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Water Impacts and Effluent Quality Regulations of Canadian Mining

Zauresh Atakhanova

School of Mining and Geosciences, Nazarbayev University, Astana 010000, Kazakhstan; zatakhanova@nu.edu.kz

Abstract: Energy transition relies on the scaling up of mineral production and may lead to increased pressure on water resources due to the intensity of water use in mining. The status of Canada as a major mineral producer and a country with effective environmental regulations prompted our study of the water impacts of Canadian mining. In 2002, the Canadian government introduced effluent quality regulations that targeted metal mining companies. By analyzing regional and sectoral data, we find that such regulations were important for mitigating both the water quality and water quantity impacts of metal mining. Despite increasing output, metal mining reduced its contribution to total mining withdrawals and discharge from 85% in the pre-regulation period to 62–65% in the post-regulation period. In the absence of such regulations, non-metallic mineral mining and, in particular, coal mining, increased their pressure on water resources. Finally, we find that since 2002, over 90% of regulated operations have met effluent quality standards. However, we document increased flows of discharge to mine tailings, a development which requires further analysis.

Keywords: water footprint; intensity of use; environmental regulations

1. Introduction

A large land area, attractive geologic conditions, skilled labor, and effective mineral policy support the status of Canada as a global leader in mineral production. Canada is a leading producer of potash (#1 globally), diamonds, platinum (#3), aluminum, uranium, titanium (#4), gold, (#5) nickel, cobalt (#6), iron (#8), zinc (#9), and copper (#11) [1]. In 2021, gold was Canada's top mineral product by value and rate of output growth (See Table 1). The direct and indirect contribution of mining to Canada's Gross Domestic Product (GDP) is around 5%. Furthermore, minerals account for 20% of Canada's exports and 12% of jobs held by Indigenous Peoples [1].

Increasing demand for clean energy will continue to support traditional mineral exports, as well as production of rare earths and battery minerals [1,2]. Continued expansion of mining operations requires heightened awareness of environmental, social, and governance (ESG) standards. According to a global survey of mining executives, 76% of respondents cited water stewardship as their top ESG risk, followed by geopolitics and climate change. This is related to the fact that 70% of mining operations from the six largest mining companies are located in water-stressed countries [3]. Obtaining water use and discharge permits has become increasingly difficult for mining companies due to competition with other water users and pollution caused by mines [4]. As a result, our study seeks to answer the question of how the water impacts of mining have changed over time and what has been the role of environmental regulations in shaping this change. We use Canada as a case study due to the prominence of its mining industry, long history of environmental regulation, and availability of data on water use in the mining industry.

We find that despite increasing its output by 0.5% per year on average, Canadian mining reduced its average annual water withdrawals from 0.502 million cubic meters (MCM) during 1986–1996 to 0.486 MCM during 2005–2020. We relate this finding to changing water use practices in metal mining, the largest consumer of water in the mining

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industry. In the 1980s and 1990s, metal mining accounted for 85% of both water withdrawals and discharge in Canadian mining. After 2000, these shares decreased to 65% and 62%, respectively. We believe that this was due to the regulation of discharge quality that has applied to metal ore mining companies since 2002. Our data analysis indicates that over 90% of regulated mining operations consistently met these discharge standards. In the absence of such regulations, coal and non-metallic mineral mining intensified their pressure on water resources, as total mining industry discharge increased from 0.620 MCM during 1986–1996 to 0.640 MCM during 2005–2020.

Table 1. Top Canadian mineral products.

	Unit	2011 Quantity	2011 Value (CAD Million)	2020 Quantity	2020 Value (CAD Million)
Gold	ton (t)	102	4143	182	12,321
Iron ore	1000 t	36,504	5944	60,060	5610
Coal	1000 t	67,113	7472	40,792	3958
Copper	1000 t	552	4819	476	3860
Potash	1000 t	10,686	7569	13,410	3736
Nickel	1000 t	211	4787	167	2834
Platinum	t	22	750	31	1818
Sand and Gravel	1000 t	222,288	1560	181,471	1729
Stone	1000 t	161,729	1592	141,201	1633
Diamonds	1000 carat	10,752	2509	15,036	1542

The effectiveness of environmental regulations depends on a country's overall governance. Since the mid-1990s, Canada has consistently scored in the 90th–95th percentile worldwide for government effectiveness, regulatory quality, and control of corruption [5]. In addition, during 1990–2022 Canada had a higher level of environmental policy stringency compared with other major OECD mineral producing countries [6]. Furthermore, the Canadian government has a long history of regulating water access and discharge quality. The *Fisheries Act* was one of Canada's first laws following the country's confederation. Enacted in 1868, this law aimed at protecting fish habitats and, since then, has been expanded on several occasions. In general, enforcement of regulations related to water access and discharge in Canada is considered effective [4]. A key element, the National Pollutant Release Inventory, began in 1993. It requires that industrial enterprises monitor and disclose levels of pollutants to the air, land, and surface water. According to this inventory, during 2011–2020, the minerals sector decreased releases of copper, mercury, nickel, and vanadium. However, releases of zinc, manganese, cadmium, and cobalt increased. Overall, metal contamination of surfaces waters by the minerals industry decreased by 12.4% between 2011 and 2020 [1].

In addition, the 1990s saw significant progress towards streamlining federal and provincial regulation of effluent quality specific to metal mining operations. The process involved a multi-stakeholder group, analysis of 700 reports from 95 mine sites, and 18 in-depth case studies [7]. These studies and discussions provided the basis for formulating regulations that came into effect in 2002 [8]. Currently, the Canadian government regulates the quality of metal mining discharge into water frequented by fish, based on the Metal and Diamond Mining Effluent Regulations. The number of metal mines covered by these regulations increased from 73 in 2003 to 140 in 2019. In addition, five diamond mines were included in 2018. These regulations set authorized limits for seven types of pollutant, total suspended solids, pH levels, and fish toxicity. The extent of compliance with these regulations enables monitoring of the effectiveness of methods and practices of water pollution control. Violations of effluent quality regulations may result in warnings, fines, penalties, and court orders on conviction [1]. The government is in the process of finalizing the Coal Mining Effluent Regulations that will apply to 28 existing coalmines. There is no indication of forthcoming specialized effluent regulations for non-metallic mineral mining operations (with the exception of diamond mining). In comparison, the US Clean Water Act and the related National Pollutant Discharge Elimination System regulate water discharge from all three types of mining in the USA. In addition, the Abandoned Mine Lands and Good Samaritan initiative of the US Environmental Protection Agency aim to accelerate restoration of historical mine sites in the USA.

In general, mining operations use water for mineral processing, dust suppression, equipment cooling and cleaning, diluting of reagents, and storing waste [9]. As a result, mining has water quantity and water quality impacts [10]. In terms of water quantity, mining uses between 2–4.5% of total water used in Chile and Australia. In the USA, even though mining accounts for only 1% of national water withdrawals, such withdrawals by mining increased by 39% between 2005 and 2010, while its groundwater withdrawals increased by 54%. Mining operations often source water from nearby rivers, lakes, or groundwater. This may lead to conflicts with other water users, such as local communities, farmers, and environmental organizations. Water withdrawals may change the structures of riparian zones [11] and alter the natural hydrological cycle, leading to water scarcity [12]. Finally, mining activities may result in the release of contaminants into the environment. One of most damaging types of water pollution is acid mine drainage, which has adverse effects on water quality, human health, and biodiversity [10,13].

Addressing the water impacts of mining requires water accounting as an important first step. In 2017 and 2021, the International Council on Mining and Metals (ICMM) issued guidance for water reporting, tailored to the mining industry [14]. The guidance considers various ways in which mining and mineral processing operations interact with water resources, depending on local hydrology, management practices, and processes used. Reporting categories are grouped into four major classes: withdrawals, internal use, consumption, and discharge. Sub-classes refer to aggregate flows to/from a specific source or sink (i.e., groundwater, surface water, marine water, or third parties) and subsets of flows to each source or sink (e.g., aquifer reinjection or seepage).

In Canada, most industrial water is self-supplied and discharged directly into water bodies. Provincial governments issue intake and discharge permits on a first come, first served basis. As self-supplying is virtually free, water acquisition costs represent a very small fraction of total production costs of industrial companies in Canada [15]. Similarly, a study of Brazilian manufacturing confirmed that introducing a water charge did not lead to a large increase in total costs for producers [16]. In some jurisdictions, such as the USA and Chile, water permits are traded in water markets, which stimulates water investment and efficiency [4]. Because industrial companies discharge large quantities of used water directly into receiving water bodies, this practice may lead to poor water quality for third parties. As a result, industrial effluent quality is commonly regulated. Studies have found that regulation of effluent quality in the USA and high effluent charges in China were effective in promoting water conservation in industry [17,18]. An important aspect of water use by industrial consumers is its close link to energy use. Studies have found that higher water prices result in increased energy consumption, which may be related to greater capital use for water treatment and recirculation [16]. Finally, unlike other users, industrial companies recirculate large quantities of water in order to save energy, recover materials, or reduce discharge. Analysis of manufacturing companies in British Columbia, Canada demonstrated that water intake and water recirculation act as substitutes [19]. A subsequent study of manufacturing firms in all Canadian provinces found that recirculation is a substitute for both intake and discharge: "raising the cost of water intake or discharge will lead manufacturing firms to increase their use of in-plant water recirculation" ([20], p. 403).

To summarize, relevant literature includes studies of water use in industry, primarily focusing on manufacturing. Our research contributes to the existing literature by analyzing water use in the mining industry in one of the largest mineral producing countries. We investigate water use from the 1980s to 2020 in Canada's mining industry and propose our interpretation of the drivers of change. Our research findings are relevant to mining stakeholders in Canada, as well as other countries that strive to improve the sustainability outcomes of their mining industries [21,22]. The Canadian experience shows that mining effluent quality regulations, if enforced and developed based on thorough analysis and multi-stakeholder engagement, lead to higher effluent water quality. We find that, in addition, such regulations may provide an incentive for mining companies to invest in water management and decrease the water use intensity of their operations. Such improvements in the water impacts of mining are of paramount importance given the growing global scarcity of fresh water, on the one hand, and growing demand for renewable energy and minerals on the other hand.

2. Materials and Methods

There are two main economic theories that are relevant to environmental regulation. The first one, public interest theory, is based on the premise that public officials design regulations in order to correct market failures [23]. Such market inefficiencies may arise from monopoly power, imperfect information, or the presence of externalities. In the latter case, parties external to the production process (e.g., local communities, flora and fauna, and future generations) bear some costs of production, such as pollution. With the introduction of environmental regulations, e.g., emissions taxes or discharge standards, the producer internalizes the external cost. The resulting reduction of the environmental impact of an economic activity serves the interest of the public, hence the name of this theory. In contrast, private interest theory postulates that regulations are designed and implemented in response to demand from interest groups. Such groups seek to obtain direct financial support from the state, increase barriers to entry to their own industries, or to achieve desired outcomes in related industries that produce complements or substitutes. Thus, regulations support the private interests of those industries that 'capture' the regulatory process [24,25]. On the supply side of regulations are politicians who pursue private interests rather than the socially optimal allocation of resources [26]. As a result, if our study identifies improvement of the water impacts of Canadian mining in response to environmental regulations, then our results would be consistent with the public interest theory of regulation.

Regarding data sources, our study utilizes the Industrial Water Survey (IWS) and other data reported by Statistics Canada. The IWS was conducted every five years between 1972 and 1996. Initially, it collected information on water use in manufacturing. The mining and thermal electricity generation industries were added to the survey in the 1980s [27]. Starting from 2005, the survey was performed on a biennial basis. In 2020, the survey's sample included 921 mining locations and 383 mining units, which submitted the questionnaire. The IWS reports country-level data for three mining sectors: coal, metallic ores, and non-metallic minerals (excluding sand, gravel, clay, ceramic, and refractory minerals). In addition, regional data are reported, but without sectoral disaggregation. Water use data include four types of indicator: volumes of water *intake*, *recirculation*, *discharge,* and *mine water*. The latter is defined as water that must be pumped from a mine or quarry to allow operations to continue. Because *mine water* data is missing for a number of years, we cannot analyze water consumption using its ICMM definition as a sum of intake, recirculation, and mine water, net of discharge. As a result, to analyze volumes of water used in production and its reuse, we define *gross water use* and *recirculation rate* as in [28]:

$$Gross\ water\ use_{i,t} = Intake_{i,t} + Recirculation_{i,t} \tag{1}$$

$$Recirculation\ rate_{i,t} = Recirculation_{i,t} / Intake_{i,t} \tag{2}$$

where i indicates the sector (coal, metallic ores, and non-metallic minerals) and t indicates the year. Next, analysis of water use due to changes in production levels requires estimates of output. Following ref. [1], we use value of shipments as a measure of mining output in current prices, i.e., nominal output. To remove the effect of changes in mineral prices on output value, we use the relevant sector's Raw Materials Price Index to obtain *Real Output*:

$$Real\ Output_{i,t} = 100 \times Nominal\ Output_{i,t} / Price\ Index_{i,t} \quad (3)$$

In a similar manner, when we analyze regional data we use the Commodity Price Index for Metals and Minerals reported by the Bank of Canada to deflate the aggregate output of the mining industry. Using data on production levels and price indices of mining and its sectors allows us to study trends in water intensity, which we define as in [29]:

$$Gross\ water\ intensity_{i,t} = Gross\ water\ use_{i,t} / Real\ Output_{i,t} \quad (4)$$

This indicator of water intensity is consistent with other resource intensity indicators used in the literature [30]. In addition, we define *intake intensity* and *discharge intensity* as ratios of the corresponding water use indicators to real output, similar to (4).

Commonly, analysis of impacts of regulations involves a difference-in-differences (DID) methodology [31]. This approach compares outcomes in the treatment and control groups before and after introduction of regulations. The DID method assumes that both groups exhibit the same outcomes or trends prior to treatment. In our study, metal mining (but not coal or non-metal mining) became subject to effluent quality regulations in 2002. If firm-level data were available, we would use the DID method to study the effect of such regulations on the water impacts of metal mining, as opposed to unregulated mining sectors. However, application of the DID method is not feasible in this study due to the small number of observations.

Below we describe an alternative approach which allows us to evaluate the effect of effluent quality regulation using regional data. Starting from 1991, the IWS reports water use in mining industries of five Canadian regions: the Atlantic region, Quebec, Ontario, the Prairies, and British Columbia & Territories. This allows us to analyze determinants of *gross water intensity* using a pooled OLS procedure:

$$Gross\ water\ intensity = \beta_0 + \beta_1 Metal\ mining\ share + \beta_2 Year + \beta_3 Electricity\ price + \boldsymbol{\beta}\ \boldsymbol{Region} + \varepsilon \quad (5)$$

This specification accounts for regional factors of water use intensity (e.g., regional differences in water availability, institutions, and regulations), as well as temporal factors (the business cycle, changes in technology, yearly changes in precipitation). Here, ***Region*** is a vector of dummy variables: Atlantic region, Quebec, the Prairies, and British Columbia & Territories (Ontario is omitted to avoid collinearity). *Year* refers to the ten years between 1991 and 2020, when the IWS was conducted. Next, *Electricity price* is the industrial price index of electricity in a specific region and year. This variable is included because processing of ore, as well as water treatment and pumping require energy. Energy may be considered both a complement and a substitute for water as the relation between these two inputs would depend on their relative prices and the technologies used. *Metal mining share* is the ratio of metal mining output in a given region to output of this region's entire mining industry. We include this variable because additional costs of meeting regulatory standards should incentivize water saving and efficiency in those regions where metal mining accounts for a greater share of total mining output. To evaluate the effect of the 2002 effluent quality regulations, we will estimate (5) using the full 1991–2020 sample and 2005–2020 subsample. If effluent quality regulations were effective, then applying model (5) to 2005–2020 data would result in a lower coefficient estimate of *Metal mining share* than its estimate from the full 1991–2020 sample. Finally, we use such an approach and the same explanatory variables as in (5) to analyze *intake* and *discharge intensities*.

3. Results

According to the 2005–2020 IWS data, mining water intake in Canada is mostly self-supplied, primarily from surface water bodies (See Table 2). However, municipal water and self-supplied groundwater are significant in the case of mineral mining. In all three sectors, most water is used for processing. Recirculation (mostly intended for processing) is over 100% in metal ore and mineral mining. However, it is less than 50% in coal mining. Used water is discharged primarily to surface water bodies. In addition, the destination of 20% of water discharge is groundwater in the case of mineral mining, and tailings ponds in the case of metal ore mining. Indicators of water treatment before discharge are similar across the three subsectors, as 42–43% of water discharge undergoes primary or mechanical treatment. Most of the remaining water is discharged without treatment. The exception is metal ore mining where around 6% of discharged water undergoes secondary or biological treatment.

Table 2. Water use parameters (2005–2020 average values).

Water Use Parameter	Alternatives	Coal	Metal Ores	Minerals
Water intake by source, % of total intake	municipal	-	3	12
	surface water bodies	74	82	58
	groundwater	7	13	20
Water intake by purpose of initial use, % of total intake	process water	50	88	60
	cooling, condensing and steam	-	5	25
Recirculation, % of total intake		48	115	102
Water discharge by point of discharge, % of total discharge	surface water bodies	81	72	55
	groundwater	-	8	19
	tailing ponds	6	20	6
Water discharge by type of final treatment, % of total discharge	not treated before discharge	54	49	60
	primary or mechanical treatment	43	43	40
	secondary or biological treatment	0	6	0

As seen in Figure 1, since the introduction of effluent quality regulations, the percentage of mining operations that meet water quality standards has been above 98% in the cases of arsenic, copper, cyanide, lead, nickel, radium, and zinc concentrations, and pH levels. Meeting fish toxicity and total suspended solids limits was more difficult as the share of compliant operations was between 92% and 98% in most years.

Mining and some forms of petroleum extraction are notorious for generating large volumes of tailings. Tailings are fine waste from a processing plant. This waste is suspended in water and stored in specially engineered ponds. Tailings may seep or break out, leading to pollution of underground and surface water. In addition, evaporation of tailings may results in air and ground pollution. According to the IWS, metal mining is the main contributor of discharge flows to tailings ponds (see Figure 2). However, the contribution of metal mining to total mining tailings discharge decreased from 88% on average before 2005 to 83% in the years after 2005. A worrisome sign is the increase in the total volume of tailings flows since 2011, as well as the growing share of tailings discharge of metal mining in the total discharge of this sector.

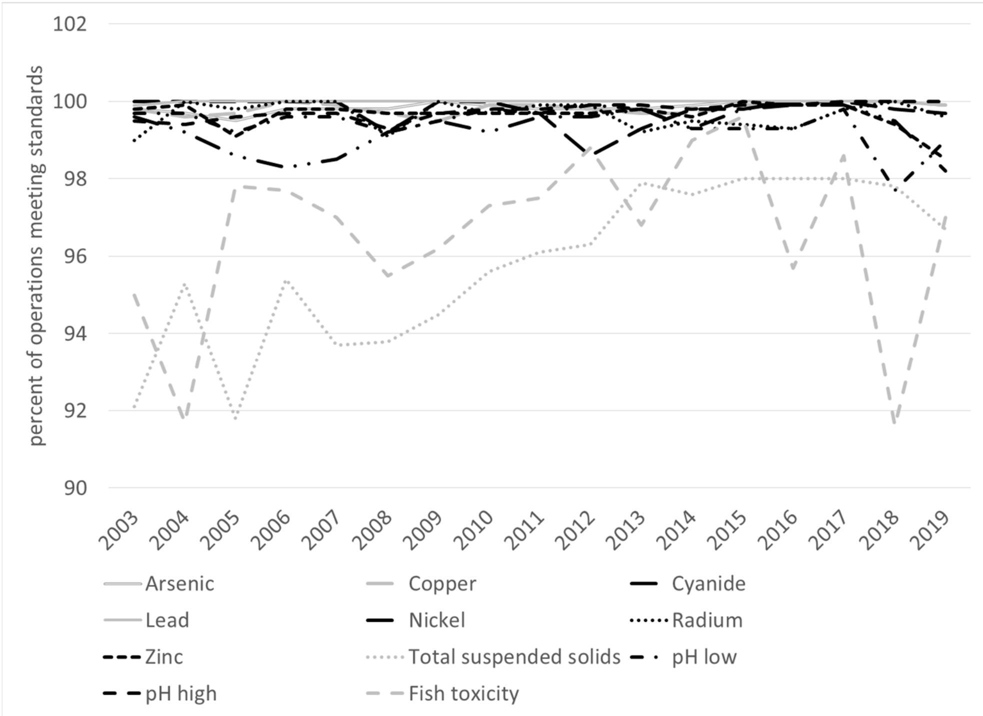

Figure 1. Metal and diamond mining operations meeting discharge quality standards.

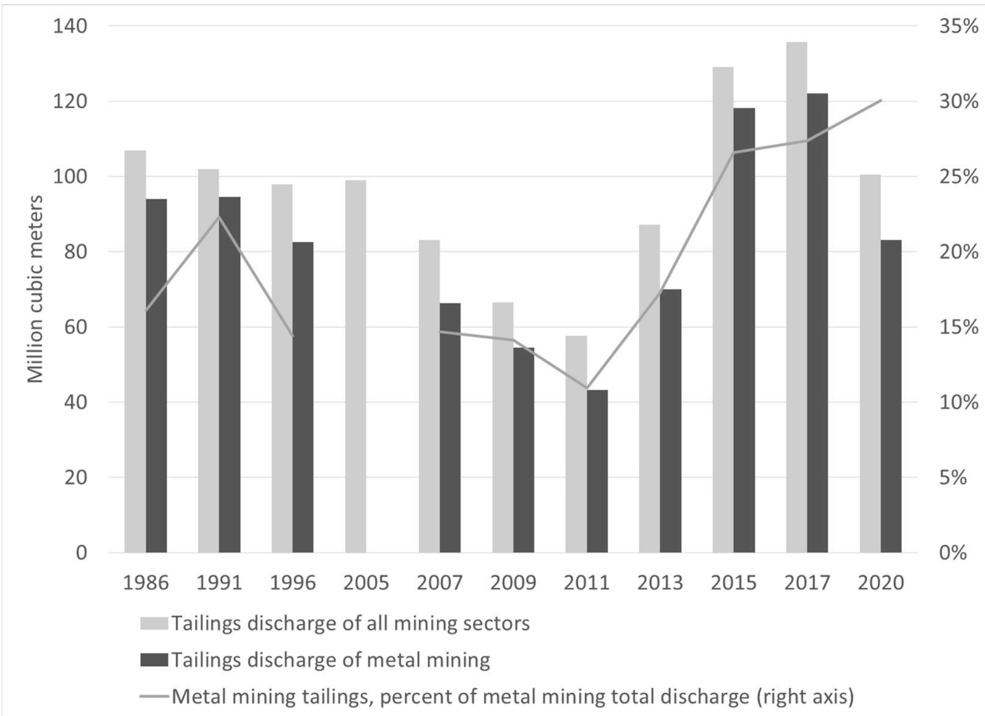

Figure 2. Discharge to tailings.

As for expenditures on water management, water cost data reported by the IWS are limited. They indicate that during 2005–2015, total water costs of the mining industry increased by 6% per year on average. In metal mining, over half of water expenditures were related to water discharge. The second largest water expenditure item was water recirculation. Acquisition costs, which include licenses for water intake payable to federal or provincial governments, operation and maintenance costs (excluding water treatment), and public utility costs, were the third largest water expenditure items in metal mining. On average, during 2005–2015 metal mining accounted for 69% of total industry water expenditures. In comparison, in 1996 metal mining water costs represented 81% of the mining industry's total costs. This is consistent with the change in metal mining's share of total industry intake from 87% during 1991–1996 to 71% during 2006–2017. Note that the average share of metal mining's output of the total mining industry's output during the 1990s and after 2000 did not change and was around 50%. During the later period of 2007–2021, the contribution of each sector to the total mining output value was 11.5%, 53%, and 35.5% for coal, metal ore, and mineral mining, respectively. Each of these sectors experienced different dynamics. During 2007–2021, non-metallic mining output increased by 1.2% annually, but its prices declined by 1.7% per year. Prices of the metal mining sector increased by 0.5% per year, but its real output annual growth rate during 2007–2021 was around zero. Real output value and prices of coal mining contracted by 3% and 4.4% per year on average, respectively.

According to Table 3, the period following the introduction of effluent quality regulations saw a considerable reduction of intensity of intake in metal mining and accelerated reduction of discharge intensity in metal mining. This implies that managing inefficiencies, water saving, and introducing new technologies must have been in place. This and continued reliance on recirculation are reflected in a moderate decline in gross use intensity in metal mining. In non-metal mineral mining, gross use intensity continued increasing and intake intensity stopped growing after 2005. However, this sector's discharge intensity continued to increase. As for coal mining, it was characterized by a very high rate of growth of intake during the 1980s and 1990s. This was partially offset by the initial high rates of recirculation and relatively low rates of growth of discharge. However, after 2005 a large reduction of the coal mining sector's recirculation rate and continuous high growth of intake resulted in extremely high gross use and discharge intensity, each increasing annually by 20% and 19%, respectively.

Table 3. Recirculation and water intensity.

Sector	Period	Recirculation Rate (Period Average)	Change in Intensity (Per Cent Per Year)		
			Gross Use	Intake	Discharge
Coal	1981–1996	2.50	5.4	11.0	2.8
	2005–2020	0.48	19.9	14.9	19.1
Metal mining	1981–1996	2.55	0.0	0.3	−4.0
	2005–2020	1.15	−0.5	−5.1	−5.9
Non-metal mineral mining	1981–1996	3.11	−5.8	4.6	4.2
	2005–2020	1.02	−4.8	−0.3	2.6

Next, we use model (5) and regional data to study the impact of effluent quality regulations while controlling for other factors of water use intensity. Results from Table 4 indicate that *regional* factors were very impactful: mines located in the Atlantic region had significantly higher intensity of gross use, intake, and discharge, as compared with those in Ontario. In addition, mines in Quebec had higher gross and discharge intensity than mines in Ontario. Mining operations in the Prairies or British Columbia tended to have the same or lower water intensity as compared with Ontario mines; however, their coefficient estimates are not statistically significant, except for the last set of results. Next, we find that *Electricity price* does not affect mining water use intensity, which could be related to the fact that energy may be both a complement and a substitute for water used by industrial consumers. Our key variable of interest, *Metal mining share,* is associated with reduced ***gross water intensity*** based on the full sample results. Due to the low number of observations, the effect of *Metal mining share* on this type of intensity could not be assessed based on the 2005–2020 subsample. As for ***intake intensity***, our results do not confirm the positive impact of effluent quality regulations, which we identified in the sectoral data analysis (see Table 3). However, regression analysis results confirm our expectation that *Metal mining share* is associated with reduced ***discharge intensity***. The relevant coefficient estimate is not statistically significant in the full sample model, but it turns negative and significant when the 2005–2020 subsample is used. We interpret this latter result as evidence of the effectiveness of effluent quality regulation of metal mines in reducing their discharge intensity.

Table 4. Assessing the impact of 2003 regulations on intensity; regression analysis results.

	Gross Use	**Intake**		**Discharge**	
	1991–2020	**1991–2020**	**2005–2020**	**1991–2020**	**2005–20**
Atlantic	0.519 *** (0.102)	0.162 *** (0.025)	0.180 *** (0.032)	0.205 *** (0.024)	0.236 *** (0.029)
Quebec	0.194 *** (0.092)	0.030 (0.022)	0.042 (0.026)	0.067 *** (0.023)	0.084 *** (0.084)
Prairies	−0.167 (0.156)	0.019 (0.038)	0.007 (0.045)	−0.052 (0.035)	−0.089 * (0.051)
British Columbia & Territories	−0.046 (0.120)	0.020 (0.030)	0.001 (0.037)	−0.017 (0.035)	−0.055 (0.044)
Electricity price index	0.000 (0.003)	0.000 (0.000)	0.000 (0.000)	−0.000 (0.000)	−0.000 (0.000)
Metal mining share	−0.005 *** (0.002)	0.000 (0.000)	0.000 (0.000)	−0.001 (0.001)	−0.002 *** (0.001)
Year	−0.006 (0.007)	0.000 (0.000)	0.000 (0.000)	−0.001 (0.001)	−0.002 (0.002)
Constant	14.325 (14.148)	−0.397 (2.831)	2.767 (4.871)	−1.768 (2.985)	3.910 (4.817)
Observations	36	44	34	48	38
Prob > F	0.000	0.000	0.000	0.000	0.000
Adjusted R^2	0.503	0.546	0.544	0.689	0.721

Note: *** indicates significance at 1%, * indicates significance at 10%.

4. Discussion

What do our results imply for each mining sector? Our study has found evidence of a positive impact of effluent quality regulation on metal mining. Using sectoral data, we found that metal mining companies decreased both water intake and discharge at higher rates than before the introduction of regulations. We were able to confirm statistically the finding of the positive impact of regulations on water discharge using regional data analysis. Let us consider other potential reasons for the observed change. Falling water use intensity in metal mining may be related to the effect of effluent quality regulations (i) or the changing composition of metal mining output towards less water intensive products (ii). Let us evaluate the latter hypothesis. During the last decade, the top two products of metal mining were iron ore and gold. They experienced significant increases in output volume (by 65% and 78%, respectively). Although gold mining is characterized by higher water use intensity compared with iron ore mining (0.745 cubic meters per ton (CM/t) vs. 0.588 CM/t, see [32]), differences in output volumes (1000 tons vs. 36.5 million tons, see Table 1 above) make changes in the composition of metal mining output an unlikely explanation for decreasing water use intensity in metal mining. This provides support for our first hypothesis that discharge quality regulations were the key driver behind falling water use intensity of Canadian metal mining operations. Regarding water quality impacts, we find that most metal mining companies met discharge standards, although requirements for suspended solids and fish toxicity were more challenging to achieve. Another issue of concern that requires further research is increasing flows of discharge to tailings ponds and a growing share of tailings in the total discharge of metal mining firms. This development is undesirable as tailings present complex sustainability risks [33].

Our study has identified a significant increase in all types of water use intensity in coal mining. We believe that this development is related to the increasing export orientation of Canadian coal mining companies. During our study period, Canadian power plants significantly reduced their consumption of coal: from 51 tons in 2008 to 26 tons in 2018 [1]. This reflects their adjustment to the Canadian government's plans to phase out traditional coal-fired generation by 2030 [1]. As a result, Canadian coal producers have become increasingly oriented towards export markets, with the top destinations being South Korea, Japan, and India. While in the 2000s 46% of Canadian coal was exported, in 2020 this number had increased to 60%. High levels of impurities in raw coal result in very high long-distance transportation costs for coal, considering the amount of energy it contains. As a result, according to Canadian legislation [34], all coal destined for export must undergo preparation. Coal preparation (mostly in the form of coal washing) reduces the ash and sulfur content of raw coal. As this process results in increased efficiencies of coal-burning power plants, customers value coal preparation. A study of Indian power generating plants found that greenhouse gas emissions decreased by 12% when washed rather than raw coal was used [35]. However, coal preparation is highly water intensive: 5–10 tons of water are required for washing one ton of high-ash coal [36]. This information allows us to explain our finding of a significant increase in the coal sector's water use intensity. We believe that the main contributor to these developments was efforts of Canadian coal producers aimed at increasing coal quality. Our findings indicate that greater orientation of domestic producers towards long-distance exports increases the water footprint of coal mining. Our results highlight the urgency of developing the proposed coal mining effluent regulations that have been under consideration in Canada since 2017.

As for non-metallic mineral mining, this sector's output is mainly distributed between potash, aggregates (sand, gravel, and stone), and diamonds (40%, 26%, and 14% of sector GDP, respectively). In fact, Canada is the number one producer of potash globally and is among the top three countries in terms of diamond mining. Concerning the volume of mined materials, aggregates account for close to 90% of materials mined in this sector. Canada's Industrial Water Survey does not cover water usage in the mining of aggregates. This implies that our findings on the increasing water consumption and use intensity in mineral mining underestimate their true magnitude. Another source of concern is that mineral mining has a high level of withdrawal and discharge to groundwater (see Table 2). Yet, discharges to groundwater are not subject to the National Pollutant Release Inventory. So far there is no indication that mineral mining (other than diamond mining) will become subject to specialized effluent quality regulations, similar to the ones already in place for metal mining and soon to be applied to coal mining. This provides an additional argument for close monitoring of water use and its intensity in non-metal mineral mining.

5. Conclusions

Opportunities for water saving, recycling, and reuse have been identified at all stages of mineral production. However, it is not likely that companies will take full advantage of these opportunities unless they have strong incentives to implement them. The traditional price mechanism has limited applicability in the case of mining, as most water used by mines is self-supplied, i.e., there is minimal payment for water withdrawals. However, our research suggests that environmental regulations reduce not only the water quality impacts of mining but the water quantity impacts as well. Our results are consistent with similar findings for water use by manufacturing companies [20,37]. By increasing the cost of water treatment, such regulations incentivize water saving, recirculation, and adoption of water-efficient technologies. Our findings suggest that mining effluent quality regulations help mining companies reduce their impact on the quality of water and its availability for other water users. We arrived at these conclusions based on evidence from Canada, but they are relevant to multiple mining jurisdictions. We make our inferences based on the analysis of sectoral and regional data. Future research should rely on analysis of firm-level data to identify factors that incentivize water stewardship among mining companies. Such research is very important given the growing demand for minerals and sustainable energy.

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