sustainability

MDPI

Article

Analysis of Artisanal and Small-Scale Gold Mining in Peru under Climate Impacts Using System Dynamics Modeling

Fatih Aranoglu [1,*], Tulay Flamand [2] and Sebnem Duzgun [1]

[1] Department of Mining Engineering, Colorado School of Mines, Golden, CO 80401, USA; duzgun@mines.edu
[2] Department of Economics and Business, Colorado School of Mines, Golden, CO 80401, USA; tflamand@mines.edu
* Correspondence: aranoglu@mines.edu; Tel.: +1-720-427-55-72

Abstract: In this paper, we propose a system dynamics (SD) model to examine the dynamics of an informal artisanal and small-scale gold mining (ASGM) supply chain that has interactions with the illegal gold supply chain in the Amazon rainforest region, Madre de Dios (MdD), Peru. In order to examine the system under climate impacts and validate the model, we run it under a flood scenario, which is one of the main climate impacts that causes disruption in mining activities. Our findings suggest that the dynamics of informal mines are highly affected by the illegal mercury supply, fuel supply, and availability of workers. In addition, the model under the flood scenario suggests that any external variable that could directly affect fuel and mercury supply would result in a disruption of informal and illegal gold production.

Keywords: system dynamics modeling; informal gold supply chains; artisanal and small-scale gold mining; artisanal and small-scale gold supply chain; supply chain disruptions

check for updates

Citation: Aranoglu, F.; Flamand, T.; Duzgun, S. Analysis of Artisanal and Small-Scale Gold Mining in Peru under Climate Impacts Using System Dynamics Modeling. *Sustainability* **2022**, *14*, 7390. https://doi.org/10.3390/su14127390

Academic Editor: Rajesh Kumar Jyothi

Received: 3 April 2022
Accepted: 14 June 2022
Published: 16 June 2022

1. Introduction

Supply chains of artisanal and small-scale mining (ASM) of metals and minerals are hard to follow and study. Among those, we specifically focus on the supply chain of artisanal and small-scale gold mining (ASGM) which has high interactions with other supply chains. ASGM contains formal and informal activities that interact in a socio-technical system and result in indirect and direct environmental damages. The gold supply chain is the network of several tiers through which gold flows, starting from the mine in the form of ore, and going through processing, transportation, refinery, and market. Finally, the chain ends with the final customer in the form of pure gold or an alloy.

Peru is the eighth largest gold producer in the world and the largest gold producer in Latin America [1]. In 2016, Peru's reported gold production was 4920 thousand ounces; however, the reported exports accounted for 5810 thousand ounces [2]. This reveals a gap, indicating that over 15% of the gold produced in Peru was not reported but was exported, which reflects the informal nature of the gold production in Peru. Informal mining is associated with artisanal and small-scale gold mining, and 80% of ASGM operations in Peru are classified as informal [2].

Illegal and informal mining are two terms that are usually used interchangeably; however, there are differences between them. Mainly, illegal mining represents the mining activities that are conducted outside of a specific mining concession [3]. Illegal mining in Peru can be seen in protected areas, such as national parks, riverbanks, indigenous reserves, or archaeological sites [2]. It is also considered illegal mining if the miners use illicit techniques or substances [4]. Such ASGM is responsible for deforestation and mercury release to the environment, specifically, to rivers and other related ecosystems that interact with these polluted rivers. On the other hand, informal mining refers to the mining activities that take place within legally designated mining regions, yet without governmental permission [5]. It does not take place in environmentally sensitive areas. Informal miners may work within legally designated mining areas using approved techniques and substances. Yet, they do not own the concessions and do not have official permission from the state to perform mining [4].

Understanding the ASGM sector is important because it provides employment for up to 300,000 people in Peru [6]. Also, it is associated with high rates of mercury use and deforestation [7]. Globally, it is estimated that 675 to 1000 tons of mercury are emitted into the atmosphere every year from ASGM [8]. The contribution of ASGM in mercury release to the environment in 2015 was 1225 tons in total [8]. In this paper, we use system dynamics modeling to model and examine the dynamics of an informal ASGM supply chain by considering its interactions with other chains. We analyze the ASGM supply chain in Peru by focusing on ASGM activities in Madre de Dios (MdD) since over 70% of the informal gold production in Peru comes from the southeastern region of MdD, in the Amazon rainforest bordering Bolivia and Brazil [2]. Our study aims to examine the system dynamics of this supply chain to reveal the interplay between gold production, supply of assets, and the external factors that affect the production rate in ASGM in MdD. Since MdD has an abundance of alluvial gold deposits, alluvial ASM methods are used widely, such as channeling, sluicing, dragging, caranchera, suction, and raft gringo [9]. In this paper, the caranchera alluvial mining method is examined. The caranchera method is used mainly on the river beaches, and it is affected directly by the river levels, therefore by precipitation. In this method, a diver with a suction hose (4″–6″) connected to a pump (35–60 HP), which is generally diesel-powered, sucks up the gold-bearing material (riverbed) that lies below the subterranean water level into a bin to store the materials [10]. Figure 1 shows the visualization and flow chart of the caranchera mining method. The mine site on the river can be seen on the left-hand side of Figure 1. On the right-hand side, a flowchart of the method is shown. It contains the main steps of the method that will be further analyzed in this paper. These steps start with the ore deposit (i.e., riverbed) from which the ore material is sucked, going through a pump that helps transport the ore to the processing unit (i.e., sluice) via hoses. The sluice has a carpet at its end to capture the concentrate that is taken after that to the chemical processing, namely amalgamation. The byproducts (i.e., tailings) are sent to the tailings' ponds, as shown in Figure 1.

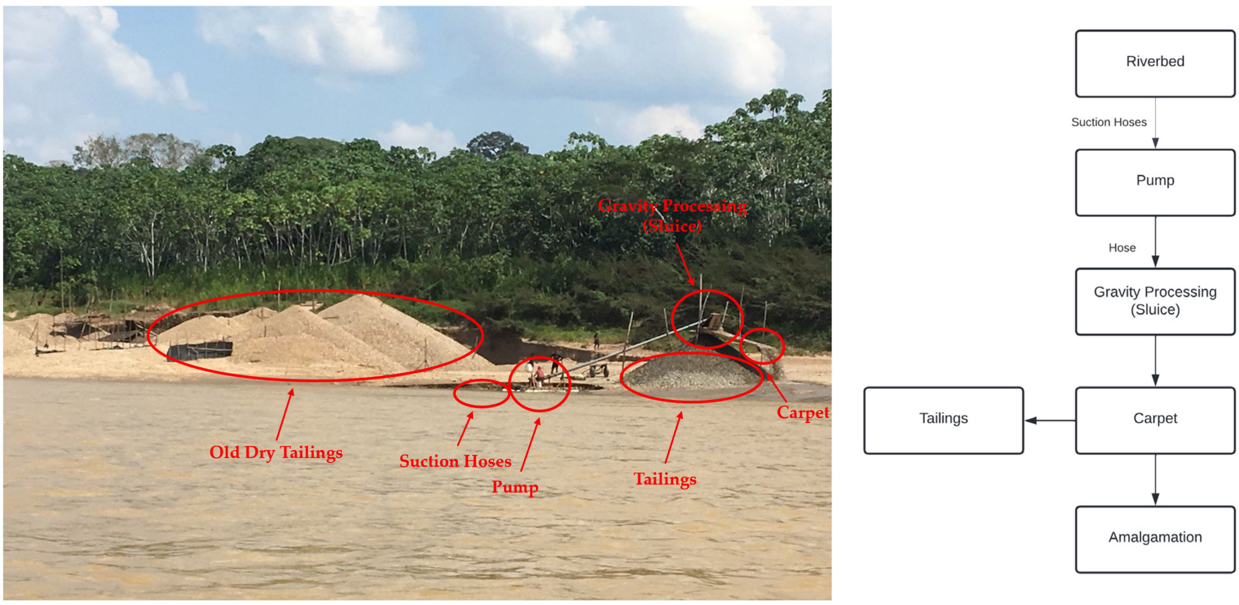

Figure 1. Visualization of Caranchera Mining Method and Flowchart of the Caranchera Mining Method.

This method is common in the Tambopata region in MdD which is shown in Figure 2, for which the model validation data are collected and analyzed. As shown in Figure 2, the green area represents MdD, and the red region represents the Tambopata province. Tambopata is the largest province in MdD, with a population of 111,474 in 2017, 91.6% of which live in the urban areas [11].

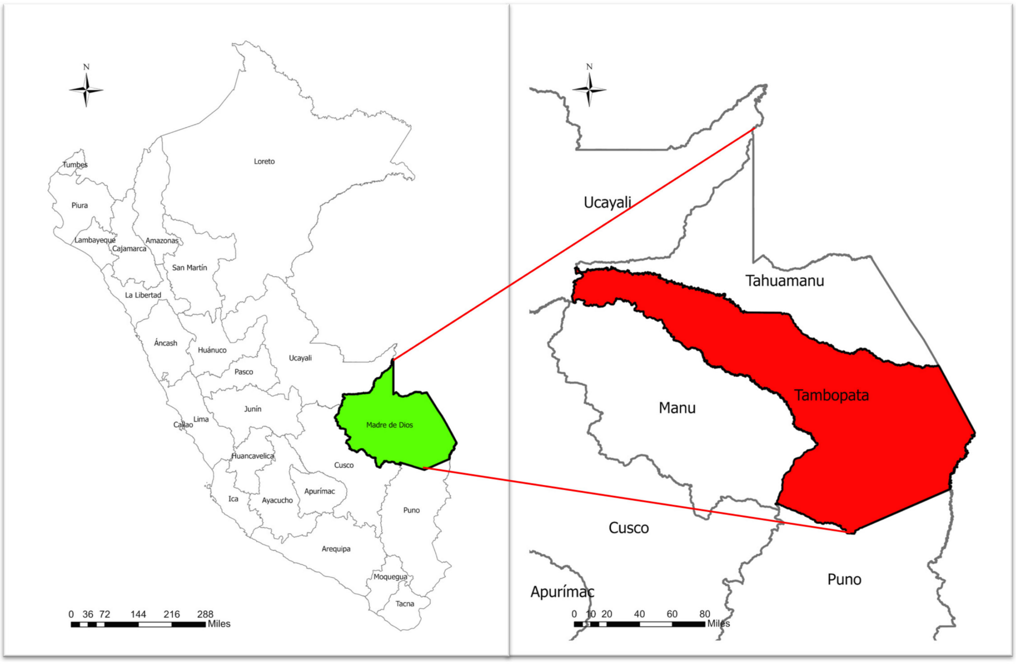

Figure 2. The Map of Tambopata that is Located in MdD in Peru.

In MdD and along the Amazon River region, climate change significantly impacts people who live in the forests along the rivers. Specifically, floods have the highest impact of all on their lives since they raise the water level of rivers, which affects their living space and causes major disruptions in ASGM activities, which are their primary source of income. These disruptions usually occur in a causal loop; the deforestation within Amazon rainforests due to alluvial mining operations causes fluctuations in precipitation levels. These fluctuations result in floods that cause disruptions in production activities of the alluvial gold mining [12]. This causal loop diagram is given in Figure 3.

As seen in Figure 3, red arrows represent the relations between the nodes. The plus signs next to the arrows indicate that the relationship between the two connected nodes is positive (reinforcing); if the first variable increases, the connected one increases, and vice versa. The minus signs represent a negative relation, where one variable's increase decreases the other correlated one. The black arrow with a plus sign shows a reinforcing feedback loop. In other words, the increase in deforestation leads to an increase in the precipitation fluctuations and, as a result, an increase in flood events. However, the increase in flood events leads to a decrease in alluvial gold production. When gold production decreases, the number of alluvial mines increases to maintain required gold production, resulting in deforestation increase, which is a reinforcing feedback loop.

In order to examine these climate impacts on ASGM activities, we consider the caranchera mining method under a flood scenario. Specifically, we examine the precipitation as an external factor that directly impacts alluvial mining activities and perform an SD model under this external impact over time. Analyzing the system under a flood scenario is considered as the extreme external variable that affects the system. There are other possible external scenarios such as shortages of assets, fuel and mercury, and lack of workforce; however, climate change (i.e., precipitation and therefore floods) has the highest impact, which provides a baseline for ASGM's resilience. Examining a flood scenario also provides a detailed understanding of how the system reacts to climate impacts and identifies the directly affected system components. Comparing our findings with the historical behavior of the system also provides validation for our model. In addition, this analysis helps us identify nodes that tend to get highly affected by an external variable and are worth further investigation to prescribe ways to disrupt illicit activities within the ASGM supply chain in MdD.

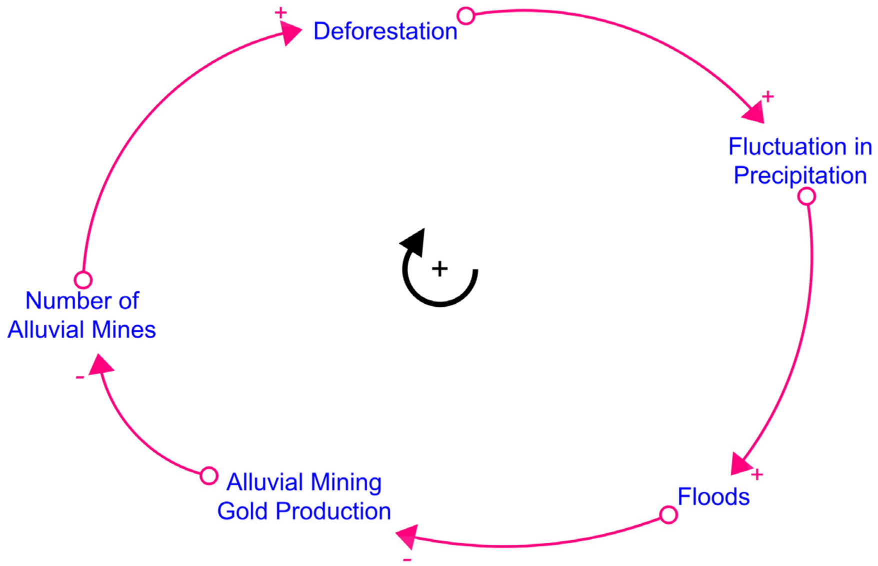

Figure 3. The Causal Loop Diagram of the Relationship between Deforestation, Precipitation, and ASGM.

This paper makes the following contributions: To the best of our knowledge, this is the first paper that examines a gold supply chain using system dynamics modeling to provide qualitative insights and address the environmental impacts of ASGM. Usually, obtaining quantitative data is challenging. We convert qualitative interviews into quantitative inputs. We propose a methodology for constructing and implementing the system dynamics modeling for examining such data-scarce supply chains: (i) we examine an informal ASGM supply chain in MdD, Peru, specifically for the carancherа mining method, by conducting a system dynamics model, (ii) we also analyze this system under a flood scenario, (iii) we provide insights on how the informal gold production gets affected by a flood, (iv) and we validate the proposed model by comparing the model results with actual effects. It is to be noted that the methodology we presented is applicable to other ASGM systems, which are mainly opaque and do not allow quantitative evaluation of their environmental impacts, transparency, and resilience.

2. Literature Review

A variety of papers define the mineral supply chain globally or locally. Ref. [13] examined the gold supply chain in Peru and divided the supply chain into four main stages that interact with each other: the supply of chemicals and equipment, production, wholesale trade, and retail sales. Further, they illustrated the differences between legal, illegal, and informal activities in the supply chain and provided a detailed sketch of the gold supply chain in Peru. Ref. [14] determined the leverage points that prevent artisanal gold miners in Ecuador from selling their gold to authorized governmental buyers. Similarly, Ref. [15] examined the mercury supply chain and its interaction with artisanal and small-scale gold mining to determine the role of each stakeholder in reducing the consumption of mercury in the gold mining industry. Additionally, Ref. [16] investigated five critical elements. These elements are byproducts from copper mining and processing in the primary copper pyrometallurgical supply chain. Likewise, we consider a critical element (i.e., mercury) and its intersection with the ASGM supply chain.

ASGM-related studies are conducted to characterize issues related to this sector qualitatively. Ref. [17] identified and described the bacterial strains that result from mercury water pollution due to ASGM in Peru. Ref. [18] analyzed the overall sustainability aspects of ASGM in Antioquia-Colombia. Ref. [19] studied the environmental-related issues and sustainability of the ASGM in Ghana.

System dynamics (SD) modeling is a relatively new approach to studying supply chains, especially in the mineral industry. The studies on mineral supply chains using SD modeling are scarce. Ref. [20] examined the global supply and demand of platinum group metals over 500 years using SD modeling. The authors consider the time delays between the supply and demand peaks due to recycling and the time required to start production in new mines in the model. Ref. [21] linked the dynamics of fluctuating commodity prices with the raw material markets. They implemented the cobweb theorem using SD modeling to show how SD modeling may provide a better explanation for the recent price declines and predicted its future behavior. Several studies use SD modeling for sustainable supply chain management, transportation, manufacturing, logistics, life cycle sustainability assessment, and renewable energy supply chains (e.g., [22] and references therein).

SD modeling in supply chains is considered in many different sectors. Ref. [23] used the SD approach to examine the behavior of disrupting a multi-echelon supply chain. They tested the impact of partial and complete disruptions on the supply chain regarding different aspects such as cost, profit, and inventory levels. Ref. [24] examined the problem of demand amplification (i.e., bullwhip effect) for a part of the supermarket supply chain in the United Kingdom using SD modeling. The authors examined different types of delays: physical delays (e.g., the delay of the delivery of the stores) and information delays (e.g., delivery policies and information sharing). The simulation analysis of the SD model provides insights regarding these delays. Ref. [25] used SD modeling to examine joint decisions in manufacturing for integrated supply chains. Ref. [26] addressed impacts of risk in food transportation systems using SD modeling. The supply chain of non-perishable products was examined and analyzed using SD modeling to understand the dynamics and relationships within food supply chains [27]. Ref. [28] utilized SD modeling to compare simulations, fuzzy programming, and spreadsheet approaches to analyze the supply chain procurement transportation problem. Ref. [29] used SD modeling to improve the broad-oriented policy framework required to achieve a more sustainable energy supply by focusing on the dynamics of information flow. Ref. [30] examined a medium-sized manufacturing company that operates with a make-to-order (MTO) system and built an SD model for its supply chain. Ref. [31] used SD modeling to examine the closed-loop supply chain of an electrical manufacturing company by focusing on variables that increase the recycling rate and customer satisfaction. Ref. [32] conducted SD modeling with neural networks and eigenvalues approaches to analyze the supply chain behavior of an electronics manufacturing company.

Several studies have recently been conducted on gold supply chains and illegal mining activities [13,14] without considering the SD approach. A few studies use SD modeling to examine illicit activities on different supply chains rather than the gold supply chain. Specifically, Ref. [33] examined cocaine use for 15 years using SD modeling. He examined several scenarios to predict the directions in which the market was heading. In addition, the policies that Colombian and American law agencies created to control the cocaine trade were examined using SD modeling [34]. The research shows that the current policies contribute to an increase in the amount of cocaine planting and a decrease in its prices while also suggesting an alternative policy [34]. Ref. [35] used the SD modeling approach to illustrate the willingness of Indonesian villagers to engage in illegal activities based on the factors that increase their desire for engagement. The study considers causal loop diagrams to model the system and a case study to validate it. In the same context, Ref. [36] examined illicit wood harvesting in the wood supply chain in Pakistani forests using an SD approach. The authors used historical data on the forests and wood harvesting in Pakistan from 1990 to 2010 to simulate and predict the output until 2030 and provided suggestions applicable to reducing the illicit activities in Pakistani forests.

Alluvial ASGM activities in MdD have significant environmental impacts. Ref. [37] estimated that 3900 hectares of area is lost per year due to the alluvial ASGM in MdD. Specifically, deforestation causes a climate phenomenon called El Niño Southern Oscillation (ENSO) that leads to fluctuations in the level of precipitation in the Amazon region [38]. Due to the increasing rate of deforestation, this phenomenon is becoming permanent with arising environmental impacts [39]. Note that these occur in a causal loop; that is, deforestation due to mining activities causes climate changes, and these changes result in a disruption of these activities. Ref. [12] analyzed the environmental impacts of the life cycle of alluvial ASGM and examined how those affect the alluvial ASGM activities using the life cycle assessment approach.

The extensive literature review points out the lack of studies that utilize SD modeling to examine the mineral supply chains, such as gold and mercury supply chains, that strongly interact. Moreover, informal ASGM systems are data-scarce supply chains that do not allow the implementation of quantitative methods like SD. In this paper, we present a methodology to quantitatively analyze ASGM by converting collected qualitative data into quantitative inputs to be used in SD modeling. This allows us to determine leverage points that have the highest effect on the supply chain.

3. Proposed Methodology

Figure 4 shows the four stages of the proposed methodology: (i) Collecting qualitative data, (ii) identifying the system's components and quantitative inputs, (iii) building the system dynamics model, and (iv) validating the model using a case study.

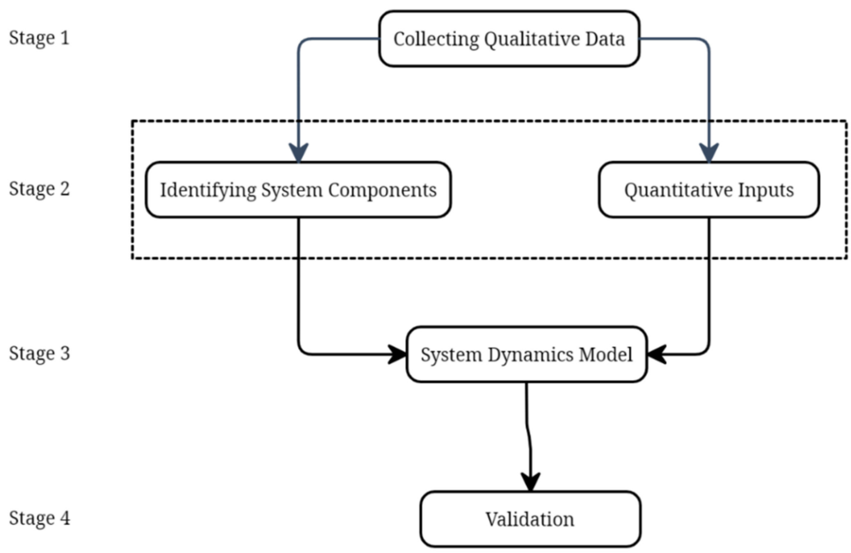

Figure 4. The Proposed Methodology.

Collecting Qualitative Data is the first stage of the proposed methodology. The data for a typical ASGM is not readily available. Hence, a set of qualitative data needed to be collected from different sources such as previous literature, interviews, field studies, and government records, if possible. Such data can be used as the general input for further data collection procedures; for instance, it can be used to guide to more specific sources from which more detailed data can be obtained. Qualitative data also include the dynamics of information flow throughout the supply chain and how that flow affects the dynamics of the materials' flow along different stages of the supply chain.

The second stage in the proposed methodology is identifying system components and quantitative inputs. Once the system components are identified, and the general flow of the supply chain is obtained, each of the system components can be examined in more detail using the information flow to get quantitative data for the materials' flow. Moreover, the information flow of each stage can be converted to quantitative data by using scaling methods depending on the effect of these information flows on the system.

The third stage of the proposed methodology is system dynamics (SD) modeling, which has strong characteristics of analyzing, simulating, and optimizing the variables so that the flow can be controlled over time. It is also capable of revealing the effect of changing one variable on the whole system. In addition, SD modeling helps to identify the leverage points in the system so that specific activities and decisions can be optimized.

4. Implementation of the Methodology to the Caranchera Mining Case

In this section, we provide details of the gold supply chain examined, specify our data, and propose the system dynamics model specific to the caranchera mining case.

4.1. Collecting Qualitative Data

This study considers different sources of information that provided necessary inputs to the proposed model. Several interviews are conducted with different actors, namely authorities, miners, and the mining community, identified in the gold supply chain to obtain primary data. Due to the global concern of COVID-19, all interviews are carried out virtually. They are conducted with the support of professionals in Peru. Other potential informants who participate in this study are identified from key contacts. In total, 15 interviews (six government officials, one expert, four non-governmental organization (NGO) representatives, three staff from Activos Mineros, S.A.C., and CINCIA, and a miner) are conducted with government officials and professionals, experts, and locals who are knowledgeable about the territory. From these, both qualitative and quantitative information has been obtained that feeds into the model together with the secondary information collected. This information consists of an exhaustive search for regulations, scientific articles, government production reports, reports from NGOs, and videos. We also utilize academic media in both English and Spanish. This media centers on the extraction, benefit, and commercialization of gold in Peru, especially in Madre de Dios.

4.2. Identification of System Components and Materials Flow

Most artisanal and small-scale gold mining in Peru is concentrated in MdD. In fact, out of 80% of ASGM that is considered informal, 70% occurs in Madre de Dios, which makes MdD more important to be studied [2]. In addition, about 97–99% of the mining activities in the same region are illegal [5]. In order to identify and understand the system components, we examine a common mining method in the region that would enable us to understand how each variable would change and affect the system over time. Specifically, the caranchera alluvial mining method is chosen, and the model is built based on the detailed components of this mining method and the flow of gold in several phases.

Figure 5 shows an overview of the phases of the gold supply chain.

The blue boxes in Figure 5 represent the stocks or the sites where the gold in different forms is transformed and exchanged. The bullet points above the blue boxes refer to the list of variables or materials and human inputs required at each stage. The arrows represent the flow of gold in different forms. A typical ASGM supply chain starts from the gold mine where the ore is extracted using workforces and various equipment such as excavators for surface mines, pumps for alluvial mines, and explosives for hard rock mines. The extracted ore is hauled to the mineral processing plant via trucks, rail cars, or pipes. The mineral processing plants vary based on the ore type and production method; however, the primary role of processing plants is beneficiation of the gold grade from the run of mine (ROM) by crushing and grinding the ore and then applying physical methods such as size separation and gravity separation to obtain a gold concentrate. These processes require workforces, special equipment, and primary resources such as water and energy. After applying the physical processing, the concentrate is mixed with mercury so that the mercury captures the gold in the concentrate. As a result of the mixing process, the amalgam is produced, which is a mix of gold and mercury. After that, the amalgam is sold to the gold shop, where it is burned to get rid of the mercury by vaporizing it. After evaporating the mercury, the remaining mixture is called 'dore', which is also a mixture of gold and mercury; yet the concentration of gold is over 90%. The dore is traded to the refinery in which the pure gold is produced and then distributed to the market, where it is sold to different types of customers.

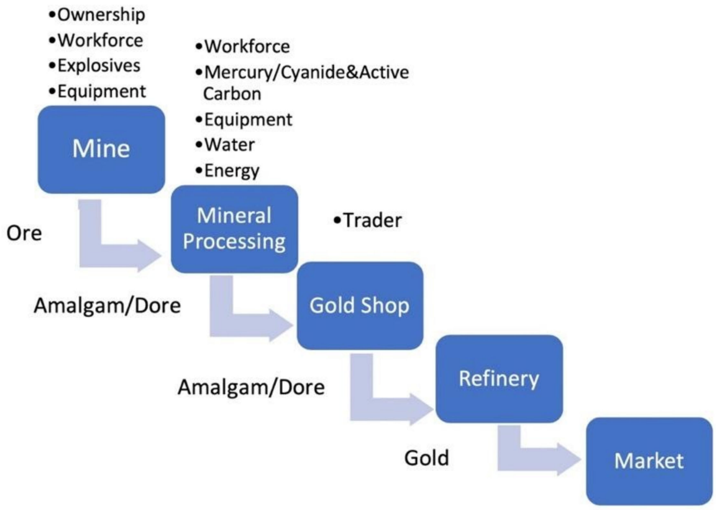

Figure 5. General View of Artisanal and Small-scale Gold Supply Chain.

In this paper, an SD model is built and validated for the first two stages of the supply chain, namely mine and mineral processing up to the gold shop. Based on the collected data and relations, the model describes and simulates the illicit gold production in ASGM and its interaction with mercury and the fuel supply. For the validation of the model, it is examined under a flooding cycle scenario and validated with actual data.

4.3. Obtaining Inputs for the System Dynamics Model

The collected qualitative data are analyzed and categorized according to the main flow of the system dynamics model. The categories are based on the possible inputs and nodes that may exist in gold mining in MdD and in relation to the caranchera method. Parameters and relationships between the connected nodes and the variables that affect them are defined. An additional data collection procedure on monthly rainfall is also carried out in the studied region to validate the model. This procedure is described later in the validation section.

4.4. System Dynamics Model of Carancher a Mining Method

In this section, we describe the system dynamics approach in detail for an informal ASGM that applies the caranchera mining method in MdD. As shown in Figure 5, the first two stages of the supply chain consist of the mine and the mineral processing plant up to the gold shops. Since most ASGMs process the ore at the same mine site, these two nodes are examined together in the SD model. The proposed model considers the regular flows of gold, fuel, and mercury to and from the mine site based on data collected from MdD.

The complete model is shown in Figure 6. The model was built and run via Stella Architect version 2.1.2. The model is run for 365 days with 12-h time periods (two steps per day). In the model, boxes represent stocks, double-lined arrows represent flows, and the single-lined arrows represent variables.

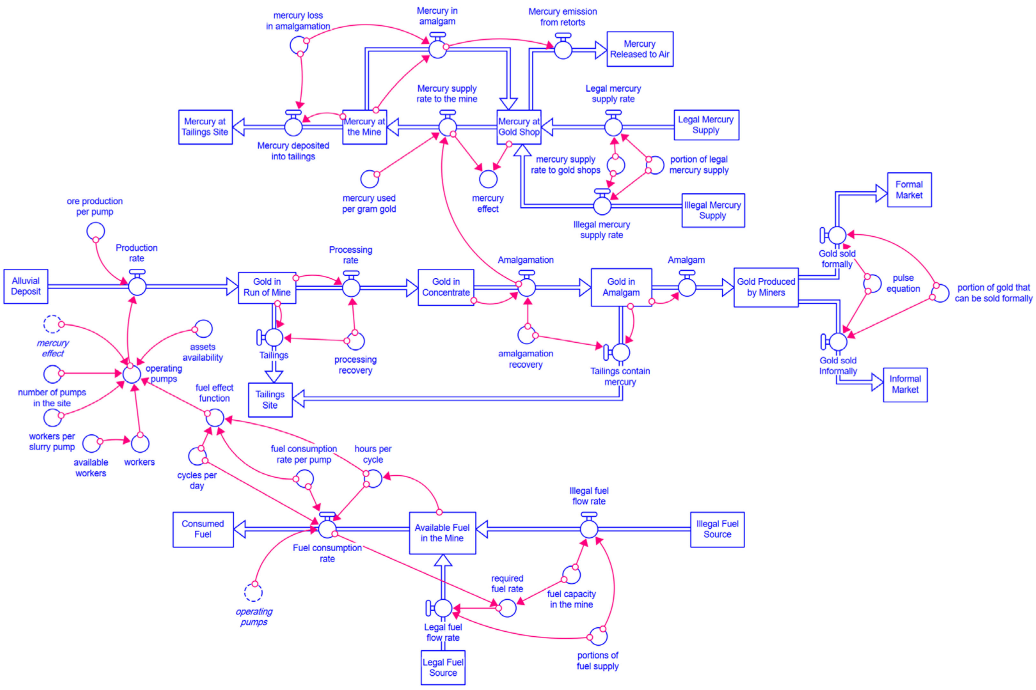

Figure 6. System Dynamics Model for Caranchera Mining Method (Stella Software).

The model in Figure 6 contains three main flows: fuel (in liters), ore (gold), and mercury. These flows interact with each other via relations and variables obtained from collected data and official interviews. Figure 7 shows the fuel flow component of the supply chain that examines fuel flow (in liters) by considering the interplay between illegal and legal fuel supplies with the mine.

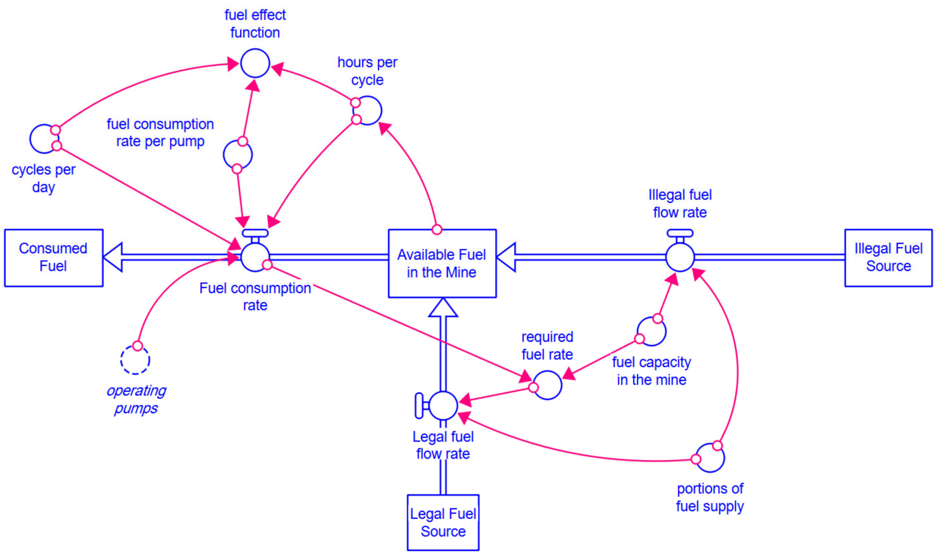

Figure 7. Fuel Flow.

As shown in Figure 7, fuel flow starts from two possible sources (i.e., stocks represented by boxes); (i) legal source, which represents the fuel suppliers that sell the fuel legally by obeying the legislation such as tax, fuel limit per miner, and prices, (ii) illegal source, from where miners buy the excess amount of fuel to meet their demands from suppliers who get their fuel from illegal sources or do not obey the local legislations. The fuel from these two sources flows to the mine's storage with a flow rate represented by the 'Available fuel in the mine' stock in Figure 7. The flow rate of fuel to the mine's storage, represented by double arrows, is affected by several variables and other flows, such as the 'fuel capacity in the mine' variable (represented by a blue circle) and 'Fuel consumption rate' flow. The 'Fuel consumption rate' flow represents the fuel consumption rate by available operating machinery in the mine, mainly by operating pumps. It also affects the fuel flow from the sources by determining the daily demand, which creates a feedback loop so that the operating machines and available resources balance the supply and demand of the fuel. This flow ends at the stock of 'Consumed fuel', it shows the cumulative fuel consumed during the run time of the model (i.e., 365 days). Note that Figure 7 shows the fuel flow only, which is connected to other flows via ghost variables. Such variables are used to connect different flows, and they are represented in dashed circles in Figures 7–9. The dashed variable 'operating pumps' in Figure 7 is a variable that initially exists in the gold flow, as shown in Figure 8. Note that it is presented in the fuel flow in Figure 7 as a ghost variable to demonstrate its effect (i.e., the effect of gold flow on fuel flow), which makes the connection between the two flows. Specifically, to run operations in the gold flow, pumps should be used that consume some amount of fuel. The description of all nodes is shown in Tables 1–3.

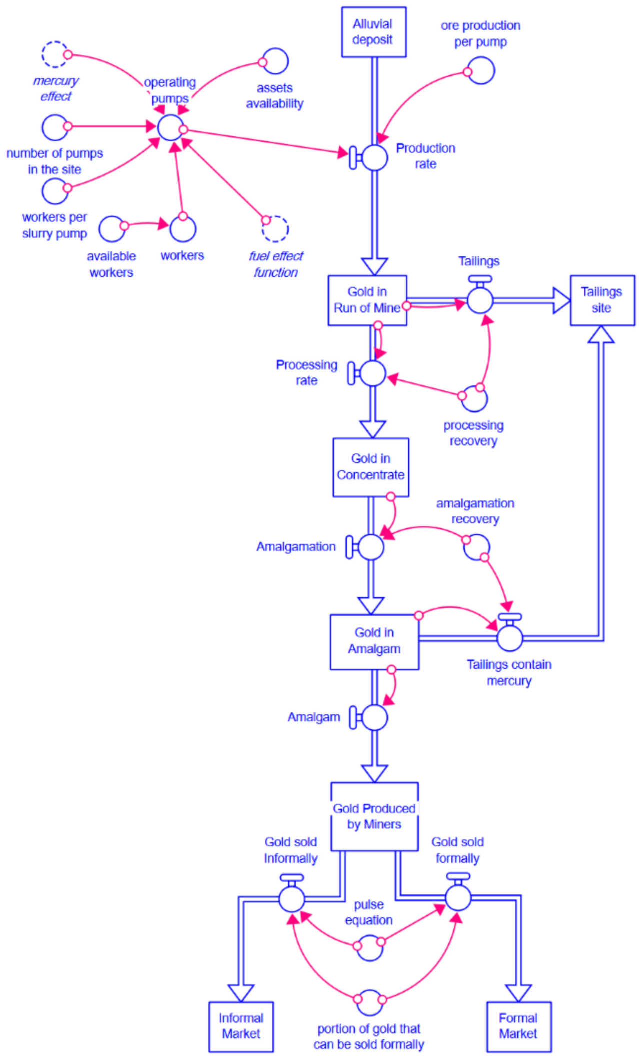

Figure 8. Gold (Ore) Flow.

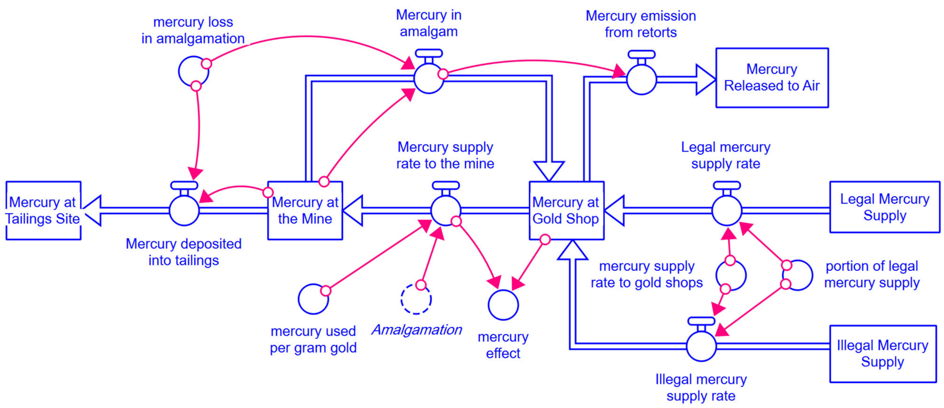

Figure 9. Mercury Flow.

Table 1. Description of the Stocks.

Stock Name	Location in the Model	Description
Illegal Fuel Source	Fuel Flow	The source of the illegal fuel supplier
Legal Fuel Source		The source of the legal fuel supplier
Available Fuel in Mine		The maximum fuel consumption has a feedback loop that is controlled by the capacity of fuel storage and the capacity of mine—it affects the equation that determines the number of pumps to operate every day
Fuel Consumed		The cumulative of the consumed fuel along the run time
Alluvial Deposit	Gold Flow	The riverbed from where alluvium is pumped to the processing site
Gold in Run of Mine		The daily amount of ore extracted in units of gold content. Note that according to interviewees' experience, only 30% to 50% of the gold is caught on carpets
Tailings Site		The amount of gold that is lost to the tailings site
Gold in Concentrate		The captured gold in the carpets that will be amalgamated with mercury at the end of the day to be sent to gold shops
Gold in Amalgam		The captured gold in the amalgam after the amalgamation process
Gold Produced by Miners		The amount of gold that miners have, who sell it on a monthly basis either to legal or illegal markets
Formal Market		The cumulative amount of gold sold to the formal market
Informal Market		The cumulative amount of gold sold to the informal market
Mercury at Gold Shop	Mercury Flow	The amount of mercury in the gold shop that is related to a specific mine
Mercury at the Mine		The accumulated mercury at the beginning of the day in the mine that will be used in amalgamation during the day
Mercury at Tailings Site		The mercury that is disposed to the tailings site
Mercury Released to Air		The cumulative amount of the mercury vapor released into the air via retorts

Gold flow is shown in Figure 8. It is the main component of the model, and it starts from the alluvial deposit, represented by the top box, where the ore is extracted. The mine type for the shown flow is an alluvial mine located on the riverbank. To extract the ore, slurry pumps are used, which work with fuel, and workers dive down to the riverbed to direct the pumps' hoses to suck the required slurry. This process is controlled by the primary variable 'operating pumps'. It determines how many pumps are working during the shift and the amount of ore extracted and processed accordingly. The sucked ore, represented by the 'Gold in Run of Mine' box, is then transferred directly to the sluice, where the physical processing is applied at a specific processing rate. Sluice is a process that separates waste materials from the gold carrying material to increase the gold concentration in the extracted ore. The remaining waste materials are dumped at the tailings site. The processing operation is controlled by the 'processing recovery' variable, which determines the percentage of gold in the ore that is kept in the concentrate and the gold lost to the tailings. After sluice (i.e., gravity separation), the concentrate is captured by the carpet, which is the last part of the sluice that holds the concentrate. After collecting the concentrate from carpets, the amalgamation process starts. In this process, the mercury is mixed with the concentrate to capture the gold, producing the amalgam. This process is also controlled by the recovery variable, namely 'amalgamation recovery', and it determines the mercury demand. The produced gold after amalgamation, represented by the 'Gold Produced by Miners' box, is sold to the market in two ways; (i) formally, to local authorized buyers; however, miners cannot sell all of the produced gold to formal markets because there is a limited amount that can be sold based on the mine's scale, (ii) informally, to buyers that buy the gold with a lower price and introduce it to the market using illegal ways.

Table 2. Description of the Flows.

Flow Name	Location in the Model	Description
Illegal Fuel Flow Rate	Fuel Flow	The rate at which the illegal fuel is supplied to the mine
Legal Fuel Flow Rate		The rate at which the legal fuel is supplied to the mine
Fuel Consumption Rate		It is a function affected by the number of working pumps each day, the consumption rate for each pump, the number of cycles per day, and the number of hours per cycle
Production Rate	Gold Flow	The rate at which alluvium is mined, and it is measured by grams of gold. The production rate is based on the number of pumps working and the production per pump
Processing Rate		The amount of gold processed physically in the mine
Tailings		The rate at which gold is lost to tailings
Tailings from Amalgamation		The amount of mercury produced during the amalgamation process. Due to the COVID-19 pandemic, the amalgamation processes are performed in miners' houses
Amalgamation		The rate of gold amalgamated and transferred to gold shops per day. It is affecting the mercury supply rate that comes into the mine
Amalgam		The flow of amalgam that accumulates with miners before being sold to market
Gold Sold to Market Formally/Informally		These are based on the fixed amount of gold that can be sold formally per month. The rest of the gold production is sold informally if the monthly gold production exceeds the amount of the gold that can be sold formally per month, which happens frequently
Legal and Illegal Mercury Supply Rate	Mercury Flow	This is the amount of the legal and illegal mercury supplied to the gold shop
Mercury Supply Rate to the Mine		This is the amount of mercury required for amalgamation; it is determined according to mercury per gram of gold, which is two grams of mercury per gram of gold [9]
Mercury Deposited into Tailings		The rate at which mercury is lost to the river is determined by the mercury loss during the amalgamation
Mercury in Amalgam		The rate at which mercury is going back to the gold shop in amalgam form. It is affected by mercury loss in amalgamation
Mercury Emission from Retorts		The amount of mercury vapor that was not captured by the retorts while burning the amalgam. According to the literature, this amount is 5% of the total mercury used [40], while our interviewees stated that it is about 50% of this amount of mercury that exists in the amalgam

As shown in Figure 8, the 'operating pumps' variable is the main variable that affects the 'production rate' flow. In fact, this variable is presented as a ghost variable in the fuel flow, and its effect is applied in that flow. The same variable, 'operating pumps', is affected by other ghost variables such as 'fuel effect function' and 'mercury effect'. The 'Fuel effect function' variable originally exists in the fuel flow, as shown in Figure 7. It ensures the effect of fuel flow on the gold flow. This shows another feedback loop: the gold flow affects the fuel flow and vice versa. On the other hand, the 'mercury effect' variable initially exists in mercury flow, as shown in Figure 9, and it affects the 'operating pumps' variable. The description of all nodes is shown in Tables 1–3.

Mercury flow examines the flow of the mercury, which is accompanied by the gold in the amalgam phase of the main flow or is alone in other parts, starting from either legal or illegal sources, as seen in Figure 9.

Table 3. Description of the Variables.

Variable/Parameter Name	Location in the Model	Description
Required Fuel Rate	Fuel Flow	The rate at which the mine is supplied with fuel. It is based on the fuel consumption rate of the working pumps and the other external factors such as the flooding effect. This rate is controlled by the fuel storage capacity of the mine
Fuel Effect Function		This node connects the fuel availability in the mine with the number of pumps that should work during a specific day. It is affected by the connected parameters and affects the working pumps
Working Pumps	Gold Flow	This is the primary node that determines the production rate—it is a function of available workers, workers per pump, the number of pumps in the mine, assets availability, and the availability of fuel. It affects the fuel consumption rate, creating a loop and affecting the production rate. It is also affected by the mercury supply through the mercury effect function
Workers		A node affected by the availability of the workers
Asset's Availability		A variable that provides the logistic parts availability in percentage
Ore Production per Pump		Input that illustrates the amount of gold produced per working pump per day
Processing Recovery		The percentage of the gold recovered throughout the processing phase
Amalgamation Recovery		The percentage of the gold recovered throughout the amalgamation phase
Pulse Equation		A function that simulates the monthly selling of gold
Mercury Supply Rate to Gold Shops	Mercury Flow	The rate of overall mercury supplied to the gold shop
Mercury Used per Gram Gold		This is the amount of mercury required to catch one gram of gold
Mercury Loss in Amalgamation		This is the percentage of the supplied mercury that is lost during the amalgamation process
Mercury Effect		This node connects mercury availability with the production rate. It is equal to 1 if mercury in gold shops is greater than the mine's demand

Only 5% of the mercury comes from legal sources (represented by the 'Legal Mercury Supply' box in Figure 9) that are reported to the government. The remaining 95% comes illegally (represented by 'Illegal Mercury Supply' in Figure 9) through the country's borders, mainly from Bolivia. The mercury comes to the gold shops (usually illegal gold buyers), represented by the 'Mercury at Gold Shop' box in Figure 9. The traders in the gold shops sell the mercury to miners (represented by the 'Mercury at the Mine' box) to use it in the amalgamation and repurchase the amalgam from them. However, part of the mercury is lost to the tailings during amalgamation before going back to gold shops. In the gold shops, the amalgam is burned so that the mercury is vaporized in the air, while the remaining product, dore, contains over 90% gold. All nodes are described in detail in Tables 1–3. The 'mercury effect' variable presented in gold flow in Figure 8 as a ghost variable applies the effect of the mercury flow on the gold flow based on mercury availability that tells miners to operate their pumps or not (i.e., perform ore production). Moreover, the mercury flow is affected by the gold flow via 'amalgamation' ghost flow. It indicates the amount of mercury required for the amalgamation process within the gold flow, which applies the effect of the gold flow on the mercury flow (i.e., feedback loop).

5. Model Validation Process

Model validation in SD does not have a single and specific definition [41]. Yet, we follow the proposed validation methodology that is explained by [41]. The model is constructed based on the literature, official interviews, and experts' knowledge. The structure is built and presented to the experts, and the equations are used as inputs to the nodes. Then, the model is run with the obtained data from the literature and official interviews, and the results are discussed with the experts in the field. Later, the model is run various times by changing a specific parameter only while fixing all others. The leverage variables are obtained and discussed with the experts and miners in further interviews. The behavior pattern test is conducted using actual historical data of gold production in the studied area and precipitation records of the same area. The data are analyzed, and the effect of the wet season is obtained. Then, an external variable is applied to the model that simulates the precipitation patterns. The outputs of the model are compared with the real outcomes. Further explanation of this stage is shown in Section 6. Finally, results and discussions are obtained and provided in Section 7.

6. Examining the Gold Supply Chain in Peru under a Flood Scenario

In this section, we examine the gold supply chain under a flood scenario. The qualitative data collection indicates that floods mainly disrupt ASGM in MdD due to excessive precipitation. In the following subsections, we provide the data specification, associated system dynamics model, model validation, and qualitative insights into our findings.

6.1. Description of the Scenario

In this section, we provide details regarding the flood scenario considered in the model. Data related to national, regional, and local production in Peru, as well as monthly precipitations, are collected and used to analyze the percentage changes in production during flood seasons. We analyze the relations between precipitation and gold production for the Tambopata province in MdD, Peru. These relations are converted to production reduction percentage ranges. The obtained ranges are used as inputs to the model, and further validation is conducted by comparing the actual production records with the simulation production results.

6.2. Implementation of the Model under the Flood Scenario

For the validation of the model, a flooding cycles scenario is considered, and additional modifications to the main model are conducted. Specifically, additional variables are added to the main model as external factors affecting production throughout three main points. The flooding period in MdD starts in October and ends in April while peaking in January. The complete validation model is shown in Figure 10.

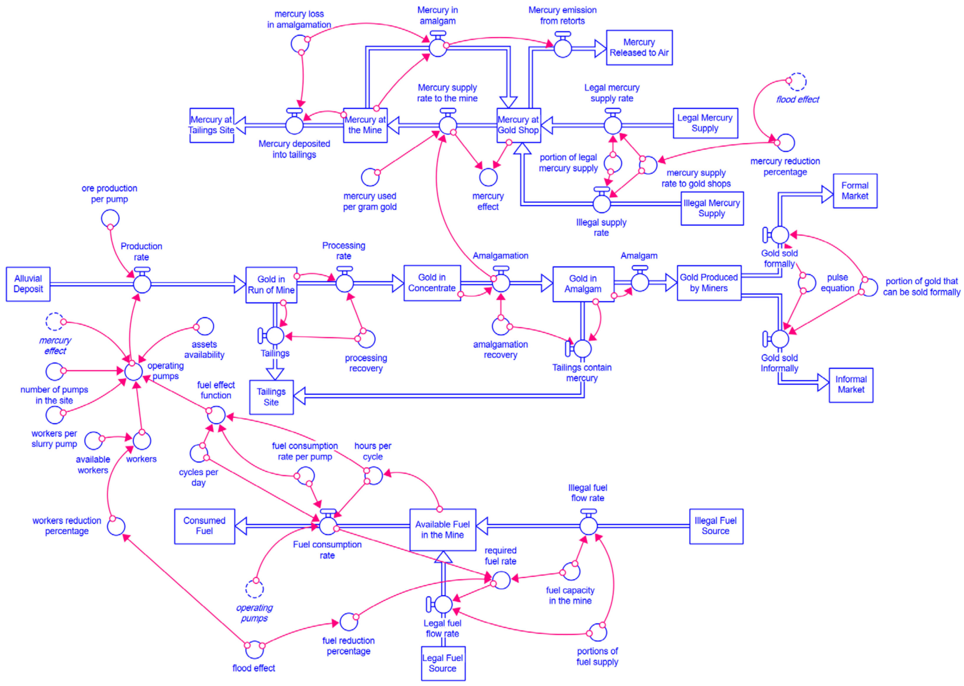

Figure 10. The Model with the Flooding Cycles Scenario (Stella Software).

The validation model in Figure 10 shows that the flood effect is added and activated throughout the flooding period. During this period, the workers, fuel supply, and mercury supply are reduced by an average range from 30% to 50%, according to our analysis. The effects of external variables can be described as a 'flood effect', which is a function that activates fuel reduction, workers reduction, and mercury supply reduction in percentages at certain times of the year (from October to April/May).

The results of the model are discussed in detail in the next section. We compare these results with the actual records, which yield a 90% accuracy that validates the proposed model.

7. Results and Discussions

After the detailed examination of the model and the validation of the model, several insights were obtained, and several leverage points in the model were determined as detailed below:

In this case study, we examine the flooding scenario by considering the rain season as an extreme external variable that affects gold production on river beaches. Based on the validation analysis, it is found that there is a relationship between increasing/decreasing precipitation and average monthly gold production as shown in Figure 11. Figure 11 is divided with dashed red lines to show the wet seasons' beginning and end (October to April/May). When the wet season starts in October, the gold production begins to decrease, reaching its minimum in January when the peak precipitation occurs. This is valid especially for mines near rivers because the water level rises with high precipitation. In addition, miners have difficulties in accessing the mining site. Due to the challenges caused by the reduced accessibility, the supply of mercury and the supply of assets and fuel are also reduced, which yields a reduction in production.

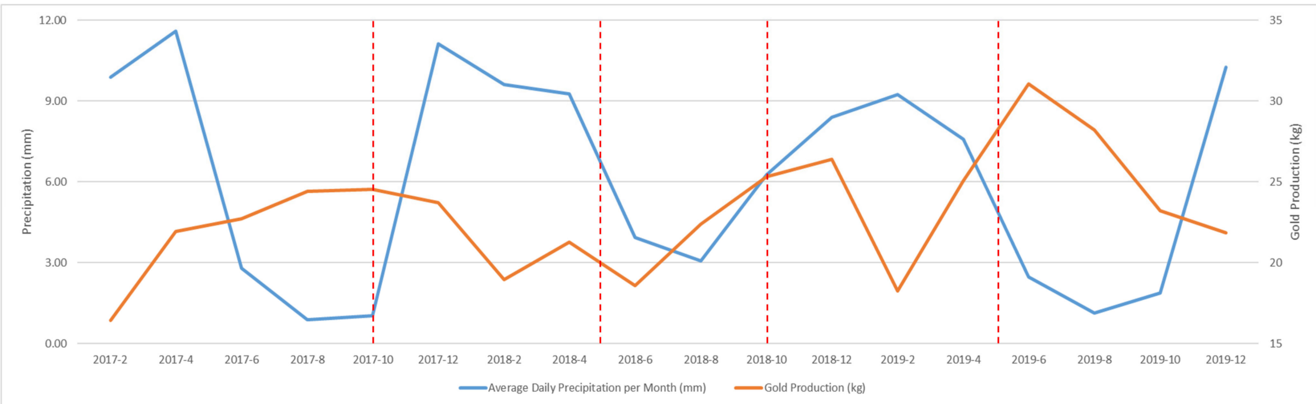

Figure 11. Monthly Gold Production and Precipitation Along the Studied Period.

Our analysis shows that the gold production rate is significantly sensitive to the changes in the rain season. Specifically, the wet season reduces production by 30% to 50%, as shown in Figure 12. A similar analysis can be done for any other external variable that may directly affect the accessibility of supplies. Day zero represents the beginning of July for all figures with an x-axis of time (days).

We conduct a sensitivity analysis by changing levels of different supplies to determine those which have the highest effect on the production rate. The analysis shows that the number of workers available on site significantly affects the production rate. Specifically, reducing one worker results in a 50% decrease in production, as seen in Figure 13. In Figure 13, the x-axis represents time in days, the primary y-axis represents gold production, and the secondary y-axis represents the number of workers. Notably, there are two pumps in the mine, and each requires two workers to operate, one worker dives down to the riverbed to direct the sucking hose, and the second one controls the pumping rate to the sluice. Therefore, by reducing one worker, one pump stops working. This insight may imply that more legislation on the illegal workforce would significantly reduce the illegal gold production rates.

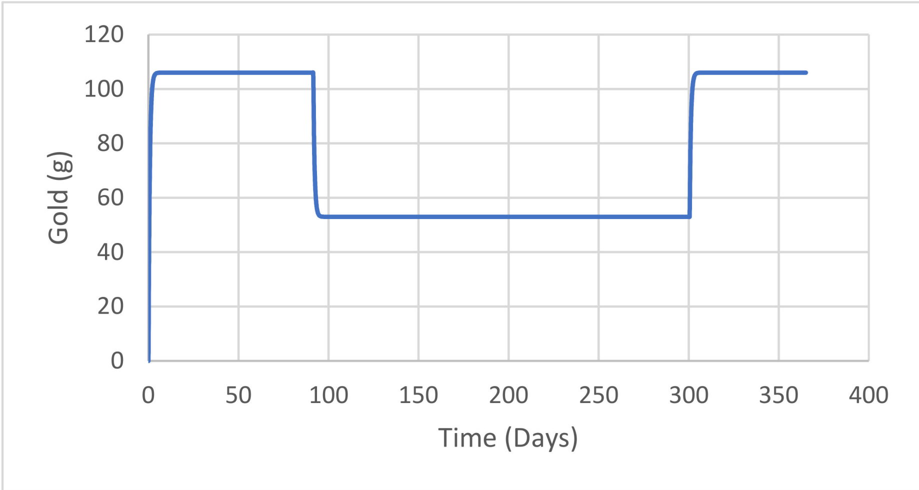

Figure 12. The Effect of Wet Season on the Average Gold Production.

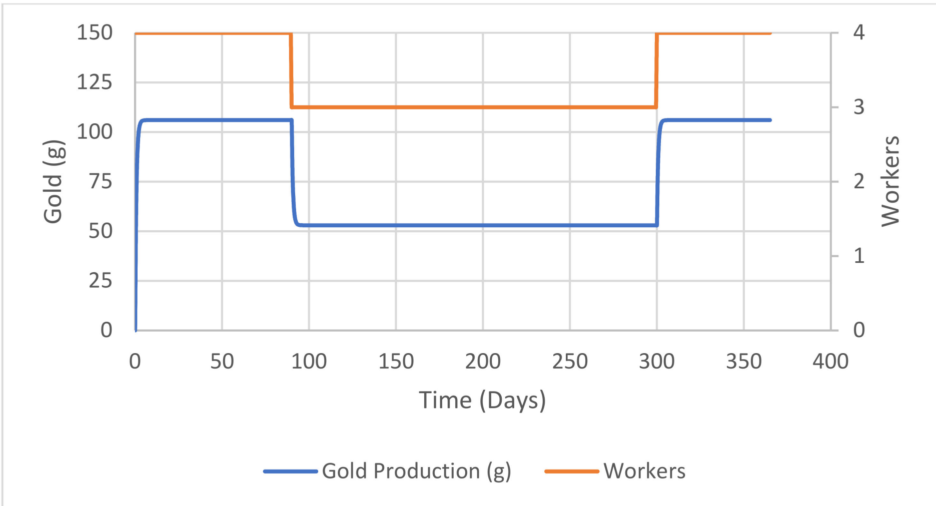

Figure 13. The Effect of Reducing One out of Four Workers on Gold Production.

There is a 95% gap in reported mercury level supplied legally compared to the amount of mercury needed for the reported gold production. Only 5% of the total mercury supply needed to produce the reported amount of gold is legal. This is due to the legal restriction on the supply of mercury. Even formal mines acquire some level of mercury illegally beyond the legal level to meet their gold production targets. This implies that if the government enforces ways to cut the illegal mercury supply, this will significantly decrease illegal gold production. Reducing the legal mercury supply does not affect illegal gold production. After the validation results that are mentioned earlier in Section 6, it is shown that the model is a good representation of the caranchera mining method; as a result, applying changes to different variables in the system gives representative results as well. For example, Figure 14a,b show the effect of reducing the legal and illegal mercury supply by 50% for 100 days starting at day 150 (i.e., the beginning of January). Such reduction is significant for the illegal supply only.

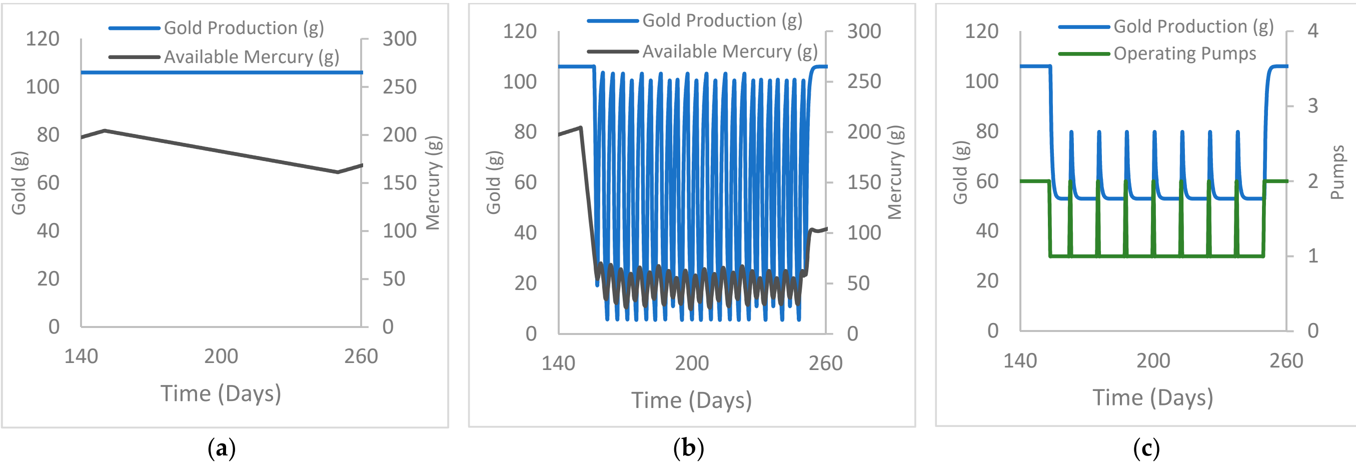

Figure 14. The Effect of 50% Reduction of Legal (**a**) and Illegal (**b**) Mercury Supply and (**c**) Fuel Supply Reduction on Gold Production for 100 Days from Day 150 to 250.

The x-axis represents time in days, the primary y-axis represents gold production, and the secondary y-axis represents available mercury with the miners. As shown in Figure 14a, gold production continues at its steady condition after applying a random 50% reduction in legal mercury supply for 100 days starting on day 150. In contrast, Figure 14b shows that the production is at its steady condition before applying a 50% illegal mercury reduction for 100 days starting on day 150, and the gold production starts fluctuating five days after the illegal mercury supply is cut to half; however, gold production continues with an average reduction between 50–60% due to the resilience of the system. On the other hand, the system recovers two days after the mercury shortage ends, as shown in Figure 14b. It also shows that a reduction in the mercury supply results in a fluctuation in production due to the fact that miners take the mercury from gold shops, use it to recover gold, produce the amalgam, and sell the amalgam back to gold shops, where gold shops burn the amalgam to obtain dore and recover the mercury to give it again to miners. As gold shops do not have an excess amount of mercury, they wait until they recover it by burning the amalgam in the retorts, which creates the oscillating pattern in the figure.

Running the SD model for the selected mining method shows that 1.13 g of mercury are released into the environment for each gram of gold produced, 82% of which is emitted into the air by burning the amalgam to produce the dore.

Formal mines have access to the amount of fuel required for production. However, since the informal mines cannot purchase a large amount of fuel, people need to acquire fuel individually from fuel stations. Nonetheless, there is a limit on the daily legal available fuel amount that can be purchased by an individual, which makes the mines limited in scale (usually two main pumps per mine in the studied area). By reducing the legal amount of fuel that each individual can purchase or monitoring the destination of the sold fuel, illegal gold production may also be reduced. Decreasing the fuel supply creates fluctuations in production, as shown in Figure 14c. In Figure 14c, the x-axis represents time in days, the primary y-axis represents gold production, and the secondary y-axis represents the number of operating pumps. Applying the same reduction of 50% on fuel supply for 100 days starting on day 150 results in an average gold production reduction of 45% with fluctuations in the number of working pumps and, as a result, in the production, as shown in Figure 14c. This fluctuation is because the pumps do not work for half of the shifts (i.e., binary variable).

Although the detailed consideration of gold shops is out of scope in this paper, the collected data shows that each mine owner is allowed to sell only 100 g of gold to formal gold buyers per month, which makes the miners search for informal buyers to sell the rest of the produced gold. Thus, the sold gold becomes part of the informal supply chain, as seen in Figure 15.

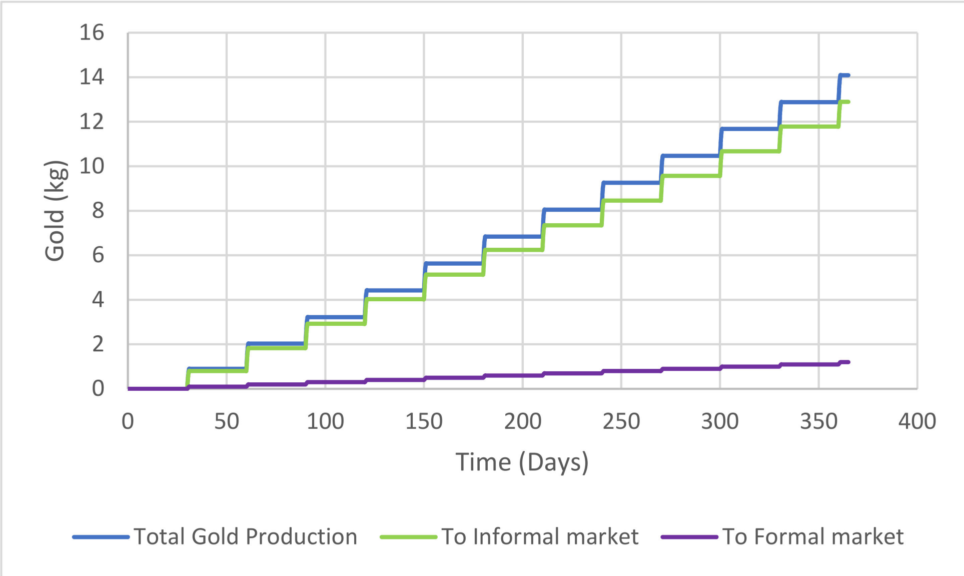

Figure 15. Cumulative Gold Sold to Formal vs. Informal Markets.

The gravity separation process removes gold from the gang (tailings), resulting in the concentrate. The concentrate is caught by the carpets. This is the stage before processing the ore with mercury. The recovery of this process is 40% of the gold in the ore. Moreover, the obtained gold with mercury is 95% of the gold within the concentrate during the amalgamation process. As a result, fixing the mercury supply amount and improving the recovery of the physical processing would not increase the overall gold production in a given period; however, it would decrease the quantity of the ore extracted for the same overall production per period (e.g., one month), which in fact would decrease the deforestation rate in the region. Since each pump can either work or not (a binary variable), any shortage of its spare parts in case of a failure in operation results in a complete stop for at least one cycle (e.g., one day). When there is a 10–40% shortage in maintenance, one pump completely stops. This potentially drops the illegal production rate by 50% in usual mines that contain two pumps. A maintenance shortage of more than 40% results in the halt of two pumps yielding no production (i.e., 100% reduction in gold production). As a result, tracking the logistics of the main spare parts of pumps would reduce the illicit gold production rate.

8. Conclusions

This paper explicitly outlines an informal ASGM supply chain for the caranchera mining method in MdD, Peru. The explicit analysis of the ASGM supply chain using SD modeling allows quantification of the gold production under different external disruptions by examining the caranchera mining system. Moreover, the mercury release to the environment (1.13 g of mercury per gram of gold produced) and how mercury release changes based on different external effects can be analyzed. Additionally, such an explicit analysis of the ASGM supply chain indicates transparency and resiliency of the system against external disruptions such as floods. We examine the system under a flood scenario as an external impact of climate change. The result of the model yields a 90% accuracy rate compared to the actual results, which validates the proposed model. We note that, although there is a 30–50% decrease in gold production due to the climate effect during the wet season, the production continues and never stops with the ability of the system to recover quickly in a few days after the external disruption ends.

This analysis could be done using other methods such as discrete event simulation; however, identifying disruptions and their impacts would have not been explicitly followed via analyses over time. An explicit analysis of the gold supply chain from the caranchera mining method sheds light on ASGM supply chain transparency and its impacts on the environment, namely mercury release to the Amazon River. Considering the large number of mining activities in this area, our analysis can help predict the quantitative values of mercury use and release to the environment, fuel consumption, assets use, and informal workforce involved, as well as the informal gold production from this area. For example, for a single mine that operates without an external effect with the caranchera mining system using two pumps, 14.1 kg of gold is produced, 16.0 kg of mercury is released into the environment, and 112,110 L of fuel are consumed per year. This yields that 1.13 g of mercury and 7.95 L of fuel are consumed to produce one gram of gold. On the other hand, by applying the climate change effect on the system during the wet season, the annual gold production, mercury release, and fuel consumption are dropped by 4.2 kg, 4.6 kg, and 32,030 L, respectively. This yields an increase in mercury release and fuel consumption per gram of gold produced. Specifically, 1.15 g of mercury are released per gram of gold produced, and 8.09 L of fuel are consumed per gram of gold produced.

We perform several runs to obtain leverage points for which decisions can be made to have the most effective changes to the system. Note that we examine an informal ASGM supply chain because it has common activities with the illegal gold supply chain. For example, our analysis shows that the illegal mercury supply and workers' availability are the most effective variables in the whole system. Since these analyses were done during the COVID-19 pandemic, we relied on virtual interviews and remote data collection without visiting the studied area. However, the obtained accuracy in the validation reveals that similar approaches can be conducted for other ASGM supply chains. Additionally, this paper highlights the possible changes that have the most effect on the system yet does not provide the optimal ones.

To the best of our knowledge, this is the first study that examines an informal ASGM using SD modeling to produce quantitative results, which has previously been analyzed qualitatively only. We plan to conduct additional SD models for examining different mining methods in other regions of Peru under different external variables. The boundaries of the SD models are planned to be extended by including further stages of the ASGM supply chain. By combining all these analyses, we plan to formulate an optimization model in order to prescribe optimal decisions regarding the gold supply chain in Peru that minimizes the illicit activities throughout the supply chain.

Author Contributions: Conceptualization, F.A., T.F. and S.D.; Methodology, F.A., T.F. and S.D.; Software, F.A.; Validation F.A., T.F. and S.D.; Formal Analysis, F.A., T.F. and S.D.; Investigation, F.A., T.F. and S.D.; Resources, F.A., T.F. and S.D.; Data Curation, F.A., T.F. and S.D.; Writing—Original Draft Preparation, F.A., T.F. and S.D.; Writing—Review & Editing, F.A., T.F. and S.D.; Visualization, F.A.; Supervision, T.F. and S.D.; Project Administration, T.F. and S.D.; Funding Acquisition, T.F. and S.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by National Science Foundation (NSF) grant number 1935630 and The APC was funded by one of the author's research funds.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author, Fatih Aranoglu, upon reasonable request.

Acknowledgments: This material is based upon work supported by the National Science Foundation under Grant No. 1935630. Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. We also would like to thank Nicole Smith, Jaramillo Urrego, Alejandro Garcia, and Gerardo Martinez for conducting interviews and their help in data extraction for the proposed model.

Conflicts of Interest: The authors report there are no competing interests to declare.

References

1. USGS. *Mineral Commodity Summaries 2021*; U.S. Geological Survey: Reston, VA, USA, 2021.
2. World Bank. *The World Bank Annual Report 2019*; World Bank: Washington, DC, USA, 2019.
3. Bruckner, K.D.; Smith-Roberts, A.; Bellido, V.M.; Ossandón, H.F.; Nyak, M.; Smith, N.; Urrego, L.J. *Peru's Environmental and Social Management in the Gold Mining Sector in the Midst of the COVID-19 Pandemic*; Sustainable Development Strategies Group: Gunnison, CO, USA, 2020.
4. Piñeiro, V.; Thomas, J.; Elverdin, P. *The Agricultural Sector as An Alternative to Illegal Mining in Peru: A Case Study of Madre de Dios (Discussion Paper No. 1582)*; International Food Policy Research Institute: Washington, DC, USA, 2016. Available online: https://www.ifpri.org/publication/agricultural-sector-alternative-illegal-mining-peru-case-study-madre-de-dios (accessed on 5 November 2021).
5. Langeland, A.L.; Hardin, R.D.; Neitzel, R.L. Mercury levels in human hair and farmed fish near artisanal and small-scale gold mining communities in the Madre de Dios River Basin, Peru. *Int. J. Environ. Res. Public Health* **2017**, *14*, 302. [CrossRef]
6. UNEP. *Annual Report 2012*; United Nation Environment Programme: Nairobi, Kenya, 2013.
7. Duff, P.M.; Downs, T.J. Frontline narratives on sustainable development challenges. *Extr. Ind. Soc.* **2019**, *6*, 552–561.
8. UNEP. *Global Mercury Assessment 2018*; UN Environment Programme: Geneva, Switzerland, 2019. Available online: https://www.unep.org/resources/publication/global-mercury-assessment-2018 (accessed on 7 February 2022).
9. Kuramoto, J.R. *Artisanal and Informal Mining in Peru*; International Institute for Environment and Development: Lima, Peru, 2001.
10. Ministerio de Energía y Minas. *Minería Aurífera Aluvial—Exposiciones Técnicas*, 3rd ed.; Ministerio de Energía y Minas: Lima, Peru, 2001.
11. Informatica Instituto Nacional de Estadistica e Informatica. (14 de November de 2018). Censos 2017: En Madre de Dios Viven 141 070 Personas. Available online: http://censo2017.inei.gob.pe/censos-2017-en-madre-de-dios-viven-141-070-personas/#:~:text=La%20provincia%20más%20poblada%20es,y%20en%20Tahuamanu%2011%20047 (accessed on 25 May 2022).
12. Kahhat, R.; Parodi, E.; Larrea-Gallegos, G.; MestaIan, C.; Vázquez-Rowe, I. Environmental impacts of the life cycle of alluvial gold mining in the Peruvian Amazon rainforest. *Sci. Total Environ.* **2019**, *662*, 940–951. [CrossRef]
13. Valk, N.V.; Bisschop, L.; Swaaningen, R.V. When Gold Speaks, Every Tongue Is Silent: The Thin Line Between Legal, Illegal, and Informal in Peru's Gold Supply Chain. In *Illegal Mining*; Palgrave Macmillan: Cham, Switzerland, 2020; pp. 299–327.
14. Thomas, M.J.; Veiga, M.M.; Marshall, B.G.; Dunbar, W.S. Artisanal gold supply chain: Measures from the Ecuadorian Government. *Resour. Policy* **2019**, *64*. [CrossRef]
15. Galvan, M.D.; Fritz, M.M.; Šimunović, N.; Stern, T.; Rauter, R. The mercury supply chain, stakeholders and their responsibilities in the quest for mercury-free gold. *Resour. Policy* **2016**, *50*, 177–192.
16. Moats, M.; Alagha, L.; Awuah-Offei, K. Towards resilient and sustainable supply of critical elements from the copper supply chain: A review. *J. Clean. Prod.* **2021**, *307*, 127207. [CrossRef]
17. Fernandez, F.F.; Lopez, C.P.; Febres-Molina, C.; Gamero-Begazo, P.L.; Gómez, B.; Bernabe-Ortiz, J.C.; Cáceres-Huambo, A.; Aguilar-Pineda, J.A. Identification and characterization of Peruvian native bacterial strains as bioremediation of Hg-polluted water and soils due to artisanal and small-scale gold mining in the Secocha Annex, Arequipa. *Sustainability* **2022**, *14*, 2669. [CrossRef]
18. Baena, Ó.J.R.; Mendoza, L.E.M. Sustainability of the artisanal and small-scale gold mining in northeast Antioquia-Colombia. *Sustainability* **2021**, *13*, 9345. [CrossRef]
19. Frimpong, A.E.; Lixiao, Z.; Sai, L.; Mingyue, P.; Shoujuan, T. Emergy perspectives on the environmental performance and sustainability of small-scale gold production systems in Ghana. *Sustainability* **2017**, *9*, 2034.
20. Sverdrup, H.U.; Ragnarsdottir, K.V. A system dynamics model for platinum group metal supply, market price, depletion of extractable amounts, ore grade, recycling and stocks-in-use. *Resour. Conserv. Recycl.* **2016**, *114*, 130–152. [CrossRef]
21. Gloser-Chahoud, S.; Hartwig, J.; Wheat, I.D.; Faulstich, M. The cobweb theorem and delays in adjusting supply in metals' markets. *Syst. Dyn. Rev.* **2017**, *32*, 279–308. [CrossRef]
22. Rebs, T.; Brandenburg, M.; Seuring, S. System dynamics modeling for sustainable supply chain management: A literature review and systems thinking approach. *J. Clean. Prod.* **2019**, *208*, 1265–1280. [CrossRef]
23. Olivares-Aguila, J.; ElMaraghy, W. System dynamics modeling for supply chain disruptions. *Int. J. Prod. Res.* **2020**, *59*, 1757–1775. [CrossRef]
24. Ge, Y.; Yang, J.-B.; Proudlove, N.; Spring, M. System dynamics modeling for supply-chain management: A case study on a supermarket chain in the UK. *Int. Trans. Oper. Res.* **2004**, *11*, 495–509. [CrossRef]
25. Gu, Q.-L.; Gao, T.-G. Joint decisions for R/M integrated supply chain using system dynamics methodology. *Int. J. Prod. Res.* **2011**, *50*, 4444–4461. [CrossRef]
26. Rathore, R.; Thakkar, J.J.; Jha, J.K. Impact of risks in foodgrains transportation system: A system dynamics approach. *Int. J. Prod. Res.* **2020**, *59*, 1814–1833. [CrossRef]
27. Kumar, S.; Nigmatullin, A. A system dynamics analysis of food supply chains—Case study with non-perishable products. *Simul. Model. Pract. Theory* **2011**, *19*, 2151–2168. [CrossRef]
28. Mula, J.; Campuzano-Bolarin, F.; Díaz-Madroñero, M.; Carpio, K.M. A system dynamics model for the supply chain procurement transport problem: Comparing spreadsheets, fuzzy programming and simulation approaches. *Int. J. Prod. Res.* **2013**, *51*, 4087–4104. [CrossRef]

29. Bunn, D.; Dyner, I. Systems Simulation to Support Integrated Energy Analysis and Liberalised Planning. *Int. Trans. Oper. Res.* **1996**, *3*, 105–115. [CrossRef]
30. Ozbayrak, M.; Papadopoulou, T.C.; Akgun, M. Systems dynamics modeling of a manufacturing supply chain system. *Simul. Model. Pract. Theory* **2007**, *15*, 1338–1355. [CrossRef]
31. Golroudbary, S.R.; Zahraee, S.M. System dynamics model for optimizing the recycling and collection of waste material in a closed-loop supply chain. *Simul. Model. Pract. Theory* **2015**, *53*, 88–102. [CrossRef]
32. Rabelo, L.; Helal, M.; Lertpattarapong, C.; Moraga, R.; Sarmiento, A. Using system dynamics, neural nets, and eigenvalues to analyse supply chain behaviour. A case study. *Int. J. Prod. Res.* **2007**, *46*, 51–71. [CrossRef]
33. Homer, J.B. A system dynamics model of national cocaine prevalence. *Syst. Dyn. Rev.* **1993**, *9*, 49–78. [CrossRef]
34. Jaen, S.; Dyner, I. Criminal cycles in the illegal drug industry: A system dynamics approach applied to Colombia. In Proceedings of the 2008 Winter Simulation Conference, Miami, FL, USA, 7–10 December 2008; pp. 1429–1436.
35. Dudley, R.G. A System Dynamics Examination of the Willingness of Villagers to Engage in Illegal Logging. *Theor. Approaches Underst. For. Gov.* **2014**, *19*, 31–53. [CrossRef]
36. Nazir, N.; Schmitt Olabisi, L. Illegal logging and wood consumption: Estimation and projection of illegal wood harvesting in Pakistan through system dynamics. *Pak. J. Commer. Soc. Sci. (PJCSS)* **2017**, *11*, 406–427.
37. Asner, G.P.; Tupayachi, R. Accelerated losses of protected forests from gold mining in the Peruvian Amazon. *Environ. Res. Lett.* **2016**, *12*, 094004. [CrossRef]
38. Horel, J.D.; Cornejo-Garrido, A.G. Convection along the Coast of Northern Peru during 1983: Spatial and Temporal Variation of Clouds and Rainfall. *Mon. Weather Rev.* **1986**, *114*, 2091–2105. [CrossRef]
39. Wara, M.W.; Ravelo, A.C.; Delaney, M.L. Permanent El Niño-Like Conditions During the Pliocene Warm Period. *Science* **2005**, *309*, 758–761. [CrossRef]
40. Fritz, M.; McQuilken, J.; Collins, N.; Weldegiorgis, F. *Global Trends in Artisanal and Small-Scale Mining (ASM): A Review of Key Numbers and Issues*; Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development (IGF): Ottawa, ON, Canada, 2017.
41. Barlas, Y. Formal aspects of model validity and validation in system dynamics. *Syst. Dyn. Rev.* **1996**, *12*, 183–210. [CrossRef]