NAVIGATING WATER SUSTAINABILITY IN MINERAL MINING WITH A SYSTEMS THINKING-BASED APPROACH

Gilrandy Respati1*, Utomo Sarjono Putro2

1 School of Business and Management, Institut Teknologi Bandung, Bandung, West Java, Indonesia
2 School of Business and Management, Institut Teknologi Bandung, Bandung, West Java, Indonesia
*gilrandy_respati@sbm-itb.ac.id

ARTICLE INFO

Published: June 25th, 2023

This paper provides a comprehensive review and analysis of the sustainable management of water resources in the mining industry. It presents an overview of various sustainable development frameworks for the mining sector, emphasizing the need for a more comprehensive and integrative approach to managing water resources. The paper also highlights the critical role of water in mining operations and the increasing pressure on water resources due to mining activities. Consequently, it underscores the significance of sustainable water management practices such as stakeholder engagement, catchment-based approaches, and adequate water management strategies.

Keywords: sustainable water management, mining industry, systems thinking, system dynamics modeling, sustainability frameworks in mining

INTRODUCTION

Historically, mining and mineral resources have been essential to human societies’ development, economy, and welfare. Metal mining has provided the necessary raw minerals for construction, technological innovation, and improving the quality of human life. The mining industry has created jobs, increased life expectancy, contributed to proper income distribution, and improved infrastructure, public health services, and education. Metals and minerals are crucial to achieving low-carbon futures and improving global well-being and welfare (Bainton et al., 2021; Hosseinpour et al., 2022; World Bank Group, 2020).

However, the benefits and impacts of mining operations must be carefully balanced and managed to ensure sustainable development. The concept of sustainable development holds that any human activity, including mining, should provide a net positive contribution to people and minimize risks to the environment. The total benefits of mining should outweigh its costs, ensuring that the industry supports the broader balance of benefits and impacts (ICMM, 2022).
Despite the industry’s notable progress, water management remains a pressing issue, particularly in the context of sustainable mining practices. This paper aimed at introducing a conceptual framework for sustainable water management in mineral mining operations, applying a systems thinking approach. It seeks to illuminate how this innovative strategy can navigate the complex dynamics of water sustainability in mining, thereby contributing to the overall sustainable development goals of the industry.

**METHOD**

The researcher combined a qualitative approach with a methodology for conducting a literature review. The majority of the articles and other sources used to compile the study's data were books and academic publications that examined relevant subjects (Water sustainability, mineral mining, system thinking-based approach). The three-stage Miles and Huberman (2014) approach, which includes data reduction, data visualization, and conclusion drawing/verification, was then used by the researcher.

**RESULT AND DISCUSSION**

**Mining and Sustainable Development**

The term 'sustainable development' has been interpreted in various ways. Yet, the most universally accepted definition originates from the Brundtland Report, released by the World Commission on Environment and Development (1984). According to the report, sustainable development is "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." This definition underscores the crucial balance between economic, social, and environmental elements to ensure the well-being of current and future generations.

During the early development stages, developed nations achieved growth by exploiting natural and mineral resources. However, this led to adverse environmental consequences due to intensified mining activities, necessitating a heightened focus on the environment. Furthermore, economic development in these countries has caused several social issues, such as poverty, inequality, natural resource destruction, and class division. These factors contributed to the emergence of the sustainable development concept in 1992 (Asr et al., 2019; Hustrulid et al., 2013).

Mining activities often negatively impact environmental, social, economic, and political dimensions. These impacts, including substantial land disturbance, community displacement, and potential health and safety risks, are frequently long-lasting, highly visible, and emotionally charged (Hilson & Murck, 2000).

For a minerals industry project to be considered sustainable, it must be financially viable, technically suitable, environmentally responsible, and socially accountable. Governments, the mining industry, and society must balance these socioeconomic and environmental concerns to maximize benefits while minimizing or eliminating harm and degradation (Worrall et al., 2009). Conscientious corporations should implement sustainable initiatives that lessen environmental impact and uphold social responsibilities within the economic development framework (ACSMP,
Navigating Water Sustainability in Mineral Mining with a Systems Thinking-Based Approach

In light of these challenges and opportunities, the role of water management in sustainable mining practices emerges as a critical area of focus, warranting further exploration and innovative approaches.

Contributions of Mining to Sustainable Development

The impact of mining operations on various aspects of sustainable development, including environmental, societal, and economic factors, has been the subject of extensive research across diverse mining methodologies and regions (Alves et al., 2018; Amirshenava & Osanloo, 2019; Azapagic, 2004; Phillips, 2013; Syahrir et al., 2020). Despite the positive societal impacts of mining, much of the literature has predominantly focused on its negative aspects (Esteves, 2008b).

Mining contributes significantly to the economy by generating essential goods and services, providing direct and indirect employment opportunities, and serving as a wealth source for companies, institutional and private investors, and governments at all levels through taxes, royalties, and levies (Esteves, 2008b, 2008a). Moreover, from an economic standpoint, mining positively influences revenue capture and reinvestment, a foundational principle of mineral economics since the 1970s (Solow, 2018).

The sustainability of mining can be enhanced by reducing the depletion rates of known reserves. This allows research, development, and technological innovation to devise alternative materials and methodologies, improve resource recovery, enhance recycling, and adopt cleaner production practices. The proliferation of these technological advancements throughout the industry is crucial, especially among developing mining nations, to avert the technological and environmental missteps previously made by more developed mining countries (Van Berkel, 2000; Wellmer & Becker-Platen, 2002).

Managing resources extracted by the mining industry is an increasingly significant issue, given the finite nature and non-renewability of mineral resources on a human timescale. Moreover, mining activities often have severe and lasting impacts on the natural and social environment, including modifications to topography, changes to geologic and hydrologic conditions, vegetation removal, and altered fauna habitat conditions (Cowell et al., 1999; Hilson, 2002; Mudd, 2007; Mulligan, 1996; Rajaram et al., 2005; Sahu et al., 2015).

Mining companies could adopt eight critical practices to further their contributions to sustainable development. These include insisting on cleaner production methods, acknowledging limits, embracing recycling, admitting faults and trade-offs, self-policing, supporting transparency and systematic monitoring, accepting and respecting external regulations, and ensuring they contribute their fair share economically (Frederiksen & Banks, 2022).

Mining Sustainability Frameworks

Several scholars have put forth various frameworks for sustainable development in the mining industry as catalysts for improved practices. For instance, Azapagic (2004) proposed a set of indicators that align with the Global Reporting Initiative guidelines (2005). This approach
emphasizes identifying pertinent stakeholders and understanding their interests to craft meaningful sustainability indicators apt for large-scale mining.

The International Council on Mining and Metals (ICMM) has developed the 'Mining Principles,' outlining a framework of good practice environmental, social, and governance requirements for its corporate members. This framework follows a principles-criteria-indicators approach toward sustainable development and aligns with the global objectives of the UN Sustainable Development Goals and the Paris Agreement on climate change (ICMM, 2003).

Laurence (2011) suggested that mining could achieve sustainable operations by concentrating on five key areas: economic performance, environmental performance, community benefit, safety, and efficiency. The World Bank, on the other hand, has defined sustainable development in mining as encompassing financial viability, environmental integrity, social responsibility, effective governance, and enduring community value (Mitchell, 2003).

The Global Reporting Initiative (GRI) (2005) identified a comprehensive set of indicators, 15 economic, 56 social, and 39 environmental, with an additional 13 being specific to the minerals sector. These indicators are primarily targeted at larger entities in the active mining sector (Worrall et al., 2009).

In recent work, Adomako and Tran (2022) found a positive correlation between sustainable environmental strategies and a mining company's competitiveness and financial performance. They recommend governments in developing countries provide a vision to assist firms in integrating sustainability issues into their strategic planning. This guidance could be a policy roadmap to foster and promote sustainable innovation.

**Water Management in Mining**

Water is an indispensable resource crucial for all living beings' survival (WHO, 2011). In the context of mining operations, it is of utmost importance to minimize the usage of new freshwater extracted from the natural environment to ensure long-term sustainability. As ICMM (2014) indicated, water stewardship in the mining sector necessitates using water in socially equitable, environmentally sustainable, and economically beneficial ways. With the escalating pressure on global water resources, achieving water resource sustainability necessitates a comprehensive approach to water management. To this end, ICMM (2014) has proposed three frameworks for effective water management in mining operations: stakeholder engagement, a catchment-based approach, and sound water management practices.

Water balance and hydrologic models are employed to monitor operational performance and address water availability and quality challenges. The water balance reflects the amount of water withdrawn, consumed, and discharged. The total water utilized across mining operations is sourced from several avenues, including dewatering, surface water sources, and recycled water from treatment plants. It's important to note that the risks associated with water in mining heavily depend on geographic and climate factors specific to the mining location.

The importance of sustainable water resource management in mining operations cannot be overstated, as it is pivotal for mitigating the negative impacts of mining activities on the
environment and local communities while ensuring the long-term feasibility of mining operations. The literature underscores the importance of responsible and efficient water resource usage, community engagement, and the employment of suitable technologies to minimize water consumption, reduce waste, and prevent water pollution.

**Systems Thinking**

Systems thinking offers a unique approach to problem-solving and decision-making by treating a problem or situation as a complex system comprising interconnected components and feedback loops. Instead of viewing problems as isolated events or issues, systems thinking considers them part of a broader system. Haraldsson (2014) posits that systems thinking is a science that employs structured logic and integrates multiple disciplines to understand the patterns and relationships within complex problems. It acknowledges that problems cannot be solved merely by breaking systems down into constituent parts. Instead, it uses an organized and methodical approach to comprehend problems and identify potential solutions.

In his work, Edson (2019) presents a simplified diagram illustrating three crucial elements of systems thinking: synthesis, analysis, and inquiry (Figure 1). Synthesis involves assessing the system by bringing its parts together, while analysis focuses on dissecting the system and understanding its parts and behaviors. Inquiry, on the other hand, seeks solutions through systematic investigation. Ackoff (1999) emphasized that synthesis and analysis are essential and complementary facets of systems thinking.

![Figure 1. System Thinking as Three Highly Synergistic Activities (Edson, 2008)](image)

Arnold and Wade (2015) proposed a definition of systems thinking as a set of synergistic analytic skills used to improve the capability of identifying and understanding systems, predicting their behaviors, and devising modifications to them to produce desired effects. These skills work together as a system. This definition can be expanded in terms of its content and illustrated in a systemigram, as shown in Figure 2.
Arnold and Wade (2015) define systems thinking as a cohesive set of analytical skills to enhance the ability to identify and understand systems, predict their behavior, and devise modifications to produce desired effects. These skills function in synergy, like a system. This definition can be expanded and depicted visually in a systemigram, as shown in Figure 2.

Systems thinking involves grasping the interconnections between system components and pinpointing the root causes of a problem to create effective and sustainable solutions. It finds applications in diverse fields, such as business, economics, engineering, healthcare, and environmental management. Within system analysis, two main branches exist: 'hard methods,' which employ quantitative solutions for system design, and 'soft methods,' which take a more qualitative and collaborative approach. According to Checkland (2000), while hard methods focus on engineering systems to achieve specific objectives, soft methods tackle real-world problems where the desired outcomes are unknown, adopting a phenomenological perspective.

Edson (2008) provides an alternative viewpoint on applied systems thinking, illustrated in Figure 3. This representation underscores that applied systems thinking is a subset of the broader systems thinking construct and incorporates both hard and soft methodologies. Côte et al. (2010) showed that a simple systems model is adequate as an appropriate tool for assessing water system performance and providing guidance to improve performance through strategic planning and for guiding adoption of site objectives with the case study of 7 coal mines in Australia.
System Dynamics for Water Resources Management

Water resources are integral to the socio-economic-environmental system and have been increasingly influenced by the complexities of hydrological cycles, socioeconomic factors, and divergent stakeholder perspectives, as well as issues related to water usage (Langsdale et al., 2007; Sušnik et al., 2013; Tidwell et al., 2004). Comprehending the dynamic interactions and feedback mechanisms among hydrological, social, economic, and environmental factors is essential for strategic water resource planning and management (Han et al., 2017; Sun & Yang, 2019; Z. Zhang et al., 2014).

Despite this, decision-making in water resources management is complex and uncertain, which creates challenges (Kotir et al., 2016; Simonovic, 2012; Stave, 2003; X. H. Zhang et al., 2008). Traditional linear causal thinking and mechanistic models often fall short because they handle the interactions and dynamics of different subsystems separately (Mirchi et al., 2012; Sterman, 2000). Consequently, it's often necessary to understand the root causes of problems more deeply to formulate strategic water management policies (Davies & Simonovic, 2011; Gohari et al., 2017).

Recognizing and capturing feedback loops within water resource systems can provide insight into the potential consequences of system disturbances, thus offering a suitable platform for sustainable water resource planning and management at a strategic level (Mirchi et al., 2012; Simonovic, 2012). Therefore, system dynamics modeling, with its holistic approach to the complex dynamics, feedback processes, and interdependencies between hydrological, social, economic, and environmental processes, has been argued by many authors to be beneficial for decision-making in water resource management (Ahmad & Simonovic, 2004; Bakhshianlamouki et al., 2020; Gies et al., 2014; Gohari et al., 2013; Mirchi & Watkins, 2013).

System dynamics modeling has been widely applied as a decision-support tool for water management and planning, given its ability to integrate and analyze hydrological, social, economic, and environmental components and management measures under different scenarios in one comprehensive model. It helps understand the dynamic behavior of complex water resource
Navigating Water Sustainability in Mineral Mining with a Systems Thinking-Based Approach

systems (Gastelum et al., 2018; Karimlou et al., 2020; Phan et al., 2018; Sahin et al., 2015). Moreover, system dynamics modeling encourages stakeholder involvement from the problem-scoping to modeling processes, making it possible to identify effective options for the modeled system under future scenarios (Phan et al., 2021). Hence, system dynamics can aid water managers in identifying problematic trends, understanding their root causes, and evaluating appropriate management measures for strategic decision-making (Mirchi et al., 2012; Simonovic, 2012).

Phan et al. (2021) conducted a systematic literature review of system dynamics applications in water resource management, revealing that only 40% of the reviewed articles developed causal loop diagrams. Most of the reviewed publications applied scenario-based approaches (82%) to evaluate the effectiveness of management measures. Structural behavior and behavior-pattern tests were primarily used to assess the validity of the model structure. About 90% of the reviewed studies incorporated scenarios or measures into their system dynamics models to understand the dynamic behavior of complex water resource systems. Various system dynamics software packages were found to be used for constructing causal-loop diagrams and stock and flow diagrams, capturing the feedback for water resources systems, with Vensim being the most frequently used (57%).

Figure 4. System Dynamics Framework for Water Resources Management (Phan et al., 2021)

A traditional system dynamics modeling framework consists of four phases: problem scoping and structuring, model conceptualization, model implementation, and testing, and scenario analysis (Sterman, 2000). To manage complex water resource systems with high uncertainty, Phan et al. (2021) suggested an enhanced system dynamics modeling framework, as illustrated in Figure 4, which includes nine phases.

Summarizing the analysis, it's clear that system dynamics modeling is a powerful tool for simulating complex water systems' behavior over time, and it has broad applications in water resources management. For instance:
Navigating Water Sustainability in Mineral Mining with a Systems Thinking-Based Approach

a. Water balance management: System dynamics models can simulate water supply and demand over time, considering population growth, land use changes, and climate variability. This can help identify potential water shortages and devise strategies for managing water resources to meet future demand.

b. Watershed management: System dynamics models can simulate water flow through a watershed, considering factors like land use and runoff. This can help identify potential pollution sources and devise strategies for reducing the impacts of land use on water quality.

c. Flood management: System dynamics models can simulate the behavior of waterways during floods, considering factors such as rainfall intensity and land use. This can help to formulate strategies for managing flood risk and mitigating the impacts of floods on communities.

d. Groundwater management: System dynamics models can simulate the behavior of groundwater systems, considering factors such as groundwater recharge, pumping rates, and water quality. This can help devise strategies for managing groundwater resources sustainably and minimizing the impacts of groundwater pumping on surface water resources.

Development of the Conceptual Framework

In the pursuit of generating robust strategies for sustainable underground mine water management, a conceptual framework acts as an essential research compass. This framework is designed to channel our exploration of research issues, navigate our methodology, and pave the way toward our intended conclusions. The researchers have constructed the current study's framework based on a comprehensive analysis of prior research findings, weaving these insights into a tailored structure that encapsulates our specific research aim.

The lens through which we approach this investigation is grounded in systems thinking. This research methodology propels us to scrutinize the intricacies within each stage of water use in underground mining operations - from the water input stage through the processing phase, and up to the output stage. Our quest is to glean insights that will fuel the development of superior water management strategies in underground mining. The envisioned strategies aim to foster social equity, environmental sustainability, and economic benefit, mirroring the guiding principles established by ICMM (2014).

Figure 5 captures our research framework graphically. This figure is an adaptation and modification of the structures proposed by ICMM (2014) and Zhang et al. (2014), specifically redesigned to mirror our research objectives and the unique characteristics of underground mining water management. In this framework, each component reflects an element of the water management process. The structure also highlights the interconnectedness of these processes, emphasizing the need for a holistic approach to developing sustainable strategies.

Our research framework, visually depicted in Figure 4, is built on three fundamental premises: the responsible and efficient use of water resources, the long-term viability of mining operations, and the minimization of negative impacts from mining activities. These three core principles are extrapolated to align with practical mining activities, creating a three-pronged goal for the systems thinking analysis. The goals include minimizing water input (through a reduction
in groundwater inflow, surface runoff, and precipitation), optimizing water system processes (through enhancing water use efficiency, promoting water recycling, and managing water-related risks), and minimizing output (by reducing consumption, maintaining water quality, and limiting wastewater discharge).

Applying systems thinking to these defined goals aims to achieve the ultimate objective of sustainable mineral mining water management. This ultimate objective encompasses the following three dimensions: social equity, environmental sustainability, and economic benefits. In essence, the systems thinking approach aids in deconstructing the complex dynamics of water use in mining, thereby guiding the development of strategies that promote sustainable water management.

**Figure 5. The Conceptual Framework for Applying Systems Thinking to Mine Water Management**

Figure 5 provides a visual representation of this conceptual framework. The figure conveys the interconnectedness of these processes and emphasizes the central role of systems thinking in navigating the complexities of water management in mining. It illustrates how the foundational principles guide the goal-setting for water input, process, and output, and how applying systems thinking to these goals leads towards the ultimate objective of socially equitable, environmentally sustainable, and economically beneficial mining practices. This framework, therefore, serves as the blueprint for our research, steering our analysis toward strategies that promote sustainable water management in the mining industry.
CONCLUSION

This paper has highlighted the critical issues surrounding the sustainable management of water resources in the mining industry. A comprehensive literature review outlined various sustainability frameworks, water management principles, and the application of systems thinking and system dynamics in addressing complex environmental problems.

Due to its substantial impact on water resources, the researchers emphasized that the mining industry needs a comprehensive framework to manage these resources sustainably. Several frameworks were discussed, each with its unique focus but converging on the need for economic viability, environmental soundness, and social responsibility.

The paper also highlighted the centrality of water in mining operations and how its sustainable management requires a holistic approach, given the increasing pressure on global water resources. Mining operations can effectively steward water resources by adopting best practices and utilizing strategies like stakeholder engagement, catchment-based methods, and adequate water management.

The paper stressed the need to shift from traditional mechanistic models and linear thinking to a more holistic and dynamic systems thinking approach when addressing the complexities of water resources management in mining. System dynamics modeling was proposed as an efficient tool to understand the complex dynamics of water resource systems, predict their behavior, and devise modifications for desired outcomes.

In developing the conceptual framework, the paper synthesized knowledge from prior research and adapted it to fit the research aim of devising sustainable underground mine water management strategies. The developed framework, guided by the principles of systems thinking, provided a strategic roadmap towards a more socially equitable, environmentally sustainable, and economically beneficial water management strategy in the mining industry.

This study sets the foundation for further research to refine these strategies and enhance their practicality and effectiveness. It invites mining companies, policy-makers, and other stakeholders to adopt a systems-thinking approach to manage water resources sustainably and ethically in the mining industry. The ultimate goal is to ensure the longevity and social license of the mining operations while safeguarding the valuable water resources upon which we all depend.

REFERENCE


Navigating Water Sustainability in Mineral Mining with a Systems Thinking-Based Approach


Haraldsson, H. V. (2004). *Introduction to system thinking and causal loop diagrams* (pp. 3-4). Department of Chemical Engineering, Lund University.


ICMM. (2003). *Our principles*. ICMM.

ICMM. (2014). *Role of mining in national economies*. ICMM.


Navigating Water Sustainability in Mineral Mining with a Systems Thinking-Based Approach


Navigating Water Sustainability in Mineral Mining with a Systems Thinking-Based Approach

Solow, R. M. (2018). The economics of resources or the resources of economics. In Discounting and Environmental Policy. https://doi.org/10.4324/9781315199818-17


Sun, B., & Yang, X. (2019). Simulation of water resources carrying capacity in Xiong’an New Area based on system dynamics model. Water (Switzerland), 11(5). https://doi.org/10.3390/w11051085


Van Berkel, R. (2000). Integrating the environmental and sustainable development agendas into minerals education. Journal of Cleaner Production, 8(5). https://doi.org/10.1016/S0959-6526(00)00045-7


