Mine water discharge quality – a review of classification frameworks

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Abstract

Mining activities are commonly associated with impacts on water resources. Water protection, management and treatment is considered to be one of the most complex and costly issues of mining activities. Water classification in general has become an important tool for assessment and management of surface water bodies and several recognised systems exist for characterisation and classification of water quality. A prominent example is the EU Water Framework Directive (2000/60/EC), which was designed to classify surface waters according to ecological and chemical status. However, most water classification systems are impractical for mine water assessment.

A review of specific mine water classification systems showed that the number is limited, frameworks are predominantly geared towards Acid- and Metalliferous Mine Drainage (AMD/MMD) and classification is mostly based on geochemical parameters. This approach could be called historical as sulphide mineral oxidation has been the dominating water contamination process in mining for decades. Consequently, other types of mining induced water contamination, such as salinity, are neglected in both mine water classification and regulation. Non-metalliferous types of mine discharge/effluent are often handled and regulated on a case-by-case basis or not at all, leading to uncertainty for key stakeholders and in some cases to unnecessary deterioration of water quality.

A new mine water classification framework linked with water treatment is necessary if mine water issues are to be addressed at a more comprehensive and consistent basis for multiple issues around the globe. Successful application of interdisciplinary or impact-based systems has been demonstrated on a regulatory level and the lessons-learned could be used for broader implementation. Based on a review of existing frameworks the most important aspects and advantages as well as suitable classification parameters were compiled. We then lay the foundation of a revised mine water classification framework that would contribute to the improvement of mine water management.

Key words: Mine water, classification, Acid Mine Drainage, salinity, framework

Introduction

In the years to come the mining industry will face the challenge of adopting more integral and sustainable practices all over the life-cycle of resource projects. Mine effluent in particular is a common community and environmental concern, as it can have serious impacts on water quality, aquatic life, ecosystems and drinking water resources. Because of decreasing ore grades and increasing scale of mining activities, rock exposure to atmospheric conditions due to excavation, blasting, drilling and subsidence as well as the sheer mass of waste rock, tailings and overburden is increasing over time. As a result, water contamination, especially Acid Mine/Rock Drainage (AMD/ARD), has become the number one problem associated with modern mining activities (Franks et al. 2014, Pokhrel & Dubey 2013). In this context, mine water management on a local, regional and national scale is one of the key aspects of mining operation and regulation (IIED 2002). Differing international practices in assessment, classification and regulation of mine water can be a limiting factor for the mining industry, impeding transnational investment and at times denying downstream water resource users adequate pollution protection.

Classification of mine water can help avoid uncertainty amongst stakeholders and consequential adverse effects on water resources by categorising mine effluent and providing information on typical contamination processes, hazards, risks and suitable mitigation or treatment options (Wildeman & Schmiermund 2004). Over time a number of classification systems have developed and been proposed, reported or discussed in the literature (e.g. Younger 1995). The objective of this paper is to provide a literature based review of the current status of mine effluent classifications and to make recommendations with regard to future improvements and the development of a suitable framework for more widespread application. It is noted that the terms mine discharge, effluent and drainage are used interchangeably throughout the paper.

Mine Water Contamination

Contamination of mine water is usually the result of a number of different interrelated factors, including but not limited to geological background, climate, geochemistry, biochemistry, commodity, mine type and processing method. However, a number of prevalent processes are commonly associated with mining activities. For decades attention of regulators, industry, research and communities has predominantly been focused on AMD as archetypal mine water pollution. AMD is commonly associated with low pH (1 – 5), low dissolved oxygen and high concentrations of toxic metals, metalloids and sulphate (Morin & Hutt 1997). Beyond that, non-acidic Metalliferous Mine Drainage (MMD), also known as Neutral Mine Drainage (NMD), has been distinguished and acknowledged as an independent type of mine effluent in recent decades. MMD is commonly associated with circum-neutral pH (6 – 8), low dissolved oxygen and medium to high concentrations of sulphate and metals that are soluble (e.g. Cu, Zn, Cd) or insoluble (Fe, Al, Mn) under aerobic conditions. Even slightly enhanced iron content in surface waters, not yet considered metalliferous, can lead to distinctive staining of creek-, stream- or riverbeds due to ochre formation (Belmer et al. 2014, Gray 1996a).

Mine effluent or process water from non-sulphidic lithologies or low-sulphur coal and lignite mines can be highly saline due to major cations and anions without containing elevated metal concentrations. Because of the substantial change in water chemistry, this type of mine water must be considered as contaminated, albeit being neither AMD nor MMD (Lincoln-Smith 2010, Palmer et al. 2010, Wildeman & Schmiermund 2004, Wright 2011). In the literature this type of mine water is sometimes referred to as Saline (Mine) Drainage (SD). SD is generally considered to be non-toxic to humans and ecosystems (at least short-term), however, it can have serious long-term impacts on water quality, aquatic life and the aesthetics of surface waters (Bernhardt & Palmer 2011, Cañedo-Argüelles et al. 2013, Hall & Anderson 1995, Lincoln-Smith 2010, van Dam et al. 2014). In general, water salinity is deemed insignificant compared to AMD, as both perceived threat and visible effects are by far less prominent. For this reason, it is much less frequently dealt with or described in studies and often no consistent regulations exist, mandating mitigation or treatment (Wildeman & Schmiermund 2004, Wright 2011). This grey area needs to be addressed by regulators to provide consistent protection of water resources on the one hand and facilitate straightforward water management for mine operators on the other hand.

Mine Water Classification Schemes

Mine water classification approaches are usually tailored for a specific type of drainage, commonest AMD/ARD as it is the worst and most prominent type of mine water pollution. The most important classification frameworks and some minor ones specifically designed for mine water assessment are described below.

Physico-chemical Classification

Classification of mine water is predominantly focused on water chemistry. Consequently, most classification systems use physico-chemical parameters to distinguish between different types of mine water. The most prominent example of such a system can be found in the Global Acid Rock Drainage (GARD) Guide, an online-based open-source compilation of methods and technologies for the prediction, prevention, mitigation, management and monitoring of mine water contamination with a focus on AMD generation as a result of sulphide mineral oxidation (INAP 2009). The GARD Guide classification framework is kept very simple and it should be noted, that the terms and characterisations have been present in literature long before the GARD Guide. Mine water is categorised in three classes that are roughly outlined and defined by max. four parameters only (cp. Table 1). The lack of more quantitative definitions is acknowledged by the authors.

Table 1 *The GARD Guide mine water classification (INAP 2009)*

GARD Guide classification	Class description	Thresholds
Acid Rock Drainage / Acid and Metalliferous Mine Drainage	• Acidic pH • Moderate to elevated metals • Elevated sulphate	• pH < 6
Neutral Mine Drainage (NMD)	• Near-neutral to alkaline pH • Low to moderate metals • Low to moderate sulphate	• pH > 6 • Sulphate < 1,000 mg/L • TDS < 1,000 mg/L
Saline Drainage (SD)	• Neutral to alkaline pH • Low metals (only moderate Fe) • Moderate sulphate, Mg and Ca	• pH > 6 • Sulphate > 1,000 mg/L • TDS > 1,000 mg/L

Other mine effluents not deriving from sulphide mineral oxidation can be assessed as well, but as the system is focused on dissolving and leaching of acid generating or neutralising minerals and salts, other waters are categorised almost exclusively according to their sulphate content. In most cases this would lead to SD or NMD classification, however, if little sulphate is present, saline mine water containing vast amounts of major cations and anions could even be classified as freshwater.

The two to four-pronged GARD Guide classification approach (usually AMD/ARD – MMD/NMD – SD – Freshwater) can be found in several other systems and definitions, such as the Canadian Mine Environment Neutral Drainage program (e.g. MEND reports 1.16.1b, 1.20.1 and 10.1) and a number of mine water classifications in international literature (e.g. AUS DITR 2007, Glover 1975, Hedin et al. 1994, Hill 1968, Morin & Hutt 1997, Wildeman & Schmiermund 2004). These physico-chemical classifications are predominantly defined by pH, metal and sulphate content, which limits the framework to AMD-related water pollution. Morin & Hutt (1997) tried to solve the problem by adding a fourth class labelled “Other” to account for mine drainage from non-metal mines that is not primarily characterised by pH or metal concentrations. A different, more itemised rating is provided by the Irish Acid Mine Drainage Index (ARDI) and subsequent modifications (Gray 1996b, Kuma et al. 2011). Another framework primarily concerned with pyrite oxidation and AMD formation was developed to compare mine water of various origins by using a diagram with sulphate concentration on the abscissa and neutralisation potential, as a cumulative parameter for acidic or buffering species, on the ordinate (Schoepke & Preuss 2012). This system was developed with regard to groundwater seepage and pit lakes from lignite mining and the applicability to other commodities is limited.

A more holistic approach was prepared by the Minerals Council of Australia (MCA) as part of the Water Accounting Framework (WAF) for the minerals industry. The framework features three categories according to water quality and treatment requirements for classification of water input and output of mining operations and facilities (cp. Table 2). Assessment is primarily based on chemical parameters such as pH, TDS and harmful or toxic constituents, and secondarily on biochemical constituents such as coliforms or pesticides/herbicides. A level of treatment is assigned that would be necessary to achieve human consumption standards as described in recognised drinking water standards (MCA 2014, Timms & Holley 2016).

Table 2 *The WAF mine water classification (MCA 2014)*

WAF classification	Class description	Thresholds
Category 1 **High water quality**	Minimal effort necessary to achieve drinking water quality	• pH = 6 – 8.5, TDS < 1,000 mg/L • No turbidity after sedimentation, no/traces of pesticides/herbicides or harmful constituents • Coliforms < 100 cfu/100ml
Category 2 **Medium water quality**	Moderate treatment necessary for individual constituents	• pH = 4 – 10, TDS = 1,000 – 5,000 • Coliforms > 100 cfu/100ml
Category 3 **Low water quality**	Significant treatment necessary to achieve satisfactory water quality	• pH < 4 or > 10, TDS > 5,000 mg/L

Both the GARD Guide and WAF classifications use pH and TDS as a primary water quality indicator. However, whereas the GARD Guide is focused on sulphate concentration as the system is adapted for sulphide mineral oxidation and AMD, the WAF classification uses a number of parameters that are harmful to human health and provides a decision tree for simple categorisation. The WAF system provides wide-ranging applicability, but as it was designed specifically for the minerals industry, the decision tree lacks a component to account for AMD (e.g. sulphate). The WAF classification could form the basis for mining related discharges to be accounted for in the Global Sustainability Reporting Initiative (GRI). As discussed by Leong et al. (2015) and Mudd (2008), the EN22 indicator of the GRI is to report the total volume of discharge by destination and water quality, so to understand the potential for environmental impacts. However, there are no specific guidelines provided beyond these principles, for which the WAF could provide a way forward.

Table 3 *Mine drainage pollution classes (Hill 1968)*

Hill (1968)	Class description	Thresholds (Ac=Acidity [mg/L $CaCO_3$])		
Class I	Acid drainage	• pH = 2.0 – 4.5 • Ac = 1,000 – 15,000	• Fe^{2+} = 500 – 10,000 mg/L • Fe^{3+} = 0 mg/L	• SO_4 = 1,000 – 20,000 mg/L • Al = 0 – 2,000 mg/L
Class II	Partially oxidised and/or neutralised	• pH = 3.5 – 6.6 • Ac = 0 – 1,000	• Fe^{2+} = 0 – 500 mg/L • Fe^{3+} = 0 – 1,000 mg/L	• SO_4 = 500 – 10,000 mg/L • Al = 0 – 20 mg/L
Class III	Oxidised and neutralised/alkaline	• pH = 6.5 – 8.5 • Acidity = 0	• Fe^{2+} = 0 mg/L • Fe^{3+} = 0 mg/L	• SO_4 = 500 – 10,000 mg/L • Al = 0 mg/L
Class IV	Neutral and not oxidised	• pH = 6.5 – 8.5 • Ac = 0	• Fe^{2+} = 0 – 500 mg/L • Fe^{3+} = 0 mg/L	• SO_4 = 500 – 10,000 mg/L • Al = 0 – 2,000 mg/L

An older framework can be found in Hill (1968), where classification is based on mine water chemistry related to distance from pollutant formation (cp. Table 3). The categorisation proposed by Hill (1968) is primarily focused on (natural) thermodynamic processes taking place with increasing distance from the pollution source. Class III mine water could be considered as the natural equilibrium after incremental oxidation and neutralisation, comparable to actively or passively treated mine water. Apart from the outdated focus on point sources the system is very similar to current classification schemes and therefore displays the same limitations. This clearly shows, that approaching mine water classification with a rather one-dimensional focus on sulphide mineral oxidation has not changed significantly in the past 50 years.

Deposit Based Classification

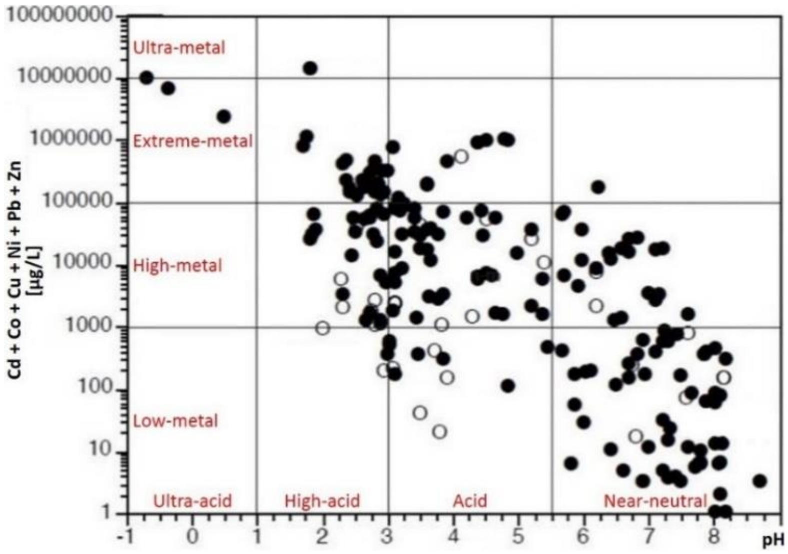

Figure 1 *Ficklin diagram of natural waters (open circles) and mine waters (closed circles) draining diverse mineral-deposit types (modified, cp. Plumlee et al. 1992, 1999)*

The USGS developed an empirical system postulating that similar mineral deposit geologies produce similar drainage water (Plumlee et al. 1999, Seal & Foley 2002). Databases were used to create the necessary geoenvironmental models of mineral deposits and results can be plotted in a classification diagram. In these so-called "Ficklin diagrams" drainage pH is plotted against the sum of six dissolved heavy metals (Cd, Co, Cu, Ni, Pb, Zn) typical for acid generating environments (cp. Figure 1). Classification is based on these two indicators and combines one out of four pH-dependent attributes (near-neutral to ultra-acid) with one out of four metal-content-dependent attributes (low to ultra-metal) to form the respective category (Ficklin et al. 1992, Plumlee et al. 1992, 1999).

The diagrams are based on the assumption that effluent quality is largely dependent on geology and climate, which is why the plots and diagrams can be used for AMD and MMD as well as for naturally occurring ARD. As the system is based on deposit geology, the most important metals of sulphide mineral oxidation (Fe, Al, Mn) are excluded, as their omnipresence would obliterate the connection between background geology and effluent composition (Kuma et al. 2011, Plumlee et al. 1999). Obviously, the system is unsuitable for saline mine effluent, as major cations and anions are disregarded except for sulphate. The system is, however, highly applicable and meaningful for metal mines and can be used to link deposit paragenesis and mine water pollution (Kauppila & Räisänen 2015, Seal & Foley 2002).

Chemical-ecological Classification

An environmental impact assessment (EIA) derived by the UK National Rivers Authority (now: Environment Agency) estimates the impact of mine discharge on surface waters by assessing six different chemical, ecological and visual impact categories (cp. Table 4). For each category four subcategories (A = high; B = medium; C = low; D = none) are outlined with physicochemical impacts specifications (Davies et al. 1997, Jarvis & Younger 2000, UK Environmental Agency 1996):

Table 4 *UK classification of mine water impacts on surface waters (Jarvis & younger 2000)*

Physicochemical parameter (in decreasing order of importance)	**Impact on receiving waters**			
	A – High	**B – Medium**	**C – Low**	**D – None**
Area affected [m^2]	A1: > 10,000 A2: 2,500 – 10,000	B1: 1,000 – 2,500 B2: 10 – 1,000	< 10	0
Length affected [km]	> 0.50	0.01 – 0.50	< 0.01	0
Substrate quality for salmonid reproduction	Rocks / stones / gravel	Bedrock / boulders / rocks	artificial channel / sand / silt	–
Iron deposition (visual)	High	Medium	Low	None
Total iron [mg/L]	> 3.0	2.0 – 3.0	< 2.0	0
pH, DO [%], total Al [mg/L]	3 failures*	2 failures	1 failure	No failures

***Failures:** pH < 7; DO (dissolved oxygen saturation) < 70%; total Al > 1.0 mg/L

The classification system was successfully used to rank mine effluents and surface waters in the UK according to severity of impact (Davies et al. 1997). In a second phase additional impact assessments on benthic macroinvertebrates and fisheries' potential of the respective surface waters were used to determine an environmental quality index (EQI), which indicated sites with the most urgent need for action (Banks & Banks 2001, Jarvis & Younger 2000). The system proved to be effective and highlighted the benefits of a good classification system. Moreover, chemical and ecological aspects were innovatively combined in a more holistic approach (Jarvis & Younger 2000). Although especially visual and biological components make the application more difficult in terms of everyday use, the system is nonetheless very useful from a rehabilitators and regulators point of view.

A simple, descriptive index for the assessment of biological impacts of mine effluent was developed by Gray (1996a) with a focus on river bed substrate as the most important habitat for macroinvertebrates, fish and macrophytes in lotic systems. The index is based on visual assessment of AMD precipitates (ochre or yellowboy) in receiving watercourses and a qualitative indication of the severity is provided. The system is very simple and inexpensive, but at the same time very limited, as only seeable iron flocculation and precipitation and the consequential impact on substrate and biota are taken into account.

Environmental Pressure Based Classification

A different approach for assessment and classification of mine water was developed and published by Puura & D'Alessandro (2005) by relating environmental pressures to mine water discharge. The system uses water flow and quality to classify mine water discharge and to subsequently develop a ranking of polluted mine sites. Effluent characterisation is based on "the number of times any environmental standard (maximum permissible concentration, MPC) is exceeded" (Puura & D'Alessandro 2005). The system comprises five categories, incrementally representing the number of MPC exceedances (A = >1,000; B = 100 – 1,000; C = 10 – 100; D = 1 – 10; E = 0). Results can be plotted in a graph with metal emissions on the ordinate and MPC exceedance on the abscissa (cp. Figure 2). Ultimately, a pressure factor (PF) is calculated (PF = log(MPC-exceedance) + log(flow rate)), which can be directly related to the potentially polluted volume of clean water per day ($V_{polluted} = 10^{PF}$).

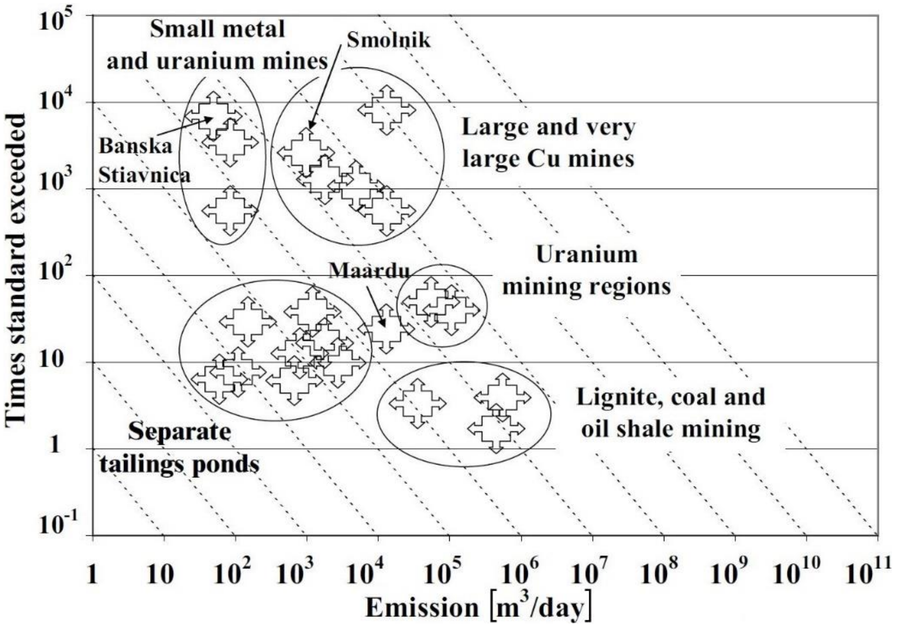

Figure 2 *Metal emissions plotted against MPC exceedance (cp. Puura & D'Alessandro 2005)*

The system is very versatile and can be adapted for different situations and purposes, including individual and multiple contaminants as well as different mine sites, as long as respective environmental standards are in place. Nevertheless, it did not receive much attention in literature.

A somewhat similar approach is described by Mullinger (2004), where the impact of mine discharge on surface waters was ranked by incrementally scoring transgression of water quality standards for metal loads (Cd, Cu, Pb, Zn) and ecological impacts. On this basis an environmental quality standard (EQS) failure score can be determined for classification and ranking of different mine sites (Mullinger 2004).

Mine water classification and regulation in practice

As of yet, none of the mine water classification schemes described above is being used or referenced as a standard classification system on a regular basis and transregional scale. The reason for this is that the vast majority of studies related to mine water deal with AMD or MMD, where the category is obvious and classification efforts would be redundant. Whilst strict regulations are in place for AMD and MMD, most regulations fail to identify or classify other contaminants including turbidity and salinity. In cases where limitations or trigger values are in place (e.g. for sulphate, sodium, EC, TDS etc.), these are often ignored or discounted with reference to dilution (Belmer et al. 2014, Cañedo-Argüelles et al. 2013, Palmer et al. 2010, Wildeman & Schmiermund 2004, Wright 2011). A current guideline for mine water discharge quality in Western Australia allows for variations of +/–10% on natural seasonal background water quality indicators (e.g. EC, TSS, DO, radionuclides) (WA 2000). These guidelines may be difficult to practically achieve with limited baseline data for projects in environments with substantial seasonal variation. At some mine sites in Australia (e.g. NSW OEH 2012), site specific triggers are developed based on eco-toxicity studies of local invertebrates, a more expensive but more effective approach than adopting default national water quality limits for freshwaters as outlined in the ANZECC 2000.

Discharge limits are mostly determined on a case-by-case basis during the licensing procedure, varying significantly from country to country (Puura & D'Alessandro 2005). Although this makes sense in terms of site specific background (especially catchment geology and climate), the environment and downstream users of water resources (communities, agriculture, drinking water production etc.) are usually the ones to live with the consequences of degraded water quality (Cañedo-Argüelles et al. 2013, Wright 2011). A large number of methods, tools and systems for characterisation and classification of mine wastes can be found in the literature. However, mine water classification is lacking comprehensive frameworks that are widely adopted in practice. This is surprising, as classification systems such as the Richter scale, Köppen climate classification, USDA soil taxonomy etc. are used in most natural sciences to simplify the scientific dialogue and numerous studies exist for AMD/ARD prediction. A limiting factor might have been the complexity of water pollution by mining activities. Classification systems in general need to be straightforward, coherent and as comprehensible and simple in application as possible (Horton 1965). A suitable classification framework specially tailored for mine effluent could be beneficial in many different ways to the key stakeholders of mining activities (cp. Figure 3).

Key stakeholders concerning mine water isssues / Advantages of a suitable classification frameworks used consistently worldwide	Mine operators	Regulators	Environmental groups and communities	Scientific community	Downstream users
Informative characterisation of mine water discharges, including flow rates and volumes	X	X	X	X	X
Improving comparability of mine sites (optimally worldwide) as well as revealing temporal and spatial variation		X		X	
Providing a basis for consistent mine effluent regulation and rating	X	X	X		X
Providing a basis for integration in environmental impact assessments (EIA)	X	X	X		
Providing a basis for cost-benefit analysis (CBA)	X				
Using water quality classification downstream or along transects to assess spatial development of dilution, amelioration, neutralisation etc. with due regard to both concentration and loads (based on flow rates)	X	X	X	X	X
Improving understanding and awareness of mine water discharge and its impacts		X	X	X	X
Facilitating and improving communication between stakeholders	X	X	X	X	X
Providing information on hazards and risks as well as applicable management, mitigation and treatment options for typical types of mine water to provide a direct link between classification scheme and effective treatment options	X	X			X

Figure 3 *Benefits and beneficiaries of a suitable classification framework*

Another shortcoming of current mine water quality classification schemes is the lack of consideration of water quality mitigation or treatment options. There are few independent guides available for first-pass consideration of the suitability and limitations of treatment options (e.g. PIRAMID Guidelines or US EPA Reference Guide 542-R-14-001). It is possible that classification schemes could be adjusted to reflect options for treatment technologies (e.g. threshold TSS that reduces AMD treatment). However, separate studies are therefore often required for consideration of technically feasible and cost effective solutions to water quality issues through mitigation, active and/or passive treatment. Technologies for water quality treatment are developing in part as a response to the rapidly growing market for mine water treatment (Bluefield Research 2014).

Summary

This review of mine water classification systems reveals a long established focus on AMD and MMD. For both mining regulators and operators acidity and metal toxicity are the major concerns, as the worst impacts on water quality can be expected and strict regulations apply. For this reason it is not surprising that almost all classification systems use pH and metal concentration as key characteristics for the segregation of categories. However, this does not address emerging awareness of broader water quality issues. Current systems are very vague in terms of mine water salinity, and sulphate is the only major ion that can be found in multiple schemes as it correlates strongly with sulphide oxidation (Plumlee et al. 1999).The importance of salinity and other characteristics (e.g. turbidity, toxicity) with regard to water quality and impact on aquatic ecosystems is increasing worldwide and should find entrance into existing mine water classification systems to attract the attention of regulators and industry (Belmer et al. 2014; Cañedo-Argüelles et al. 2013). As of yet, none of the mine water classification schemes described above is being used or referenced as a standard classification system on a regular basis.

It is challenging for one water classification framework to incorporate a broader range of relevant factors and processes, yet remain practical for application (Horton 1965). However, assessment and subsequent ranking of mine sites in the UK and Ireland using straightforward mine water classification has proven effective and demonstrated the benefits and utility of such a system (Jarvis & Younger 2000). The same can be said about application of the WAF framework by 90 % of mine sites in the Australian Hunter Valley coalfield (Timms & Holley 2016). An improved and extended mine water classification framework could be a valuable tool to help regulators close the remaining gap in water and mining policies.

Conclusions / Recommendations

A revised mine water classification framework could play a major role in addressing mine water issues on a larger scale and on a catchment, national and international basis. As water impacts are investigated by numerous (local) experts from different disciplines and countries, it is recommended that the revised framework be straightforward and based upon unambiguous, standard characteristics. A combination of chemical, ecological and other key parameters (cp. Figure 4) is advisable as well as depending on the water resource in question (mine discharge, surface water, groundwater). In addition, the classification system should be applicable to any mining activity regardless of mine-type or commodity and describe typical formation, occurrence, properties, hazards, management, mitigation, treatment and monitoring options for defined types of mine water, as well as providing appropriate references.

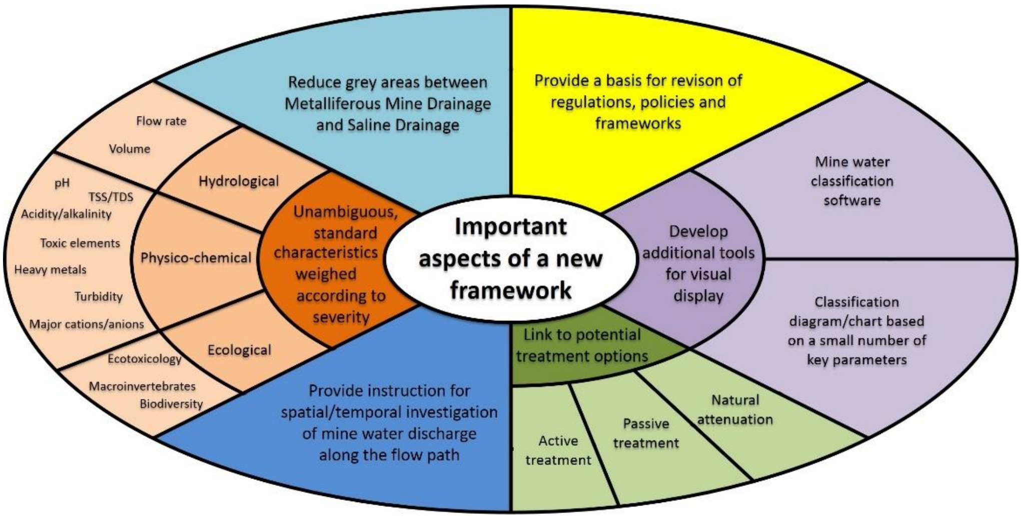

Figure 4 *Recommendations for a new classification framework*

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