Columbia Water Center

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MINING & WATER RISK: DIAGNOSIS, BENCHMARKING, AND QUANTITATIVE ANALYSIS OF FINANCIAL IMPACTS

A Synthesis of Key Findings

Research Project Report for research supported by Norges Bank Investment Management (NBIM)

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ABSTRACT

The mining sector has seen challenges with respect to access to water, as well as regulatory and social pressures related to water contamination and resource impacts. These factors influence current mining production and costs, and may pose risks for long term investments in the sector. This chapter summarizes the key findings of a 3 year academic research project aimed at understanding how investors and mining companies could approach the quantitative identification and financial valuation of water related risks in mining. Given their importance to the growing global economy, copper and gold were used as the context for developing data and a risk quantification framework. Physical, economic, social and regulatory factors associated with water in the main countries where these metals are principally mined were considered. The perspective is that of investor and companies concerned with long term environmental risks that are not necessarily well priced by the market.

As with many other environmental and social risk factors, water risks related to mining are seen as site specific and idiosyncratic issues, whose attributes are not easily disclosed or quantified. Water scarcity and increasing costs of water management, climate extremes such as floods and droughts, social conflict resolution, changing regulatory factors and reputational risks receive media and industry attention, but are difficult to quantify as financial risks. A theoretical framework for addressing these challenges as well as data for empirical analyses are lacking. This was addressed considering both asset and portfolio level risk, in our project.

The main findings and contributions of the research are summarized as:

- Capital and operating costs for water use in mining and material processing, including water provision, dewatering, and treatment vary by site. They can contribute to as much as 10% of production costs, and have been increasing, especially in water scarce areas and in areas where there are social conflicts over water and mining. Declining ore grades lead to more water use and cost. Increases in water use efficiency and water re-use, as well as the use of renewable energy sources are changing the use and cost spectrum. These costs and the associated carbon footprint are assessed and disclosed by the major mining companies. While the industry wide cost curve may increase in the future due to water management costs, market mechanisms appear to reasonably price these costs into net asset values.
- Publicly available water scarcity risk measures and water footprint analyses do not directly inform financial risk, but may provide useful benchmarks for assessing company performance on sustainability.
- Mining companies actively address water and climate risks through engineering, insurance, and stakeholder engagement. As a result, material financial risks for long term investors emerge from risks that are residual to these efforts, or are incorrectly estimated.
- Our longitudinal analysis of quarterly reports from mining companies revealed that projected remediation and site closure costs consistently increase as a mine approaches closure, even accounting for inflation, changes in production, reserves and other variables. This consistent bias of under-reporting long run costs is an example of a miss-specification of future costs and risks. Further research into decomposing bias and uncertainty in company disclosures of environmental risk factors is needed.
- Asset stranding is perhaps the most significant financial risk for a long term investor. This can emerge due to a combination or interaction of factors that are inherently stochastic in nature. Even where an asset is not stranded, significant impacts on production or reconstruction may be incurred. The drivers include:
    - Persistent decline in global metal prices.
    - Low probability, high impact events, often related to climate extremes or seismic hazards that result in major infrastructure failure. Examples include extreme rainfall and flooding, unanticipated long-lasting drought, catastrophic failure of tailings dams, cumulative effects of pollution, and failure of site remediation and pollution controls.
    - Social conflict and regulatory pressure that emerges due to the degradation of a regional water source, due to a combination of water use or pollution by mining activity, regulatory failure and climate, and other socio-political factors.

- Mining companies respond to these inter-dependent, stochastic factors by making "optimal" decisions at the time these events are triggered, considering the residual value of the mine at the time and the costs of mitigating the risk. This dependence on the time sequence of composite risk events, and the associated decision making, induces a nonlinearity that is not readily addressed by typical discounted cash flow analyses for mine valuation under uncertainty.
- A real options, simulation-optimization model provides a framework for modeling such a situation, but requires considerably more data. Two additional factors complicate the application of such a model for the valuation of mines considering water risks. The first is the paucity of data for the estimation of the probability and the impacts of the extreme physical or social risk events. The second is that mines will typically not disclose their detailed risk analyses as to these events, i.e. these are often private risks.
- We developed a theoretical framework for robust, real options modeling that is applicable to this general class of problem and applied it to the evaluation of net asset values of mines and mine portfolios considering a stochastic hazard occurrence model for selected factors of concern. Novel, robust probability estimation techniques for the stochastic hazard occurrence model were integrated into the real options model and its calibration. The model is applied to demonstrate whether a certain mine or portfolio may be over or under valued relative to the market valuation considering specific risk factors.
- The residual risk of extreme rainfall and of droughts as potential hazards to infrastructure and production, or for aggravating water scarcity related conflicts, was explored. For varying normative risk based infrastructure design criteria that may be used by mining companies, the potential failure of the design at each site and across a company's portfolio was assessed, using globally reconstructed climate data from 1851-2014. Given the time clustering of wet/dry periods and spatial teleconnections in climate extremes we find that a) the at-site infrastructure may be significantly over/under designed depending on whether the actual time period (e.g., 1960 to 1980) used to design the infrastructure was a wet or dry period; and b) especially for more extreme events (e.g., 100 year return period) that may lead to catastrophic failure, the risk faced by a portfolio of copper or gold mines may be significantly (3 to 5x) higher than expected by chance. Value at risk and conditional value at risk for each threshold was computed for major copper and gold mining companies. Properly characterizing past and future climate risk manifest through water requires an analysis of past climate cycles as well as future projections.
- Tailing storage facility failures are a catastrophic risk factor. Most common triggers are overtopping and geotechnical failure. Resulting damage due to the resulting wave of water and toxic materials can be a significant liability. A probabilistic model was developed to predict the range of downstream area that may be impacted as a function of the physical attributes of the dam. A procedure for a probabilistic hazard rating for each facility based on downstream population and ecological assets that could be affected was developed. Since no global inventory of tailing dams exists, a machine learning approach that uses publicly available satellite imagery to identify the dams and some key attributes was developed.
- Cumulative effects in space and time from water pollution due to mining were identified as a significant long-term risk. Existing environmental impact assessment and regulatory processes do not adequately monitor trends in pollution and attribute them to specific activities in a way that can permit corrective action before a serious environmental degradation occurs that can then lead to a significant threat to the license to operate for the mining industry in a region. We propose a new scientifically based, statistically rigorous approach to address this situation, that would benefit all stakeholders.
- Using a novel data set we developed for Peru on social conflict related to water and mining, and relevant co-variates we developed a Bayesian model to predict he probability of conflict. The past history of conflict, drought, water quality degradation, mining intensity, fines for pollution, indigenous communities, population, and the magnitude of tax transfers to local governance organizations from mining tax revenues emerge as significant predictors.
- A comparative analysis of regulations covering water allocation, permits, tariffs, discharges, reporting obligations, community engagement and enforcement in the major copper and gold mining countries was prepared.

These research findings were presented at a workshop at NBIM in January 2018. Data sets on climate, water use and discharge, water pollution, production, costs and revenues, tailing dams, water conflict and other factors were compiled. These data, the real options model, the climate risk assessment model, the tailings dam hazard identification tools, and the conflict probability model, and journal papers published under the project are available through the Columbia Water Center.

Water related risks have been highlighted as a concern by social, government and industry organizations and the media. However, a structured approach to the financial valuation of these risks has not evolved, even though "water risk" disclosure requirements have emerged, and data collection and disclosure of water footprints and water balances at the aggregate company level has become common. Many companies are also engaging NGOs and communities around their operations to assess and mitigate these risks, but have not yet developed an approach to risk analysis. These activities recognize the social concern over water scarcity and increasing competition. The "water risk" metrics being used reflect a desire to see sustainable water use practices, but typically do not price risk. To address the long term risks associated with water, investors and companies need to consider risk exposure pathways related to water scarcity, flooding, water pollution, infrastructure failure and their ensuing impacts on asset operations, as well as on ecosystems and society that could be adversely impacted.

Low-probability high-impact events can have a catastrophic impact on local communities and on company and portfolio valuations / returns. Long term stakeholders need to be cognizant of these risks in their decision processes and encourage better alignment between themselves and management.

Companies need to develop risk mitigation strategies for each exposure pathway that translates into a significant operational or financial or reputational risk. Exposure pathways that lead to a potential for asset stranding or loss of license to operate, even with a relatively low probability, are particularly important to assess. Tailings dam failures induced by overtopping or other factors are an example of a low probability, high impact infrastructure failure whose exposure pathway needs to be assessed. Climate extremes and seismic hazards emerge as a critical factor for long term water risk exposure pathways for mines and hence companies need to assess and disclose their efforts towards the mitigation of these risks, as well as the potential impacts associated with the failure of their risk mitigation plans. Climate change considerations may amplify these risks, but given that the multi-year persistence of wet and dry regimes of climate has only recently been scientifically understood, many of the traditional approaches to assessing the risk of extreme rainfall or drought, or other climatic factors, are likely to have been based on inadequate or non-representative data, and may need to be re-examined. Further, most such risk analyses are done at the asset level and assume that risks at other assets owned by the company of relevant to their supply chain will likely not be affected by climate extremes in the same year. Since our analyses show that globally distributed mining asset portfolios can experience multiple climate induced failures in the same year, reflecting spatial-teleconnections in climate risk, it is important for companies and investors to consider a spatial assessment of portfolio risk related to physical climate factors, at least using a screening tool to assess the potential of multiple "hits" to their portfolio in the same year. Global climate data sets that extend back at least a century are available and can be used for such risk assessments.

Discounted cash flows should not be the only methodology relied upon for decision making. Our robust real options approach is superior for risk based valuation with limited data.

Due to rising concerns about the physical exposure of mining companies to climate change, we recommend the implementation of a systematic and comprehensive approach which quantifies the impact of these risks. We recommend that companies follow a quantitative approach which recognizes both the stochasticity and the lack of enough data required to precisely quantify the risk derived from these exposures. We recognize the challenges that these elements of uncertainty bring about in developing such an approach. In an effort to mitigate these challenges, a significant portion of our research focused on the study of a wide range of methods which can be used to quantify financial and risk valuations in the context of ambiguities derived, for example, from lack of complete data. We put forward practical valuation tools which are rooted in fundamental decision-theoretic principles. As a part of these tools, we developed a real-options valuation calculator with a module which quantifies model ambiguity in physical risks with potential material impact. This provides a more robust assessment of a risk weighted valuation than discounted cash flow methods typically used. While we do not necessarily recommend that companies follow a specific valuation methodology, the tools that we provided can be freely used and, more importantly, can be used as a blueprint which exemplifies a systematic approach to quantify stochasticity and lack of information.

Investors, local communities, employees and regulators need to be cognizant that mine study work is prone to bias – different stakeholders need to find ways to hold mine management accountable for consistently providing unbiased information.

It is well recognized that mine reserves, production, environmental factors, and market valuations are highly uncertain over the 20-70 years that a mine may operate. However, systematic under/over valuation of costs/revenues in early to mid-life of mines can translate into a significant long term risk for investors. Our research focused only on remediation costs given our interest in water and the environment. Our findings of systematic under-valuation of these costs as a function of mining stage suggest that investors should develop tools to more systematically analyze longitudinal financial reporting and risk disclosures by mining companies and mining companies review these estimates to assess the sources of systematic bias in estimation and their potential correction.

Long-term stakeholders need to be aware of risks that can slowly manifest themselves over time, such as cumulative pollution effects. Through better disclosure, companies will be able to identify and encourage companies to mitigate these risks before the problem escalates to a level that is financially or technically unsolvable.

Cumulative pollution can occur in a river basin, even if each mine and other industry or cities conform to their pollutant discharge permits. This situation can emerge since many regulators as well as mine operators may only look at their own pollutant discharge to surface and groundwater bodies, and assume that the water availability in the future for diluting the pollution may be similar to what it has been in the past. As cumulative effects of pollution and water depletion in natural bodies emerge, social and regulatory pressure is likely to impact the entire industry and lead to significant operational risks and concerns over license to operate. For mine operators, this translates into the need to assess water quality, pollutant discharge, and water quantity trends for their operations, as well as in the river basins where they operate, and to be proactive to address cumulative and emerging problems collectively with other stakeholders. Disclosure of such efforts to investors should improve the perception of long term risk exposure.

Stakeholders can use a data driven approach to identify the likelihood of water related social conflict. The key parameters inducing conflict can be identified, which can help shape decision processes by investors, regulators and company management.

Social conflict and regulatory pressures related to water scarcity, and/or pollution emerge and are sustained once there is evidence of or perception of resource damage, and stakeholder groups organize around these or related issues. Often drought, flooding, infrastructure failure, pollution, ecosystem degradation and other physical factors may be a trigger for social conflict, but socio-political-economic factors and the history of labor relations, as well as community interactions and development by the mining company and the effectiveness of governance and regulatory factors may dominate the reasons for the persistence of social conflict. To develop a quantitative approach to assess the potential impact of these diverse factors, data collection across space and over time is essential. Investors and companies should work with governments and non-government organizations to develop a systematic, long term data collection strategy to facilitate the detection and assessment of the key factors that emerge/dominate in a given area, and hence conceptualize strategies to mitigate these risks. Including these factors in the risk exposure pathway analysis is very important.

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INTRODUCTION

Water risks have emerged as a significant concern for long-term investors, corporations and policy makers. Many mines face increasing costs for water management, and related social conflicts and regulatory actions. This has led to efforts towards the assessment, mitigation and valuation of these risks. Four types of activities are noted.

First, disclosure processes (e.g., by Global Reporting Initiative, CDP Water, ICMM, Queensland Water Accounting Framework, IRMA, SASE, SASB) are being developed to characterize water risks for investors. Disclosure by publicly held mining companies is usually at the corporate sustainability level, and provides aggregate measures of water use, wastewater discharge or water footprint with some quantification of total costs, and guidance as to trends in water re-use/efficiency improvement, desalination and social conflicts that may apply to specific mining projects.

Second, general water risk mapping and analysis tools focused on scarcity, pollution and/or flooding potential are developed by organizations such as the World Resources Institute, the World Wildlife Fund, Ceres and Ecolab. These tools use limited archival data on estimated hydrologic conditions and water use to assess water scarcity for watersheds, and may facilitate some water cost and value analyses to support water stewardship and resource management activities.

Third, consultants work with mining companies to identify and implement technologies, stakeholder engagement processes, and handle permitting and regulatory tasks for risk mitigation and management. Detailed at-site physical, social and environmental data is collected as part of such efforts. Typically, only summaries of such information are disclosed.

Fourth, public sector regulators require reporting of a variety of water use, quality and watershed restoration activities, including an initial environmental impact assessment and risk analysis with some estimates of remediation and related costs, as part of the permitting and environmental regulation process. The associated data could potentially be very useful for long term risk assessment and evaluation studies. However, in most jurisdictions, the associated longitudinal data are neither readily available, nor routinely used by regulators for risk attribution to specific mining enterprises.

These are very useful activities. However, they provide limited information on the physical, social, regulatory and financial risk for a specific mining operation, or for a portfolio of mines. Investors have a wide range of time scales of interest, from seconds for high frequency trading, to decades for pension funds. We are particularly interested in how to better understand, quantify and inform water related risks that are material for long-term investors, given that mines usually have a multi-decade life. Water availability as well as water related hazards are closely tied to climate. The financial industry has been developing guidance for climate related financial disclosure (https://www.fsb-tcfd.org/). Such disclosures are now well developed for an industry's carbon footprint. However, physical and transition risks associated with climate are identified, but processes for robustly translating these into long-term material financial risks in this context are still needed. Our analyses in the mining context provide one of the first sectoral approaches to the assessment of physical climate risk as related to water.

Exposure to floods, droughts and aridity, i.e., climatic factors, is a determinant of material financial risks for mining companies. Mine designs mitigate these risks to a degree through a combination of infrastructure and insurance. Wastewater treatment, storage and discharge may also depend on climatic factors, e.g., receiving streamflow conditions, and may or may not properly account for the cumulative effects of multiple polluters. Failure of the infrastructure or persistent negative impacts on the environment can lead to significant financial liabilities, reputational risk, social conflict, regulatory pressure and stranded assets. The interaction of physical, social, environmental and regulatory factors, rather than a single readily indexed water factor may thus translate into the financial risk exposure of a particular mine. Further, since global climate exhibits significant spatial correlations and temporal clustering of floods and droughts, related to climate modes such as the El Nino Southern Oscillation, there is a potential for many such "risk" events to be triggered over the same financial reporting cycle for a mining company, enhancing mining portfolio risk.

Given this background, the specific objectives for our research project were to:

- Develop a quantitative approach to financial risk analysis for water and mining
    - Assess data available relative to critical exposure pathways
    - Explore how available climatic, hydrologic, social and economic data may inform the risk
    - Design and test an approach that addresses the paucity and asymmetry of information
- Assess Social, Legal and Regulatory factors and their implications for risk
    - Comparative Analysis of water related mining regulations across countries
    - Identify significant covariates of social conflict associated with water and mining
    - Evaluate current water disclosure and its utility
- Synthesize and Summarize recommendations based on selected case studies

Following initial discussions and analyses, the scope of the research was limited to:

- Primarily Copper & Gold mining given its significance for economic development, and the recent increase in valuation and production in areas where social conflicts and increasing costs related to aridity or pollution are manifest
- The USA, Chile, Peru, Canada, S. Africa and Australia as the main settings of interest (as the main copper and gold producers for which data is accessible and likely to be of better quality)
- The following physical factors and their inter-relationships as part of the exposure pathways:
    - Climate: Extreme rainfall/flooding and Drought/Scarcity
    - Cumulative Effects of mining on surface or ground water pollution
    - Failure of Tailings Dams and related polluted water discharge and ecological impacts

A perspective on how we construe the important aspects of financial risk in this context is offered next. The remainder of the chapter is organized in 3 sections: Financial, Physical and Social risk. A high level summary of our proposed approach for financial risk assessment is presented first. The physical risk section includes key findings from investigations into the role of climate risk; an overview of the issues related to tailing dam failures and the development of a hazard index given basic parameters of a tailings dam; and an overview of findings from statistical analyses for cumulative effects is. The social risk section summarizes the key findings from the quantitative analyses of covariates for social conflict in Peru and Mexico, and their implications; findings from a comparative review of legal and regulatory processes across countries; and an evaluation of current disclosure of water risks. Data and software products developed by the project and publicly available by request are itemized at the end.

A PERSPECTIVE ON WATER RISK IN MINING

In this section, we develop a perspective for financial risk related to water in the mining sector. The main points are:

- General metrics of water scarcity or water management costs are useful for sustainability perspectives and asset valuation. However, uncertainties as to climate, infrastructure failure, social conflict and regulation associated with water rather are more likely to determine water related financial risks for long-term investors

- Bottom up (mine level) and portfolio (company) level analyses are needed. Correlations and temporal clustering induced by climate and commodity prices need to be considered in risk aggregation.
- An identification of risk exposure pathways, and associated trigger indicators can help focus on what data is available to quantify these uncertainties
- The social, environmental and economic exposure pathways include low probability, high impact events, and also persistent changes over time. Robust quantification of these factors requires long time series data on mine as well as regional social and environmental variables. Such data does not exist globally. Hence, an approach for risk quantification, that precludes extensive at-site data collection, needs to identify a few critical factors or triggers for which there is a reasonable expectation of data availability.
- Discounted cash flow based approaches to valuation of mining companies may not appropriately account for the social-environmental risk factors for long-term investors. Market mechanisms price in some of the water and environmental risks based on financial disclosures by companies and analyst ratings of social and environmental risk factors.
- Consequently, the misclassification of the long-term risks or the risks residual to those already priced by the market became the objective of the research.

RISK DUE TO INCREASING WATER MANAGEMENT COSTS

Water management costs for mining operations will continue increasing in the future due to:

1. Increasing water scarcity, pollution, and conflict over access to the resource
    a. Increasing climate variability and exposure to droughts
    b. Increasing competition for the resource
    c. Move to market based water allocation mechanisms
2. The consequent need to develop new and more efficient water use strategies
    a. Desalination and long distance pumping with high lift
    b. Additional on-site water storage
    c. Wastewater treatment and re-use
    d. The use of dry tailings and better pollution controls
3. Declining ore grades at existing mines and across the industry
    a. Higher water use per ton of metal produced

Northey et al (2017) and Mudd et al (2018) provide data that illustrate these points, but also note the wide variation in these costs and the cost trends across mining operations that cannot be explained directly by readily available covariates. Water management costs have increased to as much as 10% of capital and operation costs at some mines, and there are examples of asset stranding due to social conflict. Our review of the literature and interviews with mining companies support these analyses. We note that metal market unit prices exhibit annual fluctuations that are often in the range of 30-300%, reflecting variation in supply and demand (Figure 1). These prices have generally increased over the last two decades, in part due to the economic development of China and other countries. Many of the water cost factors listed above are expected to maintain their trends across the industry. Thus, it is likely that they will define the new marginal cost curve for the industry. Projections from one company suggest that efficiency improvements in water use will occur without a substantial change in the marginal cost curve for production (Figure 2). The Chilean Copper Commission also reports reductions in copper cash cost curves due to efficiency improvements, despite the country being a poster child for high water management costs. In the absence of substitution of copper by another substance, revenue uncertainty may then dominate the shift in the production cost increases due to water management, and hence the financial risk.

Figure 1. Fluctuations in Copper prices[1]. Significant fluctuations are noted even outside the two recession periods marked in gray

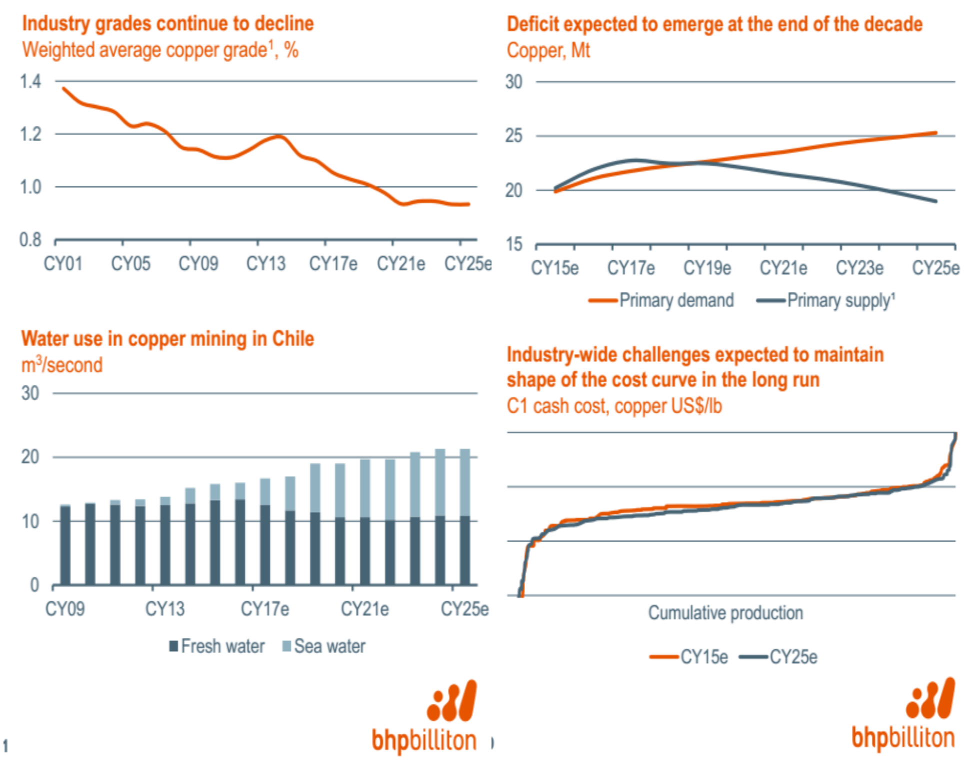

Figure 2.

BHP Billiton[2] projections of future copper ore grades; supply-demand deficit indicating direction of copper price trends; shifts in water use that suggest higher unit costs; and projected cost curve that shows increases only at the highest production levels.

[1] http:\www.macrotrends.net\1476\copper-prices-historical-chart-data
[2] https://www.bhp.com/-/media/bhp/documents/investors/news/2015/151201_coppersitetourday1.pdf?la=en

From an investment perspective, a mining portfolio may consist of existing mines that may be operating or on care and maintenance, as well as new mines that are not yet operational. For new mines, water and wastewater permitting can be a risk, and detailed disclosures of these risks are common practice. For existing, operating mines, an increase in future operational costs related to water is a concern, but is subject to annual disclosure by the mining company. For mines that are on a “care” status, the mine may become operational again if the commodity prices increase and are favorable for redevelopment, even considering the higher marginal costs. These may include the costs of environmental remediation and risk management. In practice, many mines may also be listed in this status to defer post-closure remediation actions. New and restarted mines may face significant regulatory pressure and social conflict related to water issues, especially if there is a negative history of the company or of the location in that regard. There is often considerable uncertainty as to the outcome of such processes. Financial issues that are well assessed and disclosed do not translate into risks, while those with a high degree of uncertainty are potential risks for investors.

Beyond the financial disclosures from mining companies, market analysts review potential revenue and cost risks, including social and environmental factors. A key question then is whether the Net Asset Value of a mine or mining company, or the associated credit rating is properly benchmarked by the market. This is especially a concern for long-term investors who are interested in the fundamental valuation of these assets, and may face a long-term exposure that results from poor environmental performance of a company or sector, or from regional socio-political change that leads to asset stranding. Discounted cash flow analysis techniques used by short-term investors will likely not adequately capture such long-term social and environmental risk factors.

WATER RISK MEASURES

The key points are:

- Publicly available measures of "water risk" are unlikely to provide a quantifiable measure of financial risk faced by mining operations
- Water footprint and water balance analyses are useful to compare the water management efficiency of mining operations, but do not directly inform financial risks, or their mitigation.
- Developing detailed databases of water use, treatment, associated costs and details of the technologies used could be useful to develop a cost curve for water management, and for a residual risk analysis.
- We have assembled such a data base in collaboration with Prof. Gavin Mudd, through his interviews and site visits to over 100 mines. The data collected is available through Amazon Web Service.

A number of water risk indices were introduced in the last decade that purport to inform investors and policy makers as to location specific water risk. The Aqueduct product produced by the World Resources Institute has become the most popular. Their basic water scarcity index is based on an estimate of the ratio of estimated average annual water use to average annual renewable water supply at a location. TetraTech provides a similar measure that also includes climate change projections. Yet, very limited data on water use are available globally. The renewable water supply is estimated using rather coarse meteorological data used with a hydrological model. Very little global hydrologic data is available to calibrate the model parameters. As a result, both the numerator and the denominator in these calculations, and hence the result present high uncertainty. Consequently, while such indices may be useful to get a general comparative assessment of which locations are more stressed than others, they may not actually inform water or financial risk faced by mining operations or investors. Our analyses using regressions of market assessments of Net Asset Value or Credit Ratings of mining companies, using the Aqueduct water scarcity measures did not reveal an association between the financial and the water risk measures. This may mean that either the market does not price in this water risk information, or that the information is not consistent with analyst valuation of the financial risk.

Northey et al (2016) evaluate the ability to perform and the utility of water footprint and life cycle analyses at mines. They identify that the data to do such analyses is very limited. Further, even if data were available, it would not shed light on cumulative effects, flooding, drought, dam failures and other sources of risk. With appropriate data collection and development they could help with the benchmarking of different mines' water management processes, price competing technologies and their performance and add content to corporate sustainability reports. We note that pursuing such analyses should be encouraged to promote sustainability in the industry, but may not be directly useful for financial risk analysis at this point. We collaborated with Stephen Northey, Gavin

Mudd and Tim Werner to compile as extensive a data set on water use for this purpose as could be put together at this time. This data is made available within the repository.

EXPOSURE PATHWAYS

Examples of three mine level financial risk pathways that can lead to asset stranding are shown in Figure 3. For the first two pathways induced by drought and extreme rainfall exposure respectively, climate is clearly the trigger, but the planning and risk mitigation strategies of the mining company determine both the costs incurred, the liabilities from impacts on others and the revenue. The data collected by Mudd et al (2018) shows significant impacts on production and unit costs due to drought and flood disruptions. However, mining companies typically ramp up production subsequently, if the demand for the metals is high, leading to lower unit costs and higher production in that period. Thus, in terms of short-term cost and revenue, the impacts of these events may be restricted to the overlap between the duration of the event, and the financial reporting cycle. However, a revision of the infrastructure design and implementation for risk mitigation may also occur and this would add an increment to the longer term capital cost. Such a decision would be contingent on a re-evaluation of the climate risk exposure for the mine and also for the communities to be impacted. Often, initial design of infrastructure to address flooding and drought targets an event return period ranging from 10 to 10000 years. However, the design level is generally estimated from very short (~5-50 years) at-site data sets. This leads to high uncertainty in the level of risk protection achieved, especially given that climate exhibits significant quasi-periodic variability and hence clustering of extremes at inter-annual and decadal time scales, even where anthropogenic climate change is not of interest.

The third example highlights the role of cumulative effects of mine wastewater discharges on regional water quality. This may be a factor even where all mines meet pollutant discharge requirements. From the perspective of misclassification or residual risk relative to mine operator and market analyst ratings, this led us to examine:

- Climate risk exposure at the mine and portfolio level, for both dry and wet extremes
- Design criteria and failure impacts for tailing dams
- Quantification of cumulative effects of mining on water quality
- How these factors may intersect with social conflict and regulatory processes

Social conflicts may emerge where mining has led to adverse water access or water quality impacts. The regulatory process plays a key role in this outcome, but is difficult to quantify. We reviewed both the nature of regulations in different countries and the effectiveness of the regulatory process in selected countries. The fragmentation of regulatory oversight that is endemic in all countries, but especially where conflicts have emerged became a focal point of this analysis, and has led us to develop a new science based proposal for how the regulatory process should be applied to assure early detection, attribution and resolution of emerging problems.

In the sections that follow, we summarize the approach and findings for each of these individual analyses, recognizing that the dispersed nature of the data and the literature available did not allow us to do a comprehensive integration of these discrete analyses into a comprehensive evaluation globally or for any specific region.

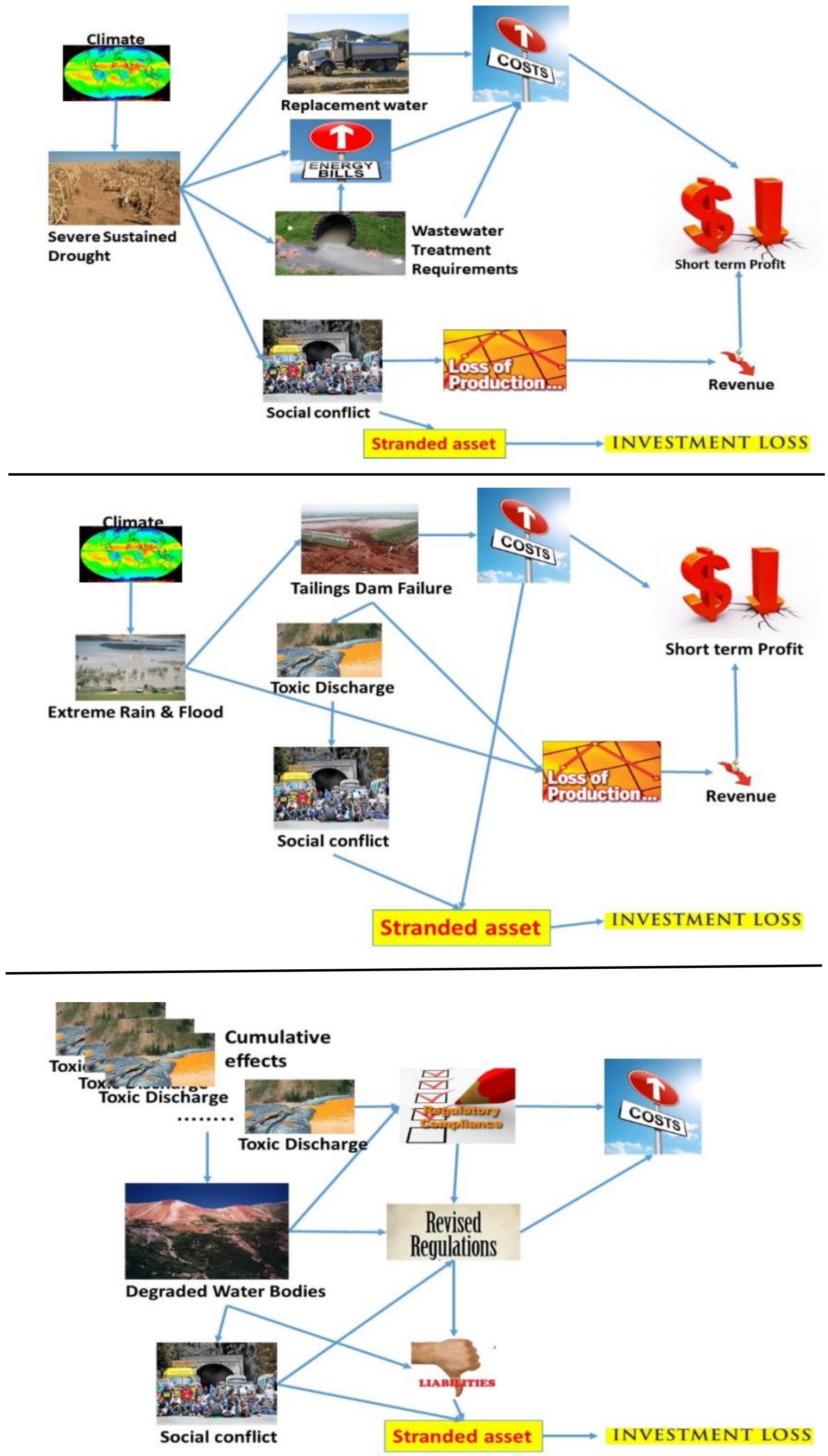

Figure 3.

Three examples of exposure pathways for water related risk for long-term mining investors

a) Risk induced by a severe sustained drought

b) Risk induced by extreme rainfall and flooding

c) Risk induced by cumulative effects from water pollution

REMEDIATION AND MINE CLOSURE

A special area of risk consideration for a long-term investor is the strategy used by mining companies for mine closure and site remediation. These considerations include addressing residual risks for water and soil contamination at a site and beyond, after mining operations have ceased. An assessment of these needs is made as part of the permitting process used for mine initiation and expansion, through appropriate environmental impact assessments and remediation plans. Mining companies assess the associated “closure” costs and post them as a bond or as a guarantee as part of the mine permitting and re-authorization process. The intention is to assure that funds are available for site remediation at the end of mine life or if a mine becomes uneconomical to operate due to a drop in the price of the commodity mined or a degradation in ore quality. However, in almost all the countries we have studied, environmental (soil and water quality contamination) problems due to legacy mining activities exist. These problems translate into either a) social conflict for the mining industry; b) remediation costs to be borne by the State (e.g., through the highly oversubscribed Superfund program in the USA); c) pressure for regulatory and enforcement reform; and d) stranded assets or inability to invest in new mining operations in the region. Some mining companies may try to minimize the allocation towards the remediation bond. Deferral of these financial outlays would improve their discounted cash flow and viability projections, but translate into subsequent liabilities and risks for long-term investors. An assessment of the potential bias between projected and actual remediation costs is needed for financial risk quantification.

APPROACH TO FINANCIAL RISK ASSESSMENT

Quantitative financial risk analysis entails two key components – a probabilistic characterization of the uncertainties associated with investment outcomes, and an identification of the corresponding value at risk. These two elements are used to derive measures such as Value at Risk (VaR) or conditional Value at Risk (CVaR). Stochastic valuation methods then work in the framework of discounted expected cash flow, in conjunction with such risk measures to provide investor guidance. In the water/climate and mining context, there are a number of challenges associated with a straightforward application of such analyses. These include:

- *Private risks dominate*: Unlike some financial data (e.g., copper prices) for which time series and covariates are readily available, much of the data that could be used for assessing water related financial risks for mines is private. This motivates a need for disclosure of information, but so far disclosure requests and metrics pertains more to corporate social responsibility actions and benchmarking than they do to measures that provide spatial or temporal information material for a quantitative risk analysis.
- *Risk Misspecification*: Even if mining companies were to disclose water/climate specific risks in probabilistic terms, it is quite likely that these estimates may be biased. This may be due for instance to climatic changes relative to the period used by mine analysts for risk assessments; to flawed analysis (e.g., limited exploration of the likely modes of failure of a tailings dam); to operational practices that diverge significantly from those used in engineering design (e.g., rate of mining and waste/pollution generation); to inadequate assessment of risks of social conflict or site remediation requirements.
- *Inter-dependence of risk factors:* As indicated in the section on Exposure Pathways, the physical, socio-economic and environmental factors involved in water related mining risk translate into a complex dependence structure which also entails a consideration of inter-acting decisions made by the mining company as well as by other actors, such as NGOs, market trend makers and governments. The outcomes from such a setting could be simulated, but they also require assumptions as to the economic and decision making frameworks of the actors involved.
- *Sequential decisions:* Mines operate over decades, and respond to commodity price fluctuations, as well as to environmental risks with discrete choices and investments over these periods. Consequently, their financial risk profile depends on dependence of the actual mine response on the time sequence and timing of events, relative to the mine stage and to the commodity market prices and other stochastic

factors. Real options models, rather than discounted cash flow allow the consideration of these nonlinear interactions.

A review of the financial engineering literature led us to the conclusion that these issues will apply broadly to many emerging risk analysis problems, notably with regard to climate, seismic and other hazards that lead to private risk mitigation actions by companies, and may be contingent on an assessment of potential losses to and actions by other users. There may be limited risk hedging opportunities for these factors. A common factor is also that the information sources for the risk assessment are likely to be limited, sparse and biased. This led us to develop novel probabilistic and statistical techniques whose goal is to make prediction and estimation in the presence of model misspecification. The motivation for the need of this type of development arises from the lack of data and structural information in crucial portions of risk assessment in mining from an asset as well as a portfolio perspective.

The robust real options model developed in our research addresses this general problem. However, a modeling tool that is specific to the mining situation, where detailed and precise information as to the water and climate risks is limited and or not efficiently disclosed was developed and is available from our repository. The intention is to provide an integrative framework for the financial valuation of a variety of factors (environmental, social or other) whose occurrence and impacts may not be well quantified, and may occur stochastically at different times over the life of the mine (investment) leading to production disruption, cost increases and/or asset stranding. The new techniques that we propose are justified by economic reasoning and by strongly desirable statistical properties, in particular, making fundamental connections to widely applied machine learning techniques. The statistical aspects are focused on the robust estimation of the underlying probabilistic structure from limited data. A key innovation is how to identify bounds on potential misspecification of the underlying probability model and to then use these in the decision analysis. A real options modeling framework that provides the flexibility to address the general set of issues identified is then used to derive asset and portfolio valuation using these measures in a sequential optimization framework. The ideas are detailed and explained in the chapter titled *"Private Risk and Valuation: A Distributionally Robust Optimization View"*. Methodological details are also presented in the archival journal publications cited below.

Specifically, for our project, applications of this approach were developed for portfolios of copper and gold mines subject to disruption due to stylized climate events or tailing dam failures. Generally, any kind of hazard that occurs stochastically with some process rate, including co-dependence on other stochastic hazards could be included. Using our robust analysis methods with the limited data available on those processes, we are able to calculate upper and lower bounds over all the probability models within a certain distance from the original model. We suggest two different approaches for mine and company valuation based on this technique. The first, and more direct approach, calibrates the distance of probability measures from a set of known mine transactions and prices a mine (with currently unknown value) using the modeling distance from the training set of mines. The second approach uses historical precipitation data from a mine site, to calculate a worst case disaster arrival process from the actual physical data, and the mine is then priced using this process.

Due to time limitations, and especially the difficulty in acquiring consistent data on other risk factors across the geographies of interest in time, a comprehensive risk analysis and valuation of mines/portfolios considering all the risk exposure pathways discussed in this report was not attempted. Rather, a stylized model was considered and applied to the mine level data collected. Over a finite time horizon, the decisions available to the operator were considered to be to Open (Re-open), Close or Abandon a mine. The mine was considered to have the following parameters: initial reserve level, extraction rate, unit extraction cost, annual maintenance cost, switching costs associated with a decision, tax rate, property tax, cost growth rate, a stochastic Poisson process arrival rate of hazards, and spot market prices. Mine transaction data are used for the robustification of the estimates, and the predicted and observed transaction values of the mines are compared. The process then allows one to compare whether mines were under or over-valued relative to the hazard/risk process, and their relative ranking in terms of the expected risk value. The second approach was to robustify using climate data, and in this case, the assumption was made that the industry standard is to design tailing dams and other infrastructure to protect from a 100 year return period rainfall event on average. The Generalized Extreme Value (GEV) distribution was used as the candidate model, but we consider that its application may be inefficient due to data limitations, and use our model to derive robust bounds on the probabilities associated with the GEV model. These bounds for annual failure probabilities are then used with the real options model to derive bounds on the valuation of each mine relative to the data and the parameters specified.

The App developed for the robust real options model can be used by investors for arriving at a probabilistic assessment of the net asset value of mines and mining companies subjected to climate shocks. It can be updated to consider other types of shocks and their associated impact by providing information on the potential hazard rate or rate of occurrence of that shock, for other types of assets. The approach supports relative ranking and absolute valuation of assets and companies and represents a new direction for the integration of physical climate risk and related socio-economic factors into a valuation framework. In summary, we were motivated by the problem of financial risk assessment for water and mining to develop and exemplify a new theoretical approach that has broader applicability than just this problem, and have provided practical examples and tools for future investigation. The App developed in the mining/water/climate context provides the basis for a more general approach for the financial valuation of physical climate risk where the asset locations of a company are known and can be used with the Climate Re-analysis data for the last 160 years linked at our repository or with future IPCC climate projections that are appropriately examined for their biases with regard to key climate extremes of interest.

DATA PRODUCTS:

1. Global precipitation gridded time series from NOAA's 20CR reanalysis
2. Net Asset Values and mine transactions data over time for Copper and Gold Mines

SOFTWARE PRODUCTS:

1. Robust Real Options Modeling App with User's Manual for general applications

PUBLICATIONS:

1. Blanchet J. and K. R. A. Murthy, 2016, On distributionally robust extreme value analysis. arXiv preprint arXiv:1601.06858.
2. Blanchet, J., Kang, Y., and Murthy, K., 2016, Robust Wasserstein profile inference and applications to machine learning. https://arxiv.org/abs/1610.05627.
3. Blanchet, J. and Murthy, K., 2016, Quantifying distributional model risk via optimal transport, https://arxiv.org/abs/1604.01446.
4. Dolan, C., 2017, Distributionally Robust Performance Analysis with Applications to Mine Valuation and Risk. Ph.D. Dissertation in Statistics, Columbia University, NYC, US.
5. Dolan, C., Blanchet, J., Iyengar, G., and Lall, U., 2017, A model robust real options valuation methodology incorporating climate risk, *Resources Policy* .
6. Blanchet J. and U. Lall, 2017,"Private Risk and Valuation: A Distributionally Robust Optimization View"*, (to be submitted)*

APPROACH TO PHYSICAL RISK ASSESSMENT

The key findings from the analyses related to climate extremes, tailing dam failures, cumulative impacts from water contamination, and mine water analyses are summarized in this section.

RISK FROM CLIMATE EXTREMES

The approach developed here is not specific to the mining industry. It is also useful for physical risk characterization for other investment portfolios, and could be considered for the TCFD guidance for investors.

Droughts and extreme rainfall/flooding were identified as key triggers for the risk exposure pathways. Mines are engineered to consider specified return periods for extreme rainfall and for droughts. The location specific data that goes into these estimates usually from 5 to 50 years long, leading to a high uncertainty associated with these design thresholds, and a correspondingly high residual risk. Since the global climate exhibits quasi-periodic behavior with periods of approximately 4, 10, 18, and 60 years, the specific time period for which data was available could represent an anomalous, persistent wet or dry phase in a given location. Using this data to select the design risk level for drought or extreme rainfall can then lead to a significant under-design or overdesign in the following period when the mine is actually operating, as the climate period switches to the other phase[3]. Exceedance of an extreme rainfall event relative to design could have consequences such as tailing dam overflow and/or failure or flooding at the site. Similarly, rainfall below a prescribed threshold over some duration (e.g. 0.5, 1, 3, or 5 years) may lead to increased competition with other users, social conflict or production stoppage due to inadequate water access. Ideally, each mine would disclose their design thresholds, so that an analysis of the residual risk can be done. Since this is not always the case, an app was designed to consider user specified thresholds and assumptions as to the potential financial impact (as a fraction of the mine's net asset value of annual production value). Failures of the mine design and impacts are then recorded as exceedances of these thresholds.

We selected re-analysis climate data sets for gridded precipitation and temperature, a global gridded data set for Palmer Drought Severity Index and Standardized Precipitation-Evaporation indices (drought measures) derived from historical station observations. Reanalysis outputs are derived from global ocean-atmosphere circulation models that assimilate daily observed climate data across the world and produce 6 hourly, daily and monthly chronologies at prescribed spatial grids. In all cases, this provides us with century or longer data series with global coverage. The long records are needed to reduce the uncertainty associated with the estimates of the exceedance rates (risk) of extreme event thresholds.

The following questions were explored:

- Climate over the last century exhibited natural inter-annual and decadal variations in addition to a long term trend that may be due to anthropogenic climate change. Given these multi-year cycles, what is the projected rate of failure of a risk mitigation strategy that may be based on a specific time period of data at that location. For instance, if a mine were constructed in 1980, and may have had access to data from (1970-1980, 1960-1980 or 1920-1980), how often is the rainfall or drought threshold for the T-year event estimated from that data set exceeded in the subsequent period? This provides a measure of realized vs specified risk, or through a Monte Carlo process it can provide the uncertainty associated with the specified risk.

[3]Jain, S., & Lall, U. (2001). Floods in a changing climate: Does the past represent the future? Water Resources Research, 37(12), 3193-3205.

- Is there evidence of clustering in the threshold exceedance process at a site, i.e., is the probability of experiencing multiple failures (e.g., 3) over a consecutive period of d (e.g., 2) years much greater than what would be expected by chance? This is important to understand how different types of insurance contracts held by the mine may perform in the real world setting. An assessment of experiencing either or both a flooding and a drought event over the d years is included in this consideration.
- Is there evidence of spatial correlation in the threshold exceedance process across sites in a mining portfolio? How does this map to portfolio risk in a return period setting? Again, one could consider flood or drought or both in the same reporting period.
- Is there evidence of trends (increasing or decreasing) in the threshold exceedance process, globally, regionally or for a portfolio of mines? Are these trends consistent with what is expected from climate change scenarios as represented in climate model integrations?

We recognize that the global climate data sets used often do not match observations taken at each specific site, even where the global climate data sets grid includes the observation site. However, we recommend the use of the global data sets since:

a) they provide a complete space-time coverage for a century or more;
b) there are multiple sources of data, allowing for a sensitivity analysis as to the choice of a particular data set;
c) their results can be compared directly to models used for climate change simulations, so that a verification of the consistency in trends and projections is feasible;
d) inter-annual and decadal climate variations, as well as climate change impacts are manifest over relative large regions, thus if changes in risk associated with these features are of interest, the global data sets are expected to be informative as to the shifts in the frequency of climate events; and
e) since our analyses focus on the exceedance of estimated quantiles of the data for each series analyzed, biases in the data sets as to the mean or other statistics of rainfall are properly dealt with and a clear basis for the comparison of results in clustering or trends of the exceedance process and hence the risk is available.

We identified the asset locations, production and net asset values for the mines owned by leading copper and gold mining companies, and developed measures similar to Value at Risk (VAR) and conditional Value at Risk (cVAR) for each mine and for each company relative to assumptions as to thresholds and potential impact at each site. The *main findings* from our analyses are:

- *Risk concentration*: Mining companies exhibit significant spatial and temporal clustering in their exposure to exceedances of a T-year rainfall or drought event. The number of exceedances of the thresholds considered in some years is dramatically higher than would be expected by chance, leading to a very fat tailed distribution of risk for both drought and flood impacts for a company with many assets (Figure 4) that highlights the concern for catastrophic portfolio risk.
- *Company rankings*: Companies were ranked based on total $ value exposure to extreme rainfall or to drought, and also based on exposure relative to their total production or net asset value. This allows a comparative analysis or ranking of the companies in terms of this risk metric. Since, the actual risk mitigation strategies of the companies are unknown, we are only able to compare exposure, until these elements are brought into a financial risk disclosure guideline. Some mining companies rank high in exposure for both droughts and floods.
- *Trends*: There is evidence for increasing incidence of extreme daily rainfall events impacting mining portfolios, especially from 1850 to 1970. These trends are punctuated by strong inter-annual variations, such that Rio Tinto's portfolio experiences 36 (24) exceedances of the 10 year return period 30-day rainfall across its 40 mines in 1982-83 and 1997-98, both of which are El Nino years. Results for trends

across the different data sets are more consistent post-1950, when more observational data becomes available. However, water scarcity as exemplified in the SPEI index (Precipitation-Potential Evapotranspiration) presents changing trends in wet and dry exceedances (see Figure 5 for the expression at global copper mines). Exceedances of the share of production exposed to a 10-year average recurrence events increase and then decline, but with increased variability and co-occurrence of hits from wet and dry events.

- We recommend that companies assess their potential exposure across their assets using the actual time period of the data used for their infrastructure design, but benchmarked on the 160 year time series we provide with the App, and disclose the resulting residual risk of exposure and the associated Value and Conditional Value at Risk as computed by the App.

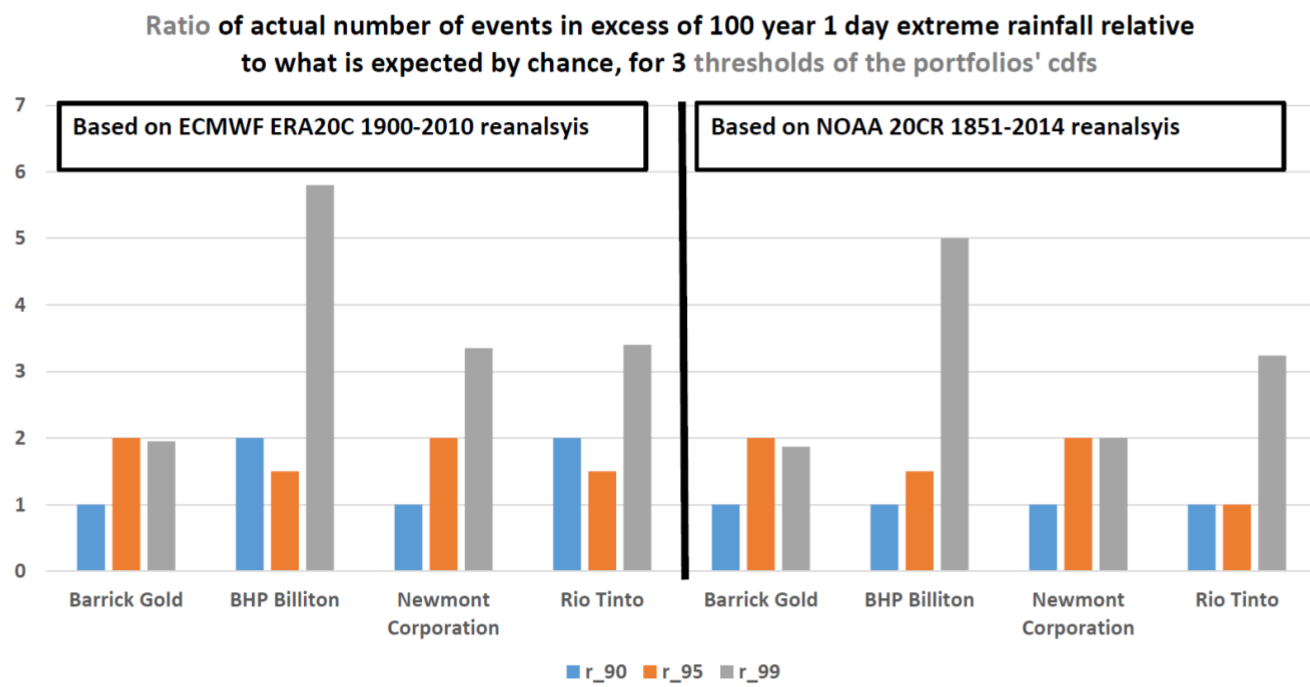

Figure 4: An analysis of the tail risk (10%, 5% and 1% annual risk events) exposure for 4 companies using 2 different global climate data sets for the 100-year 1 day rainfall estimated from the full historical data. Note that the 1% tail risk for BHP Billiton is 5 to 6 times what would be expected with no clustering of events in time and space.

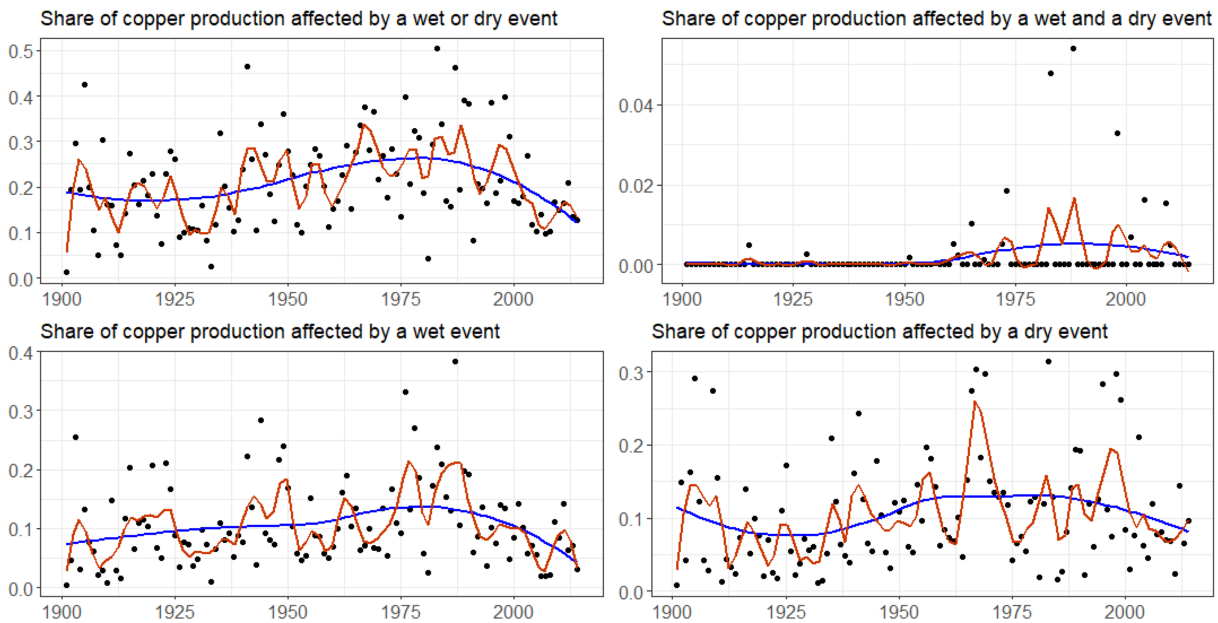

Figure 5: Fraction of 2014 copper production affected by events exceeding the 10-year, 12-month SPEI index: wet or dry event in a year (top left), wet and dry event in the same year (top right), wet event (bottom left), and dry event (bottom right).

DATA PRODUCTS:

1. Daily gridded precipitation and temperature data from NOAA-CIRES v2 re-analysis 1871-2012 and version V2c from 1851-2014
2. Daily gridded precipitation and temperature data from ECMWF 20C re-analysis 1900-2010
3. Dai's gridded Palmer Drought Severity Index (PDSI) data 1951-2015
4. SPEI v 2.4 data set from 1901-2014
5. Derived annual gridded exceedances of selected rainfall /SPEI/PDSI thresholds and return periods for specified durations from these data sets
6. Mine Valuation data extracted from TD Securities

SOFTWARE PRODUCTS:

An App to process re-analysis data and do precipitation risk analyses at specified locations and aggregate to portfolio level VAR and C-VAR like measures

PUBLICATIONS:

1. Bonnafous, L., Lall, U., & Siegel, J. (2017). An index for drought induced financial risk in the mining industry. Water Resources Research, 53(2), 1509-1524.
2. Bonnafous, L., Lall, U., & Siegel, J. (2017). A water risk index for portfolio exposure to climatic extremes: conceptualization and an application to the mining industry. Hydrology and Earth System Sciences, 21(4), 2075.
3. Bonnafous, L., and U. Lall, (2017) The changing risk of global wet and dry extremes. (In revision)

RISK FROM TAILING DAM FAILURES

The main points from this analysis are:

- Tailing dams store mine wastes. They fail at a rate 3 to 5 times higher than river dams, and lead to significant potential damage, liability and disruption of production. They differ from river dams in that they are invariably earthen structures, and are raised in stages rather than constructed at one time. Since they store wastes, leakage or failure leads to release of toxic materials rather than water. These wastes need to be contained beyond the life of the mining operation, their design and safety is critical for long-term investors since the liabilities may accrue beyond the early productive stage of the mine life.
- Overtopping due to inadequate storage capacity to contain runoff from extreme rainfall events, and geotechnical failure are the primary mechanisms of failure. Storage capacity varies but is often designed for a 10-year rainfall event, while the spillway may be designed for up to a 1000 year event. Data for estimating these return periods are limited. Recent failures (Samarco and Mt. Polley) were attributed to high loading rates of mine waste and subsurface soils failure.
- Damages from failure vary depending on downstream assets and conditions and dam attributes. Samarco's failure generated a multi-billion dollar liability, production stoppage and reputation risk.
- Using data on historical dam failures, and dam attributes, an empirical statistical model was developed to estimate probabilistic dam runout distances (the distance to which the plume may travel) on failure and to encode this into a hazard rating of dams considering assets exposed downstream. This model was applied to a section of Brazil which includes Samarco and several other tailings dams. The 95% probability interval for runout covers the observed Samarco impact. Other dams in the region were identified as having even higher hazard ratings. The limited data on past dam failures constrains its range of applicability. We recommend using the uncertainty distribution of runout and hazard rating predicted by the model rather than the mean value of these statistics for this reason, since the prediction intervals provided by the model will address some of the uncertainty of extrapolation
- Unlike river dams, there is no international inventory of tailing dams and their attributes that could be used to rapidly generate a hazard rating using our model. However, mine locations are available from data sets such as SNL. Using these mine locations and satellite imagery, a machine learning approach was developed to automatically identify tailing dams, and their areal extent. The intention is to use this algorithm to automatically identify tailing dams and to foster disclosure on their attributes by companies, and/or to monitor change in their conditions (e.g., height increase, % filled) as part of a hazard monitoring effort.
- We recommend that tailing dams be incorporated into a special section of the International registry of large dams, including information as to the construction type, design risk level, data used for risk assessment and potential impact hazard rating. This type of centralized disclosure will facilitate a comparative risk analysis and third party financial valuation of risk. The ICOLD efforts in this direction should be supported.

DATA PRODUCTS:

1. Data set on failed tailing dam physical attributes, discharge volume and runout distance
2. Data base with attributes of over 2000 non-failed tailing dams around the world to which the probabilistic hazard rating analysis could be applied
3. Satellite images used for training machine learning algorithms to identify tailing dams
4. Links to spatially explicit Ecological and Population databases from other sources

SOFTWARE PRODUCTS:

1. R-Shiny App for tailings dam hazard rating analysis
2. App for tailing dams identification from satellite imagery

PUBLICATIONS:

1. Larrauri, Paulina Concha and Upmanu Lall, 2017, Assessing Risks of Mine Tailing Dam Failures, Columbia Water Center White Paper, 32pp.
2. Larrauri, Paulina Concha and Upmanu Lall, 2017, Tailings dams failures: Updated Statistical Model for Discharge Volume and Runout, *J. of Hazardous Materials*, (in review)
3. Campos, J.P., L. Bonnafous, U. Lall, "Tailings Storage Facility Detection by Transfer Learning with Deep CNN" (in revision)

RISK FROM CUMULATIVE IMPACTS OF MINING ON WATER

Cumulative effects of mining on water quality can emerge when multiple mines are operated in a watershed, even if each mine is regulated to a certain permissible discharge of pollutants. The water quality conditions deteriorate from the collective release of pollutants, and their interaction with regional hydrology and climate, other pollutant sources, sedimentation and erosion processes, and withdrawals from water sources. It is difficult to estimate and predict cumulative effects a priori, and it has also been difficult to find quantitative analyses of basin scale cumulative effects from mining and relate them to permitted and un-permitted activities. This is unfortunate, given their potential importance for water related risk through social conflict and their ecological impact. A comprehensive study of the metal and sulfate contamination and its human and ecological health impacts is needed.

The Rimac river basin in Peru constitutes the primary water supply for Lima, a city of 8.5 million people. The historical pollution of this supply has led to significant increases in water treatment costs for the city, and also to social conflict for mines in the basin. We were able to assemble a 2004-2011, spatially explicit data set covering hydrology, climate, water quality (metals) and mining activity, and explore temporal and spatial cumulative effects.

The main findings from this analysis are:

- Most of the metal contamination by mining may have occurred prior to the period for which we have data. However, over the 7 years there are statistically significant trends for metal pollution, particularly for extreme violations (5^{th} and 99^{th} percentiles) of the water quality standards.
- High levels of metal contamination are found in the river near the mining locations, with better water quality at intermediate locations, followed by significant deterioration as one reaches Lima where much historical sediment deposition has taken place, and above which streamflow is reduced by diversions.
- This case study illustrates the need to do a routine monitoring and attribution of cumulative effects to specific mining and other activities, accounting for both spatial effects and episodic, large exceedances of water and soil quality parameters for an effective regulatory process that also helps mines that are doing a better job of managing their wastewater discharges. Unfortunately, often, in Peru, and in other countries, the government regulators for pollutant discharge, and government agencies that monitor ambient water quality are not the same. Their lack of coordination leads the regulator to allow "permitted discharges" defined over some averaging period from all mines while the environmental and water agency may or may not note and communicate the continuing deterioration of water quality and pollutant accumulation in certain receiving waters. This contributes to an eventual risk of conflict and thus asset stranding for the mines that is difficult to quantify in the current setting.
- We have developed a concept note for an improved regulatory process that would replace the current reliance on an initial environmental impact assessment that is expensive to develop and yet is not predictive of future impacts. We propose a formal design of data monitoring networks, and an ongoing statistical process for water quality trend analysis and the attribution of these trends to permitted regulatory discharges and to other potential sources. This process would reduce the possibility of long

term degradation of water bodies, and subsequent risks of more stringent regulations or social conflict, and lead to a better identification of who is actually responsible for the impacts, thus helping de-risk investments that are performing well as well as help investors identify companies that are consistently not performing well.

DATA PRODUCTS:

1. Rimac Basin, Peru, Hydrologic and Water quality data, augmented with Mine Production Data
2. US EPA STORET, and USGS NWIS water quality and flow data extracts for Colorado and Montana + Water Quality Standards and Scripts to readily extract similar data for other US locations

PUBLICATIONS:

1. Butler, L., U. Lall, and L. Bonnafous, 2017, Cumulative heavy metal contamination in mining areas of the Rimac, Peru basin, *J. of Cleaner Production*, (in review)
2. Bonnafous, L., U. Lall, and L. Butler, 2017, Concept note for a new environmental regulatory process for mining and its pilot application in Peru. (White Paper)

MINE WATER BALANCE AND COSTS ANALYSES

Efforts were focused on assessing how reliable data on mine water balance (input and output water and associated water qualities) could be acquired and processed to determine relationships between ore grade, processing methods, water use, wastewater generation, tailings dam capacities, and the capital and operating costs associated with treatment, storage and provision of water. Case studies and data reported in the literature were reviewed and aggregated. A team led by Dr.'s Gavin Mudd, Stephen Northey, and Tim Werner was commissioned to consolidate their efforts on data collection through mine level visits and interviews and provide a summary analysis of such data in the context of a financial risk analysis. This data product is now available. Initial statistical investigations did not provide the ability to assess either trends or strong relationships for water use or costs across the relatively large number of mines polled. It is likely that there are considerable variations from site to site, as claimed by mining companies, that preclude the use of easily constructed indices or variables for such an assessment that does better than typical unit cost estimates reported (with high uncertainty) in the literature.

A collaboration with the Sustainable Mining Institute at Queensland University on a related topic led to a similar conclusion, and a recommendation that a comprehensive data archive to which mining companies could contribute, and could be hosted by ICMM or a University may help. However, the development of such an initiative within the duration of our project was not feasible.

DATA PRODUCTS:

1. Mine water balance, production, ore grade and cost data sets compiled from literature and interviews

PUBLICATIONS:

1. Mudd, G. M., S. A. Northey, and T. Werner, 2017, Water Use and Risks in Mining, Unpublished Report.
2. Ossa-Moreno, J., McIntyre, N., Ali, S., Smart, J. C., Rivera, D., Lall, U., & Keir, G., 2018. The Hydro-economics of Mining. Ecological Economics, 145, 368-379.

APPROACH TO SOCIAL AND REGULATORY FACTORS

COVARIATES OF SOCIAL CONFLICT RELATED TO WATER AND MINING

Latin America is a region with high social conflict over water and mining. Peru, Mexico and Brazil have the highest incidence. Spatially specific data sets on conflict incidence were available for Peru and Mexico, and this provided the impetus to assemble and explore covariates that may provide insights into factors that may be determinants of social conflict in these settings. Socio-economic, and physical covariates were identified and their ability to predict conflict incidence was explored using traditional and Bayesian regression methods. The main findings are:

- For Peru, a past history of conflicts in a given location emerges as the strongest predictor. Drought and water quality considerations, the canon tax, and regions with higher mining investment also emerged as significant predictors that change the coefficients for past conflict and the water related variables.
- For Mexico, indigenous communities, population, income inequality and the mining and energy capacity emerged as the key determinants of the probability of conflict.
- The predictors selected as significant in these two modeling efforts are not a surprise. We were not able to access data on the impact of conflict on the short or long term financial impacts on mining companies, either through increased costs for corporate social responsibility or legal defense, or through reduction in revenue or foregone opportunities. However, we were able to demonstrate that a statistical model that can provide probabilistic predictions of potential conflict using covariates that are typically collected by different government agencies is feasible. If impacts data could be collected then the probabilistic model developed could conceivably be used to inform regional economic development as well as the valuation and decision process for mining companies to expand into an area, and target specific issues. The probabilistic model can also be used with the robust real options model to generate potential conflicts and their financial impacts.

DATA PRODUCTS:

1. Peru (Spatially indexed time series): Water related Violent and Non-violent Social conflicts, Water related fines, Rainfall, Mining company investments, Mining revenues and transfers to sub-national governments, election data, and corruption perception index, assembled from diverse government sources and surveys
2. Mexico (Spatial): Energy related Social conflicts, Mining related Social Conflicts, Energy Installation Location, Renewable and Non-renewable Energy Capacity, environmental vulnerability index, Population and GINI index by Municipality, Mining Location, and Mining Revenue.

PUBLICATIONS:

1. Salem, J., Y. Amonkar, N. Maennling, U. Lall, L. Bonnafous, and Khyati Thakkar, 2017, An Analysis of Peru: Is Water driving mining conflicts?, *Resources Policy*, (in review)
2. Salem, J., Y. Amonkar, N. Maennling, U. Lall, E. Moreno, and L. Bonnafous, 2017, Mitigating Socio Environment Risk By Understanding Social Conflict In Mexico's Extractive Sector, *Resources Policy*, (in preparation)

COMPARATIVE ANALYSIS OF LEGAL AND REGULATORY REQUIREMENTS

A comparative analysis of legal and regulatory requirements pertaining to water and wastewater associated with mining was conducted through a review of the regulations, and through interviews with mining companies. The countries compared included Australia, Canada, Chile, China, Peru, Philippines, S. Africa, and the USA. The main findings were:

- Water pollution problems from legacy mines tend to have more stringent discharge and post-closure requirement
- Water scarce jurisdictions or regions with a significant amount of competing water users tend to have more stringent water allocation regimes and have set up markets to trade water rights
- Determinants of the perceived regulatory risk by investors is composed of the timeliness of water licenses being processed, the probability of licenses being granted, and the likelihood of the licenses being contested.
- Water allocation mechanisms are closely linked to the relevant countries' legal tradition, and how the responsibility for the administration of the water rights is assigned between the central and local level depends on the level of decentralization of the country
- Regions with a long mining history tend to have more advanced and complex water regimes, whereas frontier-mining countries have a less-developed legal framework
- Enforcement of laws and regulations and actual permit issuance vary markedly across the countries and may be a more important determinant of financial risks faced by companies than the actual laws and regulations. While some indicators such as target permit timelines vs actual permitting time lines can be quantified, enforcement effectiveness is difficult to quantify.

PUBLICATIONS:

1. Thomashausen, S., Maennling, N., & Mebratu-Tsegaye, T. (2017). A comparative overview of legal frameworks governing water use and waste water discharge in the mining sector. *Resources Policy*. (in press)

FINANCIAL REGULATORY DISCLOSURE OF ESG RISKS RELATED TO WATER

A number of environmental disclosure programs and the specific water related disclosures by mining companies were reviewed and summarized in intermediate project reports. Institutional investors indicate needs for ESG disclosure suitable for financial risk analysis of companies. The number of companies voluntarily reporting on detailed metrics for their ESG programs is growing, especially as it relates to metrics for climate and GHG emissions. Water related disclosures are also increasing. These broader conclusions and the movement towards mandatory rather than voluntary disclosures applies to mining companies as well, even though this sector is perhaps at the forefront of internal risk analysis of these factors.

Given our identification of the risk exposure pathways in this project, and an assessment of the current water related disclosures by the mining sector, our conclusion is that at this point the state of disclosure does not meet the needs for a rigorous financial risk analysis. The publication by Mardirossian and Condon presents examples of the kind of disclosure elements that would be more useful. These correspond to the areas highlighted in this report. Their conclusion is that the systematic underassessment of environmental risk is due, in part, to a lack of demand for longer-term risk assessment. Institutional investors therefore, have a role to play in driving this demand. They note the 2017 climate-related shareholder engagements as an indication that other large investors are acknowledging this role as well.

PUBLICATIONS:

1. Parthasarathy, V., M. Condon, L. Bonnafous and U. Lall, 2018, Voluntary initiatives in the mining industry, *J. of Environmental Investing*.
2. Mardirossian, N., and M. Condon, 2017, Institutional Investors & The Push For More Robust ESG Reporting, (Unpublished Report)

BIASES IN DISCLOSED REMEDIATION COSTS

There is very little data available on projected and actual realized remediation costs. From the case studies, we noted that the projected remediation costs and bonds posted may grossly under-estimate the actual costs incurred on mine closure. Lacking formal data for a quantitative risk analysis, we constructed a longitudinal data from company quarterly reports of their mine remediation costs and the variation of these costs, as a function of changing production, reserves and remaining mine life. The underlying idea was that as mine life increases, uncertainty in the estimation of production, reserves and remediation costs decreases. Consequently, if remediation costs were to continue to increase, even accounting for revised production and reserve estimates, then a quantification of the risk of understating remediation costs would be possible.

The key findings from this research are:

- Statistically and financially significant biases in remediation cost reporting are found from a Bayesian regression analysis of mining company filings over time. Since adequate data on actual remediation costs was not available, one of the statistically significant regression predictors is percent of mine life remaining. The coefficient for the percent of mine life remaining is 1.68 with a standard error of 0.38. The coefficient for this predictor suggests that accounting for other factors such as changes in estimated reserves and production, and country and metal effects, significant and systematic under-reporting of remediation costs occurs in the early stages of mine operation.
- Since mine net asset values and credit terms are based on discounted cash flow analyses, understating and deferring remediation and other environmental costs, allows mining companies to get better market analyses, while increasing the residual tail end risk. The large number of mines that end up on care and maintenance status or are traded at a late production stage, correspond to a further deferral of these liabilities. Collectively, this translates to a high residual risk for long-term investors and the industry.
- We compared our model with a recently released model for remediation cost estimation by the US EPA. For its model, the US EPA uses only a single report, typically the first estimate of the closure cost provided by a mine. As we note from our analysis, this is likely grossly under-reported, and is expected to be highly uncertain. Further, the US EPA does include some data on observed mine closure costs. However, this includes only mines that have gone through remediation and not the large number of abandoned or end of life mines. It is possible that this is also a non-representative sample, since it may either contain mines that became super-fund sites, or were relatively easy to remediate. The uncertainty (R^2) in the estimates from the US EPA model is high (low), suggesting that the use of their equations directly may not be informative. The use of a probabilistic approach to provide conditional quantiles (i.e., the closure cost will be between $x and $y with 90% confidence) may be more informative whether their model or ours is used.
- Given the high uncertainty and potential bias in remediation cost estimates, it makes sense to require mining companies to post remediation bonds that are either insured to cover up to the 90th percentile of the estimated cost, or to file bonds that cover up to that amount, so that the risks are not passed on to society or to the underlying investor.

DATA PRODUCTS:

1. Longitudinal data manually scraped from mining company quarterly reports, and SNL sources on estimated and updated reclamation costs and associated mine attributes
2. US EPA data sets on estimated reclamation costs and associated mine attributes

SOFTWARE PRODUCTS:

1. Regression model for reclamation cost prediction

PUBLICATIONS:

1. Campos, U. Lall, J. Siegel, 2017 “Evaluating Systematic Bias in Reclamation Liability Estimates”, *Resources Policy*, (in review)

ANCILLARY INFORMATION

Over the course of three years, a variety of data sets were compiled, several apps were developed and over 20 journal articles were published or submitted to journals for publication. One Ph.D. dissertation (with 1 more in progress) and two Masters of Science theses were completed. The active project team included 3 faculty from Columbia University, 1 from the Royal Melbourne Institute of Technology, as well as over 15 researchers with backgrounds in mining, water and environmental engineering, climate, statistics, financial engineering, law and economics. The apps that were developed and the data that was collected will be made publicly available on our website and through Amazon Web Service.