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SCIENCE POLICY REPORT • OCTOBER 2019

A new vision of sustainable management in mining and post-mining landscapes

The authors and their affiliations are listed in the appendix. The report exclusively reflects their views and vision of water and sustainability management in mining and post-mining landscapes.

Imprint

Publishers
Deutsche Akademie der Naturforscher Leopoldina e.V.
Nationale Akademie der Wissenschaften
German National Academy of Sciences Leopoldina
Jägerberg 1
06108 Halle (Saale), Germany

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Brazilian National Institute of Science and Technology on Mineral Resources, Water and Biodiversity
Av. Pres. Antônio Carlos, 6627
Pampulha, Belo Horizonte – MG, 31270-901, Brazil

Design
unicommunication, Berlin

Print
Schäfer Druck & Verlage GmbH
Köchstedter Weg 3
06179 Teutschenthal, Germany

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Publication Date
October 2019

ISBN: 978-3-8047-4026-6

Title Picture

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A new vision of sustainable management in mining and post-mining landscapes

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Table of Contents

Foreword

Extraction and use of minerals through mining is essential for industrial and societal development. However, the mining industry carries significant risks of long-lasting negative impacts on the environment, particularly on water resources and landscapes, as well as on local communities. Catastrophies such as the Brumadinho dam collapse in Brazil in January 2019 and in Nachterstedt, Germany, in 2009, where three people died because parts of an inhabited settlement slipped into a flooded open-cast mining area, call for action and can provide momentum for change. A transition towards mining in sustainable landscapes is necessary to ensure that the future of this industry operates with a sufficient degree of resilience and in a manner that can adequately respond to and align with the 2030 Agenda for Sustainable Development of the United Nations and its Sustainable Development Goals (SDGs).

An interdisciplinary group of 23 young scientists from Brazil, Germany, Canada, Chile and Peru participated in a workshop entitled “Sustainable Water Management in Mining and Post-Mining Landscapes”, held in Belo Horizonte, Brazil, in October 2018. The workshop aimed to formulate science-based recommendations for policy-makers, the mining industry and civil society. The event was organized jointly by the Brazilian Academy of Sciences (ABC), the German National Academy of Sciences Leopoldina, the Centre for Water and Environmental Research at the University of Duisburg-Essen (ZWU), Germany, and the Brazilian National Institute of Science and Technology on Mineral Resources, Water and Biodiversity (INCT-Acqua). The workshop was a continuation of the series “Water and Regional Development”, initiated by the Leopoldina and the ABC in São Carlos, Brazil, in 2014.

The present Science Policy Report is the result of this workshop. The participating young scientists are united by the belief that their policy recommendations can significantly contribute to the management of water and to sustainability in mining and post-mining landscapes.

The science organizations mentioned above wish to extend particular thanks to Professor Peter Fritz (Member of the Leopoldina), Professor José Tundisi (Member of the ABC), as well as to Professor André Niemann (ZWU) for providing guidance and support for this workshop. They are also very thankful to the Minas Gerais State Foundation for Research and Development (FAPEMIG) for its generous financial support. The organizers also thank the Royal Society of Canada for financing the attendance of two young scientists from Canada.

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Executive summary

Extraction and use of minerals through mining is essential for industrial and societal development. However, mining activities and catastrophic mining accidents across the globe have caused severe environmental impacts with long-term consequences and cast a burden on many people. The frequency with which such disasters occur and the increasing socio-economic and environmental effects both call for an urgent paradigm shift in the structure and processes of the mining industry. This science policy report outlines a new vision for mining activities and proposes several measures that can guide this paradigm shift towards sustainable mining landscapes.

Four overarching fields of action summarize the recommendations made in this document:
(1) Adoption of a landscape-scale and water management perspective;
(2) Mandatory funding of independent research centers by the mining industry and mandatory collaboration between mining companies and Scientific Advisory Boards (SABs);
(3) Establishment of international standards and transparency of knowledge management;
(4) Proactive development of contingency plans and failure mitigation efforts.

All recommendations envision mining activities (i.e. planning, management, monitoring, prevention, revitalization) that involve all stakeholders. Thus, information and power should be shared with all relevant parties from the beginning to the end of mining operations.

These recommendations are designed with the following objectives:
- Encourage local involvement and capacity-building;
- Create opportunities for science to become an integral and open-access part of the overall mining process;
- Create an international, law-abiding standard to guarantee due diligence and transparency, while simultaneously sharing generated data with stakeholders;
- Institutionalize effective participation of stakeholders during all phases of mining to mitigate the effects of mining and ensure socio-economic prosperity for all involved parties.

This science policy document was developed with the goal of improving the current mining scenario in many countries. The authors of this document believe that a paradigm shift towards mining in sustainable landscapes is possible if initiated by joint efforts from policy makers, mining companies, science and the general public.

Sumário executivo

A extração e a utilização de recursos minerais provenientes da atividade minerária são essenciais para o desenvolvimento industrial e social. No entanto, este tipo de atividade extrativista e seus devastadores acidentes em todo o planeta causaram graves danos ambientais com consequências de longo prazo e representam um fardo para muitas pessoas. A frequência com que esses desastres ocorrem e o aumento dos efeitos socioeconômicos e ambientais exigem uma urgente mudança de paradigma na estrutura e nos processos da indústria da mineração. Este relatório de política científica destaca uma nova visão para as atividades minerárias e propõe diversas medidas que podem levar a esta mudança de paradigma em direção a um cenário de extração mineral mais sustentável.

Quatro áreas de ação principais resumem as recomendações feitas neste documento:
(1) Adoção de uma perspetiva focada na gestão dos recursos hídricos e do território;
(2) Financiamento obrigatório de centros de pesquisa independentes pela indústria da mineração, e colaboração obrigatória entre empresas e Conselhos de Aconselhamento Científico;
(3) Estabelecimento de normas internacionais e de transparência na gestão do conhecimento;
(4) Desenvolvimento proativo de planos de contingência e de esforços para a mitigação de potenciais falhas.

Todas as recomendações consideram atividades minerárias (por exemplo, planejamento, gestão, monitoramento, prevenção e revitalização) que envolvem todas as partes interessadas. Consequentemente, informação e poder devem ser compartilhados com todas as partes relevantes envolvidas do início ao fim das atividades de mineração.

Estas recomendações foram concebidas com os seguintes objetivos:
- Incentivar o envolvimento e a capacitação da população local;
- Criar oportunidades para que a ciência se torne parte integral e de livre acesso em todo o processo de mineração;
- Criar uma norma internacional que respeite a lei e garanta a devida diligência e transparência, compartilhando simultaneamente os dados gerados com as partes interessadas;
- Institucionalizar a participação efetiva das partes interessadas em todas as fases da atividade minerária para mitigar os seus efeitos e garantir a prosperidade socioeconômica de todos os envolvidos.

Este documento de política científica foi desenvolvido com o objetivo de melhorar o cenário atual da mineração em muitos países. Os autores deste relatório acreditam que uma mudança de paradigma em direção a uma atividade minerária mais sustentável é possível se for iniciada com os esforços conjuntos dos formuladores de políticas públicas, das empresas mineradoras, da comunidade científica e do público em geral.

Kurzfassung

Die Gewinnung und Verwertung von Bodenschätzen ist für die industrielle und gesellschaftliche Entwicklung unerlässlich. Bergbautätigkeiten und schwere Minenunfälle haben jedoch ernsthafte Umweltbeeinträchtigungen verursacht mit langfristigen Konsequenzen für Natur und Mensch. Die Häufigkeit solcher Katastrophen und deren sozioökonomische und ökologische Auswirkungen erfordern einen dringenden Paradigmenwechsel in den Strukturen und Prozessen der Bergbauindustrie. Der vorliegende wissenschaftspolitische Report skizziert eine neue Vision des Bergbaus und präsentiert Maßnahmen, mit denen dieser Paradigmenwechsel hin zur nachhaltigen Gestaltung von Bergbau(folge)landschaften gesteuert werden kann.

Die in diesem Dokument abgegebenen Empfehlungen lassen sich in vier übergeordneten Handlungsfeldern zusammenfassen:

(1) Perspektivenwechsel mit neuem Fokus auf die Landschaftsskala und die Bedeutung von Wassermanagement;
(2) Obligatorische Finanzierung unabhängiger Forschungszentren durch die Bergbauindustrie und verpflichtende Zusammenarbeit zwischen Bergbauunternehmen und wissenschaftlichen Beiräten;
(3) Festlegung internationaler Normen und Schaffung von Transparenz im Wissensmanagement;
(4) Proaktive Entwicklung von Notfallplänen und Maßnahmen zur Schadensbegrenzung.

Die im Report aufgezeigten Handlungsempfehlungen richten sich an alle relevanten Akteure und umfassen alle Phasen von Bergbauaktivitäten, d.h. Planung, Management, Überwachung, Prävention und Rekultivierung. In diesem Sinne sollten während der gesamten Dauer des Bergbaubetriebs Informationen und Befugnisse zwischen allen relevanten Parteien geteilt werden.

Diese Handlungsempfehlungen wurden mit den folgenden Zielsetzungen entwickelt:

- Förderung des lokalen Engagements und des Aufbaus von Kapazitäten;
- Schaffung von Möglichkeiten für die Wissenschaft, ein integraler Bestandteil des gesamten Bergbauprozesses zu werden und ihr freien Zugang zu Daten zu ermöglichen;
- Festlegung von internationalen und gesetzeskonformen Standards, um Sorgfalt und Transparenz zu gewährleisten und gleichzeitig die generierten Daten zwischen den Interessengruppen auszutauschen;
- Institutionalisierung einer effektiven Beteiligung von Interessengruppen in allen Phasen des Bergbaus, um so seine Auswirkungen zu minimieren und sozioökonomischen Wohlstand für alle Beteiligten sicherzustellen.

Dieser wissenschaftspolitische Report zielt darauf ab, die aktuelle Bergbausituation in vielen Ländern zu verbessern. Die Autor*innen sind überzeugt, dass ein Paradigmenwechsel hin zu nachhaltigen Bergbau(folge)landschaften möglich ist, wenn er durch gemeinsame Anstrengungen von Politik, Bergbauunternehmen, Wissenschaft und Öffentlichkeit eingeleitet wird.

Resumen ejecutivo

La extracción y uso de recursos minerales es fundamental para el desarrollo industrial y de la sociedad. Sin embargo, las actividades mineras han causado graves impactos medioambientales y sociales, tanto en sus operaciones como en la ocurrencia de eventos catastróficos. En particular, la frecuencia y alcances de estos desastres exige un cambio de paradigma en la estructura y los procesos de la industria minera. En este reporte de políticas científicas, se presenta una nueva visión para las actividades mineras y se proponen una serie de medidas orientadas a materializar dicho cambio de paradigma, hacia una minería ambientalmente sustentable.

Cuatro campos de acción resumen las recomendaciones propuestas en este documento:
(1) Adopción de una perspectiva de escala de paisaje y gestión del agua;
(2) La financiación obligatoria de centros de investigación independientes por parte de la industria minera y la colaboración obligatoria entre las empresas mineras y los Consejos Asesores Científicos;
(3) Establecimiento de estándares internacionales y de transparencia en la gestión del conocimiento;
(4) Desarrollo proactivo de planes de contingencia y mitigación de catástrofes.

Las recomendaciones contemplan todas las actividades mineras (i.e. planificación, gestión, monitoreo, prevención, revitalización) involucrando a todas las partes interesadas. Por lo tanto, la información y el poder debe compartirse entre las partes interesadas desde el principio hasta el final de las operaciones mineras.

Estas recomendaciones han sido formuladas con los siguientes objetivos:
- Fomentar la participación y capacitación local;
- Crear oportunidades para que la ciencia se convierta en una parte integral y la información de libre acceso durante la operación minera;
- Crear un estándar internacional y respetuoso de las leyes que garantice la debida diligencia, transparencia y al mismo tiempo, comparta la información generada con las partes interesadas;
- Institucionalizar una participación efectiva de las partes interesadas en todas las fases de la operación minera, para mitigar los impactos de esta y garantizar la prosperidad socioeconómica de todos los grupos involucrados.

Este documento de políticas científicas se desarrolló con el objetivo de mejorar el escenario minero internacional actual. Los autores de este documento tienen la convicción de que un cambio de paradigma hacia una minería ambientalmente sustentable es posible, si se construye mediante esfuerzos conjuntos de los responsables políticos, las compañías mineras, la comunidad científica y el público en general.

Four fields of action for mining and water management in a more sustainable landscape

Four fields of action for mining and water management were identified, which will be discussed in detail in the sections to follow. The fields refer to (1) sustainable landscape management, (2) integration of state-of-the-art science development and practices to improve mining management and water use and protection, (3) international standards and transparency of knowledge management, as well as (4) proactive development of contingency plans (Table 1).

Table 1: Overview of the recommendations within the four fields of action throughout the overall mining process

1 Adoption of a landscape-scale and water management perspective	2 Mandatory collaboration between scientists and mining companies to support landscape sustainability and research innovation	3 Establishment of international standards and transparency of knowledge management	4 Proactive development of contingency plans and failure mitigation efforts throughout the overall mining process
Recommendation 1.1 Develop concepts for an integrated and adaptive landscape management approach to minimize negative impacts during mining and post-mining activities. **Recommendation 1.2** Build up effective governance networks during all stages of the mining activity. **Recommendation 1.3** Build local communities' capacities and capabilities to ensure an ongoing process of self-sufficiency in post-mining scenarios.	**Recommendation 2.1** Create long-term collaborative relationships with independent research institutions with public funding and mandatory funding from the mining industry and with oversight from Scientific Advisory Boards. **Recommendation 2.2** Integrate and implement novel and emerging technologies in a timely fashion.	**Recommendation 3.1** Create open-access platforms (Knowledge Management Systems, KMS) for exchanging and sharing knowledge about mining activity according to international standards. **Recommendation 3.2** Institutionalize transparency and effective participation of all stakeholders during all phases of mining.	**Recommendation 4.1** Conduct environmental preservation, monitoring and risk prevention throughout the mining process. **Recommendation 4.2** For the case of major failure, prepare immediate action plans as well as structured follow-up activities.

1

Adoption of a landscape-scale and water management perspective

Mines are not islands. They constitute parts of complex socio-ecological systems (Rüttinger & Scholl, 2017) in which water is an essential element. As such, we strongly encourage the adoption of a *sustainable landscape management* approach (Giurco & Cooper, 2012; Sayer et al., 2013; Ros-Tonen et al., 2018) to handle societal and ecological challenges specifically as they relate to water management. Only such a landscape approach integrated into pre-mining, mining and post-mining contexts allows for the complexity of various social, economic and environmental aspects within a mining landscape to be disentangled. This is particularly essential in areas where mining significantly alters environmental integrity.

A *sustainable landscape management approach* embraces the multifunctionality of landscapes and considers—in an encompassing manner—multiple scales, sectors and human perspectives. Pressures, trade-offs and complexities in land and water use become apparent, which in turn facilitates the investigation of impacts with different courses of action and future scenarios for landscape development. Recent contributions highlight key principles of landscape management (Sayer et al., 2013, 2015; Freeman et al., 2015) and provide evidence for the effectiveness of this approach (Ros-Tonen et al., 2018).

A *sustainable landscape approach* does not serve as an alternative institutional framework to existing structures. Rather, it may be seen as a perspective with additional approaches for more comprehensive and sustainable planning that offers spaces for collective mobilization, negotiation, and vision-building. We recognize that following this approach is not trivial, as a landscape scale may interfere with the established administrative scale. Following such a framework will likely require considerable efforts in coordination and capacity development (Ros-Tonen et al., 2018). Therefore, we provide three concrete recommendations to build up management capacities and to strengthen stakeholder participation.

Recommendation 1.1

Develop concepts for an integrated and adaptive landscape management approach to minimize negative impacts during mining and post-mining activities.

Mining and post-mining landscapes are complex and involve an array of different dimensions that are usually not assessed jointly. Landscape approaches, taking into account local and regional aspects, offer an organizational framework to embrace and reflect upon this diversity. Hence, we recommend the development of an integrative and comprehensive procedure of landscape management to ensure social, economic and ecological integrity, avoiding fragmentation of the landscape, degradation of land and environment, and exhaustion of natural resources. This entails the following actions:

1) Define the boundaries of the landscape that include the mining sites, local communities, environmental and cultural areas to protect, water as well as natural and cultural resources, along with all stakeholders and institutions.
We recommend a sustainable landscape management approach that is *integrated*, and that brings together different societal dimensions in resource management and planning. The approach should also be *adaptive*, as it must account for the change in use and perception of landscape over time. These processes must be open and should ideally start even before landscapes become mining sites, instead of as an afterthought.

2) Identify key ecosystem functions and services (and their relative importance) through analysis and valuation.

Ecosystem functions provide ecological, socio-cultural and economic values, which again deliver a number of goods and services. Examples include water supply, soil formation, agricultural and horticulture activities that require the regulation of nutrients and pollination, habitats and ecosystems, naturally growing food, raw material (e.g. for mining), settlements and areas for recreation (IPBES, 2018). Identifying the key functions and services aids in the implementation of multipurpose and flexible land-use planning. Mining landscapes should be understood as spaces of multifunctionality rather than mono-functionality. This means that the landscape is capable of sustaining diverse uses at given times (from contributions to economic well-being, to biodiversity conservation or ecosystem services). Background studies for the different compartments (socio-economic and environmental) should be conducted to ensure that this assessment takes into account previous impacts and proposed uses.

Image 1: *Aerial of an asphalt opencast mine in Reichshof Germany.*

3) Involve all affected stakeholders and actors and carry out transparent, fair and commonly accepted conflict analysis.

Navigating diverging views and perspectives in conflicts is an essential component of deliberation and rule-making negotiation. Platforms and mechanisms involving local communities and different stakeholders must therefore be integrated from the early stages of planning and decision-making processes onwards (Webler & Tuler, 2006; Kusters et al., 2018). Within these platforms, particular care should be taken to mitigate power imbalances, including issues of gender and ethnicity, and to be responsive to rather “soft”, non-monetary issues, such as cultural values. Stakeholders in mining contexts are often motivated to participate after they have recognized a specific threat of natural resource depletion due to mining activities (e.g. Budds & Hinojosa, 2012) or the overburdening of community structures. An alternative should be sought for the existing public hearing process, which occurs during the permitting process of new mining projects, as this procedure no longer effectively promotes discussions among the different stakeholders. The establishment of a panel of community representatives of recognized expertise as well as increased knowledge of the potential impacts should be striven for in order to discuss the positive and negative aspects of implementing a new mining project.

Recommendation 1.2

Build up effective governance networks during all stages of the mining activity.

For successful landscape management, people in governing positions at multiple levels need capacities to carry out various tasks. This includes the execution of regulatory and controlling responsibilities and the coordination of complex governance processes providing the legal foundation for sustainable development of local communities and environmental resources (OECD, 2015; Ros-Tonen et al., 2018).

Government actors regulate the licensing, operation and remediation of mining sites with high potential for economic, social and environmental impacts, often operated by large corporations. This means that they are facing vast additional regulatory burdens that extend far beyond the actual sites and that, especially in developing countries, may overburden the available capacities. In order to strengthen the independence and capacities of government authorities to effectively handle these challenges posed by the mining industry, we believe the following actions need to be taken:

1) Consistently apply existing laws and regulations that will address many issues of landscape and water governance (Sayer et al., 2015).
Improving implementation of these regulations requires adequate funding for implementing agencies and training in tandem with raising awareness among government actors.

2) Actively build up inclusive, cross-sectoral governance networks and their capacities.
Such networks facilitate long-term planning, fair and equitable rules for the negotiation of rights for usage, steady, impartial and accountable monitoring, and clear responsibilities and sanctioning mechanisms in case of accidents and misconduct.

3) Regulatory agencies need to require mining companies to submit extended impact assessments.
These assessments must be integrated, multi-disciplinary and multidimensional to include not just impacts that are usually covered by environmental impact assessments (e.g. ecological and economic dimensions). Such assessments would draw on multidisciplinary viewpoints (including insights from anthropology, sociology, economics, in addition to insights from the natural sciences) considering the multiple dimensions of impact on existing economic activities, social and community structures (i.e. cultural heritage sites). Inviting multiple stakeholders to these processes is important to make sure all societal interests are heard during the assessment (Hochstetler, 2018; Everingham, 2012). These assessments need to be completed throughout the pre-mining and exploration phase and afterward updated at regular intervals. Risk analysis also needs to be included.

4) Limit delegation of government tasks to private companies.
This may appear to be an efficient alternative to government agencies with limited capacities. However, those practices undermine democratic accountability and hide the development of government actors' capacity, thus creating further power imbalances (Arts et al., 2017). In practice, private involvement in water management is frequently contested (Santos & Milanez, 2015), especially when mining companies act as "de facto water managers without systems holding them accountable for their actions" (Boelens et al., 2014). This can result in significant alterations of the hydrology (or what many scholars call the "waterscape") and societal institutions of a given region. Consider, too, the review of environmental impact studies and environmental monitoring by expert consultants listed and previously approved and selected by the agencies with billing to mining companies. The same should be applied to environmental monitoring to enhance the existing self-monitoring process by mining companies.

Recommendation 1.3

Build local communities' capacities and capabilities to ensure an ongoing process of self-sufficiency in post-mining scenarios.

Stakeholder involvement goes well beyond establishing regular participation meetings. Mining companies tend to wield too much power in local contexts in which governments lack the ability to provide services and infrastructure. Communities become dependent on this exogenous support, making them more vulnerable as this weakens ties to other economic sectors (IIED, 2002). The most effective and sustainable way of public involvement is to build capacity in order to encourage local autonomy. We thus recommend building local capacities and capabilities to ensure an ongoing process of self-sufficiency that will safeguard livelihood during post-mining periods through the following actions:

1) Create formal and informal platforms for the exchange of traditional, local, and scientific knowledge to facilitate the recognition of local assets, the understanding of limitations and vulnerabilities, and the identification of problems and common objectives.
For example, establish local and regional research and education centers, social support centers for vulnerable groups (such as women and indigenous communities), local community facilities for meetings, training workshops and other relevant community-related activities, cooperative associations for work, etc. (see also Chapter 3).

2) Identify economic and social capacities and skills that need to be built for the integrated landscape approach. These are not limited to mining activities and take account of local and regional vocations of the land and the environment.
Economic capacities include means to earn livelihood such as construction skills, agricultural methods and technologies, skills and knowledge for water quality monitoring, management and recycling of solid waste, etc. Social capacities prepare communities for decision-making processes for land-use and infrastructure planning (Thaxton et al., 2017) targeting investments in the mining and post-mining landscapes. At the same time, social capacities encourage community building and cohesion, thus strengthening cultural identities.

2

Mandatory collaboration between scientists and mining companies to support landscape sustainability and research innovation

There is an urgent need for the increased involvement of scientists during all phases of mining, including exploration, development and closure to establish holistic science-based approaches to water management. Ultimately, the integration of scientists with multidisciplinary backgrounds (i.e. in the fields of geochemistry, surface processes, microbiology, toxicology, landscape ecology, social sciences, economics, etc.) will improve the effectiveness of mining operations in which significant water usage affects downstream water quality, as well as the overall (water) landscape.

Although water is a common factor of various components of mining, current management approaches and research efforts are compartmentalized and limited. Furthermore, data acquisition is heavily focused on operations rather than monitoring and research. This dichotomy is one of the main restrictions impeding better water management. An improvement to this current state would be mutually beneficial for scientists and mining companies. For scientists, mining environments provide unique *in situ* conditions to conduct research. Mining companies, on the other hand, would have the opportunity to maximize monitoring and development of new and innovative ideas and technologies throughout all stages of the mining process by supporting research initiatives.

Recommendation 2.1

Create long-term collaborative relationships with independent research institutions with public funding and mandatory funding from the mining industry and with oversight from Scientific Advisory Boards.

The swift practical application of state-of-the-art scientific findings to water management in mining operation requires close and continued interaction between mining companies, governing bodies, scientists and the local community (Fraser, 2018). In order for the mining industry to efficiently move towards an approach where interdisciplinary water management is standard practice, there must be an established network to facilitate synergy between scientists, the mining industry and local communities.

This includes the creation of independent long-term institutes with mandatory funding from the mining industry and governing bodies, where scientists from various disciplines can become engaged in holistic research during all stages of the mining operation. International research cooperation is also essential. We foresee a mandatory funding arrangement enforced by national governments where a consistent proportion of revenue gained through mining must be reinvested in research. These financial commitments would be reported to the public, thereby creating a measure of the efforts taken by mining companies that is comparable across international boundaries.

These research networks would engage in basic and applied sciences (natural sciences, technology and engineering) as well as social and political science to better understand and improve the strong relationships between stakeholders—especially between local communities, and the bodies that oversee water management. The scientific community is uniquely positioned here and may play many different roles. Scientists can help companies to access knowledge relevant to their operations and they can help decide between competing scientific accounts. In any case, bringing in scientists helps both the evidentiary basis on which mining companies make decisions and the reflection on more thoughtful mining activities.

One important step constitutes establishing independent Scientific Advisory Boards (SAB) with participation of scientists, representation from local communities and government as well as a "permanent" secretariat. These SABs must: (i) meet at regular intervals, (ii) have the power to visit the active mining sites and (iii) be granted access to most if not all operational data (there may be some privileged information). They should be able to act flexibly, fund academic sabbaticals for researchers and call upon specialists when needed. All reports should be public and transparent giving mining companies the right to read any document prior to publication.

These SABs should be able to facilitate worldwide alliances and partnerships with institutions that have valuable knowledge on management of mining as well as being already engaged in discussing and solving issues associated with mining activities. For instance, INAP (International Network for Acid Prevention) obtains valuable information from research and studies to manage acid rock drainage including research on closure of pit lakes and waste dumps. This might considerably reduce time spent on research as well as any associated costs.

While there is a significant foreseeable benefit in establishing these collaborative relationships as part of mining operations, the current framework requires serious improvement. Moving forward, joint efforts between industry and scientists aimed at optimizing water management need to become standard practice on a global scale. This will not only reduce redundancy in research efforts (occurring when mines and research labs operate as "islands" as discussed previously), but also facilitate interdisciplinary efforts to address complex issues. Furthermore, such internationally operating research entities should be tasked with leading initiatives for dissemination of research in a timely manner and on an ongoing basis to:

1) Improve water management strategies in real-time;
2) Aid in the evidence-basis of decisions in terms of water monitoring and treatment strategies;
3) Communicate with governing bodies to ensure compliance with long-term goals and timely integration of emerging science;
4) Engage in scientific public outreach initiatives (ensuring transparency and education).

Recommendation 2.2

Integrate and implement novel and emerging technologies in a timely fashion.

Timely integration of state-of-the-art, science-based technological or methodological advancements into regular mining operations requires multi-stage communication between scientists, mining companies and regulatory bodies. The creation of research institutes and Scientific Advisory Boards (as described in Recommendation 2.1) would give mining companies a forum to present water management challenges they are encountering to scientists with different scientific backgrounds. Scientists (or teams of collaborating scientists) can then engage in research where timely communication of research results to mining companies is an ongoing/scheduled activity with stakeholders present. Once technologies and approaches are available after the research phase, implementation will occur through various phases including framing of the concept, formulating the feasibility of implementing the concept (including financial and training considerations), continued development and validation and finally implementation. We emphasize that governing bodies have the responsibility to create norms and actions concerning the recommendations we address below or to revisit regulatory guidelines regularly in order to allow water guidelines to reflect these scientific advances.

1) Effectively monitor biogeochemical interactions in mining waters.

Understanding the biogeochemical processes governing the chemistry of mining impacted waters is paramount to a better prediction and mitigation of adverse impacts. Effective monitoring of these biogeochemical interactions (e.g. the microbiome governing the geochemistry of these waters) can provide early indications of conditions with significant ecological impacts such as acid rock/mine drainage development (Johnson & Hallberg, 2003; Bernier & Warren, 2005; Whaley-Martin et al., 2019). Across the global mining industry, current practices aiming to predict water chemistry are largely based on abiotic models ignoring the microbiological controls that govern these waters.

2) Carry out reliable risk assessments of water toxicity.

Reliable risk assessments of water toxicity are essential to avoid harmful effects to human health and ecological systems. At present, monitoring mostly relies on physicochemical, i.e. abiotic, parameters and biologically limited analysis (i.e. LC50/LD50; Lethal Concentrations/Doses for 50% of model organisms, derived through artificial laboratory conditions). Although standardized and therefore comparable, these approaches far from reflect the actual impact of mining water on exposed aquatic (and at times also terrestrial) life and may underestimate the impact at ecosystem level. Ideally, different biological responses have to be considered in a multi-systemic approach to better understand the potential effects at different hierarchical levels (Pond et al., 2008; Zhou et al., 2008).

3) Integrate remote sensing technologies to improve monitoring of mining water bodies and landscape changes.

Remote sensing technologies should be more frequently applied in mining and these digital technologies should be expanded to improve monitoring of mining water bodies and landscape changes. This includes continued analysis and monitoring of mining activity over extended spatial and temporal scales and can be addressed by the improved integration of remote sensing data—for example, the creation of a Toolbox in open-access GIS based software—or the use of drones for spectral exploration. Once the system is assessed, mathematical modeling is applied to predict the impact of the operation over long time scales, crucial for post-mining landscape development. Thus, an adequate strategy to obtain a reliable diagnostic should incorporate data from traditional chemical analysis, as well as their potential effects caused in biological communities (Van der Oost et al., 2003). In essence, monitoring and restoration strategies including physicochemical conditions, biological responses and high-resolution geochemistry are vital to addressing future water-sustainability issues within the industry.

4) Develop efficient technologies for mineral processing and wastewater treatment.

It is imperative that new, cost-effective technologies for mineral processing and wastewater treatment be developed. They should use less water and chemicals and be more energy efficient (Mudd, 2008). The mining industry spends a large amount of water throughout its operations and a wide range of—usually toxic—chemical agents. Water recovery and reuse practices in the mineral industry are often in conflict with technical feasibility issues related to the water quality required for mineral processing (e.g. Aldi, 2009). Developing new technologies that minimize the volume of chemical reagents or replacing them with the least-toxic biodegradable substances in the different processes is economically and environmentally beneficial (Pearse, 2005). These benefits can potentially include reduced cost for water treatment, reduced operating costs and, by means of early intervention, increased risk mitigation of potential harm caused by toxic chemicals. Moreover, there is a need for the development of efficient techniques of tailings dewatering, aiming at a dry (or paste) disposal into piles, thus eliminating the use of dams for tailings disposal (e.g. new flocculation technologies).

3
Establishment of international standards and transparency of knowledge management

We emphasize that sustainable management of water in a mining context is contingent on transparency with stakeholders (local communities, governing entities, companies etc.). Mining operations must improve the efficacy of their communication regarding the ways in which operations affect local and regional land- and waterscapes. We recognize that a vast amount of data is created during all phases of mining operation from a variety of sources. Thus, in order to assure efficient and transparent management, it is crucial to create a platform where this data can be stored, curated, analyzed and shared among stakeholders. The input for this platform will be raw data (see examples in recommendation 3.1) as well as reports related to the mining process produced by the government, the mining company, and other private companies.

Recommendation 3.1

Create open-access platforms (Knowledge Management Systems, KMS) for exchanging and sharing knowledge about mining activity according to international standards.

The recognition that business is built on both relationships and knowledge led to a paradigm shift for decision-making in a complex world. Data can be easily captured, stored, and shared. Knowledge, on the other hand, is intangible, boundless, context-specific, relational, dynamic and humanistic (Wang & Wang, 2016). Thus, there must be specific tools to manage this intellectual capital. In the field of Knowledge Management, this kind of platform is called Knowledge Management System (KMS—Becerra-Fernandez & Sabherwal, 2010). Beyond a data repository that is flexible enough to handle heterogeneous data from multiple and independent sources, KMS also allow users to integrate, analyze, and model data with the objective to produce syntheses and, ultimately, knowledge. Utilizing information technology creates an environment that facilitates local and global knowledge sharing and collaboration. The implementation of such systems will enable efficiency and innovation, ensuring interoperability, reduce redundancy and provide information transparency. In addition, they will also be a tool for a science- and evidence-based decision support, allowing all stages of the mining operation to be supervised by all parties involved. Examples of inputs include GIS-referenced data on biotic and abiotic variables related to surface and groundwater quality, information on the mining process, licensing, maps of the landscape, and data on social aspects of local communities. This system will also collect information processes and procedures, document experiences, solutions to recurring problems, and lessons learned. We recommend the following actions regarding a Knowledge Management System (KMS):

1) Implement facilities with specialized staff in order to manage the system and the knowledge management process.

2) Verify, classify, describe, organize and store data and respective metadata, assuring quality, consistency, and reliability, also making them available for retrieval.
These processes should be coordinated by specialized staff and should be as automated as possible, by applying techniques of artificial intelligence, machine learning and data mining.

3) Follow international standardization.
In order to ensure standardization and interoperability, the KMS must follow international protocols with standards (e.g. vocabularies, formats, taxonomies, etc.) for each type of data (i.e. environmental, social and economic). These norms and actions should be integrated into regulatory frameworks.

4) Apply statistical and mathematical modeling.
The data available in this system should be processed using exploratory and inferential statistical techniques in order to test specific hypotheses and answer specific questions. The data should also be used to model future scenarios.

5) Create useful outputs and involve the general public.
Identify or develop better alternatives (e.g. optimize processes), identify areas of conflict, identify exceedances of thresholds, reliant supervision/monitoring of the use of natural resources (e.g. water usage). Governing bodies, mining companies and the scientific community can work together on this task. However, it is strongly suggested that the public takes part in this process as well, receiving clear summary reports and participating in meetings organized to discuss decisions. The language used to address the public should be understandable. Technical terms should be put in a simple non-technical language. This allows local populations to understand the contents, assuring their participation, supervising and improving decision making, and also taking responsibilities in the long-term scenario envisioned for the landscape. Knowledge about processes and conditions, as well as skills necessary to understand data should be provided to the population by organizations related to mining and under the supervision of government and scientists. The interaction between actors should be stimulated through regular meetings and social-media divulgation (see Chapter 1). It is important to highlight that the data stored in these systems are also crucial for providing the communities and the government with adequate knowledge regarding the diversification potential of the economy.

Recommendation 3.2

Institutionalize transparency and effective participation of all stakeholders during all phases of mining.

The implementation of this Knowledge Management System (KMS) should begin during the planning of mining activity and should be a prerequisite for obtaining permission to operate. The mining company should specify the structure of its KMS, as well as its open data policy. This open data policy should state clearly which types of data the company will produce, and which will be made publicly available. There must also be an international guideline for open data policies stating which types of data should have intellectual property rights (i.e. copyright) and which type of data should be openly accessible. The amount of data kept proprietary should be as small as possible. We recognize that it is reasonable to have some degree of privacy during early phases of the mining process. However, the majority of data should be made available during the operation of the mine through and with the Scientific Advisory Board (Figure 1).

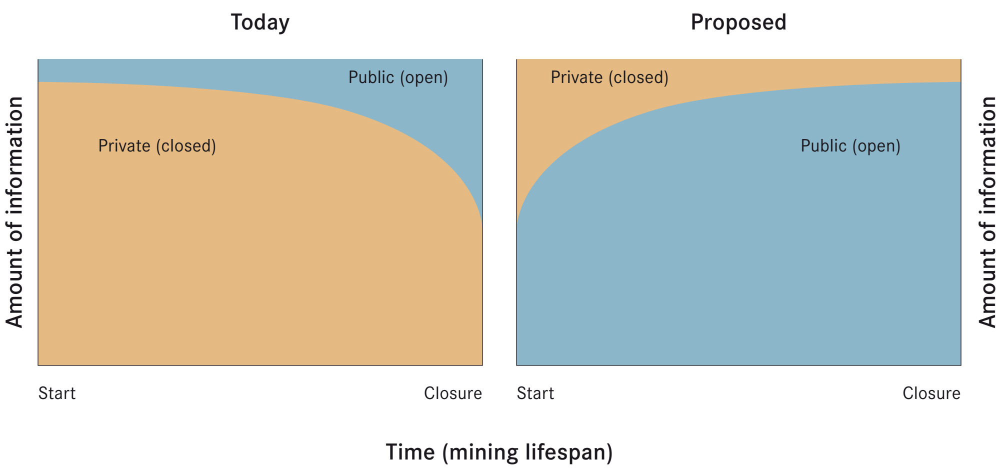

Figure 1: *Comparison between the current state and a proposal of the proportions of private and public information over the duration of the mining operation.*

Knowledge Management is a profound paradigm shift that companies must adopt. There are some obstacles that need to be addressed, such as the shortage of skilled professionals and the lack of international agreement on standards, particularly regarding how to measure and evaluate the contribution and the effectiveness of Knowledge Management. However, these obstacles should not hinder the implementation of this innovative technology. In the era of Web 2.0, where websites are widely available on personal computers and cell phones, and where social media has made this environment more participative and democratic, companies are seen as knowledge-creating entities and thus need to become more searchable, analyzable and navigable (Nonaka et al., 2000; McAfee, 2006). We expect that a public database coupled with a network structure will contribute to academic research aimed at scientific understanding of impacts and risks of mining activity as well as the development of technology and innovation that can enhance mining in a sustainable landscape.

4

Proactive development of contingency plans and failure mitigation efforts throughout the overall mining process

Recent mining catastrophies such as the tailings dam failures at Rio Doce, Brazil (2015), Brumadinho, Brazil (2019) and in Mount Polley, Canada (2014) (Petticrew et al., 2015) as well as in Nachterstedt, Germany, in 2009, where parts of an inhabited settlement slipped into a flooded open-cast mining area, have had tragic consequences including loss of human life and detrimental effects to entire landscapes and ecosystems (Wilson et al., 2016). These events demonstrate a critical need for effective failure mitigation, including preventive measures and contingency plans for immediate response actions. The proactive development of contingency plans is essential for decreasing risks inherent to regular mining operations as well as in the case of major failures (Sánchez et al., 2018). Therefore, any recommendation made in the public-industry-science discussions must be considered by the company and noncompliance must be documented.

Image 2: *Aerial photograph of the flooded areas after the Brumadinho tailings dam rupture in January 2019.*

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◂ ***Image 3:*** *Impression of the deserted village of Paracatu de Baixo, Mariana (2018) following the Fundão tailings dam rupture in Minas Gerais, Brazil in 2015. The brown lines at the buildings' facades indicate up to where the buildings were submerged during the flood.*

© Kelly Whaley-Martin

Image 4: *In the Nachterstedt accident in Germany in 2009 three people died because parts of an inhabited settlement slipped into a flooded open-cast mining area.*

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While the creation of contingency plans is not uncommon in the (mining) industry, recent disasters highlight that some current practices are insufficient in the event of major failures. Thus, we want to point out that the development of those plans needs to be initiated at the start of the mine-planning phase and then be continuously updated. The early and transparent development of such plans will support the acceptance of mining in a region and allow the project to be seen as a driver of regional development rather than solely a risk. Consequently, such actions may create time efficiency during licensing processes and possibly prevent unintended interruptions during mining operation. Furthermore, we see a significant advantage in the extension of these plans beyond the period of active mining operation, which means including the post-mining plans to re-establish sustainable landscapes.

Recommendation 4.1

Conduct environmental preservation, monitoring and risk prevention throughout the mining process.

1) Promote ecologically resilient landscapes that can absorb and recover from minor disturbances.

Landscapes with resilient ecosystems inherit the ability to absorb minor negative impacts. However, we need to make clear that we do not see resilient landscapes and ecosystems as able to resist fully against major failures such as leakages, spill events or dam failures. Ecologically resilient landscapes comprise, among other things, rivers with floodplains that can retain floodwater and particulate matter, vegetated shores and slopes that reduce erosional tendencies and enhance retention of fine sediment, and rivers and soils with self-purification capabilities as a result of rich and active microbial, fungal and invertebrate communities. Ecologically resilient landscapes are also characterized by structurally and functionally diverse terrestrial and aquatic communities that can recover from short-term stress episodes. Promoting, preserving and restoring such healthy ecosystems is of great value. As prevention helps to avert damage, these efforts are compensated via reduced follow-up costs and reduced needs for restoration. Therefore, preventative measures should be a central feature throughout the mining cycle. For controlling the implementation and success of these efforts, continuous monitoring is required.

2) Conduct integrated and effective monitoring that is flexible and adaptive.

Mining in sustainable landscapes strongly depends on an integrated monitoring program. This includes monitoring surface water and groundwater quality as well as quantity, air quality and concentrations of toxicants in soil and biota before and after mining (Gomes et al., 2017). In order to detect changes relative to a baseline, monitoring needs to be conducted throughout the entire mining operation from start to closure or reclamation. If it is not possible to have pre-mining monitoring programs, a reference area or system must be included to allow for comparisons. The monitoring of major engineered structures such as tailings ponds, dams and other water containment facilities is also of great import. The reliable and continuous monitoring of water levels and vibrations is essential as an indication in relation to the safe storage volume and as early warning sign, respectively.

All monitoring activities should be externally overseen. They should be accompanied and supported by scientists and should make use of emerging technologies (see Chapter 2).

3) Set up risk assessment and contingency plans to prepare for emergencies.

We recommend developing and continuously updating contingency plans. For cases of major failure and catastrophic accidents, these should include human and environmental risk assessments (e.g. on areas of high risk, on contaminant behavior, etc.), immediate action plans as well as action plans for damage containment and for the damage restoration and compensation phase. Here again, we strongly recommend collaborative work with scientists and other stakeholders.

Such plans should follow internationally standardized protocols and methods that guarantee an integrated and comparable view of the main tasks. Since mining activities are dynamic and prone to changing conditions, the plans warrant regular reviews and updates by the mining industry, science and other key actors. This means that assessing and managing risks as well as preparing emergency measures is an ongoing task. Contingency plans must be up to date throughout the entire mining progression to ensure improved protection possibilities and cost reduction.

Prevention and risk reduction measures have to be derived from the risk assessment. These measures aim to minimize the probability of accidents and prevent or reduce harmful consequences. It is obvious that public communities and the environment will profit strongly from the protection from failures. However, profiting actors include also the mining industry: Averting accidents strongly reduces costs and efforts for restoration and compensation. Similarly, making serious efforts in terms of prevention and mitigation transparent will most likely lead to an increased acceptance by local communities.

4) Develop socio-economic and environmental diagnostics of downstream areas impacted in the case of dam failures.

The development of a consistent and robust integrated diagnostic of the social, environmental and economic status of the downstream areas can be an important tool to define strategies and proactive actions to minimize impacts in case of a dam breach. These studies should be conducted similarly to an EIA (Environmental Impact Assessments) to identify the current social and economic conditions within communities located downstream from dams as well as identifying the most relevant ecological, environmental sensitive areas and infrastructure for water and energy supplies. By establishing a baseline for these compartments, a better understanding of associated risks and management of them will be facilitated.

Recommendation 4.2

For the case of major failure, prepare immediate action plans as well as structured follow-up activities.

1) Have immediate plans of action in place for the event of major failure or accidents.

Immediate actions following major failures or accidents need to be carefully planned beforehand, discussed with all relevant stakeholders and be rooted in science. In the case of catastrophic events, an emergency communication infrastructure needs to be installed and regularly checked and an information chain prepared beforehand (e.g., to downstream communities, to downstream drinking water extraction). Emergency communication is essential to save lives and, for example, can be realized via television, radio and cell phones (via text, social media, apps). Where population evacuation is required, contingency plans need to be prepared for this occasion. Different scenarios should be planned and prepared to avoid uncoordinated reactions. This requires efficient monitoring with automatic alarm systems that do not depend on the decision of individuals or companies to be triggered. Emergency drills have to be executed at regular intervals.

Image 5: *A rescue team searches flooded areas for missing persons after Brumadinho dam failure in January 2019.*

© Diego Baravelli

On-site first response actions for damage containment include on-demand contamination reduction measures (i.e. sediment traps). Furthermore, an emergency monitoring plan needs to be prepared and externally checked beforehand. This can comprise airborne imagery and the rapid estimation of quantity, quality and discharge rate of water/mud released, as well as impacts on downstream water bodies (via sampling of water, sediment and organisms). Note that all significant impacts—including direct, indirect and cumulative impacts—should be considered. Together with on-demand risk simulation (depending on the type and scale of emergency), this will allow the scope of the affected area to be identified. As mentioned before, emerging technologies can support these tasks.

Nature-based engineering solutions and constructional erosion control measures (e.g. mudslide reduction) based on previously realized surface flow and erosion assessments or simulations can be both preventive measures and measures following a failure event.

2) Allow immediate public review investigations of accidents or major catastrophic events.
In the event of an accident or major failure, there is currently no global standard as to how the event should be reviewed and how results should be presented to the public. Thus, we want to emphasize the need for public and transparent investigations of the circumstances around the event, including a review process of the existing contingency plans on whether or not they were effective. Besides answering the question of responsibility and liability, learning from such events is vital to establishing a global standard of safety in mining operations.

3) Instead of restoring the watershed to its previous state, build an integrated, nature-based and economically as well as ecologically sustainable landscape.
Restoration following major disturbances is essential. It comprises, for example, the removal of tailings deposited on riverbanks, dredging of tailings retained in the river channel or in dams, and restoring vegetation, forest and water springs. These remediation actions need to be externally supervised and supported by agencies and science. It is additionally necessary to involve the general public in the remediation process.

Here we acknowledge that restoring pre-existing conditions is an ambitious and almost impossible goal. Instead, we urge the mining industry to develop plans that can facilitate the creation of a transformed yet functioning landscape (Larondelle & Haase, 2012) based on the developed vision (see following chapter “Vision”). Making this vision reality requires input from all actors (see Chapter 1), especially from local communities who inherit these post-mining landscapes.

Vision

Over the course of human history, mining has had a profound—and unfortunately at times negative—influence on the environment, culture and societal development. However, we envision a future in which sustainable development is a central aspect of mining activities and in which socio-economic and environmental concerns are considered on a global scale. This includes a process dedicated to transformation that is more efficient, science-based and responsible, transparent and less environmentally and socially harmful. Key to this is a democratic, accountable and transparent approach built on trusting collaboration between all actors involved (governmental bodies, mining companies, the local population, researchers, nature protection agencies, and the public). The desired outcomes of such a successful transformation process are restored and sustainable post-mining landscapes. These will be socio-ecological systems—resilient to shocks/disturbances and with a self-confident identity—that have been repurposed, for instance, for recreation or renewable energy production and that are able to self-sustain their ecosystem functions and services. Hence, sustainability-oriented mining must acknowledge the environmental, economic and social dimensions of mining from the beginning and must aim at minimizing environmental impacts while assuring lasting socio-economic prosperity for all parties involved.

Image 6: *The Inhotim Institute in Minas Gerais, Brazil was designed in an area that previously was degraded by mining and farming activities.*

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Industries that do not constantly learn and adapt may easily miss important technological and commercial opportunities. State-of-the-art science will therefore have to play an even bigger role for the mining business in the near future, especially as natural resources are limited. We see research, co-designed with the mining industry but conducted by independent scientists, as the key to not only improve effectiveness but, more importantly, to build sustainable landscapes and prosperity, and to improve the relationship with stakeholders. This concerns not only technical and economic aspects, but in particular a reduction in energy and water consumption as well as emissions per unit of production. This has the potential to revolutionize mining practices going forward.

While the industry should be fully committed to a zero-failure target, it should also remain prepared in the best possible way for any issues in the future. Contingency plans, delineated in the planning phase, must be subjected to real-time adaptation based on new insights and emerging technologies. Data transparency, efficient monitoring systems (combining macro-and microbiological indicators, high-resolution geochemistry and remote sensing techniques) together with early warning-systems for the local population could easily help prevent large-scale disasters and mitigate the impacts of those disasters if they occur. Apart from thinking about contingency measures to prevent failures, an integrated landscape approach must also be able to hold all relevant stakeholders accountable, whether in government, science or industry.

At the same time, decisions about mining and mining landscapes should not be made in corporate headquarters alone, as these are often far removed from the environmental and societal impacts on the ground. The decision to transition from a pre-mining to a mining landscape, or from a mining to a post-mining landscape, should not be made purely for economic reasons. Instead, we envisage a sustainable landscape approach as a perspective with which societies are democratically empowered to make decisions about the future of landscapes, ideally balancing values of sustainable development and commercial interests. At the very least, such an approach raises the visibility of friction, trade-offs, and often incommensurable values—an inevitable part of any political system—and allows policy-makers, as well as the wider public, to reflect upon mining as an activity that can be shaped and improved for collective benefit. Scientists in particular can foster such a discussion, and provide scientific input.

We believe that such a paradigm shift towards **a new vision of water and sustainability management in mining and post-mining landscapes**, initiated by joint efforts from policy makers, mining companies and the public, is possible.

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Image 7: *The authoring group of young scientists, senior experts and academy representatives at the Workshop "Sustainable Water Management in Mining and Post-Mining Landscapes" from 1–5 October 2018 in Belo Horizonte, Brazil.*

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ISBN: 978-3-8047-4026-6