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Assessment of government supervision on the loss of sea sand resource in China

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ABSTRACT

Illegal mining activities on offshore sands have recently increased dramatically in China owing to the strong demand of the construction industry and restriction of river sand mining. By studying the loss mechanism of marine sand resources, this study proposes a simplified linear programming model to quantitatively analyse the control effects related to resource loss and law enforcement costs. To accurately simulate the effectiveness of law enforcement activity, a set of variables is designed in the model to describe the severity of illegal mining and enforcement skills of the officers. Subsequently, based on different settings of law enforcement capability, the model can not only make reasonable projections for sand losses but also provide a minimum cost solution for marine sand control for government agencies. Finally, various regulatory measurements and suggestions are discussed to improve the effectiveness of the government's regularisation and cost optimisation for law enforcement.

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1. Introduction

Since the mid-1990s, owing to the rapid development of China's infrastructure industry, environmental disasters caused by excessive exploitation of river sand, such as destruction of cultivated land, water sources, and vegetation, have become more severe (de Leeuw et al., 2010). The state restricts excavation of river channels and land and strictly controls exploitation of lake sand (*People's Daily*, 2000). With construction of various large-scale projects and rapid development of the real estate market, continuous reduction of freshwater sand resources and pressure of environmental protection greatly stimulates the market's demand for sea sand. At its peak, the Pearl River Estuary had more than 100 sand mining vessels and more than 1,000 sand carriers conducting sea sand mining and transportation, with a daily sand mining volume of more than 100,000 tons (Li, 2018).

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However, because of the strict examination and approval of mining permission by the government, only a few sand farms have obtained mining licenses through a process of legal application or bidding. Since 2013, because of the decentralisation of the approval power by the State Oceanic Administration, the acceptance of the administrative examination and approval for sea sand mining has been completely stopped. Permission to use sea areas for sand mining has been transferred in a market-oriented manner. Imbalance between supply and demand has caused China's sea sand prices to soar for years. For example, sand prices in the Pearl River Estuary rose from 5 to six $yuan/m^3$ in 2001 to about 20 $yuan/m^3$ in 2010. It reached a peak of nearly 50 $yuan/m^3$ during the construction of the Hong Kong–Zhuhai–Macao bridge from 2012 to 2016 (Li et al., 2018). The market price of sea sand after desalination increased rapidly from 450 $yuan/m^3$ in 2013 to approximately 750 $yuan/m^3$ in 2018 and even to 880 $yuan/m^3$ in 2019.

Profiteering has led to a wide range of illegal sand mining processes. Moreover, it has formed a complete national interest chain of shipbuilding, illegal mining, sand washing, transportation, and sand sale. For example, the investment cost for a sand suction ship with a load capacity of nearly 1000 tons is approximately 10 million yuan. The ship can absorb approximately 350–400 m^3 of sea sand hourly. If sea sand price is approximately 50 $yuan/m^3$, monthly profit may be more than 10 million yuan, which is almost equal to the cost of the ship. Owing to the low cost, low threshold, low risk, and high return of illegal exploitation of sea sand, enterprises and individuals flock to it. Even gangs are involved in these processes.

Sea sand mining also changes the natural properties of sea areas (Saviour, 2012; Thornton et al., 2006). Sea sand mining has severe impact on the water environment, hydrodynamic conditions, seabed topography, seabed material composition, and marine ecological environment (Hitchcock & Bell, 2004). For cost reduction, criminals usually operate ships with simple mining equipment in waters near the coast or sand dams banned for any mining activities. For a long time, serious illegal sand mining activities have been found in many Chinese provinces, such as Hainan, Fujian, Guangdong, and Zhejiang. This has become challenging for marine resources and environmental management. This has also incited anger among the locals. To avoid aggravating situations, law enforcement departments have organised a series of actions for reducing illegal mining activities. However, owing to restrictions of multiple government departments and administrative divisions and the unusual astuteness of criminals, completely stopping illegal sand mining is difficult for the government.

This study focuses on the current situation of illegal sand mining and difficulty of its supervision in China's offshore areas. Our study attempts to find a solution for controlling the loss of sand resources with minimum law enforcement costs. A simplified linear programming model was proposed in this study by quantitatively analysing the loss mechanism of marine sand. This model simulates the effectiveness of law enforcement and severity of illegal mining. From our model, an optimised supervision scheme for law enforcement costs was provided with a reasonable projection of sand loss. It can be used as a quantitative basis and scientific reference for improving government policies.

2. Literature review

Research in this area mainly focussed on case studies and discussed the exploitation of sea sand or river sand around the world and its impact on the marine environment. Cao (2007) systematically introduced the development and management concepts of sea sand resources in the Netherlands. Moreover, he explained the implementation of the sustainable development of resources and the environment regarding its approval, exploration, exploitation, and monitoring procedures. Khan and Sugie (2015) analysed the law and rules for sediment extraction in the river sand mining process in Tangail, Bangladesh. Additionally, they investigated its commercial use and social impact in the process of rural industrialisation and urbanisation. The illegal exploitation and transportation of river sand is controlled by local influential residents through "rent-seeking". Such violence not only corroded riverbanks and destroyed the ecological environment but also caused social problems, such as displacement of riverbank residents. However, the author did not provide suggestions or countermeasures to solve and alleviate these challenges. Pitchaiah (2017) reviewed the impacts of sand mining on river, dune, marine, hydrological, biological, and other dependent environments via collected worldwide case studies.

Regarding the rationale for using quantitative analysis, a number of approaches for decision-making under risk and uncertainty exist, such as single-point estimates, scenario analysis, break-even analysis, decision trees, and Monte Carlo simulations (Park, 2007). Yoo et al. (2018) used a conceptual ecological model (CEM) with an energy flow diagram (EFD) to predict the effects of offshore sand mining on the Chilean island ecosystem. The results showed that sand mining activities caused long-term damage to benthic ecosystems. Moreover, it threatened seabird communities by reducing fish populations throughout the food chain. Hence, the different ranges of uncertainty provided by a Monte Carlo simulation may mean that sand mining may have undesirable consequences.

Research in China has mainly focussed on the present situation and existing problems of sea sand mining. Moreover, it also qualitatively analysed the present situation and influence of sea sand mining in various sea areas. A range of government supervision countermeasures and punishment suggestions from the resource development perspective have been proposed. From the geology perspective, Bai et al. (2010) first analysed sea sand resource exploration and its distribution characteristics, exploitation, and sustainable development. They then proposed that the nearshore shallow sea sand would soon be the main goal of the mining industry, as sand extraction from the coastal zone has already caused many negative environmental effects and should therefore be completely stopped. Wang and Liang (2019) conducted a comprehensive study of hydrology, geology, chemistry, biology, and ecological remote sensing. Finally, they provided an evaluation method for the environmental impact assessment of marine sand exploration.

Conversely, some researchers have proposed specific implementation measures for a certain region or a new policy on sea sand mining. Su and Wang (2010) discussed the government's management countermeasures by analysing existing problems in China's sea sand mining. Peng et al. (2014) proposed various countermeasures and suggestions for marine sand mining through a case study in Fujian Province, China.

Zeng and Huang (2017) researched issues related to marketisation of the right to use the sea areas for sea sand mining and proposed reasonable suggestions to strengthen management of sea areas for sand mining via bidding, listing, and auctioning. Shi (2020) proposed several suggestions for sea sand mining management related to the bidding, auctioning, and listing of the "two rights" of sea sand. After investigating the Beibu Gulf, Gu (2019) suggested that the development and utilisation of sea sand needed to be completed under the coordination of land, ocean, environmental protection, construction, and quality supervision. Lin et al. (2020) believed it necessary to reasonably plan the legal mining of sea sand and increase the punishment for illegal mining. All departments from the government should collaborate to improve the long-term mechanism of sand control and use modern information technology to assist with the supervision of sand mining. Although these studies are closely related to the reality of China, they all belong to empirical studies regarding research methods lacking quantitative analysis. Therefore, the conclusions and countermeasures proposed in this study are quite similar. Finally, it needs to be tested in practice.

Compared to previous research, this study adopts the quantitative analysis method of mathematical models and numerical simulations in theoretical economics. Moreover, it analyses the supervision scheme of law enforcement to minimise costs when the government successfully curbs illegal offshore sand mining.

3. Mathematical model analysis

The loss of marine sand resources directly depends on the duration of illegal mining. In our illegal mining model, we consider the process to have two stages. The first stage begins from time $t = 0$, when illegal mining is started. The second stage begins from time $t = t_1$, when illegal mining activity is discovered. During the period of $0 < t < t_1$, marine sand is stolen without any government intervention. After time $t > t_1$, local officers will take a ship to conduct on-site supervision to curb illegal mining. The number of law enforcement vessels and personnel is crucial in the government decision-making process as it is directly related to management costs. The higher the number, the stronger the law enforcement capability and smaller the loss of marine sand resources. However, this will result in a higher law enforcement cost. If the number is too small, the law enforcement capacity will be insufficient to stop illegal mining.

Therefore, the government should focus on balancing mine resource losses and control costs. To stop illegal mining, a reasonable mathematical model should be designed to determine the optimal number of law enforcement officers and vessels with a minimum total cost.

3.1. Loss of marine sand resources

The earlier an illegal mining incident is discovered, the sooner the mine's loss will be controlled. Three time points are related to this duration: the first is the starting time of the illegal mining incident when $t = 0$. The second is the time when local officers are alerted and start law enforcement when $t = t_1$. Finally, illegal mining is stopped

when $t = t_2$. The duration of illegal mining depends on the ability and effectiveness of government law enforcement supervision related to the number of law enforcement officers and vessels in this model.

If we use $V(t)$ to represent the stolen sand volume at time t, the total stolen sand volume can be denoted as $V(t_2)$. $\frac{dV}{dt}$ represents the speed of the sand stolen. $\frac{dV}{dt}$ is expected to increase with time during $0 \leq t \leq t_1$ owing to the motivation to achieve great benefits and lack of supervision. Hence, we can assume that $\frac{dV}{dt} = \beta t$ during $0 \leq t \leq t_1$. When time $t = t_1$, $\frac{dV}{dt} = \beta t = b$.

When $t_1 \leq t \leq t_2$, the government is taking action to curb illegal mining. Generally speaking, strict and powerful supervision is effective, which means that $\frac{dV}{dt}$ decreases with time. If x officers have been sent for enforcement action, new sand loss rate will be changed to $\frac{dV}{dt} = b + \left(\beta - \frac{\lambda}{b+1}x\right)(t - t_1)$. $\frac{\lambda}{b+1}$ represents the average supervision effect of each officer, and λ is the daily supervision effect when $b = 0$. This assumption means that the supervision effect is negatively related to time t_1 when it begins. A larger t_1 indicates that the law enforcement process starts later. This will cause more sand loss and result in higher supervision costs to stop illegal mining. Here, we assume that illegal mining can be stopped completely at t_2, such that:

$$\frac{dV}{dt} = b + \left(\beta - \frac{\lambda}{b+1}x\right)(t - t_1) = 0 \tag{1}$$

From Equation (1), it can be deduced that if $\beta < \frac{\lambda}{b+1}x$, $\left(\beta - \frac{\lambda}{b+1}x\right)(t - t_1) < 0$ during $t_1 \leq t \leq t_2$.

As shown in Figure 1, the total sand loss is the area of ΔABC, that is,

$$V(t_2) = \int_0^{t_2} \frac{dV}{dt} dt = \int_0^{t_1} \beta t \ dt + \int_0^{t_2} \left(b + \left(\beta - \frac{\lambda}{b+1}x\right)(t - t_1)\right) dt = \frac{1}{2} b t_2 \tag{2}$$

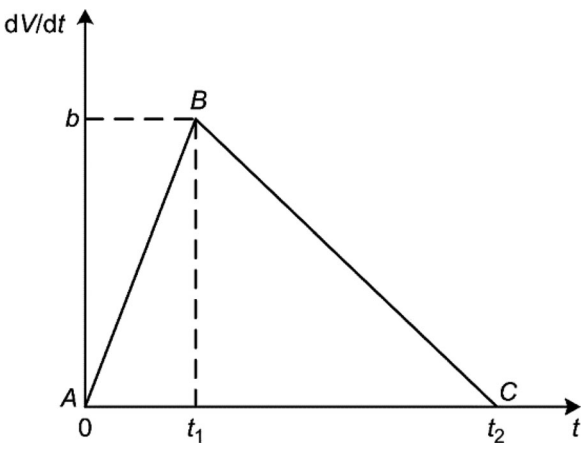

Figure 1. The losing rate of sand with time, where the area of ΔABC represents the total sand loss.
Source: Authors.

It can be derived from Equation (1) that

$$t_2 = t_1 - \frac{b(b+1)}{\beta(b+1) - \lambda x} \tag{3}$$

Substituting Equation (3) and $b = \beta t_1$ into Equation (2) yields

$$V(t_2) = \frac{\beta t_1^2 \lambda x}{2(\lambda x - \beta(\beta t_1 + 1))} \tag{4}$$

Because the value of the stolen sand is proportional to its volume, the total value loss of the stolen sand, C_1, can be calculated using Equation (5). c_1 is the market price of sea sand per unit volume.

$$C_1 = c_1 V(t_2) = c_1 \frac{\beta t_1^2 \lambda x}{2(\lambda x - \beta(\beta t_1 + 1))} \tag{5}$$

3.2. Supervision costs for controlling sea sand loss

The government will attempt to curb illegal mining once a mining activity has been discovered. The expenditure involved in such an action includes two factors: 1) labour costs, which depend on the number of law enforcement officers and the supervision time, and 2) fixed expenditure including equipment costs, such as law enforcement vessels.

The labour costs for each officer per unit time are assumed to be c_2. Thus, the total labour cost per person during the entire period of supervision is $c_2(t_2 - t_1)$. The cost of the law enforcement vessels and personal equipment is proportional to the number of officers and is denoted as $c_3 x$. c_3 is the cost coefficient of each officer. Thereafter, the total cost of government supervision, C_c, can be represented as follows:

$$C_c = c_2(t_2 - t_1)x + c_3 x \tag{6}$$

3.3. Optimisation of the total cost

The total cost owing to illegal mining is the sum of the value of the stolen sand and the government's supervision cost is as follows:

$$C_t = C_1 + C_c \tag{7}$$

Substituting Equations (3), (5), (6), and $b = \beta t_1$ into Equation (7) yields the following:

$$C_t = c_1 \frac{\beta t_1^2 \lambda x}{2(\lambda x - \beta(\beta t_1 + 1))} + c_2 \frac{\beta t_1(\beta t_1 + 1)}{\lambda x - \beta(\beta t_1 + 1)} x + c_3 x \tag{8}$$

The minimum cost due to illegal mining can be achieved when $\frac{dC_t}{dx} = 0$. By substituting it in Equation (8), the optimum number of law enforcement officers can be obtained as follows:

$$x = \frac{\beta(\beta t_1 + 1)}{\lambda} + \frac{\beta}{\lambda}\sqrt{\frac{t_1((2c_2\beta + \lambda c_1)t_1 + 2c_2)(\beta t_1 + 1)}{2c_3}} \tag{9}$$

Subsequently, by substituting Equation (9) with Equation (8), the minimum cost due to illegal mining, C_t, can be estimated.

As shown in Equation (9), the number of law enforcement officers, x, is composed of two parts. The first part, $\frac{\beta(\beta t_1+1)}{\lambda}$, represents the minimum number of officers needed to stop illegal mining. The values of β and λ are approximated according to the severity of illegal mining and officers' enforcement skill.

Here, we can assume that β is a linearly increasing function of c_1, such that $\beta = \alpha c_1 (\alpha > 0)$, and α is a constant. This hypothesis implies that with an increase in the price of sea sand, the practice of illegal mining will become more vigorous, and the acceleration of sea sand loss will increase. Hence, the government can estimate the values of α a nd λ. λ depends on the erosion of sea sand or the presence of law enforcement personnel. Substituting $\beta = \alpha c_1$ in Equation (9), we obtain the following:

$$x = \frac{\alpha c_1(\alpha c_1 + 1)}{\lambda} + \frac{\alpha c_1}{\lambda}\sqrt{\frac{t_1[t_1 c_1(2\alpha c_2 + \lambda)](\alpha c_1 + 1)}{2c_3}} \tag{10}$$

The second part is $\frac{\beta}{\lambda}\sqrt{\frac{t_1((2c_2\beta+\lambda c_1)t_1+2c_2)(\beta t_1+1)}{2c_3}}$, which depends on multiple parameters. Generally, x increases with an increase in β and c_1, whereas it decreases with an increase in $\frac{\lambda}{\beta t_1+1}$ and c_3. Additionally, x increases with an increase in c_2. The increase in c_2 means that the government's supervision will encounter a more challenging task, which requires more officers to be involved. Moreover, a larger b value indicates a higher sand loss rate before supervision begins. This also requires more officers to curb illegal mining.

In Figure 1, the slope of line BC is $\left(\beta - \frac{\lambda}{b+1}x\right)$. If it intersects with the horizontal axis, illegal mining can be completely stopped at a certain time, and $\left(\beta - \frac{\lambda}{b+1}x\right) < 0$. This is consistent with the basic assumptions of the mathematical model.

4. Sensitivity analysis

From the above analysis, the minimum total cost C_t and the number of corresponding officers, x, depend on variables c_1, c_2, c_3, β, λ, and t_1. Let us assume that c_1=50 $yuan/m^3$, c_2=200 yuan/(person·day), c_3=500 yuan/person, $\beta = 3c_1 m^3/\text{day}^2$, $\lambda = 2000m^6/(\text{day}^3 \cdot \text{person})$, and t_1=10 days. By substituting them in Equation (9), the optimum number of enforcement officers, x, is 19. Subsequently, by substituting it into Equation (8), the minimum total cost, C_t, is 53 thousand yuan. Using the values of these parameters as a reference, the sensitivity of C_t and x with respect to each parameter is evaluated in the following subsection.

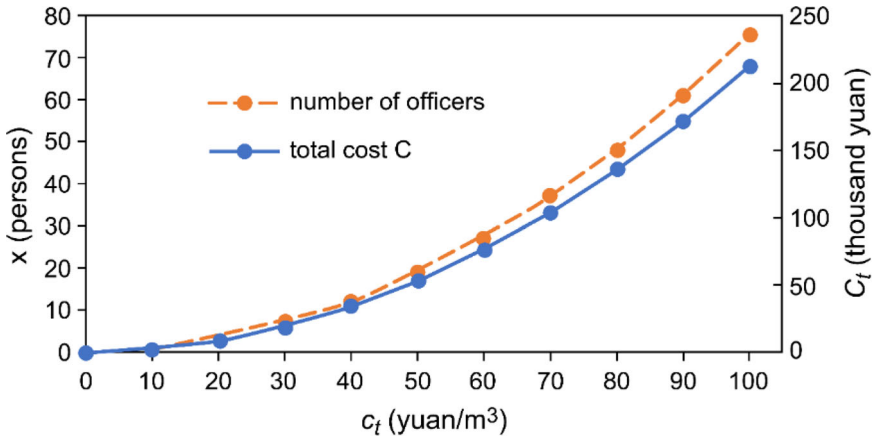

Figure 2. The minimum national loss and corresponding law enforcement officer number change with c_1.
Source: Authors.

4.1. Sensitivity analysis with respect to c_1

Figure 2 shows the variation of C_t and x with changes in c_1, where total cost increases with an increase in the market price of marine sand. Correspondingly, more officers are needed to curb illegal mining to reduce total costs. Generally, C_t and x decrease with respect to c_1. When c_1 is 0, it means that the sea sand is worthless, illegal mining is non-existent, and government supervision is unnecessary.

4.2. Sensitivity analysis with respect to c_2

Figure 3 shows the variation of C_t and x with changes in c_2, where total cost increases with the increase in labour cost for each law enforcement officer per unit time. Thus, more officers are required. When c_2 increased, both C_t and x increased.

4.3. Sensitivity analysis with respect to c_3

Figure 4 shows the variation in C_t and x with changes in c_3. With an increase in the equipment cost for each officer, the total cost increases and the number of enforcement officers decreases. In the case of low supervision costs, increasing the number of officers can effectively reduce total cost. However, when the law enforcement cost is high, increasing the number of officers may increase total cost.

4.4. Sensitivity analysis with respect to β

Figure 5 shows the variation in C_t and x with changes in β. An increasing number of officers are needed as illegal mining becomes more rampant. Consequently, the total cost is significantly higher. Particularly, the rate of increase in C_t and x increased with an increase in β. Based on the previous assumption that $\beta = \alpha c_1 m^3/d^2$, beta is essentially a function of α. This indicates the sensitivity of β to c_1 of sea sand price

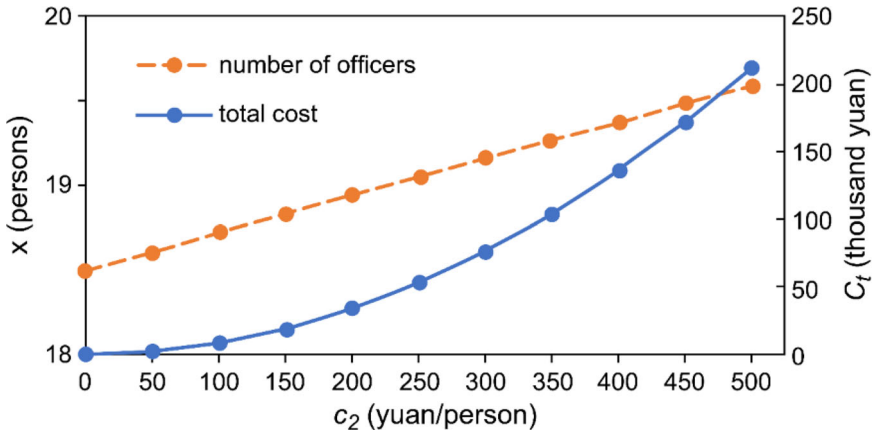

Figure 3. Minimising the state losses and the corresponding number of the law enforcement personnel with c_2 changes.
Source: Authors.

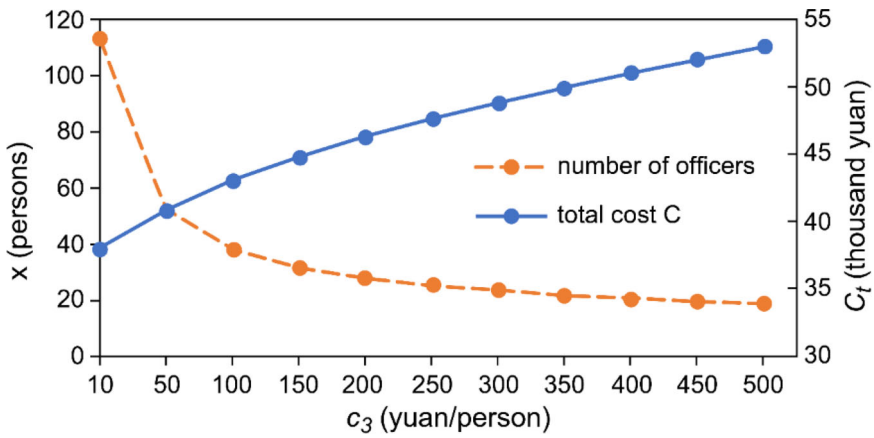

Figure 4. Minimising state losses and the corresponding number of law enforcement personnel changes with c_3.
Source: Authors.

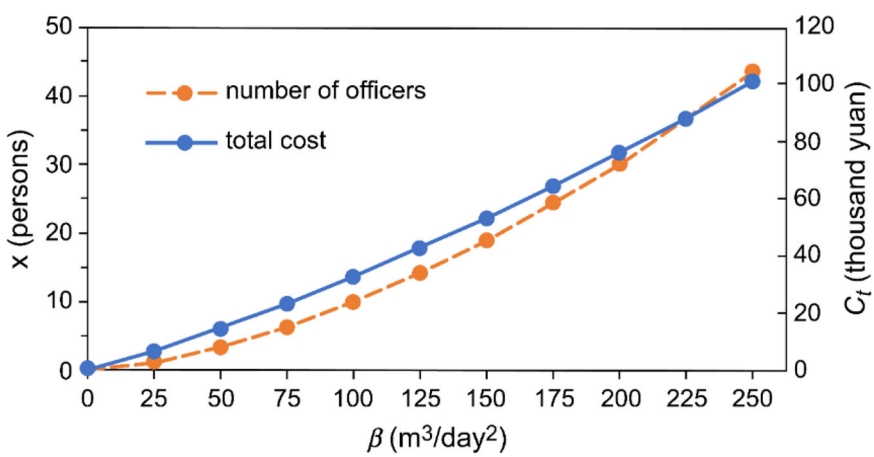

Figure 5. Variation of C_t and x with β, where β represents the severity of illegal mining.
Source: Authors.

for the acceleration of sea sand loss. This chart is essentially the same as that shown in Figure 2.

4.5. Sensitivity analysis with respect to λ

Figure 6 shows the variation of C_t and x with changes in λ, where the officer's supervision effect is critical in determining the total cost and the number of officers. When the supervision effect is low, $\lambda < 7000m^6/(\text{day}^3 \cdot \text{person})$, for instance, the promotion of the supervision effect can significantly reduce the total cost, and less manpower is needed. However, when the supervision effect is high, $\lambda > 13\ 000m^6/(\text{day}^3 \cdot \text{person})$ for instance, the supervision effect progressively decreases.

4.6. Sensitivity analysis with respect to t_1

Figure 7 shows the variation in C_t and x with changes in t_1. The time when law enforcement starts, t_1, is also considered an important parameter affecting the total cost and number of officers. With an increase in t_1, C_t and x increase exponentially. If illegal mining is not detected in time, it will become increasingly rampant. After a long period of unregulated activities, a great challenge will be encountered when the government starts curbing illegal mining. Therefore, timely detection of illegal mining and immediate suppression would be more effective in reducing the total cost and enforcement power. Thus, law enforcement agencies should execute daily inspections and other measures to strengthen prevention of illegal mining.

5. Discussion and proposal

Based on the mathematical model and the case study, the following countermeasures are proposed for law enforcement agencies to curb illegal marine sand mining.

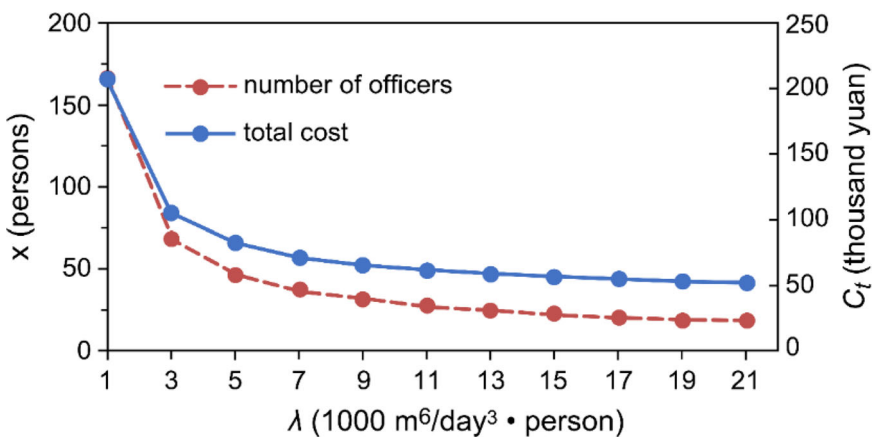

Figure 6. Variation of C_t and x with λ, where λ represents the enforcement skill of the officers.
Source: Authors.

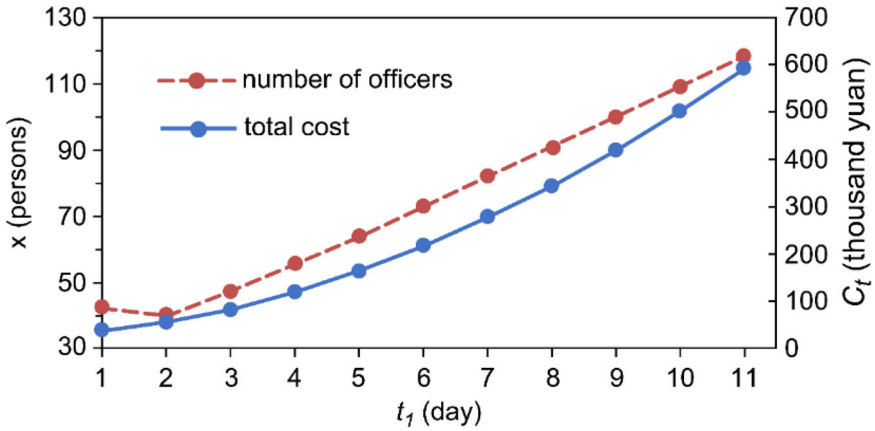

Figure 7. Variation of C_t and x with t_1, when the law enforcement starts its supervision to stop illegal mining.
Source: Authors.

5.1. Increase skill training for law enforcement officers

The values of β and λ should be estimated according to the actual loss rate of marine sand due to illegal mining and the current skills of law enforcement officers. As demonstrated in Equation (9) and Figure 5, more officers are required when the sand loss rate, β, increases. Consequently, as shown in Equation (9) and Figure 6, fewer officers are needed as the average supervision effect of each officer increases. Therefore, for areas where marine sand resources are rich or illegal mining is quite common and frequent, improving the professional skills of law enforcement officers through real training and continuing education is necessary.

5.2. Building a monitor system to detect early illegal mining activities

As indicated in Figure 7, an early debut of law enforcement can significantly reduce total cost and manpower. In law enforcement practice, the key to addressing illegal mining is the timely collection of evidence. Therefore, strengthening the detection capability for measures against illegal mining as soon as possible is necessary. To achieve this goal, some technologies, such as remote-sensing satellites, can be applied for real-time monitoring. Furthermore, a public information platform can be established to share monitoring data from multiple departments.

For example, Yantai, a city in Shandong Province, has established a special website for reporting marine violations. The municipal marine surveillance detachment and all the brigades have established open telephone lines for monitoring and reporting violations. Special personnel are assigned to be on duty 24 hours daily to promptly investigate and address any illegal sea use reported by the public and solve the problems immediately. The Zhejiang Marine and Fishery Law Enforcement Corps has established a digitalised emergency command system that can monitor sea dynamics in real time. In addition to being applied in fishery supervision, it can effectively control the inbound and outbound movements of all types of vessels and access the intelligence information on the violations of laws and regulations at sea. Additionally, it

can conduct precise strikes against all types of violations. The comprehensive on-site law enforcement mechanism has helped regular patrol and supervision over the waters limit accommodation of illegal sand mining and transport vessels. Measures such as law enforcement at different times and in different places have made supervision more effective.

5.3. Enhancing cooperation over multiple law enforcement departments

More law enforcement officers are required with an increase in the market price of the sea sand, c_1, and the labour cost of each officer, c_2. However, an increase in c_2 indicates a long trip and more work for law enforcement personnel. This means that opposing illegal mining is more difficult. In law enforcement practice, owing to restrictions across multiple administrative divisions, curbing mobile mining activities is extremely difficult. Therefore, strengthening the joint enforcement from various agencies in neighbouring regions is necessary.

On 20 March 2019, the Fujian Maritime Administration, together with the Department of Oceans and Fisheries, the Department of Public Security, and seven other departments, jointly deployed 17 law-enforcement vessels and two aircraft to conduct the operation "Hai'an Battle" along the coastal areas of Fujian. Owing to the joint operation, illegal sand mining in the coastal areas of Fujian was successfully stopped. On 22 November 2018 the Hainan Marine and Fishery inspection team transferred a case involving the illegal mining of sea sand across the province to the Hainan Coast Police Department.

5.4. Cost balancing and control

As indicated by Figure 4, fewer law enforcement officers are required with the increase in equipment cost for each officer, c_3. In fact, if more officers are deployed, illegal mining activities can be stopped much faster. However, this can be considered irrational from the cost control perspective, as it increases total cost. Therefore, one should determine the number of officers participating in enforcement based on minimum total cost. Therefore, the value loss of the stolen sand and the enforcement cost must be thoroughly considered.

5.5. Marketisation of marine sand mines

From an economic perspective, the issue of illegal mining of marine sand is essentially because of market failure. Marine sand mines are considered quasi-non-renewable resources owned by all Chinese citizens. For individuals, a conflict of interest is found between personal and group benefits. Limited marine sand resources cause market failure and foster illegal mining activities. This inevitably leads to the loss or even exhaustion of marine sand resources. Therefore, solving the problem of market failure of marine sand resources from both demand and supply perspectives is necessary. Regarding reasonable supply, we suggest promoting marketisation of marine sand mining with a reasonable auction of mining rights.

Since 2013, some areas decided to sell the right to use sea sand mining areas nationwide through auctions and listings. The time restriction for right to sea sand mining was established to be no more than 3 years. Simultaneously, deep-sea sand mining technologies are recommended nationwide.

5.6. Seeking alternatives for marine sand

Sand alternatives (e.g., manufactured sand using coal tailings as raw materials) should also be sought to reduce the demand for marine sand. It can be made from newly mined stones or tailings of some minerals. Mechanical sand is a good substitute for concrete-filling materials. To alleviate the contradiction between the supply and demand of sand, establishing a long-term mechanism to replace desalination of sea sand, river sand, and lake sand is necessary. Inert materials (public fillers) are also ideal for reclamation projects with high sand consumption. In Hong Kong's urban renewal program, replacement of demolished old buildings with high-rise buildings generates a large amount of construction waste. Approximately 14 million tons of inert materials are disposed of annually in Hong Kong. These are mostly used for reclamation in bay areas such as TseungKwan, TuenMun, and Victoria Harbour.

6. Conclusion

By studying the loss mechanism of marine sand and illegal mining activities in China, we present a simplified linear programming model to quantitatively analyse the control effects related to both resource loss and law enforcement costs. Given the different settings of the law enforcement capability, we demonstrate that a reasonable projection of sand losses can be estimated by our model with a minimum law enforcement cost.

Based on our analysis, we proposed a set of regulatory measurements and suggestions to improve the effectiveness of the government's regularisation and cost optimisation for law enforcement. For example, for areas with frequent illegal mining activities, improving the professional skills of law enforcement officers through real training and continuing education is necessary. Based on our analysis, we also find that the number of officers participating in the operation is closely related to the minimisation of the total cost. Therefore, joint enforcement from various agencies over neighbouring regions is recommended for regular operation. New technologies, such as remote-sensing satellites and video surveillance systems, are strongly recommended for improving real-time monitoring and detection of illegal mining. Regarding the supply chain, we propose promoting marketisation of mining rights by auctions. Furthermore, sand alternatives, such as manufactured sand from coal tailings, can be used to reduce demand for marine sand in the long term.

However, during the model establishment and parametric analysis in this study, we only considered the value of the stolen sand itself without considering the impact of illegal mining on coastal protection structures (such as embankments) and coastal ecosystems (such as fisheries and landscapes). These topics will be further investigated in future studies. Rahman et al. (2016) described a quantitative approach for assessing

the economic return from increasing tree cover in agricultural landscapes in two tropical locations. They found that a trade-off between short-term agricultural income and long-term economic gain from planting trees in a farmland exists. Applying this idea to the study of sea sand might reveal a trade-off between short-term economic losses and long-term gains from strictly regulating sea sand extraction .

In other areas related to environmental intervention, such as air pollution and carbon emissions, several studies have been conducted. Zeng et al. (2020) discussed a regression discontinuity approach to measure the short- and long-term policy effects of the air quality improvement plan during the G20 Hangzhou Summit. Zeng et al. (2021) proposed an extended synthetic control method with multiple units for evaluating the dynamic treatment effects on air quality improvement. Hu et al. (2020) performed an analysis of environmental regulation, innovation quality, and firms' competitiveness in carbon emission trading. We will follow these studies to further evaluate both short- and long-term effects of marine sand regulation policies and protection of coastal structures and ecosystems.

Disclosure statement

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