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# Sustainable water management and improved corporate reporting in mining

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ABSTRACT

The advent of corporate sustainability reporting and water accounting standards has resulted in increased disclosure of water use by mining companies. However, there has been limited compilation and analysis of these disclosures. To address this, we compiled a database of 8314 data points from 359 mining company reports, classified according to mining industry water accounting guidelines. The quality of disclosures is shown to have improved considerably over time. Although, opportunities still exist to improve reporting practices, such as by ensuring that all relevant water flows are reported and to explicitly state non-existent flows (e.g. discharges). Initial data analysis reveals considerable variability in water withdrawals, use efficiency and discharges between mining operations. Further work to improve industry coverage and to analyse the influence of mine specific factors such as ore processing methods and local climate will provide insights into the interactions of mining and water resources at a global scale.

## 1. Introduction

The United Nations Sustainable Development Goals (SDGs) provide an ambitious set of targets for improving environmental sustainability, economic development, social cohesion and human development by 2030 [42]. Meeting these goals will require improvements in the way that water resources are utilised, managed and protected. For instance, SDG6 is focused on 'Clean Water and Sanitation' and within this there are targets for improving access to safe drinking water, improving water quality, increasing water-use efficiency, capacity-building and involving local communities in water management issues. There are many opportunities for the mining industry to contribute towards this [43], such as through implementing sustainable water management practices that ensure shared benefits for local communities [46]. However, understanding these contributions requires the development of rigorous assessment methods and data sources, so that rates of progress in the mining industry can be measured.

Mining and mineral processing operations have the potential to substantially impact local hydrology and water quality. The magnitude and nature of these impacts are highly site specific due to a variety of underlying factors [30]. Mining and mineral processing operations must adapt their mineral separation and metal production processes based upon the physical and geochemical nature of the ore being mined, resulting in differences in the water required for ore processing. The approaches adopted for storing and managing large-scale mine waste (e.g. waste rock and tailings) can significantly alter mine site water balances and the optimal

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approach is dependent upon local factors, such as site topography. Furthermore, the hydrological and climate contexts that the mining industry operates within and must adapt to are diverse [31–33]. This requires further tailoring of site processes and infrastructure to manage associated risks, such as flooding or the potential for water shortages [8,18]. Additionally, the regulatory environments that dictate the ability of mining operations to access, use, and discharge water - as well as transparency requirements related to this - are also diverse across countries and states [20,40,41]. The combination of these factors results in large variability in the water use efficiency of mining operations and their hydrological impacts [25]. Because of this variability, it is very difficult to fairly benchmark water use efficiency in the mining industry and to determine what is an acceptable level of water use, or water use impact, for any individual mining and mineral processing operation.

Given the potential for significant hydrological impacts, mining companies will often invest considerable resources into developing water and environmental management strategies so that potential impacts to surrounding industry and community stakeholders, as well as the environment, are reduced or avoided. When mining companies fail to effectively implement or communicate these strategies, then a mining project may lose its so-called 'social license to operate', resulting in substantial opposition to the mining project by communities, governments, or competing sectors such as agriculture [14,37,45]. To meet the diverse needs of stakeholders and government regulatory authorities, mining companies have become more transparent regarding their water management practices. Over the past two decades, the mining industry has increasingly made public disclosures of water use as part of environmental management and corporate sustainability reporting. These disclosures represent a valuable data source to improve understanding of the interactions between the mining industry and water resources.

The reporting of water use in the mining industry has become increasingly standardised over time through the development of industry specific water accounting schemes. The Minerals Council of Australia (MCA) developed the Water Accounting Framework for the Minerals Industry (WAFMI) to provide greater rigour and consistency for mines that report to schemes such as the Global Reporting Initiative [21]. More recently, the International Council on Mining & Metals (ICMM) has provided additional guidance, particularly as it relates to assessment and reporting of local water risks [15]. As this guidance and standardisation is implemented throughout the mining industry, it is anticipated that there will be an improvement in the transparency, quality and consistency of mining industry water use disclosures through time.

Previously, some compilation and quantitative analysis of the water use data reported by the mining industry has been undertaken by several authors. Mudd [25] conducted a preliminary assessment of water use disclosures within sustainability reporting and confirmed that lower ore grades are generally associated with higher water requirements per unit of production. Additionally, it was observed that there was considerable inconsistency in the metrics and communication of water use data between mining companies. Glaister and Mudd [9] assessed water use disclosures of platinum group metal mining companies. Northey et al. [28] compiled data from sustainability reporting to evaluate the variability in water use requirements of copper operations. Gunson [12] also compiled a dataset of reported mine water use to evaluate the water use intensity and global water withdrawals associated with non-fuel mineral production for the years 2006–2009. Buchspies et al. [3] compiled water withdrawal and recycling data for platinum group element production in South Africa. Beyond this, several authors have performed assessments of the types of water use information being disclosed by the mining industry and the general compliance of the mining industry with sustainability reporting standards such as the Global Reporting Initiative [1,2,20]. Although these studies have assessed various aspects of mining company water use reporting and the data contained therein, the scope of analysis and the extent of industry coverage included within these studies has been limited. Many studies have been limited to assessing only a geographic or commodity sub-sector of the mining industry. Additionally, many studies have only compiled data for a single aspect of mine-water interactions, most commonly water abstractions or withdrawals by mining operations. Thus, the large amount of data publicly reported by mining companies on other aspects of water use, such as internal reuse efficiency or discharges, has largely remained unassessed.

Efforts to more systematically compile and analyse this data would provide a significant opportunity to improve our understanding of: how water use varies across the mining industry, the overall magnitude and impacts of this water use, and the potential opportunities for improving water management outcomes in the mining industry. To facilitate improved compilation of this data, this study aimed to: 1. Establish a database structure to enable systematic compilation of public water use disclosures by the mining industry, 2. Test the database structure through the compilation of an initial dataset, 3. Analyse compiled data to understand trends in industry reporting and the variability of mine site water balances, and 4. Provide recommendations for further work to better understand and evaluate the interactions of the mining industry with water resources.

## 2. Methods and data sources

To support future assessments of water use efficiency in the mining industry and the potential environmental or societal impacts of this, we have compiled a comprehensive database of publicly disclosed water use statistics for the mining industry. The reported water use database was developed in two stages. First, water accounting standards for the minerals industry were reviewed to identify suitable data categories for describing water flows between mining operations and surrounding environments, as well as possible internal flows within mining operations. Secondly, these data categories were used to classify data reported in mining company sustainability and environmental compliance/management reporting, enabling a detailed database of mine water disclosures to be developed. Finally, an assessment of reporting trends and the temporal variability of mine site water balances was performed to better understand data availability and the potential applications of this data to advance research and industry understanding.

### 2.1. Water use reporting in the mining industry

The mining industry has increasingly reported water use statistics within corporate sustainability and environmental management reporting [36]. These disclosures may include mandatory reporting, such as environmental compliance reporting to regulatory authorities that may be made public in some jurisdictions. In other cases, mining companies voluntarily disclose water use data through initiatives such as corporate sustainability reporting and market disclosures [20]. Most existing studies that assess these activities have focused upon the degree of compliance with the various reporting standards that guide these disclosures, such as the Global Reporting Initiative [7,17]. However, there has been limited analysis of the actual water use data being communicated within these reports.

The Global Reporting Initiative (GRI) provides a framework for corporate sustainability reporting to aide in the communication of a company's social, economic and environmental performance [10]. Despite being a voluntary initiative, there has been strong uptake of GRI based sustainability reporting by major mining companies [7,36]. The GRI has evolved over time to meet the needs of stakeholders and to improve the meaningfulness or requirements of reporting indicators. As a result, reporting supplements specifically for the mining industry have been made available to improve the quality of disclosures being made by the sector [11]. The main indicators of relevance to water related issues under the reporting standard GRI4 include [10]:

- G4-EN8 – Total water withdrawal by source.
- G4-EN9 – Water sources significantly affected by withdrawal of water.
- G4-EN10 – Percentage and total volume of water recycled and reused.
- G4-EN22 (EN21 in GRI3) – Total water discharge by quality and destination.
- G4-EN26 – Identity, size, protected status, and biodiversity value of water bodies and related habitats significantly affected by the organisations discharges of water and runoff.

Typically, mining operations will be subject to environmental and permitting regulations that require them to submit compliance, planning or management reports to government authorities and regulatory bodies. In some jurisdictions these reports are made public, either voluntarily by the company or as a requirement of their permitting [20]. The contents of this reporting are often highly site specific as they are tailored heavily to understanding the impacts of the mine in the context of the surrounding natural or regulatory environment. Often these reports contain information on water quality monitoring, groundwater abstractions and impacts to aquifers, surface water withdrawals, or the management of major site infrastructure such as tailings dams. In this article and the compiled database, these forms of reporting are referred to as 'Environmental Management Reports'.

Previously there have been weaknesses and inconsistencies identified in mining industry water related GRI disclosures [25]. To address this, the mining industry has developed industry specific water accounting and reporting standards to improve the consistency and rigour of information being communicated through GRI based sustainability reporting and other stakeholder engagement processes. The Water Accounting Framework for the Minerals Industry (WAFMI) was developed by the Sustainable Minerals Institute (University of Queensland) for the Minerals Council of Australia [21]. The WAFMI provides a framework for mining and mineral processing operations to enable consistent estimation and recording of water flows throughout the site and to/from surrounding environments. This accounting framework enables more standardised communication of water use data by mining companies and is sufficiently flexible to enable implementation by a mining operation, regardless of local hydrologic or climatic factors [5]. MCA member companies were required to adopt the WAFMI by 1 July 2015 [22]. More recently, the International Council on Mining & Metals (ICMM) released another guidance document for the industry, 'A practical guide to consistent water reporting', which is required to be implemented by ICMM member companies by November 2018 [15]. The ICMM's guidance document was heavily modelled upon the earlier WAFMI, although with some minor alterations of terminology and significant additional guidance on the assessment and communication of local water contexts and risks.

### 2.2. Database structure

The database was structured to provide a flexible and accurate depiction of public water use disclosures made by the mining industry. The database structure was developed through review of the data categories and water quality classifications provided by the WAFMI [21] and the ICMM's [15] guidance document. As a significant proportion of mining industry water use reporting predates the development of these water accounting frameworks, non-complying reported data has been mapped to the closest equivalent data category. Given the historic variability and often unclear water use reporting practices of mining companies, some data points required considerable judgement of the authors to assign a suitable data category. In these cases, the authors endeavoured to cross-validate data points through comparison with data available for other data categories or time periods. Explanatory comments explaining decisions made were incorporated into the database as necessary.

#### 2.2.1. Data categories

There are a range of ways that mining and mineral processing operations interact with water resources. The flows of water through an operation can be quite site specific depending upon the local hydrology, management practices and processes employed on the site. Fortunately, the WAFMI and the ICMM's guidance document outlines flexible water accounting categories that can be used by mining companies to consistently report water use data. The various water use categories and definitions provided have been adapted to determine the main data categories included in our database.

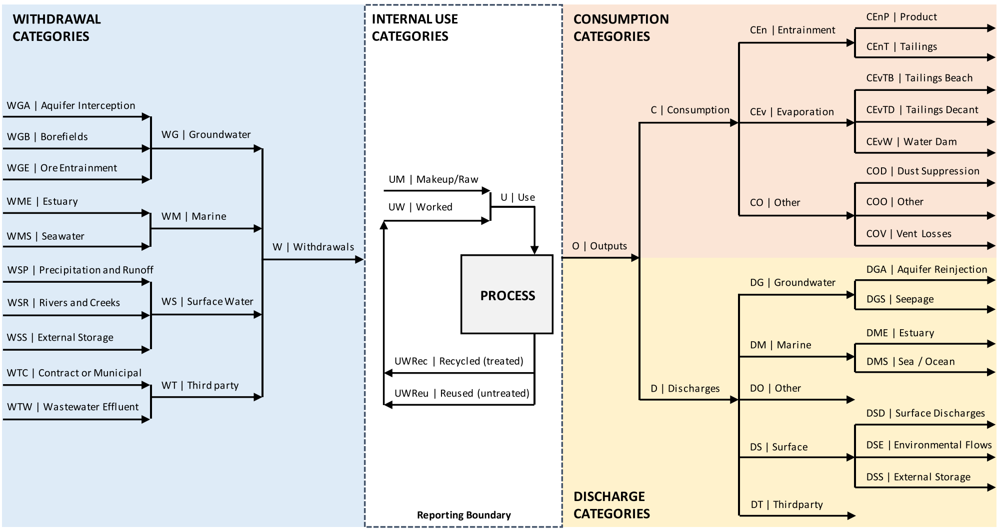


**Fig. 1.** Aggregation hierarchy of water related data categories, adapted from MCA (2014) and ICMM [15].

The data categories used are shown in Fig. 1, with definitions for each data category provided in Appendix A. As can be seen, there are four major classes of data categories defined to describe the interactions between mining / mineral processing operations and water resources. These are: withdrawals, internal use, consumption and discharge. Within each of these major data classes, an aggregation hierarchy exists reflecting the fact that reported data may only reflect a specific aspect of a mine's hydrological interactions. So further sub-classes are also used that reflect either the aggregate water flows to/from a specific source or sink (i.e. groundwater, surface water, marine water, or third parties), or that reflect a sub-set of flows to each sources or sinks (e.g. aquifer reinjection or seepage).

In this case, an important distinction is made between water consumption and water use. Water consumption is the mode by which water is made unavailable to be returned to surrounding environments, whereas water use is simply a reflection of the water inputs to site processes. Both consumptive and non-consumptive uses of water are possible, depending upon if the water is returned to the surrounding water sources. The consumption categories reflect the ultimate destination of water that is not reused or discharged back into water resources or third parties.

### *2.2.2. Water quality categories*

Water quality categories have been assigned in situations where the definitions provided by the MCA [21] or ICMM [15]'s reporting standards were used. Further detail is provided in Appendix A. Where reporting specifically makes a qualitative distinction between water quality, such as 'potable', 'fresh', 'brackish', 'impounded' or 'poor-quality', then a judgement was made to assign a category based upon the likely equivalent water quality category under the MCA [21] or ICMM [15] reporting standards. It should be noted that most of data reported by the industry does not indicate a water quality description or parameters specifically. Therefore, in these cases the default water quality category applied to the data point is 'T | Total', indicating that the data point is believed to represent all flow or volumes rather than a subset.

Alternative water quality classification approaches are also possible, which may be more relevant for an individual mine site's operation. An example is provided by Cocks et al. [4] who describe a hierarchical classification approach, developed for Kalgoorlie Consolidated Gold Mines (KCGM; 'The Superpit') and the Boddington Gold Mine in Australia. In this case, the potential water source and quality categories are highly tailored to the regional context of those mines and so there is detailed descriptors provided for different aquifer and water source characteristics. However, to ensure consistency with future industry reporting, the water quality categories defined by the MCA's [21] and ICMM's [15] reporting standards were adopted.

## 3. Results and discussion

The compiled database, which we refer to as 'Database of Publicly Reported Water Data by the Mining Industry v1.0′, is available in the electronic supplementary material accompanying this article.

### *3.1. Extent and types of captured water use reporting*

From the water use reporting surveyed in this study, it is clear that there are substantial amounts of water-related data being disclosed by the mining industry. In total 8314 data points were compiled from 359 mining company reports. Several examples of database entries are provided in Table 1.

Table 2 shows the number of data points that were compiled for each data category, the sources of these data (i.e. environmental

**Table 1**
Examples of Mine Water Database entries.

| Database Entry Items | Example 1 | Example 2 | Example 3 |
|---|---|---|---|
| **Country**[a] | Argentina | Cote d'Ivoire | India |
| **Company**[a] | Xstrata Copper | Newcrest Mining Limited | Vedanta |
| **Name**[a] | Alumbrera | Bonikro | VAL-Jharsugada |
| **Aggregation**[b] | Operation | Operation | Division |
| **Time Period**[a] | 2009 | FY2013 | FY2011 |
| **Data Category**[b] | DSD \| Surface Water | DG \| Groundwater | UW \| Worked |
| **Value**[a] | 1253438 | 799 | 2.37 |
| **Unit**[a] | kL | ML | % |
| **Water Quality Category**[b] | T \| Total | 2 \| Suitable for Some Uses | T \| Total |
| **Data Type**[b] | Reported_Value | Reported_Value | Inferred_or_Calculated |
| **Reference**[a] | Xstrata Copper, Minera Alumbrera, Sustainability Report, 2009. | Newcrest Mining Limited, Sustainability Report 2013, GRI Data Tables. | Vedanta, Sustainable Development Report 2011–2012. |
| **Comment**[a] | DP2 canal. | – | Recalculated from worked divided by raw to worked divided by total. |

Notes.
[a] Manually inputted.
[b] Selected from a list of possible classifications defined in Appendix A.

management reports or sustainability reports), and the degree to which water quality classification was possible. The breakdown of data sources was (Table 2):

- 29% (2451 of 8314) from Environmental Management Reports,
- 67% (5587 of 8314) from GRI based Sustainability Reports,
- 3% (277 of 8314) from non-GRI based Sustainability Reports.

When comparing the number of data points compiled for each data category, substantially more data is reported by the industry for water withdrawals and the water inputs to processes (both raw and worked water). Comparatively, substantially less data is reported for volumes of water discharges, modes of consumption (i.e. evaporation, tailings entrainment, etc.), or other related metrics such as changes in on-site water storage or local climatic factors. Due to this, it is currently not possible to describe the complete water balance of most mining operations using publicly reported data. Generally, this is only possible when companies have fully adopted and comply with either the WAFMI (MCA, 2014) or the ICMM's water accounting guidelines. Newcrest Mining Ltd was one of the earliest adopters of the WAFMI and this has resulted in consistent long-term reporting of water balances for their mines in Australia and Papua New Guinea, which includes classification of water flows into discrete water quality categories, as well as some assessment of data confidence or uncertainty.

It's unexpected that water discharge volumes were far more commonly reported in sustainability reports rather than environmental compliance reporting. This appears to be because environmental compliance reports place a much greater emphasis on monitoring compliance with water quality targets at specified locations downstream of discharge points, rather than the actual volumes of discharged water. By comparison, companies and sustainability reporting standards, such as the GRI, appear to prioritise communicating volumetric measures, with emphasis on water inputs rather than discharges or specific modes of consumption. Possibly this could be due to mining companies having a better understanding of their compliance with water withdrawal limits and water inputs to processes, however they may have more limited understanding of the ultimate destination of water on their site and the specific modes of water consumption or losses occurring (i.e. evaporation, tailings entrainment, seepage, etc.).

Water quality classifications were also assigned to data points where possible. The breakdown of assigned water quality classification was (Table 2):

- 7.6% (629 of 8314) were assigned category 1 (near potable),
- 5.4% (447 of 8314) were assigned category 2 (suitable for some Uses),
- 0.4% (39 of 8314) were assigned category 3 (unsuitable for most uses),
- 0.9% (76 of 8314) were assigned category N (not applicable),
- 83.7% (6958 of 8314) were assigned category T (total),
- 2.0% (166 of 8314) were assigned category U (unknown).

The high proportion of data being assigned the default category T (Total) is indicative of the fact that most companies don't specify water quality categories when reporting, rather the presented data can just be assumed to be the total water flows/volumes with no segmentation based upon quality. However, in several cases mining companies have defined their own water quality classifications that make interpretation more difficult. For instance, in Rio Tinto's reporting from 1997 to 2003 the term 'freshwater' is defined as water with total dissolved solids (TDS) of less than 1500 mg/L. Some Rio Tinto reports from this era also specify 'impounded water' and 'poor quality water'. However, some reports don't specifically include reporting according to these additional

**Table 2**
Number of data points compiled by data category, reference type and water quality category.

| Code | Description | Total | Reference Type | | | Water Quality Category | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Environmental Management Report | Sustainability Report, GRI | Sustainability Report, Non-GRI | 1 | 2 | 3 | NA | T | U |
| W | Withdrawals | 553 | 67 | 486 | – | 57 | 41 | 18 | 2 | 435 | – |
| WG | Groundwater | 332 | 42 | 285 | 5 | 29 | 26 | 1 | – | 276 | – |
| WGA | Aquifer Interception | 133 | 50 | 80 | 3 | 1 | 8 | – | 2 | 122 | – |
| WGB | Borefields | 485 | 376 | 107 | 2 | 11 | 2 | – | 1 | 471 | – |
| WGE | Ore Entrainment | 24 | 13 | 11 | – | – | 5 | – | – | 19 | – |
| WM | Marine | 54 | 14 | 40 | – | 13 | 13 | – | – | 28 | – |
| WMS | Seawater | 16 | – | 16 | – | – | 3 | – | – | 13 | – |
| WS | Surface Water | 276 | 29 | 244 | 3 | 25 | 22 | – | – | 229 | – |
| WSP | Precipitation and Runoff | 109 | 26 | 80 | 3 | 9 | 5 | – | 1 | 94 | – |
| WSR | Rivers and Creeks | 78 | 21 | 57 | – | 10 | – | – | 2 | 66 | – |
| WSS | External Storage | 32 | 3 | 28 | 1 | 2 | – | – | – | 30 | – |
| WT | Third-party | 150 | 17 | 128 | 5 | 26 | 15 | – | 6 | 103 | – |
| WTC | Contract or Municipal | 126 | 19 | 104 | 3 | 6 | – | – | 1 | 119 | – |
| WTW | Wastewater Effluent | 40 | 11 | 29 | – | 7 | – | – | 1 | 32 | – |
| | **Withdrawals Sub-total** | **2408** | **688** | **1695** | **25** | **196** | **140** | **19** | **16** | **2037** | – |
| U | Use | 144 | 17 | 124 | 3 | – | – | – | – | 144 | – |
| UM | Makeup/Raw | 2540 | 887 | 1526 | 127 | 357 | 222 | 2 | 27 | 1766 | 166 |
| UW | Worked | 1223 | 248 | 918 | 57 | 2 | – | – | – | 1221 | – |
| UWRec | Recycled (treated) | 18 | 10 | 8 | – | – | – | – | – | 18 | – |
| UWReu | Reused (untreated) | 20 | 10 | 10 | – | – | – | – | – | 20 | – |
| | **Use Sub-total** | **3945** | **1172** | **2586** | **187** | **359** | **222** | **2** | **27** | **3169** | **166** |
| C | Consumption | 43 | 3 | 40 | – | – | – | – | 1 | 42 | – |
| CEn | Entrainment | 39 | 17 | 22 | – | 1 | 12 | – | – | 26 | – |
| CEnP | Product | 4 | 2 | 2 | – | – | – | – | – | 4 | – |
| CEnT | Tailings Entrainment | 4 | 3 | 1 | – | – | – | – | 1 | 3 | – |
| CEv | Evaporation | 58 | 21 | 37 | – | 20 | 6 | – | 2 | 30 | – |
| CEvTB | Tailings Beach Evaporation | 5 | 4 | 1 | – | – | – | – | – | 5 | – |
| CEvTD | Tailings Decant Evaporation | 4 | 4 | – | – | – | – | – | – | 4 | – |
| CEvW | Water Dam Evaporation | 10 | 10 | – | – | – | – | – | – | 10 | – |
| CO | Other | 15 | 15 | – | – | 5 | 5 | – | – | 5 | – |
| COD | Dust Suppression | 11 | 2 | 6 | 3 | – | – | – | 1 | 10 | – |
| COO | Other | 16 | 13 | 2 | 1 | 2 | 6 | – | 1 | 7 | – |
| COV | Vent Losses | 10 | 10 | – | – | 4 | – | – | – | 6 | – |
| | **Consumption Sub-total** | **219** | **104** | **111** | **4** | **32** | **29** | – | **6** | **152** | – |
| D | Discharges | 611 | 40 | 549 | 22 | 8 | 2 | 6 | 2 | 593 | – |
| DG | Groundwater | 48 | 11 | 34 | 3 | 1 | 16 | – | – | 31 | – |
| DGS | Seepage | 27 | 16 | 11 | – | – | 5 | – | – | 22 | – |
| DM | Marine | 10 | 1 | 9 | – | – | 1 | – | – | 9 | – |
| DME | Estuary | 11 | – | 11 | – | – | – | 1 | – | 10 | – |
| DMS | Sea/Ocean | 28 | – | 28 | – | – | 5 | 3 | – | 20 | – |
| DO | Other | 46 | – | 45 | 1 | – | 1 | – | – | 45 | – |
| DS | Surface Water | 124 | 11 | 105 | 8 | 14 | 12 | – | – | 98 | – |
| DSD | Surface Discharges | 23 | – | 23 | – | – | – | – | – | 23 | – |
| DSE | Environmental Flows | 16 | 10 | 6 | – | 5 | – | – | – | 11 | – |
| DSS | External Storage | 9 | – | 9 | – | – | – | – | 3 | 6 | – |
| DT | Third-party | 61 | 2 | 47 | 12 | – | – | – | – | 61 | – |
| | **Discharges Sub-total** | **1014** | **91** | **877** | **46** | **28** | **42** | **10** | **5** | **929** | – |
| **O** | **Outputs (C + D)** | **150** | **20** | **130** | – | **14** | **14** | **8** | – | **114** | – |
| Div | Diversions | 7 | 1 | 6 | – | – | – | – | – | 7 | – |
| SA | Accumulation | 16 | 1 | 15 | – | – | – | – | 1 | 15 | – |
| SC | Storage Capacity | 9 | 8 | 1 | – | – | – | – | – | 9 | – |
| SE | Storage at End of Period | 16 | 10 | 6 | – | – | – | – | – | 16 | – |
| SES | Storage at Start of Period | 16 | 10 | 6 | – | – | – | – | – | 16 | – |
| VOMC | Ore Moisture Content | 5 | 4 | 1 | – | – | – | – | – | 5 | – |
| VP | Pan Evaporation | 59 | 33 | 26 | – | – | – | – | – | 59 | – |
| VR | Rainfall | 411 | 301 | 109 | 1 | – | – | – | 13 | 398 | – |

(*continued on next page*)

**Table 2** (*continued*)

| Code | Description | Total | Reference Type | | | Water Quality Category | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Environmental Management Report | Sustainability Report, GRI | Sustainability Report, Non-GRI | 1 | 2 | 3 | NA | T | U |
| VS | Size of Affected Water Source | 10 | – | 10 | – | – | – | – | 8 | 2 | – |
| VTSD | Tailings Solids Density | 29 | 7 | 8 | 14 | – | – | – | – | 29 | – |
| | **Other Sub-total** | **578** | **375** | **188** | **15** | – | – | – | **22** | **556** | – |
| | **Grand Total** | **8314** | **2450** | **5587** | **277** | **629** | **447** | **39** | **76** | **6957** | **166** |

classifications. In these cases, it is difficult to determine based upon the reporting whether the water use data being reported reflects that only 'fresh water' was being used or whether there was also poorer quality water being used that went unreported.

Most of the data captured was for individual mining operations, however it is also very common for aggregated divisional or company totals to be reported – often without the more detailed data for the individual operations. The breakdown of data aggregation was (Table 3):

- 12.9% (1074 of 8314) were company totals,
- 20.1% (1673 of 8314) were divisional totals,
- 67.0% (5568 of 8314) were operational totals.

Important information on the local context and potential impacts of water use are lost when aggregating water use data to divisional and company totals, especially when a company's operations are not co-located in the same hydrological region. Aggregation of data appears to be more common for larger companies that have mines located in multiple countries. In these cases, divisional totals commonly reflect either a commodity grouping (e.g. iron ore, copper) or grouping by countries or regions (e.g. North America). There were also instances where data was reported for a mining operation, however due to company mergers or asset sales, a mine would subsequently be included in aggregated divisional reporting. In these cases, there can be discontinuities in the availability of water use data for mines due to the different reporting practices of the various operating companies.

The presentation of data and the ability to accurately record data points is dependent upon how the information is presented in company reports. The breakdown of data disclosure 'type' or estimation method was (Table 3):

- 88.8% (7380 of 8314) were directly reported values,
- 7.3% (606 of 8314) were reported within graphs without data labels,
- 3.8% (319 of 8314) were inferred or calculated from other data in the report,
- 0.1% (10 of 8314) were best estimates based upon the authors judgement.

Graph readings, inferences and estimates could be considered to have a slightly lower data quality than the data points sourced from numeric values in the text or tables of a report.

Most of the reported data are for annual time periods and there are substantially less data available for sub-annual timescales (Tables 3 and 4). The split was that:

- 87.4% (7270 of 8314) were reported for annual time periods,
- 12.6% (1045 of 8314) were reported for sub-annual (mostly monthly) time periods.

In fact, a large proportion of sub-annual data are monthly data for BHP Billiton's Olympic Dam mine site in South Australia, where bore water withdrawals (WGB) from the Great Artesian Basin are reported on a monthly timescale. Monthly rainfall data was also reported for some mines over long periods of time. Some monthly data for Rio Tinto's Oyu Tolgoi mine in Mongolia was also available for raw water use (UM), worked water use (UW), evaporation (VP) and groundwater withdrawals (WG).

The total water use by major data category over time are shown in Table 4 and Fig. 2. Most of the pre-2000 data are water use data. It is quite possible that for this period, water withdrawals were being reported as 'water use' by several companies. However, it was not possible for authors to further distinguish between reported values and so the data descriptions presented by companies must be taken on face value.

Table 5 provides an indication of the data coverage across countries and companies, and the commodity groups represented (coverage not shown due to limitations in reporting for aggregated divisions and minor co-/by-production). The initial data collection had a bias towards copper producing companies and those with operations in Australia. Substantial additional data are available in the public reporting of mining and mineral production companies not included in this list. It is therefore anticipated that the industry coverage of the water reporting dataset could be expanded considerably in the future by further surveying the reporting of additional mining companies. The authors note that compiling data directly from industry reporting is an extremely time-consuming task, particularly due to the frequency of mergers and acquisitions in the industry that break reporting for individual mine sites across multiple companies. So considerable effort and care is required to develop consistent, long-term datasets for individual mining operations.

**Table 3**
Number of data points compiled by data category, aggregation, data type and reporting period.

| Code | Description | Aggregation | | | Data Type | | | | Period | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Company | Division | Operation | Best Estimate | Inferred or Calculated | Reported, Graph Reading | Reported, Value | Annual | Sub-annual |
| W | Withdrawals | 133 | 156 | 264 | – | 17 | – | 536 | 540 | 13 |
| WG | Groundwater | 46 | 85 | 201 | – | 16 | 39 | 277 | 284 | 48 |
| WGA | Aquifer Interception | 19 | 2 | 112 | – | 8 | 24 | 101 | 105 | 28 |
| WGB | Borefields | 20 | 2 | 463 | – | 52 | 73 | 360 | 189 | 296 |
| WGE | Ore Entrainment | 12 | – | 12 | – | 2 | – | 22 | 24 | – |
| WM | Marine | 6 | 26 | 22 | – | – | – | 54 | 54 | – |
| WMS | Seawater | 10 | – | 6 | – | – | – | 16 | 16 | – |
| WS | Surface Water | 49 | 87 | 140 | – | 14 | – | 262 | 274 | 2 |
| WSP | Precipitation and Runoff | 26 | 19 | 64 | – | 8 | – | 101 | 106 | 3 |
| WSR | Rivers and Creeks | 15 | 7 | 56 | – | 9 | – | 69 | 76 | 2 |
| WSS | External Storage | 11 | 3 | 18 | – | – | – | 32 | 32 | – |
| WT | Third-party | 38 | 36 | 76 | – | 15 | – | 135 | 150 | – |
| WTC | Contract or Municipal | 30 | 34 | 62 | – | 3 | – | 123 | 124 | 2 |
| WTW | Wastewater Effluent | 12 | 6 | 22 | – | 3 | – | 37 | 40 | – |
| | **Withdrawal Sub-total** | **427** | **463** | **1518** | – | **147** | **136** | **2125** | **2014** | **394** |
| U | Use | 12 | 53 | 79 | – | 5 | 4 | 135 | 144 | – |
| UM | Makeup/Raw | 166 | 606 | 1768 | 10 | 46 | 196 | 2288 | 2368 | 172 |
| UW | Worked | 128 | 315 | 780 | – | 29 | 49 | 1145 | 1115 | 108 |
| UWRec | Recycled (treated) | 1 | 2 | 15 | – | – | – | 18 | 18 | – |
| UWReu | Reused (untreated) | 2 | 2 | 16 | – | – | – | 20 | 20 | – |
| | **Use Sub-total** | **309** | **978** | **2658** | **10** | **80** | **249** | **3606** | **3665** | **280** |
| C | Consumption | 6 | 6 | 31 | – | 8 | – | 35 | 43 | – |
| CEn | Entrainment | 14 | – | 25 | – | 1 | – | 38 | 39 | – |
| CEnP | Product | – | – | 4 | – | – | – | 4 | 4 | – |
| CEnT | Tailings Entrainment | – | – | 4 | – | 3 | – | 1 | 4 | – |
| CEv | Evaporation | 17 | 1 | 40 | – | 1 | – | 57 | 57 | 1 |
| CEvTB | Tailings Beach Evaporation | – | – | 5 | – | 1 | – | 4 | 5 | – |
| CEvTD | Tailings Decant Evaporation | – | – | 4 | – | – | – | 4 | 4 | – |
| CEvW | Water Dam Evaporation | – | – | 10 | – | 3 | – | 7 | 10 | – |
| CO | Other | – | – | 15 | – | 3 | – | 12 | 15 | – |
| COD | Dust Suppression | 1 | – | 10 | – | 1 | – | 10 | 11 | – |
| COO | Other | – | – | 16 | – | – | – | 16 | 16 | – |
| COV | Vent Losses | – | – | 10 | – | – | – | 10 | 10 | – |
| | **Consumption Sub-total** | **38** | **7** | **174** | – | **21** | – | **198** | **218** | **1** |
| D | Discharges | 83 | 185 | 343 | – | 24 | – | 587 | 602 | 9 |
| DG | Groundwater | 20 | 3 | 25 | – | 1 | – | 47 | 48 | – |
| DGS | Seepage | 10 | 1 | 16 | – | – | – | 27 | 26 | 1 |
| DM | Marine | 6 | – | 4 | – | – | – | 10 | 10 | – |
| DME | Estuary | 10 | – | 1 | – | – | – | 11 | 11 | – |
| DMS | Sea/Ocean | 12 | 3 | 13 | – | 2 | – | 26 | 28 | – |
| DO | Other | 26 | 1 | 19 | – | 1 | – | 45 | 46 | – |
| DS | Surface Water | 30 | 21 | 73 | – | 6 | – | 118 | 123 | 1 |
| DSD | Surface Discharges | 3 | 3 | 17 | – | 2 | – | 21 | 23 | – |
| DSE | Environmental Flows | 3 | – | 13 | – | 2 | – | 14 | 16 | – |
| DSS | External Storage | – | – | 9 | – | – | – | 9 | 9 | – |
| DT | Third-party | 39 | 8 | 14 | – | – | – | 61 | 61 | – |
| | **Discharges Sub-total** | **242** | **225** | **547** | – | **38** | – | **976** | **1003** | **11** |
| **O** | **Outputs (C+D)** | **44** | – | **106** | – | **17** | – | **133** | **150** | – |
| Div | Diversions | 7 | – | – | – | – | – | 7 | 7 | – |
| SA | Accumulation | 5 | – | 11 | – | 1 | – | 15 | 16 | – |
| SC | Storage Capacity | – | – | 9 | – | 2 | – | 7 | 9 | – |
| SE | Storage at End of Period | – | – | 16 | – | 2 | – | 14 | 16 | – |
| SES | Storage at Start of Period | – | – | 16 | – | 2 | – | 14 | 16 | – |

(*continued on next page*)

**Table 3** (*continued*)

| Code | Description | Aggregation | | | Data Type | | | | Period | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Company | Division | Operation | Best Estimate | Inferred or Calculated | Reported, Graph Reading | Reported, Value | Annual | Sub-annual |
| VOMC | Ore Moisture Content | – | – | 5 | – | 2 | – | 3 | 5 | – |
| VP | Pan Evaporation | – | – | 59 | – | 1 | 24 | 34 | 11 | 48 |
| VR | Rainfall | – | – | 411 | – | 4 | 197 | 210 | 112 | 299 |
| VS | Size of Affected Water Source | 2 | – | 8 | – | – | – | 10 | 10 | – |
| VTSD | Tailings Solids Density | – | – | 29 | – | 2 | – | 27 | 17 | 12 |
| | **Other Sub-total** | **14** | – | **564** | – | **16** | **221** | **334** | **219** | **359** |
| | **Grand Total** | **1074** | **1673** | **5567** | **10** | **319** | **606** | **7379** | **7269** | **1045** |

**Table 4**
Number of data points compiled for each time period.

| Year[a] | Total | Data Category Sub-totals | | | | | | Water Quality Categories | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Withdrawals | Use | Discharges | Consumption | Outputs | Others | 1 | 2 | 3 | N | T | U |
| 1986 | 1 | 1 | – | – | – | – | – | – | – | – | – | 1 | – |
| 1987 | 1 | 1 | – | – | – | – | – | – | – | – | – | 1 | – |
| 1988 | 2 | 1 | – | – | – | – | 1 | – | – | – | – | 2 | – |
| 1989 | 4 | 1 | 2 | – | – | – | 1 | – | – | – | – | 4 | – |
| 1990 | 4 | 1 | 2 | – | – | – | 1 | – | – | – | – | 4 | – |
| 1991 | 4 | 1 | 2 | – | – | – | 1 | – | – | – | – | 4 | – |
| 1992 | 4 | 1 | 2 | – | – | – | 1 | – | – | – | – | 4 | – |
| 1993 | 4 | 1 | 2 | – | – | – | 1 | – | – | – | – | 4 | – |
| 1994 | 5 | 1 | 3 | – | – | – | 1 | – | – | – | – | 5 | – |
| 1995 | 5 | 1 | 3 | – | – | – | 1 | – | – | – | – | 5 | – |
| 1996 | 8 | 1 | 6 | – | – | – | 1 | – | – | – | – | 8 | – |
| 1997 | 277 | 1 | 275 | – | – | – | 1 | 55 | 56 | – | – | 109 | 57 |
| 1998 | 268 | 1 | 266 | – | – | – | 1 | 54 | 54 | – | – | 106 | 54 |
| 1999 | 275 | 2 | 271 | – | – | – | 2 | 55 | 54 | – | – | 112 | 54 |
| 2000 | 165 | 2 | 129 | 32 | – | – | 2 | 44 | 14 | – | 22 | 84 | 1 |
| 2001 | 51 | 2 | 38 | 9 | – | – | 2 | 3 | 1 | – | – | 47 | – |
| 2002 | 182 | 16 | 133 | 27 | – | – | 6 | 4 | 1 | – | – | 177 | – |
| 2003 | 208 | 11 | 155 | 32 | 4 | – | 6 | 3 | – | – | 2 | 203 | – |
| 2004 | 187 | 26 | 123 | 26 | 7 | – | 5 | 3 | – | – | 2 | 182 | – |
| 2005 | 231 | 48 | 136 | 30 | 10 | – | 7 | 4 | 1 | – | 3 | 223 | – |
| 2006 | 304 | 66 | 170 | 39 | 17 | – | 12 | 17 | 14 | 1 | 13 | 259 | – |
| 2007 | 308 | 94 | 169 | 33 | 6 | – | 6 | 17 | 12 | 1 | 13 | 265 | – |
| 2008 | 514 | 147 | 260 | 88 | 6 | 1 | 12 | 32 | 16 | 11 | 1 | 454 | – |
| 2009 | 369 | 95 | 193 | 59 | 5 | 2 | 15 | 9 | 7 | 4 | – | 349 | – |
| 2010 | 395 | 120 | 177 | 71 | 2 | 2 | 23 | 7 | 6 | 3 | – | 379 | – |
| 2011 | 590 | 173 | 257 | 83 | 28 | 31 | 18 | 31 | 21 | 2 | – | 536 | – |
| 2012 | 592 | 204 | 212 | 106 | 18 | 32 | 20 | 24 | 19 | 1 | – | 548 | – |
| 2013 | 544 | 191 | 175 | 96 | 29 | 27 | 26 | 56 | 34 | 3 | – | 451 | – |
| 2014 | 586 | 198 | 180 | 108 | 43 | 36 | 21 | 83 | 69 | 4 | 8 | 422 | – |
| 2015 | 569 | 278 | 161 | 81 | 26 | 9 | 14 | 46 | 19 | 4 | – | 500 | – |
| 2016 | 575 | 328 | 137 | 72 | 17 | 10 | 11 | 64 | 44 | 4 | – | 463 | – |
| NA[b] | 37 | – | 26 | 11 | – | – | – | – | – | – | – | 37 | – |
| Sub-annual[c] | 1045 | 394 | 280 | 11 | 1 | – | 359 | 18 | 5 | 1 | 12 | 1009 | – |
| **Grand Total** | **8314** | **2408** | **3945** | **1014** | **219** | **150** | **578** | **629** | **447** | **39** | **76** | **6957** | **166** |

Notes.
[a] Calendar year and financial year ending data has been aggregated for presentation purposes.
[b] Not applicable (NA) includes 2 raw water use (UM) data points for the unspecified construction periods of the Las Bambas (Peru) and Antapaccay (Peru) operations. The remainder is data covering the multi-year period 1991–2001 for 11 of Barrick Gold Corporation's operations (plus company totals).
[c] Sub-annual data points are predominantly monthly data (997 of 1045). However, some data points are for 6-month time periods (48 of 1045) due to changes in ownership of mining operations mid-year.

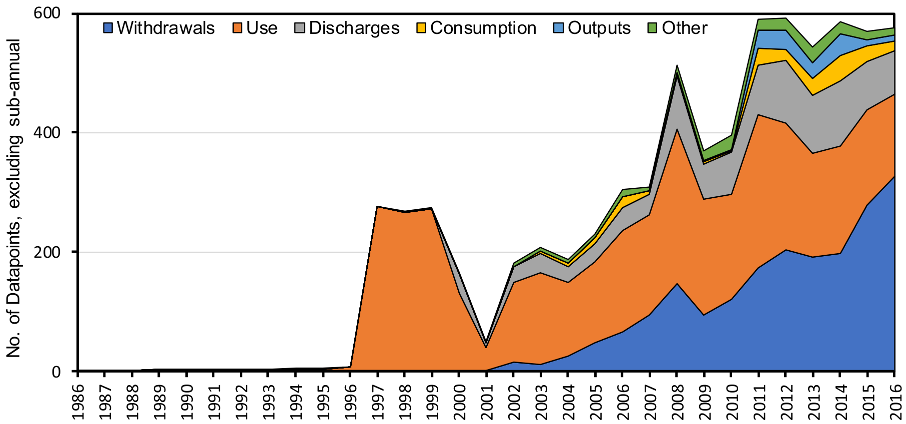


**Fig. 2.** Aggregated number of data points compiled for each major data category through time. Excludes sub-annual data.

**Table 5**
Number of datapoints by country and company (including subsidiaries). Commodity groups known to be represented in the dataset are also shown.

| No. | Countries | No. | Companies (including subsidiaries) | Commodity Groups |
|---|---|---|---|---|
| 167 | Argentina | 1145 | Barrick Gold Corporation | Ag |
| 2681 | Australia | 1239 | BHP Billiton | Al |
| 55 | Brazil | 85 | Chinese Molybdenum Co | Au |
| 123 | Canada | 738 | Codelco | B |
| 1144 | Chile | 152 | Collahuasi | Coal |
| 48 | Cote d'Ivoire | 17 | Compania Minera Antamania S.A. | Cu |
| 7 | Dem. Rep. of Congo | 11 | Cu-River Mining Australia | Diamonds |
| 26 | Dominican Republic | 46 | Evolution Mining | Fe |
| 19 | Fiji | 311 | Glencore (incl. Glencore Xstrata) | In |
| 28 | France | 209 | Hillgrove Resources | Mo |
| 10 | Germany | 2 | IMX Resources | Ni |
| 243 | India | 309 | MMG | Pb |
| 84 | Indonesia | 875 | Newcrest Mining Limited | Pd |
| 19 | Ireland | 54 | Oxiana Limited | Pt |
| 64 | Laos | 143 | Oyu Tolgoi | Rh |
| 5 | Madagascar | 231 | OZ Minerals Limited | Salt |
| 143 | Mongolia | 20 | Porgera Joint Venture | Se |
| 1 | Mozambique | 1315 | Rio Tinto | Talc |
| 35 | Namibia | 599 | Vedanta | Te |
| 17 | New Zealand | 967 | Xstrata | Ti |
| 221 | Papua New Guinea | 22 | Zinifex Limited | U |
| 203 | Peru | | | Vermiculite |
| 17 | Philippine | | | Zn |
| 5 | Saudi Arabia | | | |
| 203 | South Africa | | | |
| 37 | Spain | | | |
| 1 | Suriname | | | |
| 79 | Tanzania | | | |
| 39 | United Kingdom | | | |
| 472 | United States | | | |
| 82 | Zambia | | | |
| 72 | Zimbabwe | | | |
| ***1964*** | ***Not Applicable*** | | | |

### *3.2. Water use statistics*

The reported data provides a strong basis for establishing a deeper understanding of how the global mining industry interacts with and impacts water resources. This includes developing an improved understanding of the potential magnitude of water consumption and use impacts, how water balances of mining operations vary across regions, and how the water consumption of mining operations can vary through time in response to changing mine conditions, management decisions and local hydrology or climate.

Water withdrawals, use and discharges at mine sites over time are shown in Fig. 3, with summary statistics shown in Table 6. These were developed through combination of the water related data with mine site production statistics that the authors have previously compiled (e.g. [26]), with some minor updates to increase coverage. Water withdrawals, when normalised per tonne of ore mined or processed, display several orders of magnitude of variability between mining operations – with 90% of mining

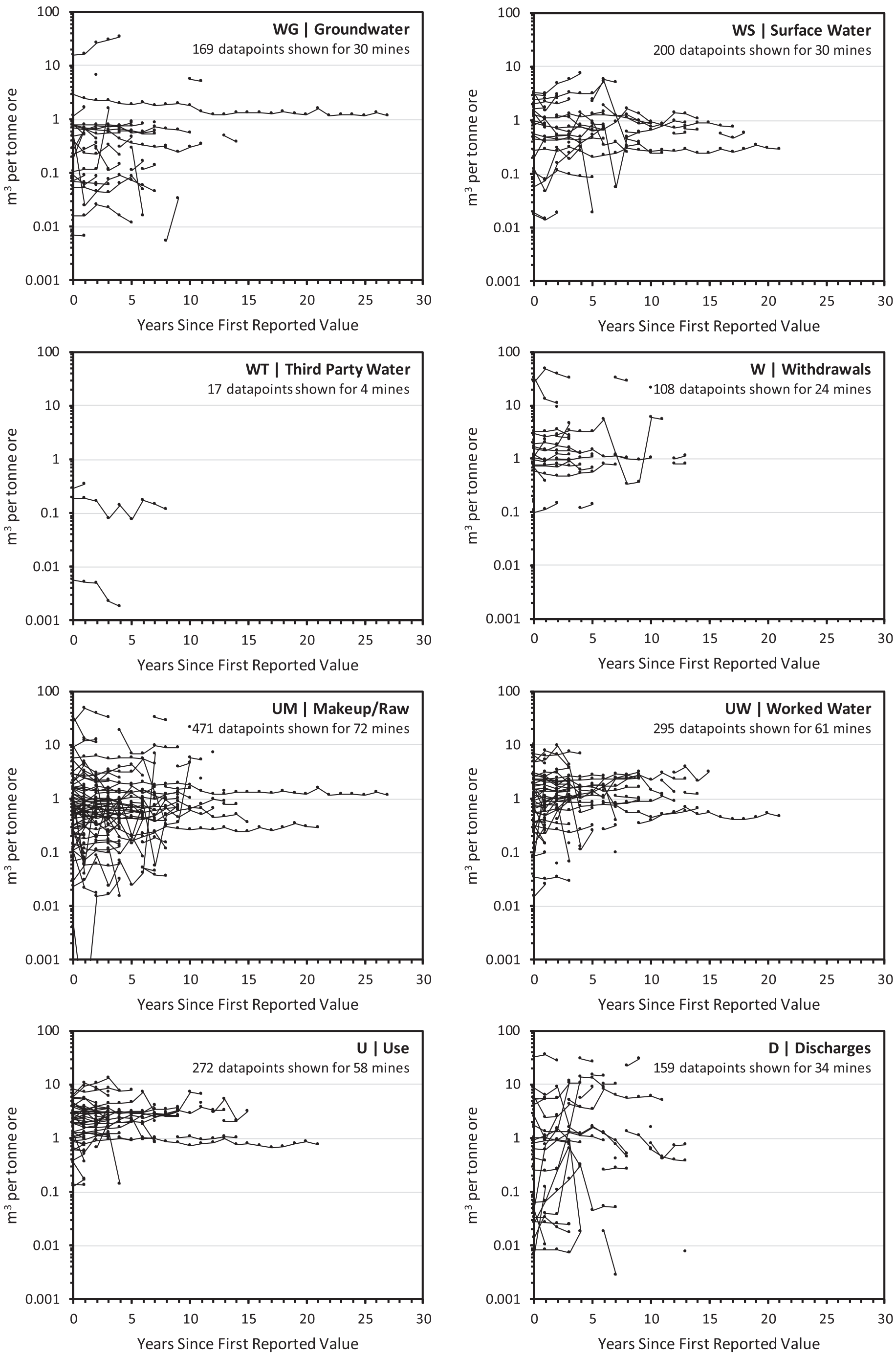


**Fig. 3.** Mine water withdrawals, use and discharges over time, normalised per tonne of ore processed. Additional data points for total water use (U) were inferred from reported makeup (UM) and worked water (UW) data. Breaks in data series indicate periods of no reporting.

operations withdrawing between 0.13 and 17.29 $m^3$ per tonne of ore processed. Even for the same mine site there can be significant variation in water withdrawals through time, as shown in Fig. 4 where data has is expressed relative to the first year of reported data for each mine site. This intra-annual variability can also range to an order or two of magnitude. Mining operations can vary considerably in terms of their source of water, therefore the variability shown for total water withdrawals is also reflected in the data available for surface water, groundwater and third party water withdrawals. Fig. 5 shows rates of groundwater withdrawals in relation to surface water withdrawals, demonstrating that mines are very diverse in terms of their reliance on either surface water or groundwater withdrawals. Further investigation is required to determine whether the exact drivers of this, but it is likely due to the

**Table 6**
Summary statistics for mine site water withdrawals, use, discharges and reuse efficiency.

| | | $m^3$ per tonne ore | | | | | |
|---|---|---|---|---|---|---|---|
| **Code** | **Description** | **Mean**[a] | **Median**[a] | **Standard Deviation**[a] | **5th Percentile**[a] | **95th Percentile**[a] | **No. Mines** |
| W | Withdrawals | 3.51 | 1.12 | 7.38 | 0.13 | 17.29 | 24 |
| WG | Groundwater | 1.46 | 0.52 | 4.45 | 0.04 | 3.46 | 30 |
| WS | Surface Water | 1.16 | 0.84 | 1.11 | 0.05 | 3.27 | 30 |
| WT | Third Party Water | 0.12 | 0.07 | 0.15 | 0.00 | 0.29 | 4 |
| U | Use | 2.39 | 1.98 | 1.91 | 0.34 | 6.27 | 58 |
| UM | Makeup/Raw | 1.79 | 0.63 | 4.55 | 0.06 | 4.93 | 72 |
| UW | Worked Water | 1.55 | 1.10 | 1.79 | 0.09 | 5.42 | 61 |
| D | Discharges | 2.92 | 0.63 | 5.71 | 0.03 | 9.94 | 34 |
| | Reuse Efficiency, % | 56.9 | 61.8 | 26.8 | 12.5 | 93.9 | 59 |

Notes.
[a] Determined from the mean for each individual mine.

substantial differences in local climates and groundwater and surface water availability in different mining regions.

The water use required for mining and mineral processing operations are constrained by the required processing conditions and ore throughput rates, which is reflected in the lower apparent variability of total water use. Water use varies between 0.34 and 6.27 $m^3$ per tonne ore processed for 90% of mining operations (Table 6). However, the components of the total water use, raw water and worked water, display a much greater degree of variability (Figs. 3 and 4). A key contributor to this variability is likely the influence of variability in local hydrology on the mining operations water balance, as year to year variations in rainfall, on-site storage and regional water availability can significantly alter the potential water reuse or recycling rates achievable (or desirable). For instance, during periods of low rainfall, a mining operation may be forced to rely less on external water sources and draw down reserves of worked water from tailings storage facilities or worked water stores. Alternatively, during periods of high rainfall, a mining operation may have easier access to external surface water sources or be able to divert rainfall and surface run-off to water storages for subsequent uses in site processes. There are many potential variations to this depending upon local climate, site water management objectives and infrastructure and site operation strategies [18]. Due to these factors, water reuse efficiency varies substantially between mining operations, as shown in Fig. 6. Mining operations vary from sourcing process water almost entirely from reused or recycled water, whereas other mine sites have very limited reuse of water and are sourcing water from external sources or the interception of rainfall or ground water on-site.

Although there is less discharge data available for mining operations (mine sites specifically reporting zero discharges were excluded from Figs. 3 and 4), the data that are available suggest very high intra-annual variability in discharge requirements. Again, this is likely to be coupled to both operational and climatic factors. Throughout the life of a mining operation, the morphology of tailings storage facilities may change considerably due to the cumulative disposal of tailings, which may alter water storage capacity and the water balance of the facility over time. Alternatively, the expansion of tailings storage facilities to accommodate further tailings deposition may significantly increase water storage capacity. This has considerable implications for potential rates of impounded water reuse, as well as evaporation rates and discharge requirements. Additionally, variability in groundwater infiltration, rainfall, runoff and evaporation over the life of a mine may also translate into substantial variability in discharge requirements. Some complex examples exist, such as the Lihir gold mine in Papua New Guinea, where more than 200 GL of saline infiltration from Louise Harbour towards the pit is discharged continually back into the marine environment.

### *3.3. Limitations and inconsistencies in existing water use reporting*

A range of limitations and inconsistencies were identified in the historic water reporting practices of the industry. For instance, there is considerable inconsistency in accounting for surface water withdrawals between operations or companies, and even at the same operation over time. What is reported as surface water withdrawals, in many cases will simply be the active withdrawal from nearby rivers or lakes that are metered - for which there may be a formal water allocation license that needs to be complied with. In other cases, what is reported as surface water withdrawals may exclude precipitation and runoff that has been intercepted in site water storage infrastructure or within open pits. In yet other cases, what has been reported as a 'surface water' withdrawal may simply be the surface water used in processing operations, rather than the total surface water withdrawals associated with the site, which is not typically known by mine site personnel (i.e. a full site-wide water balance will often be unavailable).

There have also been a range of different ways that water reuse or recycling have been accounted for by the industry. The MCA's [21] and ICMM's [15] standards state that water reuse metrics should exclude the additional rainfall or surface runoff intercepted by worked water stores or tailings storage facilities. However, reporting for many mining operations, particularly older reporting prior to the adoption of these standards, are likely to simply reflect the total water transfers from either tailings storage facilities, tailings thickeners or worked water stores. The presentation of raw water and worked water use efficiency as percentages has also been inconsistent historically. The recommended definition of water reuse efficiency by current reporting standards is worked water use divided by total water use (raw + worked). Whereas, historically several mining companies have reported water use metrics based upon raw water use divided by worked water use. When developing the database, the basis of water reuse efficiency calculations were

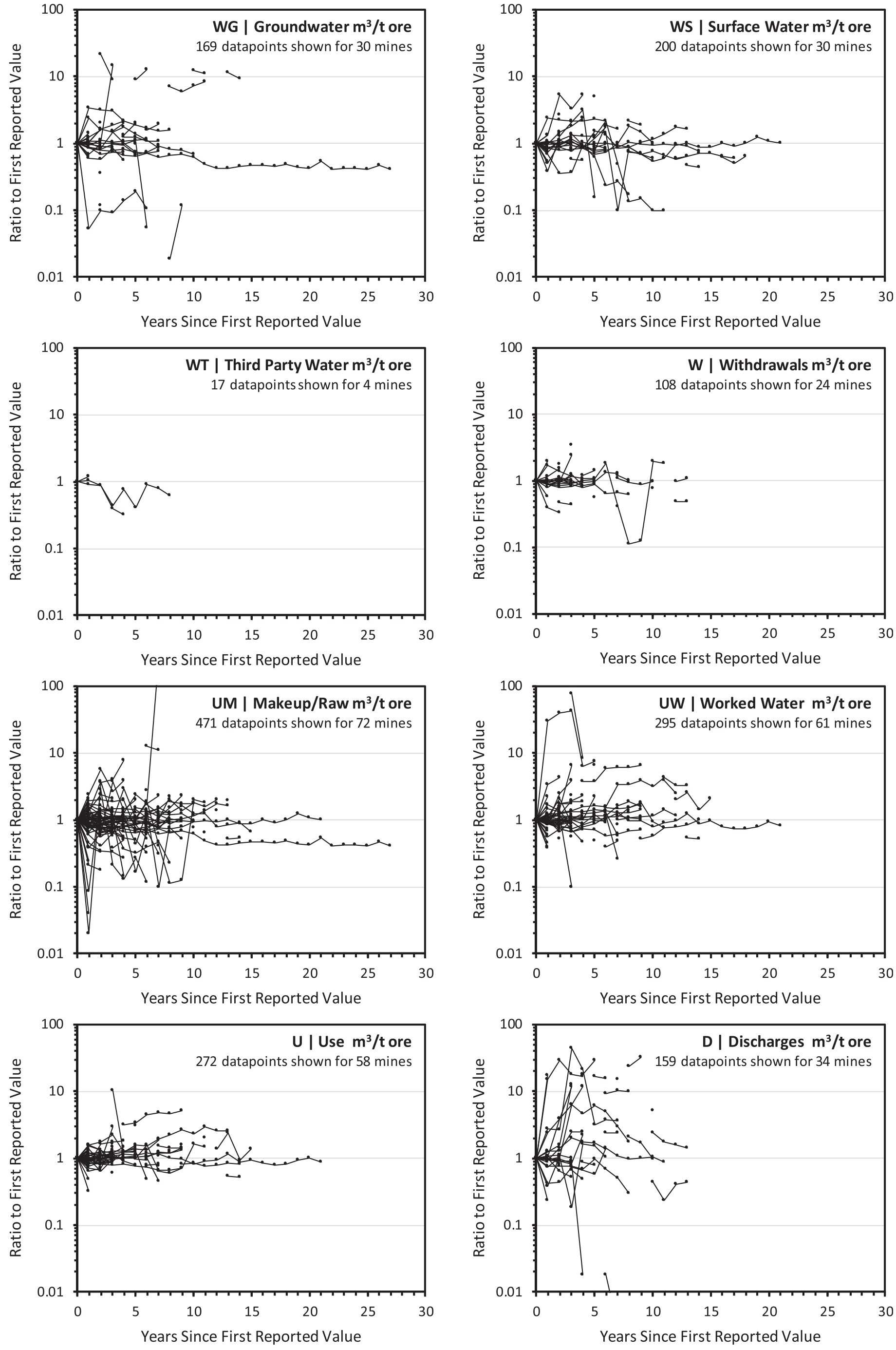


**Fig. 4.** Variability of mine water withdrawals, use and discharges over time. Data normalised per tonne of ore processed and expressed relative to the first reported value for each mine. Additional data points for total water use (U) were inferred from reported makeup (UM) and worked water (UW) data. Breaks in data series indicate periods of no reporting.

validated and some percentage-based values were recalculated to meet the current accepted definitions. Examples exist in the reporting of companies recognising these issues when reporting water use and reuse. For instance, in 2012–2013 Vedanta restated water use values from 2011 to 2012 to represent total water use, rather than raw 'fresh water' use. In addition, Vedanta changed from reporting 'recycled' water values based on reused water divided by raw water to instead report reused water divided by total water use. Other potential inconsistencies with reporting exist, for instance Xstrata North Queensland reporting in 2010 indicated that the reported total water use excluded water used from groundwater and aquifer dewatering. Therefore, it is important to consider the

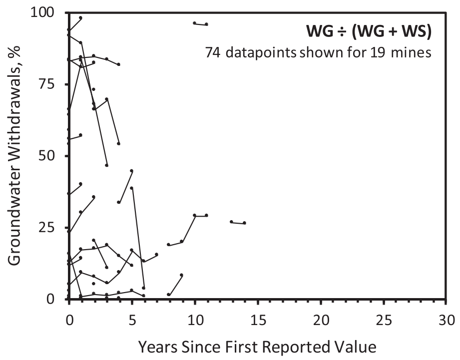


**Fig. 5.** Proportion of groundwater withdrawals (WG) relative to combined surface and groundwater withdrawals (WG + WS). Excludes 12 mines only reporting surface water withdrawals (WS) and 10 mines only reporting groundwater withdrawals (WG) (this does not imply that these mines only withdraw from surface or groundwater systems). Breaks in data series indicate periods of no reporting.

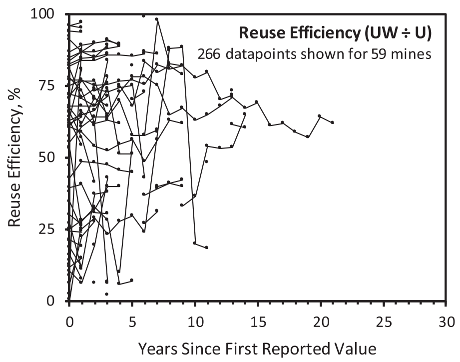


**Fig. 6.** Water reuse efficiency of mines through time. Calculated as worked water use (UW) divided by total water use (U; raw plus worked), expressed as a percentage. Breaks in data series indicate periods of no reporting.

potential for inconsistencies in the reporting definitions between companies and through time when analysing water use data for the industry.

Many mines and mineral processing facilities are effectively zero discharge operations, as evaporation from dams and water storages may be sufficient to prevent the accumulation of water on-site. As a result, many mining operations may not have reportable discharges. However, the absence of water discharges is still a valuable piece of information to communicate to stakeholders. Where a mine does not report any information on discharges, then stakeholders are unable to evaluate whether no discharges from with are occurring, or whether the discharges do occur, but the company isn't reporting these. Therefore, it is recommended that companies report against all major water categories, even when these flows are zero, as this provides stakeholders with a more complete understanding of site water balances.

It is also possible to evaluate how reporting changes when a mining operation is bought, sold or incorporated into another mining company. Examples of this include reporting changes associated with transfer of operations between Oxiana, OZ Minerals and MMG. In these cases, there are periods of time where only half-year reported data was available for mining operations whose ownership was being transferred. The merger of Xstrata and Glencore also provides another opportunity to understand the influence of company structure and reporting practices on the disclosure of data for individual mine sites. Water use data was available for Xstrata at various levels of aggregation. Generally, a lot of data were available for individual operations and divisional aggregations. However, upon merger with Glencore, the reporting practices largely took on those of Glencore and much of the site-based data reporting subsequently ceased. In both these cases, presumably the same detail of water flow monitoring and metering was being undertaken by the mine site personnel, merely the type of public disclosures changed due to corporate transitions.

Very few companies or operations report detailed information on the ultimate destination or sinks of water being consumed. Previous analyses have shown that the rates and balance between different modes of water consumption (e.g. evaporation, tailings entrainment, etc.) can vary significantly between operations and is heavily influenced by local climate, ore characteristics, processing conditions, tailings characteristics, water storage and waste management practices [6,8,13,16,18,23,24,29,44]. The MCA's [21] and ICMM's [15] water accounting standards provide guidelines for the reporting of specific modes of water consumption. The implementation of these appears to be responsible for the increased reporting of water consumption categories in recent years (Table 4). Measurement of water flows and losses can be difficult in practice, and so the standards also provide guidance on communicating the confidence levels associated with reported flows (i.e. high, medium or low) and their quantification method (i.e. measured, estimated or simulated) as part of an accuracy statement. Only limited reporting to date has included accuracy statements alongside reported data.

Some additional data was also collected for process variables, such as ore moisture contents and tailings thickener underflow solids densities, which are important for understanding internal rates of water reuse and the amount of water entering tailings storage facilities (Tables 2 and 3). There is limited public reporting of these variables in environmental management and sustainability reporting, partially because mining companies may view these as having limited value for external stakeholders and measurements can be highly very variable through time.

### 3.4. Types of water disclosures not captured in the database

There are significant additional data on water related aspects of mining operations that were not captured in the data compilation efforts. Large quantities of water quality monitoring data are available for some mining operations available as part of environmental management and regulation compliance reporting. The water quality implications of mining operations are highly site specific and so monitoring activities must be tailored to the local situation. This monitoring may be quite varied but will commonly include monitoring of upstream or downstream surface water quality, bore water levels and quality, and sediment samples. The exact monitoring requirements will depend heavily upon local environmental regulation and the specific risks associated with the operation, which is a dependent upon a range of factors such as mine type, geochemistry, climate and site management practices. Due to this, the water quality parameters reported by mining companies vary considerably, but will generally include pH, total dissolved solids (TDS), total suspended solids (TSS), conductivity, ferric or ferrous ions, or specific metal cations or anions relevant to the risks of the project and downstream ecology. Generally, specific water quality targets at particular locations or points downstream of a mining operation are defined by environment regulatory authorities and so mining operations conduct monitoring to ensure compliance with these targets. Historically, this monitoring has been manually conducted and often with limited frequency. However, approaches and instrumentation to enable more frequent and automated capture of water quality data are increasingly being implemented in the industry.

Long-term water quality baseline data for periods prior to commencement of mining may not be available in all cases. As a result, it can be difficult to determine how individual mining operations are influencing regional water quality. This then complicates efforts to attribute observed water quality impacts to a mining operation, especially when there are cumulative impacts from other nearby mining operations, land-uses changes or competing water users such as agriculture.

Limited data on local water contexts is included within mining company sustainability reporting. The most notable example is from Rio Tinto's reporting in the late 1990s and early 2000s, where reported water consumption by operations was grouped according to climate zones. This lack of local context in sustainability reporting is being addressed by the ICMM's [15] recent water reporting guidelines, which outline approaches for evaluating and reporting the local catchment setting and water risks facing mining operations. In recent years, studies have begun to report on how the global mining industry is distributed in relation to a range of climatic and water risks, such as water scarcity [31–33]. It is anticipated that this type of information will increasingly be communicated by the mining industry.

### 3.5. Implications for water footprint and life cycle assessment studies

Water footprint and life cycle assessment-based studies of the mining industry have sought to understand the magnitude in terms of volumetric consumption and potential impacts of water consumption associated with producing mined products [27,29,30,35,38]. However, Santero and Hendry [39] determined that water scarcity impacts should not be reported for life cycle assessment studies of metal production due to limitations in inventory data and impact assessment methods. Therefore, there is a need for improved data sources to enable adequate assessment of water consumption occurring throughout the global mining industry. There is also a need to develop models that reliably determine environmental impact. The data collected by this study provides a starting point for improving water consumption data present in life cycle inventories of mined products. Additional work is required to improve the industry coverage, incorporate production and co-production data, and to translate the water source and water quality categories of this study into the equivalent data categories that are used by LCA.

Recent assessments of the spatial distribution of mining operations in relation to water use impact characterisation factors demonstrate the value of watershed-based impact assessment [31,32]. Therefore, water use inventories for the mining industry should ideally be developed and presented on a site-by-site basis. However, if inventory developers are required to aggregate mine site inventories to avoid disclosing commercially sensitive information, then we strongly encourage that watershed, rather than national, boundaries of aggregation are utilised. This is due to a bias for existing national average water use impact characterisation factors to, on average, overestimate water use impacts for the mining industry when compared with watershed based assessment [32]. In addition, inventory data to determine indirect water use impacts should also be developed and additional life cycle impact categories (e.g. climate change, toxicity, etc.) should also be assessed and presented alongside water use impacts.

### 3.6. Further work

The current research has only captured a fraction of the available water related data being publicly reported by the mining industry. Further work could be undertaken to expand the industry coverage of the dataset to include the reporting of a greater number of mining companies. These data compilation efforts are highly time consuming, however once compiled, the data is very valuable for future research efforts. Considerable reported data also exists for other aspects of relevance to sustainable development-oriented research that is yet to be compiled and analysed in detail. This includes material and reagent consumption data, waste generation, land occupancy and transformations (i.e. disturbance, rehabilitation). Additionally, there is significant amounts of information being reported by the industry at mining industry conferences, and in technical literature more generally, that if compiled in a systematic way would be a very valuable data source for understanding technology deployment, resource efficiency and the impacts of the mining industry. We encourage other researchers to compile and analyse data contained within mining industry reporting, so that the data limitations faced by many current analyses of the industry can be overcome. Any researchers who wish to collaborate to extend the database to include greater industry coverage, additional data categories or perform derivative analyses are encouraged to contact the authors.

Substantial amounts of water use data are also available for the mining industry that have been aggregated to the level of national or state economic sectors (e.g. [47]). With further data compilation for mining operations in individual regions, this highly aggregated data for economic sub-sectors could potentially be used in conjunction with mine-by-mine data to better understand the magnitude of water use data that is not being publicly reported by the industry.

Data is available suggesting improvements to water use efficiency overtime in the Chilean copper sector [19]. However, there is limited understanding of whether similar trends would be observed in other regions. Based upon the compiled dataset, additional work is required to: 1. combine the dataset with production statistics (e.g. ore throughputs, production rates, recovery factors, etc.) and climate data, 2. classify mine site processing routes and waste management techniques, and 3. use this to develop a nuanced understand of the drivers and trends of water use efficiency in the industry. These drivers are diverse and may include: process related constraints, local weather and climatic factors, water stress and availability in regions, drought and flood recurrence frequency, regulatory factors or societal pressures. Systematic evaluation of how water use in the industry varies in relation to these drivers would enable the development of meaningful schemes for benchmarking water use efficiency in the industry. This would also aide in the assessment of regional water use allocations and the economic value generated by water use in the mining industry [34].

## 4. Conclusions

Effective management of water resources requires a firm understanding of how water is used and consumed in different sectors of the economy. Despite the importance of the mining industry to many regional and national economies, there is still limited understanding of the magnitude and variability of water consumption between mining regions. Due to this limitation, it is difficult to determine what is an appropriate or acceptable level of water consumption for any individual mining operation. Assessing progress in water use efficiency in the mining industry requires the development of benchmark statistics to enable fair and meaningful comparison of water use at different mine sites.

In this article, we have demonstrated that considerable amounts of water use data are being publicly reported by the mining industry. Research efforts to compile and analyse these forms of water use disclosures have the potential to significantly improve our understanding of how the mining industry interacts with water resources, both at an individual site level and across regions and industry sub-sectors. For instance, it was identified that all major components of individual mining operation water balances can vary significantly between both operations and through time. Opportunities exist for further work to improve industry coverage, to develop datasets suitable for water footprinting and life cycle assessment, and to develop water use efficiency benchmarking schemes for the mining industry.

Further implementation of the water accounting and reporting schemes available for the mining industry is encouraged to improve the comprehensiveness and consistency of industry reporting. Increased public disclosure of mine-water interactions has value for investors, communities, regulators and the mining industry itself. Compilation and analysis of these disclosures can provide valuable insights regarding water risks in the mining industry, water management outcomes and the potential contribution of the mining industry to meeting the UN's Sustainable Development Goals.

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## Electronic supplementary material

The 'Database of Publicly Reported Water Data by the Mining Industry v1.0′ is available in an excel format (.xlsx) as accompanying electronic supplementary material to this article.

## Declaration of interest

The authors declare no competing interests.

## Appendix A. – Definition of data point classifications

see: Tables A1–A4

**Table A1**
Aggregation level definition and implementation notes.

| Aggregation | Definition | Implementation Notes |
|---|---|---|
| Company | Value provided for entire company or major subsidiary company. | – |
| Division | Value provided for a mining company division that includes multiple distinct operations. | – |
| Operation | Value for a single mining and mineral processing or metal production operation. | – |

**Table A2**
Data category definitions and implementation notes.

| Data Category | Definition | Implementation Notes |
|---|---|---|
| **Water Consumption** | | |
| C \| Consumption | Total water consumed and not directly returned to surrounding surface water, marine water or groundwater systems. | – |
| CEn \| Entrainment | Water lost to entrainment within product, tailings, heaps or waste rock piles. | – |
| CEnP \| Product | Water entrained in product(s). | – |
| CEnT \| Tailings | Water entrained in settled tailings. | – |
| CEv \| Evaporation | Total water evaporation. | – |
| CEvTB \| TSF Beach | Evaporation from the beach of a tailings storage facility. | – |
| CEvTD \| TSF Decant | Evaporation from a tailings storage facility decant pond. | – |
| CEvW \| Water Dam | Evaporation from a water storage dam. | – |
| CO \| Other | Total consumption not specified elsewhere | – |
| COD \| Dust Suppression | Water applied to surfaces to prevent dust generation. In most cases this could be assumed to evaporate. | – |
| COO \| Other | Consumption not specified elsewhere. | – |
| COV \| Vent Losses | Evaporative losses from ventilation shafts. | – |
| **Water Discharges** | | |
| D \| Discharges | Discharges or flows to surface water, marine water and ground water systems, or transferred to third parties. | – |
| DG \| Groundwater | Recharge of groundwater aquifers. | – |
| DGA \| Aquifer Reinjection | Discharge to groundwater aquifers through injection wells. | – |
| DGS \| Seepage | Seepage to groundwater aquifers. | – |
| DM \| Marine | Total discharge to marine water systems [estuaries (DME) & oceans (DMS)]. | – |
| DME \| Estuary Discharge | Water discharged to an estuary (sea-river brackish zone). | – |
| DMS \| Sea / Ocean Discharge | Water discharged to sea or ocean. | – |
| DO \| Other | Discharge with an unknown destination or not accounted for elsewhere. | – |
| DS \| Surface Water | Total discharges to surface water systems. | – |
| DSD \| Surface Discharges | Discharges to a creek or river system, excluding discharges specifically to meet environmental flows. | – |
| DSE \| Environmental Flows | Discharges to a creek or river system specifically to maintain environmental flows. | – |
| DSS \| External Storage | Discharge to an external storage system, such as a lake or dam. | – |
| DT \| Thirdparty | Discharges or transfer of water to a third-party (e.g. community, company, etc.) | – |
| **Total Water Outputs** | | |
| O \| Outputs (D + C) | Sum of water consumption and discharges. | – |
| **Water Storage and Accumulation** | | |
| SA \| Accumulation | Water accumulated in on-site storage (dams, pits, tanks, etc.) over the period. | – |
| SC \| Storage Capacity | Water storage capacity of a dam, pit, tank or other on-site reservoir. | Typically specified for a specific infrastructure item outlined in the data comment. |

(*continued on next page*)

**Table A2** (*continued*)

| Data Category | Definition | Implementation Notes |
|---|---|---|
| SE \| Storage at End of Period | Water stored at the end of the time period. | Typically specified for a specific infrastructure item outlined in the data comment. |
| SS \| Storage at Start of Period | Water stored at the start of the time period. | Typically specified for a specific infrastructure item outlined in the data comment. |
| **Internal Water Use** | | |
| U \| USE | Total water use, sum of raw and worked water. | – |
| UM \| Raw | 'Make-up', 'raw' or previously unused water utilised by site processes | Percentage values provided as a fraction of total water use ('U'). Many data points recalculated to ensure consistency. |
| UW \| Worked | Sum of recycled (UWRec) and reused (UWReu) water. | Percentage values provided as a fraction of total water use ('U') Many data points recalculated to ensure consistency. |
| UWRec \| Recycled | Recycled (treated) water. | Percentage values provided as a fraction of total water use ('U') Many data points recalculated to ensure consistency. |
| UWReu \| Reused | Reused (untreated) water. | Percentage values provided as a fraction of total water use ('U') Many data points recalculated to ensure consistency. |
| **Other Water Related Variables or Flows** | | |
| Div \| Diversion | Water diverted around mine site infrastructure. | – |
| VOMC \| Ore Moisture Content | Moisture content of mined ore. | Typically, a percentage on a weight per dry weight basis. |
| VP \| Pan Evaporation | Pan evaporation over the period. | Units are typically in 'mm' or occasionally 'mm/day'. |
| VR \| Rainfall | Rainfall over the period. | |
| VS \| Size of Affected Water Source | Size of affected water sources affected by operations. | Included as it is a GRI reporting category. However, data captured appears to be methodologically inconsistent and have limited practical value. |
| VTSD \| Tailings Solids Density | Solids density of tailings thickener underflow or tailings discharged to a storage facility. | Typically, a percentage on a weight per dry weight basis. |
| **Water Withdrawals / Inputs / Abstractions** | | |
| W \| Withdrawals | Total water withdrawn | – |
| WG \| Groundwater | Water abstracted from a groundwater aquifer | – |
| WGA \| Aquifer Interception | Infiltration of groundwater into site infrastructure (open pits, underground mine voids, dams, etc.) | – |
| WGB \| Borefields | Abstraction of groundwater via bores. | – |
| WGE \| Entrainment | Groundwater entrained in mined ore or waste rock. | – |
| WM \| Marine | Water abstracted from sea, ocean and estuary environments. | – |
| WME \| Estuary | Abstraction of water from estuaries or brackish sea-river zones. | – |
| WMS \| Sea_Ocean | Abstraction of water from the sea or ocean. | – |
| WS \| Surface Water | Abstraction of water naturally open to the atmosphere, excluding sea, ocean and estuary waters. | When a company report specifies both 'rainfall' and 'surface water' abstraction, surface water is assigned to WSR and 'rainfall' is assigned to WSP. |
| WSP \| Precipitation & Runoff | Captured precipitation (rain, snow or hail) and surface runoff. | – |
| WSR \| Rivers and Creeks | Water abstracted from a river or creek. | – |
| WSS \| External Storage | Water abstracted from an external storage, such as a lake or dam. | – |
| WT \| Thirdparty | Water supplied by a third-party entity or through a long-distance pipeline. | – |
| WTC \| Contract or Municipal | Water purchased/transferred from a third-party or municipality / township. | – |
| WTW \| Wastewater Effluent | Wastewater effluent (treated or untreated) purchased/ transferred from a third-party. | – |

**Table A3**
Data type classification definitions and implementation notes.

| Data Type | Definition | Implementation Notes |
|---|---|---|
| Reported_Value | Data point value presented directly in the reference. | – |
| Reported_GraphReading | Data point value read from a graph in the reference. | Graph readings were aided by software to improve accuracy. |
| Inferred_or_Calculated | Data point value that was inferred or calculated from other data in the reference, or that was recalculated to ensure consistency with data category definitions. | Commonly used when data is converted between a percentage or volumetric basis, or an intensity (litres per tonne) and volumetric basis. Commonly also used where a value for a data category can be inferred from values available for other data categories (e.g. summing raw water (UM) and worked water (UW) to obtain a total water use value (U)). |
| Best_Estimate | Data point value was estimated coarsely based upon other information in the reference. | Coarse data estimates were typically avoided. |

**Table A4**
Water quality category definitions and implementation notes.

| Water Quality Category | Definition | Implementation Notes |
|---|---|---|
| 1 \| Near Potable | Water that is close to drinking water standards. | Assigned when the WAFMI [21] water quality category definitions have specifically been used. Or else when water quality descriptors or parameters are provided that strongly suggest likely compliance with the definition. |
| 2 \| Suitable for Some Uses | Water that is suitable for some end uses, such as agriculture. | Assigned when the WAFMI [21] water quality category definitions have specifically been used. Or else when water quality descriptors or parameters are provided that strongly suggest likely compliance with the definition. |
| 3 \| Unsuitable for Most Uses | Water that is unsuitable for most end-uses. May be defined as TDS $> 5000$ mg/L, pH $< 4$ or $> 10$, or constituent concentrations are harmful to human health. | Assigned when the WAFMI [21] water quality category definitions have specifically been used. Or else when water quality descriptors or parameters are provided that strongly suggest likely compliance with the definition. |
| T \| Total | Total water; sum of category 1,2 & 3 water. | Most data points have been assigned this category unless quality categories or parameters were specified in the reporting. |
| U \| Unknown | Unknown water quality. | Typically, only assigned when multiple water quality descriptors have been used in the reporting and it is unclear how to assign a value. |
| N \| Not Applicable | A water quality category cannot be applied to the data category. | – |

The tables in this Appendix A provide definitions for the various classification categories assigned to each data point.

## Appendix B. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.wri.2018.100104.

## References


[1] T.M. Aksham, H.M. Van der Poll, Water sustainability of selected mining companies in South Africa, Sustainability 9 (2017) 957, https://doi.org/10.3390/su9060957.
[2] M.J. Botha, S.L. Middelberg, Evaluating the adequacy of water-related reporting and disclosure by high-impact users in South Africa, J. Environ. Assess. Policy Manag. 18 (1) (2016) 1650003, https://doi.org/10.1142/S1464333216500034.
[3] B. Buchspies, L. Thormann, C. Mbohwa, M. Kaltschmitt, PGE production in Southern Africa, Part II: environmental aspects, Minerals 7 (2017) 225, https://doi.org/10.3390/min7110225.
[4] R.J. Cocks, G.E. Ho, M. Anda, S. Dallas, An assessment of Kalgoorlie Consolidated Gold Mines and Boddington Gold Mine water sources and proposed water auditing framework underpinning improved water allocation compliance and reporting, Min. Technol. 118 (3/4) (2009) 225–231, https://doi.org/10.1179/174328610X12682159815145.
[5] A.N. Danoucaras, A.P. Woodley, C.J. Moran, The robustness of mine water accounting over a range of operating contexts and commodities, J. Clean. Prod. 84 (2014) 727–735, https://doi.org/10.1016/j.jclepro.2014.07.078.
[6] M. Donoso, P.A. Robles, E.D. Gálvez, L.A. Cisternas, Particle size effect on the efficient use of water and energy in mineral concentration processes, Ind. Eng. Chem. Res. 52 (2013) 17686–17690, https://doi.org/10.1021/ie402099n.
[7] A. Fonseca, M.L. McAllister, P. Fitzpatrick, Sustainability reporting among mining corporations: a constructive critique of the GRI approach, J. Clean. Prod. 84 (2014) 70–83, https://doi.org/10.1016/j.jclepro.2012.11.050.
[8] L. Gao, B.A. Bryan, J. Liu, W. Li, Y. Chen, R. Liu, D. Barrett, Managing too little and too much water: robust mine-water management strategies under variable climate and mine conditions, J. Clean. Prod. 162 (2017) 1009–1020, https://doi.org/10.1016/j.jclepro.2017.06.101.
[9] B.J. Glaister, G.M. Mudd, The environmental costs of platinum – PGM mining and sustainability: is the glass half-full or half-empty? Miner. Eng. 23 (2010) 438–450, https://doi.org/10.1016/j.mineng.2009.12.007.
[10] GRI, G4 Sustainability Reporting Guidelines: Reporting Principles and Standards Disclosures, Global Reporting Initiative (GRI), Amsterdam, Netherlands, 2013.
[11] GRI, G4 Sector Disclosures - Mining and Metals Sector Disclosures, Global Reporting Initiative (GRI), Amsterdam, Netherlands, 2013.
[12] A.J. Gunson, Quantifying, Reducing and Improving Mine Water Use (Ph.D. Thesis), The University of British Columbia, 2013, p. 285.
[13] A.J. Gunson, B. Klein, M. Veiga, S. Dunbar, Reducing mine water requirements, J. Clean. Prod. 21 (2012) 71–82, https://doi.org/10.1016/j.jclepro.2011.08.020.
[14] E.A. Holley, C. Mitcham, The Pebble Mine Dialogue: a case study in public engagement and the social license to operate, Resour. Policy 47 (2016) 18–27, https://doi.org/10.1016/j.resourpol.2015.11.002.
[15] ICMM, A Practical Guide to Consistent Water Reporting, International Council on Mining & Metals (ICMM), 2017 (Last accessed 26 February 2018) Available from: 〈https://www.icmm.com/water-disclosure-standard〉.
[16] C.F. Ihle, W. Kracht, The relevance water recirculation in large scale mineral processing plants with a remote water supply, J. Clean. Prod. 177 (2018) 34–51, https://doi.org/10.1016/j.jclepro.2017.12.219.
[17] H. Jenkins, N. Yakovleva, Corporate social responsibility in the mining industry: exploring trends in social and environmental disclosure, J. Clean. Prod. 14 (2006) 271–284, https://doi.org/10.1016/j.jclepro.2004.10.004.
[18] N.C. Kunz, C.J. Moran, The utility of a systems approach for managing strategic water risks at a mine site level, Water Resour. Ind. 13 (2016) 1–6, https://doi.org/10.1016/j.wri.2016.02.001.
[19] G. Lagos, D. Peter, A. Videla, J.J. Jara, The effect of mine aging on the evolution of environmental footprint indicators in the Chilean copper mining industry 2001–2015, J. Clean. Prod. 174 (2018) 389–400, https://doi.org/10.1016/j.jclepro.2017.10.290.
[20] S. Leong, J. Hazelton, R. Taplin, W. Timms, D. Laurence, Mine site-level water reporting in the Macquarie and Lachlan catchments: a study of voluntary and mandatory disclosures and their value for community decision-making, J. Clean. Prod. 84 (2014) 94–106, https://doi.org/10.1016/j.jclepro.2014.01.021.
[21] MCA, Water Accounting Framework for the Minerals Industry, User Guide, Version 1.3, Minerals Council of Australia (MCA), 2014 Available from: 〈www.minerals.org.au/leading_practice/water_accounting_framework_for_the_australian_minerals_industry〉 (last accessed 5 February 2018).
[22] MCA, WAF-MCA Member Explanatory Note, Minerals Council of Australia (MCA), 2014 Available from: 〈www.minerals.org.au/leading_practice/

water_accounting_framework_for_the_australian_minerals_industry> (last accessed 5 February 2018).
[23] P.A. Moreno, H. Aral, J. Cuevas, A. Monardes, M. Adaro, T. Norgate, W. Bruckard, The use of seawater as process water at Las Luces copper-molybdenum beneficiation plant in Taltal (Chile), Miner. Eng. 24 (2011) 852–858, https://doi.org/10.1016/j.mineng.2011.03.009.
[24] A.H. Mwale, P. Musonge, D.M. Fraser, The influence of particle size on energy consumption and water recovery in comminution and dewatering systems, Miner. Eng. 18 (2005) 915–926, https://doi.org/10.1016/j.mineng.2005.02.014.
[25] G.M. Mudd, Sustainability reporting and water resources: a preliminary assessment of embodied water and sustainable mining, Mine Water Environ. 27 (2008) 136–144, https://doi.org/10.1007/s10230-008-0037-5.
[26] G.M. Mudd, The environmental sustainability of mining in Australia: key mega-trends and looming constraints, Resour. Policy 35 (2) (2010) 98–115, https://doi.org/10.1016/j.resourpol.2009.12.001.
[27] T.E. Norgate, R.R. Lovel, Sustainable water use in minerals and metal production. Proceedings of Water in Mining Conference 2006, Brisbane, QLD, Australia: 331-339, 2006.
[28] S. Northey, N. Haque, G. Mudd, Using sustainability reporting to assess the environmental footprint of copper mining, J. Clean. Prod. 40 (2013) 118–128, https://doi.org/10.1016/j.jclepro.2012.09.027.
[29] S.A. Northey, N. Haque, R. Lovel, M.A. Cooksey, Evaluating the application of water footprint methods to primary metal production systems, Miner. Eng. 69 (2014) 65–80, https://doi.org/10.1016/j.mineng.2014.07.006.
[30] S.A. Northey, G.M. Mudd, E. Saarivuori, H. Wessman-Jääskeläinen, N. Haque, Water footprinting and mining: where are the limitations and opportunities? J. Clean. Prod. 135 (2016) 1098–1116, https://doi.org/10.1016/j.jclepro.2016.07.024.
[31] S.A. Northey, G.M. Mudd, T.T. Werner, S.M. Jowitt, N. Haque, M. Yellishetty, Z. Weng, The exposure of global base metal resources to water criticality, scarcity and climate change, Glob. Environ. Change 44 (2017) 109–124, https://doi.org/10.1016/j.gloenvcha.2017.04.004.
[32] S.A. Northey, C. Madrid Lopez, N. Haque, G.M. Mudd, M. Yellishetty, Production weighted water use impact characterisation factors for the global mining industry, J. Clean. Prod. 184 (2018) 788–797, https://doi.org/10.1016/j.jclepro.2018.02.307.
[33] S.D. Odell, A. Bebbington, K.E. Frey, Mining and climate change: a review and framework for analysis, Extr. Ind. Soc. (2018), https://doi.org/10.1016/j.exis.2017.12.004.
[34] J. Ossa-Moreno, N. McIntyre, S. Ali, J.C.R. Smart, D. Rivera, U. Lall, G. Keir, The Hydro-economics of Mining, Ecol. Econ. 145 (2018) 368–379, https://doi.org/10.1016/j.ecolecon.2017.11.010.
[35] C.A. Peña, M.A.J. Huijbregts, The blue water footprint of primary copper production in Northern Chile, J. Ind. Ecol. 18 (1) (2014) 49–58, https://doi.org/10.1111/jiec.12036.
[36] F. Perez, L.E. Sanchez, Assessing the evolution of sustainability reporting in the mining sector, Environ. Manag. 43 (2009) 949–961, https://doi.org/10.1007/s00267-008-9269-1.
[37] J. Prno, An analysis of factors leading to the establishment of a social license to operate in the mining industry, Resour. Policy 38 (2013) 577–590, https://doi.org/10.1016/j.resourpol.2013.09.010.
[38] N. Ranchod, C.M. Sheridan, N. Pint, K. Slatter, K.G. Harding, Assessing the blue-water footprint of an opencast platinum mine in South Africa, Water SA 41 (2) (2015) 287–293, https://doi.org/10.4314/wsa.v41i2.15.
[39] N. Santero, J. Hendry, Harmonization of LCA methodologies for the metal and mining industry, Int. J. Life Cycle Assess. 21 (2016) 1543–1553, https://doi.org/10.1007/s11367-015-1022-4.
[40] K. Spitz, J. Trudinger, Mining and the Environment: From Ore to Metal, CRC Press, 2009.
[41] S. Thomashausen, N. Maennling, T. Mebratu-Tsegaye, A comparative overview of legal frameworks governing water use and waste water discharge in the mining sector, Resour. Policy (2018), https://doi.org/10.1016/j.resourpol.2017.11.012.
[42] United Nations, Transforming Our World: The 2030 Agenda for Sustainable Development, (2015) (last accessed 10 April 2018), <https://sustainabledevelopment.un.org/post2015/transformingourworld>.
[43] UNDP. Mapping Mining to the SustainableDevelopment Goals: An Atlas. White Paper. United Nations Development Programme (UNDP), Columbia Centre for Sustainable Development, United Nations Sustainable Solutions Network, World Economic Forum. <http://www3.weforum.org/docs/IP/2016/IU/Mapping_Mining_SDGs_An_Atlas.pdf> (last accessed 10 April 2018).
[44] C. Wels, A. Robertson, Conceptual model for estimating water recovery in tailings impoundments. In: Tailings and Mine Waste, Proceedings of the Tenth International Conference (Colorado State University, October 12), 15: 87-94, 2003.
[45] H. Wessman, O. Salmi, J. Kohl, P. Kinnunen, E. Saarivuori, U.-M. Mroueh, Water and society: mutual challenges for eco-efficiency and socially acceptable mining in Finland, J. Clean. Prod. 84 (2014) 289–298, https://doi.org/10.1016/j.jclepro.2014.04.026.
[46] N. Yakovleva, J. Kotilainen, M. Toivakka, Reflections on the opportunities for mining companies to contribute to the United Nations Sustainable Development Goals in sub-Saharan Africa, Extr. Ind. Soc. 4 (2017) 426–433, https://doi.org/10.1016/j.exis.2017.06.010.
[47] C. Zhang, L.D. Anadon, Life cycle water use of energy production and its environmental impacts in China, Environ. Sci. Technol. 47 (2013) 14459–14467, https://doi.org/10.1021/es402556x.