Waterminer – a regional spatio-temporal approach to water reuse management in mining areas in Vietnam

S. Greassidis, V. Trinh Quoc, K. Brömme and H. Stolpe

ABSTRACT

Mining is usually associated with draining of large quantities of water. On the other hand, mining operations themselves are water users for purposes like coal or ore washing, dust mitigation, recultivation, etc. The normally existing water surplus can be seen as a resource for public purposes instead of discharging the water to rivers and the sea. It is typical for the mining operation that these water amounts vary spatio-temporally according to the mining process. The R&D project WaterMiner investigates the example of the Hon Gai hard coal mining area in Ha Long, Vietnam, as to how and to what extent under the variable spatio-temporal conditions the mine water can cover the water demand in the mines themselves and contribute to the public water supply in the surrounding settlement area of Hon Gai. The spatio-temporal change of mine water drainage, mine water treatment and mine-internal water use and the potential mine-external water use volumes in the project region are investigated by a material flow model and visualized by Sankey diagrams, maps, and tables. Several options for delivery of mine water for mine-external water uses as a contribution to the public water supply are shown.

Key words | material flow analysis, mine water management, mine water treatment, mine water use, spatio-temporal, Vietnam

S. Greassidis (corresponding author)
V. Trinh Quoc
K. Brömme
H. Stolpe
Environmental Engineering and Ecology,
Ruhr University of Bochum,
Universitaetsstr. 150, 44801 Bochum,
Germany
E-mail: *sandra.greassidis@rub.de*

HIGHLIGHTS

- The combination of material flow analysis and a geoinformation system is a strong instrument for water reuse management, taking into account the spatial and temporal changes in mining.
- Treated mine water can be regarded as a complementary water resource for public purposes instead of discharging the water into rivers and the sea.

INTRODUCTION

Mining is usually associated with draining of large quantities of water, which up to now, have mostly been discharged unused. On the other hand, mining operations themselves often represent water users for purposes such as coal washing, dust mitigation, etc. Treated mine water can be regarded as a complementary water resource for public purposes instead of discharging the water into rivers and the sea. It is typical for the mining operation that these water amounts vary spatio-temporally depending on the mining process.

The joint R&D project WaterMiner investigates under different spatio-temporal situations how and to what extent the existing water demand in the mines and parts of the water demand in the surrounding urban area can be met using treated mine water. Over the course of stricter implementation of environmental legislation as well as transition from open pit to underground mining, there is a need for a comprehensive approach in mine water management.

doi: 10.2166/wrd.2020.045

The joint R&D project WaterMiner 'Spatio-temporally coordinated recycling and reuse of mining waste water exemplified by an urban mining area' (established in 2016, project coordination by EE + E Environmental Engineering + Ecology, Ruhr University, Bochum) was sponsored by the German Federal Ministry of Education and Research (BMBF).

The WaterMiner project consists of the following work packages: project coordination (EE + E); basic and system analysis, material flow analysis, water management system (EE + E); GIS for water infrastructure (Disy Informationssysteme Ltd, Karlsruhe); monitoring information system (ribeka Ltd, Bornheim); technical concept for water and sediment management (DGFZ, Dresden); economic concept (environmental economics, University of Koblenz-Landau); exemplary technical implementation of water and sediment management (DGFZ, Dreseden and LUG Engineering Ltd, Cottbus); project host and cooperation (VINACOMIN Vietnam National Coal and Mineral Industries Holding Corporation Ltd, Hanoi).

PROJECT AREA: HON GAI

The Hon Gai hard coal mining area is located in Quang Ninh province in the northeast of Vietnam. The project area covers the eastern part of the city of Ha Long, the Hon Gai peninsula, with an area of 125 km^2 (see Figure 1).

The coal is mined in open pit mines and increasingly also in underground mines (VN PC Ha Long City 2014). The open pit mining will be continued until 2025, the underground mining beyond the year 2030 (GoV 2016). The spatio-temporal changes in the mining process and also increasing improvements in the treatment of mine water, lead to continuous changes in the location, quality, and quantity of mine water (VINACOMIN 2013).

Currently, 13 mines (open pit and underground mines) are operating, all belonging to the state-owned parent company Vietnam National Coal and Mineral Industries Holding Corporation Ltd (VINACOMIN). Within the mining area of Hon Gai, also mining infrastructure facilities exist such as coal processing plants, a coal-fired power plant, coal stores, mine water treatment plants, facilities for the mine workers like canteens, washing rooms, etc.

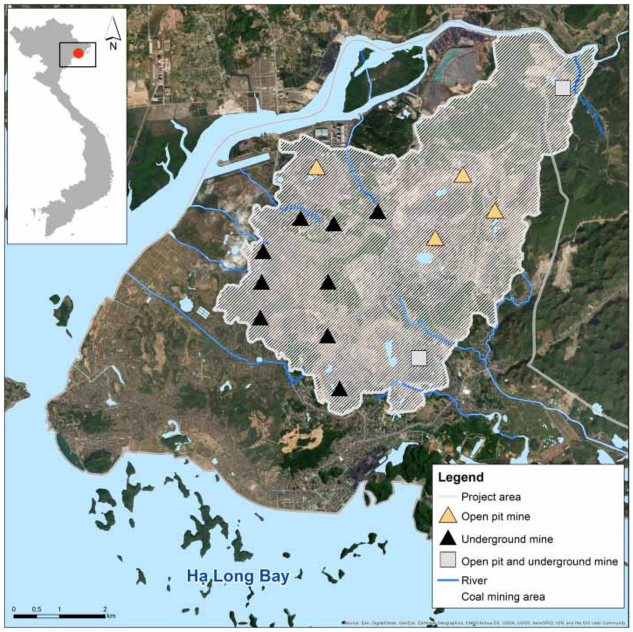

Figure 1 | Project area in Hon Gai.

Basic investigations and the development of environmental protection concepts for the mining area including mine water treatment have been performed by the R&D project RAME (Research Association Mining and Environment) from 2005 to 2015 (Broemme et al. 2014; Broemme & Stolpe 2015).

The average annual rainfall in Hon Gai area is 1,800 mm/year, but the rainfall is very unevenly distributed in two seasons. The rainy season starts from May and ends at the end of October. The rainfall in the rainy season accounts for 85% of the annual rainfall. The dry season starts from November and ends in April. The average rainfall is very low (mostly of less than 100 mm/month). The rainfall in the dry season accounts for 15% of the annual rainfall.

The uneven distribution of the annual rainfall usually means large drainage rates from the open pit mines in the rainy season and low drainage rates in the dry season. The drainage from the underground mines is partly independent of the annual rainfall distribution. Surpluses after deduction of mine-internal water uses occur mainly in the rainy season.

The water supply in Quang Ninh province, and particularly in Hon Gai, is operated by the Quang Ninh Clean Water Joint Stock Company (QUAWACO). The project area Hon Gai is supplied with approximately 20,000 m^3 per day.

The water is taken from the Cao Van reservoir. The water resource of the reservoir is limited and the supply is difficult in the dry season. The current water resources plan of Quang Ninh province prognoses a water deficit for Ha Long City including Hon Gai during the dry season (DONRE Quang Ninh 2016).

Against the background of the growing water demand in Hon Gai due to the increasing tourism in the form of numerous newly built apartments, the use of additional water resources will be essential for the further development of Hon Gai.

METHODOLOGY

The investigation for mine water management using the example of the Hon Gai hard coal mining area under the existing continuously changing spatio-temporal conditions consists of the following work steps:

1. **System analysis**: identification of the system boundaries and the relevant system elements of mine waters in the project area (mine drainage water, mine water treatment, mine-internal water uses, potential mine-external water uses), defining of interconnections of the mine water infrastructure and GIS based visualization.
2. **Spatio-temporal investigation:** investigation of the mining and the water amounts in the project area for the existing situation, the situation 2021–2026, and the final situation from 2030 onwards. The spatio-temporal investigation is performed by using Geoinformation System (GIS).
3. **Material flow analysis (MFA):** based on the system analysis and the spatio-temporal investigation, material flows (mine drainage water, mine water treatment, auxiliary material, sludge, etc.) for the existing situation in 2016, the situation 2021–2026, and 2030 onwards are estimated. The MFA is done by using the software Umberto® NXT Efficiency (ifu 2016).
4. **Recommendations:** the recommendations for the future water management are derived. The recommendations refer to general options for development of the mine water management and water delivery for mine-external water uses as a basis for general decisions. Based on such general decisions, further technical and economic studies should be carried out.

The results form the basis for developing strategies in the utilization of treated mine water in the Hon Gai peninsula, Vietnam. The results of this study can be transferred to other coal mining areas in Vietnam or areas with similar climatic and socio-economic conditions.

RESULTS AND DISCUSSION

The results of the single above-mentioned work steps are reported and discussed in detail.

System analysis

A detailed system analysis was performed to define the system boundaries, the relevant system components, and the system interconnections. In the area of the individual mines, this system differs in detail; the generalized result of the system analysis is shown in Figure 2.

Figure 2 shows the following main mine water-related system components and interactions.

The surface runoff and (possible) treatment is the objective of another WaterMiner part project (Ulbricht *et al.* 2018; Ulbricht & Bilek 2020).

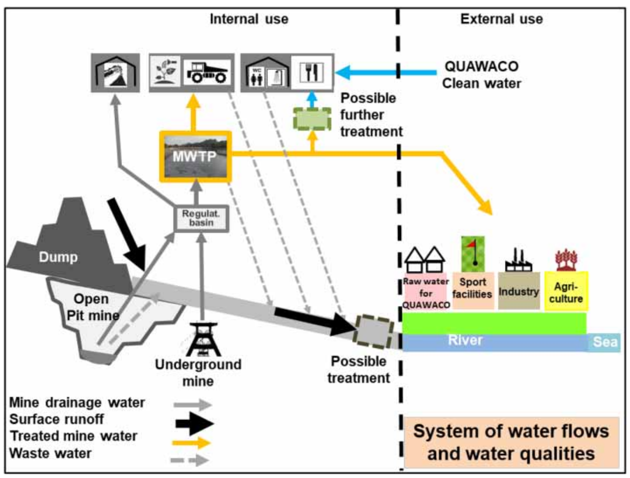

Figure 2 | Generalized mine water system.

The mine water sources (mine drainage water), mine water treatment plants (MWTP), mine-internal water use and the potential mine-external water use are objectives of this study. The mine water sources include also clean water from the water supply system (QUAWACO, drinking water). Another component of the mine water system is also wastewater, e.g., from coal screening, car washing, domestic wastewater, etc.

The mine drainage water flows via regulating basins to the mine water treatment plants (MWTPs) and is treated there mainly by removing iron and manganese and, by compensation, the acidity. In the rainy season, and especially during heavy rainfall events, mine drainage water is only partially treated or discharged into the surface waters without treatment.

Existing mine-internal and potential mine-external uses of mine water are also included in the system description. Mine water from the regulating basin without treatment is used for coal screening. Mine water after treatment is used mine-internal for irrigation of recultivation areas, truck washing, and dust mitigation. With further treatment, mine water also can be used for additional mine-internal services like drinking water or in canteens and can substitute the water from QUAWACO.

Potential mine-external water uses are shown in the right-hand part of Figure 2: raw water for QUAWACO for further treatment, water for irrigation of agriculture and sport facilities, water for industry (e.g., cooling water for the thermal coal power plant in Hon Gai).

Spatio-temporal investigation

The mining process causes continuous spatio-temporal changes by closing mines (open pit mines), opening mines (underground mines), by dumping mine waste material, by refilling open pit mines, by revegetation and reuse of abandoned mining areas. This study focuses on the resulting effects on the sources and quantities of mine water.

The general spatial mine water situation, shown in Figure 2, varies in the different drainage units (DUs) of the mining area. The DUs, shown in Figure 3, are five small water basins within the mining area belonging to different mines or groups of mines: Dien Vong, Lo Phong, Ha Tu, Cai Da, and Suoi Lai.

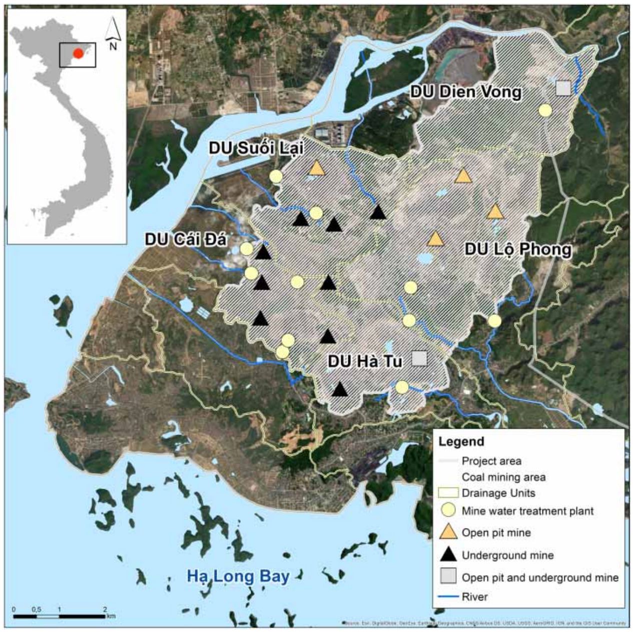

Figure 3 | Drainage units (DUs), mine water sources (open pit and underground mines), and mine water treatment plants (MWTPs).

The relevant temporal mine water related situations are defined as follows:

- Existing situation at the project start (2016)
- Intermediate situations (2021, 2026)
- Final situation (2030 onwards).

The existing situation characterizes the situation when the project was established. The intermediate situations were selected due to significant changes in mine drainage water volumes and the enforcement of environmental legislation. The final situation is the year in which the current National Coal Mining Master Plan ends (GoV 2016).

Within the five DUs, 12 mine water treatment plants (MWTPs) are located (see Figure 3). Table 1 shows the number of MWTPs in the related DUs according to the defined temporal situations.

In the existing situation, 12 MWTPs are operating in the mining area. The number will be reduced to six MWTPs by the year 2030. The proportion of treated mine water averages 74% (VINACOMIN 2014). Especially during heavy rainfall events, mine water is only partially treated. This is improved particularly by extending MWTPs and modifying the operation management.

Table 1 | Number of mine water treatment plants within the drainage units

Drainage unit	2016 (MWTPs)	2021 (MWTPs)	2026 (MWTPs)	2030 (MWTPs)
Cai Da	5	5	3	2
Suoi Lai	2	2	2	2
Ha Tu	1	1	1	1
Lo Phong	3	3	0	0
Dien Vong	1	1	1	1
Total	**12**	**12**	**7**	**6**

As mine operations close down gradually, the mine drainage water will decrease, the MWTPs will reduce or end their operation and the water consumption for mining purposes will reduce. At the same time, along with the expansion of industry, urban areas, and tourism, the water demand of external users will increase.

Material flow analysis (MFA)

The Umberto® NXT Efficiency software (ifu 2016) is applied to identify, quantify, and assess the potentials in recycling and reuse of mine water in the individual DUs and summarize for the entire mining area. The investigated materials are water, auxiliary substances, and sludge (Broemme *et al.* 2018). As well, energy and costs are considered by the material flow analysis and by a separate study (Do *et al.* 2018).

Figure 4 shows the general structure of the material flow models, as they were built in a modified way for each DU. The material flow (mainly water flow) takes place from the left side from mine water sources, via mine water treatment to mine-internal and mine-external water use.

According to the respective structures of the water flows within the individual DUs, the water flows were recorded and modeled by the Umberto software. The basis was the quantity data provided by the mines. The quantities were combined into a total flow of the year 2016 in order to determine plausible proportions of partial flows: starting with the mine drainage water quantities, through the mine water treatment quantities, to the internal water uses. On this basis, simulations for future changes in mine drainage water quantities and thus also for the determination of water surpluses for external water uses were possible.

In addition to this quantity consideration, cost sharing is also possible by linking the costs of energy, auxiliary substances, maintenance costs, etc.

For all five DUs the relevant water-related components and interconnections were identified and the material balances of the components were estimated and implemented in the Umberto model (see Figure 4):

- Mine water sources (mine drainage water)
- Mine water treatment
- Mine-internal water uses
- Mine-external water uses.

Based on the existing situation in 2016, the defined future situations (2021, 2026, 2030) are simulated. The results were compiled in the form of water flow diagrams

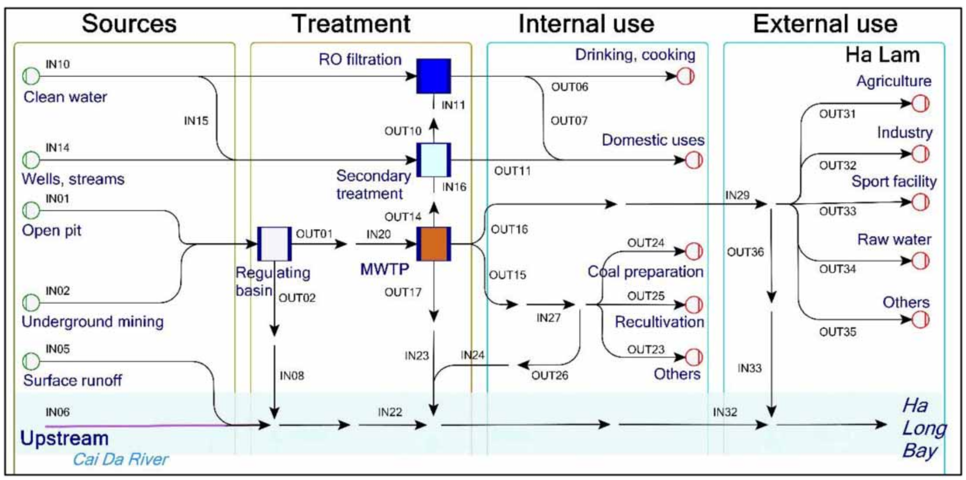

Figure 4 | Generalized material flow model (IN = input; OUT = output (section of the complete model, therefore numbering not continuous)).

(Sankey diagrams) and water balance tables for the individual DUs. Here, the results are presented in summarized form.

Within the Umberto model, the treated mine water volume is seen as the water source to cover the mine-internal water uses and as a possible complementary source for mine-external water uses.

Table 2 shows the summarized average amounts of treated mine water for the investigated spatio-temporal situations. From 2016 to 2021, there is an increase of the treated mine water volumes as all the large open pit mines are still active and the MWTPs further increase their operation to fulfill the stricter environmental regulations. After 2021, most of the open pit mines end their operation and the total mine water volume decreases, as the drainage volumes of underground mines are smaller.

Figure 5 illustrates the amounts of treated mine water within the DUs. The treated amounts within the individual DUs are each part of the total amount of treated mine water within the Hon Gai mining area.

In the following, the treated mine water amounts are compared with the mine-internal and the mine-external water demands. The amounts for potential mine-external water uses are calculated after deduction of mine-internal uses, if there is a surplus, mine-external water demands can be covered.

The annual mine-internal water demands (see Table 3) take into account all water demands for mining activities such as coal selecting, dust control, truck washing, revegetation, as well as domestic uses for mine staff (e.g., canteens, laundry, bathrooms). From the perspective of mining, the mine-internal water uses have priority.

Table 2 | Results of the material flow model: average amounts of treated mine water

Drainage unit	2016 (m³/d)	2021 (m³/d)	2026 (m³/d)	2030 (m³/d)
Cai Da	27,000	20,000	19,000	22,000
Suoi Lai	6,000	21,000	14,000	14,000
Ha Tu	12,000	34,000	27,000	27,000
Lo Phong	13,000	7,000	0	0
Dien Vong	3,000	7,000	11,000	11,000
Total	**61,000**	**89,000**	**71,000**	**74,000**

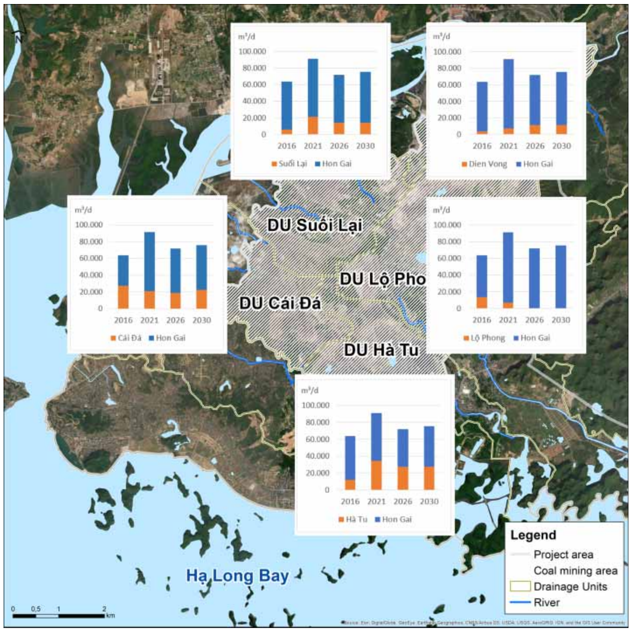

Figure 5 | Treated mine water within the drainage units as part of the summarized treated mine water within the Hon Gai mining area.

Table 3 | Results of the material flow simulation: average amount of mine-internal water uses

Drainage unit	2016 (m³/d)	2021 (m³/d)	2026 (m³/d)	2030 (m³/d)
Cai Da	5,000	3,000	3,000	3,000
Suoi Lai	1,000	1,200	1,000	1,000
Ha Tu	4,500	4,000	3,000	3,000
Lo Phong	3,000	3,000	0	0
Dien Vong	1,000	1,000	1,000	500
Total	**14,500**	**12,200**	**8,000**	**7,500**

Mine-external water demands (see Table 4) are demands for domestic water supply, tourism and public services, irrigation of urban green and golf courses, road cleaning, etc. With the rapid development of Ha Long City, according to the urban planning of housing areas (2010: 230,000 inhabitants; 2030: 350,000 inhabitants), of recreation areas, tourism (2010: 2 million international tourists, 3 million national tourists), and of services and industries, the water demand of Ha Long City, respectively Hon Gai, will apparently increase, requiring substantial additional water sources in the future.

Table 4 shows the expected development of the annual mine-external water demands of the settlement area of

Table 4 | Expected mine-external water demand in Hon Gai (VIUP 2013), amount for 2026 extrapolated by the author

Mine-external water demand	2016 (m^3/d)	2021 (m^3/d)	2026 (m^3/d)	2030 (m^3/d)
Domestic	16,000	23,000		37,000
Irrigation urban green, golf courses	1,300	2,000		3,000
Tourism, public services	1,300	2,000		4,000
Industry	2,000	2,000		2,000
Leakage	3,000	5,000		7,000
Water supply plant (QUAWACO)	1,000	2,000		2,500
Total	**24,600**	**36,000**	**46,000**	**55,000**

Hon Gai area according to the 'Review of the construction plan of Ha Long City' carried out by the Vietnam Institute for Urban and Rural Planning (VIUP 2013). The sum for 2026 was extrapolated by the authors from 2021 and 2030.

Table 5 compares the surplus amounts of treated mine water (treated mine water minus mine-internal water uses) with the mine-external water demands and shows that there is normally a surplus of treated mine water.

The comparison shows, that the mine water can generally cover parts of the mine-external water demand, particularly for the later spatio-temporal situations (2021, 2030). However, seasonal variations of the water amounts have to be considered, e.g., less available water during the dry season and water storage in the rainy season.

This general result needs to be viewed critically and further specified with regard to the question of water quality for the different applications and with regard to the seasonal variation of precipitation.

Table 5 | Surplus amounts of treated mine water, compared with mine-external water demand

Water amounts	2016 (m^3/d)	2021 (m^3/d)	2026 (m^3/d)	2030 (m^3/d)
1. Treated mine water	61,000	89,000	71,000	74,000
2. Mine-internal water demand	14,500	12,200	8,000	7,500
3. Surplus water amount[a]	**46,500**	**76,800**	**63,000**	**66,500**
Mine-external water demand	24,600	36,000	46,000	55,000

[a]The surplus water amount is the difference between 1. Treated mine water and 2. Mine-internal water demand.

It should be considered that the treated mine water complies with the Vietnamese water quality standard QCVN 40 (2011) and is usable, e.g., for irrigation of urban green or some industrial purposes. For drinking water purposes, a further treatment is needed according to the Vietnamese Quality standard for drinking water (QCVN 01 2009).

The water amounts in Tables 3–5 are averages. The seasonal variability of the water amounts must be taken into account by establishing water reservoirs, e.g., in the form of small reservoirs to store the surplus water in the rainy season and to compensate for the water deficit in the dry season.

A potential additional water resource can be the residual lake in the area of Lo Phong DU if it is established.

Recommendations

The WaterMiner project results are conceptual as a basis for general considerations and decisions. The following detailed studies show the feasibility of selected alternatives. Treated mine water for mine-external uses can be delivered at the boundary of the mining area to the public water supply (e.g., QUAWACO).

The selected alternatives are in the form of:

- Decentralized delivery of treated mine water (quality standard according to QCVN 40 2011) from the different Dus.
- Centralized or semi-centralized delivery of treated mine water (quality standard according to QCVN 40 2011) using collection pipes.
- Decentralized delivery of further treated mine water for irrigation (according to QCVN 39 2011).
- Decentralized delivery of further treated mine water for drinking water purposes (according to QCVN 01 2009).

The selected alternatives of delivery have to be investigated by the mine owner with the question: what is possible from the point of view of mining and water occurrence and, on the other hand, by the potential water user (e.g., QUAWACO) with the question: what is possible from the view of the technical infrastructure and distribution of water demands in Hon Gai.

It is recommended the two parties have a detailed discussion for finding suitable alternatives, to start further investigations of feasibility, and to set up a road map for further investigation and planning steps.

CONCLUSIONS

The R&D project WaterMiner shows the usability of the implemented research steps: system analysis, spatio-temporal investigation, material flow analysis, and deriving of recommendations of optional concepts of mine water reuse under the spatio-temporally changing conditions of mining.

The developed procedure enables a flexible prediction and management of mine water flows. In particular, the material flow modeling is an approach, which can be adapted to the sometimes quickly changing situations of mining.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

Broemme, K. & Stolpe, H. 2015 *Handbook Mining and Environment in Vietnam.* Handbook on the results of the project 'Mining and environment in Vietnam 2005-2015', Bochum, Germany, p. 535. doi:10.2314/GBV:868016799.

Broemme, K., Stolpe, H., Jolk, C., Greassidis, S., Borgmann, A. & Zindler, B. 2014 Development of a methodology for post-mining land use planning in Quang Ninh, Vietnam. In *Hanoi University of Mining and Geology: Proceedings of the Third International Conference on Advances in Mining and Tunneling*, 21–22 October 2014, Vung Tau. Publishing House for Science and Technology, Hanoi, pp. 526–534.

Broemme, K., Trinh, V. Q., Greassidis, S. & Stolpe, H. 2018 Material flow analysis for spatiotemporal mine water management in Hon Gai, Vietnam. In *Proceedings of the International Mine Water Association Congress IMWA*, 10–14 September 2018, Pretoria, South Africa.

Do, H. H., Trinh, V. Q. & Froer, O. 2018 The Economic Benefit Of Mine Water In Halong Peninsula, Vietnam. In: *Proceedings of the International Mine Water Association Congress IMWA*, 10–14 September 2018, Pretoria, South Africa.

DONRE Department of Natural Resources and Environment Quang Ninh 2016 *Quy Hoạch tài Nguyên Nước Tỉnh Quảng Ninh đến năm 2020, Định Hướng đến năm 2030 (Water Resources Plan of the Province Quang Ninh Until 2030, Strategy Until 2030)*, Quang Ninh, Vietnam.

GoV 2016 *Decision No. 403/QĐ-TTg Dated 16 March 2016, on Adjusted Master Plan for Vietnam's Coal Industry Development by 2020, with Perspective to 2030*, Hanoi, Vietnam.

ifu 2016 *Umberto® NXT Efficiency (v7.1.13)* User Manual. Hamburg, Germany. www.ifu.com; www.umberto.de

QCVN 01 2009 *National Technical Regulation on Drinking Water Quality*. QCVN 01:2009/BYT, Hanoi, Vietnam.

QCVN 39 2011 *National Technical Regulation for Water Quality for Irrigation*. QCVN 39:2011/BTNMT, Hanoi, Vietnam.

QCVN 40 2011 *National Technical Regulation on Industrial Waste Water*, QCVN 40:2011/BTNMT, Hanoi, Vietnam.

Ulbricht, A. & Bilek, F. 2020 Planning and assessment of water and sediment retention measures within a mining area based on a rainfall-runoff and sediment transport model. *Journal of Water Reuse and Desalination*. (this issue).

Ulbricht, A., Bilek, F. & Broemme, K. 2018 Development of a technical concept of spatial and temporal coordinated mine water recycling exemplified by a mining area with urban influence. In *Proceedings of the International Mine Water Association Congress IMWA*, 10–14 September 2018, Pretoria, South Africa.

VINACOMIN 2013 Đề án bảo vệ môi trường vùng than Quảng Ninh đến 2020, định hướng 2030 (Project on environmental protection in Quang Ninh coal area till 2020, orientation of 2030), Ha Long City, Vietnam.

VINACOMIN 2014 *Evaluation of the Effectiveness of Technology, Techniques and Management for the Mine Water Treatment Stations*, Ha Long City, Vietnam.

VIUP Vietnam Institute for Urban and Rural Planning 2013 Điêu chính quy hoạch chung xây dựng Thành phố Hạ Long – tỉnh Quảng Ninh đến năm 2030, tầm nhìn ngoài năm 2050 (Review of the construction plan of Ha Long City – Quang Ninh province until 2030, vision after 2050), Hanoi, Vietnam.

VN PC Ha Long City 2014 Environmental protection planning for Ha Long City until 2020, vision to 2030, Ha Long City, Vietnam.

First received 6 May 2020; accepted in revised form 10 November 2020. Available online 7 December 2020