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Geochemical Classification of Global Mine Water Drainage

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Abstract: This paper evaluates the geochemical distribution and classification of global Acid Mine Drainage (AMD) sources. The geochemical compositions of AMD from 72 mine water sites in 18 countries across 6 continents were referenced from literature. The secondary data were analysed for statistical distribution and mine water classification against the Hill (1968) framework. The research found that the global mine water displayed geochemical concentrations within 2%, 11%, 5%, 9% and 8% of the aluminium, sulphate, acidity, total iron and zinc distribution ranges, respectively, at the 75th percentile. The study also found that 46%, 11.1% and 2.7% of mine water sites met the criteria for Class I, Class II and Class III of the Hill (1968) framework, respectively, while the remaining 40% of sites were omitted by the framework's geochemical specifications. The results were used to optimise the Hill (1968) framework. The revised framework was proposed for effective AMD geochemical classification, regulation and remediation.

Keywords: Acid Mine Drainage (AMD); geochemical classification; mine water geochemistry; mine water characteristics

1. Introduction

The formation of Acid Mine Drainage (AMD) water streams is a naturally occurring phenomena and occurs in suitable environments where oxygenated water comes into contact with sulphide minerals in the presence of aerobic microorganisms [1–3]. Large-scale commercial mining operations enabled by technological advancements and the growing economic need for mineral resources has resulted in significant increases in the volumes and toxicity of AMD generated globally [4,5]. This is a result of the fragmentation of rocks during mining operations leading to increased surface area of rock faces with an abundance of sulphide minerals [4,6]. AMD streams are typically characterised by low pH and high concentrations of heavy metals and sulphate [7,8]. The geochemical processes leading to the formation of AMD can be summarised into four interdependent reactions as defined in Equations (1)–(4) [9,10].

$$2FeS_2(s) + 2H_2O + 7O_2(aq) = 2Fe^{2+} + 4SO_4^{2-} + 4H^+ \quad (1)$$

$$4Fe^{2+} + 4H^+ + O_2 = 4Fe^{3+} + 2H_2O \quad (2)$$

$$Fe^{3+} + 3H_20 = Fe(OH)_3(s) + 3H^+ \quad (3)$$

$$FeS_2(s) + 14Fe^{3+} + 8H_2O = 15Fe^{2+} + 2SO_4^{2-} + 16H^+ \quad (4)$$

The decant of AMD from mine tailings, of abandoned mines in particular, poses serious environmental hazards including the contamination of rivers, destroyal of aquatic life, bioaccumulation of toxic metals by organisms and plants, impairment to biodiversity and damaging natural habitats [2,11–13]. The release of AMD and the associated pollution poses long-term environmental hazard due to sulphide mineral rich mine sites being able to continue generating AMD centuries after commercial mining operations have ceased [6,14]. This long-term effect coupled with the severity of pollution has made AMD one of the greatest environmental challenges associated with the mining industry globally [5,15,16]. Prevention of AMD formation is the most ideal solution and may be achieved using techniques such as coating of the exposed mine rock surface and creating oxygen barriers to prevent the dissolution and oxidation of sulphide minerals respectively [17,18]. However, the majority of AMD is associated with abandoned or closed mining sites where the ground water table has risen inside of mine shafts and pits allowing for exposure to sulphide minerals [19–21]. Once AMD is formed in these abandoned and closed mining sites the process is difficult to control and remediation is the most immediate solution [17]. Figure 1 shows the effects of abandoned mine AMD on the surrounding environment.

Figure 1. Environmental effects of Acid Mine Drainage (AMD) from an abandoned coal mine in KwaZulu-Natal, South Africa.

In 2010, a total of 6152 abandoned mines were identified in South Africa [22,23]. In the United States, it has been estimated that there are more than 500,000 abandoned or closed mines affecting 25,000 km of water streams [24,25]. Australia has recorded more than 50,000 abandoned mines [26] and in the United Kingdom, the number of abandoned mines is estimated to be over 2000 [18,27]. Many of these and other abandoned mines across the globe continue to generate AMD leading to numerous scholarly works on the remediation of the pollutant to limit environmental degradation [6,17,28–34]. Conventional pH correction has been the most widely implemented AMD remediation technique globally due to its operational simplicity, low capital investment costs, and scalability [6,35]. However, this remediation method, like any other, has its limitations. The selection of suitable remediation methods for mine water sites remains a critical task for local governments and organisations managing AMD streams. The suitability of an AMD remediation technique is influenced by many site-specific factors including the AMD geochemical composition, AMD flow rates, topography and site location amongst others [17,34,35].

Over the past three decades, mine water management has become a key regulatory and policy requirement in many mining nations to counter the environmental hazard posed by AMD [36–39]. Legal frameworks governing mine water differ by jurisdiction and typically include discharge permits, tailing storage and post-mine closure obligations [40]. To avoid uncertainty amongst stakeholders and adverse effects on the environment, classification frameworks for AMD have been proposed to indicate the contaminant levels and geochemistry of AMD streams [38,41]. These classification frameworks have proven useful for site rehabilitators and environmental regulators in decision making [42]. The most prominent classification method is the Global Acid Mine Drainage (GARD) guide [36]. The GARD guide is a simple classification framework that uses pH and Total Dissolved Solids (TDS) as primary indicators for AMD categorisation [36,43]. Other AMD categorisation methods include the Water Accountability Framework (WAF), which uses pH, TDS and coliforms [44,45], the Gray Acid Mine Drainage Index (AMDI), which uses pH, SO_4, Fe, Zn, Al, Cu and Cd [46,47] and the framework by Hill (1968), which classifies AMD using acidity, SO_4, pH, Al and Fe concentrations [36,48].

The use of existing mine water classification frameworks has been limited to specific regions due to practical limitations and the high geochemical variability of global mine water [45,49,50]. Some practical limitations of existing frameworks include the criteria used for classification and the frameworks' applicability to mine waters generated from vastly different rock geology and environmental conditions [47,51]. The high geochemical variability of global mine water sources requires additional research to improve mine water classification frameworks for global adoption. An ideal global AMD classification framework would enable mine water regulation and site rehabilitation while being simply understood, comprehensively specified and applicable to any mine water system. The framework by Hill (1968) remains one of the most comprehensive yet simple AMD geochemical classification methods available today and was therefore evaluated and optimised for AMD categorisation in this study. Table 1 shows the Hill (1968) framework.

Table 1. Acid mine drainage classification [48] adopted from [36].

Class	Class Description	Thresholds		
Class I	Acid mine drainage	pH = 2.0–4.5 Acidity = 1–15 g/L	Fe^{2+} = 500–10,000 mg/L Fe^{3+} = 0 mg/L	SO_4 = 1–20 g/L Al = 0–2000 mg/L
Class II	Partially oxidised and/or neutralised	pH = 3.5–6.6 Acidity = 0–1 g/L	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	Neutral and not oxidised	pH = 6.5–8.5 Acidity = 0 mg/L	Fe^{2+} = 0–500 mg/L Fe^{3+} = 0 mg/L	SO_4 = 500–10,000 mg/L Al = 0–2000 mg/L
Class IV	Oxidised and neutralised/alkaline	pH = 6.5–8.5 Acidity = 0 mg/L	Fe^{2+} = 0 mg/L Fe^{3+} = 0 mg/L	SO_4 = 500–10,000 mg/L Al = 0 mg/L

The Hill (1968) framework was developed based on distance of AMD streams from the original AMD sources [36,48]. Naturally occurring neutralisation and oxidation processes take place over the distance travelled by a stream, which affects the AMD stream's quality until a completely oxidised and neutralised stream is achieved. In this framework, the greater the class number the better the water quality with the AMD stream at the mine source being presented as Class I and the fully oxidised and neutralised AMD stream presented as Class IV [36,48]. The Hill framework indicates the pollution potential of an AMD stream and the level of oxidation and/or neutralisation required to achieve Class IV. This framework accounts for metals Fe^{2+} and Al, which tend to fully precipitate within the neutral pH range resulting in the neutralised and oxidised Class IV being specified with dissolved Fe^{2+}, Al and acidity concentrations of zero. However, the framework does not include an indicator species of the cytotoxic metals present in AMD, which can cause serious ecological damage and require alkaline conditions to effectively precipitate as metal hydroxides. These cytotoxic metals, which include zinc (Zn), nickel (Ni), lead (Pb), arsenic (As) and cadmium (Cd), all tend to precipitate at pH greater than 8.5 [52]. The presence of these cytotoxic metals in AMD influences the selection of AMD treatment technology and the ecological pollution potential of AMD, therefore understanding their concentration distribution in global AMD sources is essential for AMD categorisation [33].

This paper evaluates the geochemical distribution and classification of global AMD sources using secondary data. The Hill (1961) framework was evaluated as a categorisation baseline. Cation Zn^{2+} was added to the analyses as an indicator species for the cytotoxic metals present in AMD. The geochemical compositions of AMD from 72 mine sites from 18 countries across 6 continents were referenced from literature. The dataset was analysed for statistical distribution with the results used to propose improvements to the Hill framework for effective global AMD classification. The resulting improvements to the framework were proposed to enable effective mine water remediation decision making and legislative governance.

2. Research Methodology

Chemical composition data of AMD from mine sites across the world were gathered from literature to form an indicative global AMD sample dataset. Secondary data were gathered for mine water sites in Africa, Asia, Europe, North America, Oceania, and South America. In each continent, with the exception of Oceania, three major mining countries were selected, and in each country, four AMD sites were randomly selected. In Oceania, due to the limitation of mining nations, two countries (Australia and New Zealand) were added to the dataset with four AMD sites selected in each country. Additionally, four mining sites from major mining nation Russia were added to complete the dataset. The referenced dataset comprised of coal, cupper (Cu), diamond, gold (Au), iron (Fe), lead (Pb), nickel (Ni), pyrite, rare earth minerals (REMs), silver (Ag), tin (Sn), uranium (U) and zinc (Zn) ore mines. The data were comprised of the highest concentrations of acidity, Al, pH, SO_4, total Fe and Zn recorded in the referenced literature for each site. Table 2 shows the referenced sites, countries located, mineral ores mined and the literature references. The global AMD dataset's geochemical distribution range was analysed using quartile interval scales and distribution plots. The global AMD dataset was also analysed for classification in the Hill (1968) framework. The analysis results gathered were used to propose an optimised Hill (1968) framework for effective mine water geochemistry classification.

Table 2. Global AMD sites.

No	Country	Minerals	Sites	References
1	Australia	Au	Mount Ida Goldfield	[18,53–55]
		Sn	Jumna mine	
		Ag	Montalbion mine	
		Au, Cu	Mount Morgan mine, Arnold's Gully	
2	Brazil	Coal	Coal mining area southern Brazil, Pedras stream	[56–60]
		Au	Iron Quadrangle, Velhas river basin	
		U	Osamu Utsumi uranium mine, Pocos de Caldas	
		Coal	Coal mine in Figueira municipality, State of Paraná	
3	Canada	Zn, Cu, Pb, Ag	Mattabi Mine	[61–66]
		Fe	Lorraine mine site	
		Zn, Au, Ag	Les Mines Gallen	
		Au	Doyon mine, Québec	
4	China	Coal	Xingren mine	[65–68]
		Rare earth metals	Sitai mine	
		Cu	Tongling mine	
		Pyrite	Xiang Mountain sulphide mine	
5	Chile	Cu	Active copper mine	[69–73]
		Cu	Chuquicamata porphyry copper mine	
		Cu, Au	Punta del Cobre belt	
		Cu	Andean mountain mines—Azufre River	

Table 2. *Cont.*

No	Country	Minerals	Sites	References
6	Germany	U	Konigstein mine	[74–78]
		Coal	Lusatian Lignite District	
		U	Gessenhalde near Ronneburg, Thuringia,	
		Lignite	Mine pit, Lake Bockwitz, south of Leipzig	
7	Ghana	Ag	Tarkwa gold-mining district	[79–82]
		Ag	Lower Offin basin	
		Ag	Lower Pra Basin	
		Ag	Iduapriem Gold Mine	
8	Japan	Au	Tomitaka	[83–86]
		Coal	Hokutan Horonai coal mine	
		As	Honshu	
		As	Nishinomaki	
9	Mexico	Ag, Zn, Pb	Taxco Mining Area	[87–90]
		Zn, Pb, Cu, Ag, Au	Estado de Mexico	
		Cu	Buenavista del Cobre Mine	
		Ag	Huautla mine	
10	Morocco	Au, Ag, Cu	Tiouit mine	[91–94]
		Cu, Mo, W	Azegour mine	
		Pb	Zeïda mine	
		Pyrrhotite ore	Kettara mine site	
11	New Zealand	Coal	Mangatini stream	[95–99]
		Coal	Stockton coal mine—Mangatini stream catchment	
		Coal	Stockton Denniston Plateau	
		Cu, Pb, Zn	Tui Mine	
12	Russia	Coal	Levikha mine	[100–103]
		Coal	Berikul tailing	
		Cu, Zn	Ursk tailings, Kemerovo region	
		Coal	The Kizel Coal Basin	
13	South Africa	Au	Western basin	[104–106]
		Au	Witwatersrand basin	
		Au	Central Basin	
		Coal	Witbank	
14	Peru	Zn, Pb, Ag, Bi, Cu	Polymetallic Cerro de Pasco deposit	[107–111]
		Ag, Cu, Pb, Zn	Kingsmill Tunnel, Central Andes	
		Ag, Au, Cu	Rio Santiago Stream, Cordillera Negra	
		Cu, Zn	Antamina mine	
15	South Korea	Cu	Ilgwang	[112–115]
		Coal	Donghae mine area	
		Coal	Dogye coal mine	
		Au, Ag	Kwangyang	

Table 2. *Cont.*

No	Country	Minerals	Sites	References
16	Spain	Ag, Au, Cu, Fe, Pb, Tn	Iberian Pyrite Belt (from 25 mines)	[116–119]
		Ag, Au, Cu, Fe, Pb, Tn	Odiel River basin	
		Ag, Au, Cu, Fe, Pb, Tn	Tinto river	
		Cu, Fe, Zn	Peña de Hierro, Riotinto area	
17	United Kingdom	Cu	Parys Mountain copper mine	[24,51,120–122]
		Coal	Yorkshire colliery	
		Coal	Derbyshire colliery	
		Sn, Cu	Wheal Jane	
18	United States	Coal	South Carolina	[25,123–125]
		Coal	Solomon Creek, Pennsylvania	
		Cu	Racoon Creek, Ohio	
		Cu	Friendship Hill	

3. Results and Discussions

3.1. Geochemical Distribution of the Global AMD Dataset

Figure 2 shows box and whisker plots of the pH, Al, SO_4, acidity and total Fe distribution for the global AMD referenced dataset. The dataset distribution ranges were 0.5 to 7.6 for pH, 350 mg/L to 56,240 mg/L for SO_4, 0.6 to 12,240 mg/L for total Fe, 4 to 38,342 mg/L for acidity and 0.01 to 17,689 mg/L for Al. The large distribution ranges indicate the high degree of AMD chemistry variation across the sites and illustrate the complexity of developing classification frameworks for global mine water. It was found that the distribution of Al, SO_4, acidity and total Fe data was heavily skewed towards the bottom end of the total range with the fourth quartile (upper 25th percentile) accounting for more than 80% of the total range. The 75th percentile data distribution for Al, SO_4, acidity and total Fe were determined to be within the initial 2%, 11%, 5% and 9% of the total range, respectively. This finding suggests that the majority of global mine water sites can be classified within a narrow geochemical range.

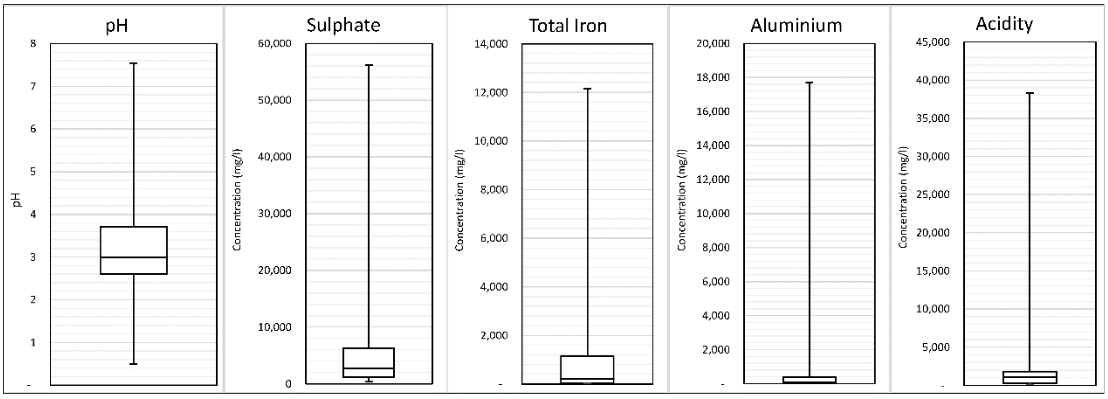

Figure 2. Box plots of the geochemical distribution of global AMD sources.

The pH distribution was more symmetrical with a median pH of 3.0 and maximum pH of 7.55. The observed circum-neutral pH range of between 6 and 7.55 may be attributed to the presence of Neutral Mine Drainage (NMD) sites in the referenced global AMD dataset. NMD has been distinguished as an independent mine water effluent due to its unique characteristics [36]. Mine water from five sites in the referenced dataset may be characterised as NMD. These sites displayed high geochemical concentrations with ranges between 0 to 8000 mg/L for SO_4, 0 to 1200 mg/L for total Fe and between 0 to 800 mg/L for Al. The 75th percentile data distribution for pH was determined to be within the initial 49% of the distribution range. Table 3 summarises the quartile interval scales of the global AMD dataset's geochemical composition.

Table 3. pH, Acidity, Al, total Fe and SO_4 global distribution summary.

Distribution	pH	Acidity	Aluminium	Sulphate	Total Iron
25th percentile (Q1)	0–2.6	0–215 mg/L	0–11 mg/L	0–1217 mg/L	0–40 mg/L
50th percentile (Q2)	2.6–3.1	215–712 mg/L	11–56 mg/L	1217–2444 mg/L	40–209 mg/L
75th percentile (Q3)	3.1–4.0	712–1788 mg/L	56–343 mg/L	2444–6081 mg/L	209–988 mg/L

Figure 3 shows a box and whisker plot of the concentration distribution of Zn from the referenced dataset. Figure 4 shows a distribution plot of pH vs. zinc for the referenced dataset. The concentration of Zn at the first quartile exceeded the agricultural irrigation and safe permissible discharge limit for industrial effluents of 1 mg/L, respectively [41,125]. In total, 95% of the mine water data exceeded the safe environmental discharge limits of Zn. The total data distribution range for Zn was between 0 to 1912 mg/L. The dataset distribution of Zn was also found to be heavily skewed towards the bottom end of the range. The 75th percentile data distribution for Zn was determined to be within the initial 8% of the total range. Table 4 summarises the distribution range of the Zn dataset by quartiles. The sample frequency was greatest between the pH range of 2.0 and 4.0, which accounted for 78% of total site data. The highest concentrations of Zn were found between pH 3.0 and 4.0.

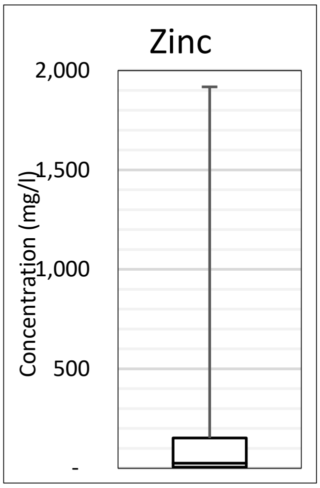

Figure 3. Box plot of Zn concentration distribution.

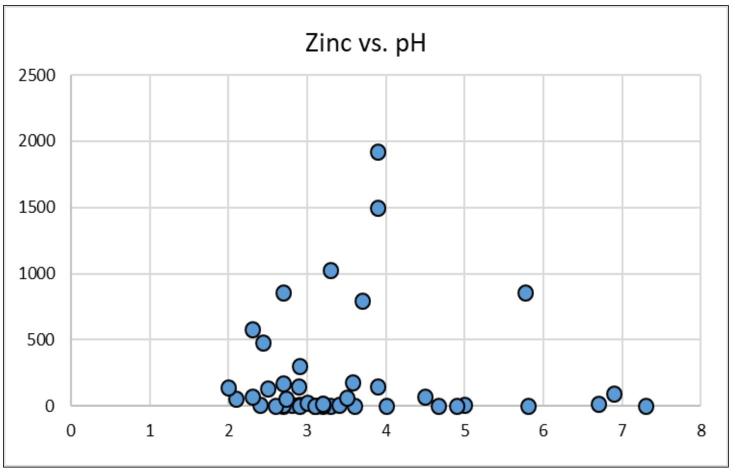

Figure 4. Data distribution of Zn vs. pH.

Table 4. Zn global distribution summary.

Distribution	Zinc
25th percentile (Q1)	0–5 mg/L
50th percentile (Q2)	5–25 mg/L
75th percentile (Q3)	25–152 mg/L

3.2. Classification of the Global AMD Dataset Using the Hill (1968) Framework

Figure 5 shows the distribution of Al, SO_4, acidity and total Fe concentrations vs. pH with the data displayed against the Hill (1968) framework's classifications. Approximately 75% of the referenced global mine water sites had pH values between 2.0 and 4.5. This pH range is categorised as Class I AMD in the Hill (1968) framework. When evaluating the dataset distribution against the entirety of the Hill (1968) framework it was found that only 46% of the mine sites met the criteria for Class I AMD. The other 29% of sites within the Class I pH range exceeded the specification limits for either Al, SO_4, acidity or Fe.

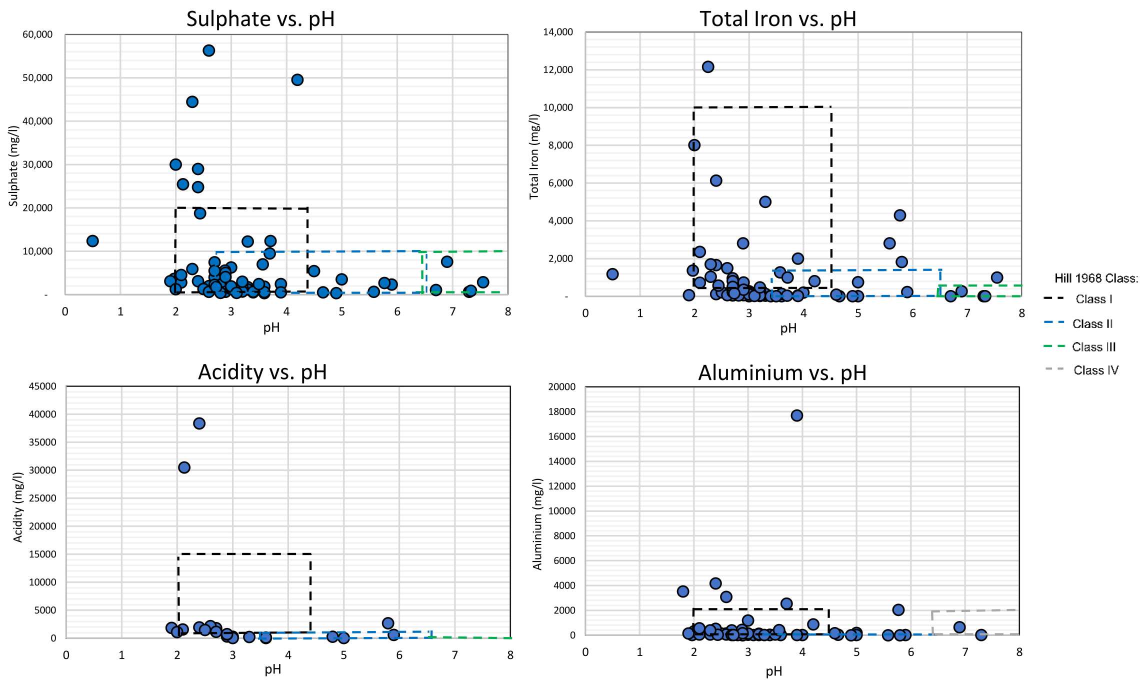

Figure 5. Dataset distribution against Hill (1968) framework.

A total of 11.1% of the mine sites met the criteria for Class II and 2.7% of the sites met the criteria for Class III. The referenced sites in Class II and Class III were comprised of the five mine water sites considered to be NMD. The remaining 40% of the referenced mine water sites were outside of the Hill (1968) framework. Of the referenced sites outside of the Hill (1968) framework 10.7% exceed the 20,000 mg/L SO_4 upper limit for Class I AMD, 23.6% were below the 500 mg/L Fe limit and/or below the 1000 mg/L SO_4 lower limit for Class I AMD and 4.2% were below the pH 2 limit for Class I AMD. The classification percentage of the global AMD dataset against each geochemical parameter of the Hill (1968) framework is summarised in Table 5.

Table 5. Global AMD distribution on Hill (1968) framework.

Classification	AMD Geochemistry Distribution			
	Acidity vs. pH	**Total Fe vs. pH**	**Aluminium vs. pH**	**Sulphate vs. pH**
Class I	53.3%	46%	76.2%	69.5%
Class II	20%	12%	11.1%	11.1%
Class III	10%	4%	2.7%	4.2%
Class IV	-	-	1.6%	-
Outliers	16.7%	38%	22.2%	15.2%

3.3. Evaluation of Results and Framework Optimisation

As mentioned in the introduction, an ideal AMD classification framework would enable mine water regulation and site rehabilitation while being simply understood, comprehensively specified and applicable to any mine water system. The Hill (1968) framework provides a good geochemical categorisation baseline for mine water sources; however, the framework's classification omits some mine water sites as shown in this study. In addition, the cytotoxic metal ions Zn, Pb, As, Co and Ni are not allowed for in the framework, which can limit the ability to conceptualise remediation solutions and AMD ecological hazards when making use of the framework. The framework required optimisation to increase applicability to global mine water sources and improve data comprehension for decision making.

Class I specifications of the Hill (1968) framework limit the upper geochemical concentrations of AMD. These specifications were all well exceeding by some sites in the global AMD dataset, which were highly acidic and highly contaminated. The highly contaminated and highly acidic sites accounted for 11.1% of the total mine water dataset in this research. The mine waters from these sites are highly toxic when considering geochemical composition and they require extensive remediation processes to neutralise, oxidise, precipitate solids, and manage sludge. The researchers propose the inclusion of a Class 0 into the framework, which can categorise these highly acidic and highly contaminated AMD mine waters.

For Class I of the framework, a total of seven sites had acidity concentrations below the 1000 mg/L lower limit and were therefore unclassifiable. The highest omissions on Class I, totalling 23.6%, were as a result of the lower limit of 500 mg/L on Fe^{2+} and the lower limit of 1000 mg/L for SO_4. The researchers propose a reduction of the lower limits for Fe^{2+}, SO_4 and acidity to cater for the vast geochemical variation amongst Class I AMD sites.

The results for Zn showed that the highest concentrations were between pH 3.0 and 4.0 while 75% of the Zn samples had a total concentration below 153 mg/L. The Zn concentration distribution was found to be highly variable across all pH and acidity ranges of the mine water sites. The researchers proposed adding a simple category for Zn^{2+} at the bottom of the framework. The proposed categorisation includes a category for concentrations up to the discharge limit of 1 mg/L represented as low (L), concentrations up to the dataset median of 25 mg/L represented as medium (M), and concentrations exceeding the dataset median represented as high (H).

Class II and Class III of the Hill (1968) framework were considered effective at categorising the global AMD referenced dataset with all but one site unclassified. Table 6 shows the proposed optimised Hill framework based on the discussed findings and proposal.

Table 6. Proposed Optimised Hill Framework.

Class	Class Description	Thresholds		
Class 0 **	Highly concentrated and acidic mine drainage **	pH = 0.5–3 ** Acidity = 5–45 g/L **	Total Fe = 1000–12,000 mg/L **	SO_4 = 10–60 g/L ** Al = 1000–18,000 mg/L **
Class I	Acid mine drainage	pH = 2.0–4.5 Acidity = 0–15 g/L **	Fe^{2+} = 0–10,000 mg/L ** Fe^{3+} = 0 mg/L	SO_4 = 0–20 g/L ** Al = 0–2000 mg/L
Class II	Partially oxidised and/or neutralised	pH = 3.5–6.6 Acidity = 0–1 g/L	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	Neutral and not oxidised	pH = 6.5–8.5 Acidity = 0 mg/L	Fe^{2+} = 0–500 mg/L Fe^{3+} = 0 mg/L	SO_4 = 500–10,000 mg/L Al = 0–2000 mg/L
Class IV	Oxidised and neutralised/alkaline	pH = 6.5–8.5 Acidity = 0 mg/L	Fe^{2+} = 0 mg/L Fe^{3+} = 0 mg/L	SO_4 = 500–10,000 mg/L Al = 0 mg/L
	Category **	L = Zinc ≤ 1 mg/L**	M = Zinc ≤ 25 mg/L **	H = Zinc > 25 mg/L **

** indicate the revisions proposed to improve the framework.

4. Conclusions

This paper investigated the geochemical distribution and classification of 72 global mine water sites from 18 countries across 6 continents using quartile interval scales and distribution plots. The Hill (1968) framework was tested for global mine water classification and results were used to propose improvements to the framework. The research found that the global mine water displayed geochemical concentrations within 2%, 11%, 5%, 9% and 8% of the Al, SO_4, acidity, Fe and Zn total distribution ranges, respectively, at the 75th percentile. The Hill (1968) framework was found to be inefficient at global mine water categorisation with 40% of the referenced mine water sites being omitted from the classification's specifications. To contribute towards effective global mine water classification for regulators and mine water remediators, the following revisions were proposed by the researchers to optimise the Hill (1968) framework:

1. The addition of Class 0 to the framework for highly acidic and high concentration baring AMD. The research results found that 11% of the referenced mine water sites exceeded Class I specifications. Class 0 is proposed as an addition to aid policy makers identify these sites as uniquely contaminated mine waters and aid remediators to identify suitable remediation techniques.
2. Revisions to Class I to enable the classification of all the geochemical variations of non-neutralised and unoxidised mine water sources. The research results showed that 38.7% of non-neutralised and unoxidised referenced mine waters did not meet the specification of the original Class I of the Hill (1968) framework. The proposed revisions comprised of changes to the lower limits of Fe^{2+}, acidity and SO_4 concentrations to enable the classification of all mine water sources.
3. The addition of an indicator species for cytotoxic cation AMD contaminants Zn, Ni, Pb, As and Cd. Zinc was selected as the indicator species for these contaminants with a categorisation of low, median and high proposed for classification. The proposed addition of Zn will enable regulators and mine water remediators to greater understand the environmental impacts of the AMD source and the mine water remediation requirements.

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References

1. Braungardt, C.B.; Achterberg, E.P.; Elbaz-Poulichet, F.; Morley, N.H. Metal geochemistry in a mine-polluted estuarine system in Spain. *Appl. Geochem.* **2003**, *18*, 1757–1771. [CrossRef]
2. Byrne, P.; Wood, P.J.; Reid, I. The Impairment of River Systems by Metal Mine Contamination: A Review Including Remediation Options. *Crit. Rev. Environ. Sci. Technol.* **2012**, *42*, 2017–2077. [CrossRef]
3. Kefeni, K.K.; Msagati, T.A.; Nkambule, T.T.; Mamba, B. Synthesis and application of hematite nanoparticles for acid mine drainage treatment. *J. Environ. Chem. Eng.* **2018**, *6*, 1865–1874. [CrossRef]
4. McCarthy, T.S. The impact of acid mine drainage in South Africa. *South Afr. J. Sci.* **2011**, *107*, 1–7. [CrossRef]
5. Younger, P.L.; Banwart, S.A.; Hedin, R.S. *Mine Water: Hydrology, Pollution, Remediation Dordrecht*; Kluwer Academic Publishers: Dordrecht, The Netherlands, 2002.
6. Johnson, D.B.; Hallberg, K.B. Acid Mine Drainage Remediation Options: A Review. *Sci. Total. Environ.* **2005**, *338*, 3–14. [CrossRef] [PubMed]
7. Edwards, K.J.; Gihring, T.M.; Banfield, J.F. Seasonal Variations in Microbial Populations and Environmental Conditions in an Extreme Acid Mine Drainage Environment. *Appl. Environ. Microbiol.* **1999**, *65*, 3627–3632. [CrossRef]
8. Sarmiento, A.M.; Nieto, J.M.; Olías, M.; Cánovas, C.R. Hydrochemical characteristics and seasonal influence on the pollution by acid mine drainage in the Odiel river Basin (SW Spain). *Appl. Geochem.* **2009**, *24*, 697–714. [CrossRef]
9. Akcil, A.; Koldas, S. Acid Mine Drainage (AMD): Causes, treatment and case studies. *J. Clean. Prod.* **2006**, *14*, 1139–1145. [CrossRef]
10. Gray, N.F. Environmental Impact and Remediation of Acid Mine Drainage: A Management Problem. *Environ. Earth Sci.* **1997**, *30*, 62–71. [CrossRef]
11. de Klerk, A.R.; Oberholster, P.J.; van Wyk, J.H.; Truter, J.C.; Schaefer, L.M.; Botha, A.M. The Effect of Rehabilitation Measures on Ecological Infrustructure in Response to Acid Mine Drainage from Coal Mining. *Ecol. Eng.* **2016**, *95*, 463–474. [CrossRef]
12. Shabalala, A.N.; Ekolu, S.O.; Diop, S.; Solomon, F. Pervious concrete reactive barrier for removal of heavy metals from acid mine drainage—Column study. *J. Hazard. Mater.* **2017**, *323*, 641–653. [CrossRef] [PubMed]
13. Simate, G.S.; Ndlovu, S. Acid mine drainage: Challenges and opportunities. *J. Environ. Chem. Eng.* **2014**, *2*, 1785–1803. [CrossRef]
14. Rose, P. Long-term sustainability in the management of acid mine drainage wastewaters—Development of the Rhodes BioSURE Process. *Water South Afr.* **2013**, *39*, 583–592. [CrossRef]
15. Udayabhanu, G.; Prasad, B. Studies on environmental impact of acid mine drainage generation and its treatment: An appraisal. *Indian J. Environ. Prot.* **2010**, *30*, 953–967.
16. Mafanya, L. Flow Model for the Treatment of Acid Mine Drainage Using Pervious Concrete. Master's Thesis, University of Johannesburg, Johannesburg, South Africa, 2020.
17. Kefeni, K.K.; Msagati, T.A.; Mamba, B.B. Acid mine drainage: Prevention, treatment options, and resource recovery: A review. *J. Clean. Prod.* **2017**, *151*, 475–493. [CrossRef]
18. Park, I.; Tabelin, C.B.; Jeon, S.; Li, X.; Seno, K.; Ito, M.; Hiroyoshi, N. A review of recent strategies for acid mine drainage prevention and mine tailings recycling. *Chemosphere* **2019**, *219*, 588–606. [CrossRef]
19. Mafanya, L.; Kallon, D.V.V.; Simelane, S.P. Chemical Analysis of AMD Properties Based on Factorial Method. In Proceedings of the Open Innovations Conference, OI 2019, Cape Tow, South Africa, 2–4 October 2019.
20. Mafanya, L.; Kallon, D.V.V.; Simelane, S.P. Flow Properties Upon Treatment of Acid Mine Drainage Using Pervious Concrete Slabs. In Proceedings of the SAIIE NeXXXt, Port Elizabeth, South Africa, 30 September–2 October 2019; 399–403.
21. Soni, A.K.; Mishra, B.; Singh, S. Pit lakes as an end user of mining: A review. *J. Min. Environ.* **2014**, *5*, 99–111.
22. Department of Mineral Resources. *Progress on the Management and Rehabilitation of Derelict and Ownerless Mines: Presentation to the Parliamentary Select Committee on Finance*; DMR: Pretoria, South Africa, 2010.
23. Van Zyl, H.; Bond-Smith, M.; Minter, T.; Botha, M.; Leiman, A. *Financial Provisions for Rehabilitation and Closure in South African Mining*; Discussion document of challenges and recommended improvements; WWF–South Africa: Cape Town, South Africa, 2012.

24. Dean, A.P.; Lynch, S.; Rowland, P.; Toft, B.D.; Pittman, J.K.; White, K.N. Natural Wetlands Are Efficient at Providing Long-Term Metal Remediation of Freshwater Systems Polluted by Acid Mine Drainage. *Environ. Sci. Technol.* **2013**, *47*, 12029–12036. [CrossRef]
25. DeGraff, J.V. Addressing the toxic legacy of abandoned mines on public land in the western United States. *Rev. Eng. Geol.* **2007**, *17*, 1–8.
26. Unger, C.; Lechner, A.M.; Glenn, V.; Edraki, M.; Mulligan, D.R. Mapping and prioritising rehabilitation of abandoned mines in Australia. In Proceedings of the Life-of-Mine Conference, Brisbane, Australia, 10–12 July 2012; pp. 259–265.
27. Johnston, D.; Potter, H.; Jones, C.; Rolley, S.; Watson, I.; Pritchard, J. Abandoned Mines and the Water Environment. In *Environment Agency Science Project SC030136-41*; Environment Agency: Bristol, UK, 2008.
28. Caraballo, M.A.; Macías, F.; Rötting, T.S.; Nieto, J.M.; Ayora, C. Long term remediation of highly polluted acid mine drainage: A sustainable approach to restore the environmental quality of the Odiel river basin. *Environ. Pollut.* **2011**, *159*, 3613–3619. [CrossRef]
29. Clyde, E.J.; Champagne, P.; Jamieson, H.E.; Gorman, C.; Sourial, J. The use of a passive treatment system for the mitigation of acid mine drainage at the Williams Brothers Mine (California): Pilot-scale study. *J. Clean. Prod.* **2016**, *130*, 116–125. [CrossRef]
30. Dinu, L.; Stefanescu, M.; Balaiu, M.; Cosma, I.; Criste, C.; Badescu, V. Acid mine water treatment using the high density sludge technology. *J. Environ. Prot. Ecol.* **2014**, *15*, 1700–1717.
31. Fu, F.; Dionysiou, D.D.; Liu, H. The use of zero-valent iron for groundwater remediation and wastewater treatment: A review. *J. Hazard. Mater.* **2014**, *267*, 194–205. [CrossRef] [PubMed]
32. Papirio, S.; Villa-Gomez, D.K.; Esposito, G.; Pirozzi, F.; Lens, P.N.L. Acid Mine Drainage Treatment in Fluidized-Bed Bioreactors by Sulfate-Reducing Bacteria: A Critical Review. *Crit. Rev. Environ. Sci. Technol.* **2013**, *43*, 2545–2580. [CrossRef]
33. Skousen, J. Overview of Acid Mine Drainage Treatment with Chemicals. *Acid Mine Drain. Rock Drain. Acid Sulfate Soils* **2014**, *26*, 325–337. [CrossRef]
34. Taylor, J.; Pape, S.; Murphy, N. A summary of passive and active treatment technologies for acid and metalliferous drainage (AMD). In Proceedings of the 5th Australian Workshop on Acid Mine Drainage, Frementle, Australia, 29–31 August 2005.
35. Naidu, G.; Ryu, S.; Thiruvenkatachari, R.; Choi, Y.; Jeong, S.; Vigneswaran, S. A critical review on remediation, reuse, and resource recovery from acid mine drainage. *Environ. Pollut.* **2019**, *247*, 1110–1124. [CrossRef] [PubMed]
36. Opitz, J.; Timms, W. Mine water discharge quality—A review of classification frameworks. In Proceedings of the International Mine Water Association, IMWA, Leipzig, Germany, 11–15 July 2016; pp. 17–26.
37. McCourt, J.L. Environmental legislation and water management issues during mine closure in South Africa. In Proceedings of the International Mine Water Association 1999, Sevilla, Spain, 29 September–4 October 2012.
38. Stark, L. *Breaking New Ground—Mining, Minerals, and Sustainable Development: The Report of the MMSD Project*; Earthscan: London, UK; Sterling, TX, USA, 2002.
39. Obreque-Contreras, J.; Pérez-Flores, D.; Gutiérrez, P.; Chávez-Crooker, P. Acid Mine Drainage in Chile: An Opportunity to Apply Bioremediation Technology. *J. Waste Water Treat. Anal.* **2015**, *6*, 1–8. [CrossRef]
40. Thomashausen, S.; Maennling, N.; Mebratu-Tsegaye, T. A comparative overview of legal frameworks governing water use and waste water discharge in the mining sector. *Resour. Policy* **2018**, *55*, 143–151. [CrossRef]
41. Kaur, G.; Couperthwaite, S.J.; Hatton-Jones, B.W.; Millar, G.J. Alternative neutralisation materials for acid mine drainage treatment. *J. Water Process. Eng.* **2018**, *22*, 46–58. [CrossRef]
42. Jarvis, A.P.; Younger, P.L. Broadening the scope of mine water environmental impact assessment. *Environ. Impact Assess. Rev.* **2000**, *20*, 85–96. [CrossRef]
43. INAP. Global Acid Mine Drainage Guide (GARD Guide). 2009. Available online: http://www.gardguide.com (accessed on 10 July 2020).
44. AUSTRALIA MC. Water Accounting Framework for the Minerals Industry. 2014. Available online: https://minerals.org.au/sites/default/files/WAF_UserGuide_v1.3_(Jan_2014).pdf (accessed on 12 July 2020).
45. Timms, W.; Holley, C. Mine site water-reporting practices, groundwater take and governance frameworks in the Hunter Valley coalfield, Australia. *Water Int.* **2016**, *41*, 351–370. [CrossRef]

46. Gray, N.F. The Use of an Objective Index for the Assessment of the Contamination of Surface Water and Groundwater by Acid Mine Drainage. *Water Environ. J.* **1996**, *10*, 332–340. [CrossRef]
47. Kuma, J.S.Y.; Younger, P.L.; Buah, W.K. Numerical Indices of the Severity of Acidic Mine Drainage: Broadening the Applicability of the Gray Acid Mine Drainage Index. *Mine Water Environ.* **2010**, *30*, 67–74. [CrossRef]
48. Hill, R.D. *Mine Drainage Treatment: State of the Art and Research Needs*; U.S. Department of the Interior, Ed.; Mine Drainage Control Activities, Federal Water Pollution Control Administration: Cincinnati, OH, USA, 1968.
49. Xiong, W.; Chen, X.; Zhu, C.; Zhang, J.; Lan, T.; Liu, L.; Mo, B.; Chen, X. Arabidopsis ribosomal proteins RPL23aA and RPL23aB are functionally equivalent. In *Comprehensive AMD Index to Evaluate Environmental Impacts of Mining in Malaysian Metallic Ex-Mines*; Research Square: Durham, NC, USA, 2020.
50. Antunes, I.; Valente, T.; Gomes, P.; Costa, M.R.; Fonseca, R.; Moreno, F. Spatial Distribution of Acid Mine Drainage Indexes in Different Water Environments. In Proceedings of the International Mine Water Association, Perm, Russia, 15–19 July 2019; pp. 334–338.
51. Johnson, D.B. Chemical and microbiological characteristics of mineral spoils and drainage waters at abandoned coal and metal mines. *Water Air Soil Pollut.* **2003**, *3*, 47–66. [CrossRef]
52. Ayres, D.M.; Davis, A.P.; Gietka, P.M. *Removing Heavy Metals from Wastewater*; Engineering Research Centre; University of Maryland: College Park, MD, USA, 1994; p. 90.
53. Edraki, M.; Golding, S.; Baublys, K.; Lawrence, M. Hydrochemistry, mineralogy and sulfur isotope geochemistry of acid mine drainage at the Mt. Morgan mine environment, Queensland, Australia. *Appl. Geochem.* **2005**, *20*, 789–805. [CrossRef]
54. Harris, D.L.; Lottermoser, B.G.; Duchesne, J. Ephemeral acid mine drainage at the Montalbion silver mine, north Queensland. *Aust. J. Earth Sci.* **2003**, *50*, 797–809. [CrossRef]
55. Parbhakar-Fox, A.; Edraki, M.; Hardie, K.; Kadletz, O.; Hall, T. Identification of acid rock drainage sources through mesotextural classification at abandoned mines of Croydon, Australia: Implications for the rehabilitation of waste rock repositories. *J. Geochem. Explor.* **2014**, *137*, 11–28. [CrossRef]
56. Galhardi, J.A.; Bonotto, D.M. Hydrogeochemical features of surface water and groundwater contaminated with acid mine drainage (AMD) in coal mining areas: A case study in southern Brazil. *Environ. Sci. Pollut. Res.* **2016**, *23*, 18911–18927. [CrossRef]
57. De Andrade, R.P.; Figueiredo, B.R.; De Mello, J.W.V.; Dos Santos, J.; Zandonadi, L.U. Control of geochemical mobility of arsenic by liming in materials subjected to acid mine drainage. *J. Soils Sediments* **2008**, *8*, 123–129. [CrossRef]
58. Fernandes, H.M.; Franklin, M.R. Assessment of acid rock drainage pollutants release in the uranium mining site of Poços de Caldas—Brazil. *J. Environ. Radioact.* **2001**, *54*, 5–25. [CrossRef]
59. Lichtner, P.C.; Waber, N. Redox front geochemistry and weathering: Theory with application to the Osamu Utsumi uranium mine, Poços de Caldas, Brazil. *J. Geochem. Explor.* **1992**, *45*, 521–564. [CrossRef]
60. Campaner, V.P.; Luiz-Silva, W. Physico-chemical Processes in Acid Mine Drainage in Coal Mining South Brazil [Processos Físico-químicos Em Drenagem Ácida De Mina Em Mineração De Carvão No Sul Do Brasil]. *Química Nova.* **2009**, *32*, 146–152. [CrossRef]
61. Mackasey, W.O. Abandoned Mines in Canada. In *A Review for Mining Watch Canada*; WOM Geological Associations Inc.: Sudbury, ON, Canada, 2000.
62. Genty, T.; Bussiere, B.; Paradie, M.; Neculita, C.M. Passive biochemical treatment of ferriferous mine drainage: Lorraine mine site, Northern Quebec, Canada. In Proceedings of the IMWA, Freiberg, Germany, 11–15 July 2016.
63. Lyew, D.; Sheppard, J.D. Effects of physical parameters of a gravel bed on the activity of sulphate-reducing bacteria in the presence of acid mine drainage. *J. Chem. Technol. Biotechnol.* **1997**, *70*, 223–230. [CrossRef]
64. Sracek, O.; Choquette, M.; Gélinas, P.; Lefebvre, R.; Nicholson, R. Geochemical characterization of acid mine drainage from a waste rock pile, Mine Doyon, Québec, Canada. *J. Contam. Hydrol.* **2004**, *69*, 45–71. [CrossRef]
65. Wu, P.; Tang, C.; Liu, C.; Zhu, L.; Pei, T.; Feng, L. Geochemical distribution and removal of As, Fe, Mn and Al in surface water system affected by acid mine drainage coalfield in Southwestern China. *Environ. Geol.* **2009**, *57*, 1457–1467. [CrossRef]
66. Zhao, F.; Cong, Z.; Sun, H.; Ren, D. The geochemistry of rare earth elements (REE) in acid mine drainage from the Sitai coal mine, Shanxi Province, North China. *Int. J. Coal Geol.* **2007**, *70*, 184–192. [CrossRef]

67. Hao, C.; Wang, L.; Gao, Y.; Zhang, L.; Dong, H. Microbial diversity in acid mine drainage of Xiang Mountain sulfide mine, Anhui Province, China. *Extremophiles* **2010**, *14*, 465–474. [CrossRef]
68. Chen, L.-X.; Hu, M.; Huang, L.-N.; Hua, Z.-S.; Kuang, J.-L.; Li, S.-J.; Shu, W.-S. Comparative metagenomic and metatranscriptomic analyses of microbial communities in acid mine drainage. *ISME J.* **2015**, *9*, 1579–1592. [CrossRef]
69. Pino, L.; Vargas, C.; Schwarz, A.; Bórquez, R. Influence of operating conditions on the removal of metals and sulfate from copper acid mine drainage by nanofiltration. *Chem. Eng. J.* **2018**, *345*, 114–125. [CrossRef]
70. Dold, B. Evolution of Acid Mine Drainage Formation in Sulphidic Mine Tailings. *Minerals* **2014**, *4*, 621–641. [CrossRef]
71. Dold, B.S.; Fontboté, L. A mineralogical and geochemical study of element mobility in sulfide mine tailings of Fe oxide Cu–Au deposits from the Punta del Cobre belt, northern Chile. *Chem. Geol.* **2002**, *189*, 135–163. [CrossRef]
72. Abarca, M.; Guerra, P.; Arce, G.; Montecinos, M.; Escauriaza, C.; Coquery, M.; Pastén, P. Response of suspended sediment particle size distributions to changes in water chemistry at an Andean mountain stream confluence receiving arsenic rich acid drainage. *Hydrol. Process.* **2016**, *31*, 296–307. [CrossRef]
73. Montecinos, M.; Coquery, M.; Alsina, M.A.; Bretier, M.; Gaillard, J.-F.; Dabrin, A.; Pastén, P. Partitioning of copper at the confluences of Andean rivers. *Chemosphere* **2020**, *259*, 127318. [CrossRef] [PubMed]
74. Arnold, T.; Baumann, N.; Krawczyk-Bärsch, E.; Brockmann, S.; Zimmermann, U.; Jenk, U.; Weiß, S. Identification of the uranium speciation in an underground acid mine drainage environment. *Geochim. Cosmochim. Acta* **2011**, *75*, 2200–2212. [CrossRef]
75. Geller, W.; Klapper, H.; Salomons, W. (Eds.) *Acidic Mining Lakes: Acid Mine Drainage, Limnology and Reclamation*; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2012.
76. Haferburg, G.; Reinicke, M.; Merten, D.; Büchel, G.; Kothe, E. Microbes adapted to acid mine drainage as source for strains active in retention of aluminum or uranium. *J. Geochem. Explor.* **2007**, *92*, 196–204. [CrossRef]
77. Grawunder, A.; Lonschinski, M.; Merten, D.; Büchel, G. istribution and bonding of residual contamination in glacial sediments at the former uranium mining leaching heap of Gessen/Thuringia, Germany. *Geochemistry* **2009**, *69*, 5–19. [CrossRef]
78. Ulrich, K.-U.; Bethge, C.; Guderitz, I.; Heinrich, B.; Neumann, V.; Nitsche, C.; Benthaus, F.-C. In-Lake Neutralization: Quantification and Prognoses of the Acid Load into a Conditioned Pit Lake (Lake Bockwitz, Central Germany). *Mine Water Environ.* **2012**, *31*, 320–338. [CrossRef]
79. Kuma, J.S.; Younger, P.L. Water quality trends in the Tarkwa gold-mining district, Ghana. *Bull. Int. Assoc. Eng. Geol.* **2004**, *63*, 119–132. [CrossRef]
80. Kortatsi, B.K.; Tay, C.K.; Anornu, G.; Hayford, E.; Dartey, G.A. Hydrogeochemical evaluation of groundwater in the lower Offin basin, Ghana. *Environ. Earth Sci.* **2007**, *53*, 1651–1662. [CrossRef]
81. Tay, C.K.; Hayford, E.K.; Hodgson, I.O.A. Application of multivariate statistical technique for hydrogeochemical assessment of groundwater within the Lower Pra Basin, Ghana. *Appl. Water Sci.* **2017**, *7*, 1131–1150. [CrossRef]
82. Akabzaa, T.M.; Jamieson, H.E.; Jorgenson, N.; Nyame, K. The Combined Impact of Mine Drainage in the Ankobra River Basin, SW Ghana. *Mine Water Environ.* **2009**, *28*, 50–64. [CrossRef]
83. Herrera, P.; Uchiyama, H.; Igarashi, T.; Asakura, K.; Ochi, Y.; Iyatomi, N.; Nagae, S. Treatment of acid mine drainage through a ferrite formation process in central Hokkaido, Japan: Evaluation of dissolved silica and aluminium interference in ferrite formation. *Miner. Eng.* **2007**, *20*, 1255–1260. [CrossRef]
84. Fukushi, K.; Sasaki, M.; Sato, T.; Yanase, N.; Amano, H.; Ikeda, H. A natural attenuation of arsenic in drainage from an abandoned arsenic mine dump. *Appl. Geochem.* **2003**, *18*, 1267–1278. [CrossRef]
85. Yamaguchi, K.; Tomiyama, S.; Metugi, H.; Ii, H.; Ueda, A. Flow and geochemical modeling of drainage from Tomitaka mine, Miyazaki, Japan. *J. Environ. Sci.* **2015**, *36*, 130–143. [CrossRef]
86. Kano, K. Prevention of hazard in mining waste heap. In Proceedings of the Third Asia-Pacific Regional Workshop on Hazardous Waste Management in Mining Industry, APCHW, Beijing, China, 19–21 April 2000.
87. Romero, F.M.; Núñez, L.; Gutiérrez, M.E.; Armienta, M.A.; Ceniceros-Gómez, A. Evaluation of the potential of indigenous calcareous shale for neutralization and removal of arsenic and heavy metals from acid mine drainage in the Taxco mining area, Mexico. *Arch. Environ. Contam. Toxicol.* **2011**, *60*, 191–203. [CrossRef]

88. Jallath, J.E.S.; Romero, F.M.; Argüelles, R.I.; Macedo, A.C.; Arenas, J.G. Acid drainage neutralization and trace metals removal by a two-step system with carbonated rocks, Estado de Mexico, Mexico. *Environ. Earth Sci.* **2018**, *77*, 86. [CrossRef]
89. Rivera-Uria, M.Y.; Romero, F.M.; Sedov, S.; Ramos, D.; Solleiro-Rebolledo, E.; Díaz-Ortega, J. Effects of the interaction between an acid solution and pedogenic carbonates: The case of the Buenavista del Cobre Mine, Mexico. *Rev. Mex. Cienc. Geológicas* **2019**, *36*, 308–320. [CrossRef]
90. Esteller, M.; Domínguez-Mariani, E.; Garrido, S.E.; Avilés, M. Groundwater pollution by arsenic and other toxic elements in an abandoned silver mine, Mexico. *Environ. Earth Sci.* **2015**, *74*, 2893–2906. [CrossRef]
91. Lghoul, M.; Maqsoud, A.; Hakkou, R.; Kchikach, A. Hydrogeochemical behavior around the abandoned Kettara mine site, Morocco. *J. Geochem. Explor.* **2014**, *144*, 456–467. [CrossRef]
92. Nadeif, A.; Taha, Y.; Bouzahzah, H.; Hakkou, R.; Benzaazoua, M. Desulfurization of the Old Tailings at the Au-Ag-Cu Tiouit Mine (Anti-Atlas Morocco). *Minerals* **2019**, *9*, 401. [CrossRef]
93. Goumih, A.; El Adnani, M.; Hakkou, R.; Benzaazoua, M. Geochemical Behavior of Mine Tailings and Waste Rock at the Abandoned Cu–Mo–W Azegour Mine (Occidental High Atlas, Morocco). *Mine Water Environ.* **2013**, *32*, 121–132. [CrossRef]
94. Iavazzo, P.; Ducci, D.; Adamo, P.; Trifuoggi, M.; Migliozzi, A.; Boni, M. Impact of Past Mining Activity on the Quality of Water and Soil in the High Moulouya Valley (Morocco). *Water Air Soil Pollut.* **2011**, *223*, 573–589. [CrossRef]
95. Davies, H.; Weber, P.; Lindsay, P.; Craw, D.; Pope, J. Characterisation of acid mine drainage in a high rainfall mountain environment, New Zealand. *Sci. Total. Environ.* **2011**, *409*, 2971–2980. [CrossRef] [PubMed]
96. Gray, D.; Harding, J. Acid Mine Drainage Index (AMDI): A benthic invertebrate biotic index for assessing coal mining impacts in New Zealand streams. *N. Z. J. Mar. Freshw. Res.* **2012**, *46*, 335–352. [CrossRef]
97. Pope, J.; Trumm, D. Controls on Zn Concentrations in Acidic and Neutral Mine Drainage from New Zealand's Bituminous Coal and Epithermal Mineral Deposits. *Mine Water Environ.* **2015**, *34*, 455–463. [CrossRef]
98. Giles, E.; Jenkins, I.; Williams, S.; Kirk, A.; Fellows, D.; Press, R. *Tui Mine Remediation Detailed Design Report. Underground Mine, Access Road, Waste Rock Stack Remediation Works*; URS Ltd.: Waikato, New Zealand, 2010.
99. Morrell, W.J. An Assessment of the Revegetation Potential of Base-Metal Tailings from the Tui Mine, Te Aroha, New Zealand: A Thesis Presented in Partial Fulfilment of the Requirements for the Degree of Doctor of Philosophy in Soil Science at Massey University. Ph.D. Thesis, Massey University, Palmerston North, New Zealand, 1997.
100. Rybnikova, L.; Rybnikov, P. Water quality of the abandoned sulfide mines of the Middle Urals (Russia). In Proceedings of the 13th International Mine Water Association Congress—Mine Water & Circular Economy, Lappeenranta, Finland, 25–30 June 2017.
101. Myagkaya, I.; Lazareva, E.; Zaikovskii, V.; Zhmodik, S. Interaction of natural organic matter with acid mine drainage: Authigenic mineralization (case study of Ursk sulfide tailings, Kemerovo region, Russia). *J. Geochem. Explor.* **2020**, *211*, 106456. [CrossRef]
102. Khayrulina, E.; Khmurchik, V.; Maksimovich, N. The Kizel Coal Basin (the Western Urals, Russia): Environmental problems and Solutions. In Mining Meets Water-Conflicts and Solutions. In Proceedings of the IMWA2016 Annual Conference, Leipzig, Germany, 11–15 July 2016; pp. 761–767.
103. Myagkaya, I.; Lazareva, E.V.; Gustaytis, M.; Zhmodik, S. Gold and silver in a system of sulfide tailings. Part 1: Migration in water flow. *J. Geochem. Explor.* **2016**, *160*, 16–30. [CrossRef]
104. Tutu, H.; McCarthy, T.; Cukrowska, E. The chemical characteristics of acid mine drainage with particular reference to sources, distribution and remediation: The Witwatersrand Basin, South Africa as a case study. *Appl. Geochem.* **2008**, *23*, 3666–3684. [CrossRef]
105. Aurecon. *Feasibility Study for a Long-Term Solution to Address the Acid Mine Drainage Associated with the East, Central and West Rand Underground Mining Basins: Treatment Technology Options*, 1st ed.; Study Report No. 5.4 P RSA 000/00/16512/4; Council for Geoscience: Pretoria, South Africa, 2013.
106. Expert Team of the Inter Ministerial Committee. *Mine Water Management in the Witwatersrand Gold Fields with Special Emphasis on Acid Mine Drainage-Report to the Inter-Ministerial Committee on Acid Mine Drainage*; Council of Geoscience: Pretoria, South Africa, 2010.
107. Dold, B.S.; Wade, C.; Fontboté, L. Water management for acid mine drainage control at the polymetallic Zn–Pb–(Ag–Bi–Cu) deposit Cerro de Pasco, Peru. *J. Geochem. Explor.* **2009**, *100*, 133–141. [CrossRef]

108. Kuyucak, N.; Chavez, J.; Castillo, J.R.; Ruiz, J. Technical Feasibility Studies and Uses of Treated Acid Mine Drainage at Kingsmill Tunnel, Peru. In Proceedings of the Sixth International Conference on Acid Rock Drainage, Cairns, Queensland, Australia, 12–18 July 2003.
109. Sevink, J.; Verstraten, J.M.; Kooijman, A.M.; Loayza-Muro, R.A.; Hoitinga, L.; Palomino, E.J.; Jansen, B. Rare Moss-Built Microterraces in a High-Altitude, Acid Mine Drainage-Polluted Stream (Cordillera Negra, Peru). *Water Air Soil Pollut.* **2015**, *226*, 201. [CrossRef]
110. Wade, C.; Dold, B.S.; Fontboté, L. Geochemistry and Mineralogy of the Quiulacocha Tailings Impoundment from the Polymetallic Zn-Pb-(Ag-Bi-Cu) Deposit Cerro de Pasco, Peru. *J. Am. Soc. Min. Reclam.* **2006**, *2006*, 2198–2206. [CrossRef]
111. Peterson, H.E. Unsaturated hydrology, evaporation, and geochemistry of neutral and acid rock drainage in highly heterogeneous mine waste rock at the Antamina mine, Peru. Ph.D. Thesis, University of British Columbia, Vancouver, BC, Canada, 2014.
112. Chon, H.-T.; Hwang, J.-H. Geochemical Characteristics of the Acid Mine Drainage in the Water System in the Vicinity of the Dogye Coal Mine in Korea. *Environ. Geochem. Health* **2000**, *22*, 155–172. [CrossRef]
113. Kim, D.H. Study on mine reclamation regimes for redeveloping closed mines of Korea. *Econ. Environ. Geol.* **2009**, *42*, 619–626.
114. Kim, J.J.; Kim, S.J.; Kim, Y.Y. Mineralogy of evaporation residues and geochemistry of acid mine drainage in the Donghae mine area. *Econ. Environ. Geol.* **2003**, *36*, 103–109.
115. Park, C.Y.; Jeong, Y.J. Seasonal variation of heavy metal content in acid mine drainage from Kwangyang mine. *J. Korean Soc. Min. Energy Resour. Eng.* **1999**, *36*, 91–102.
116. España, J.S. Acid mine drainage in the Iberian Pyrite Belt: An overview with special emphasis on generation mechanisms, aqueous composition and associated mineral phases. *Macla Rev. Soc. Española Mineral.* **2008**, *10*, 34–43.
117. Olías, M.; Nieto, J.; Sarmiento, A.; Cerón, J.; Cánovas, C. Seasonal water quality variations in a river affected by acid mine drainage: The Odiel River (South West Spain). *Sci. Total. Environ.* **2004**, *333*, 267–281. [CrossRef]
118. Nieto, J.M.; Sarmiento, A.M.; Olías, M.; Canovas, C.R.; Riba, I.; Kalman, J.; DelValls, T.A. Acid mine drainage pollution in the Tinto and Odiel rivers (Iberian Pyrite Belt, SW Spain) and bioavailability of the transported metals to the Huelva Estuary. *Environ. Int.* **2007**, *33*, 445–455. [CrossRef]
119. Romero, A.; González, I.; Galán, E. Stream water geochemistry from mine wastes in Peña de Hierro, Riotinto area, SW Spain: A case of extreme acid mine drainage. *Environ. Earth Sci.* **2011**, *62*, 645–656. [CrossRef]
120. Burnside, N.M.; Banks, D.; Boyce, A.J. Sustainability of thermal energy production at the flooded mine workings of the former Caphouse Colliery, Yorkshire, United Kingdom. *Int. J. Coal Geol.* **2016**, *164*, 85–91. [CrossRef]
121. Banks, D.; Athresh, A.; Al-Habaibeh, A.; Burnside, N. Water from abondoned mines as a heat source: Practical experiences of open- and closed-loop strategies, United Kingdom. *Sustain. Water Resour. Manag.* **2019**, *50*, 5–29.
122. Kay, C.M.; Rowe, O.F.; Rocchetti, L.; Coupland, K.; Hallberg, K.B.; Johnson, D.B. Evolution of microbial "streamer" growths in an acidic, metal-contaminated stream draining an abandoned underground copper mine. *Life* **2013**, *3*, 189–210. [CrossRef] [PubMed]
123. De Rose, L.M. Physical and Chemical Controls on Natural and Anthropogenic Remediation of Two Streams Impacted by Acid Mine Drainage in the Raccoon Creek Watershed, Ohio. Ph.D. Thesis, Ohio University, Athens, OH, USA, 2011.
124. Hammarstrom, J.M.; Sibrell, P.L.; Belkin, H.E. Characterization of limestone reacted with acid-mine drainage in a pulsed limestone bed treatment system at the Friendship Hill National Historical Site, Pennsylvania, USA. *Appl. Geochem.* **2003**, *18*, 1705–1721. [CrossRef]
125. Zwain, H.M.; Vakili, M.; Dahlan, I. Waste Material Adsorbents for Zinc Removal from Wastewater: A Comprehensive Review. *Int. J. Chem. Eng.* **2014**, *2014*, 1–13. [CrossRef]