Final Report: Water Use and Risks in Mining

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Summary:

1. Overview

The mining industry can be a major consumer of water as well as presenting significant risks to water resources – all of which can contribute to the financial (and social and environmental) costs or impacts of mining. Water resource risks related to mining are often a key area of community concern. Whilst there is widespread recognition of the need for the mining industry to be responsible in its approach to water resources and mine site water management, there is very little academic literature which analyses in detail the amount of water used by various mining projects, especially the links between water use and the local climate regime and the financial costs of water management. Over recent years, however, there is a growing wealth of water-related data being reported by mines and mining companies, often through regulatory reporting but commonly through sustainability and related styles of corporate reporting and disclosures (e.g. Global Reporting Initiative or GRI; CDP Water). In this report, we outline research work for the Columbia Water Center which compiles an extensive database of water use in mining and land use mapping information to address this weakness in the literature.

2. Methods

Our approach to compiling data is based on standard industry and academic practice and the wide availability of data from public corporate reporting. The overall approach is based on life cycle assessment methodology (i.e. input-output analysis).

- *Mine Production:* all data is sourced from company annual or quarterly reporting (and sometimes sustainability reporting). Data collected is on an annual basis and includes ore processed, ore grades, concentrates produced, metals extracted and waste rock excavated. Data is only collected for the years of relevant water data. For a range of mines, complete historical production statistics are compiled to estimate cumulative production to the year of the imagery used for land use mapping (see below).
- *Land Use Area:* all data is mapped using Google Earth, with key features of mining projects outlined in polygons, including open pits, waste rock dumps (WRD's), tailings storage facilities (TSF's), infrastructure (mill, workshops, roads, miscellaneous buildings), water ponds, heap leach piles (HLP's). These areas are then related to annual or cumulative production data, and allows an estimate of the areal footprint of a mine, which can be used for water aspects (e.g. flood risk for TSFs, evaporation rates, groundwater sinks from former pits, etc), or other aspects (e.g. biodiversity). All site features have been verified using technical or corporate reports for each mine (e.g. distinguishing WRD's from HLP's). An example of outlining is shown in Figure 1. Where satellite imagery in Google Earth is poor resolution, other sources were used, such as site technical reports (e.g. Canadian-based NI43-101 reports), websites (especially aerial imagery) or technical and academic literature (e.g. conference or journal papers).
- *Water Use:* based on sustainability reporting by many mining companies, we add detailed water data to each year of production for a given mine. Specifically, we account for water inputs and their source (groundwater, surface water, marine or third party supplied), use (raw water, worked or recycled water) and any discharges to the environment. The framework is based on a detailed analysis of a typical mine's imports and exports of water, effectively giving a water balance for a given mining project. This is outlined in detail in Appendix 1, with the overall approach shown in Figure 2 below.
- *Mine Case Studies and Examples:* where possible, specific case studies have been compiled to show the impact of poor water management on mine production costs. These are intended to be indicative only, but they do highlight the potential costs due to an accident (e.g. TSF failure), poor engineering design, major storm event (e.g. open pit or underground mines flooding) or lack of water supplies – it must be remembered that all mine sites are unique in their design, construction and operation with respect to water risks, and this variability must be considered in assessing the financial implications of such water risks. In addition, we compile a range of examples of costs to mines due to a variety of reasons (as noted above). Overall, the case studies complement the detailed production, water use and mapping data.

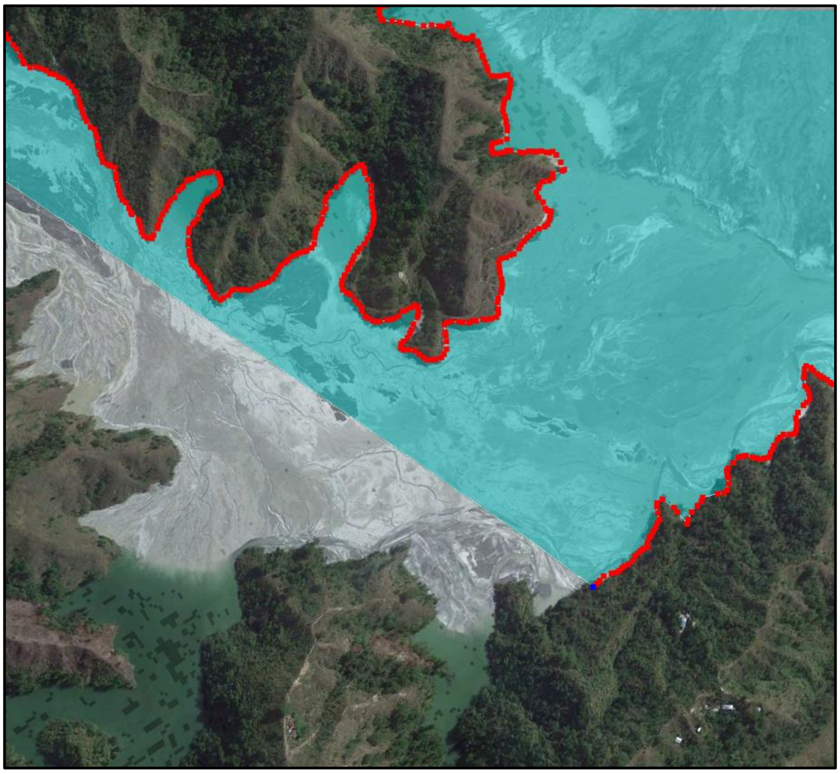
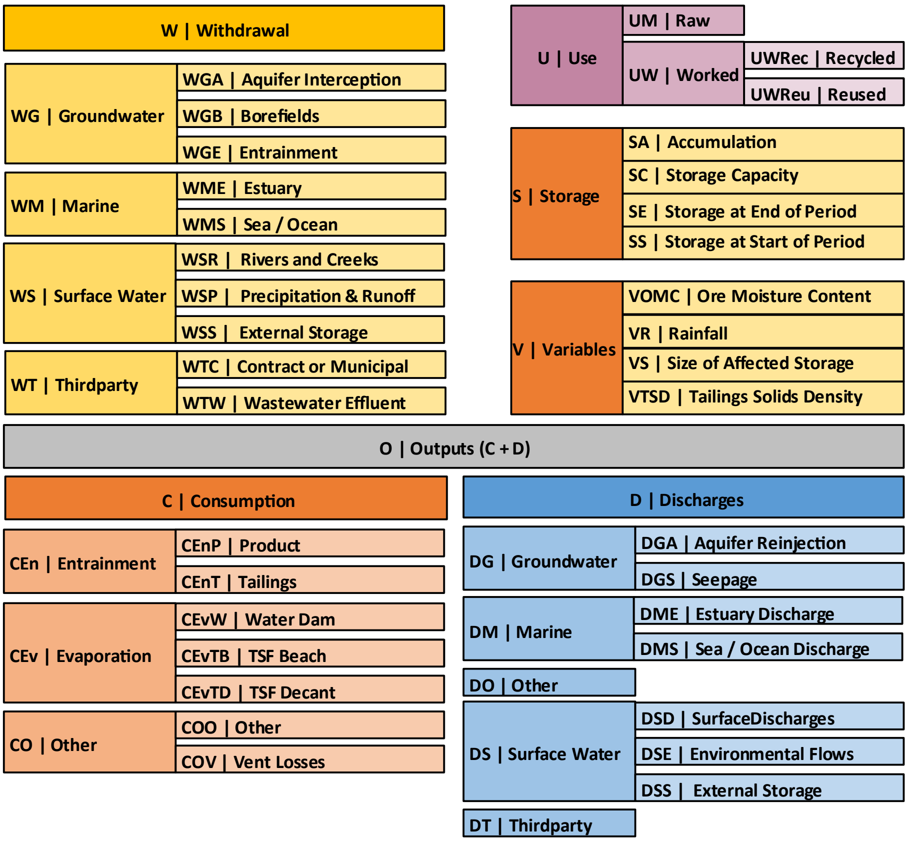


Figure 1: Example delineation of a tailings dam area at the Padcal Cu mine, Philippines (Google Earth image date 15 April 2017; co-ordinates approximately 16° 14’ 26.16” N, 120° 40’ 12.07” E)



- W | Withdrawal
  - WG | Groundwater
    - WGA | Aquifer Interception
    - WGB | Borefields
    - WGE | Entrainment
  - WM | Marine
    - WME | Estuary
    - WMS | Sea / Ocean
  - WS | Surface Water
    - WSR | Rivers and Creeks
    - WSP | Precipitation & Runoff
    - WSS | External Storage
  - WT | Thirdparty
    - WTC | Contract or Municipal
    - WTW | Wastewater Effluent
- U | Use
  - UM | Raw
  - UW | Worked
    - UWRec | Recycled
    - UWReu | Reused
- S | Storage
  - SA | Accumulation
  - SC | Storage Capacity
  - SE | Storage at End of Period
  - SS | Storage at Start of Period
- V | Variables
  - VOMC | Ore Moisture Content
  - VR | Rainfall
  - VS | Size of Affected Storage
  - VTSD | Tailings Solids Density
- O | Outputs (C + D)
- C | Consumption
  - CEn | Entrainment
    - CEnP | Product
    - CEnT | Tailings
  - CEv | Evaporation
    - CEvW | Water Dam
    - CEvTB | TSF Beach
    - CEvTD | TSF Decant
  - CO | Other
    - COO | Other
    - COV | Vent Losses
- D | Discharges
  - DG | Groundwater
    - DGA | Aquifer Reinjection
    - DGS | Seepage
  - DM | Marine
    - DME | Estuary Discharge
    - DMS | Sea / Ocean Discharge
  - DO | Other
  - DS | Surface Water
    - DSD | SurfaceDischarges
    - DSE | Environmental Flows
    - DSS | External Storage
  - DT | Thirdparty

Figure 2: Key data categories included in the mine water reporting database, which was largely based upon the reporting categories outlined by MCA (2014) and ICMM (2017) (see Appendix 1 for further details)

3. Results

3.1 Water Use

The detailed database of water use reported by mining companies is provided as a Digital Appendix to this report, with the key metrics shown in Table 1. As can be observed, there is considerable variability between mine sites, even for some very close to each other. For example, the extent of worked (recycled) water use varies from 0% (Porgera, Au), to 96% (Spence, Cu). For the adjacent mines of Radomiro Tomic and Chuquicamata in northern Chile, the intensity of raw water use varies from 0.10 to 1.04 kL/t ore, respectively, while worked (recycled) water use is also 0.29 to 0.59 kL/t ore, respectively. There are also somewhat unexpected examples, such as the high fraction of worked water use (69.7%) at the Ok Tedi (Cu-Au-Ag) mine in the tropical highlands of Papua New Guinea or the extent of discharged waters at the Antamina (Cu-Zn-Ag-Mo) mine in Peru or El Teniente (Cu-Mo-Au-Ag) mine in Chile – despite the modest rainfall.

There are many factors which could explain this wide variability, such as ore type and hardness, process configuration (mine-mill, mine-heap, the presence of a smelter and/or refinery), water quality, climate regime (annual rainfall and evaporation rates), slurry densities during processing and tailings disposal, ore grades, mine age, water infrastructure and design, costs, regulatory conditions, community concerns and issues (especially adjacent communities which are reliant on water resources, especially agriculture) and policy considerations. On the basis of the data compiled, it is difficult at present to discern any principal factors which appear the most dominant in affecting water use. This will be the subject of further analyses as this work is prepared for academic publications.

3.2 Land Use

Examples of the mapping of selected mines are shown below, including the Frontier Cu mine in Zambia in Figure 3 before and after development and the Escondida and Zaldivar Cu mines in northern Chile mapped in Figure 4.

The results for land use versus cumulative mine production are given Figures 5 and 6 and in the digital appendices, showing the expected result that as mines get larger in rock mined, the area of open cuts, tailings storage facilities and waste rock dumps gets correspondingly bigger, albeit with some variability. For some mines, this is due to pre-mine topography such as a mountain which has been excavated during mining – meaning large tonnages but a more modest area (e.g. Bingham Canyon, Grasberg). Curiously, Grasberg shows a very modest WRD area despite the high tonnage mined – which is simply due to the fact that it allows considerable erosion of its WRD’s into the Ajkwa River system (along with direct disposal of tailings into the Ajkwa River). For heap leach piles, however, there is considerable scatter and no obvious or clear relationship between area and tonnage placed. This is likely to be related to the variations in design and topography, as well as individual site economics, as this can lead to different HLP designs.

Table 1: Key water use metrics for various mines (full data in the Digital Appendices)

Mine / Operation	Years of Data Coverage	Mine Type	Process Configuration	Metals	Withdrawal												Use												Discharges		
					Groundwater			Surface Water			Marine Water			Third Party Water			Total			Raw			Worked			Worked					
					kL/t ore	±SD	(No.)	kL/t ore	±SD	(No.)	kL/t ore	±SD	(No.)	kL/t ore	±SD	(No.)	kL/t ore	±SD	(No.)	kL/t ore	±SD	(No.)	kL/t ore	±SD	(No.)	%	±SD	(No.)	kL/t ore	±SD	(No.)
Alumbrera	2005-2012	OC	F	Cu-Au	0.56	0.05	6										2.00	0.50	7	0.57	0.03	7	1.44	0.45	8	73.5	1.5	7	0.026	0.008	4
Andina	2003-2016	OC-UG	F	Cu-Mo-Ag	0.33	0.09	5	0.79	0.21	8							1.49	0.50	12	1.05	0.11	9	0.89	0.08	12	45.3	3.3	7	0.73	0.51	13
Antamina	2012-2015	OC	F	Cu-Zn-Mo-Ag	0.065	0.004	4	0.46	0.08	2																			0.89	0.05	4
Bald Mountain	2008-2014	OC	C	Au																0.47	0.71	7							0	0	6
Bingham Canyon	1997-2013	OC	F-S-R	Cu-Au-Mo-Ag													1.95	0.47	6	0.75	0.35	6	1.13	0.14	7	61.8	9.0	6	0.32		1
Black Mountain	2012-2013	UG	F	Pb-Zn-Ag-Cu	0.01	0.00	2	2.96	0.13	2							0.76	0.56	2	0.52	0.68	2	0.23	0.12	2	13.5	1.1	2	0	0	2
Bonikro	2011-2016	OC	C	Au	0.28	0.31	2	0.78	0.50	2							0.75	0.24	3	0.20	0.05	3	0.55	0.29	3	80.2	16.6	5	0.40	0.03	2
Cadia Group	2008-2015	OC-UG	F	Au-Cu-Ag	0.062	0.017	8	0.77	0.46	9				0.14	0.043	9	2.13	0.97	8	0.43	0.16	13	1.64	0.86	8	74.4	11.4	10	0.15	0.22	8
Cannington	2000-2010	UG	F	Pb-Zn-Ag	0.67	0.08	11													0.70	0.07	3	10.1		1						
Chuquicamata	2011-2016	OC	F-HL-S	Cu-Mo-Ag-Au	0.91		1	1.19	0.03	3							7.83	0.49	5	1.01	0.13	5	6.82	0.45	5	87.1	1.4	5			
Cobar-CSA	1999-2015	UG	F	Cu-Ag				1.06	0.19	15										1.06	0.19	15									
Codelco Norte	2011-2016	OC	F-HL-S	Cu-Mo-Ag-Au	0.13	0.15	5	0.42	0.08	9							2.93	0.26	8	0.43	0.03	9	2.49	0.26	8	84.8	1.6	8	0.07	0.14	8
Collahuasi	2003-2015	OC	F-HL	Cu-Mo-Ag	0.74	0.05	7							0.004	0.002	5	3.15	0.32	10	0.69	0.04	10	2.46	0.34	10	77.4	1.5	10			
Cortez	2008-2016	OC-UG	HM-C-HL	Au	0.30	0.21	8	1.30	0.24	3																89.8	2.5	4	0	0	6
Cowal	2008-2014	OC	HM	Au-Ag	0.28	0.08	5	0.16	0.13	6				0.006		1				0.45	0.09	6				98		1	0	0	2
Cracow	2005-2011	UG	C	Au													1.61	0.07	2	0.96	0.33	7	0.95	0.30	2	76.3	8.8	2			
Darlot	2002-2003	UG	C	Au													5.04		1	3.26	1.61	2	0.63		1	12.6		1	0	0	2
El Teniente	2002-2016	UG	F-S	Cu-Mo-Ag-Au	0.14	0.10	5	1.07	0.32	8							2.91	0.59	12	1.25	0.29	12	1.67	0.36	12	57.5	3.9	12	1.07	0.42	13
Ernest Henry	2003-2012	OC-UG	F	Cu-Au	0.62	0.10	5	0.49	0.13	7										0.46	0.12	10									
Escondida	2003-2008	OC	F-HL	Cu-Au-Ag	0.80	0.04	6				0.039	0.029	3				1.06	0.004	2	0.76	0.03	2	0.28	0.03	6	28.3	2.6	2			
Eskay Creek	2002-2003	UG	C	Au													0.58		1	0.52	0.12	2	0.14		1	24.7		1	5.45	0.12	2
Gabriela Mistral	2012-2016	OC	F	Cu	0.11	0.03	6	0	0	4							0.43	0.57	4	0.10	0.06	4	0.33	0.56	4	51.7	44.2	4			
Golden Grove	2005-2014	UG-OC	F	Zn-Cu-Pb-Au-Ag	0.48	0.73	4										3.61	0.84	3	1.51	0.19	5	2.37	0.80	5				0.53		1
Golden Sunlight	2008-2016	OC	C	Au													1.16	0.08	4	0.56	0.20	8	0.57	0.34	4	48.5	28.4	4	0	0	6
Goldstrike	2008-2016	OC-UG	C	Au													2.45	0.42	4	1.26	0.29	10	1.05	0.06	4	43.9	5.8	5	0	0	11
Greens Creek	1997-2000	UG	F	Au-Pb-Zn-Ag													7.97	2.02	4	2.14	0.24	4	5.84	1.87	4	72.2	6.0	4	3.35		1
Hemlo JV	2002-2016	OC-UG	C	Au													1.50	0.59	3	0.31	0.17	9	1.18	0.45	3	85.5	10.7	5	0.96	0.26	10
Hidden Valley	2010-2016	OC	F-C	Au-Ag				1.04	1.07	3							1.47	0.87	4	0.43	0.16	5	1.10	0.86	4	68.4	19.0	5	0.16		1
Holt-McDermott	2002-2003	UG	C	Au													2.05		1	0.92	0.15	2	1.23		1	60.2		1	5.39	0.09	2
Kinsevere	2012-2016	OC	HM	Cu																						85	6	3			
Konkola	2007-2016	UG	F	Cu	24.52	7.97	5	4.95	1.90	5							9.10	2.57	6	10.43	3.60	9	1.84	1.60	6	17.4	13.7	6	12.08	10.62	8
Lagunas Norte	2008-2016	OC	HL-C	Au													1.41	0.14	2	0.02	0.02	7	1.36	0.15	2	97.3	1.0	4	0.17	0.12	9
Lawlers	2002-2003	UG	C	Au													1.67		1	0.64	0.09	2	1.10		1	65.9		1	0.20	0.28	2
Lihir	1997-2016	OC	HM-C	Au-Ag																32.9	8.59	7				0	0	8	30.37	4.10	5
Lomas Bayas	2004-2011	OC	HL	Cu	0.018	0.01	6	0.10	0.01	6							0.14	0.01	2	0.12	0.02	4	0.03	0.002	4	24.4	0.2	2			
Lumwana	2012-2016	OC	F	Cu													1.18	0.11	4	0.16	0.06	5	1.04	0.09	4	88.0	2.6	4	0.81	0.51	5
Marigold JV	2002-2003	OC	C	Au																0.08	0.01	2				0		1			
McArthur River	2007-2009	OC	F	Pb-Zn-Ag	0.46	0.19	3	0.01	0.01	3													5.42	1.47	2				0.04		1
Ministro Hales	2011-2016	OC	F	Cu	0.58	0.39	2	0	0	2							0.46	0.09	2	0.37	0.08	2	0.09	0.01	2	13.5	11.7	3			
Morro do Ouro	1997-2000	OC	HL	Au													2.43	0.18	4	0.62	0.15	4	1.80	0.20	4	74.2	6.2	4	0.04		1
Mount Isa (Cu)	2002-2012	UG	F-S	Cu-Ag				0.89	0.29	4							3.09	0.33	5	0.92	0.21	11	2.08	0.26	5	66.1	6.7	5			
Mount Isa (PbZnAg)	2002-2012	UG-OC	F-S	Pb-Zn-Ag	1.22		1										2.52	0.30	2	0.96	0.31	6	1.81	0.08	2	70.1	8.3	2			
Mount Lyell	2007-2014	UG	F	Cu-Au-Ag	1.40	0.36	2	2.20	0.21	4							2.38	0.95	4	2.51	0.92	3	0.22	0.21	3	6.8	7.2	3	8.79	4.12	7
Mount Rawdon	2009-2011	OC	C	Au													0.96		1	0.15	0.13	2	0.90		1	94		1	0.07	0.08	2
North Mara	2008-2013	OC	C	Au																0.25	0.22	6				100		1	0.01	0.02	5
Northparkes	2002-2016	UG-OC	F	Cu-Au													1.04	0.09	10	0.60	0.13	16	0.45	0.16	10	43.2	13.8	10			
Ok Tedi	2003-2016	OC	F	Cu-Au-Ag				0.63	0.24	14							2.36	0.89	14	0.63	0.24	14	1.73	0.83	14	70.8	12.1	14			
Olympic Dam	1988-2016	UG	F-HL-S-R-HM	Cu-U-Au-Ag	1.60	0.45	28													1.60	0.45	28									
Oyu Tolgoi	2013-2016	OC	F	Cu-Au-Ag	0.56		1										2.86	0.54	4	0.44	0.10	4	2.43	0.44	4	85.0	1.2	4			
Palabora	1994-2012	OC-UG	F-S-R	Cu				0.80	0.31	16							2.99	1.01	11	1.09	0.42	10	2.29	0.79	12	66.5	5.4	8	0.09		1
Patchway	1997-2000	OC	C	Au													2.79	0.66	4	2.30	0.88	4	0.50	0.33	4	19.7	16.4	4			
Peak (NSW)	1997-2000	UG	F	Au-Pb-Zn-Ag													3.25	0.30	4	0.89	0.13	4	2.37	0.30	4	72.7	4.3	4			
Pierina	2002-2016	OC	HL	Au													0.04		1	0.91	2.46	8	0.01		1	60.0	55.2	2	0.16	0.28	7
Plutonic	2002-2003	OC	C	Au													1.96		1	0.81	0.04	2	1.12		1	57.2		1	0	0	2
Porgera	2008-2015	OC-UG	HM	Au				0.92	0.09	2							5.24	0.64	3	5.64	0.54	8	0	0	3	0		3	8.20	2.90	7
Prominent Hill	2009-2016	OC-UG	F	Cu-Au-Ag	0.63	0.09	7	0	0	2										0.63	0.09	7									
Pueblo Viejo	2012-2016	OC	C	Au													3.74	0.33	4	4.36	2.74	5	0.58	0.53	4	15.8	14.4	4	1.53	1.29	4
Radomiro Tomic	2011-2016	OC	F	Cu-Mo-Ag-Au	0.079	0.016	3	0.02	0.002	3							0.95	0.31	5	0.11	0.02	5	0.84	0.29	5	88.2	2.7	5			
Rawhide	1997-2000	OC	C	Au-Ag													2.64	0.67	3	0.20	0.01	4	2.45	0.68	3	92.2	2.7	3			
Renco	1997-2000	OC	C	Au													4.22	0.98	4	3.18	1.29	4	1.03	0.37	4	26.5	13.2	4			
Ridgeway	1997-1999	OC	C	Au													0.25	0.12	2	0.05	0.05	3	0.19	0.07	2	78.9	11.7	2			
Rosebery	2006-2016	UG	F	Zn-Pb-Ag-Cu-Au																19.08	12.27	3							1.61		1
Rossing	1995-2016	OC	HM	U				0.27	0.03	22							0.84	0.10	22	0.27	0.03	22	0.57	0.11	22	66.8	5.7	22			
Round Mountain JV	2002-2003	OC	C	Au																0.22	0.01	2							0	0	2
Ruby Hill	2008-2016	OC	HL-C	Au																0.44	0.38	7							0	0	5
Salvador	2002-2016	OC	F-HL	Cu	0.30	0.14	7	1.22	0.33	10							2.76	0.71	10	1.56	0.33	10	1.01	0.45	11	37.9	8.5	12	0.29	0.45	13
Sepon	2009-2016	OC	HM	Cu				3.53	1.62	6													5.33	2.82	5				4.06	3.88	4
Skorpion	2012-2016	OC	HM-R	Zn				1.69	0.01	2										1.72	0.04	4	0.23	0.13	2	11.9	6.2	2	0	0	2
Spence	2007-2008	OC	HL	Cu										0.32	0.04	2	0.36		1	0.32	0.04	2	0.01		1	2.4		1			
Telfer	2009-2016	OC-UG	F-C	Au-Cu-Ag	0.89	0.02	3	0	0	2							0.97	0.12	5	0.86	0.31	7	0.13	0.08	5	12.9	8.2	6			
Tintaya-Antapaccay	2006-2012	OC	F-HL	Cu-Au-Ag				0.72	0.08	6							2.57	0.09	5	0.70	0.10	3	1.86	0.04	5	72.6	3.7	7			
Togaruci-Gosowong	2004-2016	OC-UG	C	Au-Ag	4.99	2.35	2	2.17	0.46	2							5.99	1.05	3	4.02	1.42	10	0.73	0.67	3	8.4	11.2	5	5.45	1.97	3
Tulawaka	2008-2013	OC-UG	C	Au																0.61	0.31	6							0	0	5
Veladero	2008-2016	OC	HL	Au																0.049	0.013	8				47.8	55.1	4	0.006	0.006	8
Zaldivar	2008-2014	OC	HL	Cu																0.15	0.009	6	1.78		1	93	1.4	2	0	0	6
	Mean				1.46			1.02			0.04			0.12			2.41			1.81			1.56			54.9			2.03		
	Median				0.52			0.78			0.04			0.07			2.05			0.63			1.07			65.9			0.16		
	Std. Dev.				4.45			1.12						0.15			1.96			4.61			1.84			30.8			5.05		

Notes: Mine Type: OC – open cut, UG – underground; Process Configuration: F – flotation plant, S – smelter, R – refinery, HL – heap leach, HM – hydrometallurgical plant; SD – Standard Deviation.

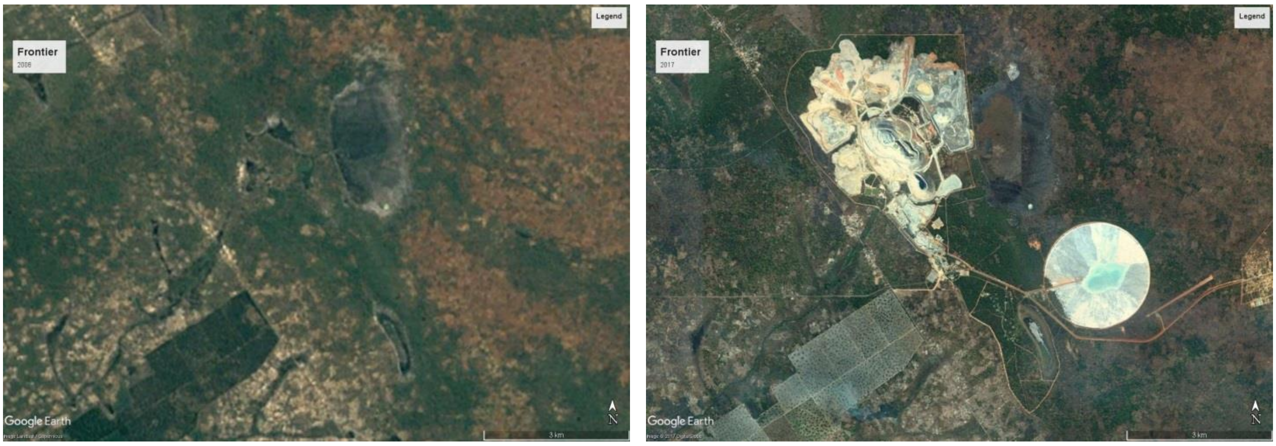


Figure 3: The Frontier Cu mine, Zambia, before (left) and after the development of mining (right)

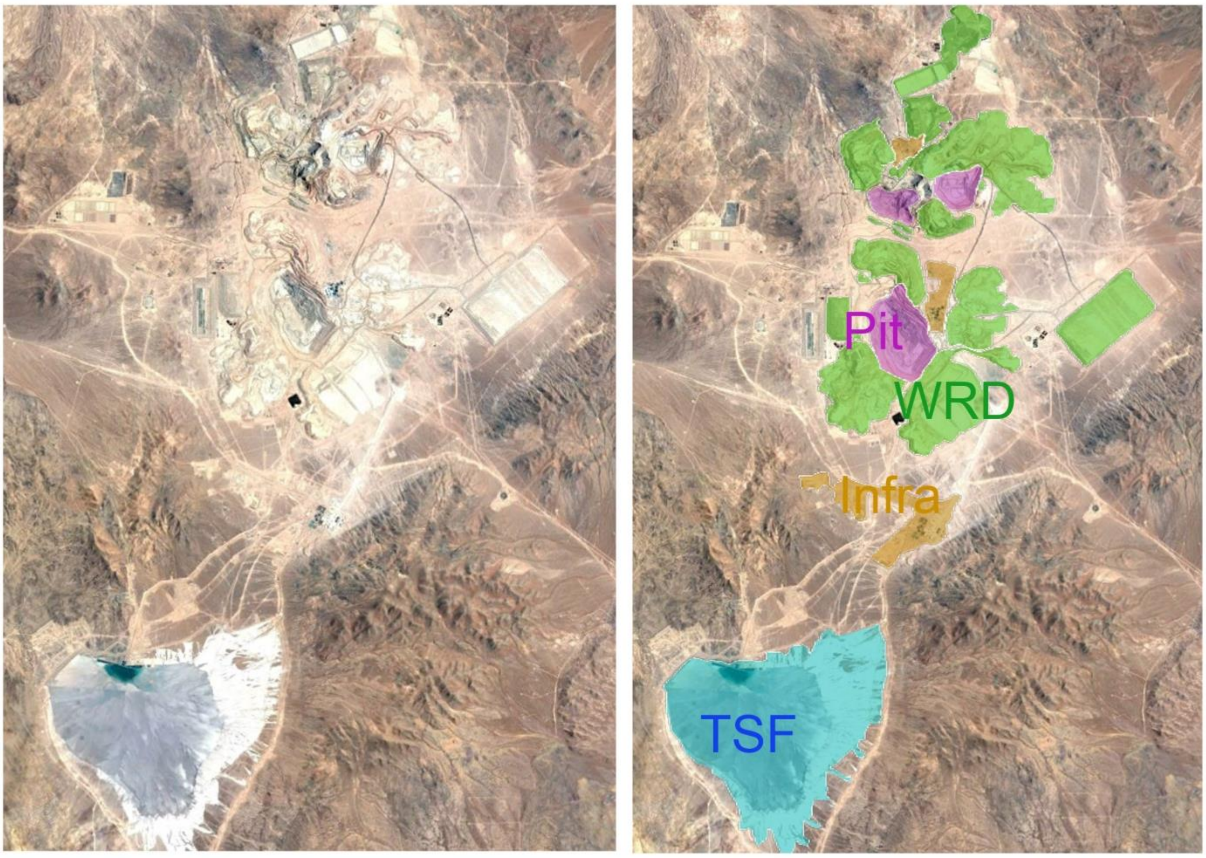


Figure 4: Mine feature mapping of the Escondida and Zaldivar Cu mines, northern Chile, showing clean image (left) and mapped features (right)

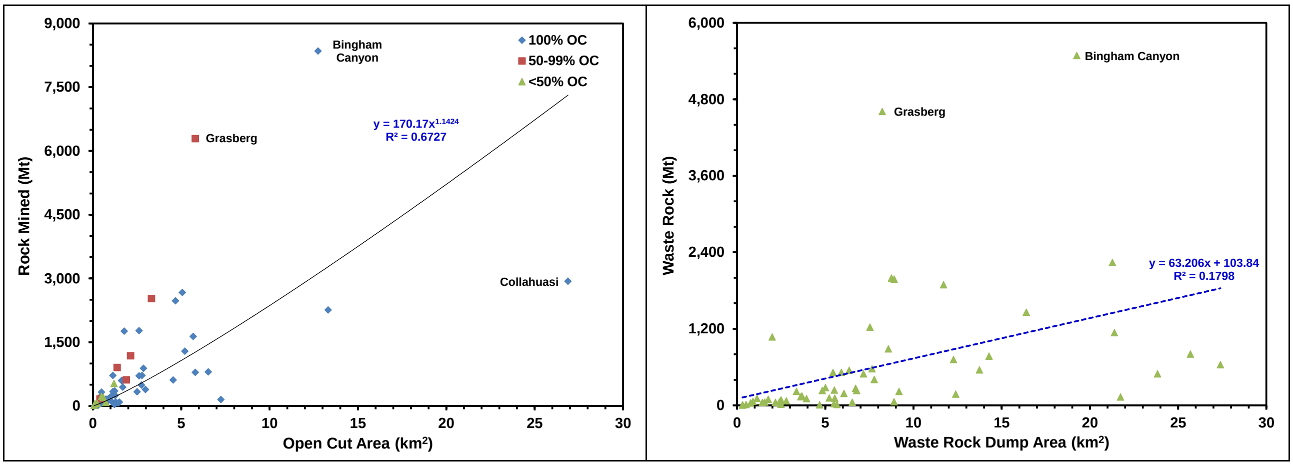


Figure 5: Regressions between the areas occupied by open cuts (left) and waste rock dumps (right) (see digital appendices for complete data set)

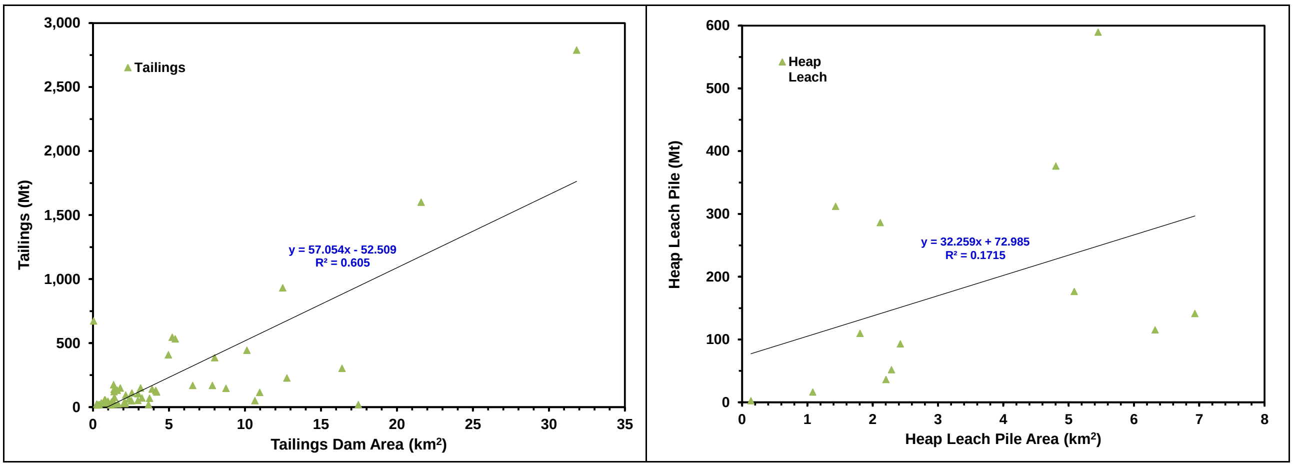


Figure 6: Regressions between the areas occupied by tailings storage facilities (TSF's; left) and heap leach piles (HLP's; right) (see digital appendices for complete data set)

3.3 Key Water-Climate-Land Relationships

Here we compare surface water or groundwater use per tonne of ore processed versus average annual rainfall, shown below, shown in Figures 7 to 9. In general, as rainfall increases there is greater use of surface water resources (left graph; R^2 0.270), although there is considerable variability. We exclude Ok Tedi from the regression since it has an extremely unusual context for water resources and project configuration (i.e. no tailings dam to allow for recycling). For groundwater, as rainfall decreases there is a strong tendency towards increase groundwater use, although again there is considerable variability (right graph; R^2 0.203).

Here we compare worked (recycled) and total water use per tonne of ore processed versus average annual rainfall, shown below. Similarly to water sources, as rainfall increases there appears to be greater use of total water overall but with considerable scatter, or as rainfall decreases there appears to be a stronger tendency towards increased worked water use but with considerable variability.

Here we compare discharges of water per tonne of ore processed versus average annual rainfall, shown below. As can be expected, as rainfall increases there tends to be greater discharges of water to the environment (typically surface waters) use of total water overall (right graph; R^2 0.440).

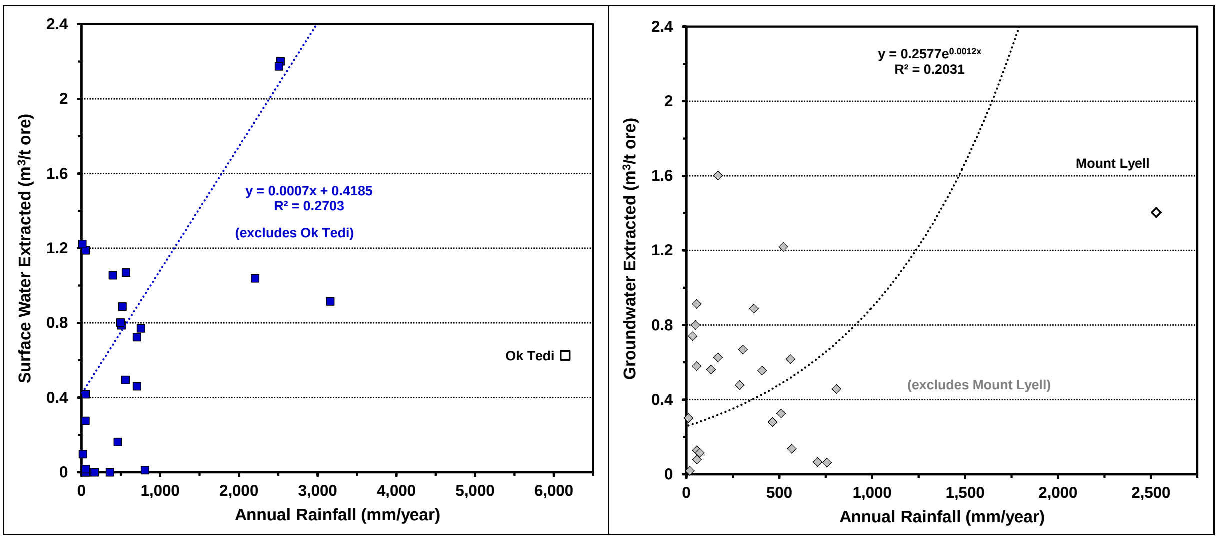


Figure 7: Regressions between the surface water (left) and groundwater (right) extracted and rainfall (see digital appendices for complete data set)

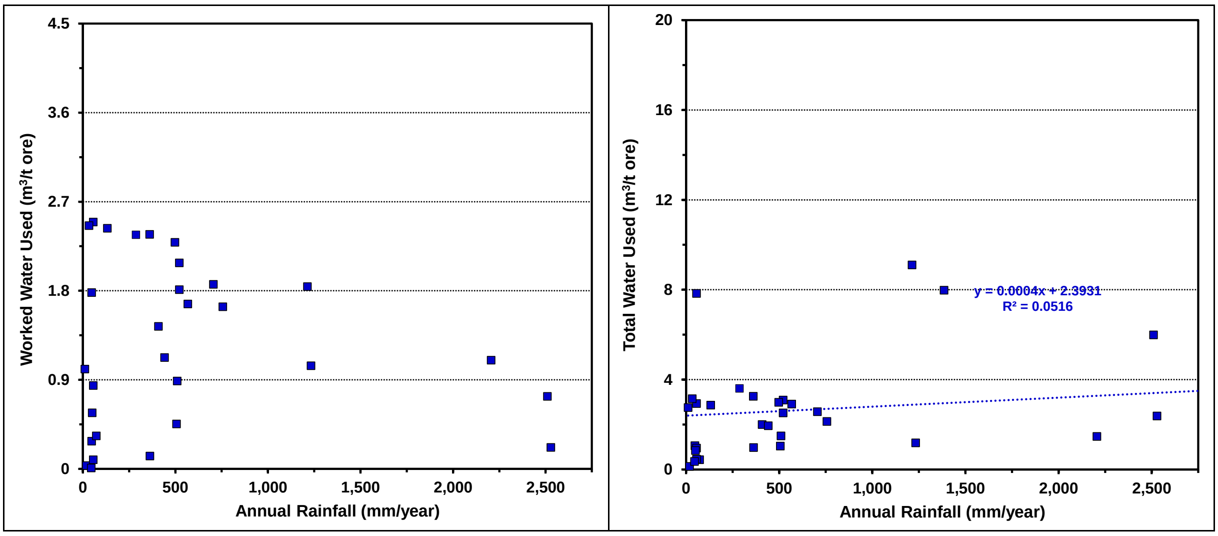


Figure 8: Regressions between the worked (recycled) water (left) and total water use (right) and rainfall (see digital appendices for complete data set)

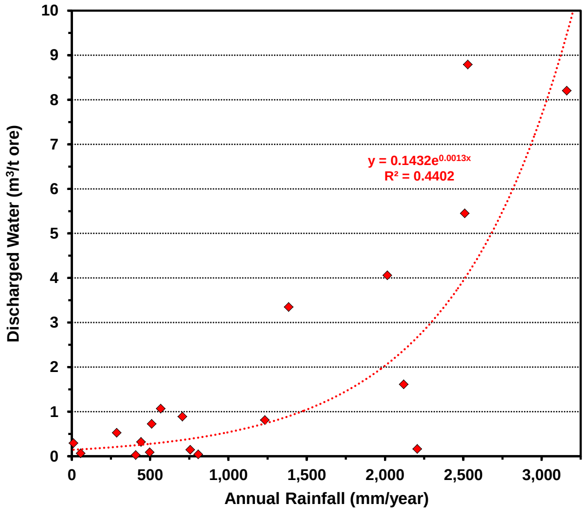


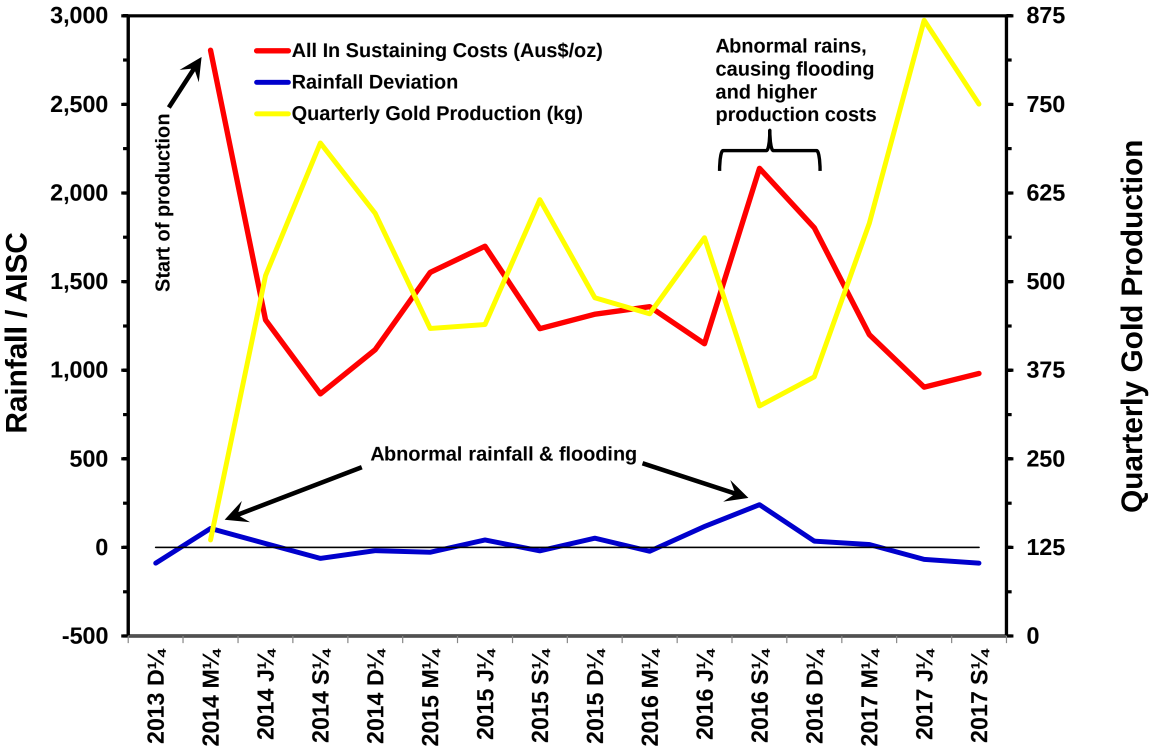
Figure 9: Regression between the discharged water and rainfall (see digital appendices for complete data set)

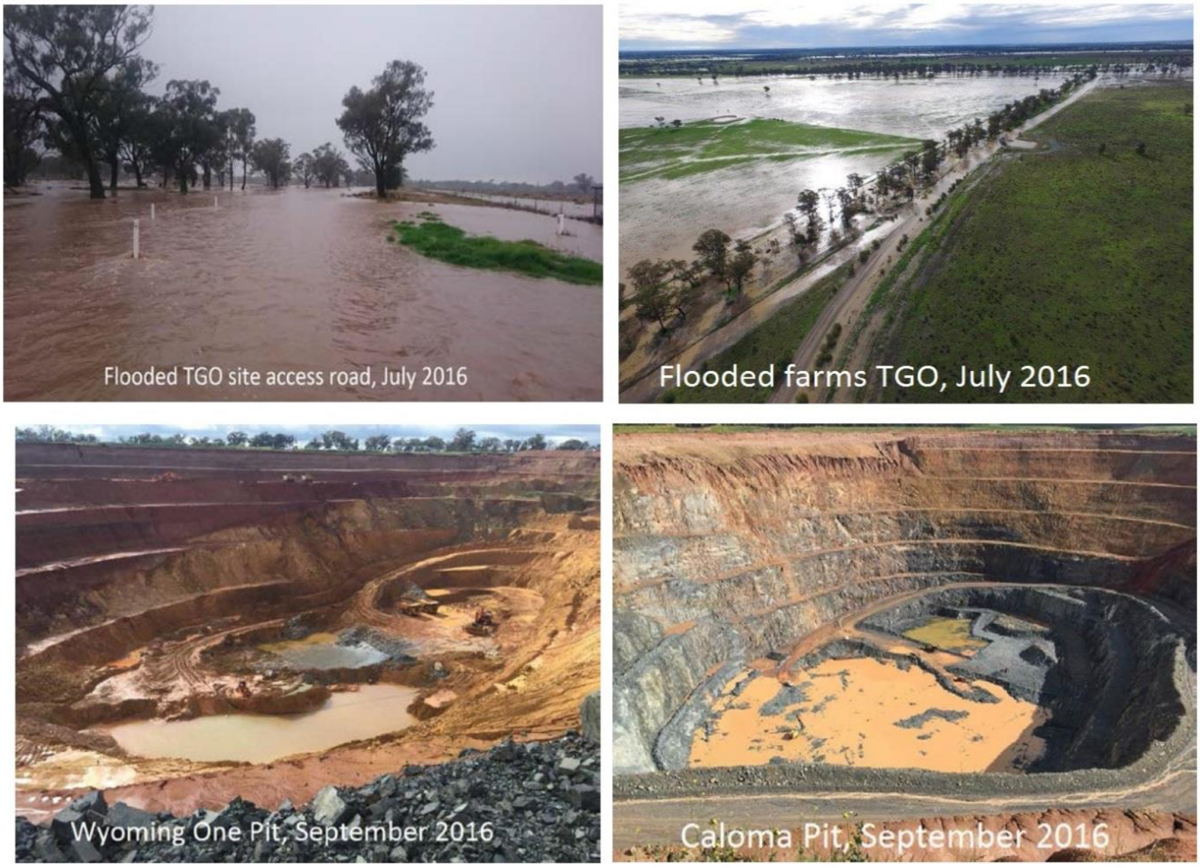
4. Case Studies & Examples

Here we present some selected case studies of the financial impacts of water risks on mines and companies, as well as a range of specific examples on the cost implications being realised at various mines.

4.1 Tomingley Gold Mine, Alkane Resources Ltd, NSW Australia

- March and June 2013 – significant rainfall affected construction, leading to major erosion and sediment reaching off-site ponds at two adjacent farms and the Newell Highway; no subsequent reported budget impacts (Annual Report 2013)
- May 2015 – NSW Environment Protection Authority (EPA) successfully enforced a prosecution against Tomingley gold mine for the March and June 2013 events, fine of Aus$95,000 (Quarterly Report, Sept. 2015)
- April to June 2016 – excessive rainfalls during the quarter, no direct impacts (Quarterly Report, June 2016)
- September and December 2016 quarters – persistent excessive rainfalls during the quarter, caused flooding of the Wyoming One pit and delaying ore supply to the mill, leading to higher unit costs; mine site water management systems held and no off-site impacts reported (Quarterly Report, Sept. 2016)
    - assuming full mill capacity (~295 kt ore processed per quarter at a grade of 2 g/t Au), this means a loss of production of ~7,227 oz Au (225 kg Au) in the Sept. 2016 quarter and ~5,906 oz Au (184 kg Au) in the Dec. 2016 quarter
    - market prices for gold in these quarters was Aus$1,760/oz Au and Aus$1,769/oz Au
    - loss of revenue is Aus$12.7 million and Aus$10.4 million
    - **this represents a loss of revenue by about one third each quarter**
    - **also means unit costs would be about one third lower – and mine operating at profit instead of a loss**





Flooding in the Tomingley area, September 2016 (Alkane Resources, Quarterly Report)

Sources: Alkanes Resources Limited – reports to the Australian Stock Exchange

- quarterly operations reports December 2013 to September 2017
- Annual Reports 2013 to 2017

4.2 Cadia Valley Operations Gold-Copper Mine, Newcrest Mining Ltd, NSW, Australia

- May 2007 – an extended 10 year drought across eastern Australia had reduced surface water flows in al streams and continually reduced water inventories held onsite. The mine, which produced about 25 kt Cu and 11.5 t Au per year, was within three months of being forced to close due to the ongoing drought. This would mean high costs of shifting to care and maintenance as well as lost production revenues of some Aus$900 million per year. The drought finally broke in June 2007, just in time to avoid mine site shutdown.

4.3 Western Queensland mines and the Lady Annie disaster, early 2009, Australia

- In early 2009, western Queensland experienced a strong monsoonal wet season, rated at about a 1-in-30 year frequency. This caused all mines in the region to have major problems with their water management systems, commonly lading to overtopping of water ponds or sometimes tailings dams also. Many of the mines were fined for their breach of regulatory conditions, including large mines such as Ernest Henry, Cannington, Century and Mount Isa.
- The worst incident was at the Lady Annie copper mine, where collapse of the sidewalls of solution ponds allowed the uncontrolled discharge of at least 447 ML of acidic heap leach solutions to the environment. This led to cattle deaths, impacts on pastoral station infrastructure (e.g. dissolution of steel fencing), severe impacts on aquatic ecosystems and biodiversity (especially fish) as well as impacts on recreation uses of the streams. The mining company was fined Aus$0.5 million dollars and had to incur clean up and remediation costs of the order of Aus$11 million.

4.4 Cerro Bayo Gold Mine, Mandalay Resources Ltd, Region IX, Chile

Management Discussion & Analysis (MDA) Reports June & September 2017

- 9 June 2017 – significant rainfall lead to flooding of the Delia NW mine, causing operations to be indefinitely suspended.
- Details remain unclear, but it appears that the major rainfall caused flooding of nearby Laguna Verde to breach into and flood the Delia NW mine workings – but not the Delia SE or Coyita mines.
- June 2017 quarter – loss of 3 weeks production amounts to ~US$4.04 million of lost revenue (based on average production levels)
    - "In addition to impacts on volumes, revenues, and cost of sales, the Company recorded $2.4 million of additional expenses incurred for the search for the miners and crisis management following the event. Other costs include a non-financial write-off of the remaining carrying value of the Delia NW mining interests of $0.8 million and a loss of $0.5 million of property, plant and equipment which will not be recovered from the flooded mine." (page 3, June 2017)
- September 2017 (and future) quarters – loss of entire production amounts to ~US$14.13 million of lost revenue per quarter, excluding ongoing care & maintenance costs of US$5.5 million for the quarter (due to mine being formally shut down), with future quarterly costs reducing to ~US$1.5 million/quarter – the timing of re-opening remains unknown and unclear as it depends on when approval will be granted by the Chilean regulator to re-start operations.
- **Lost revenue for 2017 alone can be estimated to be of the order of US$32.3 million plus care & maintenance costs of ~US$8.5 million – with no clarity yet on the impact of any regulatory decisions and associated costs (e.g. possible engineering works to reduce mine flooding risks).**

4.5 Duketon Group Gold Mines, Regis Resources Ltd, Western Australia, Australia

- Relatively new gold mines, Moolart Well (start production ~August 2010), Garden Well (start production ~September 2012), Rosemont (start production ~October 2013)
    - "Production was materially affected by a severe rainfall event and subsequent flooding of Garden Well and Rosemont pits on 13th February 2014." (ASX Quarterly Report, March 2014, page 1)
    - "As previously reported, gold production during the quarter at Garden Well was hampered by lower than expected head grades exacerbated by the commencement of a cut-back and significant rainfall which impacted the ability to deliver higher than run of mine grade material to the mill." (ASX Quarterly Report, March 2015, page 2)
- **Based on expected mill production rates, lost revenue for the March and June 2014 quarters for both Garden Well and Rosemont can be estimated to be ~Aus$83.9 million – reducing revenues by ~17.6%. Regis Resources was still able to deliver a maiden profit to shareholders, but this was clearly reduced by the financial impact of the flooding event.**

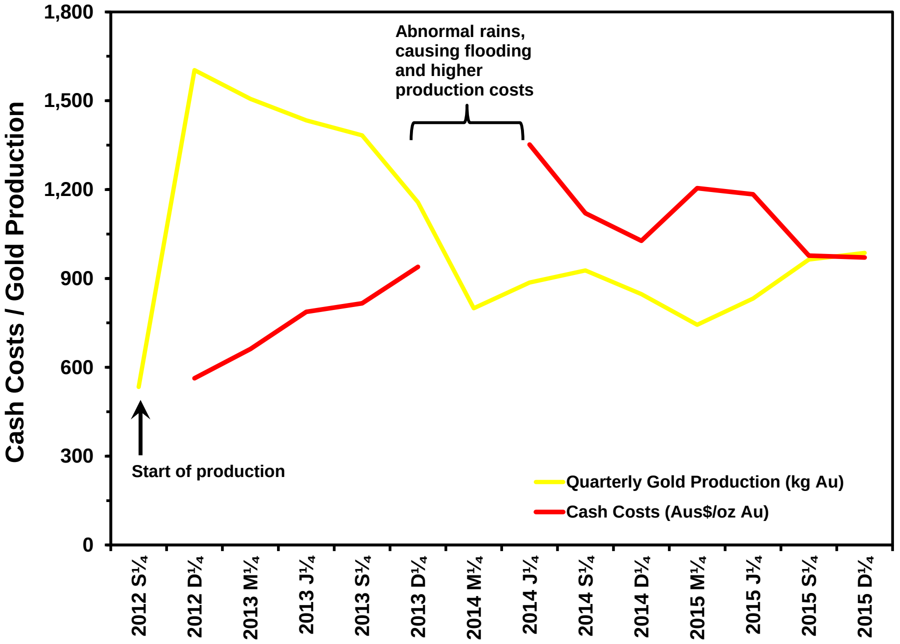


Figure: Garden Well quarterly gold production and unit cash costs

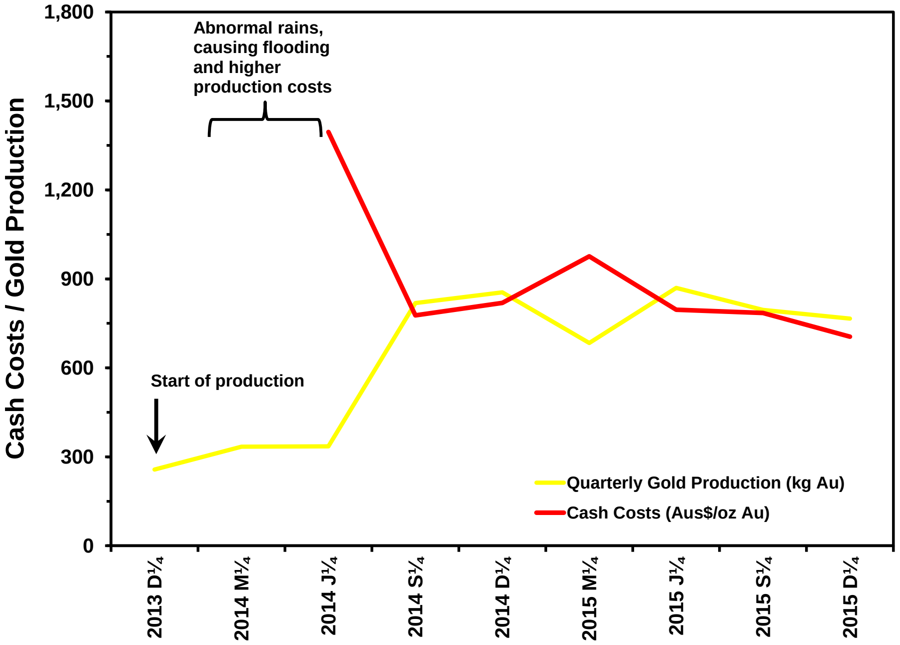


Figure: Rosemont quarterly gold production and unit cash costs

4.6 CDP Water Disclosures

The Carbon Disclosure Project ('CDP'), originally designed to gather information about the financial risks posed by exposure to climate change risks, developed a new approach for the reporting of water risks – simply called CDP Water. Although disclosures through the CDP Water system are often not available on mining company websites, they are available at CDP Water, and provide numerous examples of the financial risks posed by various types of water risks and challenges for mining projects.

Some examples of disclosures to CDP Water (CDP Water 2013):

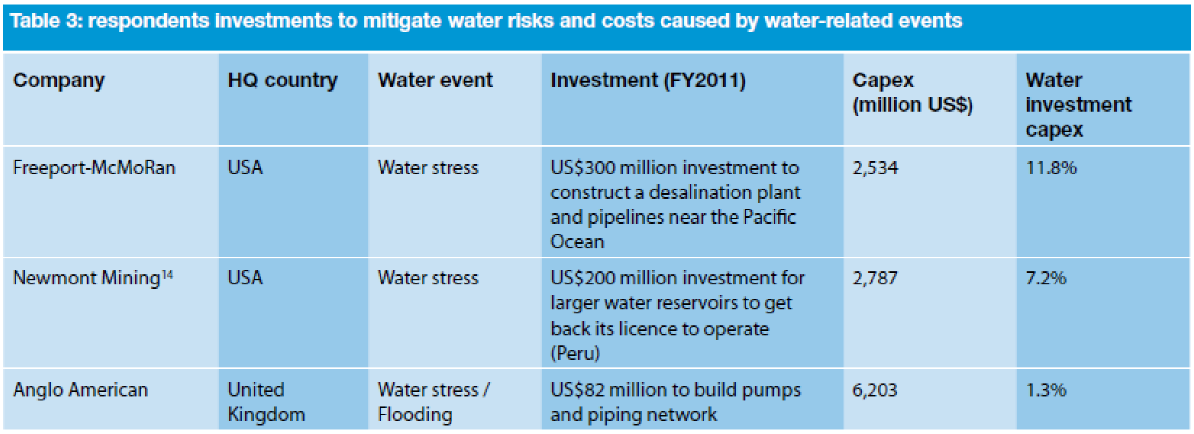


Table 3: respondents investments to mitigate water risks and costs caused by water-related events

Company	HQ country	Water event	Investment (FY2011)	Capex (million US$)	Water investment capex
Freeport-McMoRan	USA	Water stress	US$300 million investment to construct a desalination plant and pipelines near the Pacific Ocean	2,534	11.8%
Newmont Mining[14]	USA	Water stress	US$200 million investment for larger water reservoirs to get back its licence to operate (Peru)	2,787	7.2%
Anglo American	United Kingdom	Water stress / Flooding	US$82 million to build pumps and piping network	6,203	1.3%

Company responses to the CDP Water questionnaire are available through the online CDP database and these are occasionally also presented on company websites.

CDP Water 2016 Information Request - Anglo American – Period 1 Jan 2015 to 31 Dec 2015

Los Bronces, Salado River Basin, Chile

Financial Impact:

$90.5 million reduced revenue (18,000 tonnes lower copper production)

$180 million expenditure (investment in water recycling systems)

Impact Description:

"Los Bronces is Anglo American's largest operation in Chile and one of the largest copper deposits in the world. Los Bronces is currently experiencing its 6th consecutive dry year. The water constraints have resulted in production constraints. This has forced the team to develop and implement a series of water-efficiency measures and seek alternative, non-competing sources of water to ensure the continuity of adequate water supply for the operation."

Response Description:

"The water constraints are part of our mining and processing plans for the year - which include actively managing the use of our two processing plants - and we are progressing according to those plans. At Los Bronces, the operation has continued to implement technical solutions to prevent further business impacts: water is now transported via a 56-kilometre pipeline from the Las Tórtolas tailings dam to Los Bronces, using a special water-recycling system. Other reduction initiatives include reducing the evaporation in tailing dams as well as improving tailings deposition. The site will be adopting evaporation covers, expanding the use of thickeners, and investigating other technology to recover water from tailings dams in 2016. In August the installation of a new cyclone station was completed to increase the recovery of water in the dam. Los Bronces is currently recycling more than 78% of available water. In the long-term, more stringent environmental conditions, competing demand and continued dry conditions will continue to challenge security. A project to support the operation to help it achieve Copper's stated goal of "water resilience" by 2020 is underway."

"Progress in implementing our water strategy is driven through our water management programme, which has three areas of focus: driving operational excellence; investing in technology; and engaging and partnering with our stakeholders. The programme is supported by a mandatory Group water standard and delivered via operation-specific water-action plans. Los Bronces has continued to implement technical solutions to prevent further business impacts: water is now transported via a 56-kilometre pipeline from the Las Tórtolas tailings dam to Los Bronces, using a special water-recycling system. Other reduction initiatives include reducing the evaporation in tailing dams as well as improving tailings deposition. The site will be adopting evaporation covers, expanding the use of thickeners, and investigating other technology to recover water from tailings dams in 2016. In August, the installation a new cyclone station was completed to increase the recovery of water in the dam. Los Bronces is currently recycling more than 78% of available water. The water recycling system at the Los Bronces operation was a significant investment of $180 million, which was a direct capital expenditure cost derived from invoices."

CDP Water 2016 Information Request - Anglo American – Period 1 Jan 2015 to 31 Dec 2015

<u>Mogalakwena, Limpopo River Basin, South Africa</u>

Financial Impact:

$250,000 increased operational costs (community water)
$5 million expenditure (municipal sewage works)

Impact Description:

"All of our operations within the Limpopo river basin are located in water stressed areas. In addition, there are challenging socio-economic circumstances with high poverty levels and poor infrastructure. These conditions are exacerbated by the drought conditions experienced in southern Africa as a result of the El Nino effect. This means that access to secure water and community opposition is a risk. For example, in August 2015 Mogalakwena mine experienced community protests and public violence. When consultations between government and the mines and communities took place, one of the issues highlighted by communities was the lack of potable water provision by the government."

Response Description:

"While the delivery of services lies within the remit of local municipalities, as a temporary measure (until a long-term solution is found) the mine offered to assist with water provision. This is especially important as the province is undergoing a period of drought, which has impacted borehole water levels. The mine therefore is extracting water from its deeper boreholes and distributing it to the community by bowser. It is also engaging with the municipality in finding a permanent. Since November 2015, a total of 12 villages, with a population of approximately 35,000 residents, have been supplied with water by the mine on a temporary basis. In addition, the families that have not yet been relocated as part of the ongoing resettlement at Motlhotlo are also being supplied with water until the process is completed. We also provide water to Podile Primary School at Ga-Molekana and Seritarita High School as the water from their borehole is of poor quality. To ensure the long-term security of water availability for our operations and surrounding communities, Anglo American Platinum have also developed a bulk-water strategy and infrastructure plan, to protect, manage and maintain the water supply."

CDP Water 2016 Information Request - Anglo American – Period 1 Jan 2015 to 31 Dec 2015

De Beers Snap Lake underground mine, Mackenzie River Basin, Canada
Financial Impact:
$100 million per year (water management)
Impact Description:
“De Beers Snap Lake underground mine operation in Canada is located in an area of excessive water where the host rock surrounding the ore body is fractured. This has resulted in the inflow of excess water including ancient, naturally occurring “connate” groundwater that has been trapped in the rock deep underground for thousands of years. This groundwater is high in mineral salts and requires special attention so that the mine remains in compliance with water licence requirements. The major impacts include increased water management costs linked to more stringent license conditions related to the volume and quality of discharge.”
Response Description:
“Snap Lake mine was storing large volumes of water underground due to high concentrations of dissolved solids including mineral salts, which required treatment before discharge to conform to prescribed limits. The excess water also limited access to certain parts of the mine, which reduced the mineable ore level. As a result of market conditions, the operation was placed into care and maintenance on December 4, 2015. Water quality at the operation continues to be managed and monitored in line with its approved care and maintenance plan. The mine is involved in technical studies, stakeholder engagement and legal processes to evaluate options should it remain in extended care and maintenance.”

CDP Water 2015 Information Request – Anglo American – Period 1 Jan 2014 to 31 Dec 2014.

Mantos Blancos & Mantoverde, Copiapó and Lao River Basins, Chile
Financial Impact:
660 tonnes reduced copper production (Mantos Blancos – safety stoppages & water supply)
2,000 tonnes reduced copper production (Mantoverde – shutdown from damaged powerline)
$2 million (supporting reconstruction of Chanaral and El Salado)
Impact Description:
“The north of Chile was affected by abnormally heavy rainfall over the 24th and 25th of March, 2015. This affected mainly Antofagasta, Copiapo and Chanaral with floods, landslides and avalanches causing a great amount of damage to cities and small towns. This caused mudslides and rivers to breach their banks, leaving residents stranded, flooding cities, and cutting power supply. Anglo American’s Mantoverde mine was halted due to safety stoppages and restricted water supply. Mantos Blancos was halted after a power failure. None of Anglo American’s employees or contractors were injured.”
Response Description:
“Our social team developed a plan to provide immediate support to the communities affected by this catastrophe, providing food, water and other basic supplies, shelter in the company’s facilities and providing support to the local authorities. Anglo American established a $2 million fund to support the reconstruction of Chanaral and El Salado, with a focus on education, including the construction of two pre- school facilities and supporting small and medium sized entrepreneurs to restart their businesses.”

CDP Water 2015 Information Request – Anglo American – Period 1 Jan 2014 to 31 Dec 2014.

Nickel, niobium and phosphate businesses, Sao Francisco River Basin, Brazil

Financial Impact:

US$560,000 capital expenditure (water savings project)

Impact/Risk Description:

"Water availability in the Catalão region is a risk to nickel, niobium and phosphates businesses in Brazil. The risk has increased due to the dry season affecting the region and the increased water demand."

Response Description:

"The risk is mitigated in the short term by an agreement signed with a peer company, which allows us to abstract water from their tailings dam. To mitigate long term risk, a water use license was obtained for abstraction from the São Marcos River. In 2014, Catalão experienced savings of 10 ML from WETT projects and a total capital cost for projects of approximately US $ 560 000."

CDP Water 2016 Information Request – African Rainbow Minerals – Period 1 Jul 2014 to 30 Jun 2015

Khumani Mine & Black Rock Mine, Orange (WMA) River Basin, South Africa

Financial Impact:

R15 million (augmentation to Sedibeng Water Supply

Impact/Risk Description:

"The risk is the potential loss of production or lost opportunity at Khumani mine and at Black Rock mine due to the shortage of water and interruption in continuous water supply hampering the continuous running of the plant resulting in a reduction in production and resultant lost revenue. Black Rock mine is at the end of the Sedibeng water supply line and therefore ongoing expansion in water supply has to be planned closely with availability in mind to manage water supply risk."

Response Description:

"Investment in water infrastructure (e.g. Assmang assisted Sedibeng with the upgrade and expansion of the Beeshoek pump station (debottlenecking); Khumani funded the upgrade of the Olifantshoek bulk water infrastructure; and various investments in maintenance) Investment in on-site water storage, Collaboration with the Sedibeng Water Board and the DWS (regional water study) Reduced consumption through efficiencies (e.g. Reduced water consumption for mining activities through the use of "additives". The mine uses a "paste" technology for tailings disposal to reduce consumption. Up to 85% of water is recovered. Water balance and monitoring Implementing various efficiencies including Water conservation measures implemented, such as storm water trenches and dams. Nkomati has a dewatering programme in place managed by engineering services. There are various other measures to monitor and engineer pit stability."

CDP Water 2016 Information Request – African Rainbow Minerals – Period 1 Jul 2014 to 30 Jun 2015

Nkomati, Inkomati-Usuthu (WMA) River Basin, South Africa

Financial Impact:

R1.75 million

Impact/Risk Description:

"There is a risk of non-compliance to the WUL condition. The mine has submitted a WUL amendment application in order to store excess water in Pit 3. This will reduce the frequent discharges. The risk is the potential failure of the pit slopes which may result in production losses, fatalities and equipment damage. The risk is accentuated by the topography of the mine site and weather conditions."

Response Description:

"Nkomati has a dewatering programme in place managed by engineering services. There are various other measures to monitor and engineer pit stability."

CDP Water 2016 Information Request – Newmont Mining Corporation – Period 1 Jan 2014 to 31 Dec 2015

Ghana Mines, Tano River Basin, Ghana

Financial Impact:

$37 million USD (plant disruption due to interrupted hydro-electricity supply)(25% reduction in gold production)

Impact/Risk Description:

"Ghana generates 70% of its power from hydroelectric dams. Ghana is in the midst of a cyclical drought. The drought is reducing the power output from Ghana's hydroelectric dams (now at about 50%). Reduced national power output results in 1 day in each 3 days with no power during periods of load shedding. Blackouts days impact both of our Ghana operating mines."

Response Description:

"Use of technology for improving Ahafo water quality via a water treatment plant is now being developed. Recycling of sewage treated effluent for gold processing. Further, additional opportunities have been identified in Ahafo and Akyem Water Charters as part of implementing the Global Water Strategy. Installation emergency backup power."

Boddington, Hotham River Basin, Australia

Financial Impact:

$10 million USD

Impact/Risk Description:

"Our Boddington Western Australia operation requires abstraction of Hotham River water for processing purposes. Lower than average rainfall limits the amount of water available for abstraction."

Response Description:

"Site awareness programs, flocculation trials (increased tails density reducing water consumption), infrastructure modifications - rerouting pipework (recycling of water) and optimization of plan process control (increasing water efficiency)."

Community Engagement with Water Resources Issues

To facilitate better engagement with local stakeholders, mining companies will often invest in community and infrastructure development projects to ensure that the local communities benefit from the mining operation. The types of community development project that companies invest in can vary considerably depending upon the local context and should, in best practice cases, be developed through effective engagement with the community to understand and address their concerns and needs. In regions with shortages or poor access to high quality water, mining companies often work with local communities, businesses and governments to implement water treatment and supply projects. Some examples of mining company investments specifically in water related community development projects are provided in
Table **1**.

Table 1: Examples of mining company investment in water related community development and assistance.

Description	Value
Newcrest's Response to the 2010/2011 Queensland Floods (Newcrest, 2011b)	
Donation to Queensland Premiers Disaster Relief Appeal.	AU$150,000
Donation to Australian Red Cross Victorian Floods Appeal.	AU$100,000
Installation of a potable water treatment plant to assist community.	AU$250,000
Hidden Valley Project, Papua New Guinea (Newcrest, 2011b)	
Water supply projects in 20 local communities to provide safe drinking water for over 5000 people.	PGK 1,800,000 (AUD $704,415)
Sepon Mine, Laos (MMG, 2011)	
Installation of water filtration, supply and tap systems for 12 local villages.	US$800,000
Contribution to UN Habitat's urban water supply project.	US$250,000

Variable Climate Risks – Flooding, Droughts

Flooding can be a perpetual seasonal risk, such as flood risk due to inundation due with summer snow or glacial melts, or alternatively due to extreme rainfall in wet or monsoonal seasons. Many examples exist of extreme weather impacting mining operations through flooding or the failing of infrastructure. Some examples include:

- Flooding leading to overtopping of stormwater infrastructure at the Cannington Pb-Zn-Ag mine in January and April 2006 causing 'minor localised impacts' (BHP Billiton, Sustainability Report, 2006).
- Flooding of the Yallourn coal mine due to the collapse of an embankment along the Morwell River in Victoria, Australia (Mason et al., 2013);
- Flooding of coal mines in the Bowen Basin due to extreme weather and flood events that significantly impacted regions in Queensland, Australia (Sharma and Franks, 2013);
- Flooding causing damage at the Salvador Cu mine during a severe storm on 25 March 2015 (Codelco, Annual Report, 2015).

There are also examples reduced rainfall or drought conditions impacting mining operations, such as:

- The Ok Tedi mining operation in Papua New Guinea being impacted by drought events that reduced water levels in the Fly River system, thereby making the operation inaccessible by barges resulting in interruptions to production;
- Cadia Valley Operations in New South Wales, Australia being impacted by drought conditions that threatened water supply for ore processing and required negotiation with the local council to obtain a 5 ML/day temporal withdrawal permit (Newcrest, 2007);

- Extremely low rainfall at the Lihir gold mine in Papua New Guinea that reduced the freshwater available for the processing circuits, resulting in 40,000 oz Au lower production for the period (Newcrest, 2011a).

5. Publication Plan

At present, the rich data sets generated by this research are planned for multiple journal publications, focussed on the water accounting framework, life cycle assessment as well as links between water balance and water use. It is expected that all of these publications will be finalised in early 2018.

6. Discussion, Conclusions and Further Research

This study has generated extensive data sets on water use in mining as well as linking this to potential financial risks related to water resources issues. Overall, there appears to be considerable variability in wate use and risks, and this requires further complex statistical analysis which has been beyond the scope and capacity of this project. There is clearly a need for further research, and the final publications will explore these issues in greater detail. At present, however, it is clear that a mine or company's exposure to the financial costs of water resources risks are complex, highly variable and dependent on the mine's design and overall context. That is, all sites appear to be very site-specific and require individual analysis and consideration. Some major gaps still remain, however, such as the ability to address water quality risks, consistency of reporting, and the like. Despite considerable progress, there remains much to do to more fully analyse and understand the relationship between mining, water resources and financial risks.

7. References

ICMM, 2017, *A Practical Guide to Consistent Water Reporting*. International Council on Mining & Metals (ICMM), London, UK, March 2017, 72 p.

MCA. (2014). *Water Accounting Framework for the Minerals Industry, User Guide, Version 1.3, January 2014*. Prepared by the Sustainable Minerals Institute, University of Queensland for the Minerals Council of Australia (MCA).

8. Digital Appendices

Water Metrics Database – detailed water intensity data related to production data and mine site areas.
Land Use Area Dataase – detailed areal mapping of major mines to assess key mine features.

9. Report Appendix 1

Justification of a Database for Water Use in Mining

Water Use Reporting

Over the past two decades the mining industry has increasingly made disclosures of water use as part of environmental management and corporate sustainability reporting (Perez and Sanchez, 2009). 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 are voluntarily disclosing water use data through initiatives such as corporate sustainability reporting and market disclosures (Leong et al., 2014). Most existing studies that have assessed these activities have focused upon the degree of compliance with the various reporting standards that guide these disclosures, such as the Global Reporting Initiative (Fonseca et al., 2014; Jenkins and Yakovleva, 2006). However, there has been more limited analysis of the actual data being communicated within these reports and how this can be used to develop a more rigorous understanding interactions of the mining industry with the environment and society.

The Global Reporting Initiative (GRI) provides a framework for organisation's to regularly publish ‘Sustainability Reports’ that describe performance of the company on social, economic and environmental grounds (GRI, 2013a) . Despite being voluntary, there has been strong uptake of GRI based sustainability reporting by major mining companies (Perez and Sanchez, 2009; Fonseca et al., 2014). The GRI requires organisations to report against a variety of societal, environmental and economic performance indicators. The main indicators that could potentially provide useful data be reported under by the most recent reporting standard GRI4 include (GRI, 2013a):

- 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 – 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.

The GRI has evolved over time to meet the needs of stakeholders and to improve the meaningfulness or requirements of reporting indicators. Additional reporting supplements specifically for the mining industry have been made available to improve the quality of disclosures being made by the sector (GRI, 2013b).

The Carbon Disclosure Project (CDP) began as a scheme that was focused upon querying companies on their exposure to climate change risks and the actions they were taking to mitigate or adapt to these risks (CDP, 2017). Following the success of the CDP, a derivative scheme, CDP Water, was established to assess how companies are exposed to water risks and the actions they are taking in manage or address these. CDP Water is structured as a questionnaire that is sent to companies and the focus is on understanding an individual company’s exposure to water related risks. Most major mining companies now regularly report to the CDP and CDP Water schemes as part of their voluntary reporting practices. From this considerable insights are able to be reached regarding the water related risks that the mining industry faces, and their responses to these risks (CDP, 2013). CDP Water reports are accessible through an online database and readers are encouraged to explore these, as they provide unique insights into how the mining industry views water risks (GRI, 2017).

Analysis by CDP Water of the questionnaire responses of 36 mining companies showed that 92% of respondents reported having identified water risks that could alter their business operation, revenue generation or expenditure requirements within the next 5 years (CDP Water, 2013). Across these disclosures a number of substantive risks were identified, although these differ depending upon where an individual company's operations are located. Many respondents cite increased water stress in the regions they operate as a substantive risk. Risks associated with flooding are also commonly raised by respondents. Some mid- to long-term regulatory risks related to tighter regulation of water discharges are also viewed as important risks by some companies. Across shorter time horizons, changes to water withdrawal and allocation rights are considered to be a more immediate regulatory risk by many companies.

Despite the widespread reporting of mining companies using schemes such as the GRI and CDP Water, there has been substantial inconsistency in how mining companies have been reporting water use data to these schemes (Cote et al., 2012; Mudd, 2008; Leong et al., 2014) developed its' own water accounting standards to facilitate the more consistent communication and reporting of water use information by mining companies. As an example of this, the International Council on Mining & Metals recently released a water reporting framework for the industry (ICMM, 2017) that was heavily developed based upon the Water Accounting Framework for the Minerals Industry that was developed by the Sustainable Minerals Institute for the Minerals Council of Australia (MCA, 2014).

The *Water Accounting Framework for the Minerals Industry* (WAFMI) was developed for by the Sustainable Minerals Institute (University of Queensland) for the Minerals Council of Australia (MCA) (Cote et al., 2012; MCA, 2014). The framework provides a consistent way of accounting for water flows through and within a mine-site, to provide consistency in the accounting and reporting of this information. The WAFMI provides a systematic way of recording the inputs, outputs, diversion and storage of water at a site level. Water quality thresholds are used by the WAFMI to account for water inputs and outputs across three water quality categories

The WAFMI provides data in two ways. An input-output table is the main outcome of adopting the WAF. This provides a measure of all the inflows to the site, such as: rainfall, mine water infiltration, ground and surface water withdrawals, and moisture entrainment in ores. Outputs include parameters such as: seepage, evaporation, discharges and tailings entrainment. A statement of task usages is also included and contains flows into individual processes, such as: concentrators, mine site equipment, etc. Analysis as shown that the WAFMI is flexible enough to be broadly applicable to mining operations, regardless of the local climate or hydrological context of the mining operation (Danoucaras et al., 2014).

The International Council on Mining & Metals has in recent years begun to provide guidance on water management in the mining industry through the release of a range of publications listed below:

- Water management in mining: a selection of case studies (ICMM, 2012)
- Adapting to a changing climate: implications for the mining and metals industry' (ICMM, 2013)
- Water stewardship framework (ICMM, 2014)
- A practical guide to catchment-based water management for the mining and metals industry (ICMM, 2015)
- A practical guide to consistent water reporting (ICMM, 2017)

In March 2017, the ICMM released the 'Practical Guide to Consistent Water Reporting' (ICMM, 2017). The ICMM's water reporting guide was heavily modelled upon the WAFMI and so the two accounting standards share the same basic underpinnings. However, a major improvement over the WAFMI is the greater treatment given to providing guidance to describe the local water context surrounding mining operations and more broadly the communication of water risk related information.

Water Use Reporting

Several authors have previously compiled datasets of mine water use statistics, based most commonly on the corporate sustainability reporting of mining companies. The early assessment of direct water use for various metal production routes by Norgate and Lovel (2004; 2006) was based directly on data compiled from the corporate sustainability reporting of mining, mineral processing and metal producing companies – although this is not typically recognised. Considerable work was also undertaken by Mudd (2008) to compile a dataset of mine water use intensity (e.g. m^3/t product, m^3/t ore) that, despite being the most comprehensive assessment at the time, he considered to be a preliminary effort only. As he was aware of considerably more reporting by companies that was not captured by his data compilation efforts. Prior to the present doctoral studies, the author compiled a dataset of the water use intensity of copper mining operations (Northey et al., 2013). Gunson (2013) also compiled a detailed dataset of mine water use intensity for 19 mined commodities, which he used to estimate the global water withdrawals associated with non-fuel mining for the years 2005-2008 (
Table **2**). A range of limitations and shortcomings exist with these studies, including:

- They have tended to focus compiling either water 'use', 'consumption' and 'withdrawals' data for mining operations, with very limited definition or differentiation of these terms.
- Water sources (e.g. surface, groundwater, rainfall, etc.) has not been specified.
- Water discharge data has typically not been compiled.
- The water quality of withdrawals and discharges has also not been specified.
- Limited assessment how the data relates to local climate and water use contexts.

These short-comings are in large part due to the highly variable and inconsistent water use reporting practices of individual companies, which would have prevented such analysis.

Table 2: Gunson's (2013) estimate of global water withdrawals associated with non-fuel mining, based upon his ore production method.

	Withdrawals, Mm^3 H_2O			
	2006	**2007**	**2008**	**2009**
Total	**6,870**	**7,766**	**7,489**	**7,518**
Phosphate	3,046	3,258	3,187	3,052
Copper	1,337	1,233	1,301	1,363
Gold	657	942	997	1,141
Iron	589	737	555	883
Diamonds	546	713	206	305
Nickel	20	71	147	165
Zinc	195	243	82	95
Platinum	50	59	97	94
Potash	62	61	66	80
Bauxite	67	65	76	79
Molybdenum	129	102	86	58
Silver	22	21	28	40
Chromite			256	32
Lead	44	118	30	29
Tungsten	65	76	35	27
Uranium	9	12	18	25
Cobalt	3	16	26	19
Rhodium	21	31	45	16
Palladium	8	8	11	14

The development of industry water reporting guidance the such as those developed by the Minerals Council of Australia (MCA, 2014) and the ICMM (2017) is expected to lead to increasing consistency and sophistication of mine-site water use by companies. Therefore, there is an expectation of improved availability and quality of water use data for the mining industry will improve going forward, and that this will provide new sources of information that can be used to evaluate the water consumption and performance of mining operations.

Currently, the authors are involved in ongoing work to develop a detailed compilation of publically disclosed water use data for mining companies, divisions or individual mining operations. As part of this, instances of water use disclosures in corporate sustainability and environmental compliance reporting are being reviewed and retrospectively assigned to one of 55 data categories (Figure Error! No text of specified style in document..**1**), which have been developed based upon the reporting categories of the MCA's (2014) and ICMM's (2017) water reporting frameworks. The water quality categories defined by these frameworks have also been applied to these data points when sufficient information is available.

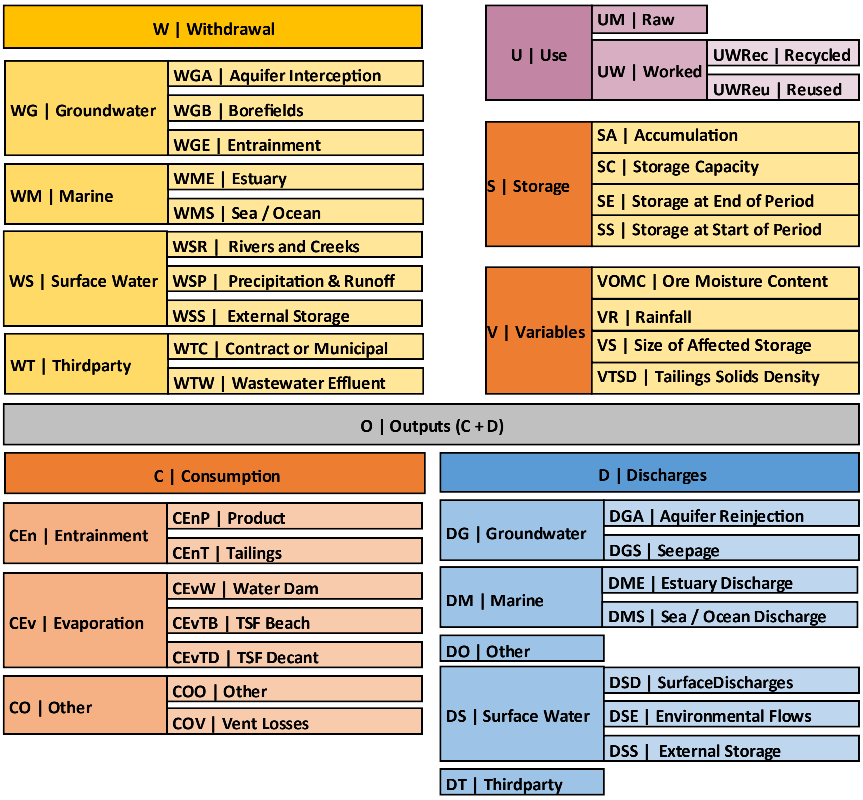


Figure **Error! No text of specified style in document.**.1: Key data categories included in the mine water reporting database, which was largely based upon the reporting categories outlined by MCA (2014) and ICMM (2017).

As the development of this database will extend beyond the duration of doctoral studies considered by this thesis, only a brief review of the dataset is provided here. Currently the database contains reported data for 225 mining operations located across 29 countries (Table 3). Additionally the database also contains aggregated reporting for entire companies or company divisions. In total, the database currently contains 8,346 data points that have been identified within 359 separate corporate sustainability or environmental management reports, and these data points have each been assigned a data category.

Table **4** shows the extent of identified reporting against each of these data categories. The most commonly reported water use metrics by the industry are water withdrawal data, often specifying the source of withdrawals, and also raw water and worked water (reused or recycled) requirements of site processes.

Discharge data also exists for many mining operations. However, reporting is less common for data categories related to the on-site storage of water and also specific modes of water consumption (e.g. evaporation, tailings entrainment, etc.).

Table 3: List of countries containing a mining operation or division that reported data has been compiled for

Countries Containing a Mining Operation or Division with Reported Data			
Argentina	Fiji	Mozambique	Suriname
Australia	France	Namibia	Tanzania
Brazil	Germany	Papua New Guinea	United Kingdom
Canada	India	Peru	United States
Chile	Indonesia	Philippine	Zambia
Cote d'Ivoire	Ireland	Saudi Arabia	
Dem. Rep. of Congo	Laos	South Africa	
Dominican Republic	Mongolia	Spain	

Table 4: Number of data points compiled for each data category

Code	**Description**	**No.**	**Code**	**Description**	**No.**
W	Withdrawals	552	C	Consumption	43
WG	Groundwater	333	CEn	Entrainment	39
WGA	Aquifer Interception	133	CEnP	Product	4
WGB	Borefields	486	CEnT	Tailings Entrainment	4
WGE	Ore Entrainment	24	CEv	Evaporation	58
WM	Marine	54	CEvTB	Tailings Beach Evaporation	5
WMS	Seawater	16	CEvTD	Tailings Decant Evaporation	4
WS	Surface Water	275	CEvW	Water Dam Evaporation	10
WSP	Precipitation and Runoff	109	CO	Other	15
WSR	Rivers and Creeks	79	COD	Dust Suppression	11
WSS	External Storage	33	COO	Other	16
WT	Third-party	151	COV	Vent Losses	10
WTC	Contract or Municipal	124		**Sub-total**	**219**
WTW	Wastewater Effluent	40	D	Discharges	610
	Sub-total	**2,409**	DG	Groundwater	48
U	Use	151	DGS	Seepage	27
UM	Makeup/Raw	2,547	DM	Marine	10
UW	Worked	1,239	DME	Estuary	11
UWRec	Recycled (treated)	18	DMS	Sea/Ocean	28
UWReu	Reused (untreated)	20	DO	Other	46
	Sub-total	**3,975**	DS	Surface Water	124
Div	Diversions	7	DSD	Surface Discharges	23
SA	Accumulation	16	DSE	Environmental Flows	16
SC	Storage Capacity	9	DSS	External Storage	10
SE	Storage at End of Period	16	DT	Third-party	61
SES	Storage at Start of Period	16		**Sub-total**	**1014**
VOMC	Ore Moisture Content	5	O	Outputs (C+D)	150
VR	Rainfall	411			
VP	Pan Evaporation	59			
VS	Size of Affected Water Source	10			
VTSD	Tailings Solids Density	30			
	Sub-total	**579**		**Grand Total**	**8,346**

Given the significant breadth of data currently being reported for the mining industry, it is possible to develop detailed understanding of the overall water balance of many mining operations. For instance, Table **5** presents a summary of key water use statistics for 35 copper mining operations currently included within the database. From this data it is clear that there is substantial variability in how mining operations are utilising and interacting with water. Some mines sites are heavily dependent upon withdrawing water from groundwater, whereas others are more dependent upon surface water systems (including rainfall runoff) or occasionally third-party sources (e.g. municipalities). There is also substantial variability in the intensity of raw water use and also the contribution of worked water (reused or recycled) to total water use. The discharge data is also highly variable and it is assumed that many of the mining operations are operated as zero discharge sites.

Understanding the factors that drive the variability in the observed withdrawal, use and discharge data is not a straightforward task. Copper mining operations are highly variable in terms of their processing configurations, although from a water perspective this can roughly be generalised into two main processing archetypes – heap leaching or flotation separation of sulphide ores – that could form the basis for further assessment (see for instance Northey et al., 2013). There is also a temporal aspect to consider, as multiple decades of data is available for some mines (e.g. Olympic Dam). Therefore, process and technology improvements through time may also be a relevant consideration, as for instance there is some evidence that Chilean copper mines are becoming more water efficient over (Lagos et al., 2017). Finally, the water balance of a mining operation is heavily influenced by variability in weather and hydrological conditions and so evaluating the dataset to identify the influence of these factors is also another potential avenue of future research.

Table 5: Summary of water withdrawals, use and discharges for 25 copper mines. Absence of a data value does not imply that the flow does not exist, rather only no public reporting was identified. Data key: Arithmetic average ± standard deviation (years of data). 'Worked' water is presented relative to total water use (raw + worked water).

Mining Operation	**Withdrawals**					**Use**		**Discharges**
	Groundwater	*Surface*	*Marine*	*Third-party*	*Total*	*Raw*	*Worked*	
	kL/t ore	kL/t ore	kL/t ore	kL/t ore	kL/t ore	kL/t ore	%	kL/t Ore
Antamina	0.07±0.00(4)	0.43±0.06(4)	-	-	0.53±0.08(2)	-	-	0.90±0.06(4)
Alumbrera	-	-	-	-	-	0.59±0.03(2)	-	-
Andina	0.20±0.14(7)	0.83±0.20(7)	-	0.00±0.00(7)	1.01±0.07(10)	1.06±0.16(11)	44.8±6.9(13)	0.80±0.52(11)
Bingham Canyon	-	-	-	-	-	1.13±0.18(6)	49.8±3.9(6)	0.32±0.00(1)
Cadia Valley Operations	0.05±0.01(9)	0.51±0.44(9)	-	0.14±0.04(9)	0.69±0.42(9)	0.40±0.14(11)	74.4±11.4(10)	0.17±0.22(8)
Chuquicamata	0.31±0.52(3)	0.89±0.59(4)	-	0.00±0.00(4)	1.12±0.14(4)	1.04±0.12(4)	87.1±1.4(5)	-
Cobar-CSA	0.29±0.00(2)	21.24±0.00(1)	-	-	-	1.04±0.20(16)	45.5±8.7(3)	-
Codelco Norte	0.10±0.16(3)	0.30±0.18(2)	-	0.00±0.00(1)	0.45±0.02(7)	0.45±0.02(7)	84.8±1.6(8)	0.06±0.14(9)
Collahuasi	0.64±0.04(10)	-	-	0.05±0.00(1)	0.64±0.04(10)	0.61±0.04(13)	77.4±1.5(10)	0.02±0.00(5)
El Teniente	0.10±0.11(5)	1.07±0.28(6)	-	0.00±0.00(3)	1.24±0.24(9)	1.24±0.26(11)	57.5±3.9(12)	1.03±0.40(11)
Ernest Henry	0.62±0.10(5)	0.49±0.13(7)	-	-	-	0.48±0.13(10)	-	-
Escondida	0.58±0.10(6)	-	0.02±0.02(3)	0.00±0.00(1)	0.53±0.06(2)	0.64±0.03(2)	28.3±2.6(2)	0.02±0.01(4)
Gabriela Mistral	0.11±0.03(6)	0.00±0.00(4)	-	0.00±0.00(4)	0.12±0.02(4)	0.12±0.02(3)	51.7±44.2(4)	-
Golden Grove	1.57±0.00(1)	-	-	-	1.51±0.19(5)	-	75.0±0.0(1)	0.37±0.23(3)
Kidd Mine	-	-	-	-	-	-	85.0±0.0(1)	-
Kinsevere	-	-	-	-	4.27±4.10(4)	-	-	-
Las Bambas	-	-	-	-	0.18±0.00(1)	-	15.2±3.7(3)	-
Lomas Bayas	0.06±0.04(8)	0.06±0.05(8)	-	-	0.11±0.02(8)	0.12±0.02(4)	24.4±0.2(2)	-
Lumwana	-	-	-	-	-	0.15±0.06(5)	88.0±2.6(4)	0.82±0.59(4)
Ministro Hales	0.58±0.39(2)	0.00±0.00(2)	-	0.01±0.00(2)	0.58±0.40(2)	0.31±0.00(1)	20.2±1.7(2)	-
Mount Isa (Copper)	-	0.89±0.29(4)	-	-	-	0.49±0.28(9)	66.1±6.7(5)	-
Mount Lyell	1.60±0.00(1)	2.37±0.40(3)	-	-	2.61±1.22(4)	2.03±0.60(2)	14.3±0.0(1)	9.36±4.39(7)
Northparkes	0.43±0.17(9)	0.18±0.10(8)	-	-	0.64±0.17(8)	1.53±2.39(14)	49.7±21.6(10)	-
Oyu Tolgoi	0.56±0.00(1)	-	-	-	-	0.48±0.06(4)	85.0±1.2(4)	-
Ok Tedi	-	0.57±0.21(12)	-	-	-	-	-	-
Olympic Dam	1.49±0.51(28)	-	-	-	-	1.15±0.10(10)	-	-
Palabora	0.34±0.16(5)	0.24±0.11(5)	-	0.50±0.08(3)	1.00±0.35(3)	0.89±0.39(18)	72.1±10.1(12)	0.09±0.00(1)
Prominent Hill	0.65±0.08(6)	0.00±0.00(2)	-	0.00±0.00(2)	0.64±0.14(3)	-	19.5±3.5(2)	-
Radomiro Tomic	0.08±0.02(3)	0.02±0.00(3)	-	-	0.10±0.02(3)	0.10±0.02(4)	88.2±2.7(5)	-
Rosebery	-	-	-	-	19.08±12.27(3)	-	-	7.86±6.58(3)
Salvador	0.58±0.46(6)	1.20±0.54(7)	-	0.00±0.00(6)	1.64±0.16(11)	1.59±0.19(12)	37.9±8.5(12)	0.31±0.45(12)
Sepon	0.05±0.02(2)	1.93±0.86(3)	-	-	3.34±1.52(8)	-	-	3.72±3.51(7)
Spence	-	-	-	0.32±0.04(2)	-	0.32±0.04(2)	96.0±0.0(1)	-
Telfer	0.91±0.00(1)	-	-	-	-	0.87±0.34(7)	12.9±8.2(6)	0.04±0.01(2)
Zaldivar	-	-	-	-	-	0.15±0.01(6)	93.0±1.4(2)	0.00±0.00(6)

The water quality parameters of input water to site processes are often well quantified by the industry as it affects ore processing and metal recovery. As a result, there have been some successful surveys of the quality of water used by the mining industry for processing. For instance, Table **6** show the results of a survey into the operating practices of medium-sized gold mines in Australia, which captured data on processing techniques, reagent and power consumption, raw water consumption and quality as well as tailings management (Sparrow and Woodcock, 1993). Given the level of detail captured by this survey across many mining operations and companies, it suggests that it may be possible to conduct successful surveys for other sectors of the mining industry to develop more rigorous life cycle inventory datasets. Such a research effort would be a significant undertaking in terms of time and effort, however the results would be highly useful for both life cycle assessment practitioners and also the mining industry more generally.

Table 6: Raw water source and quality parameters for medium Australian gold mines in the year 1990. Adapted from Sparrow and Woodcock (1993).

	Raw water		**pH**	**TDS**	**Na**	**K**	**Mg**	**Ca**	**Cl**	**SO_4**	**Other**
Mine	**kL/t**	**Source**	**pH**	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**	
Bamboo Creek	-	Bore	-	-	-	-	-	-	-	-	-
Bannockburn	1	-	7.7	900	250	12	75	45	320	170	350ppm HCO_3
Bluebird	-	Potable	-	-	-	-	-	-	-	-	-
Browns Creek	-	Fresh (from pit)	-	-	-	-	-	-	-	-	-
Comet	-	Bore	7.8	3000	300	25	150	100	500	100	20 ppm CO_3
Copperhead	1.32	Bore	7.9	112000	36500	470	3200	2250	66500	2800	90 ppm NO_3
Darlot	0.8	Bore	7.6	1080	280	45	39	57	315	216	5 ppm CO_3 70 ppm NO_3
Davyhurst	1.3	Bore	6.3	43900	12400	195	1760	5404	22500	3500	<1 ppm CO_3 7 ppm NO_3
Enterprise	-	Fresh and bore	6.6	-	48	2	26	19	7	5	225 ppm HCO_3
Fortnum	1	Fresh bore	7	650	100	11	25	20	150	80	<1 ppm CO_3 60ppm NO_3
Fraser	1.5	Saline bore	7.4	116000	25550	-	3400	870	52500	5100	-
Gidgee	1.27	Bore and pits	7.2	1500	-	-	-	-	-	-	-
Golden Crown	-	Underground discharge	7.6	58100	15350	195	1850	1130	30390	1855	<0.3 ppm CO_3
Golden Kilometre	0.85	Saline bore	6.5	100000	55000	-	2000	2000	36000	4000	-
Golden Kilometre	1	Saline bore	6.5	100000	55000	-	2000	2000	36000	4000	-
Goodall	1.32	Dam Dewater. bores	3.3 3.2	-	10 11	3 6	87 140	23 29	4 16	610 1100	-
Greenfields	1.5	W. Ford decline	8.1	30200	8650	61	1500	240	13500	4260	<1 ppm CO_3
Harbour Lights	1	Bore	7.5	2500	400	20	60	60	600	250	60 ppm NO_3
Higginsville	1	Saline bore	5.3	20000	60000	800	7000	500	11000	10500	<500 ppm

	Raw water		pH	TDS	Na	K	Mg	Ca	Cl	SO_4	Other
Mine	**kL/t**	**Source**	**pH**	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**	
				0					0		CO_3
Jubilee	-	Saline bore	3.3	50700	15400	320	2130	170	28200	4360	<2 ppm CO_3 105 ppm SiO_2
Kaltails	-	Saline bore	3.9	150000	65000	230	8700	830	109000	11000	-
Kanowna	-	Bore	6.8	40000-120000	8000	-	4000	-	-	-	-
Karonie	0.5	Bore	5	181000	52700	295	6470	690	83400	11900	<1 ppm CO_3 8 ppm Fe
Kundana	1	Saline bore	7	238000	85500	215	8000	2300	150000	5000	-
Labouchere	-	Bore	7.4	1200	200	11	55	75	300	200	<1 ppm CO_3 <1 ppm NO_3 1450 μS/cm
Lady Bountiful	1.3	-	6.8	64000	19400	29	2990	820	34000	6600	<1 ppm NO_3
Laverton operations	1.2	-	8.1	10000	2000	8550	1000	2000	70	450	-
Lawlers	1.6	Fresh bore and saline pit	8.3	600	100	8	70	10	140	120	-
Lucky Draw	-	Fresh	-	-	-	-	-	-	-	-	-
Magdala, Wonga	0.35	Mine	7.9	7400	1850	42	340	350	2400	1000	-
Maldon	1.5	Mine	7.1	2000	500	15	200	40	1000	160	450 ppm HCO_3
Marvel Loch	1.79	Saline bore	6.5	23000	6400	160	1000	275	12100	1800	110 ppm HCO_3
Matilda	1.2	Bore	7.8	3500	-	-	-	-	-	-	-
Moline	0.95	Bore and dam return	7	720	100	5	68	82	39	500	-
Mount Gibson	1.6	Bore Pit	7.5 6.4	26000 209000	7450 64000	240 2000	1100 7500	250 750	13500 120000	2000 14300	<5 ppm CO_3 90 ppm SiO_2
Nevoria	-	Saline bore	6.8	68000	11000	200	2500	1000	25000	4000	80 ppm CO_3
Nobles Nob, White Devil	-	Bore and fresh	6.6	8300	1700	85	500	570	3700	1660	400 ppm CO_3 25 ppm NO_3
Ora Banda	-	Saline bore	7.5	44000	11000	-	2600	245	20800	4350	68 ppm SiO_2
Pajingo	1.5	Bore and pits	7	3500	800	13	150	100	1150	300	700 ppm CO_3
Parkes	0.75	Sewage plant Old quarries	6.9 8.2	900 3600	160 600	18 6	19 288	36 159	216 1800	46 300	355 ppm CO_3 275 ppm CO_3
Peak Hill Resources	-	Bore	7.2	850	250	10	40	35	190	100	1 ppm CO_3 550 ppm

	Raw water		**pH**	**TDS**	**Na**	**K**	**Mg**	**Ca**	**Cl**	**SO_4**	**Other**
Mine	**kL/t**	**Source**	**pH**	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**	
											HCO_3
Polaris	2	Bore and pits	7.3	70000	300000	300	4000	600	55000	6000	40 ppm CO_3
Ravenswood	-	Open cut rainwater	7.5	1000	47	9	57	250	7	730	-
Reedy	1.1	Bore, dam return	9.2	2900	860	8	23	25	120	350	100 ppm CO_3
Sheahan-Grants	1.3	Belubula R. Dam return	8.5 8.5	-	32 1470	6 31	22 23	34 610	39 13550	15 2200	218 ppm CO_3 2000 ppm SCN
Sons of Gwalia	-	Saline bore	7.5	54000	14500	300	1500	1100	24000	3800	-
Tanami	1.43	Bore and pits	7.8	1130	167	48	64	53	165	85	289 ppm CO_3 36 ppm NO_3
Tarmoola	1.2	-	7	1200	340	50	38	70	750	240	1 ppm CO_3
Temora	1.3	Fresh dam & potable bore	6.6	-	10	5	3	2	10	2	30 ppm CO_3
Three Mile Hill	1	Saline bore	6.5	57000	17060	100	2750	140	30400	6800	128 ppm HCO_3
Tower Hill	1.3	Saline bore	7.5-8.0	80000	10000	4000	-	-	20000	7200	120 ppm HCO_3
Transvaal	1.8	-	6.7	113200	25500	630	3400	870	72500	5100	50 ppm CO_3
Tuckabianna	1.4	Fresh and bore	7.8	675	110	7	20	28	150	90	60 ppm CO_3
White Range	-	Bore	-	-	-	-	-	-	-	-	-
Youanmi	1.22	Fresh bore and saline pit	7.3	1100	275	10	47	54	400	120	-
Zoroastrian, Davyhurst	1.5	Saline bore	6.9	89100	25000	190	5000	515	47600	5200	-

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