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Research Original Article

Earthquake Risk Management for Mini-Hydro Power Plant: A Case Study Approach

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Abstract

This study evaluates the impact of an earthquake on a mini-hydropower plant (MHP) and formulates a disaster management strategy to enhance the operational resilience of MHPs against seismic events. Data was collected through interviews with relevant stakeholders, direct observations, and analysis of pertinent documents. The findings indicate that the 2018 Lombok earthquake caused severe damage to the catchment area, triggering increased sedimentation that disrupted the MHP's operation, resulting in decreased electricity production and escalated operational costs. Mitigation measures were implemented and proved effective in reducing debris-related downtime and improving electricity generation. Thes findings are expected to provide guidance for MHP operators in mitigating the negative impacts of earthquakes and similar disasters on plant operations.
Keywords: Mini-Hydropower Plant, Disaster Management, Mitigation, Earthquake, Strategy

Introduction

Hydropower is a renewable energy source that substantial promise for future development in Indonesia (Abdullah et al., 2020). By 2020, the nation had already established 379 hydropower plants, reaching an installed capacity of 5174 MW . of this total, 375 MW was contributed by mini-hydro power plants (PT PLN (Persero), 2021). However, a significant untapped potential of 96627 MW remains, including 21125 MW attributable to mini-hydro power, distributed across 7071 locations throughout the archipelago (Pranoto et al., 2021).

Mini-hydro power is categorized as a hydroelectric power plant with a capacity ranging from 1 to 10 MW (Pranoto et al., 2021). Interest in developing mini-hydro power plants is steadly increasing, driven by their abundant potential and more affordable investments cost compared to large-scale hydroelectric plants. Despite being a promising energy source, mini-hydro power plants exhibit vulnerability to natural disasters, including earthquakes, floods and landslides. This susceptibility to such hazard arises from several factors. Firstly, the construction of these plants often occurs in mountainous regions, which are inherently situated at tectonic plate boundaries, thus elevating the risk of seismic activity. Furthermore, mountainous areas are frequently in proximity to volcanic activity, including eruptions and volcanic earthquakes that can trigger seismic activity in surrounding areas. Secondly, the location of hydro power plants is often in riverine areas, which increases the risk of flooding. Dams, as part of these plants, also possess the potential to become sources of disaster, particularly if structural damage occurs, which could lead to flooding in downstream areas. Finally, mountainous regions tend to be characterized by fragile and fractured rock formations, coupled with slopes prone to landslides during periods of intense rainfall or seismic activity.

For instance, the Kokok Putih mini-hydro power plant, constructed on the slopes of Mount Rinjani in East Lombok, West Nusa Tenggara Province, sustained substantial damage due to earthquake that struck Lombok Island in 2018. This seismic event resulted in significant structural damage to its facilities, causing severe disruption to its operational capacity. This incident underscores the critical importance of effective disaster management in ensuring the safety and operational continuity of mini-hydro power plants.

The selection of the Kokok Putih mini-hydro power plant in Lombok as the focus of this research is based on several key factors. Firstly, this facility experienced significant damage from the 2018 earthquake, rendering it a pertinent case study for analyzing the vulnerability and resilience of mini-hydro power plant to seismic events. Secondly, in the aftermath of earthquake, the plant evaluated implemented various mitigation measures, the effectiveness of which can be evaluated within this study.

The study aims to evaluate the impact of the earthquake on mini-hydro power plant operations, and the steps required by mini-hydro power plant managers in dealing with and managing disaster emergency situations. This case study of operational mitigation measures at the Kokok Putih mini-hydro power plant can provide valuable insight into effective earthquake mitigation strategies to be applied to similar mini-hydro power plant in earthquake-prone areas, thereby contributing to increasing the resilience of renewable energy infrastructure in Indonesia.

Literature Review

Disaster impact management activities are primarily focused on the repair of public facilities, buildings and surrounding environment of affected areas (Nakoe & Lalu, 2022),. However, research on power plant infrastructure, particularly facilities utilizing renewable energy resources, remains limited. This scarcity of research is attributable to the inherent unpredictability of disasters. Nevertheless, several researchers have reported on the impact of disasters on hydropower facilities and their surrounding environments. These studies emphasize the necessity of post-disaster facility rehabilitation, taking into account factors such as geographical shifts, human displacement, and the replacement of turbines with suitable alternatives (Baidar et al., 2016; Goda et al., 2015).

B. Baidar et al conducted a study on the impact of the 7.6 magnitude earthquake that struck the Gorkha district of Nepal, resulting over 8000 fatalities. It affected numerous large-scale hydropower plants and damaged hundreds of micro-hydropower plants, necessitating both short-term and long-term rehabilitation efforts. Their research concluded that majority of existing micro-hydropower plants employed Pelton a crossflow turbine, despite the suitability of Francis turbines for many of these locations. An initial assessment of 61 micro-hydropower revealed that over 50% of the sites were better suited to Francis's turbines. Consequently, the study proposes a strategic rehabilitation plan for the affected power plants, which includes replacing older turbines with francis turbines in suitable locations.

Another challenge in hydropower facility management is the frequent underestimation of sedimentation during the planning of ancillary infrastructure (Cabral et al., 2024; Sidle et al., 2024). Despite sufficient surface water availability, several water resource projects have failed to meet expected outcomes primarily due to sedimentation issues. For instance, Nepal's river basins are recognized as having some of the highest sediment yields globally, yet reliable data on actual sediment production remains scarce. A case in point is the Kulekhani Reservoir in Nepal, where sedimentation processes have been studied to identify appropriate sediment management options and ensure the reservoir's long-term sustainability (Cabral et al., 2024; Sangroula, 2009).

Flood hazards have also impacted power plant operations. Damage from flooding is often attributed to inadequate forest planning and management. While the occurrence of floods is inherently difficult to predict and control, mitigation measures are necessary to reduce risks to human life and infrastructure (Amin et al., 2022; Kuniyal et al., 2019). Decisive steps are required, such as the construction of dams, which provide various economic, environmental, and social benefits, including recreation, flood control, and water supply.

Materials & Methods

Data was collected through direct access to internal company documents as well as through an interview process with individuals who were direct witnesses to the 2018 earthquake. The data collected in this research includes various sources, including Investigation reports, reports regarding damage, and documents -other relevant documents. Then also analyze post-earthquake images that visualize the impact of the damage. The data collected was then confirmed with the results of interviews conducted with related parties who had direct involvement in the incident.

Results and Discussion

1. *The Effects of Seismic Activity on Operational Performance*

Upon the occurrence of a seismic event, the mini-hydropower plant undergoes an automatic shutdown as precautionary measure. Due to the magnitude of the earthquake and the extent of the resulting damage, the system is subsequently subjected to a complete shutdown. The series of earthquakes that impacted Lombok Island in 2018 commenced on Juli 29th with a magnitude of 6.4, followed by a magnitude of 6.2 on August 5th, and culminated in two earthquakes occurring within a 10-hour interval on August 19th, registering magnitudes of 6.5 and 6.9, respectively.

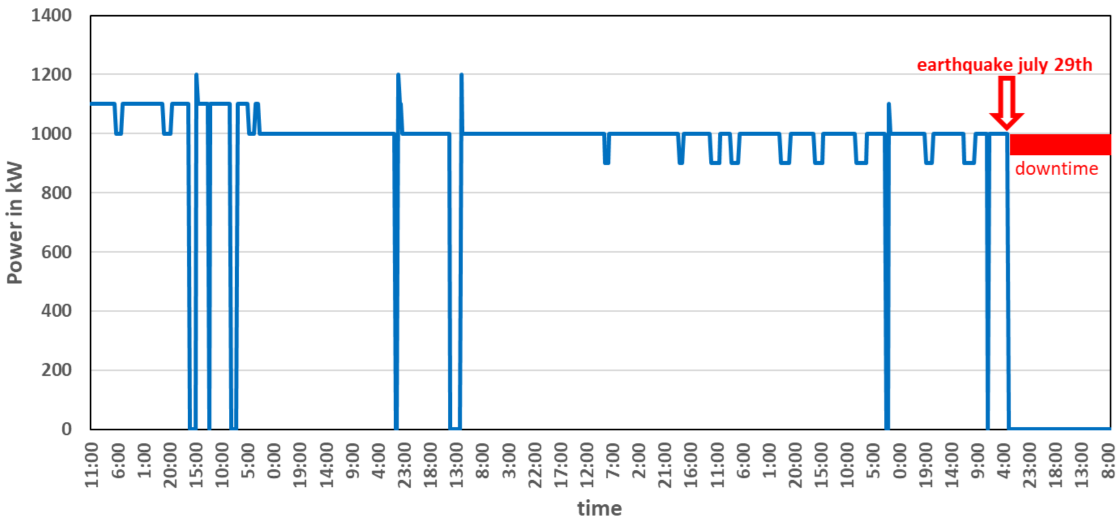

Figure 1. Power Production in July, 2018

The immediate impact of the earthquake on power production was a cessation of power generation due to damage to the electricity distribution network infrastructure in the earthquake-affected area. The collapse of electricity poles, severance of distribution cables, and damage to electrical grid structures prompted the state electricity company (PLN) to halt the power supply, consequently leading to the shutdown of the power plant. Production records indicate that on July 29th, 2018, et approximately 8:00 AM local time, the generating unit underwent an emergency shutdown due to the earthquake and remained inoperative. The power plant was subsequently brought back to online on August 13th, 2018, at 2:00 PM (Figure 2).

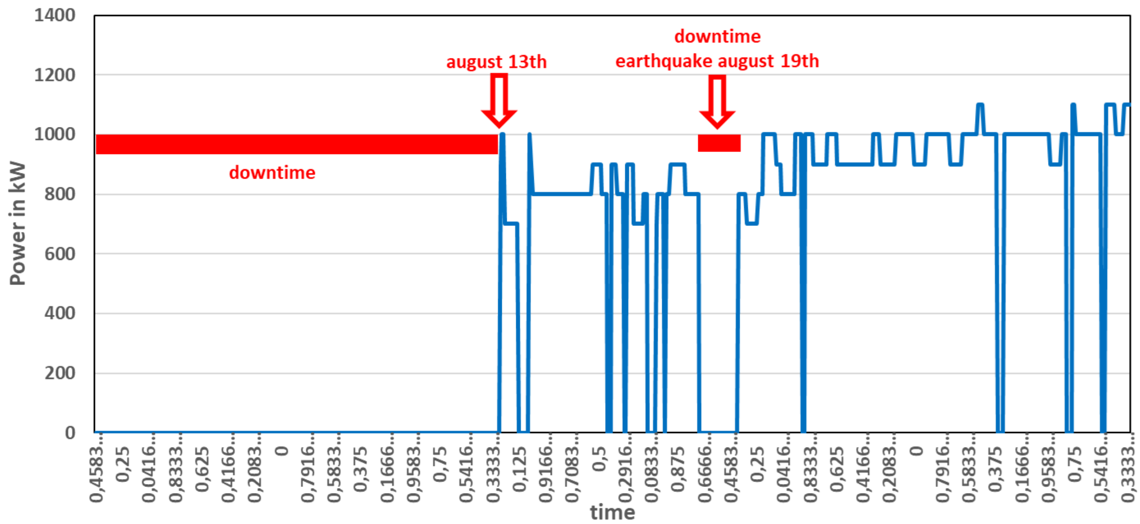

Figure 2. Power Production in August, 2018

Figure 2 also illustrates that, following the resumption of operations, the system continued to experience frequent disruptions, necessitating the shutdown of the power plant. These disruptions stemmed from disturbances within the electrical grid, primarily attributed to cable repairs, pole replacements, pole collapses, fallen trees, and other consequential events in the aftermath of the earthquake. In the instance of the seismic event on August 19th, the power plant was deactivated and rendered inoperable for a duration of 28 hours.

At the onset of the earthquake, the hydropower plant was operating at a capacity of 1 MW. However, the seismic event forced a cessation of operations for a period of 366 hours. This resulted in production loss of 366 MWh. A subsequent aftershock on August 19th further disrupted plant operations, leading to a 28-hour downtime and an additional production loss of 28 MWh. Moreover, disruptions to the electricity grid during August caused an additional 33 hours of operational downtime, contributing to a further production loss of 33 MWh. In total, cumulative production losses attributed to the earthquake and grid disturbances throughout August reached 426 MWh.

The repercussions of the earthquake persisted into September. An aftershock measuring 5.3 on Richter scale on September 11th resulted in a 6-hour operational downtime. This, coupled with 33 hours of grid repairs, led to a total downtime of 39 hours for September. Consequently, the cumulative potential production loss reached 39 MWh. Overall, the cumulative production loss due to the earthquake reached 466 MWh. Comprehensive data regarding downtime during the earthquake can be found in Table 1.

Table 1. Downtime During the Earthquake

Month	Earthquake-induced downtime (Hours)	Downtime due to grid maintenance (Hours)	Potential losses (MWh)
July	75	-	75
August	319	33	352
September	6	33	39
	Total		466

2. *Post-Earthquake Impact on Operational*

Earthquakes not only inflict immediate damage to hydropower plant infrastructure but also exert long-term effects on their operation. One significant consequence is the increased volume of sediment, rocks, and logging debris transported by water during the rainy season.

Figure 3. Image of the Channel During the Rainy Season (Documentation, January 23, 2019)

This disruption not only elevates the risk of sediment accumulation in the channel (Figure 3) but also leads to blockage of the hydropower plant intake by rocks and debris carried by the water flow. This accumulation of sediment and intake blockage directly contributes to increased operational downtime, necessitating more intensive and frequent maintenance to ensure the smooth flow of water and the continued operation of power plants.

This situation necessitates continuous channel clearing to ensure unimpeded water flow to the turbines. Consequently, this alters the operators' work patterns, requiring them to conduct more frequent patrols and channel cleaning. Furthermore, the utilization of excavators to remove blockage materials adds to the operational costs of the hydropower plant. These increases in operational costs and shifts in operator work patterns represent consequences of the earthquake's impact that must be borne by the plant.

A significant sedimentation phenomenon occurred within the hydropower plant's catchment area following the earthquake. This phenomenon commenced in November and December 2018, with a relatively low intensity. The intensity of sedimentation then escalated substantially from January to March 2019, before beginning to subside in early April 2019. This surge in sedimentation intensity is closely correlated with the rainy season in the region. High precipitation within the catchment area carries materials such as sediment, rocks, and logging debris into the rivers and streams leading to the hydropower plant. These materials subsequently accumulate in the channels and intake, leading to channel overfilling and blockage of the intake, ultimately preventing water from reaching the plant's turbine system.

It was recorded that in the rainy month (January – April) in 2018 there was no downtime caused by sediment, but after the earthquake, namely in the rainy month of 2019, downtime was recorded for 142 hours in January, 154 hours in February, and decreased in March to 47 hours and April 25 hours as the rainy season ends, as seen in Table 4.8. Total downtime due to sediment in 2019 was 368 hours and in 2020 it increased to 1541 hours.

Table 2. Downtime Due To Debris (Hours)

	2018	2019	2020
January	-	142	373
February	-	154	454
March	-	47	573
April	-	25	141
Total		368	1.541

This situation presents a challenge to the operational activities of the Kokok Putih hydropower plant. Continuous channel clearing efforts and regular monitoring of the catchment area are crucial for minimizing the negative impacts of sedimentation and maintaining smooth plant operation. However, during the subsequent rainy season, the volume of sediment and debris transported from upstream did not decrease but instead increased. Consequently, downtime escalated, reaching 373 hours in January 2020, 454 hours in February 2020, and 573 hours in March 2020, before finally decreasing to 141 hours in April 2020, coinciding with the end of the rainy season (Table 2).

3. Post-Earthquake Impact on Electricity Generation

The eastern region of Lombok Island typically experiences its rainy season from November to April, as illustrated in Figure 4, which presents rainfall data over a four-year period. The production pattern of the hydropower plant generally aligns with these distinct wet and dry seasons. The wet season, characterized by higher rainfall, occurs between November and April, while the dry season, with lower precipitation, prevails from May to October.

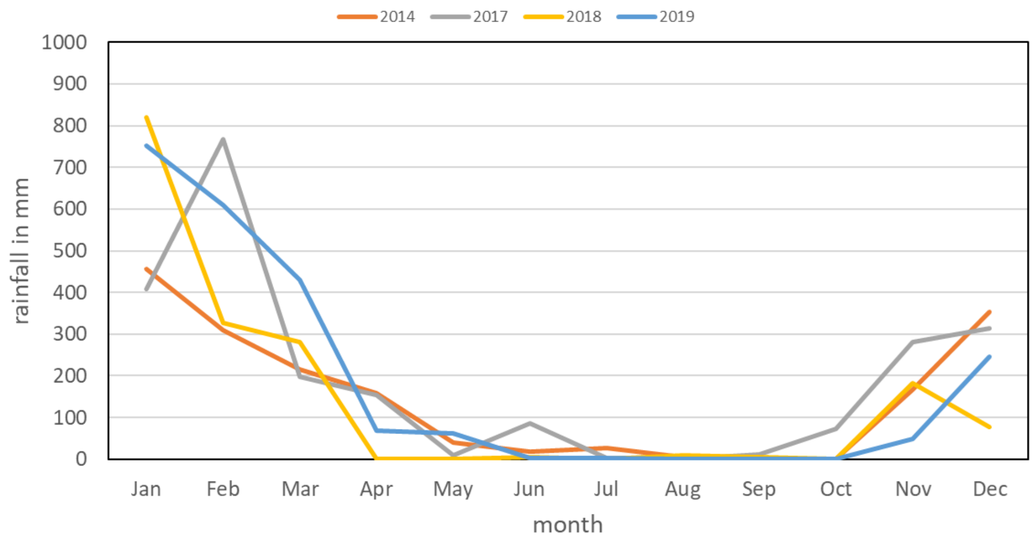

Figure 3. Rainfall *D*ata for 2014,2017,2018, and 2019 (BPS East Lombok)

This pattern is reflected in the hydropower plant's production graph (Figure 4), where electricity generation peaks between February and March, coinciding with the high-rainfall period of the rainy season. During this period, the water flow to the turbines increases, resulting in greater energy production. Conversely, during the dry season, characterized by low rainfall, water discharge in the rivers and streams declines, leading to a decrease in the plant's electricity generation. This is evident in the graph, where electricity production reaches its lowest point in August and September.

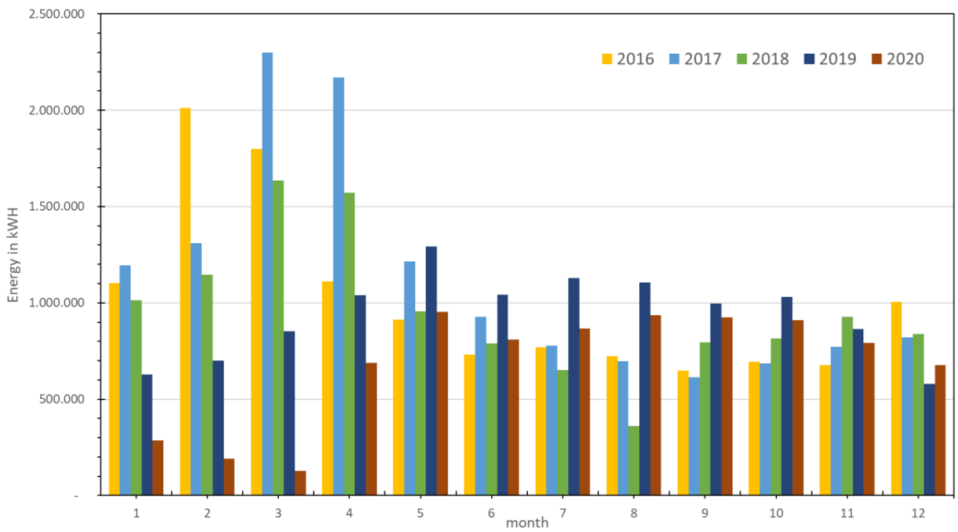

Figure 4. Electricity Production from 2016-2020

Table 3. Electricity Production from 2016-2020 (kWh)

	2016	2017	2018	2019	2020
January	1,102,608	1,194,560	1,014,160	628,880	284,720
February	2,011,968	1,309,120	1,146,480	699,600	190,960
March	1,798,992	2,298,640	1,634,560	851,600	128,880
April	1,110,960	2,169,360	1,571,920	1,040,560	689,200
May	912,888	1,216,480	956,240	1,292,080	952,640
June	730,800	927,920	788,400	1,042,880	810,400
July	767,808	776, 320	652,320	1,128,720	867,760
August	721,680	697,920	359,280	1,105,040	936,400
September	649,440	613,440	796,240	997,440	923,680
October	695,640	684,800	816,080	1.029,840	911,360
November	676,800	772,640	927,840	864,640	791,520
December	1,005,144	820,560	839,520	578,800	676,160

To examine the production changes before, during, and after the earthquake, the same data are presented in tabular form (Table 3). This tabular representation allows for a more precise quantitative analysis of post-seismic production changes. By comparing the values within the table, insights into both the immediate and long-term impacts of the earthquake on production activities can be obtained.

Prior to the 2018 earthquake, the hydropower plant's production in 2016 and 2017 followed a seasonal pattern influenced by rainfall. Production exhibited a gradual increase from January to February or March, followed by a decline in April and May. This pattern can be attributed to the abundant water availability during the rainy season and the subsequent reduction in water flow during the dry season.

Figure 4 illustrates that the hydropower plant's productivity in July and August 2018 was lower compared to previous years. This decline stemmed from a series of earthquakes in late July and August 2018, which induced downtime and consequently reduced productivity. Following the 2018 earthquake, the plant's production graph reveals a significant shift in the production pattern for 2019 and 2020. In contrast to the pre-earthquake pattern, where production consistently increased during the wet season, the post-earthquake period exhibits a decline in production during these wetter months. This is clearly evident in December 2018, where despite the onset of the rainy season, the hydropower plant experienced a decline in production compared to November. This phenomenon contrasts with the pre-earthquake pattern, in which December consistently exhibited higher production than November. To compare production changes during the rainy season before and after the earthquake, Table 4 was created, with the average monthly pre-earthquake production calculated as the mean production for the respective month from 2016, 2017, and 2018. The average pre-earthquake production data were then compared with the corresponding monthly production in 2019 and 2020, revealing the percentage decrease in production compared to the average pre-earthquake production.

Table 4. Comparison of Monthly Production Before and After Earthquake During Rainy Season (kWh)

	Pra gempa	Pasca gempa					
	2016 - 18	Tahun 2019			Tahun 2020		
	Production Average	Production	Reduction		Production	Reduction	
Month	kWH	kWH	kWH	%	kWH	kWH	%
January	1,103,776	628,880	474,896	43.0%	284,720	819,056	74.2%
February	1,489,189	699,600	789,589	53.0%	190,960	1,298,229	87.2%
March	1,910,731	851,600	1,059,131	55.4%	128,880	1,781,851	93.3%
April	1,617,413	1,040,560	576,853	35.7%	689,200	928,213	57.4%
Total	**6,121,109**	**3,220,640**	**2,900,469**	**47.4 %**	**1,293,760**	**4,827,349**	**78.9%**

Table 4 demonstrates that the downward trend in production persisted into the early months of the following year. In January-March of 2019, the hydropower plant's output exhibited figures significantly below those of previous years. For instance, production in January 2019 reached only 628,880 kWh, equivalent to 57% of the average January production from 2016 to 2018, indicating a 43% decrease. A similar phenomenon was observed in February and March 2018, as illustrated in Table 4.

The subsequent rainy season in 2020 exhibited a more pronounced decline in production during the rainy months compared to 2019. This downward trend commenced in November 2019 and persisted into December 2019. Unlike 2019, where production showed a slight increase from January to March, production in 2020 steadily declined despite the increasing rainfall intensity in January, February and March. The lowest point in production occurred in March 2020, when the hydropower plant generated only 128,880 kWh . It represents 6.7% of the average March production before the earthquake, significantly a substantial 93.3% reduction in output.

Aggregating the production for these four months to represent the decline in rainy season output, it can be concluded that in 2019, the rainy season production experienced a 47.4% decrease, and in 2020, an even more substantial 78.9 % decrease compared to the average rainy season production before the earthquake. This drastic decline highlights the long-term impact of the earthquake on the hydropower plant's performance.

The decline in electricity production during the rainy season at the Kokok Putih mini-hydro power plant exerts a dominant influence on the total annual output. This is evident in Figure 4, which illustrates that the rainy season constitutes the period of highest production, approaching the plant's maximum installed capacity. Consequently, this reduction in rainy season production significantly impact the company's revenue, potentially affect the survival business viability.

4. Mitigation measures implemented

Damage to the catchment area has resulted in long-term disruptions to the hydropower plant's operation, primarily through intake blockage and sediment accumulation in the water channels. Both of these factors contribute to reduced power generation due to decreased water flow to the turbines, sometimes even necessitating complete shutdown due to insufficient water supply. Therefore, implementing mitigation measures to address this issue is of most importance to restore and enhance the plant's productivity.

Direct mitigation within the catchment area is not programmed because the hydropower plant's catchment area falls within the Gunung Rinjani National Park, a designated area managed exclusively by government-appointed agencies. Therefore, feasible mitigation measures do not aim to rehabilitate the catchment areas itself but rather to prevent the negative impacts of catchment area itself but rather to prevent the negative impacts of catchment degradation on the plant's operation.

To address the production decline caused by frequent downtime resulting from intake blockage and sediment accumulation in the water channels, the following mitigation measures were implemented: constructing an additional intake as an alternative when the existing intake is blocked; increasing the number of excavators to expedite sediment removal from the channels; and constructing a second channel from the new intake to the settling basin, parallel to the existing channel, as an additional solution to mitigate downtime caused by sediment accumulation.

Table 5. Mitigation Measures for Catchment Area Degradation

Year	Mitigation	Purpose
2020	Constructing an additional intake	Reducing downtime attributed to intake obstruction
2021	Adding an excavator and constructing a secondary channel to the settling basin	Mitigating downtime caused by sediment accumulation in waterways

5. *Results of mitigation measures*

To analyze the changes before and after the implementation of mitigation measures, Table 6. Was complied, presenting downtime data attributed to sedimentation during the rainy season months from 2020 to 2023. This data representation facilitates a more precise quantitative analysis of fluctuations in debris-related disruption following the mitigation efforts.

Table 6. Operational Disruptions Due To Debris (Hours)

	2020	2021	2022	2023
January	373	91	5	2
February	454	116	3	1
March	573	-	-	
April	141	-	-	
Total	1.541	207	8	3
		A decline of 87% relative to the 2020 baseline	*A decline of 96% relative to the 2021 baseline*	*A decline of 98% relative to the 2021 baseline*

The initial mitigation measure, implemented in 2020, involved the construction of an additional intake. The positive impact of this supplementary intake is evident in the reduction of debris-related downtime, as illustrated in table 6. During the 2020 rainy season, downtime reached 1541 hours. However, following the addition of the new intake, it decreased substantially to 207 hours in 2021, representing an 87% reduction- a considerable achievement.

This reduction in downtime is caused by reduced occurrences of blockages at the intake. Previously, blockages in tunnel-shaped intakes by materials such as large stones and forest waste wood often caused the unit to shutdown completely because there was no water flow to the channel. Overcoming this problem takes quite a long time, especially due to access difficulties and work safety considerations during bad weather. With additional intake, the risk of blockage can be minimized, thereby reducing down time by up to 87%.

Then in Table 6. We can also see the effect of mitigation measures taken in 2021 in the form of increasing the number of excavators and building a second channel from the intake to the settling tank. These two steps were able to reduce the downtime figure from 188 hours in 2021 to 8 hours in 2022 and 3 hours in 2023. A fairly large achievement is a reduction in downtime of above 96%.

Conclusions

The 2018 Lombok earthquake severely impacted the Kokok Putih hydropower plant, highlighting a critical oversight in post-disaster recovery: while physical damage was addressed, operational disruptions from landslides in the catchment area were neglected. This led to a significant decline in productivity, unmitigated until 2020 when strategic measures, including a new intake, additional excavators, and a secondary channel, were implemented, successfully restoring pre-earthquake production levels. This experience underscores the need for comprehensive risk assessment and proactive mitigation in post-disaster recovery to ensure the resilience of hydropower plants.

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