

# Optimised water assessment process for the environmental management of mining projects

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## Abstract

Often water quality monitoring programmes increase in cost and complexity as the operation expands. Such programmes provide bulk data that are not always necessary for robust environmental management of the operation. Similarly bulk data may never be critiqued as they simply provide a number for compliance that may never be an issue. This paper introduces the optimised water assessment process (OWAP) which uses scientific arguments to support minimisation of monitoring programme scope with the objectives of improved environmental management and reduced expenditure.

Screening tools are used to assess the geochemical setting of the mine site, identifying the contaminants likely present in host rock and their mobility. Monitoring programmes should focus on elements identified as likely to be elevated by GAI and MEQ analysis.

Geochemical principles govern the solubility of a contaminant in a given aquatic environment. Often pH governs contaminant solubility. For example, elevated aluminium concentrations are unlikely to occur in circum-neutral (pH > 6) environments. Monitoring programmes should reflect these geochemical principles to avoid collection of redundant data.

Statistical observations show trends in contaminant concentrations. Where concentrations are stable and significantly below compliance limits monitoring data may be redundant. Similarly, where conservative contaminant concentrations are well correlated to a key cation/anion (*e.g.* sulfate), monitoring that key cation/anion alone may be sufficient to demonstrate compliance provided there is confidence in the correlation.

Implementing and maintaining an OWAP is intended to reduce the volume of water quality data collected and therefore expenditure. This was demonstrated, as an example, for the Reddale Coal Mine where pH conditional testing of Fe and Al would have reduced analysis 100% and 93%, respectively, saving in the order of \$1,700 per year. For larger mining operations adoption of OWAP is likely to result in significant savings.

**Keywords:** Optimised Water Assessment Process, OWAP, metal ecotoxicity quotient, MEQ, water quality monitoring.

## Introduction

A key concern for mining companies, regulators, and other stakeholders is acid and metalliferous drainage (AMD), which is the result of sulfide mineral oxidation, typically pyrite. Sulfide oxidation can lead to low pH (< pH 4.5) and elevated metals (Fe, Al, and trace metals) in streams impacted by acid mine drainage. Where host rock contains significant acidity neutralising capacity AMD impacted streams may have circum-neutral pH and negligible acidity but remain elevated in other conservative contaminants including sulfate, boron, trace metals (Cd, Cu, Cr, Ni, Zn, *etc.*), and in some instances elevated alkalinity.

Often water quality monitoring programmes increase in cost and complexity as the operation expands. Such programmes provide bulk data that are not always necessary for robust environmental management of the operation. Similarly bulk data may never be critiqued as they simply provide a number for compliance that may never be an issue. This paper

introduces the optimised water assessment process (OWAP) which uses scientific arguments to support minimisation of monitoring programme scope with the objectives of improved environmental management and reduced expenditure.

### Optimised Water Assessment Process

The initial step for the OWAP is determining the purpose of the monitoring programme in regards to the location(s), sampling frequency, analysis suite, proposed duration, and environmental receptors. Implementing an OWAP uses scientific arguments to minimise an operator's water quality data collection requirements while continuing to demonstrate effects are below compliance levels. Development of an OWAP is intended to:

- Reduce the volume of water quality data collected;
- Reduce expenditure (analysis, interpretation, and internal/external reporting) on sampling and analysis;
- Reduce water quality database complexity;
- Develop monitoring tiers with a focus on automation as part of an adaptive monitoring programme; and,
- Ensure the water quality monitoring programme is fit for purpose throughout the operation and post-closure.

While the OWAP is under development it is important to review current water monitoring programmes to ensure compliance monitoring requirements are met as a minimum, though this should be limited to Resource Consents that have actually been enacted. Implementing the OWAP may require a variation to Resource Consent conditions to reduce/change monitoring requirements with either supporting scientific arguments or data demonstrating monitoring of some parameters are redundant.

### Scientific arguments

Scientific arguments for the inclusion or exclusion of a given parameter from a water quality monitoring programme need to be made on a site specific case by case basis. The OWAP uses scientific arguments including screening tools, geochemical principles, and statistical observations.

#### Screening tools

Screening tools are used for high level analysis of laboratory and field data to determine which elements are likely present at elevated concentrations and whether non-compliance is likely.

#### Geochemical Abundance Index

Element enrichments in host rock are identified using the Geochemical Abundance Index (GAI) (Förstner *et al.*, 1993). The GAI quantifies an assay result for a particular element in terms of the average crustal abundance. The GAI (based on a log-2 scale) is expressed in seven integer increments (viz. 0 to 6). A GAI of 0 indicates that the content of the element is less than, or similar to, the average crustal-abundance. A GAI of 3 corresponds to a 12-fold enrichment above the average crustal-abundance while a GAI of 6 corresponds to a 96-fold or

greater enrichment. The average-crustal-abundances of the elements for the GAI calculations are based on the values listed in Bowen (1979).

Data collected during the pre-mining waste rock geochemical classification programme is typically used for the GAI analysis. GAI can thus be a guide to considering what contaminants of concern could be elevated; however, the GAI analysis does not consider mobility and therefore should only be used as a screening tool.

#### Metal eco-toxicity quotient

A metal eco-toxicity quotient (MEQ) analysis is used to identify contaminants of concern with respect to water quality compliance limits or trigger values. Trigger values may be set by Resource Consents, agreed community targets, or published guidelines (*e.g.* ANZECC, 2000).

A MEQ analysis can be performed on any water quality data, such as baseline stream data, field or lab column leachate, *etc.* The MEQ value for a given parameter is determined by dividing the measured concentration by the compliance limit/trigger value. MEQ values greater than 1 indicate parameters which exceed water quality guidelines. Conversely, MEQ values less than 1 are below compliance limits or trigger values and are unlikely to require routine monitoring.

### Geochemical principles

An understanding of geochemical principles in different geological settings and redox environments may be used to support the OWAP. These geochemical principles typically govern the solubility of a contaminant in a given aquatic environment.

#### Local geochemical setting

To develop an OWAP a good understanding of local overburden/host geology is required, often based on previous experience and baseline data. Valuable sources of information include:

- Acid base accounting (ABA) databases – sulfur/sulfide abundance, carbonate neutralising capacity, *etc.*
- Assay data – trace element wt% abundance.
- Laboratory/field leach testing data – acidity generation and trace element mobilisation rates, *etc.*
- Published literature (*e.g.*, Pope *et al.* (2010) presents typical drainage water quality for West Coast coal mines).

Based on these data the likely AMD type can be ascertained. Two commonly encountered AMD types in New Zealand are acidic drainage from coal mine sites and neutral drainage from metalliferous mine sites (gold). These sites produce distinct and often well documented AMD characteristics which can be exploited by the OWAP.

#### Acidic coal mine drainage

Table 1 shows the average water chemistry analysis for the Whirlwind Seep at the Stockton Coal Mine. This water is an example of the drainage from an acid forming coal mine site prior to neutralisation. The high sulfate concentration, acidity, and low pH are indicative of pyrite oxidation and acidity generation. At low pH (< pH 3.5) Fe and Al will remain dissolved even

in oxidising environments until acid neutralising materials are encountered or dilution dissipates the acidity.

**Table 1.** Stockton Coal Mine Whirlwind Seep average water analysis.

Parameter	Value	Unit
<b>pH</b>	3.5	s.u.
<b>EC</b>	37.2	mS/m
<b>SO<sub>4</sub></b>	182	mg/L
<b>Acidity</b>	160	mg CaCO <sub>3</sub> /L
<b>Al</b>	15	mg/L
<b>Fe</b>	2.5	mg/L
<b>Ni</b>	0.07	mg/L
<b>Zn</b>	0.25	mg/L

A typical monitoring programme for drainage from acid forming coal mine sites would include pH, EC, acidity, alkalinity (if pH > 4.5), Al, Fe, and SO<sub>4</sub>. Other contaminants of concern may be included (*e.g.*, As, B, Cd, Cu, Cr, Pb, Ni, Zn, *etc.*) based on concentrations observed in column leach tests, NAG tests, shake flasks, other wet tests, and field observations.

Typically pH governs which elements in a coal mine drainage are likely to be present in the dissolved form. As pH increases metals are removed by hydrolysis forming insoluble precipitates (Table 2). In oxidising environments where AMD pH exceeds the hydrolysis pH, it is unlikely that metal will be present in the dissolved form at elevated concentrations. For example, dissolved Fe is typically not present in oxidised surface water discharging from coal mines where pH exceeds 3.5, and could therefore be excluded from the monitoring suite.

**Table 2.** Hydrolysis pH for various metals in coal mine AMD (Olds, 2011).

Metal	pH
<b>Fe<sup>3+</sup></b>	3.5
<b>Al<sup>3+</sup></b>	5.2
<b>Zn<sup>2+</sup></b>	8.2
<b>Ni<sup>2+</sup></b>	9.3

These geochemical principles can be used as part of an OWAP to guide water quality monitoring programmes. The Reddale Coal Mine case study (presented later) demonstrates how geochemical principles focussing on pH can be used to minimise monitoring requirements.

#### **Neutral metalliferous mine drainage**

Neutral metalliferous mine drainages are similar to acidic coal mine drainages in that oxidation of sulfides is a major process of contaminant mobilisation. However, abundant acid neutralising capacity in host rock (*e.g.* calcite) prevents these discharges becoming net acidic resulting in suppression of acid-mobile contaminants such as Fe and Al in oxidising environments. However, concentrations of contaminants that are conservative in circum-neutral environments may be elevated.

Table 3 is an example of surface water chemistry downstream of the Devils Waste Rock Stack at the Globe Progress Mine. Sulfate is elevated (higher than that observed at the Whirlwind Seep (Table 1)), indicating significant sulfide oxidation has occurred. However the abundant host rock ANC (principally calcite) neutralised any acidity generated resulting in neutral pH and elevated Ca and Mg. Iron concentration within the waste rock stack itself are likely elevated due to pyrite oxidation. However, circum neutral and oxidising conditions in the silt pond facilitate Fe removal by hydrolysis resulting in low Fe concentrations. Residual Fe is likely present in the colloidal state rather than dissolved.

**Table 3.** Devils Creek Silt Pond 24 August 2010 (Druzicka and Craw, 2013).

Parameter	Value	Unit
<b>pH</b>	7.1	s.u.
<b>EC</b>	73.8	mS/m
<b>SO<sub>4</sub></b>	260	mg/L
<b>Alkalinity</b>	140	mg CaCO <sub>3</sub> /L
<b>Ca</b>	53	mg/L
<b>Mg</b>	58	mg/L
<b>Fe</b>	0.24	mg/L
<b>As</b>	0.10	mg/L
<b>Sb</b>	0.28	mg/L

Thus, in neutral metalliferous mine drainages from this site, monitoring data for contaminants which are acid soluble (*e.g.* Al) are likely redundant. Monitoring programmes should focus on conservative contaminants in circum-neutral oxidising environments (*e.g.* SO<sub>4</sub>, As, and Sb).

#### **Equilibrium/Redox conditions**

When considering which geochemical rules are appropriate to apply in an OWAP it is critical to consider the redox equilibrium state at the monitoring site. Typically, surface water bodies (majority of compliance monitoring sites) are oxic and from a geochemical perspective relatively stable. Changes in contaminant concentrations are largely due to dilution only.

Conversely, the chemistry of an anoxic seep discharge may change rapidly as entrainment of atmospheric oxygen changes redox conditions. At both acid and neutral mine drainage sites this can be demonstrated by oxidation of ferrous (Fe<sup>2+</sup>) to ferric (Fe<sup>3+</sup>) resulting in a rapid decrease in dissolved total iron concentration downstream of where a seep daylights. Compliance monitoring sites should be located sufficiently downstream of seeps to ensure a state of quasi-equilibrium under all flow conditions to maintain integrity of the dataset.

#### **Hardness modification**

The ANZECC (2000) guidelines allow for hardness modification of compliance trigger values for Cd, Cr, Cu, Pb, Ni, and Zn. This modification can be important for sites which experience significant sulfide oxidation, secondary trace metal mobilisation, and subsequent neutralisation by calcium based alkaline material. The Ca neutralent may be naturally present in host rock or added (*e.g.* CaCO<sub>3</sub>) in a treatment plant. Hardness modified trigger values (HMTV) are scaled from a reference hardness of 30 mg CaCO<sub>3</sub>/L. As an approximation, an increase in hardness by an order of magnitude (to ~ 300 mg CaCO<sub>3</sub>/L) will increase the HMTV by an order of magnitude. In a system where sulfide oxidation and subsequent acid



generation is proportional to acid neutralisation by a Ca-based reagent, increases in conservative trace metal concentrations such as Ni and Zn will be offset by increases in Ca potentially maintaining compliance. Caution is required when relying on HMTVs for compliance as if the Ca-based neutralant becomes exhausted hardness will decrease potentially resulting in non-compliance.

### Statistical observations

Statistical observations may be made from both pre-mining baseline datasets and after mining commences. Statistical observations include:

- Long term trends in contaminant concentrations; and,
- Correlation between contaminant concentration and other parameters (pH, EC, etc.)

### Baseline monitoring

An essential component of any water monitoring programme is the determination of baseline conditions. Baseline conditions often provide the basis for the establishment of water quality conditions for any Resource Consent. Significant resources can be allocated to baseline monitoring, particularly where previous disturbance has left the site in a degraded state prior to commencing a new mining operation. The baseline dataset may also provide valuable data showing trends and correlations between different parameters to support the OWAP.

To avoid future compliance related queries, baseline monitoring should capture:

- A full suite of water quality parameters as an initial screening exercise (major cations/anions, trace metals, pH, EC, DO, etc.). Subsequent analyses can be guided by GAI and MEQ to reduce analysis requirements and costs;
- Screening surveys must consider the level of reporting (LOR) by laboratories and ensure that the LOR is lower than ANZECC (2000) trigger values.
- Seasonal fluctuations in water quality and flow rates;
- Reactive monitoring following large rain events or a given number of antecedent dry days; and,
- Flow rates, although water quality is important for compliance, the load (flow x concentration) is critical for sizing treatment systems (passive and active).

### Significance

If monitoring data for a given parameter are 1-2 orders of magnitude below compliance limits and data are stable, or not expected to change, then it is reasonable to consider reduced sampling intervals or use of geochemical triggers before any testing recommences. Where a positive correlation can be demonstrated, triggers could be significant pH or EC change, or the commencement of activities within a catchment. For example, if the concentration of Cd is 10 times below the compliance limit, and is directly proportional to EC then it may be reasonable to use a doubling of EC as the trigger for further Cd monitoring.

### Correlations

Correlations between contaminant concentrations and other parameters (pH, EC, etc.) may also be used to reduce monitoring requirements. This is typically most appropriate for

contaminants which behave conservatively. Where sulfide oxidation is the dominant reaction process sulfate is typically well correlated with EC, particularly if sulfate is not saturated with respect to any secondary minerals. This correlation holds for acid and neutral mine drainages, as neutralisation reactions (and therefore EC) are also proportional to the original sulfide oxidation reactions, provided the monitoring site is in geochemical equilibrium.

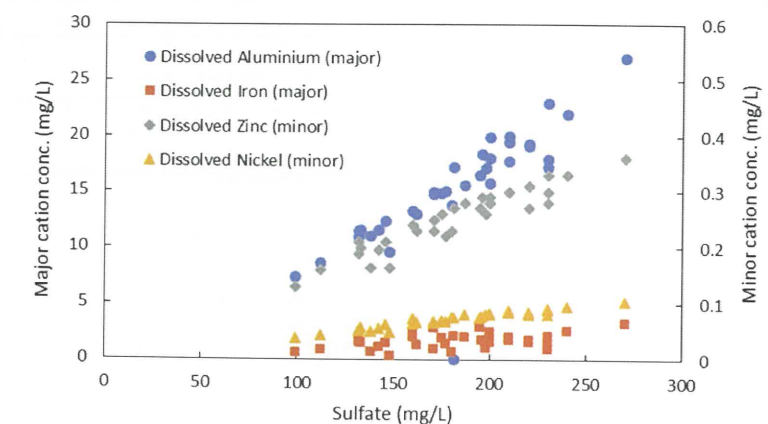


Figure 1. Correlation between sulfate and major/minor cation concentrations for the Whirlwind Seep.

Figure 1 shows the correlation between major and minor cations downstream of the Whirlwind Seep (prior to treatment) at the Stockton Coal Mine. Strong correlations exist between sulfate and Al, Ni, and Zn concentrations. The Fe correlation is weaker due to partial Fe hydrolysis (see Table 2) below the seep where pH varies between 3.2 and 4. Where strong correlations exist such as those shown on Fig. 1, monitoring of a conservative group of parameters could be reduced to one conservative parameter. In the Whirlwind example, sulfate could be adopted as the key indicator for trends in Al, Ni and Zn concentration.

An additional geochemical principle supporting the use of sulfate as an indicator of Ni concentration is presented in Weber (2006), which showed that in Brunner Coal Measures Ni occurs as a substitution for Fe in pyrite. If a compliance limit was to be set for Ni, sulfate could be used as an early indicator of non-compliance; perhaps with a lower conservative trigger value to recommence any monitoring.

### Flow rate monitoring

Accurate and continuous flow rate monitoring is an often neglected but important component of a monitoring programme. Where treatment of a mine drainage is required the contaminant load rather than concentration is typically the most important parameter. This was demonstrated in Weber (2015) for a number of sites including Fanny Creek (Mackenzie, 2010) at the Island Block Coal Mine where acidity was relatively constant for flow rates varying between 1 and 30 L/s while acidity loads varied by two orders of magnitude (Fig. 2). Numerous data sets support the conclusion that flow rate is the dominant driver of contaminant load and that fluctuations in concentration by a factor of 2-3 does not matter if the flow rate fluctuates by orders of magnitude.



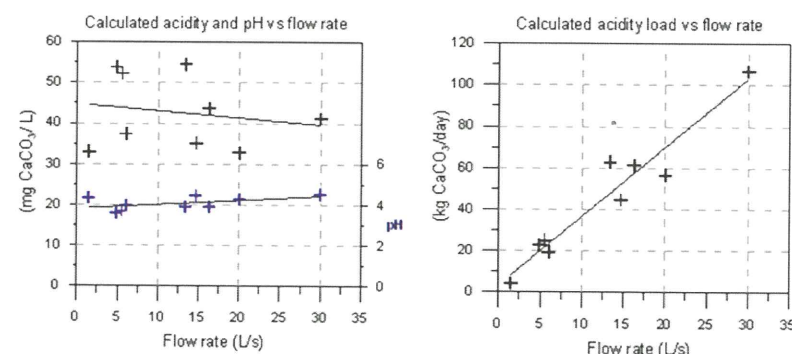


Figure 2. Fanny Creek acidity and acidity load correlated against flow rate (Mackenzie, 2010).

Understanding contaminant loads, particularly in large catchments with a number of tributaries is critical for development of an OWAP. For example it may be possible to demonstrate that some tributaries have a negligible contribution to contaminant load and therefore do not require routine monitoring. Reliable flow rate data is crucial to support these arguments.

### Reviewing and maintaining the OWAP

Best practise requires operators to review their monitoring programmes routinely and it is recommended that the OWAP principles be considered. This may include identifying parameters that should be included or excluded from the monitoring programme. More importantly it ensures the monitoring programme is fit for purpose regarding Resource Consent and operational requirements.

### Reliability

Review is often required to ensure the correct testing methodologies are being used for reliable data collection. This can include:

- Ensuring total versus dissolved metal analysis are used appropriately;
- Ensuring stable redox conditions at the monitoring site;
- Maintaining calibration records for automated flow rate and water quality monitoring systems; and,
- Ongoing review of correlations between contaminant concentrations used in the OWAP.

### Frequency

Testing frequency can often be reduced once the system is understood. This is based largely on statistical observations demonstrating contaminant mobilisation processes are well understood. It may also be reasonable to substitute reactive monitoring for routine monitoring. For example, monitoring may be linked to the number of antecedent dry days in water bodies that are typically diluted by surface runoff or shallow interflow where concentrations are only elevated during dry periods.

Longevity of monitoring requirements should also be considered and a plan to transition from intensive monitoring (~weekly) to infrequent monitoring (~quarterly) developed as part of mine closure. Post closure the focus should shift from manual to automated monitoring.

### Analysis methods

Analysis detection limits (cost versus value) and compliance limits need to be reviewed as part of the OWAP, particularly where detection limits are higher than compliance limits. Methods with lower detection limit are more expensive but may be required to demonstrate compliance. If compliance is successfully demonstrated of a statistically representative period, the more expensive monitoring programme may be ceased.

## Case studies

### Reddale Coal Mine

The Reddale Coal Mine is located near Reefton, on the West Coast of the South Island. Site discharge is monitored 400 m downstream of the mine in Burkes Creek at Red4. Red4 is monitored for a range of parameters on a weekly (pH, turbidity) and monthly (Fe, Al, Ni, Zn) basis. As of July 2015, monitoring data at the Red4 site showed pH remained circum neutral (Olds *et al.*, 2016). Figure 3 shows the vast majority of Al and Fe concentrations were below the relevant rolling median and 95<sup>th</sup> percentile compliance limits, and that the monitoring data for Fe in particular is redundant at an order of magnitude below compliance limits.

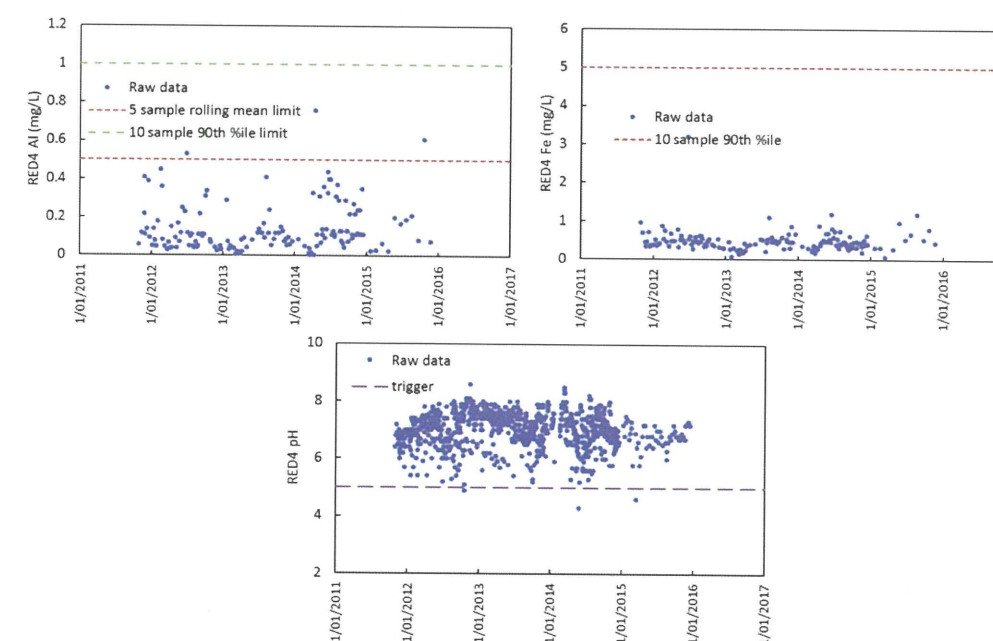


Figure 3. Red4 water quality compliance monitoring data.

The circum-neutral oxidised open channel stream environment at Red4 does not favour elevated dissolved Fe and Al concentrations with both removed as insoluble oxy-hydroxides. Thus, after applying OWAP geochemical principles an alternative water quality monitoring regime was developed (Fig. 4) which uses Red4 pH to determine whether Al and Fe analysis is required.



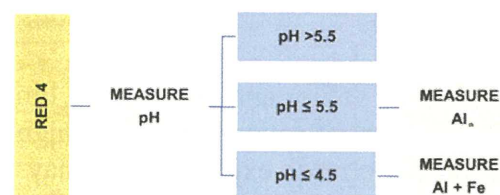


Figure 4. Process Flow pH conditional analysis of Al and Fe.

Adopting this conditional testing approach for the RED4 dataset (between 28/10/11 and 15/12/15) would have reduced the total number of Al analyses by 140 (93%) and Fe analyses by 150 (100%). At a cost of \$11.50 per sample, pH conditional testing would have saved almost \$1,700 in analysis costs from the 28/10/11 to 15/12/15 dataset. When larger datasets are at stake such savings can be significant.

### Benneydale Coal Mine

The Benneydale Underground Coal Mine is located near the Benneydale Township in the upper reaches of the Mangapehi Stream. Following an outflow of AMD from the Benneydale Adit in late 1998 an anoxic limestone drain (ALD) was constructed to neutralise the acidity. Bi-monthly water quality monitoring at five sites was required by the Resource Consent including turbidity, pH, dissolved oxygen, boron, total iron, and sulfate. However, Resource Consent compliance was measured at a single site (B4) downstream of where the adit discharges into the Mangapehi Stream.

Monitoring data show the iron and sulfate concentration discharging the ALD at B5/2 and below the settlement sump at B9 (after aeration) have decreased by an order of magnitude since monitoring began (Fig. 5). This is consistent with a decrease in acidity load discharging from the adit as sulfate would behave conservatively through the ALD.

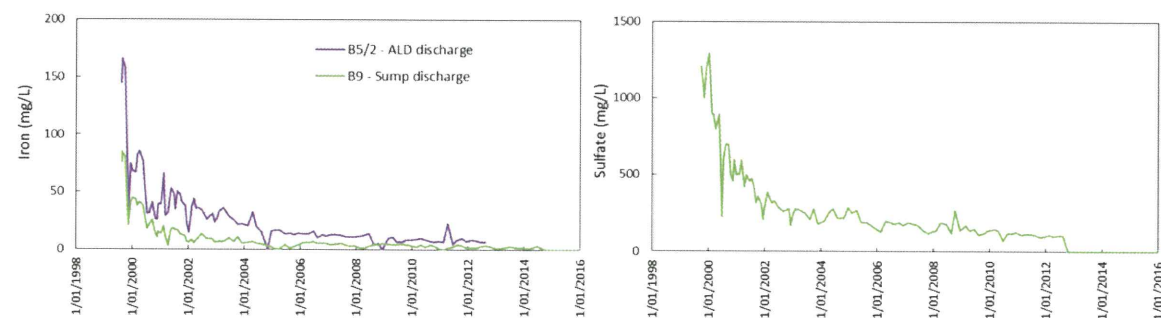


Figure 5. Benneydale adit iron and sulfate.

Mangapehi Stream pH and total iron monitoring data show that since 2004 the Benneydale Adit discharge is having minimal influence on downstream (B4) water quality (Fig. 6). Again this is consistent with a significant decrease in acidity load from the adit.

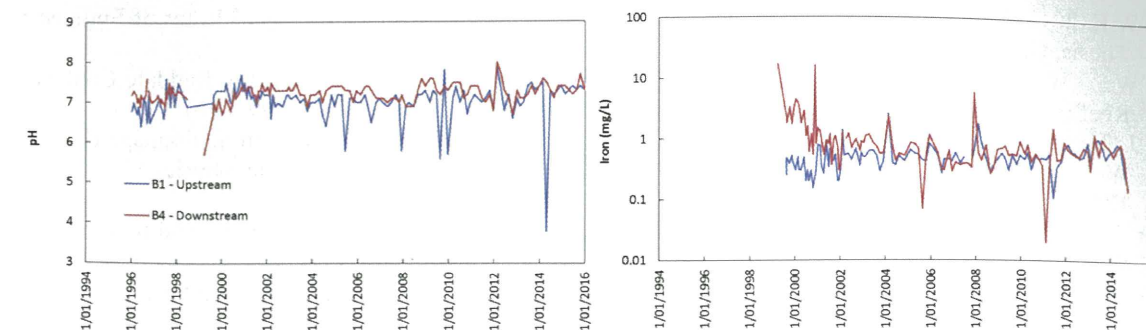


Figure 6. Mangapehi Stream pH and Iron concentration.

Applying the statistical observation principles of OWAP to Fig. 5 and Fig. 6 would support a reduction in the water quality monitoring programme at Benneydale on the basis that adit acidity has decreased significantly. Comprehensive EC data are not available, however, it is likely a significant decrease in EC would have been observed at B9 as the sulfate and iron concentration decreased. A continuously monitored and telemeterised pH, conductivity and turbidity installation may be appropriate, with conductivity being the key indicator of trends in contaminant concentration. The current quarterly water quality monitoring cost of ~\$600-700 would offset the cost of a telemeterised installation within a short timeframe.

### Conclusions

Implementing an OWAP uses scientific arguments to minimise an operator's water quality data collection requirements while continuing to demonstrate compliance. Scientific arguments include screening tools, geochemical principles, and statistical observations based on datasets.

Implementing and maintaining an OWAP is intended to reduce the volume of water quality data collected and therefore expenditure. For larger mining operations adoption of OWAP is likely to result in significant savings.

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