Optimal timing of hazardous waste clean-up under an environmental bond and a strict liability rule

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Abstract

Inadequate site clean-up and restoration by resource extraction firms leave a toxic legacy which must be dealt with by governments. This study compares the impacts of an environmental bond and a strict liability rule on a firm's incentives for cleaning up hazardous waste during resource extraction and upon termination. The firm's problem is modelled as a stochastic optimal control problem that results in a system of Hamilton Jacobi Bellman equations. The model is applied to a typical copper mine in Canada. The resource price is modelled as a stochastic differential equation, which is calibrated to copper futures prices using a Kalman filtering approach. A numerical solution is implemented to determine the optimal abatement and extraction rates as well as the critical levels of copper prices that would motivate a firm to clean up the accumulated waste under each policy. The paper demonstrates that an environmental bond provides stronger waste abatement incentives, implying that the waste is more likely to be cleaned up under the bond than the liability. The strict liability rule imposes sunk costs on a firm upon termination which would motivate it to remain inactive as a way to escape clean-up costs. However, the environmental bond raises funds *ex ante* for future clean-up costs and thus encourages site restoration.

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1 Introduction

Hazardous waste production is a significant consequence of large natural resource projects such as mines. Such waste is often disposed of into local ecosystems and can impose high risks on society during the mining operations and after a mine is abandoned. Without appropriate regulations, profit maximizing firms are likely to generate more waste than is desirable and are unlikely to undertake adequate waste clean-up. This problem is commonly dealt with through the imposition of a strict liability rule, whereby the agent is held legally responsible for waste clean-up or restoration upon termination[3]. An obligation for restoration under the strict liability rule increases the cost of mine abandonment, which may cause some firms to choose to remain inactive as a way to escape restoration costs, even when there is no hope for reactivation (Muehlenbachs 2015). Restoration requirements also increase the risk of default on environmental obligations due to insolvency or bankruptcy. Empirical studies reveal that large numbers of mining operations in the US and Canada have been abandoned due to bankruptcy resulting in significant environmental damages and clean-up costs. For example, in 1999, a Canadian company with a hazardous waste facility transferred as much as \$4 million in clean-up costs to the public (Boyd 2001). In the case of firm bankruptcy, the environmental liability may fall to government with remediation costs funded out of general tax revenue, leading to a dead-weight loss (Campbell & Bond 1997).

In practice, environmental bonds, as a complement to the strict liability rule, have been widely used to address bankruptcy issues by attempting to ensure adequate funds are available for end-of-activity restoration. Under an environmental bond, a firm estimates and reports its expected future clean-up costs based on current knowledge and deposits a bond of an equivalent amount. The amount deposited for the bond may be updated over time as the firm's expected clean-up costs are revised. The government releases the funds upon

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[3] Waste clean-up costs are mine specific, can range from millions to billions of dollars for a single mine (Boyd 2001, Grant et al. 2009), and depend on the extent of activity, the expected difficulty of restoration, etc (Grant et al. 2009).

successful closure and restoration; otherwise it retains them. Environmental bonds are intended to simulate all future adverse effects, consider them in present terms, and internalize the associated clean-up costs (Perrings 1989)[4]. However, without a specific template for cost estimations and also the absence of a third-party verification of such estimations, firms may underestimate their clean-up cost. If the bond amount is inadequate and if a firm walks away from its obligation, clean-up costs will be transferred to the government. In 2009, over 10,000 mines operating under an environmental bonding regulation in Canada were classified as abandoned without being cleaned up and with insufficient funds for restoration (Grant et al. 2009). For instance, the Faro Mine in the Yukon Territory set aside $ 93.8 million for restoration resulting in a $356 million government's liability, and the Giant Mine in the Northwest Territories deposited only $400,000 environmental bonds and transferred $399 million uncompensated clean-up costs to society (Grant et al. 2009). In addition, an adequate level of environmental bond increases the likelihood that a firm will meet its obligation to clean up a contaminated site, rather than shirking their clean-up obligations through bankruptcy. This fact is confirmed by an empirical study for the US oil and gas producers (Boomhower 2014).

Given the empirical importance of clean-up costs, it is surprising that the literature has devoted little attention to their likely impacts on mining firms' decisions. Some studies assume zero costs for restoration (Brennan & Schwartz 1985), while abandonment is completely overlooked in some other research (Mason 2001, Slade 2001, Dixit 1992, 1989). More recently, one study has examined optimal extraction of a non-renewable resource with the resource price modeled as regime switching stochastic process and assuming a positive restoration cost, and has found that abandonment timing depends on the level of reserves and the profitability of the project – which is affected by the price process (Insley 2017).

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[4] Peck & Sinding (2009) note that environmental bonds can be deposited through a variety of mechanisms such as cash deposited in a trust fund, letters of credit, and pledge of assets. The current practice of such different mechanisms are surveyed by Miller (2005), and the incentives for envirmental protection by US hazardous waste managers under each mechanisim are compared in Zhou et al. (2014).

An empirical analysis has shown that the main motivation behind temporary closures in the Canadian oil and gas industry is to avoid high costs of environmental liabilities, and not to keep the option to reactivate alive (Muehlenbachs 2015).

This study contributes to the current literature by introducing a dynamic mechanism for an environmental bond into a model of optimal decision making by a firm whose activities generate hazardous waste. The main objective of this investigation is to compare the impacts of an environmental bond versus the strict liability rule on the firm's optimal timing of clean-up of hazardous waste generated by the firm's operations[5]. We develop a stochastic optimal control model of a firm's decisions regarding the construction, operation and abandonment of a mining project in an environment of uncertain commodity prices. The price of the mine's output is modeled as an Ito process. The mine owner chooses the optimal timing to build, operate, mothball, and eventually abandon the project. During operations, the mine produces waste that accumulates and by legal requirement must be cleaned up at the end of the project. The firm can undertake abatement during the project to reduce the waste flow. The firm chooses the amount of ore produced and the level of waste abatement to maximize the value of the mining operation. The optimal control model results in a system of Hamilton Jacobi Bellman equations, solved using a numerical approach. The results allow us to contrast the firm's optimal decisions under an environmental bond compared to a strict liability rule.

To preview our results, we find that under the bonding policy the firm undertakes a larger amount of abatement during the life of the project compared to the strict liability rule. As a result, the accumulated waste from the mine is lower under the environmental

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[5] In this study, we are not concerned about the clean-up of environmental accidents associated with a waste disposal facility, such as accidental release of chemicals. However, environmental bonds and liability rules have been widely used to control environmental risks. Torsello & Vercelli (1998) provides a critical assessment of these policies for risk control, and Poulin & Jacques (2007), Gerard & Wilson (2009), Smith et al. (2012), and Davis (2015) highlight their practical challenges for different case studies relevant to environmental risks.

bond, which implies a lower restoration cost when the mine closes. In addition, the bonding mechanism guarantees clean-up funds for restoration projects. Consequently, it is less likely that the government will end up with a large bill for site clean-up if a firm goes bankrupt or walks away from its commitment for site restoration. Furthermore, the possibility of the refunding of deposited bonds will give the firm a financial incentive to eventually clean up the stock of waste. In contrast, the strict liability rule entails an upfront cost to the firm upon termination, making the project termination and site clean-up less likely. This study also demonstrates that under the environmental bond, the firm has an obligation to deal with the costs of waste generated during the construction phase and this increases the initial cost of project commencement. Therefore, the required threshold price of the mine ore to start the project is higher under the bond than the liability, making it less likely that the project will be undertaken with bonding requirements. Unlike the strict liability rule, the environmental bond also makes it less likely that the project remains mothballed during operations. Staying at the mothballed stage is one way for the firm to avoid clean-up costs.

A focus of this paper is on the trade-off between reducing waste production during mine operations versus cleaning up a waste disposal site once the project is completed. Our premise is that it is desirable to encourage firms to reduce waste accumulation in order to reduce the likelihood that a firm will walk away from its clean-up obligations, leaving governments to undertake site restoration with tax dollars. We do not explicitly model the decision by a firm to walk away from its clean-up obligation when the project is terminated. However, we do consider the decision by a firm to mothball a project rather than undertake clean-up. As noted, this is a problem faced by governments in Canada and elsewhere. To the best of our knowledge, none of these effects have been considered and analyzed in previous studies.

The next section explores the existing literature about restoration, environmental bonds, and resource-valuation models in the context of optimal decisions under uncertainty. Section 3 develops the theoretical model. The dynamic programming solution of the model and optimal strategies for extraction and abatement are in Section 4. Section 5 presents a numerical solution approach. An application of the model to the copper industry is discussed in Section 6. Results analysis are in Section 7. The last section concludes.

2 Literature review

2.1 Restoration and environmental bonds

A substantial body of literature has been devoted to the design of incentive-based policy instruments to deal with stock externalities whereby damages depend on the cumulative stock of the pollutant (Farzin 1996, Baumol & Oates 1988, among others). The results are the development of policy instruments such as Pigouvian tax, pollution permits, and their variants which put a price on emissions. These papers emphasize that optimal policy instruments must account for the damages from both the flow and the stock of pollutant. In response to such instruments, firms choose an optimal rate of pollution abatement that equates marginal social benefits of reducing pollution with its marginal costs. The main application of these policy instruments is to control for externalities associated with air and water pollution, for which the quality can be maintained only through abatement because the clean-up of the stock of the pollutant is either technologically infeasible or prohibitively expensive.

However, instruments based on emissions charges are not well suited for stock externalities for which damages can be cleaned up some time after the pollutant is initially created, such as mining waste. There are several reasons why these instruments may be inadequate. First, they encourage abatement in isolation from restoration, resulting in cost inefficiencies. Keohane et al. (2007) showed that when restoration is feasible, it is not optimal to depend only on abatement to improve the quality of the environment, as at some low levels of environmental quality or high social damage costs, abatement may become more expensive than restoration. To analyze the optimal trade-off between abatement and restoration, they considered a policy maker who seeks to maximize social welfare by jointly implementing abatement and restoration policies. In their framework, the social planner's problem is to determine the optimal timing of restoration when the quality of the environment fluctuates, and there are economies of scale in restoration in the sense that restoration entails significant fixed costs that do not increase as the environmental quality decreases. Therefore, restoration costs are not significantly affected by the size of damage, making it optimal to clean up the stock of damage only when the quality falls to a sufficiently low level that abatement becomes costlier than restoration. They found that the optimal abatement rate increases as the quality of the environment decreases, but when the project termination date nears abatement decreases and finally goes to zero at the time of restoration.

A second reason why instruments based on emissions charges may be inefficient is that restoration often occurs in the distant future and there is a great deal of uncertainty about future clean-up costs. To deal with such uncertainty, Perrings (1989) and Cornwell & Costanza (1994) suggested a *flexible* mechanism that can quickly vary with time in response to changes in damage clean-up costs. In this respect, Baumol & Oates (1988)[6] state that "*taxes ... suffer from at least one serious practical liability ...: they are very difficult to change on short notice.*". Nevertheless, Keohane et al. have shown that a time-variable tax rate levied on the flow of externality encourages optimal abatement and raises funds for the government to restore the stock of damage. A time-variable tax rate in this case implies that the policy maker sets the tax rate so that the economy moves on the optimal abatement path, and since environmental quality is stochastic, the optimal tax rate varies over time with the quality of the environment. However, in the Baumol & Oates framework, changing the tax rate re-

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[6] p. 192

quires legislative processes and must be enacted through the government, a time-consuming process. It turns out that a tax rate that needs to quickly change in response to any information received in the future is impractical[7]. Third, such a tax rate does not impose restoration obligations on firms, whereas the priority of governments is typically to make firms responsible for carrying out restoration. Fourth, Gerard (2000) argued that the possibility of insolvency and default on environmental obligations cause additional difficulties for designing an efficient mechanism to promote restoration.

Given the complexities of regulating stock externalities where environmental restoration is possible, environmental bonds represent a viable alternative policy. Perrings (1989), first, developed the mechanism of bonds as a means to encourage firms to invest in research to examine the potential adverse effects of their activities. Under an environmental bond each firm is required to conduct periodic investigations about potential damage of its current activity, and to *deposit* a bond equivalent to its own best estimations of clean-up costs for the "worst case" environmental outcome. This "worst case" outcome is called the "focus loss"[8] of the activity, given current knowledge about the future. At each point in time, if the firm can prove that the restoration costs are lower than estimated, the policy maker refunds a portion of the firm's deposit. Therefore, firms have the private incentives to increase their research or investigations of all potential consequences of their current activities until the costs of research [9] equal the resulting benefits of reduction in the value of bonds. At the end of the activity, the policy maker completely *refunds* the firm's deposit if the firm cleans up all damages. This bonding mechanism guarantees the availability of funds for future restoration should a firm default on its environmental obligation. Moreover, Shogren et al.

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[7] An exception exists for financing the clean-up of hazardous waste created in the past. Segerson (1989) shows that, instead of liability laws, funds for cleaning up waste resulting from past activities can be optimally raised through a fixed tax rate on waste generators that are not necessarily responsible parties.

[8] Focus loss does not represent the worst case scenario one can "imagine", but it is the least surprising severity of damage that may occur (Perrings 1989, Costanza & Perrings 1990).

[9] Research costs include expenditures on investigations of a mine site so that firms are better able to predict damages.

(1993) highlighted the fact that with this bonding system firms become aware of potential social costs of their current actions, and take required measures to minimize their compliance costs.

The bond mechanism developed by Perrings mimics the idea of a deposit-refund system[10]. The novel idea of such a system dates back to 1971 when Solow developed the idea of the "materials use fee". According to Solow[11], this fee is equivalent to *"the social cost to the environment if the material were eventually returned to the environment in the most harmful way possible. The fees would be refunded to anyone who could certify that he had disposed of the material"*. Cornwell & Costanza (1994) explained one simple application of a refundable deposit – the fee on glass bottles. This fee is intended to encourage the most socially desirable method of waste disposal – recycling as opposed to littering. In their study, environmental bonding is identified as a variation of the deposit-refund system. Unlike the former, environmental impacts of each disposal method are known in a deposit-refund system, and also the fee is often set lower than the cost of choosing the worst method of disposal but high enough to encourage the best method, i.e., returning the bottle for recycling. In contrast, with the bonding system all known and predicted unknown future impacts of the activity determine the exact value of the bonds.

An environmental bond, aimed at raising funds for future restoration projects, is a complement to the strict liability rule. Kaplow & Shavell (1996) argued that the strict liability rule may not be a good alternative to induce firms with limited liability to pay up-front for their potential clean-up costs due to liquidity constraints and litigation difficulties. Limited liability firms are not required to pay for any damage beyond their asset value, which has two implications. The first implication is that social welfare is compromised as a result of damage residuals potentially being extended to society. The second implication suggests that limited liability firms may simply ignore any damage costs above their asset value, which

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[10] The theory of deposit-refund systems are comprehensively surveyed by Bohm (1981).

[11] p. 502

dilutes damage prevention incentives[12]. Moreover, strict liability requires costly and lengthy processes to sue a responsible party through litigation. In this context, several authors highlighted some advantages of environmental bonds over the strict liability rule (Cornwell & Costanza 1994, Costanza & Perrings 1990, Shogren et al. 1993, Gerard 2000). One important advantage is that bonds shift the "burden of proof" from governments and society to firms, reducing the need for litigation. Instead of taking the firm to court to prove the damage caused by the firm's activities, now the firm is legally bound to reveal the true costs of its activity and deposits the equivalent amount of money with the government. Another advantage is that environmental bonds mitigate the impacts of liquidity constraints and ensure that funds are available if the constraint binds.

Bonds have disadvantages, as well, which are thoroughly discussed by Shogren et al. (1993). The most important disadvantage is moral hazard which exists for both firms and government. In the private sector, since the value of bonds relies on firms' self-reporting of expected future damage costs, firms with incentive to reduce their compliance costs may not truthfully report their environmental costs. To deal with this issue, estimations can be audited and verified by a third party such as an environmental authority to ensure that firms comply with estimations standards and truthfully report the costs of their activity. In the government sector, there is also financial incentive to claim that firms have shirked their environmental obligations, thus justifying seizing the bond. However, false bond reports have reputation costs for firms, just as false claims have repercussions for governments. Reputation costs mitigate the incentive for any false claims in both sectors because cheating by a firm increases the cost of bonds to start future activities, if the government realizes that that firm has not been truthful. Cheating by governments discourages innovative activities, and

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[12] Shavell (2004) shows that such impacts can be dealt with through a minimum asset requirement combined with liability insurance. The minimum asset reduces individuals' incentives to engage too often in activities with potential harmful impacts, and if they have engaged, the liability insurance improves damage prevention incentives. However, Poulin & Jacques (2007) argue that if a firm has not enough assets, no insurance company will participate, restricting the firm's engagement in such activities.

to offset this effect, non-credible governments can offer subsidies to investors to encourage investments.

2.2 Investment in non-renewable resources

Studies of environmental bonds are largely limited to conceptualizing and describing the theory of environmental bonds and their mechanisms. There is little analysis of the effect of this policy on firm investment decisions and its optimal choices of site clean-up, especially in a dynamic setting. Igarashi et al. (2010) studied the effect of environmental bonds on firms' exploration and extraction decisions in the oil and gas sector, through a theoretical model. They demonstrated that internalizing restoration costs only slows the resource extraction, without affecting the level of exploration and thus increases the in-ground reserve-to-well ratio. White et al. (2012) showed that insolvency leads to a deadweight loss because the restoration costs must be raised from general tax revenue, and thus with environmental bonds, the government liability will be reduced by the payout of the bonds. These studies have analyzed firms' extraction and restoration behavior in the absence of output price uncertainty, and thus the timing of initial investment and final restoration are exogenous. Price volatility affects the optimal timing of project stages, including the mothballed stage and the restoration phase, and will thus affect waste accumulation and clean-up.

The existing literature on real options deals with price uncertainty and its implications for optimal investment decisions in non-renewable resources. An early study by Brennan & Schwartz (1985) used a real options approach to analyze a firm's optimal policies for managing natural resource projects in an uncertain environment. Their study allows for three discrete choices after the original investment decisions have been made, i.e., to activate, mothball, or shut down a project, and examines the impact of the sunk costs of mothballing and reopening on the optimal timing of operation and the value of investment. Slade (2001) looked at the managerial flexibility this choice set provides for firms, and found that this flexibility increases the value of project. Flexibility in this case means that the option to become inactive should a current operation incur loss, and the option to reopen a mine when operation becomes profitable. Therefore, idle firms are willing to tolerate some losses with the expectation that commodity prices will rise in the future and make the operation profitable again. However, according to Dixit (1992), when the incurred loss in the phase of inactivity exceeds the option value of reactivation, permanent closure becomes optimal.Dixit (1989, 1992) demonstrated that once an activity is mothballed, a firm could remain in the state of hysteresis, reflecting the fact that the critical prices for reopening the activity tend to be higher than the prices that triggered inactivation in the first place. The source of hysteresis is the existence of switching costs that motivate firms to delay such irreversible costs. This phenomenon also exists when firms decide to close an already opened activity in the sense that closure occurs at lower prices than the original ones that caused the decision maker to open the mine. Mason (2001) extended Brennan & Schwartz by considering that the resource stock is exhaustible, and observed hysteresis even with low sunk costs.

The research to date has tended to evaluate the value of natural resource investment under irreversible costs of project suspension and reactivation, and firms' optimal response to clean-up costs associated with permanent closure has been largely overlooked. Brennan & Schwartz assumed that abandonment entails no costs, and Dixit, Mason and Slade did not include the option of permanent closure in their choice set. However, shutting down a mine requires costly investments to perform restoration and remediation of all disturbed areas. More recently, Insley (2017) examined optimal extraction of a non-renewable resource with the resource price modeled as regime switching stochastic process and assuming irreversible restoration costs for abandonment. She found that the critical prices that trigger abandonment depend on the stock of reserves and the profitability of the project: for low reserves and low operational profits, firms abandon the project before the lease is expired, while when the level of reserve is high firms keep the reopening option alive as there is an opportunity benefit to waiting. At the end of the lease, it is assumed that all firms were required to abandon the mine and remediate the entire site regardless of the level of remaining reserves. Muehlenbachs (2015) has studied the effect of abandonment costs for the Canadian oil and gas sector, and observes that such costs may motivate firms to strategically exercise the option to suspend operation even if the future reopening option has zero value. This phenomenon increases the likelihood that firms will walk away from their environmental obligations due to bankruptcy or insolvency. Therefore, becoming mothballed as a way to escape the environmental obligations is unambiguously welfare reducing and extends the costs of damage clean-up to society.

This study contributes to the current literature by analyzing the impacts of restoration costs on a resource extraction firm's decisions. We develop a simple mine valuation model that accounts for environmental quality, in terms of the stock of waste, as an additional state variable and is capable of analyzing the influence of an environmental bonding mechanism on abatement decisions. Clearly, abatement reduces the stock of waste and thus the final environmental liability costs. The model is also used to examine the strict liability rule where no bond is required but the firm must undertake site restoration at the end of the project. To the best of our knowledge, this is the first attempt to understand the impacts of environmental bonds, as a complement to the strict liability rule, on a firm's optimal investment strategies and its project value under price uncertainty, in a dynamic setting. This paper uses a real options approach in the spirit of Brennan & Schwartz and Mason.

3 Model formulation

3.1 Description of the decision problem

Consider a risk-neutral firm which extracts a non-renewable resource and thereby generates hazardous waste disposed of into a landfill. A government regulator requires the waste be cleaned up when the operation is terminated. This study assumes that two policies can be implemented: 1. the strict liability rule, and 2. an environmental bond combined with liability for clean-up. We refer to the latter as the bonding policy. For simplicity, we have assumed that there is no risk of accidental release of pollution from the landfill. Therefore, the only environmental obligation is the clean-up of the landfill.

To ensure compliance with an environmental policy, the regulator designs an environmental contract that determines the firm's clean-up obligations based on the requirements of each policy. Once the firm enters into the environmental contract, it can decide the optimal timing of its initial investment to develop the project, which entails significant capital costs. After the project is launched, the firm manages the level of reserve and the stock of waste by choosing the optimal rates of extraction and abatement, respectively. In addition, the firm maximizes its project value by determining the optimal timing of production, mothballing, reopening the operation, and abandoning the facility and site restoration.

The firm's optimal decisions depend on four state variables: the price of the commodity, $P(t)$, the stock of the resources, $R(t)$, the amount of waste in the land fill, $W(t)$, and the stage of operation, $\delta_i,\ i = 1, 2, 3, 4$. Stage 1 ($i = 1$) is pre-construction, Stage 2 ($i = 2$) is active extraction, Stage 3 ($i = 3$) is mothball or temporary shut down, and Stage 4 ($i = 4$) is abandonment and landfill restoration. The firm has three control variables: the rate of resource extraction, q, the rate of waste abatement, a, and the decision to move to a new stage of operation, δ. We note that δ serves as both a state variable and a control variable in the model. Cash flows depend on the current δ at a particular time t, but as described later, the firm makes choices at discrete times as to whether to move to a different stage.

The commodity price, $P(t)$, is assumed to be described by a simple one-factor Ito process, which is mean reverting in the drift term. As is discussed in Section 6.1, this model has been used by other researchers to describe commodity prices (Schwartz 1997).

$$
\begin{aligned}
dP(t) &= \kappa(\hat{\mu} - \ln P)P \; dt + \sigma P dz; \;\; P(0) \; given \\
P \; &\in [p_{\min}, p_{\max}]
\end{aligned}
\tag{1}
$$

where $\kappa, \hat{\mu}, \sigma$ are parameters reflecting the speed of mean reversion, the long run mean of $\ln(P)$, and volatility, respectively. t denotes time where $t \in [0, T]$, and dz is the increment of a Wiener process. The estimation of the parameters is described in Section 6.1. Parameters are estimated for the risk-neutral world, so that the term $\kappa(\hat{\mu} - \ln P)P$ represents a risk-adjusted drift rate.

The level of resource stock, $R(t)$, falls over time at the extraction rate q. The dynamic path of resource stock is given as:

$$
dR(t) = -qdt; \quad R(0) = r_0 \; given. \tag{2}
$$

The waste pile, $W(t)$, as a by-product of the operation, is assumed to be disposed of into a landfill with a known, maximum capacity denoted by $\bar{w}$. By assumption, $\bar{w}$ is specified by regulation and is optimal from society's point of view. During the operation phase, each unit of resource extracted adds to the stock of waste at the constant rate ϕ, and abatement at the rate a reduces the waste flow. This dynamic continues until the capacity of landfill is exhausted. Therefore, the rate of change in the volume of waste or in the stock of landfill capacity is given by

$$dW(t) = (\phi q - a)dt;\ W(0) = w_0 \tag{3}$$

in which $\phi q \lesseqgtr a$, and w_0 represents the initial level of waste reflecting the fact that the initial construction and investment in resource extraction operations involve environmental degradation by generating waste that is required to be cleaned up at the end of operations.

For intuition, we define the environmental quality in terms of the stock of waste so that waste accumulation deteriorates the environmental quality. Therefore, ϕq can be thought of as the flow rate of the environmental deterioration, assuming zero natural decay for the waste. The abatement effort is any action, such as recycling the waste, that occurs during the operation phase. Consistent with the model of Keohane et al. (2007), the abatement rate could be higher than the environmental deterioration rate (i.e., $\phi q < a$). It follows that waste abatement could affect the previously generated waste and contributes to a positive rate of change in the environmental quality. Abatement is restricted by the installed capital and cannot exceed its maximum value, $\bar{a}$, at each point of time. By assumption, this upper bound does not change over time.

We now specify admissible sets for δ, q, and a. Let Z_δ denote the admissible set for δ where

$$Z_\delta = \{\delta_1, \delta_2, \delta_3, \delta_4\}. \tag{4}$$

We define an admissible set for the extraction rate q, which depends on both the resource stock and stage of operation. Denote this admissible set as $Z_q(R, \delta)$, which is given as follows:

$$
\begin{aligned}
& q \in Z_q(R, \delta) \\
& Z_q = [0, \bar{q}], \quad \text{if} \;\; R > 0, \;\; \delta = \delta_2. \\
& Z_q = 0, \quad \text{if} \;\; R = 0, \;\; \delta = \delta_2. \\
& Z_q = 0, \quad \text{if} \;\; \delta = \delta_i, \;\; i = 1, 3, 4, \;\; \forall R.
\end{aligned} \tag{5}
$$

By assumption, the extraction rate cannot exceed its maximum rate $\bar{q}$. This upper bound is known as the capacity constraint and is assumed to remain constant during the operation.

Similarly, we define an admissible set for a, denoted $Z_a(w, q, \delta)$, as follows:

$$
\begin{aligned}
& a \in Z_a(w, q, \delta) \\
& Z_a = [0, \bar{a}], \quad \text{if} \quad W < \bar{w}, \;\; \delta = \delta_2 \\
& Z_a = [\phi q, \bar{a}], \quad \text{if} \quad W = \bar{w}, \;\; \delta = \delta_2 \\
& Z_a = 0, \quad \text{if} \quad \delta = \delta_i, \;\; i = 1, 3, 4, \;\; \forall W.
\end{aligned} \tag{6}
$$

It is assumed that $\bar{a} > \phi \bar{q}$, implying that the firm can abate at a rate that exceeds the waste level generated when extraction is at the maximum $\bar{q}$. Note that Equations (2) - (6) imply that

$$
\begin{aligned}
& 0 \leq W \leq \bar{w} \\
& 0 \leq R \leq r_0
\end{aligned} \tag{7}
$$

The characteristics of extraction costs are given in Assumption 1.

Assumption 1 *The extraction cost function* $C^q(q)$ *is linear in the extraction rate so that* $C^q(0) = 0$, $C'^q(\cdot) \geq 0$, *and* $C''^q(\cdot) = 0$.

Assumption 2 gives the cost of abatement as a convex function, implying that removing each additional unit of pollution with abatement is increasingly difficult and more costly to the firm.

Assumption 2 *The abatement cost function,* $C^a(a)$*, is assumed to be twice differentiable with* $C^a(\cdot) \geq 0$*,* $C^a(0) = 0$*,* $C'^a(\cdot) \geq 0$*,* $C''^a(\cdot) \geq 0$*, and* $C'''^a(\cdot) = 0$*.*

Unlike abatement, restoration improves the quality of the environment by affecting the stock of damage, rather than the flow. To ease the analysis, it is assumed that periodic restoration is not possible, and thus abatement is the only way to maintain the quality of the environment during the active life of the project.

3.1.1 An environmental bond

To model the mechanism of an environmental bond, we assume that the firm must deposit an amount with the government prior to project commencement sufficient to cover clean-up costs of waste generated during construction. The value of the environmental bond has to be adjusted periodically during the life of the project based on the firm's estimated restoration costs. Therefore, at the end of each period, the firm submits a revised cost estimate and the government adjusts the amount of deposited bonds according to these estimates. The value of environmental bonds in any period must completely cover the closure costs if the firm were to abandon the mine at the end of the current period. We assume that the appropriate level of restoration and the associated cost are correctly determined and thus the bond level is appropriate.

One important policy consideration is that the firm is required to estimate the closure costs based on the fact that a third party will do the restoration should the firm default. It has been found in practice that it is more costly for a third party to clean up environmental damages than for the firm itself by 15% to 30% (Ferreira et al. 2004). This additional amount internalizes third-party costs such as mobilization costs (White et al. 2012, Peck & Sinding 2009). Therefore, requiring restoration cost estimates to be made on the basis of expenses to a third party ensures sufficient funds for for the required clean-up should the firm walk away from its obligations (Grant et al. 2009, Otto 2010). This study assumes a convex cost function for clean-up given by Assumption 3. As the stock of waste increases it becomes increasingly more difficult to return the land to its pristine state. Therefore, additional waste requires additional costs for removing a greater volume of waste and, depending on the degree of toxicity, requires greater safety precautions for workers during restoration. Moreover, the cost of stabilizing the waste to prevent geographical expansion can increase with waste volume (Phillips & Zeckhauser 1998). As a result, more waste requires more clean-up effort which becomes more costly at the margin.

Assumption 3

- *We define the firm's clean-up costs by* $C^f(W)$ *and the third party's clean-up costs by* $C^{tp}(W)$*, so that* $C^{tp}(\cdot) = \nu C^f(\cdot)$ *where* $\nu > 1$ *is a constant.*
- *The firm's cost of cleaning up the accumulated waste and improving the quality from the state* W *to zero waste is given by* $C^f(W)$ *with* $C'^f(\cdot) \geq 0$*,* $C''^f(\cdot) \geq 0$*, and* $C'''^f(\cdot) = 0$*.*
- *It is assumed that* $C^f(W)$ *is truthfully estimated and reported by the firm.*

Let $B(t)$ denote the total value of the bond at each point of time. This value varies according to rate of change in the firm's restoration costs adjusted by potential expenses to the third party, $\frac{dC^{tp}(W)}{dt}$. In fact, the variation of the environmental bonds over each period (i.e., the annual cost of bonds to the firm) denoted by $\frac{dB(t)}{dt}$ is equal to the rate of change in the restoration costs, and can be written as

$$\begin{aligned}\frac{dB}{dt} &= \frac{dC^{tp}(W)}{dt} \\ &= \frac{dC^{tp}}{dW}\frac{dW}{dt} \\ &= \theta(W)(\phi q - a)\end{aligned} \tag{8}$$

where $\frac{dC^{tp}}{dW} \equiv \theta(W)$, and $\frac{dW}{dt} = \phi q - a$ is given by Equation (3). $\theta(W)$ is defined as the marginal restoration cost or the marginal rate of fine that the government collects on the waste flow over a given time interval. Therefore, the firm's rate of payment on bonds to the government at each time (i.e., $\frac{dB}{dt}$) is given by $\theta(W)(\phi q - a)$, which could be positive, negative, or zero depending on $\phi q \gtreqless a$. If the abatement rate is such that the extraction activities add to the stock of waste ($\phi q > a$), the firm will have to update the deposited bond accordingly, representing an increase in bond value. In contrast, if abatement dominates the deterioration rate ($\phi q < a$) and reduces the waste accumulation, the bond value will decline, indicating that the firm has been reimbursed an amount equal to the reduction in clean-up costs. If abatement fully offsets the current deterioration ($\phi q = a$), the net change in the stock of waste and thus the compliance cost with the bonding regulation are zero. Therefore, there is a trade-off between the decision to abate today and to post bonds for clean-up at the terminal time. Note that $\theta(W)$ increases linearly in W, and is determined based on the company's estimate of the change in restoration costs to a third party as W changes.

Let $B_0 = C^{tp}(W(0))$ cover the potential clean-up cost of the initial waste. B_0 has to be deposited with the government before the operation starts. According to Peck & Sinding (2009), this mechanism provides adequate assurance for the existence of funds for future clean-up because it "raises money according to the initial footprint and [is] linked to marginal increases or decreases in mine footprint over its life". Since the estimated restoration costs are higher than the costs to the firm by an amount ν (see Assumption 3), the difference will be returned to the firm should it remain solvent at project termination date, representing a saving for the firm. Otherwise, the entire fund will be forfeited. We refer to this saving as restoration benefit defined by Assumption (4).

Assumption 4 *Under bonding requirements, the firm's benefit (saving) from restoration at the terminal point,* T, *is* $(\nu-1)C^f(W)$[13]*, which is the difference between the firm's estimated restoration costs to a third party and its actual costs of restoration, and* $\nu > 1$.

While the project is operating, the annual compliance cost with the environmental bond has two components: 1) the cost of abatement effort, and 2) the expected bond payment. Therefore, the annual compliance cost is defined by

$$\Omega = C^a(a) + \mathbf{1}_{b=true}\theta(W)(\phi q - a). \tag{9}$$

where $\mathbf{1}$ is the indicator function and $b = true$ under the environmental bonding policy and is false otherwise.

3.1.2 The strict liability rule

Under the strict liability rule, the regulator requires the firm to clean-up the stock of waste once the project terminates, and does not require *ex ante* payments for associated costs. Moreover, termination entails sunk costs to the firm. Therefore, we can adjust Assumption 4 as follows

Assumption 5 *Under liability requirements, the firm's restoration cost at the terminal point,* T, *is* $C^f(W)$.

---

[13] According to Assumption 3, the benefit of restoration is $[C^{tp}(W) - C^f(W)] = [\nu C^f(W) - C^f(W)] = (\nu - 1)C^f(W)$ where $\nu > 1$.

While the project is operating, the annual compliance cost with the strict liability rule is associated with abatement efforts. In Equation (9) the second term on the right hand side disappears as $b =$ false.

3.1.3 Instantaneous cash flow

The firm's objective is to choose controls to maximize the discounted sum of risk neutral expected stream of future cash flows. Cash flows at any time t will depend on the firm's stage of operations, δ, rate of abatement, a, and extraction, q. Instantaneous cash flows are given as follows:

$$\pi(t) = P(t)q - C^q(q) - \left[C^a(a) + \mathbf{1}_{b=true}\theta(W)(\phi q - a)\right] - C_i^m - taxes, \quad \text{if} \quad \delta = \delta_i, \quad i = 1,2,3. \tag{10}$$

$$\pi(t) = 0, \quad \text{if} \quad \delta = \delta_4.$$

in which the term in square brackets is the compliance cost, Ω, as previously given by Equation (9). C_i^m refers to fixed costs under both the bond and strict liability policies. In the operating state, C_2^m equals the fixed costs of sustaining capital, while at the mothballed stage C_3^m is the summation of costs for sustaining capital, denoted by $C_3^{m_1}$, as well as for environmental monitoring and maintenance, denoted by $C_3^{m_2}$. Such fixed costs, taxes, and cash flows are all zero in Stage 1.

3.2 Defining state and control variables, and the value function

The resource price, $P(t)$, resource stock $R(t)$, waste pile, $W(t)$, and stage of operation, $\delta(t)$, all represent state variables in the decision problem. The value of the firm's operations is a function of these state variables and time, t, denoted as $V(P, R, W, \delta, t)$.

It is assumed that at specific discrete times, the firm makes a decision about whether to move to another stage of operation. These discrete decision times are given as follows:

$$\mathcal{T}_d \equiv \{t_0 = 0 < t_1 < ... < t_m <, ..., t_M = T\} \tag{11}$$

where we assume that the decision to move to another stage of operation occurs instantaneously at $t \in \mathcal{T}_d$. Choices regarding optimal rates of abatement, a, and extraction, q, are made in continuous time at time intervals given as follows:

$$\mathcal{T}_c \equiv \{(t_0, t_1), ..., (t_{m-1}, t_m), ..., (t_{M-1}, t_M)\}. \tag{12}$$

Since we search for the closed loop control, we assume the controls are in feedback form, i.e., functions of the state variables. Control variables can be specified as: $q(P, R, W, \delta, t)$, $a(P, R, W, \delta, t);\ t \in \mathcal{T}_c$, and $\delta^+(P, R, W, \delta, t);\ t \in \mathcal{T}_d$. Admissible sets for q, a and δ are given as Z_q, Z_a and Z_δ, specified in Equations (5) and (6), and (4). We specify a control set which contains the controls for all $t_0 \leq t \leq t_M$.

$$K = \{(\delta^+)_{t \in \mathcal{T}_d}\ ;\ (q, a)_{t \in \mathcal{T}_c}\} \tag{13}$$

Regardless of the controls chosen, the value function can be written as the risk neutral expected discounted value of the integral of cash flows, given the state variables, with the expectation taken over the controls:

$$
\begin{aligned}
V(p,r,w,\bar{\delta},t) \; &= \\
\mathbb{E}_K & \left[\int_{t'=t}^{t'=T-1} e^{-\rho t'} \; \pi(P(t'),R(t'),W(t'),\delta) \; dt \; + e^{-\rho(T-t)} V(P(T),R(T),W(T),\delta(T),T) \right. \\
& \qquad \left. \Big| P(t)=p, R(t)=r, W(t)=w, \delta(t)=\bar{\delta} \right].
\end{aligned}
\tag{14}
$$

where $(p,r,w,\bar{\delta})$ denote realizations of the random and path dependent variables (P,R,W,δ). ρ is the risk free interest rate, and $\mathbb{E}[\cdot]$ is the expectation operator. The value in the final time period, T, is assumed to be the expected net benefits from restoring and closing the mine. This is described as a boundary condition in Appendix A.

4 Dynamic Programming Solution

Equation (14) is solved backwards in time using dynamic programming. For a particular $t_m \in \mathcal{T}_d$, we define t_m^- and t_m^+ to represent the moments just before and after t_m. Specifically $t_m^- = t_m - \epsilon$ and $t_m^+ = t_m + \epsilon$, $\epsilon \to 0^+$. As a visual aid, the times around t_m and t_{m+1} are depicted below, going forward in time:

$$
t_m^- \;\rightarrow\; t_m^+ \;\rightarrow\; t_{m+1}^- \;\rightarrow\; t_{m+1}^+ \;. \tag{15}
$$

At t_m we determine the discrete optimal control δ^+, while in the interval (t_m^+, t_{m+1}^-). We solve for the optimal controls q and a in continuous time.

4.1 Determining optimal rates of abatement, a, and extraction, q, from $t_{m+1}^- \to t_m^+$

We define $\mathcal{L}V$ as the differential operator as follows

$$\mathcal{L}V = \frac{1}{2}\sigma p^2 \, \frac{\partial^2 V}{\partial p^2} + \kappa(\hat{\mu} - \ln p)p \, \frac{\partial V}{\partial p} + \rho V. \tag{16}$$

Using a standard contingent claims approach (Dixit & Pindyck 1994), we can derive a system of partial differential equations that describe the value of the resource, V, in the interval (t_m^+, t_{m+1}^-) for all operating states except for abandonment.

$$\frac{\partial V}{\partial t} + \mathcal{L}V + \max_{q,a} \Big\{ -q \, \frac{\partial V}{\partial r} + (\phi q - a) \, \frac{\partial V}{\partial w} + \pi(t) \Big\} = 0, \quad \text{for } \delta = \delta_i, \quad i = 1, 2, 3 \tag{17}$$

where we maximize with respect to the control variables a, and q.

Once the project is in stage 4, the project value goes to zero.

$$V(p, r, w, \delta = \delta_4, t = T) = 0. \tag{18}$$

4.2 Determining optimal operating stage, δ at t_m

For $t_m \in \mathcal{T}_d$, the firm checks to determine whether it is optimal to switch to a different operating stage. The firm will choose the operating stage which yields the highest value net of any costs of switching. Let $C(\delta^-, \delta')$ denote the cost of switching to stage δ^- to δ'. Recall that $t = t^-$ represents the moment before t_m and $t = t^+$ denote the instant after t_m. Solving going backward in time, and noting the optimal stage is denoted as δ^+, the value at t_m^- is given by:

$$\begin{aligned} V(p,r,\delta^-,t_m^-) &= V(p,r,\delta^+,t_m^+) - C(\delta^-,\delta^+) \\ \delta^+ &= \arg\max_{\delta'} [V(p,r,\delta',t_m^+) - C(\delta^-,\delta')]. \end{aligned} \tag{19}$$

Switching costs are the same under the bond or strict liability policies except when the mine is abandoned. Recalling from Assumption 4, the abandonment cost with bonding requirements, $C(\delta_i,\delta_4),\ i=1,2,3$, simply equals the negative of reimbursement after clean-up has been completed,$-(\nu-1)C^f(w)$. However, Assumption 5 indicates that under the strict liability rule, $C(\delta_i,\delta_4),\ i=1,2,3$, equals the firm's clean-up costs, $C^f(w)$.

4.3 Optimal extraction and abatement policies

The decision problem specified in Equations (17) and (19) has no closed form solutions and is solved using a numerical approach, which is discussed in the next section. In this section, we examine the first order conditions for extraction and abatement which hold during in stage 2, $\delta=\delta_2$, when the firm is actively producing the ore. These first order conditions reveal the nature of the optimal extraction and abatement rates, denoted a^* and q^*, and in particular whether the solutions are bang - bang.

4.3.1 An environmental bond

The optimal extraction rate, q^*, and the optimal abatement rate, a^*, under bonding requirements are obtained by maximizing Equation (17) with respect to the terms that contain q and a. The optimal extraction rate for a firm that actively extracts under a bonding policy satisfies

$$P - C'^q - \frac{\partial V}{\partial r} + \phi\Big[\frac{\partial V}{\partial w} - \mathbf{1}_{b=true}\ \theta(w)\Big] \begin{cases} \geq 0 & \Rightarrow q^* = \bar{q} \\ < 0 & \Rightarrow q^* = 0 \end{cases} \tag{20}$$

The first three terms in Equation (20) are the marginal revenue from extraction, marginal cost of extraction, and marginal value of the reserve to the firm. We have called the last term in brackets as the firm's *marginal cost of environmental deterioration* which has two components: 1) the marginal value of the waste pile to the firm, and 2) the marginal restoration cost. The last three terms give the firm's total marginal cost of extraction.

Remark: Since both the profit function and the resource stock are linear in extraction rate, the optimal extraction rate, q^*, is either zero or at capacity, hence a bang-bang solution.

It follows that given an optimal abatement rate, the firm extracts at capacity as long as the marginal effect is positive. For zero marginal effect, the firm remains indifferent between extracting at capacity or not extracting at all, and thus it is reasonable to extract at capacity. Therefore, the firm extracts at capacity as long as the marginal revenue of extraction is not lower than its total marginal costs.

The optimal abatement under a bonding policy is given by

$$-C'^{a}(a^*) = \frac{\partial V}{\partial w} - \mathbf{1}_{b=true}\ \theta(w) \Rightarrow \begin{cases} 0 \leq a^* \leq \bar{a} & \text{if} \quad w < \bar{w} \\ \phi \bar{q} \leq a^* \leq \bar{a} & \text{if} \quad w = \bar{w}. \end{cases} \tag{21}$$

Along the optimal abatement path, the marginal cost of environmental degradation, $\frac{\partial V}{\partial w} - \theta(w)$, is equal to the marginal abatement cost. If abatement is costlier than environmental degradation at the margin, the polluter reduces its abatement effort and posts environmental bonds instead, until it remains indifferent between abating and polluting. In contrast, if the costs of environmental degradation are larger than the abatement costs at the margin, the optimal strategy is to increase abatement until the equality in Equation (21) holds. Thus according to the optimal policy rule, pollution should be abated up to the point that the marginal costs of abatement equal the potential marginal costs of the environmental degradation. Once the landfill capacity is reached, the lowest optimal abatement rate equals the environmental deterioration rate. This condition ensures that the landfill does not receive waste beyond its capacity.

A comparison between optimal criteria in Equation (20) and the optimal extraction policy with no environmental interaction in Brennan & Schwartz and the subsequent studies reveals that in our study the firm has to take into account all environmental costs of extraction (i.e., $\phi\Big[\frac{\partial V}{\partial w} - \mathbf{1}_{b=true}\ \theta(w)\Big]$) when choosing the optimal extraction rate. These terms were zero in such previous studies. Therefore, the firm may require to observe a relatively higher price to start its operation, because accounting for environmental costs in the profit function increases the operational costs and reduces the private net benefit of extraction.

4.3.2 The strict liability rule

The optimal rules for extraction and abatement are also given in Equations (20) and (21) but the indicator function will be zero. The firm's *marginal cost of environmental deterioration* under the liability rule is simply the marginal value of the waste pile. Similar to the bond, the firm operating under the liability rule extracts at either zero or at capacity, because both the profit function and the resource stock are linear in extraction rate. However, a comparison between optimal criteria for extraction under the bond and the optimal extraction policy under the liability reveals that under the former the firm requires a higher price to induce a positive level of production. This higher price is because accounting for all environmental costs of extraction in the profit function increases the operational costs and reduces the private net benefit of extraction. However, under the strict liability rule, the firm does not take into account all environmental costs of extraction when choosing the optimal extraction rate. In other words, the payment for the marginal restoration cost, $\theta(w)$, in Equation (20) does not appear under the liability rule.

5 Numerical solution approach

Equations (17) and (19) represent a stochastic optimal control problem which must be solved using numerical methods. The computational domain of Equation (17) is $(p, r, w, \bar{\delta}, t) \in \Gamma$ where $\Gamma \equiv [p_{min}, p_{max}] \times [0, r_0] \times [0, \bar{w}] \times Z_\delta \times [0, T]$. More details are given in Appendix A where boundary conditions are specified for the PDEs. $\mathcal{L}V$ in Equation (17) can be discretized using a standard finite difference approach. The other terms in the equation are discretized using a semi-Lagrangian scheme as described in Chen & Forsyth (2007) and will not be described further here.

Recall that the optimal control for q which we denote by q^* is bang - bang so that $q^* \in \{0, \bar{q}\}$. To determine the optimal control we search over the set $(q, a) \in \{0, \bar{q}\} \times Z_a$. We discretize the controls $a \in Z_a$ and determine the optimal control by exhaustive search at each point in the state space (p, r, w, t).

6 An application to copper industry

To illustrate the impact of an environmental bond versus the strict liability rule on optimal firm decisions, this study considers the case of investment decisions for a copper mine. A numerical example is developed based on available data from an open-pit copper mine in British Columbia, supplemented by researcher assumptions when data is lacking. The parameters of the stochastic model assumed for copper prices are estimated using copper futures contracts. We will use these estimated parameter values to solve the mine valuation problem.

κ	0.0264 (0.001)	Root Mean Square Error	0.07
μ	2.7051 (0.079)	Mean Absolute Error	0.05
η	2.7845 (0.026)	Log-likelihood function	9652
σ^2	0.0458 (0.002)	Number of observation	937

Table 1: *Estimation results for the one-factor copper price model using Kalman Filter. RMSE, MAE, μ, and η are in terms of US \$/lb. Standard errors are in parenthesis. Weekly futures data from Aug 1st, 1996 to Jul 13th, 2015.*

6.1 Estimating the parameters of the price process

The parameters of Equation (1) are estimated in the risk-neutral world. We define the parameter $\hat{\mu} = \mu - \eta$ so that the market price of risk, η, is deducted from μ which is the long-run mean of $ln(P)$ before adjusting for the price risk. The market price of risk reflects additional returns that the firm demands over the risk-free interest rate per each unity of price volatility. Note that in the stochastic price process $\kappa > 0$, $\mu > 0$, $\sigma > 0$, and $\eta > 0$. These parameters are estimated using the data for copper futures prices, reflecting market expectations about future prices. Estimation results are provided in Table (1).

To obtain estimations, we have used a Discrete Kalman Filtering approach and a Maximum Likelihood Function[14]. This study uses weekly data for copper futures contracts traded on the London Metal Exchange (LME)[15]. The estimation is done for six futures contracts dated from August 1996 to July 2015, with 1, 6, 11, 16, 21, and 24 months to maturity[16]. To find real copper prices, futures prices are deflated by the US Consumer Price Index. Due to the lack of data on copper spot prices, futures contracts closest to maturity proxy the market spot prices (Schwartz 1997). The Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) of the estimates of log futures prices are 7 cents per pound and 5 cents per pound, respectively. Moreover, the standard deviations of all parameter estimates

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[14] These metods are explained in Schwartz (1997).

[15] Data for this study were collected from Datastream.

[16] Long maturity contracts are of most interest as the goal of this study is to value a long-term investment project.

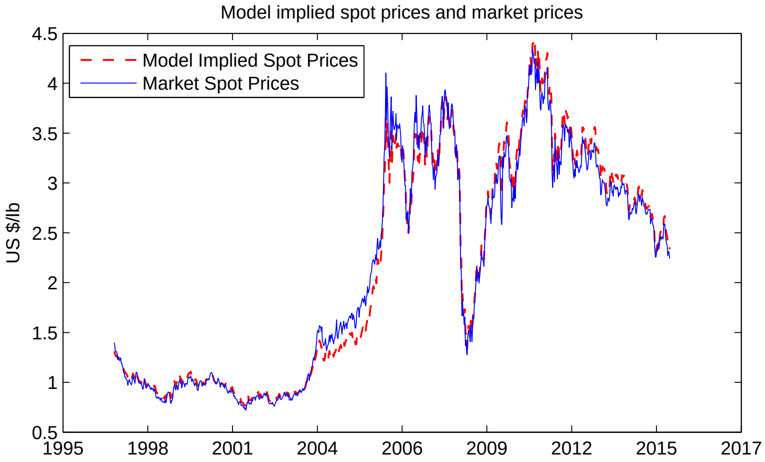

Figure 1: *Model implied copper spot prices and market copper prices. Weekly data from Aug 1st, 1996 to Jul 13th, 2015. Nominal prices are deflated by the US Consumer Price Index, base year=2007*

are small, implying that all estimates are significantly different from zero. These findings suggest that the one-factor model provides a good tracking of the copper market prices as shown in Figure (1).

6.2 Project specification

The numerical example is based on data from Copper Mountain which is an open-pit mine located in south-western British Columbia with an expected mine life of 15 years. In 2007, the Copper Mountain project proceeded to a feasibility study to construct an open-pit mine at the estimated cost of US $380 million. An additional US $5 million for the feasibility study, environmental testing and geological consulting increased the construction cost to US $385 million. This mine was targeted at producing 78.2 million pounds of copper per year, starting from June 2011, with an estimated average production cost of US $1.35 per pound of copper. The total fixed cost of sustaining capital tends to be US $25 million over the life of the mine. The mine's average strip ratio (i.e., waste/ore) is 1.5 pounds of waste per each pound of ore extracted.

Life of project		$T = 15$	years
Initial reserve		$r_0 = 1173$	million lb
Strip ratio (waste:ore)		$\phi = 1.5 : 1$	
Production capacity		$\bar{q} = 78.2$	million lb/year
Abatement ceiling*		$\bar{a} = 2\phi\bar{q}$	million lb/year
Landfill capacity*		$\bar{w} = 2260$	million lb
Extraction cost	$C^q(q) = \gamma q$	$\gamma = 1.35$	\$/lb
Abatement cost*	$C^a(a) = \alpha a^2$	$\alpha = 10^{-3}$	
Firm's clean-up cost **	$C^f(w) = \beta w^2$	$\beta = 10^{-5}$	
Adjustment factor***		$\nu = 1.15$	
Project stages		δ_1, δ_2, δ_3, δ_4	
Construction cost		\$385	million
Cost to mothball and reactivate*		\$5	million
Fixed costs of sustaining capital	C_2^m, $C_3^{m_1}$	\$1.66	million/year
Fixed monitoring costs while mothballed	$C_3^{m_2}$	\$1	million/year
Federal and provincial income tax		25%	of cash flows/year

Table 2: _Parameter values and functional forms for the prototype open-pit copper mine. All dollar values are based on 2007 US dollars. *Assumed by the authors. **β is calibrated based on landfill closure costs provided by the Government of Ontario 2011. ***From Ferreira et al. (2004)._ Other values are from 2007 feasibility study conducted by the Copper Mountain Mining Corporation.

Additional assumptions required for the numerical example are described below. By assumption, the maximum amount of waste that is allowed to be generated during the life of project is 2260 million pounds. The parameter of the clean-up cost function is calibrated based on the data provided by the financial assurance guideline for determining the closure cost of a landfill provided by the government of Ontario 2011[17]. It is further assumed that the maximum feasible rate of abatement can be twice as high as the environmental deterioration rate, i.e., $\bar{a} = 2x\bar{q}$ [18]. This assumption allows the possibility that abatement rate may exceed

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[17] In this guideline, the estimated closure cost of a landfill with $60,000$ tonnes capacity is around US \$3 million. After transforming tonnes to pounds, we have calculated the total closure cost of a landfill with 2260 capacity equivalent to US \$51.256 million, i.e., $C^f(\bar{w}) = 51.256$. Then, $\beta = 51.256/\bar{w}^2 \simeq 10^{-5}$. Note that this is not an accurate calibration and just gives us an insight about the extent of clean-up costs. This guideline is available at `https://www.ontario.ca/document/f-15-financial-assurance-guideline-0`.

[18] This study sets the abatement ceiling high enough so that the likelihood it binds is small, because

the deterioration rate.

Launching the project with liability requirements entails the fixed costs of US $380 million, whereas the bonding policy entails an additional cost to the firm that is the initial amount of the bond adjusted by the third-party expenses. The third-party cost that reflects administrative costs, mobilization costs, etc is assumed to be 15% of the firm's restoration cost. Either mothballing the mine or resuming the operations are assumed to entail the up-front cost of $5 million. It is further assumed that remaining in the mothballed stage costs $1 million per year for environmental monitoring and maintenance. Table (2) summarizes the data used for the numerical example.

7 Results analysis

This section compares the impacts of the environmental bond and the strict liability rule on the firm's optimal investment decisions determined by critical prices. In addition, we compare the project value, optimal abatement decisions, and the compliance costs under each policy at the initial time. At the end, we develop the dynamic paths for optimal abatement and waste accumulation using Monte Carlo simulations. To distinguish the results of each policy on the figures of this section, we use the superscripts b and l for the bonding policy and the strict liability rule, respectively.

7.1 Valuation results

The value of the investment project prior to construction under the environmental bonding policy is shown in Figure (2). The left-hand panel of this figure shows the value of the project across different starting prices and different levels of reserve prior to the initial investment,

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abating at high rates is prohibitively expensive.

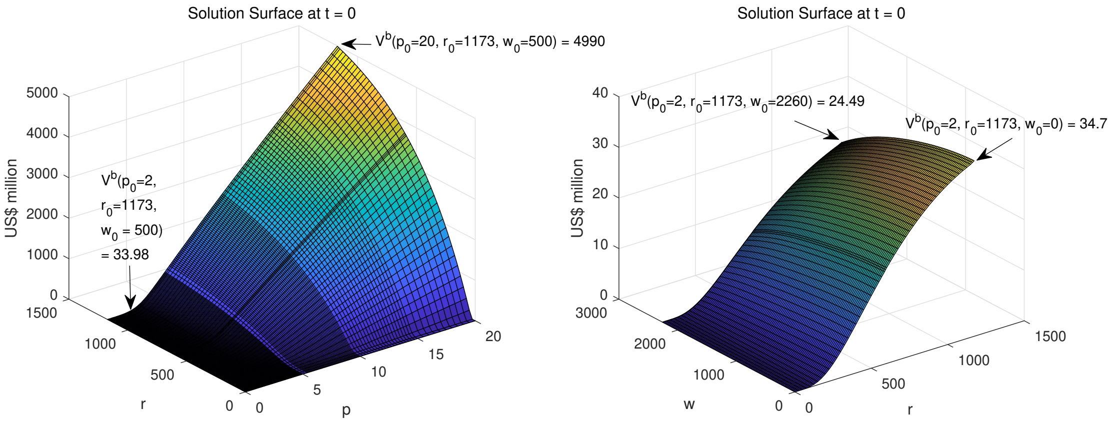

Figure 2: *Project value prior to construction under an environmental bond. In the left-hand panel, the level of waste is fixed at* $w_0 = 500$ *million pounds, and in the right-hand panel, the price is fixed at \$2/pounds.* r *: million pounds,* p *: US\$/pound,* w *: million pounds.*

when the level of waste is at 500 million pounds[19]. We observe that there is an increasing trend in the value of the project with respect to prices and reserve levels, as expected. The right-hand panel represents the value of the project across different resource stock levels and different levels of accumulated waste as a result of construction when the price of copper is \$2/pound. Clearly, the value of the project diminishes with the stock of waste because the environmental costs of project construction are internalized through the bond as shown by B_0 in Section (3.1.1). Therefore, at each level of reserve, the investment project has a higher value, the lower is the initial stock of waste. For the base case with $r_0 = 1173$ million pounds, the project's value ranges from \$35 million to \$24 million depending on the severity of damage during the initial construction.

Figure (3) shows the project value when the firm is strictly liable for the waste clean-up costs associated with construction and does not pay *ex ante* for such costs. Therefore, the only cost that the firm pays to launch the project is for construction, resulting in a higher investment value to the firm at any given level of reserve, price, and waste, as opposed to

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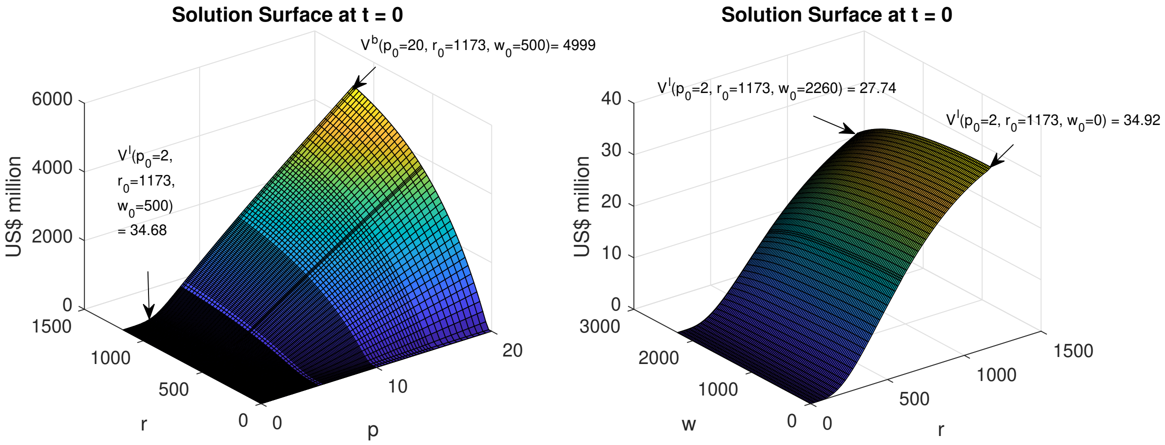
[19] This initial level of waste is chosen for the purpose of illustration only. Changing the initial level of waste changes the project value but the intuition remains the same.



Solution Surface at t = 0

$V^b(p_0=20, r_0=1173, w_0=500)= 4999$

$V^l(p_0=2, r_0=1173, w_0=500) = 34.68$

Solution Surface at t = 0

$V^l(p_0=2, r_0=1173, w_0=2260) = 27.74$

$V^l(p_0=2, r_0=1173, w_0=0) = 34.92$

Figure 3: *Project value prior to construction under the strict liability rule. In the left-hand panel, the level of waste is fixed at* $w_0 = 500$ *million pounds, and in the right-hand panel, the price is fixed at \$2/pounds.* r : *million pounds,* p : *US\$/pound,* w : *million pounds.*

the environmental bond. For example, the project value is higher by 13% at the largest amount of waste pile (i.e., $w_0 = 2260$) than the case when the environmental bond has been implemented. Although the firm's value is higher under the liability rule, in practice, this policy does not guarantee sufficient funds to cover restoration costs. Therefore, following a bankruptcy or insolvency such costs would have to be funded by the government.

The value of the project under both policies is sensitive to the parameters of the abatement and clean-up cost functions, as discussed in Appendix (B.1). If technological progress reduces the abatement cost, the project value becomes higher under both policies due to a lower compliance cost. In contrast, for a costlier clean-up project as a result of a more stringent policy in terms of restoration and closure plans, the project's profitability and thus its value are lower, in particular with bonding requirements. As a conclusion, a sizable restoration cost may reduce the project value significantly so that the firm may never invest in such projects in the first place.

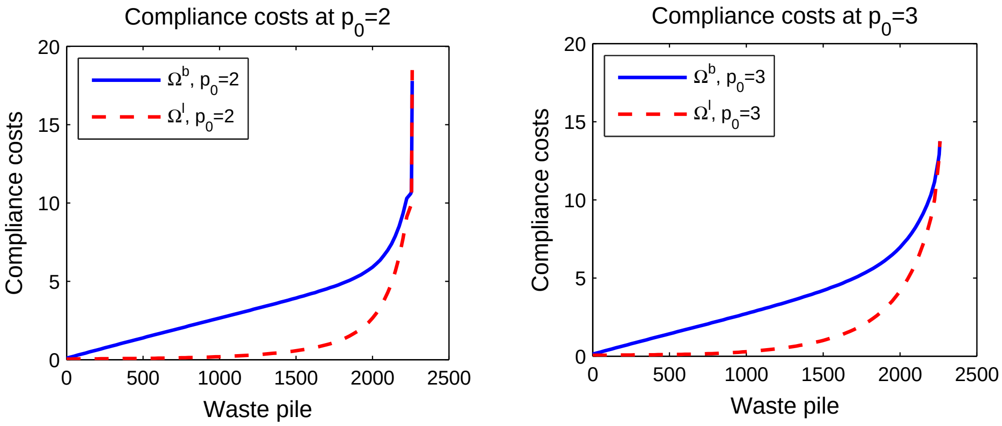


Figure 4: *A comparison of annual compliance costs (US\$ million) at the operating stage under an environmental bond versus the strict liability rule, for three price levels and* $r_0 = 1173$ *million pound.*

7.2 Compliance costs

Figure (4) compares the annual cost of compliance with each policy across different levels of accumulated waste, at time zero for two price levels. The compliance costs reflect the firm's optimal decisions regarding abatement and restoration. Although the firm's compliance cost with the two policies converges as the landfill capacity constraint binds, there is an obvious gap between such costs. This gap can be explained by comparing the abatement incentives across the waste pile under the two policies. As noted before, unlike the bond, the marginal rule for abatement under the strict liability rule does not include all environmental costs of extraction. Consequently, the firm's marginal cost of environmental deterioration (build up in the waste pile) is higher under the bond than the liability, leading to higher abatement efforts with bonding requirements. Intuitively, setting aside money in advance for future liabilities motivates the firm, as it now has a profit incentive, to reduce its environmental deterioration costs by abating more units of waste today. The bond increases the incentive for early waste clean-up through abatement which is the main reason for the existence of the gap in both abatement efforts and compliance costs. Figure (5) shows the marginal cost

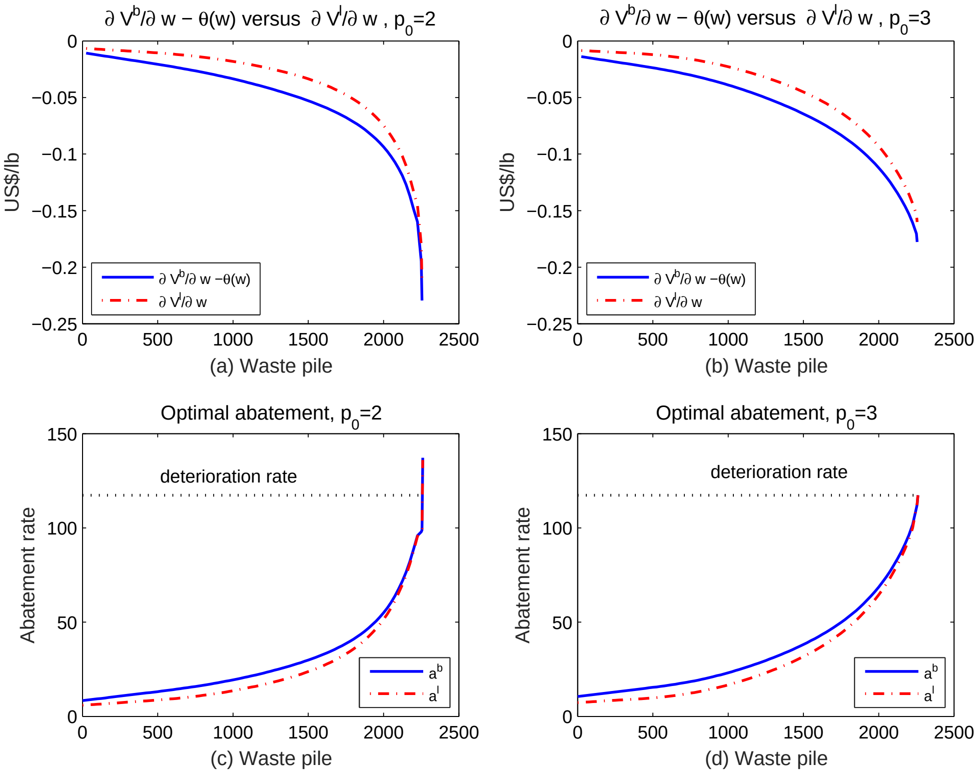


Figure 5: *A comparison of marginal environmental deterioration costs and optimal abatement incentives, at each level of initial waste under the environmental bond and the strict liability rule, for two price levels and* $r_0 = 1173$ *million pounds.*

of environmental deterioration (panels (a) and (b)) and optimal abatement rates (panels (c) and (d)) under each policy, at different initial levels of waste, for two price levels and full reserve. Note that the gap between abatement rates becomes much larger for a more costly restoration plan, as shown in Appendix (B.1).

Another interesting result is the trade-off between abatement and bond payment as shown in Figure (6). At low levels of waste, the optimal abatement rate increases as more waste accumulates but is not high enough to create a significant change in the stock of waste. Consequently, the firm's payment to the bond increases with waste accumulation. At higher levels of waste, when the landfill is reaching its capacity, the firm's optimal abatement

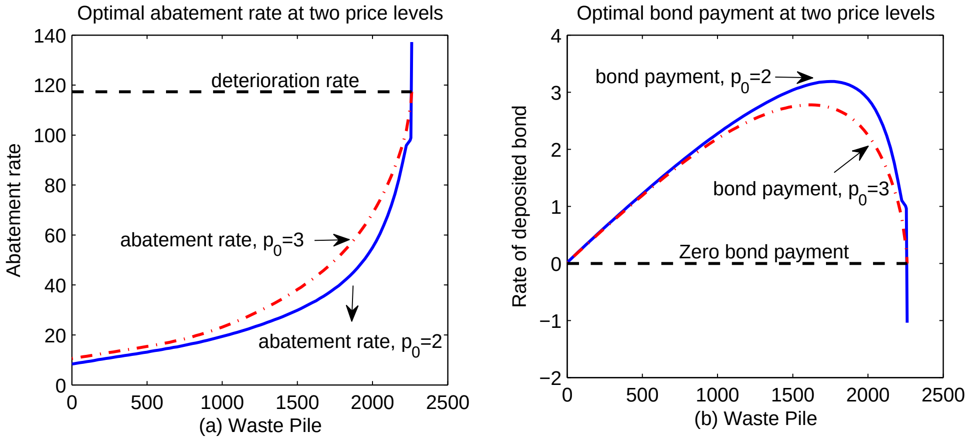


Figure 6: *Optimal rate of abatement and optimal deposited bond across waste accumulation at the operating stage under an environmental bond, for three price levels and* $r_0 = 1173$ *million pound, at time zero.*

effort progressively increases. As a result, waste accumulates at a slower rate and thus the payments to the bond gradually diminish. Once the landfill capacity is reached, the only way to continue operations is to abate at least at the expected deterioration rate. If abatement fully offsets the deterioration rate so that the level of waste does not change, the expected bond payment is zero. Finally, the bond payments become negative if abatement leads to a positive rate of change in environmental quality. This implies that the government reimburses the firm for a reduction in waste, which is more likely to happen when landfill is full. Such a trade-off does not exist under the liability rule, because restoration costs are not required until the project terminates, and the firm can avoid those costs by mothballing. Note that, in Figure (6), the abatement rate is plotted across the levels of waste generated during construction, and thus these are not the levels of waste associated with extraction processes.

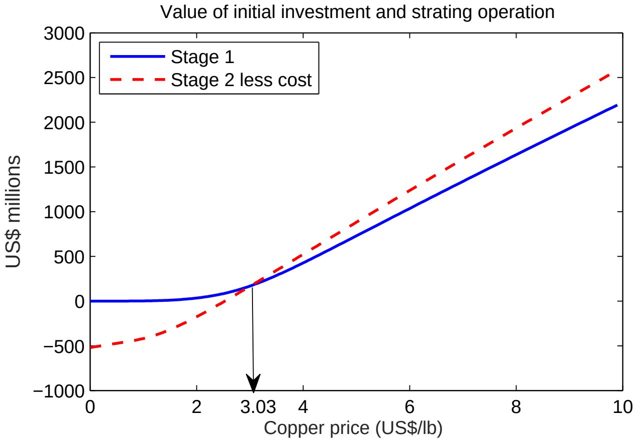


Figure 7: *Value of initial investment and begining production (Stage 1 to 2) under an environmental bond, given* $r_0 = 1173$ *and* $w_0 = 500$ *million pounds.*

7.3 Optimal choice of project stages

7.3.1 Under an environmental bond

We examine the lowest copper prices at which it is optimal to switch from one stage to another, which we refer to as critical prices. For $r_0 = 1173$ and $w_0 = 500$ million pounds, Figure (7) illustrates the value of the project prior to the initial investment (Stage 1) and once the operation has started (Stage 2) less the construction costs, versus copper prices up to US$10 per pound. It is optimal to start extraction activities once the value in Stage 2 less construction costs exceeds the value in Stage 1. Therefore, it is not optimal to incur the construction cost until copper prices increase to US$3.03 per pound. Before this threshold, the net present value prior to incurring construction costs is positive and higher than the net present value of the operating option. Thus, there is an opportunity benefit to waiting for a higher price before beginning operations.

The first column of Table (3) shows the critical prices to move from one stage to another stage when switching entails up-front costs, given $r_0 = 1173$ and $w_0 = 500$ million pounds. If per pound copper prices become as low as US$1.4, the optimal strategy is to mothball

Transition from:	$r_0 = 1173$	$r_0 = 587$
Stage 1 to Stage 2	3.03	3.45
Stage 2 to Stage 3	1.40	1.45
Stage 3 to Stage 2	1.54	1.61
Stage 2 to Stage 4	1.19	1.25
Stage 3 to Stage 4	0.77	0.85

Table 3: *Critical prices in terms of US\$/lb for full reserves at* $r_0 = 1173$ *million lb and half reserves at* $r_0 = 587$ *million lb, given* $w_0 = 500$ *million lb, under an environmental bond.*

current activity and to remain idle until the prices increase to US$1.54. This is the lowest price that encourages reactivation. If such a price increase never occurs, the inactive firm can optimally decide to terminate the project and carry out the restoration work. Critical prices that trigger termination from the mothballed stage tend to be as low as US$0.77 per pound. The firm also has the option to abandon the currently active mine without exercising the option to mothball should prices drop to US$1.19 per pound and there is no hope of a price to increase in the future.

Critical prices are sensitive to the level of reserve, which has previously been described by Insley (2017). The second column of Table (3) shows that critical prices are higher at all stages if half of the reserve is used up, assuming that the size of a waste pile is fixed at its initial level (i.e., $w_0 = 500$ million pounds). The initial investment occurs at higher prices for lower initial reserves due to the sizable fixed construction costs. After the project is launched, as the reserve depletes and becomes more scarce, its shadow value increases (i.e., a larger $\partial V/\partial r$ in Equation (17)). Thus, the firm needs to obtain higher prices to reopen or mothball the activity. Finally, the abandonment of the mine when half of the reserve is depleted will happen at a higher price, which indicates that the mine with the lower reserve is more likely to be abandoned.

What is interesting in the current study is how the critical prices vary in response to changes in the size of the waste pile, under the environmental bonding regulation. According

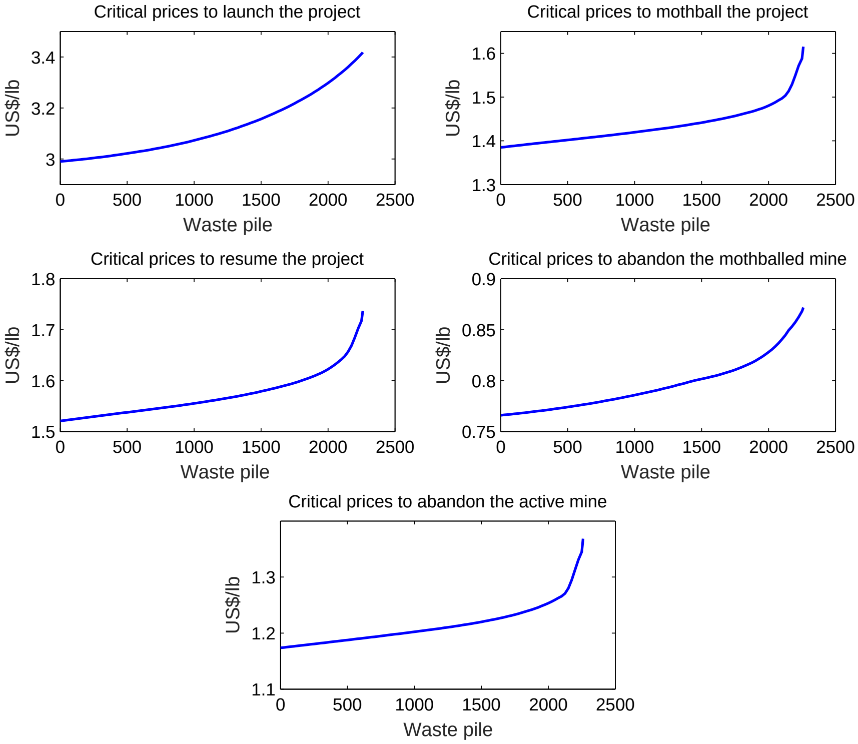


Figure 8: *Critical prices versus the waste pile under the environmental bonding regulation, given* $r_0 = 1173$ *million pounds.*

to Figure (8), an increase in the accumulated waste raises the critical prices in all stages of operation. More waste accumulation during construction imposes a higher initial bond to the firm in Stage 1 in order to reach Stage 2. This higher bond leads to a higher critical price for starting operations, making project commencement less likely at larger levels of waste. Refunding the deposited bond and the resulting saving equals to the additional costs to the third party motivate the firm to terminate the project from Stages 2 or 3 at higher prices if more waste is accumulated. Restoration of a larger quantity of waste yields a higher saving, so the firm is more likely to abandon the project as the landfill approaches its capacity.

Critical prices to mothball and reactivate operations are also higher for the mine with greater waste. As noted, the firm's compliance cost increases with more waste accumula-

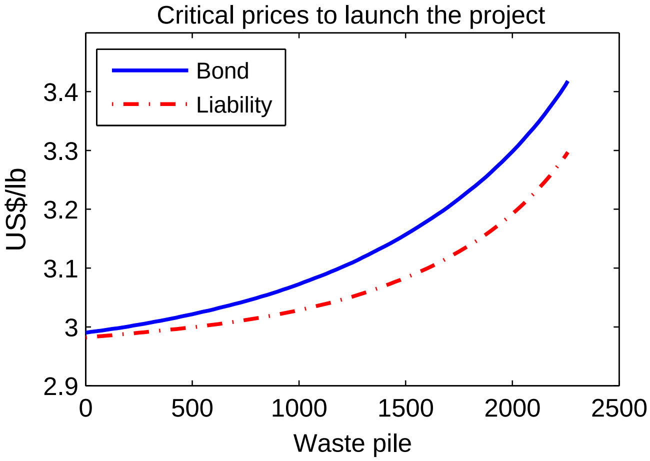


Figure 9: *A comparison of critical prices to launch the project versus the waste pile under the environmental bond and the strict liability rule, given* $r_0 = 1173$ *million pounds.*

tion, which directly reduce the operational profits. Thus, the project is more likely to be mothballed following a temporary decrease in prices, under the bonding policy. The idle firm facing more waste is less likely to reopen its mine, as the anticipated profits are smaller. Consequently, it is more difficult to cover the reopening costs until a sufficiently high price has been obtained.

7.3.2 Comparison with the strict liability rule

In this section, we examine the extent to which the environmental bond affects critical prices to launch the project and to abandon the mine, compared to the strict liability rule. The decision to move from Stage 1 to Stage 2 depends on the benefits of delaying the investment costs versus the costs of delay in gaining profits from production. As noted, the bond requires an upfront payment as well as subsequent payments during operations. It follows that the increased compliance cost and thus the reduced profitability of the project under the bond compared to the liability rule increase critical prices to begin the project under the former. This is indicated in Figure (9) which shows the gap becomes more significant for a higher

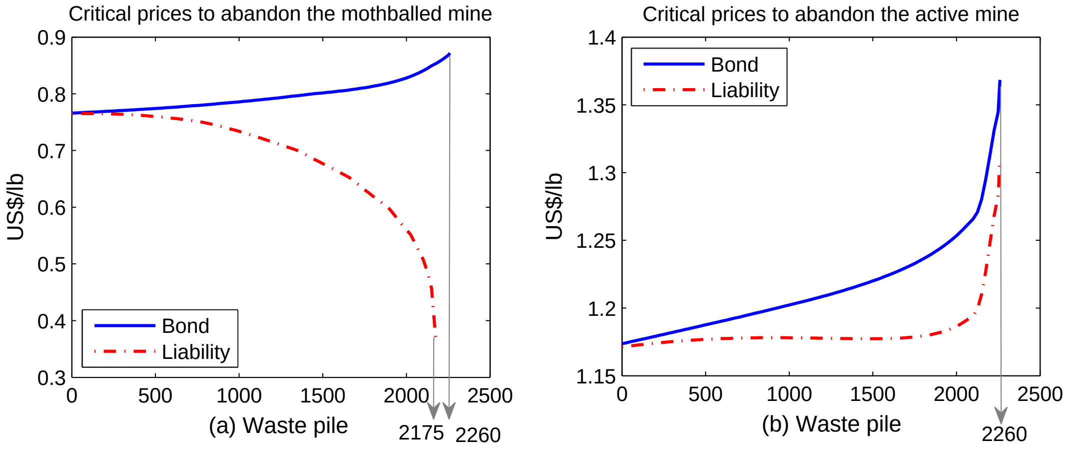


Figure 10: *A comparison of prices critical to abandoning the mine across levels of waste, under the environmental bond and the strict liability rule, given* $r_0 = 1173$ *million pounds.*

stock of waste.

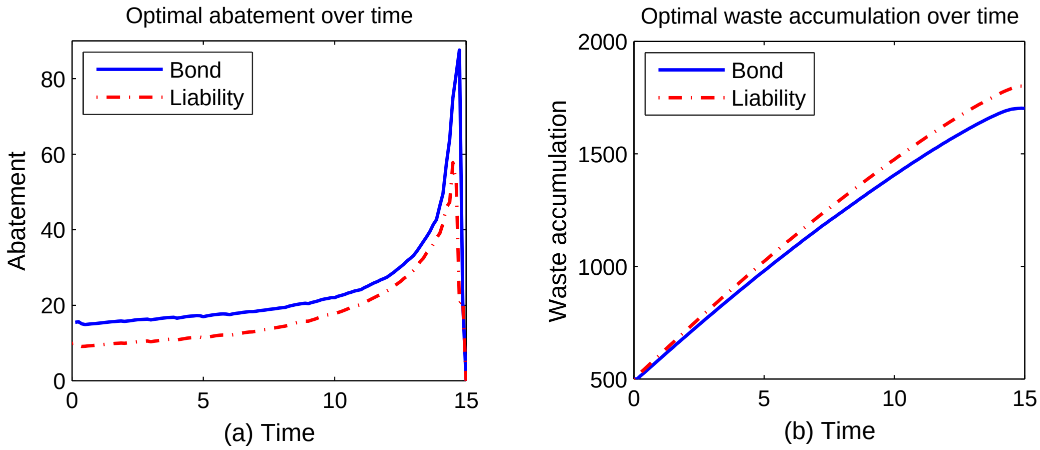
Decisions to abandon the mine are also compared and some interesting results have emerged: First, as shown in Figure (10), the critical prices for terminating the project at either the mothballed stage or the active stage are higher under the bond than the liability rule, for all levels of waste. This situation occurs due to the possibility of the government refunding the deposited bond which would yield sunk benefits to the firm upon termination. In contrast, the liability rule entails the sunk costs of restoration to the firm. Consequently, the firm's motivation to abandon the mine is stronger under the bond than the liability, implying higher critical prices under the former. Since such benefits or costs of restoration increase with waste accumulation, as more waste accumulates, this motivation becomes even stronger under the bond and weaker under the liability. This stronger versus weaker motivation widens the gap between prices as waste accumulates.

Second, the active mine will be abandoned while the operation is generating some profits under the bond and incurring some losses under the liability. Intuitively, the firm operating under the bond will abandon the active mine if the operational profit falls slightly below the restoration benefit, whereas termination under the liability rule occurs when losses during operations dominate the restoration costs. Third, looking at panel (a) of Figure (10) reveals that, with liability requirements, no critical prices are shown for abandoning the mothballed project for waste accumulation beyond 2175 million pounds. If the project is mothballed at large levels of waste (i.e., beyond 2175 million pounds), the idle firm facing low prices remains inactive indefinitely and never carries out the reclamation work. At levels of waste below 2175 million pounds, more waste accumulation increases the incentive to delay the irreversible costs of restoration, resulting in lower optimal prices that would trigger abandoning the mine. The intention for terminating the mothballed mine are even lower for a costlier restoration plan, as discussed in Appendix (B.2). Sitting idle to escape clean-up projects increases the risk of cost externalization under the liability rule, and hence is not desirable from society's point of view. These phenomena are not observed under the bond, making the project abandonment more likely with bonding requirements.

According to panel (b) of Figure (10), the pattern of prices critical to abandoning the active project under the liability increases and decreases slightly, for a range of waste accumulation. This fluctuation is not intuitive, but depends on the relative marginal change in the value of the mine and the marginal restoration costs incurred by the firm. As waste accumulates by one unit, if the reduction in the value of the operation, $\frac{\partial V^l}{\partial w}$, exceeds the increase in the future restoration cost of that additional unit of waste, $\frac{\partial C^f}{\partial w}$, the prices critical to abandoning the mine will rise. In contrast, the decreasing pattern of critical prices to terminate the active mine implies that the marginal change in the value is smaller than the marginal change in the restoration costs as more waste accumulates.

7.4 Dynamic paths for abatement and waste accumulation

In the previous sections we described optimal policies dependent on the particular values of state variables that are price, resource stock, waste pile, and project stages. It is useful to



(a) Time

(b) Time

Figure 11: *Expected dynamic paths for optimal abatement and optimal waste accumulation, under the bonding policy and the strict liability rule.*

examine the expected paths of abatement and the waste pile over time. This can be done via Monte Carlo simulation of the copper price. We first simulated the price of copper using 10,000 MC simulations with a starting price that reflects different critical prices to launch the project, for each policy. Therefore, the initial time (i.e., t=0) is defined to be when the prices are high enough to commence the project, while the operating life of the project, T, is 15 years. At the termination point (i.e., T=15), the project is abandoned and the firm will carry out the restoration of any remaining waste. It is assumed that the firm starts the operations with an initial level of waste of $w_0 = 500$ million pounds. After the project is launched, using the critical prices and the optimal controls, we kept track of the stage of operation and the optimal abatement rates along each simulated price path. Finally, the expected abatement path and the expected waste accumulation are computed by taking the average of 10,000 optimal solutions. As shown in Figure (11), the greater incentives for waste abatement under the bond results in a smaller expected waste pile and thus a lower expected clean-up cost at termination.

8 Conclusions

This paper is motivated by the observation that many resource extraction projects leave behind a toxic legacy and taxpayers are left to fund the clean-up. Firms may walk away from their clean-up obligations or may simply let projects sit idle, even when there is no intent to restart operations. An environmental bond is one mechanism to ensure that adequate funds are set aside by private firms to undertake site clean-up. In addition, an environmental bond can be structured to encourage firms to reduce waste production or clean it up as it is produced.

This study formulates a stochastic optimal control problem to examine the incentives for waste creation and clean-up with and without an environmental bond. The firm is obliged to clean up any waste left at the termination of a project, but under the bond the firm must deposit funds up-front equal to estimated clean-up costs of a third party. These funds are reimbursed to the firm as waste reduction or abatement occurs. Our optimal control model is analyzed for a representative copper mine in Canada.

Under both the strict liability and environmental bonding policies, there is no requirement for waste clean-up until the termination of the project. However, two factors, other than the bond, may give an incentive for waste abatement during the life of the project. First, there is an upper limit on the permitted size of the waste pile and when that limit is reached firms must abate their waste in order to maintain production. Second, abatement costs and eventual clean-up costs are convex with respect to waste. Depending on the specifics of the cost functions, firms may find it beneficial to do some waste abatement during project operations rather than leave it all to the end. The environmental bond provides a third incentive to abate waste during the life of the project and also provides a greater incentive to undertake final restoration of the accumulated waste.

In our numerical example we find that the bond requirement has a significant effect on the operations of a prototype copper mine. The required up-front bond payment, equal to third-party restoration costs, increases the threshold price needed for the project to go ahead, making the project commencement less likely. Since refunding the bond following a restoration yields a saving to the firm equals to the third-party costs, the firm is more likely to abandon the mine and undertake the required clean-up. In the absence of a bond (strict liability rule) the firm is more likely to leave the mine inactive, rather than abandoning and cleaning up the mine. The bond also causes the firm to abate more during the life of the mine, and the final accumulated wasted is reduced.

We do not explicitly model the decision to declare bankruptcy, which is left for future work. However, we argue that it is desirable to encourage firms to reduce waste creation so that there is less chance that the responsibility for clean-up falls to government as a result of firms refusing to fulfill their obligations due to bankruptcy or other reasons. An environmental bonding policy such as described in this paper is a useful tool to meet this objective.

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A Boundary Conditions

Boundary conditions at upper and lower bounds of p, r, w, and t are described in this section.

- Evaluation of Equation (17) as the commodity price $\boldsymbol{p} \to \boldsymbol{0}$ implies that

$$0 = \frac{\partial V}{\partial t} + \rho V + \max_{q,a} \left\{ \pi - q \, \frac{\partial V}{\partial r} + (\phi q - a) \, \frac{\partial V}{\partial w} \right\} \tag{22}$$

No special boundary condition is needed as there is no term involving p.

- As the $\boldsymbol{p \to p_{max}}$, we assume $\frac{\partial^2 V}{\partial p^2} \to 0$, which from Equation (17) implies:

$$0 = \frac{\partial V}{\partial t} + \kappa(\hat{\mu} - \ln p)p \frac{\partial V}{\partial p} + \rho V + \max_{q,a} \left\{ \pi - q \frac{\partial V}{\partial r} + (\phi q - a) \frac{\partial V}{\partial w} \right\} \tag{23}$$

  The assumption that V is linear in p is common in the literature (in 't Hout 2017).

- As $\boldsymbol{r \to 0}$, the admissible set of q collapses to zero as shown in Equation (5). No boundary condition is needed.

- As $\boldsymbol{r \to r_{max}}$, no special boundary conditions is required as Equation (17) has outgoing characteristics in the r direction.

- For the boundary $\boldsymbol{w = 0}$, no boundary condition is required as Equation (17) has outgoing characteristics in the w direction.

- At the boundary $\boldsymbol{w = \bar{w}}$, Equation (6) implies that Equation (17) has outgoing or zero characteristics in the w direction. Hence no special boundary condition is needed.

- At $\boldsymbol{(t = T)}$, the value of the mine is equal to zero, $V(p, r, w, \delta_4, T) = 0$.

B Sensitivities on the parameters of abatement and restoration costs

This section discusses the sensitivities of a firm's optimal decisions on the scaling parameters of the abatement and clean-up cost functions, α and β in Table (2). Consider the following two cases:

- Case 1: The marginal abatement becomes five times cheaper than its original value, so that $\alpha_1 = \alpha/5$. To increase project profitability, a firm operating under both policies may innovate and develop more advanced abatement technology so as to reduce its compliance costs. Therefore, the firm can achieve the same abatement rate as the base case at a lower cost, assuming zero cost for such an innovation.

- Case 2: The marginal restoration becomes five times costlier than its original value, so that $\beta_1 = 5\beta$. To enhance the environmental quality, governments may become more stringent over time in terms of restoration plans, making the clean-up work more expensive.

The changes in the scaling parameters are so that the ratios remain the same i.e., $\alpha_1/\beta = \alpha/\beta_1 = 20$. Note that reducing an additional unit of waste by abatement is still costlier than doing so by restoration in both cases. In what follows, we will see that although the relative marginal costs are reduced by the same fraction in both cases, the project value and critical prices are significantly different in each case.

B.1 Project value

Figure (12) illustrates the project value for Cases 1 and 2 under the bonding policy (the left-hand panels) and the strict liability rule (the right-hand panels). We start the intuition for the bonding policy. Case 1 has a higher project value than the base case for two reasons: first, with cheaper abatement, the firm exercises more abatement in order to reduce its future clean-up costs, resulting in lower expected bond payment and compliance costs relative to the base case. Second, with higher abatement, the life of the landfill, and thus of the operation, become longer. Therefore, the project does not simply abandon too early due to the exhaustion of the landfill capacity and the firm can earn more profits, resulting in the higher project value in Case 1. In contrast, with more expensive restoration plan, the firm's

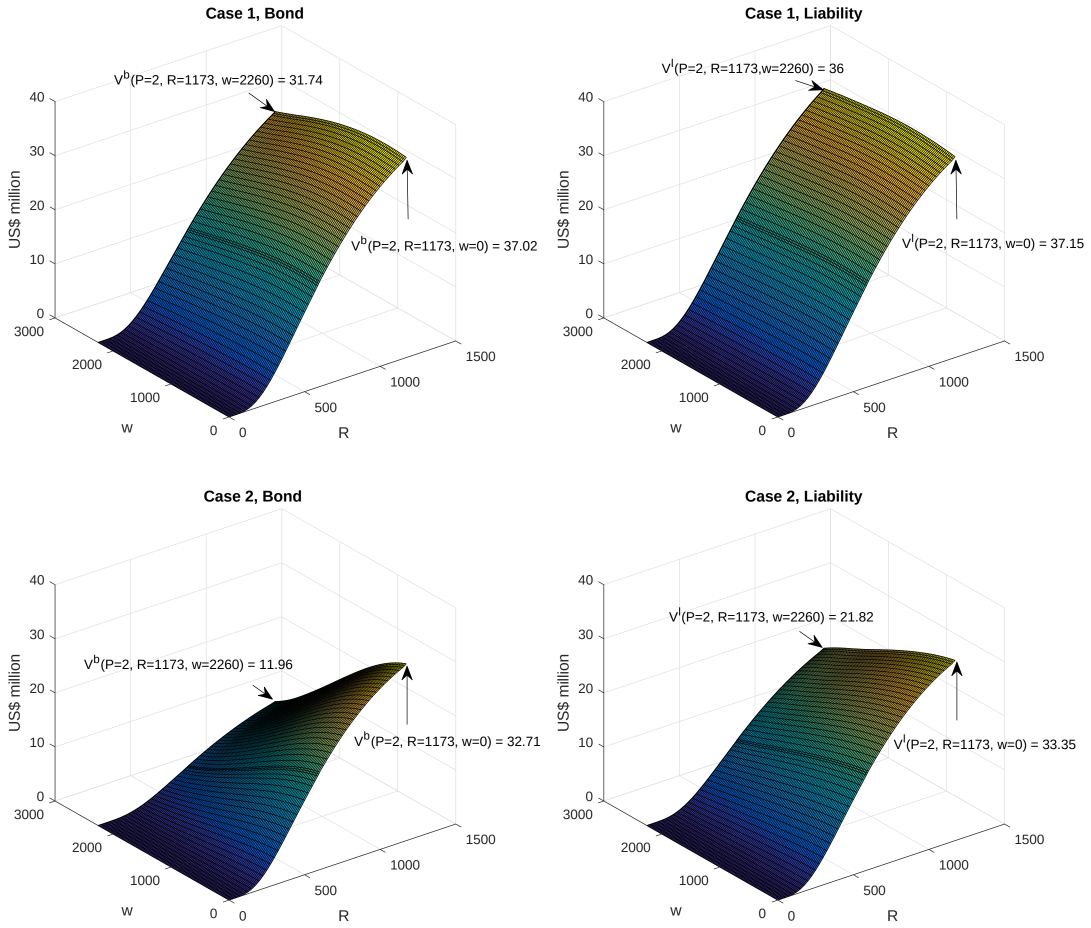

Figure 12: *Project values prior to construction for Cases 1 and 2, under the bonding policy (the left-hand panels) and the strcilt liability rule (the right-hand panels).* $p = \$2$*/pound,* r *and* w *are in million pounds.*

expected bond payment is relatively higher. This higher bond motivates the firm to abate more during operations to reduce its annual bond payment as well as its eventual clean-up costs. However, the firm's cost of compliance is still higher than the base case due to the higher abatement costs and the higher annual bond, resulting in a lower project value. The same logic exists for the liability rule but the project value is affected only by abatement decisions as there is no *ex ante* financial responsibility. The firms' abatement rate for Case 2 under both policies at p_0 =US\$2/pound and for the full reserve is shown in Figure (13).

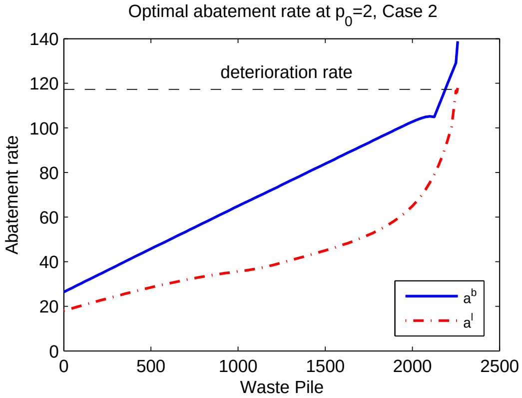

Figure 13: *Optimal abatement rates at time zero for Case 2 under an environmental bond versus the strict liability rule.* $r_0 = 1173$ *million pounds and* $p_0 = US\$2/pound$*.*

B.2 Critical prices

Figure (14) compares the critical abandoning prices of the mothballed mine for Cases 1 and 2 with those for the base case under both policies. In Case 1 for both policies, the project will terminate at lower prices, allowing the firm to operate longer. This result is because the firm can reduce its future clean-up costs by abating more today compared to the base case. In Case 2, the higher critical prices shown in the left-hand panel imply that the project will be closed earlier due to a higher restoration benefit after refunding the bond. However, the right-hand panel shows that with the liability requirements, the more expensive clean-up cost increases the firm's motivation to remain mothball forever when the level of waste is as low as 1000 million pounds. Therefore, the project never terminates beyond this level.

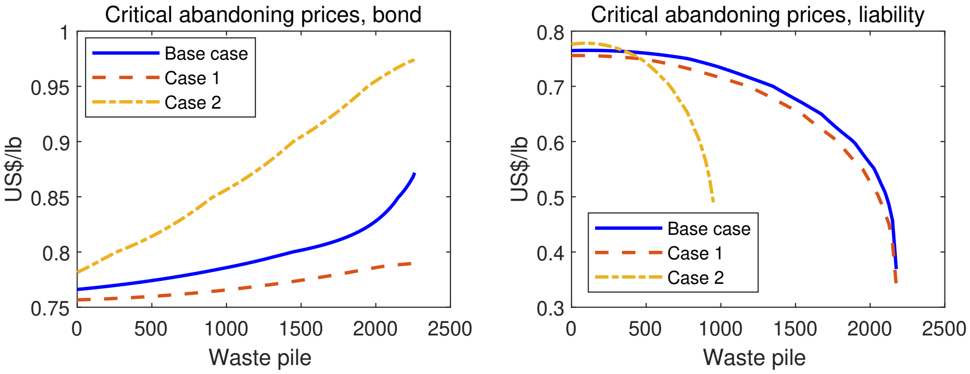

Figure 14: *Critical abandoning prices for three cases, under the bonding policy (the left-hand panel) and the strict liability rule (the right-hand panel), when* r *is at initial level.*