standard deviation) per sampling site. Figure 5B. Seasonal differences in IHAS recorded at each site.

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 6A-C). SASS scores and number of taxa at all sites, except site 14, were lower in winter than summer, sometimes quite considerably (Figure 6D and E). ASPT values were, however, more consistent seasonally (Figure 6F). 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 Good at site 13, Poor at site 10 and Fair at all other sites, a similar situation to previous monitoring undertaken in 2008. Generally scores followed a similar pattern, with sites 10, 11 and 12 on average lower than other sites sampled. This pattern mirrors the IHAS score suggesting available habitat may be a driving factor in macroinvertebrate presence/absence. Low DO and limited GSM biotope at site 10 on the Manzamnyana River are possible causes of low SASS and ASPT scores, however by site 11 scores begin increasing, possibly due to the input from the Mpisini River (site 7 on the Mpisini, immediately upstream of site 11 has the highest ASPT scores).

Average ASPT values at site 1 (reference site) and Site 7 (immediately downstream of the Smelter Site) on the Mpisini River are very similar. In fact SASS scores at site 7 are generally higher, possibly due to the presence of gravel and some stones at this site. Any impacts from smelter site activities are not being reflected in the SASS index.

Along the length of the Mdibi, the ASPT value increases from Fair at site 12 (reference site) to Good at site 13. However, after input of the combined waters from the Manzamnyana and Mpisini Rivers, the ASPT class drops to a Fair class again. However, in attempting to determine the cause of the lower ASPT score, the impact of water from the Manzamnyana and Mpisini Rivers cannot be separated from the potential effects caused by dense human settlements upstream of site 14.

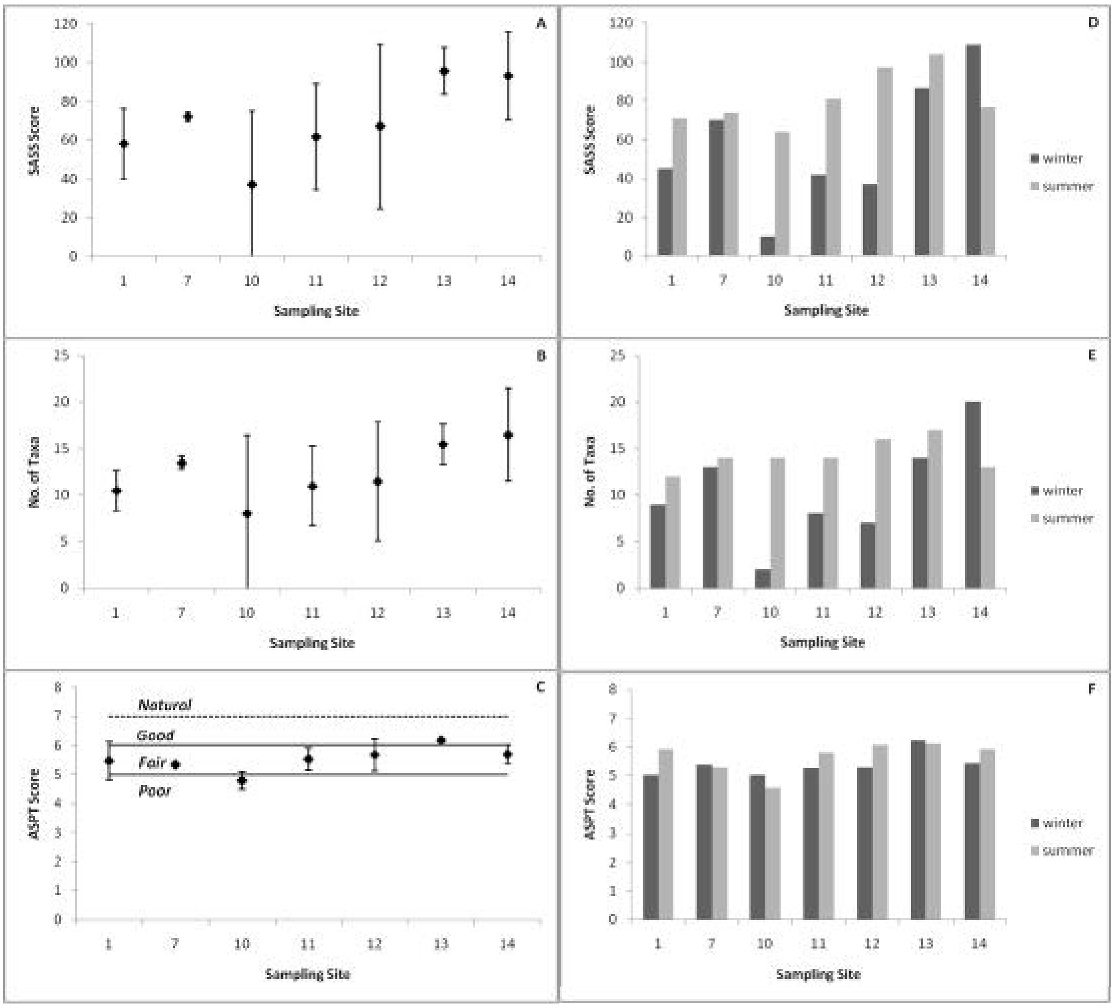

Figure 6A-C. Mean (with standard deviation) South African Scoring System (SASS) scores, number of families/taxa sampled and Average Score Per Taxon (ASPT) values determined for sites over two seasons. Default ecological categories for ASPT based on ecological Reserve determination methodologies are superimposed on graph C. Figure 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 2009 and summer 2010 shows that most sites were significantly different from one another. Only sites 1 and 12, and 11 and 12 were not significantly different P>0.05). The NMDS plot shows site 10 is considerably different from the remaining sites, while sites 7 and 13 form a group that is to a lesser degree different from sites 1, 12 and 11 (Figure 7).

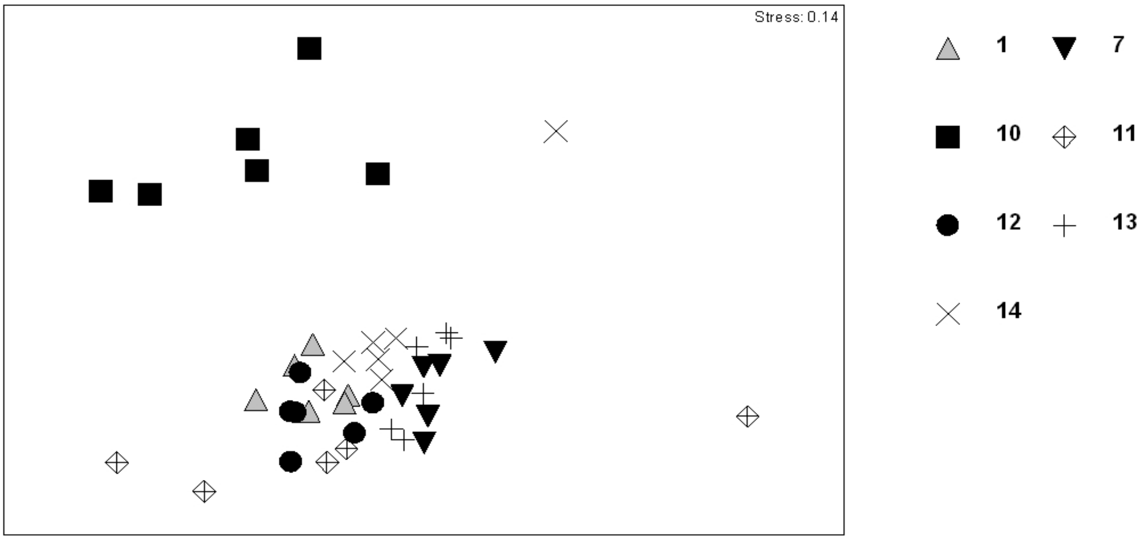

Figure 7. Non-metric multi-dimensional scaling plot of enumerated macro-invertebrate data, analysed according to location sampled.

3.4 Diatom assessment

3.4.1 Diatom indices

Mean index values for each site are presented in Figure 8. Raw data underlying these plots are presented in Appendix 1. Although there is some minor disagreement between the results of the three indices presented, some general trends across sites are apparent. According to the figures presented below, site 7 always has worse water quality than any other. This is largely borne out by statistical testing. Variation across sites was significant according to the IPS index (p=0.016) and the expert opinion classification (p=0.017). Inter-site variation is somewhat masked by seasonal variation according to the BDI-2006 index; however some variation is detected (p=0.114). In particular, site 7 is significantly worse than upstream sites 1 (IPS p=0.032, BDI-2006 p=0.030) and 12 (IPS p=0.009, BDI-2006 p=0.030).

A less apparent trend is that upstream sites 1, 10, and 12 generally have better water quality than other sites. However, the IPS index detects a large amount of variation at site 10 owing to a particularly low score in February 2010. In a similar way, the overall site score for BDI-2006 at site 12 is lowered by a low rating for February 2010. From this one could conclude that a strong seasonal pattern exists. However, inspection of the taxa in these February samples reveal that the dominant taxa (which heavily influence the score) are rare or unidentifiable. As such, they are commonly not used to derive the indices in question and index scores rely therefore on better known taxa that may be relatively rare in the samples.

For example, in the February 2010 sample from site 10, the sample was heavily dominated (95%) by an unknown species of *Brachysira*. Neither index is able to use this information, and indices are then derived using the remaining taxa. Of these four taxa, one is an unknown species, two are cosmopolitan and so might be found in impacted areas, and one is typical of clean, acidic water. The two cosmopolitan taxa have an effect on the index disproportionate to their low abundances, and act to reduce the index score.

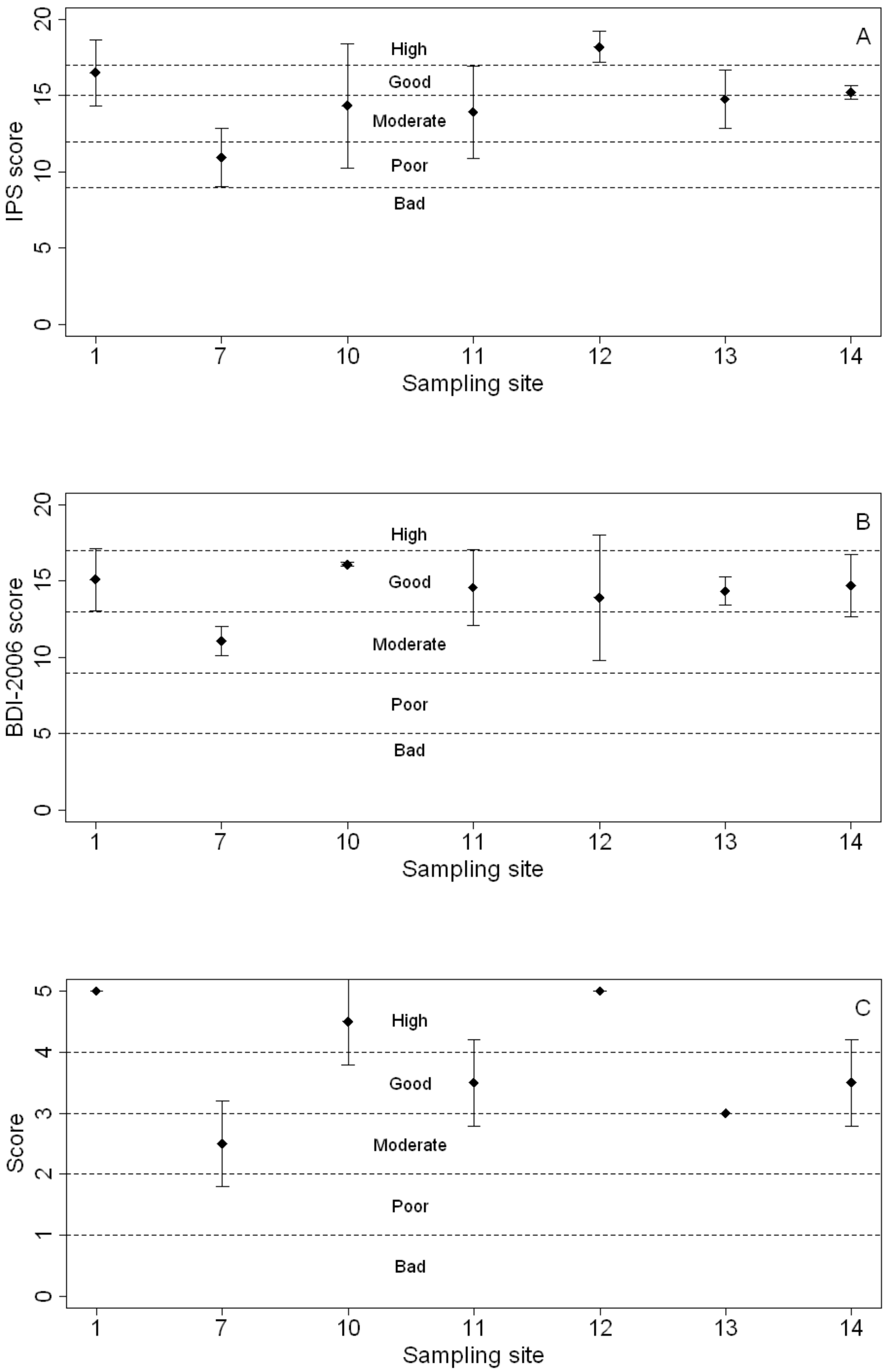

Figure 8 A-C. Mean scores (± standard deviation) of the three diatom indices used in this study. A: IPS index; B: BDI-2006 index; C: Score based on expert opinion.

The February 2010 sample from site 12 is, like the above example, heavily dominated by one taxon and contains a low number of taxa. The dominant taxon, *Achnanthes oblongella*, is used by the IPS index, but not by the BDI-2006 index. In this case, the IPS score is likely to better represent the water quality at this site. The IPS index classes this sample as High class, while the BDI-2006 index, which relies on a small fraction of the frustules in the sample for its calculations, scores the sample as Moderate class. The IPS score is in accordance here with the classification based on expert opinion.

It has been noted that sites with a high proportion of the unknown *Brachysira* species are liable to have inaccurate indices. Another taxon that may introduce inaccuracies is *Achnanthes pulviscula*, which was described from South Africa and is little known elsewhere and is not used in the derivation of either index. *Achnanthes pulviscula* occurs widely in samples from this area, particularly from less impacted sites. It is co-dominant in the sample from site 1 in February (together with the unknown *Brachysira* species and *Gomphonema angustatum*). As this sample has many taxa and none are heavily dominant, the reliance on rare taxa addressed above does not arise to the same extent. Nevertheless, 41% of the frustules counted from this sample belong to two taxa that the indices do not cover which reduces the reliability of scores from this site.

Statistical analysis identifies a strong seasonal trend in the IPS and BDI-2006 indices ($p=0.004$ and $p=0.010$ respectively). Generally, indices from September 2009 indicate better water quality than those from February 2010. This result is not supported by the index based on expert opinion. In the examples discussed above, several lowered February 2010 scores can be attributed to the presence of taxa not used in the derivation of either index dominating in samples. However, seasonal patterns are evident in samples from other sites and the conclusion that a seasonal trend exists is not a function of skewed scores from sites dominated by ill-documented taxa.

3.4.2 Descriptions of diatoms samples at each site

Site 1 (Upper Mpisini)

September 2009

This sample contained 13 taxa and had a Shannon diversity of 1.63. The site was dominated by *Achnanthidium minutissimum*, a diatom typical of clean water with high oxygen levels. An unknown species of *Brachysira* was subdominant. *Brachysira* species typically are found in oligotrophic, electrolyte-poor water, and many prefer a somewhat acid pH. Remaining taxa are all generally characteristic of clean water with low electrolyte levels.

February 2010

This sample contained 17 taxa and had a Shannon diversity of 2.32. Three taxa were codominant in this sample. The first is *Achnanthes pulviscula*, a species described from South Africa and about which little is known. In this survey it is commonly found together with *Achanthidium minutissimum* and *Achnanthes oblongella* (both of which are present in this sample) and seems therefore to indicate oligotrophic water with high oxygen levels. The same species of *Brachysira* found in the winter sample was also codominant, together with *Gomphonema angustatum*, which is tolerant of changes in pH and salinity but only common in oligotrophic water. Other taxa in this sample are typical of oligotrophic water, with some indicative of a level of acidity, and some tolerant to changes in salinity.

Site 7 (Lower Mpisini)

September 2009

This sample contained 16 taxa and had a Shannon diversity of 2.34. Four taxa were codominant in this sample. Two of them, *Achanthidium minutissimum* and *Achnanthes pulviscula*, are typical of clean water with high oxygen levels and low levels of nutrients. Of the remaining codominant taxa, *Nitzschia liebetruthii* is typical of electrolyte-rich to brackish waters, and *Navicula schroeteri* is indicative of electrolyte-rich eutrophic water. Other taxa present include several indicative of clean water and a number common where electrolyte and/or nutrient levels are elevated.

February 2010

This sample contained 21 taxa and had a Shannon diversity of 2.60. Three taxa were codominant in this sample. *Gomphonema pumilum* var. *rigidum* is found in meso- to eutrophic water with moderate electrolyte levels. *Nitzschia palea* is highly cosmopolitan but most common in eutrophic conditions where electrolyte levels are moderate to high. Finally, *Nitzschia fonticola* is typical of moderate electrolyte levels and, while this taxon may be found in polluted conditions, is not tolerant of more than moderate pollution. Remaining taxa are generally indicative of at least moderate electrolyte levels and some are common in eutrophic conditions.

Site 10 (Upper Manzamnyana)

September 2009

This sample contained 13 taxa and had a Shannon diversity of 1.45. The sample was dominated by *Achnanthidium minutissimum*, a taxon typical of clean, well-oxygenated water. The same *Brachysira* species found in samples from site 1 was subdominant and probably indicates oligotrophic, electrolyte-poor water. Several taxa making up about 5% of the sample are typical of moderate or high electrolyte levels and have been associated with water pollution.

February 2010

This sample contained only 5 taxa and had a Shannon diversity of 0.25. The sample was very heavily dominated by the same *Brachysira* species found at this site in September 2009. The few remaining taxa combined species typical of moderate to low electrolyte levels and all ranges of nutrients.

Site 11 (Confluence)

September 2009

This sample contained 13 taxa and had a Shannon diversity of 1.20. *Achnanthidium minutissimum* and *Achnanthes oblongella* were dominant in the sample. Both are indicators of clean water, usually oligotrophic and with low electrolyte levels. Most of the remaining taxa are usually associated with high levels of nutrients or electrolytes or both.

February 2010

This sample contained 16 taxa and had a Shannon diversity of 2.04. *Achnanthes oblongella* was dominant in the sample. This taxon is typical of oligotrophic, circumneutral water with high levels of oxygen. An unknown species of *Nitzschia* was subdominant. *Nitzschia* species are often associated with various kinds of pollution, but some are not and no defensible conclusions can be drawn until the specific identity is determined. Of the remaining taxa that make up more than 3% of the sample, some are typical of oligotrophic, electrolyte-poor conditions while others are associated with elevated levels of nutrients and/or electrolytes.

Site 12 (Upper Mdibi)

September 2009

This sample contained 8 taxa and had a Shannon diversity of 1.21. *Achnanthidium minutissimum*, typical of clean, well-oxygenated water was dominant. *Achnanthes oblongella*, another indicator of clean water, was subdominant. *Eunotia veneris*, the next most common taxon, is also an indicator of clean water and is common in slightly acidic water. No taxa associated with elevated nutrients or electrolytes were found in significant numbers in this sample.

February 2010

This sample contained 7 taxa and had a Shannon diversity of 0.66. The sample was heavily dominated by *Achnanthes oblongella*, indicative of clean, oligotrophic water with low electrolyte levels. The next most common taxon was *Achnanthes pulviscula*, which appears to be associated with the same conditions as *Achnanthes oblongella*. Of the remaining taxa for which ecological information is available, most are associated with oligotrophic conditions though some show tolerance to elevated electrolyte levels.

Site 13 (Middle Mdibi)

September 2009

This sample contained 17 taxa and had a Shannon diversity of 1.70. *Achnanthidium minutissimum* was the dominant taxon in the sample, suggestive of clean, well-oxygenated conditions. A superficially similar taxon, *Achnanthidium saprophilum*, was subdominant. The latter is most commonly found in organically enriched or eutrophic water. Of the remaining taxa, some are indicative of well-oxygenated oligotrophic water, but a number are taxa typical of elevated electrolyte or nutrient levels and some are known indicators of pollution.

February 2010

This sample contained 17 taxa and had a Shannon diversity of 2.22. No taxa were highly dominant. *Achnanthidium saprophilum* and *Achnanthidium minutissimum* were codominant, and, as noted for the September 2009 sample, one is indicative of clean, well-oxygenated conditions while the other is typical of nutrient or organic loading. *Nitzschia paleaeformis* and *Nitzschia archibaldii* are subdominant. The former is found in fairly well oxygenated water with low to moderate electrolyte levels, while the latter has been associated with low to moderate pollution in waters with moderate electrolyte levels and is reportedly tolerant of elevated levels of lead and zinc. Of the remaining taxa, several are associated with oligotrophic water with low levels of electrolytes, though some are typical of high levels of nutrients or electrolytes.

Site 14 (Lower Mdibi)

September 2009

This sample contained 13 taxa and had a Shannon diversity of 1.99. The sample was dominated by an unknown species of *Cocconeis*. Freshwater *Cocconeis* species are generally associated with water that is slightly alkaline, with low to moderate levels of electrolytes, moderate oxygen levels and elevated nutrient levels. This does not apply to all *Cocconeis* species and until the specific identity of this taxon is confirmed, one cannot draw firm conclusions from its dominance in this sample. *Achnanthidium minutissimum* and *Gomphonema insigne* are subdominant, the former typical of clean, well-oxygenated water and the latter typical of conditions with high levels of electrolytes. The three next most common taxa are mostly typical of oligotrophic waters with, in most cases, low electrolyte levels.

February 2010

This sample contained 20 taxa and had a Shannon diversity of 2.40. *Achnanthidium minutissimum*, *Navicula tenelloides* and *Navicula seminuloides* were codominant in the sample. The former is typical in clean, well oxygenated water. *Navicula tenelloides* is cosmopolitan and tolerant of a range of electrolyte and nutrient levels and has been found in extremely polluted conditions. *Navicula seminuloides* is typical of low electrolyte levels. *Diploneis oblongella* is subdominant. This taxon prefers conditions with high oxygen and moderate electrolyte levels and is not tolerant of organic loading. The remaining taxa include species preferring oligotrophic conditions to those preferring eutrophic conditions with organic loading, and many taxa are tolerant of elevated electrolytes.

3.4.3 Diatom community analysis

The ordination of samples based on diatom abundance is presented in Figure 9. Changes in diatom abundance between samples are significantly correlated with differences between sites ($p<0.001$) and the different times of sampling ($p<0.001$). General trends visible in Figure 9 include a trend in diatom community structure from upstream sites distributed towards the top of the plot to downstream sites in the lower right hand corner. While upstream sites show considerable variation between samples, downstream sites (with some exceptions) tend to be clustered together in the lower right hand corner. Sites 1 and 10 tend to be associated in the upper right hand corner. The winter sample from site 10, when water quality as inferred from diatom community structure was good to high was more closely associated with samples from site 1 than was the site 10 summer sample, when inferred water quality was generally lower according to the IPS and BDI-2006. The close association of samples from site 7 with the summer samples from sites 11 and 12 appears to be an artefact arising from the need to project a multidimensional space into two dimensions.

Differences between seasons are apparent in Figure 9. With the exception of site 1, variation in diatom community structure over seasons is greater in sites in the mid- and upper catchment, while sites 13 and 14 on the Mdibi river show relatively little seasonal change. Dispersion between samples is significantly greater during summer than during winter ($p=0.001$). The cause of this is not clear; however, increased multivariate dispersion has been proposed as a response to increased stress (Warwick and Clarke, 1993). Low water levels were observed at most sites during February 2010 and this may be associated with the increased dispersion. Alternately, levels of inorganic nitrogen were higher during summer, while phosphate levels were reduced.

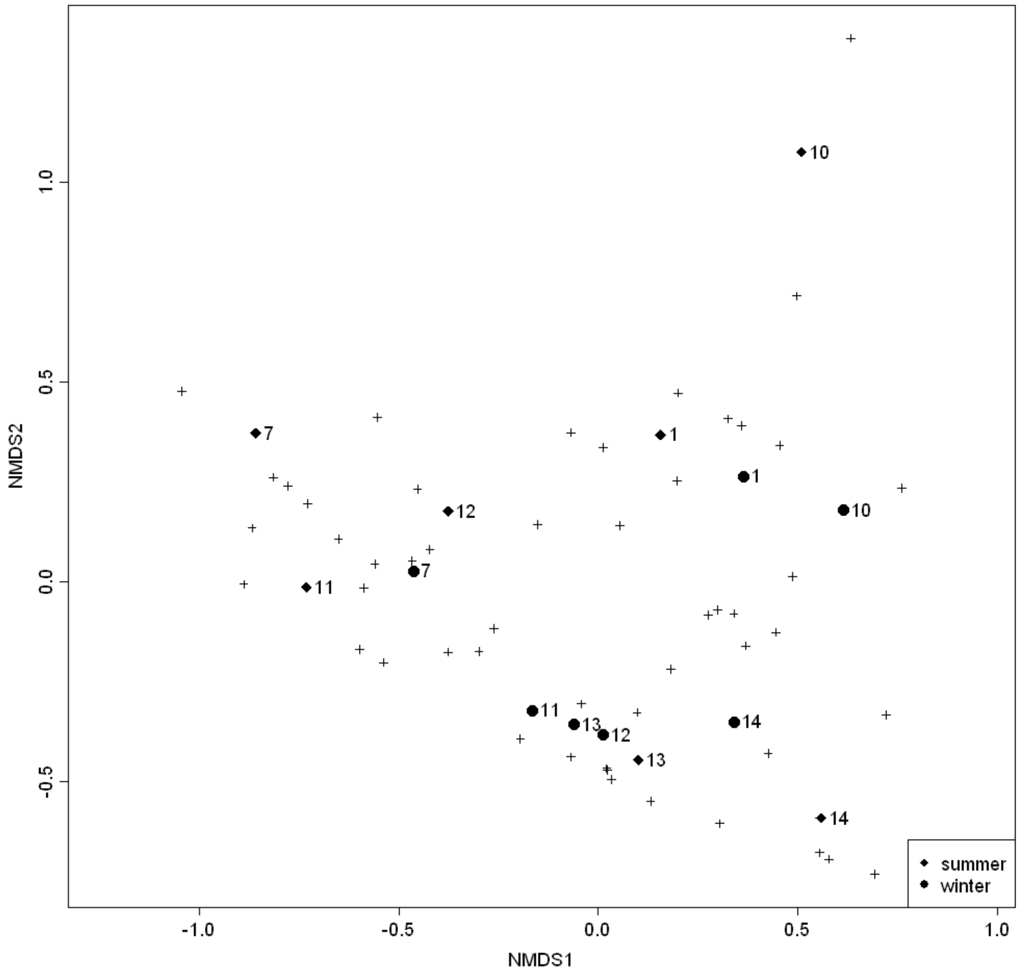

Figure 9. NMDS ordination plot of Bray-Curtis distances between all samples assessed, based on square-root transformed diatom abundances (stress: 14.1). Sites are labeled and species indicated by +.

3.4.4 Overall diatom assessment

The relatively poor water quality at site 7 has been noted before (Gordon *et al.* 2008). In the latter report, some consideration was given to potential reasons for the low diatom scores from this site. It bears repeating that in the 3 km stretch of the Mpisini River that lies between sites 1 and 7, the water quality as inferred from diatom community structure decreases significantly. As in 2008, this change in inferred water quality is accompanied by an increase in electrolyte levels as measured by electrical conductivity. This alone cannot account for the decreased diatom index scores as conductivity at site 7 is no worse than at other sites (for example, site 14) with better inferred water quality. There is a slight increase in pH along the same stretch, but the increased pH at site 7 is again much the same as other sites with better inferred water quality. TIN decreases along this stretch due mainly to a decrease in nitrate, but TIN levels at site 7 are comparable with those from most other sites surveyed.

The cause of the decreased water quality along the Mpisini between sites 1 and 7 is not clear as no water quality parameters assessed in this survey can alone account for the change. This stretch of river runs adjacent to the RBM Smelter site. Several drains from the Smelter site leading into the Mpisini are found in this stretch. Nevertheless, flow from these drains has been found in the past to be rare (Muller and Gordon 2005). Drainage from these points has resulted in increased conductivity and pH in the past, and it seems likely that Smelter site runoff, as surface flow or possibly via the groundwater, may account for the increased conductivity and pH detected during this study. Two small ephemeral streams drain forested land to the east and enter the Mpisini between sites 1 and 7, and, from the data available, these need to be considered as potential factors modifying water quality in the Mpisini river.

Generally, inferred water quality is better at upstream sites, and decreases with distance downstream. As in 2008, this is paralleled by an increase in conductivity and in pH. Two exceptions to this generalisation need to be considered.

- At certain sites, usually those where samples were heavily dominated by one or few taxa and where diversity was low, the IPS and BDI-2006 indices occasionally returned unusual values as a result of dominant taxa not being used in the derivation of the index scores either because the dominant taxa were little known or because they could not be identified. This was typical of upstream sites, as sites further downstream commonly had more cosmopolitan taxa and a greater diversity in each sample. This affected the index based on expert opinion less as other information was used to help estimate the ecological affinity of the rare or unidentified taxa.
- Although inferred water quality decreased sharply between site 1 and site 7, water quality increased between site 7 and site 11. This may be due to either improved water quality owing to recovery along the Mpisini, or dilution of Mpisini water by Manzamnyama water at site 11, or both.

The increased pH and electrolyte levels in sites lower in the catchment are reflected in changes in species compositions of samples. For example, species of *Eunotia* and *Brachysira*, both commonly acidophilous, are found in upstream sites but are less frequent or vanish lower in the catchment. Taxa from downstream samples generally have higher tolerance for elevated electrolytes and nutrients compared to those from upstream samples. Nevertheless, downstream samples often contain significant numbers of taxa that are common upstream and are associated with relatively clean water. Examples of the latter are *Achnanthidium minutissimum* and *Achnanthes oblongella*.

Seasonal patterns were detected in diatom indices and diatom community structure. Overall, the indices point at a better quality of water in winter samples. Winter samples had higher pH and phosphate levels, and lower TIN (though greater nitrite levels). With the exception of sites on the upper-mid Mdibi, conductivity is lower in winter. As lowered diatom index scores are commonly associated with the presence of taxa that are at least tolerant of moderate to elevated electrolyte levels and increased levels of plant nutrients, the generally lower conductivity and reduced TIN levels may to some extent explain changes in diatom indices. However, elevated winter phosphate levels (commonly associated with eutrophication and reduced diatom index scores) indicate that a simple explanation of changes in index values in this dataset does not exist. As there is no replication over time, the data assessed for this report cannot be used alone to generalise about seasonal patterns around the smelter site.

Table 5. Summary of site 1 on the Mpisini River

Site description: This site is upstream of the smelter site and chosen as a possible reference site. During winter 2009, low water levels limited access to marginal vegetation, although aquatic vegetation was still available. GSM biotope is dominated by mud with limited sand available, usually covered with leaf litter.

Water quality parameters: (DO: dissolved oxygen; EC: electrical conductivity; TIN: total inorganic nitrogen; SRP: soluble reactive phosphorous; Chlorophyll-*a* µg/L: phytoplankton chlorophyll-*a*; Chlorophyll-*a* mg/cm^2: periphyton chlorophyll-*a*) (water quality categories based on the ecological Reserve methodologies for water quality are provided below the values where relevant).

TºC	pH	DO (mg/L)	EC (mS/m)	TIN (mg/L)	SRP (mg/L)	Chlorophyll-*a*	
						Phytoplankton (µg/L)	Periphyton (mg/m^2)
25.3	6.6	6.3	30.4	2.49	0.048	0.51	17.5
	Natural	Good	Good	Fair	Fair	Natural	Good

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
5.5	56	4.3	Good
Fair		Natural	

Overall ecological assessment: Good

Table 6. 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: (DO: dissolved oxygen; EC: electrical conductivity; TIN: total inorganic nitrogen; SRP: soluble reactive phosphorous; Chlorophyll-*a* µg/L: phytoplankton chlorophyll-*a*; Chlorophyll-*a* mg/cm^2: periphyton chlorophyll-*a*) (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/cm^2)
24.0	7.7	6.7	53.7	1.35	0.057	0.46	24.82
	Natural	Good	Good	Fair	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	73	2.7	Good/Fair
Fair		Fair	

Overall ecological assessment: Fair

Table 7. 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 and anoxic mud. The GSM is regularly disturbed by cattle passing through and drinking.

Water quality parameters: (DO: dissolved oxygen; EC: electrical conductivity; TIN: total inorganic nitrogen; SRP: soluble reactive phosphorous; Chlorophyll-*a* µg/L: phytoplankton chlorophyll-*a*; Chlorophyll-*a* mg/cm^2: periphyton chlorophyll-*a*) (water quality categories based on the ecological Reserve methodologies for water quality are provided below the values where relevant).

TºC	pH	DO (mg/L)	EC (mS/m)	TIN (mg/L)	SRP (mg/L)	Chlorophyll-*a*	
						Phytoplankton (µg/L)	Periphyton (mg/cm^2)
23.0	6.3	2.5	49.5	4.40	0.03	2.07	32.5
	Good	Poor	Good	Poor	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
4.8	42	4.0	Fair
Poor		Good	

Overall ecological assessment: Fair

Table 8. Summary of site 11 at confluence of the Mpisini and Manzamnyana Rivers

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. The sand biotope has become limited with low flows and disturbance from cattle. In winter 2009 there was evidence of refuse being dumped in-stream.

Water quality parameters: (DO: dissolved oxygen; EC: electrical conductivity; TIN: total inorganic nitrogen; SRP: soluble reactive phosphorous; Chlorophyll-*a* µg/L: phytoplankton chlorophyll-*a*; Chlorophyll-*a* mg/cm^2: periphyton chlorophyll-*a*) (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/cm^2)
23.3	7.7	5.5	50.9	1.59	0.056	0.32	9.2
	Natural	Good	Good	Fair	Fair	Natural	Good

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
5.5	42	3.3	Good
Fair		Fair	

Overall ecological assessment: Fair/Good

Table 9. 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 mud and leaf litter decay with, at times, limited sand. On both sampling occasions, vegetation clearing occured around the site on an ongoing basis with some impact on in-stream flow. Low water levels in summer 2010 further limited sampling biotope available .

Water quality parameters: (DO: dissolved oxygen; EC: electrical conductivity; TIN: total inorganic nitrogen; SRP: soluble reactive phosphorous; Chlorophyll-*a* µg/L: phytoplankton chlorophyll-*a*; Chlorophyll-*a* mg/cm^2: periphyton chlorophyll-*a*) (water quality categories based on the ecological Reserve methodologies for water quality are provided below the values where relevant).

TºC	pH	DO (mg/L)	EC (mS/m)	TIN (mg/L)	SRP (mg/L)	Chlorophyll-*a*	
						Phytoplankton (µg/L)	Periphyton (mg/cm^2)
22.1	6.5	4.3	27.6	1.86	0.025	0.07	6.0
	Natural	Fair	Natural	Fair	Good/ Fair	Natural	Good

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
5.7	48	4.5	Good
Fair		Natural	

Overall ecological assessment: Good

Table 10. Summary of site 13 on the Mdibi River

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. Low water levels have limited the availability of vegetation biotope for sampling during 2009/2010. GSM biotope is limited, usually consisting of some mud and sand which is covered by thick shredded leaf litter. Clearing of riparian vegetation had occurred in winter 2009.

Water quality parameters: (DO: dissolved oxygen; EC: electrical conductivity; TIN: total inorganic nitrogen; SRP: soluble reactive phosphorous; Chlorophyll-*a* µg/L: phytoplankton chlorophyll-*a*; Chlorophyll-*a* mg/cm^2: periphyton chlorophyll-*a*) (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/cm^2)
22.3	7.6	6.2	36.8	1.26	0.026	0.10	35.7
	Natural	Good	Good	Fair	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
6.2	53	3.5	Good
Good		Good	

Overall ecological assessment: Good

Table 11. 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, however during both seasons there was very limited marginal vegetation due to low flows. GSM consists of good sand and mud sampling biotope. There was evidence that cattle drinking traffic had increased in summer 2010.

Water quality parameters: (DO: dissolved oxygen; EC: electrical conductivity; TIN: total inorganic nitrogen; SRP: soluble reactive phosphorous; Chlorophyll-*a* µg/L: phytoplankton chlorophyll-*a*; Chlorophyll-*a* mg/cm^2: periphyton chlorophyll-*a*) (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/cm^2)
23.0	7.3	6.6	54.0	1.43	0.019	0.07	16.6
	Natural	Good	Good	Fair	Good	Natural	Good

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
5.7	53	3.7	Good
Fair		Good	

Overall ecological assessment: Good/Fair

4 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.

Although only reflected in the diatom community assessment score, there appears to be a significant water quality impact occurring between site 1 and 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. The water quality parameters responsible for these changes in diatom community composition cannot be identified from this study and further monitoring of a broader range of physiochemical parameters is necessary in order to identify the cause of this water quality impairment.

Macroinvertebrate taxa and abundance sampled at site 10 were considerably different from those sampled at all other sites. In addition, Sass scores and ASPT values were the lowest measured at any site. Conversely, the diatom indices consistently rated site 10 as having one of the highest water quality classes. 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 and these factors could be affecting the macroinvertebrates to a greater extent than the diatom community.

River water from the Mpisini and Manzamnyana Rivers (which drain the smelter site) enter the Mdibi River between site 13 and 14. Physicochemical data and diatom indices suggest there is little downstream impact from this input. Although ASPT values are slightly lower at site 14 compared to site 13, they are no different to the uppermost site on the Mdibi (site 12), and may be an artifact of available sampling habitat. The impact of human settlements, which occur between site 13 and 14, should also be considered when assessing the water quality at these two sites.

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.

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Appendix 1. Diatom index scores from sample sites in the Smelter area September 2009–February 2010 are presented below. Site classifications based on the indices are also presented.

		IPS		BDI-2006		Expert opinion	
Site	**Date**	**Index**	**Class**	**Index**	**Class**	**Index**	**Class**
1	Sept 2009	18.0	High	16.6	Good	5	High
1	Feb 2010	15.0	Moderate	13.7	Good	5	High
7	Sept 2009	12.3	Moderate	11.8	Moderate	3	Moderate
7	Feb 2010	9.6	Poor	10.4	Moderate	2	Poor
10	Sept 2009	17.2	High	16.2	Good	4	Good
10	Feb 2010	11.4	Poor	16.0	Good	5	High
11	Sept 2009	16.1	Good	16.3	Good	4	Good
11	Feb 2010	11.8	Poor	12.8	Moderate	3	Moderate
12	Sept 2009	18.9	High	16.8	Good	5	High
12	Feb 2010	17.5	High	11.0	Moderate	5	High
13	Sept 2009	16.2	Good	15.0	Good	3	Moderate
13	Feb 2010	13.4	Moderate	13.7	Good	3	Moderate
14	Sept 2009	15.6	Good	16.2	Good	4	Good
14	Feb 2010	14.9	Moderate	13.3	Good	3	Moderate

Appendix 2. Summary of biomonitoring, water chemistry and nutrient analysis undertaken. Detection limits were as follows: Ammonium (NH_4^+): 0.01mg/L; Nitrites (NO_2^-): 0.01mg/L; Nitrates (NO_3^-): 1.0mg/L; Soluble Reactive Phosphorus (SRP): 0.01mg/L. Total Inorganic Nitrogen (TIN) were calculated by adding NH_4^+, NO_2^- and NO_3^-. Values below detection limit are shown as half the detection limit (NH_4^+= 0.005mg/L; NO_2^-=0.005mg/L; NO_3^-=0.5mg/L; SRP=0.005mg/L). TIN=0.515mg/L indicates that all added parameters were below the detection limit.

Month	Year	River	Site Code	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 [mg/cm^2]
September	2009	Mpisini	1	45	9	5.00	59	20.5	6.11	7.05	29.9	0.023	1.129	0.088	1.240	0.092	0.818	12.126
September	2009	Mpisini	7	70	13	5.38	72	20.5	5.91	8.05	49.0	0.015	0.500	0.083	0.598	0.110	0.305	14.718
September	2009	Manzamnyama	10	10	2	5.00	35	21.0	4.06	6.47	48.2	0.025	1.691	0.120	1.837	0.057	1.907	28.660
September	2009	Confluence	11	42	8	5.25	37	21.0	5.53	8.04	46.1	0.013	0.500	0.085	0.598	0.108	0.461	1.254
September	2009	Mdibi	12	37	7	5.29	49	20.0	4.58	7.18	30.3	0.015	0.500	0.064	0.579	0.045	0.076	4.065
September	2009	Mdibi	13	87	14	6.21	47	19.0	5.25	8.31	49.0	0.018	0.500	0.066	0.584	0.046	0.093	17.615
September	2009	Mdibi	14	109	20	5.45	56	21.0	6.19	7.83	46.6	0.015	0.500	0.086	0.601	0.033	0.082	26.836
February	2010	Mpisini	1	71	12	5.92	52	30.0	6.43	6.06	30.8	0.045	3.673	0.023	3.741	0.005	0.207	22.884
February	2010	Mpisini	7	74	14	5.29	74	27.5	7.42	7.25	58.4	0.051	2.037	0.014	2.102	0.005	0.610	34.917
February	2010	Manzamnyama	10	64	14	4.57	49	25.0	0.84	6.03	50.7	0.050	6.865	0.043	6.958	0.005	2.232	36.353
February	2010	Confluence	11	81	14	5.79	46	25.5		7.37	55.7	0.055	2.512	0.016	2.583	0.005	0.187	17.184
February	2010	Mdibi	12	97	16	6.06	46	24.2	3.96	5.90	24.9	0.044	3.083	0.018	3.145	0.005	0.064	7.912
February	2010	Mdibi	13	104	17	6.12	58	25.5	7.09	6.92	24.5	0.049	1.887	0.009	1.944	0.005	0.105	53.756
February	2010	Mdibi	14	77	13	5.92	50	25.0	7.06	6.85	61.4	0.054	2.176	0.018	2.249	0.005	0.055	6.354

Appendix 3. Summary of number of taxa found at each sampling site in both seasons (September=winter, February=summer). Shown are averages per site over three replicates.

Site	1		7		10		11		12		13		14	
Month	2009	2010	Sept	Feb	Sept	Feb	Sept	Feb	Sept	Feb	Sept	Feb	Sept	Feb
Year	Sept	Feb	2009	2010	2009	2010	2009	2010	2009	2010	2009	2010	2009	2010
Oligochaeta	0	0	5	0	0	0	0	0	0	1	1	0	1	0
Leeches	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Amphipoda	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Potamonautidae	0	1	2	1	0	0	9	1	0	1	1	0	1	1
Atyidae	55	131	42	136	0	69	17	104	84	133	33	0	54	50
Hydracarina	0	0	0	0	0	0	0	0	1	0	0	1	0	0
Baetidae	0	2	60	27	0	1	1	0	0	12	15	7	16	5
Caenidae	1	2	11	4	0	0	1	2	1	6	8	0	4	1
Heptageniidae	0	0	0	0	0	0	0	0	0	2	0	0	0	0
Tricorythidae	1	1	2	2	0	3	1	5	0	22	22	0	6	1
Chlorocyphidae	0	0	0	0	0	0	0	0	0	1	1	0	0	0
Coenagrionidae	0	1	0	0	1	0	0	3	1	1	4	13	1	0
Aeshnidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Gomphidae	0	0	0	0	0	0	0	1	0	0	1	5	1	3
Libellulidae	0	0	0	0	0	0	0	0	0	0	0	4	0	0
Belostomatidae	0	0	0	0	0	0	0	0	0	0	0	0	2	0
Corixidae	0	1	0	0	0	0	0	0	0	0	1	0	0	0
Gerridae	0	1	2	1	0	1	2	2	2	0	1	0	0	0
Nepidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pleidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Veliidae	0	1	1	2	0	1	0	1	0	1	1	1	0	1
Ecnomidae	0	1	0	0	0	0	1	0	0	0	1	0	0	0
Hydropsychidae	0	0	5	8	0	0	0	0	0	0	0	0	0	0
Philopotamidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hydroptilidae	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Leptoceridae	0	0	0	0	0	0	0	4	0	3	1	0	2	1
Petrothrincidae	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Dytiscidae	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Elmidae/Dryopidae	0	0	0	0	0	1	0	1	0	0	4	0	0	0
Gyrinidae	0	0	2	3	0	0	1	1	0	0	0	0	0	0

Site	1		7		10		11		12		13		14	
Year	**2009**	**2010**	**Sept**	**Feb**	**Sept**	**Feb**	**Sept**	**Feb**	**Sept**	**Feb**	**Sept**	**Feb**	**Sept**	**Feb**
Month	**Sept**	**Feb**	**2009**	**2010**	**2009**	**2010**	**2009**	**2010**	**2009**	**2010**	**2009**	**2010**	**2009**	**2010**
Helodidae	0	0	0	0	0	0	0	1	0	2	1	0	0	0
Hydraenidae	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Hydrophilidae	0	0	0	0	0	0	0	0	0	0	0	1	1	0
Ceratopogonidae	0	3	0	0	0	0	0	0	0	0	0	3	1	0
Chironomidae	15	7	11	1	5	0	1	1	4	0	3	12	5	3
Culicidae	1	0	0	1	3	0	0	0	0	0	0	2	0	0
Muscidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Psychodidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Simuliidae	0	0	3	0	0	0	0	0	0	0	3	0	4	0
Syrphidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tabanidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tipulidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ancylidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lymnaeidae	0	0	0	0	0	0	0	0	2	0	0	0	0	0
Physidae	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Corbiculidae	0	0	0	0	0	0	0	0	0	0	0	0	0	1

Appendix 4. Diatom abundances from sample sites in the Smelter area September 2009–February 2010 follow on the next page. All data are proportions of identified frustules in each sample made up of each particular taxon. Where diatoms could not be identified, morphospecies were assigned and used in all analyses.

Site	**1**		**7**		**10**		**11**		**12**		**13**		**14**	
Year	**2009**	**2010**	**2009**	**2010**	**2009**	**2010**	**2009**	**2010**	**2009**	**2010**	**2009**	**2010**	**2009**	**2010**
Month	**Sept**	**Feb**	**Sept**	**Feb**	**Sept**	**Feb**	**Sept**	**Feb**	**Sept**	**Feb**	**Sept**	**Feb**	**Sept**	**Feb**
Achnanthes oblongella		0.06	0.06				0.11	0.45	0.29	0.84	0.08	0.02	0.07	0.01
Achnanthes pulviscula	0.08	0.24	0.12					0.05	0.02	0.08	0.03			
Achnanthes sp2									0.04					
Achnanthes subaffinis														0.01
Achnanthes subcrassa										0.03				
Achnanthidium affine	0.01													
Achnanthidium eutrophilum											0.01			
Achnanthidium exiguum						0.01								
Achnanthidium minutissimum	0.44	0.07	0.18		0.50		0.70		0.56		0.49	0.23	0.20	0.23
Achnanthidium saprophilum								0.05			0.24	0.26		0.08
Amphora aff. *angusta*			0.01											
Amphora fontinalis							0.01							
Amphora veneta												0.01		
Bacillaria paradoxa							0.07							
Brachysira aff. *steindorfiana*	0.01	0.06						0.01						
Brachysira blancheana								0.02						
Brachysira brebissonii												0.02		
Brachysira sp2	0.29	0.17			0.30	0.95				0.02				
Capartogramma crucicula														0.03
Cocconeis placentula								0.01						
Cocconeis sp1													0.31	
Cymbella tumida				0.01										
Diadesmis confervacea				0.05										
Diploneis oblongella														0.10
Discostella stelligera							0.01	0.01						
Eolimna sp1	0.05													
Eunotia bilunaris		0.03			0.01						0.01		0.07	
Eunotia flexuosa														0.01
Eunotia minor	0.01	0.03					0.01						0.01	0.01
Eunotia sp2	0.01													
Eunotia veneris									0.05					
Fragilaria biceps	0.03	0.01												
Fragilaria capucina var. *vaucheriae*				0.01										
Frustulia rostrata		0.01												
Frustulia saxonica						0.01								
Gomphocymbella sp1														0.01
Gomphonema aff. *angustatum*														0.05
Gomphonema aff. *gracile*									0.03					
Gomphonema angustatum	0.03	0.16	0.08							0.01			0.07	

Site	1		7		10		11		12		13		14	
Year	**2009**	**2010**	**2009**	**2010**	**2009**	**2010**	**2009**	**2010**	**2009**	**2010**	**2009**	**2010**	**2009**	**2010**
Month	**Sept**	**Feb**	**Sept**	**Feb**	**Sept**	**Feb**	**Sept**	**Feb**	**Sept**	**Feb**	**Sept**	**Feb**	**Sept**	**Feb**
Gomphonema angustissimum													0.01	
Gomphonema angustum												0.05		0.01
Gomphonema clavatum														0.04
Gomphonema gracile					0.01									0.02
Gomphonema insigne													0.16	
Gomphonema intricatum														0.02
Gomphonema lagenula												0.01		
Gomphonema minutum			0.01											
Gomphonema parvulum				0.07	0.01			0.03	0.01				0.01	
Gomphonema pseudoaugur											0.01	0.01		
Gomphonema pumilum								0.05						
Gomphonema pumilum var. *rigidum*				0.19							0.02			
Gomphonema sp6	0.03											0.01	0.03	
Gomphonema sp7								0.02						
Gomphonema sp8			0.01						0.01				0.05	
Gomphonema venusta			0.01	0.02				0.08						
Gomphosphenia aff. *oahuensis*			0.05											
Gyrosigma scalproides							0.01							
Hippodonta lueneburgensis													0.01	
Luticola kotschyi				0.01							0.02			0.02
Luticola mutica					0.01									
Navicula arvensis	0.01	0.07									0.01			
Navicula arvensis var. *maior*														0.01
Navicula erifuga				0.01								0.03		
Navicula gregaria			0.01				0.01							
Navicula ranomafanensis		0.02								0.01				
Navicula reichardtiana						0.01								
Navicula schroeteri			0.16	0.03			0.02	0.04			0.02			
Navicula seminuloides												0.01		0.14
Navicula soehrensis				0.02										
Navicula sp1											0.02			
Navicula sp4		0.02												
Navicula sp5		0.03												
Navicula sp6											0.02			
Navicula tenelloides											0.01			0.18
Navicula vandamii			0.02											
Navicula veneta											0.01			
Neidium productum											0.01			
Nitzschia acidoclinata												0.04		
Nitzschia amphibia							0.01	0.02						
Nitzschia archibaldii												0.10		
Nitzschia bulnheimiana				0.02										
Nitzschia clausii				0.07										

Site	**1**		**7**		**10**		**11**		**12**		**13**		**14**	
Year	**2009**	**2010**	**2009**	**2010**	**2009**	**2010**	**2009**	**2010**	**2009**	**2010**	**2009**	**2010**	**2009**	**2010**
Month	**Sept**	**Feb**	**Sept**	**Feb**	**Sept**	**Feb**	**Sept**	**Feb**	**Sept**	**Feb**	**Sept**	**Feb**	**Sept**	**Feb**
Nitzschia dissipata			0.02											
Nitzschia elegantula					0.01		0.01							
Nitzschia examinanda					0.02									
Nitzschia filiformis			0.07	0.02										
Nitzschia fonticola				0.13										
Nitzschia gandersheimensis												0.03		
Nitzschia liebetruthii			0.17	0.07			0.02							
Nitzschia linearis												0.01		
Nitzschia microcephala		0.01												0.01
Nitzschia nana					0.05									
Nitzschia obtusa var. *kurzii*				0.01										
Nitzschia palea				0.14						0.01		0.05	0.01	
Nitzschia paleaeformis												0.13		
Nitzschia pura					0.03									
Nitzschia pusilla				0.07	0.01									
Nitzschia sp1								0.12						
Nitzschia sp21							0.01							
Nitzschia sp7						0.02								
Nitzschia sp9								0.03						
Nitzschia subcapitellata								0.03						
Placoneis sp2					0.01									
Sellaphora pupula					0.04						0.01			
Sellaphora seminulum														0.03
Seminavis strigosa				0.04										
Stauroneis pachycephala	0.01	0.01												
Surirella anassae		0.01												
Tabularia fasciculata			0.03	0.02										
Tryblionella debilis				0.01										