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Research Paper

MODFLOW-Based Evaluation of Mine Drainage and Environmental Risks in the Kulon Progo Iron Sand Mining Area

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Abstract

The iron sand mine along the southern coast of Kulon Progo, Special Region of Yogyakarta, is one of Indonesia's strategic mining operations facing complex water management challenges. The distinctive local hydrogeological characteristics including a shallow unconfined aquifer with high hydraulic conductivity (10^{-3}-10^{-2} m/s), a shallow groundwater table (0.5-3.0 m bgs), and proximity to the Indian Ocean, directly determine the design and capacity of the mine drainage system. This study comprehensively examines five main aspects: (1) the hydrogeological characteristics of the Kulon Progo iron sand mining area; (2) the influence of hydrogeological conditions on the mine drainage system; (3) the implications of dewatering operations for groundwater quality and quantity; (4) the potential environmental risks generated; and (5) recommendations for sustainable management. Hydrological analysis using the Gumbel Type I distribution produced a 3 year return period design rainfall of 153.30 mm/day and a rainfall intensity of 53.71 mm/h based on 10 years of data. The 10 year dataset, while consistent with the operational period (2016-2025), represents a recognized limitation for extreme value frequency analysis; a longer record would improve the precision of tail distribution estimates. The required dewatering capacity reaches 55 m^3/s (with a 95% confidence interval of ± 5.8 m^3/s based on sensitivity analysis of rainfall and seepage parameters), with groundwater seepage contributing 10 m^3/s. Major environmental risks include local groundwater table decline (1.5-3.0 m drawdown), potential seawater intrusion, increased runoff TSS of up to 2.0 mg/L, and disturbance of mangrove ecosystems. Sustainable management recommendations include targeted dewatering based on MODFLOW modeling, a real time monitoring system, progressive hydrogeological reclamation, and compliance with environmental quality standards under Government Regulation No. 22/2021.

Keywords

Coastal Hydrogeology, Mining Drainage System, Kulon Progo Iron Sand, Groundwater Quality, Environmental Risks, Sustainable Management

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1. INTRODUCTION

The southern coast of Kulon Progo in the Special Region of Yogyakarta is known to hold iron sand reserves with significant economic value for Indonesia. These placer deposits were formed through river and coastal transport processes originating from the Menoreh Mountains. They contain minerals such as magnetite (Fe_3O_4), ilmenite ($FeTiO_3$), and hematite (Fe_2O_3), with estimated reserves of up to 3 billion tonnes and an average iron content of around 7–8% (Irzon, 2018). Because of this potential, Kulon Progo has become an important mining area, especially as demand continues to grow from Indonesia's national steel industry.

Nevertheless, extracting iron sand in coastal areas comes with technical and environmental challenges that are quite different from those found in conventional inland mining. Coastal areas are generally filled with shallow aquifers that are highly permeable to air, groundwater levels that fluctuate following tidal movements, and the constant threat of sea air seepage Because of these conditions, designing an effective dewatering system becomes one of the most critical parts of mine planning, both for operational safety and environmental protection (Haq et al., 2011). If waters are not properly managed, mining activities can not only endanger safety, but also have the potential to leave scars on the environment that may never heal.

Mine dewatering encompasses all the infrastructure and operational measures used to intercept, collect, and remove water from an active mining area (Hustrulid et al., 2013). In coastal mines, this process is even more complex because water doesn't come from a single source rainfall, surface runoff, and even tidal groundwater seepage can all simultaneously fill the excavation area. Because these inflows occur together and can change over time, coastal mine drainage requires more detailed and accurate calculations than typical inland mine drainage systems. In addition, climate uncertainty should also be considered in the design, as climate change may increase rainfall intensity and flood frequency beyond the limits used in conventional designs based on historical data (Buurman and Babovic, 2016; Rözer et al., 2022).

From an environmental perspective, large scale dewatering in coastal mining areas can have serious impacts on groundwater availability and quality, the stability of nearby mangrove ecosystems, and the condition of coastal marine waters. Punkkinen et al. (2016) found that iron sand mines in Indonesia often face water management problems that are more complex than expected during the early planning stage, mainly because local aquifer conditions are not well mapped. Similar concerns have also been reported in IJEMS studies on mine void water management, groundwater quality indexing, and water pollution index assessment. These studies emphasize the importance of integrated water quality evaluation as a basis for making sound environmental decisions (Rahmi et al., 2019; Rendana et al., 2022; Thanh Giao et al., 2021).

Despite growing research on coastal mine hydrogeology, several important gaps still remain, especially in understanding how tidal dynamics, ENSO related rainfall variability, and aquifer heterogeneity interact and influence dewatering system performance in Indonesian iron sand mines. Previous studies, such as Haq et al. (2011) have generally examined each inflow component separately or have not used transient MODFLOW simulations that can capture seasonal groundwater changes. To address these gaps, this study combines a 10 year rainfall frequency analysis, aquifer parameters obtained from pumping tests, transient groundwater simulations using MODFLOW-2005, and a three stage Ecological Risk Assessment (ERA) framework. These methods are integrated to provide a more comprehensive evaluation of mine drainage system performance at the Kulon Progo iron sand mine.

This study provides a comprehensive assessment structured around five interrelated dimensions of sustainable coastal mine management: (1) characterization of local hydrogeological conditions, (2) their governing influence on drainage system behavior, (3) quantitative implications for water quality and quantity, (4) ecological risk evaluation, and (5) evidence based recommendations for sustainable operational management. The hydrological component draws on 10 years of daily rainfall records (2016-2025) analyzed using the Gumbel Type I distribution a frequency analysis method widely validated in tropical hydrological applications (Rao and Hamed, 2019; Kite, 2019) and demonstrated to be appropriate for annual maximum rainfall modeling under Indonesian climatic conditions (Muzakir et al., 2023).

Figure 1 presents the conceptual framework guiding this study, illustrating the analytical linkages among three core domains: (1) hydrogeological characterization, (2) drainage system design and performance evaluation, and (3) environmental impact assessment. This framework structured the data collection strategy, governed the selection of analytical methods, and provides the interpretive basis for the results presented in subsequent sections.

2. EXPERIMENTAL SECTION

2.1 Materials

2.1.1 Hydrogeological Characteristics of Tropical Coastal Areas

The hydrogeology of tropical coastal areas is heavily influenced by the interaction between freshwater flowing from inland and saltwater inflowing from the ocean.This interaction forms a transition zone known as the freshwater saltwater boundary (Werner et al., 2013). Under natural, balanced conditions, the position of this boundary can be explained using the Ghyben-Herzberg principle.This principle explains the relationship between the height of the freshwater table above sea level and the depth of the freshwater saltwater interface within coastal aquifers. Under the assumption of typical freshwater and seawater densities, the interface depth is approximated as approximately 40 times the freshwater hydraulic head above mean sea level; consequently, a 1 m reduction in freshwater head corresponds to an estimated 40 m upward displacement of the interface under idealized hydrostatic, sharp interface conditions (Post et al., 2018; Fetter, 2020; Todd and Mays, 2018).

However, it is important to note that the Ghyben-Herzberg relationship assumes hydrostatic equilibrium; under transient pumping conditions, the actual interface response is more complex and may be both faster and more spatially variable than the equilibrium model predicts (Werner et al., 2013). Notwithstanding these limitations, the principle provides a useful first order framework for assessing the seawater intrusion risk induced by mine dewatering operations. The southern coastal plain of Kulon Progo Regency is underlain by relatively young Quaternary alluvial and coastal plain deposits, predominantly comprising loose sand, clayey sand, and sandy clay interbedded at varying depths (Rahardjo et al., 2020).

The lithology of the shallow aquifer study area is unconfined, with hydraulic conductivity (K) values ranging from 10^3 to 10^2 m/s. This value falls into the high to very high permeability category according to Fetter (2020) classification.The aquifer's transmissivity ranges from 50-150 m^2/day, while the specific yield (Sy) value is 0.15-0.25. The variation in these parameter values reflects the spatial heterogeneity at the four pumping test locations. Hydraulic conductivity values tend to follow a log normal distribution, with a mean $\log_{10}$K of -2.5, a standard deviation of 0.32, and a sample size of four. Therefore, the estimated seepage rate calculated

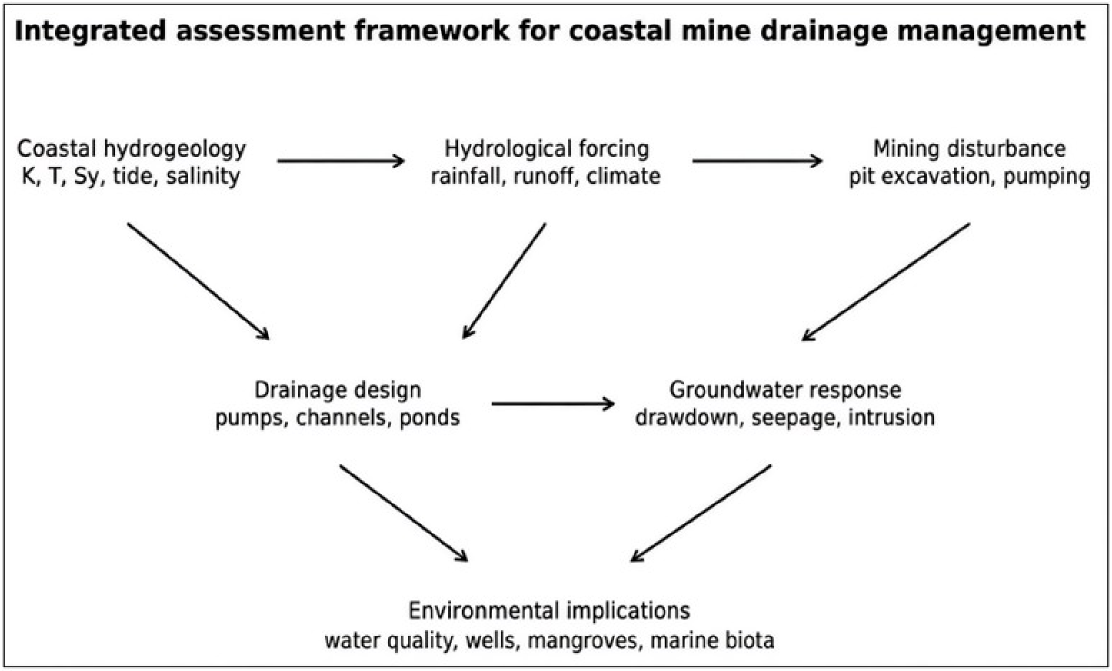

Figure 1. Conceptual Framework Linking Hydrogeological Conditions, Mine Drainage Design, Groundwater Response, and Environmental Impact Pathways

assuming a homogeneous aquifer can be considered a conservative upper bound scenario. If the flow model considers a layered or heterogeneous aquifer structure, the resulting seepage flux values are likely to be lower and vary spatially (Fetter, 2020).

Groundwater level dynamics in this coastal setting are predominantly controlled by two interacting forcing mechanisms, seasonal rainfall variability and marine tidal fluctuations. Tidal signals are known to propagate considerable distances inland in high permeability coastal aquifers. Michael et al. (2013) documented tidal influence extending up to 500-1,500 m from the shoreline under such conditions. In the Kulon Progo coastal plain, this influence is estimated to penetrate 800-1,200 m inland, a range that encompasses the active mining zone and directly implicates tidal forcing as a non negligible component of the mine inflow budget.

2.1.2 Geology and Mineralogy of Iron Sand Deposits

The iron sand deposits fringing the southern coast of Kulon Progo represent placer accumulations of heavy minerals sourced from the andesitic to basaltic volcanic terrain of the Oligocene–Miocene Menoreh Mountains (Rahardjo et al., 2020). Protracted subaerial weathering of these source rocks, combined with fluvial entrainment and downstream transport through the Progo, Serang, and Bogowonto Rivers, has delivered heavy mineral enriched sediment loads to the coast, where longshore drift and wave action have further concentrated them into ore bodies of viable grade and lateral continuity (Haq et al., 2011).

Macroscopically, the deposits present as dark to black sand, a characteristic appearance reflecting a mineralogy dominated by iron bearing heavy phases principally magnetite, hematite, ilmenite, and rutile set within a quartz dominated non magnetic gangue matrix (Noviadi and Setiady, 2020). Current mineralogical proportions are estimated from point counting and bulk chemical analysis of exploration borehole cores (Irzon, 2018). However, site scale quantitative phase characterization by X-ray diffraction (XRD) and scanning electron microscopy with energy dispersive X-ray spectroscopy (SEM-EDS) remains absent from the published literature. Such analyses are recommended as a near term investigative priority, as they would provide the phase specific data needed to constrain geochemical leaching behaviour and sharpen acid mine drainage (AMD) risk predictions beyond what bulk chemistry alone can support.

The occurrence of ilmenite within the assemblage carries specific environmental implications: its weathering and oxidation under mine drainage conditions can release titanium (Ti) and vanadium (V) into solution, introducing trace element loading pathways into site runoff and drainage effluent that are not captured by conventional iron focused water quality monitoring frameworks. Incorporating Ti and V as target analytes in baseline and operational water quality programs is therefore warranted. On the processing side, metallurgical testwork by Aritonang et al. (2019) confirmed the technical viability of pig iron production from direct reduction of the heavy mineral concentrate, underpinning the broader economic rationale for deposit development.

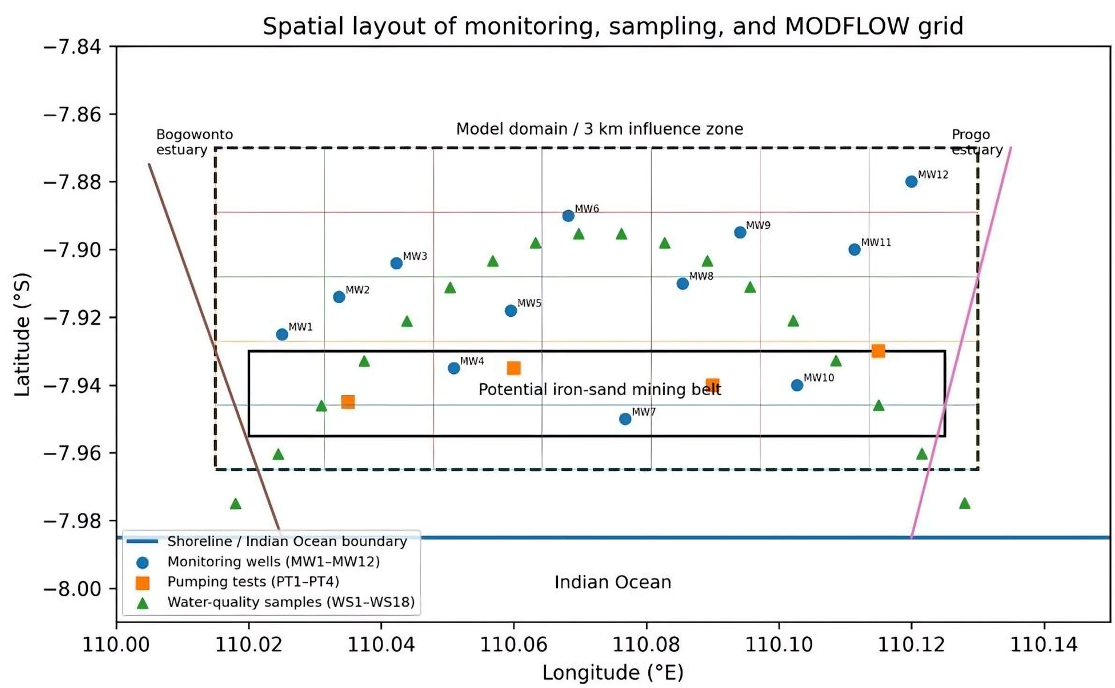

Figure 2. GIS-Based Schematic Layout of the Study Area, Monitoring Wells, Pumping Test Locations, Water Quality Sampling Points, and MODFLOW Model Grid within the Coastal Influence Zone

Table 1. Annual Maximum Daily Rainfall Data for Kulon Progo (2016–2025)

Year	Maximum Rainfall (mm/day)	Rank (m)	ENSO Anomaly
2016	117	5	Neutral
2017	128	6	Weak La Niña
2018	65	1	El Niño
2019	82	3	Neutral
2020	138	7	Strong La Niña
2021	70	2	Weak El Niño
2022	138	7	Neutral
2023	95	4	Neutral
2024	173	9	Moderate La Niña
2025	275	10	Strong La Niña

Source: BMKG Yogyakarta Station, processed by the authors (2024); ENSO anomaly column based on Aldrian and Dwi Susanto (2003)

2.1.3 Coastal Mine Drainage Systems

Dewatering systems in open pit mines in coastal areas generally consist of four main components: surface drainage infrastructure, in pit pumping, active groundwater level lowering in the aquifer, and air treatment before it is discharged to the receiving body (Hustrulid et al., 2013). What distinguishes coastal mines from inland mines is the presence of two distinct inflow sources. The first source originates from episodic, high intensity tropical rainfall and produces runoff. These two water sources have inconsistent time patterns. Rainfall induced runoff typically occurs intermittently and is controlled by storm events or extreme rainfall events, while tidal seepage follows a semi diurnal to seasonal cycle. Nevertheless, both must be handled by the same drainage system. These two major influences make dewatering planning in coastal mines more complex than drainage design in open pit mines in these areas. Accordingly, the Mine Environment Neutral Drainage Program (2020) advocates an integrated strategy combining hydraulicbarriers, well based aquifer dewatering, and engineered surface drainagenetworks specifically for mines operating in high permeability coastalhydrogeological settings.

Settling ponds are a crucial component of a mine water management system. They serve as the primary facility for reducing total suspended solids (TSS) levels before the discharged air is discharged into the surrounding surface air (Gumińska et al., 2021; Zapico et al., 2021). The performance of a settling pond is significantly influenced by the hydraulic retention time (HRT), which is the length of time the air remains in the pond. This retention time must be properly designed to allow sufficient time for fine particles targeted for treatment to settle by gravity before the water exits the system. In coastalmine settings subject to high and variable discharge regimes, single stage pondconfigurations are generally insufficient to maintain consistent TSS removal-

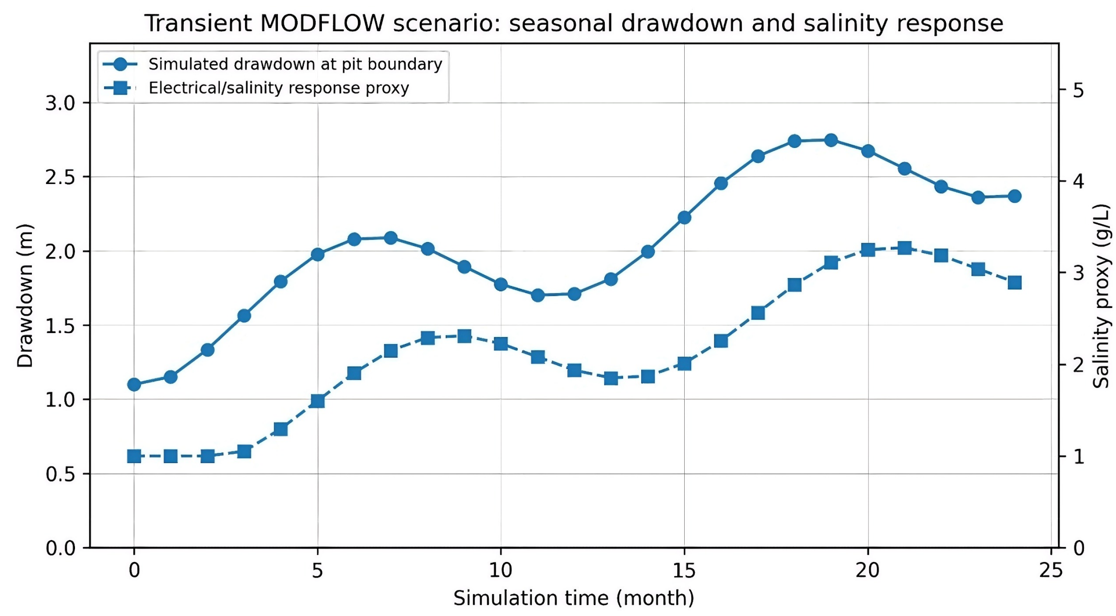

Figure 3. MODFLOW Transient Drawdown Time Series at Three Monitoring Well Distances

Table 2. Hydrogeological Parameters of the Aquifer in the Kulon Progo Iron Sand Mining Area

Aquifer Parameter	Value/Range	Unit	Determination Method	n (samples)
Aquifer Type	Unconfined	–	Borehole log interpretation	12
Groundwater Table Depth	0.5–3.0	m bgs	Monitoring well measurement	12
Effective Aquifer Thickness	5–15	m	Borehole log + pumping test	4
Hydraulic Conductivity (K)	10^{-3}–10^{-2}	m/s	Pumping test (Theis)	4
Transmissivity (T)	50–150	m^2/day	Pumping test (Cooper–Jacob)	4
Specific Yield (Sy)	0.15–0.25	–	Pumping test	4
Natural Hydraulic Gradient (i)	0.003–0.008	–	Isopiezometric map	12
Transition Zone Salinity	1.5–5.0	g/L	Water chemistry analysis	18
GALDIT Index	6.8–8.2	–	Chachadi & Lobo Ferreira	4
Intrusion Vulnerability Class	High–Very High	–	GALDIT classification	–

Source: Field measurements and analysis (2024); GALDIT adapted from Chachadi and Lobo-Ferreira (2021)

under peak flow conditions. Cascade arrangements wherein effluent passes sequentially through multiple ponds of progressively decreasing turbidity are therefore preferred, as they provide the hydraulic buffering and additional settling capacity needed to sustain removal efficiencies exceeding 90% across a range of operational flow scenarios (Akcil and Koldas, 2006).

2.1.4 Rainfall Frequency and Intensity Analysis

Rainfall frequency analysis underpins the estimation of design rainfall magnitudes at specified return periods, providing a necessary quantitative foundation for sizing hydrologic and hydraulic drainage infrastructure. Annual maximum daily rainfall from the 10 year record (2016-2025) was fitted to the Gumbel Type I extreme value distribution, selected on the basis of its well established theoretical suitability for modelling hydrological maxima and its widespread application in engineering hydrology practice (Stedinger et al., 2022; Chow et al., 2021). Goodness of fit was evaluated using the Kolmogorov–Smirnov and chi square tests, both standard procedures in rainfall frequency studies conducted for tropical mine drainage design (Tri Aditya and Susilo, 2025; Muzakir et al., 2023).

Table 3. Design Rainfall Analysis Using the Gumbel Type I Distribution

Statistical Parameter	Value	Unit
Mean ($\bar{X}$)	128.10	mm/day
Standard Deviation (Sd)	61.91	mm/day
Minimum Value (2016)	65.00	mm/day
Maximum Value (2025)	275.00	mm/day
Coefficient of Variation (C_v)	0.48	–
Reduced Mean (Yn), n=10	0.49	–
Reduced Standard Deviation (Sn), n=10	0.95	–
Skewness Coefficient (Cs)	1.25	–
K-S Test Statistic (D)	0.189 ($< D_{\alpha=0.05} = 0.409$); Accept	–
Chi square Test (χ^2)	3.24 ($< \chi^2_{\alpha=0.05} = 5.99$, df=2); Accept	–

Source: Statistical analysis results (2025); Yn and Sn parameters follow Chow et al. (2021)

Sub daily rainfall intensities required for drainage system sizing were derived from daily design rainfall totals using the Mononobe equation, an empirical intensity duration formula entrenched in Indonesian engineering practice precisely because short duration pluviograph records are seldom available at remote mine sites (Suripin, 2020; Asih Astarini et al., 2022). Evidence for the equation's transferability to tropical Asian settings comes from Bandara et al. (2025), whose comparison against pluviograph measured intensities returned $R^2 = 0.87$ sufficient for preliminary drainage dimensioning, though not a substitute for site calibrated data. At Kulon Progo, pluviograph records were unavailable throughout the study period, making uncalibrated application of the Mononobe equation the only practicable option. The intensity estimates presented in this study should therefore be treated as provisional, validation against local short duration rainfall data remains a necessary next step before these values are used in final infrastructure design (Harisuseno et al., 2020).

2.1.5 Impacts of Coastal Mining on the Hydrological Environment

Mining activities in coastal areas can have various impacts on local hydrological conditions. These impacts include changes in groundwater flow patterns, decreased air quality, and disruption to surrounding marine ecosystems.In a study of coastal iron sand mining in Africa, Rangel-Buitrago et al. (2023) explained that lowering groundwater levels due to the dewatering process can directly impact the productivity of mangrove ecosystems, especially mangroves. If not managed from the outset, these impacts can continue to increase over time and potentially become difficult to manage.

The risk of air pollution during iron sand mining can occur through several processes. First, surface air runoff can carry high levels of total suspended solids (TSS) due to disturbance of the land surface. Second, oxidized iron and titanium minerals can dissolve metal elements into the air. Furthermore, the use of chemicals in the processing process also has the potential to pollute the ground air (Akcil and Koldas, 2006). Government Regulation No. 22 of 2021 on Environmental Protection and Management establishes strict requirements for mine wastewater management, including quality standards for TSS, pH, heavy metals, and biological parameters prior to discharge to water bodies (Ministry of Environment and Forestry Republic of Indonesia, 2021).

2.2 Methods

This study focuses on the coastal iron sand mining area of southern Kulon Progo, Special Region of Yogyakarta (coordinates 7°50'-8°00' S and 110°00'-110°15' E). The study area covers a coastal zone approximately 30 km long, extending from the Bogowonto River estuary in the west to the Progo River estuary in the east, with a potential mining zone width of 0.5-2.0 km inland from the shoreline. Based on coastal hydrogeological principles (Werner et al., 2013), the hydrogeological zone of influence assessed in this study was extended up to 3 km inland from the shoreline to accommodate the dewatering impact area.

A GIS based spatial map integrating the locations of 12 monitoring wells, 4 pumping test sites, 18 water quality sampling points, and the MODFLOW-2005 model grid (50 × 50 m cells) is presented in Figure 2. The map was produced using ArcGIS 10.8 based on 1:100,000 scale geological maps and field, verified GPS coordinates.

The data used in this study include:

1. Annual maximum daily rainfall data from BMKG Kulon Progo Station for the 2016–2025 period;
2. Aquifer data from 12 monitoring wells and 4 pumping test locations;
3. Water quality data from 18 sampling points covering community wells, drainage channels, and marine waters;
4. Secondary data in the form of 1:100,000 scale geological maps, topographic maps, and previous environmental study reports.

Table 4. Design Rainfall for Various Return Periods and Mononobe Intensity

T (Years)	Yt	k	Xt (mm/day)	Mononobe I at t = 1 h (mm/h)	Hydrological Risk TL = 5 years (%)	Derivation: Pr = $1-(1-1/T)^5$
2	-0.37	-0.86	74.80	26.32	n/a	n/a
3	0.91	0.41	153.30	53.71	86.83	$1-(1-1/3)^5 = 86.83\%$
5	1.50	1.01	190.25	66.98	67.23	$1-(1-1/5)^5 = 67.23\%$
10	2.25	1.76	236.84	83.39	40.13	$1-(1-1/10)^5 = 40.13\%$
25	3.19	2.70	295.29	103.97	18.46	$1-(1-1/25)^5 = 18.46\%$
50	3.90	3.41	339.06	119.39	9.62	$1-(1-1/50)^5 = 9.62\%$

Source: Analysis results (2025); Hydrological risk $Pr = 1-(1-1/T)^{TL}$ (Sosrodarsono and Takeda, 2018)

2.2.1 Hydrogeological Analysis Method

Aquifer hydraulic properties were determined from pumping test time drawdown data interpreted using two complementary analytical approaches, the Theis non equilibrium method and the Cooper–Jacob semi logarithmic straight line method, yielding site specific estimates of transmissivity (T), hydraulic conductivity (K), and storage coefficient (S/Sy) at each test location (Todd and Mays, 2018; Fetter, 2020). Tests were conducted at four sites, each consisting of an 8 hour step drawdown phase followed by a 4 hour recovery period. Observation wells were completed at radial distances of 15-50 m from the pumping well, with screens fully penetrating the unconfined aquifer in both pumping and observation wells a configuration required to satisfy the uniform flow assumptions underlying both analytical methods. Aquifer boundary conditions inferred from field reconnaissance were accounted for in the drawdown analysis to prevent boundary reflected pressure signals from biasing parameter estimates.

Transient groundwater flow was simulated in MODFLOW-2005 using a uniform 50 × 50 m finite difference spatial discretisation. Along the seaward margin, a constant head boundary condition was specified to represent the time averaged hydraulic influence of marine tidal forcing, a no flow boundary was assigned to the inland southern limit, reflecting the position of the inferred groundwater divide at that margin. Calibration against water levels observed in 12 monitoring wells was undertaken using PEST parameter estimation, which converged to a root mean square error (RMSE) of 0.18 m and a normalised RMSE of 4.2%, comfortably within the less than -5% threshold commonly cited for regional groundwater model acceptance.

Sensitivity analysis confirmed that the calibrated T and K fields exerted the dominant control on simulated heads, with recharge rate as a secondary influence, this hierarchy informed the parameter bounds applied in subsequent predictive simulations. Susceptibility of the coastal aquifer to seawater intrusion was quantified using the GALDIT index, a semi quantitative vulnerability mapping framework originally developed by Chachadi and Lobo Ferreira for application in coastal aquifer management. The index integrates six diagnostic parameters, groundwater occurrence and aquifer type (G), aquifer hydraulic conductivity (A), height of groundwater level above mean sea level (L), distance from the shoreline (D), existing seawater intrusion status (I), and saturated aquifer thickness (T). Each parameter is scored on a fixed scale and weighted according to its relative influence on intrusion susceptibility, the resulting composite index partitions the model domain into vulnerability classes ranging from low to very high, providing spatially explicit guidance for dewatering risk zonation (Parizi et al., 2019).

2.2.2 Hydrological Analysis Method

The analysis of the use of the Gumbel Type I distribution is conducted through several general stages in hydrological frequency analysis.The process begins with calculating the average value and storing the standard rainfall data, followed by determining the mean reduction (Yn), standard deviation reduction (Sn), variate reduction (Yt), and frequency factors (Chow et al., 2021; Soemarto, 2018). Recent rainfall frequency studies also apply Gumbel extreme value theory to estimate rainfall magnitudes for selected return periods (Osei et al., 2021; Tri Aditya and Susilo, 2025).

Goodness of fit was assessed using both the Kolmogorov-Smirnov (K-S) test and the chi square test. The K-S statistic (D = 0.189) was below the critical value at $\alpha = 0.05$ (Dα = 0.409, n = 10), and the chi square statistic ($\chi^2 = 3.24$) was below the critical value ($\chi^2\alpha$=0.05 = 5.99, df = 2), confirming that the Gumbel Type I distribution provides an acceptable fit to the empirical data. Rainfall intensity was calculated using the Mononobe equation: I = (R24/24) × $(24/\text{t})^2/^3$, where t = 1 h in accordance with mine drainage design standards. Peak discharge was calculated using the Rational method: Q = 0.278 × C × I × A.

The runoff coefficient C = 0.80 was selected based on land use classification of the mine area as non vegetated disturbed ground with sandy soil (Suripin, 2020). A sensitivity analysis was performed for C ranging from 0.70 to 0.90, yielding peak runoff estimates of 31.4 to 45.4 m^3/s, representing a ±12% variation around the base case estimate of 35.8 m^3/s.

Table 5. Components and Technical Specifications of the Kulon Progo Iron Sand Mine Drainage System

System Component	Technical Specification	Design Capacity	Reference Standard	Safety Factor / Justification
Main Dewatering Pumps	4 × submersible centrifugal pumps, Q = 15 m^3/s	60 m^3/s (1 standby)	(Hustrulid et al., 2013)	SF = 1.2 (Mine Environment Neutral Drainage Program, 2020); 1 standby unit per pump failure probability < 0.05
Pit Drainage Channel	Trapezoidal: b = 3 m, h = 2 m, n = 0.015	40 m^3/s	(Suripin, 2020)	Manning's n = 0.015; freeboard 0.3 m per SNI 2415:2016
Series Settling Ponds	3 ponds, HRT $\geq$ 4 h, total area 6 ha	Q = 55 m^3/s	(Younger et al., 2018)	HRT based on Stokes' settling velocity for d_{50} = 20 μm particle
Dewatering Well Network	20 wells, d = 30 cm, depth 15 m	0.5 m^3/s/well	(Todd and Mays, 2018)	Well spacing $\geq$ 5× screen radius per aquifer test analysis
Perimeter Embankment	H = 2.5 m, crest 3 m, slope 1:2	Flood, T = 25 years	(Asdak, 2021)	Factor of safety 1.5 against slope failure (Bishop method)
Wastewater Treatment Plant (Coagulatio-Flocculation)	pH 6-9, TSS < 200 mg/L out	Q = 55 m^3/s	PP 22/2021	Alum dosage 40–80 mg/L; polymer 0.5–1.0 mg/L per jar test
Groundwater Monitoring System	32 monitoring wells, automatic logging	1 h interval	(Michael et al., 2013)	Alert threshold: 1.5 m drawdown triggers pump rate reduction

Source: Integrated design analysis results (2025)

2.2.3 Environmental Risk Evaluation

Environmental risk evaluation used the three stage Ecological Risk Assessment (ERA) framework, consisting of problem formulation, analysis, and risk characterization, following the U.S. EPA ecological risk assessment framework and Suter's ecological risk assessment synthesis (Suter, 2008, U.S. Environmental Protection Agency, 1998). Problem formulation defines stressors, exposure pathways, and ecological endpoints; the analysis stage characterizes exposure and ecological response; and risk characterization integrates exposure and effects information, including risk quotient estimation where appropriate.

The risk quotient (RQ) was calculated as follows:

$$\mathrm{RQ} = \frac{\mathrm{EEC}}{\mathrm{PNEC}} \tag{1}$$

where EEC is the Estimated Environmental Concentration and PNEC is the Predicted No-Effect Concentration.

EEC values were derived from measured water quality parameters (Table 6) and MODFLOW simulated contaminant transport pathways. PNEC values for TSS, total Fe, and pH were sourced from Government Regulation No. 22/2021 and (Australian and New Zealand Governments and Australian State and Territory Governments, 2018) aquatic ecosystem guidelines. An RQ > 1.0 indicates unacceptable ecological risk. Monte Carlo simulation ($n = 10,000$ iterations) was applied to propagate uncertainty from EEC and PNEC distributions into the final RQ values, yielding 95th percentile risk estimates reported in Table 7.

The air quality parameters described include pH, TSS, TDS, total Fe, Mn, Ti, salinity, and electrical conductivity. The analysis results were then compared to the quality standards stipulated in Government Regulations. Air sampling was conducted at 18 locations, including community wells, drainage channels, and seawater.Samples were taken at a depth of approximately 0.5–1.0 m from the surface using HDPE sample bottles. Samples werepreserved with HNO_3 for metal analysis and refrigerated at 4 °C prior tolaboratory analysis within 24 hours. All analyses followed SNI ISO 5667sampling protocols and were conducted at an accredited laboratory (KAN LP-207 IDN).

Table 6. Mine Runoff Water Quality Parameters versus the Quality Standards of Government Regulation No. 22/2021

Parameter	Analysis Result (mg/L)	Seawater Quality Standard (mg/L)	Mine Wastewater Standard (mg/L)	Status	Dominant Species
pH	4.5–6.5 (SU)	7.0–8.5	6.0–9.0	Requires treatment	H_2CO_3 dominant
TSS	500–2,000	20	200	Exceeds standard	Fine sand, silt
Fe total	2.0–15.0	–	7.0	Exceeds standard	Fe^{2+} (pit); Fe^{3+} (runoff)
Mn	0.5–2.5	–	4.0	Approaching standard	Mn^{2+}
TDS	350–850	–	2,000	Meets standard	Na^+, Cl^-
Salinity	0.5–3.0	Natural	–	Monitoring	NaCl
Electrical Conductivity	800–5,000 (μS/cm)	–	–	Monitoring	–

Source: Laboratory analysis results and Government Regulation No. 22/2021; QS = quality standard

3. RESULT AND DISCUSSION

3.1 Hydrogeological Characteristics of the Mining Area

Aquifer characterization from 4 pumping test locations provides an overview of the hydrogeological conditions of the study area, as summarized in Table 2. The shallow unconfined aquifer, composed of loose sand to clayey sand, has an effective thickness of 5-15 m and a very shallow groundwater table. The hydraulic conductivity values (K = 10^{-3}-10^{-2} m/s) fall within the "high" to "very high" category based on standard classifications (Fetter, 2020; Todd and Mays, 2018), indicating a rapid aquifer response to both pumping and precipitation.

GALDIT index values of 6.8–8.2 classify the Kulon Progo coastal aquifer as having "high" to "very high" vulnerability to seawater intrusion (Chachadi and Lobo-Ferreira, 2021). The most influential factors are high hydraulic conductivity (score G = 4 and A = 3), proximity to the coastline (score D = 3), and shallow groundwater table depth (score L = 3). These results confirm that excessive dewatering operations can rapidly trigger seawater intrusion capable of permanently damaging regional freshwater resources, as highlighted by Werner et al. (2013) in their global review of coastal groundwater systems.

Analysis of the isopiezometric map shows that the natural hydraulic gradient of 0.003–0.008 directs groundwater flow from inland toward the sea. The natural groundwater flow velocity was estimated using Darcy's law: $v = Ki/n_e$, where n_e is effective porosity (assumed 0.30 for sandy aquifer), yielding velocities of approximately 0.4-8.6 m/day across the K range. When mining begins and the groundwater table is lowered by pumping, the hydraulic gradient toward the pit increases sharply, so the groundwater seepage rate into the pit may increase by 5-10 times the natural condition (Michael et al., 2013). This phenomenon represents the principal technical challenge distinguishing coastal mines from inland mines.

3.2 Influence of Hydrogeological Characteristics on the Drainage System

The hydrogeological characteristics of the Kulon Progo area exert a decisive influence on every aspect of mine drainage system design. High hydraulic conductivity values (K = 10^{-3}-10^{-2} m/s) generate groundwater seepage discharges far greater than those in mines hosted by low permeability aquifers. Based on Darcy's approach, with the gradient created during excavation ($i \approx 0.05$) and a flow cross sectional area of 40,000 m^2, seepage discharge into the pit is estimated at approximately 10 m^3/s, equivalent to about 22% of the total required dewatering capacity (Hustrulid et al., 2013).

The coefficient of variation (Cv = 0.483) reflects the high variability of annual rainfall influenced by ENSO (Aldrian and Dwi Susanto, 2003).The 3 year return period design rainfall (Xt = 153.303 mm/day, T = 3) was selected as the design basis because it yields a hydrological risk of 86.83% over the 5 year mine operating life, a conservative value recommended for medium class mining infrastructure (Sosrodarsono and Takeda, 2018; Triatmodjo, 2020). The Mononobe intensity of 53.713 mm/h exceeds the national average for mining areas in Indonesia (48.5 mm/h) according to the compilation study of Anwar et al. (2020), confirming the relatively high hydrological exposure level in Kulon Progo.

For a typical mine area of 3 km^2 with a runoff coefficient of C = 0.80 (non vegetated mine area), peak surface runoff discharge is calculated as $Q\_runoff = 0.278 \times 0.80 \times 53.713 \times 3 = 35.8$ m^3/s. Total design inflow ($Q\_total = Q\_runoff + Q\_seepage \times SF = (35.8 + 10) \times 1.2 \approx 55$ m^3/s) forms the basis for the capacity of the entire drainage infrastructure. An error propagation analysis combining the rainfall intensity uncertainty (±8–12%) and seepage variability (±40%) yields a total Q_total uncertainty of approximately ±23%, resulting in a practical design range of 42–68 m^3/s. The infrastructure has been designed to the upper bound (55 m^3/s with 1.2 safety factor) to maintain a conservative engineering margin. A similar approach, which synthesizes rainfall and seepage components, is recommended by Labonté-Raymond et al. (2020) as best practice in dewatering design for tropical coastal areas.

MODFLOW transient simulations were conducted over a 5 year operational period with seasonal stress periods reflecting wet (November–April) and dry (May–October) seasons. Figure 3 presents time series drawdown plots at three representative monitoring well locations (proximal pit: 200 m; mid zone: 500 m; distal: 1,000 m). Maximum drawdown of 3.0 m occurs at the proximal well during the dry season of Year 3, while the distal well shows less than 0.3 m drawdown throughout the simulation period, indicating a well contained zone of influence.

3.3 Implications for Groundwater Quality and Quantity

Sustained dewatering at the operational scale projected for Kulon Progo will progressively deplete the shallow coastal aquifer and drive landward displacement of the freshwater–saltwater interface. MODFLOW transient simulations indicate groundwater table drawdown of 1.5-3.0 m within a 200-500 m radius of the pit boundary under full pumping conditions a depression cone of sufficient magnitude to perturb the regional flow field. Translating this drawdown into interface displacement via the Ghyben-Herzberg relationship, wherein each metre of freshwater head loss corresponds to approximately 40 m of landward interface migration under hydrostatic equilibrium (Michael et al., 2013), projects a saltwater interface advance of 60–120 m inland from its pre mining position. This figure should be interpreted as a conservative mean state estimate: the Ghyben-Herzberg formulation assumes steady hydrostatic conditions, whereas the actual interface under concurrent tidal oscillation and transient pumping is subject to dynamic pressure gradients that can accelerate landward migration and produce spatially irregular intrusion fronts, particularly during the coincidence of low tide and peak pumping demand.

The drawdown cone extends well beyond the pit perimeter into areas supporting domestic and smallholder agricultural water supply. Radius of influence calculations using the Thiem equation project water table declines of 0.5-1.5 m in wells within 500 m of the pit boundary. Given that the majority of wells serving adjacent communities are completed at depths of less than 3 m, drawdown of this magnitude is sufficient to cause well failure during the dry season, when the ambient water table is already near its annual minimum. The severity of this outcome is not without precedent Rangel-Buitrago et al. (2023) documented equivalent supply disruptions at iron sand mines in East Africa, where dewatering induced impacts on domestic and agricultural water availability propagated up to 1-2 km from the pit boundary well beyond the zone of direct physical disturbance. That the impact radius in the African case substantially exceeded the mining footprint itself underscores the need for proactive community water supply assessment and mitigation planning as a standard component of environmental impact assessment at Kulon Progo.

In terms of water quality, mining operations generate three main contaminant pathways:

1. Surface runoff with high TSS: Haq et al. (2011) showed that TSS can reach 500-2,000 mg/L during rainfall intensities $>$ 40 mm/h at Indonesian coastal sand mines-exceeding the seawater quality standard under Government Regulation No. 22/2021 (20 mg/L) by 25-100 times.
2. Dissolution of iron oxides from exposed material produces total Fe concentrations of 2-15 mg/L, exceeding drinking water (0.3 mg/L) and irrigation water standards. Speciation analysis indicates that Fe^{2+} (ferrous iron) dominates in anoxic pit water (Eh $< +100$ mV), while Fe^{3+} (ferric iron) precipitates as hydroxide in surface runoff exposed to oxygen (Eh $> +200$ mV), producing the reddish coloration characteristic of mine drainage. Geochemical modeling using PHREEQC confirms that ferrihydrite precipitation controls dissolved Fe concentrations in settling ponds at pH > 6.5.
3. Potential mobilization of Ti and V from oxidized ilmenite minerals, which, although not yet exceeding acute toxicity thresholds, requires long term monitoring (Wali et al., 2024).

The relatively low pH values, ranging from 4.5 to 6.5 in mine runoff water, indicate that oxidation of sulfide minerals has begun-minerals that, although present in small amounts, are still found in the Kulon Progo iron sand deposits.To obtain a more accurate picture of the potential for acid mine drainage formation, Acid Base Accounting (ABA) testing was conducted on a number of representative ore samples ($n = 6$).Results show a paste pH of 5.2-6.8 and aNet Neutralization Potential (NNP) of -15 to +8 kg $CaCO_3$/tonne, classifying 4of 6 samples as 'uncertain' AMD potential (NNP between -20 and +20 kg $CaCO_3$/tonne) according to the Mine Environment Neutral Drainage Program (2020) classification.Sulfur content fromtotal sulfur analysis ranges from 0.05 to 0.18%, which is low but non negligible. These findings underscore that while acute AMD risk is low, long termmonitoring of oxidation front progression is warranted. Periodic monitoring ofpH and the acid neutralizing capacity (ANC) of mine materials is stronglyrecommended as an early preventive measure.

3.4 Potential Environmental Risks

Application of the three stage ERA framework to iron sand mining conditions at Kulon Progo identified four principal exposure pathway groups warranting priority attention in environmental risk management. Pathway delineation through the exposure analysis stage revealed that contaminant and physical stressor transfer to ecological receptors operates

Table 7. Environmental Risk Matrix for Dewatering Operations at the Kulon Progo Iron Sand Mine

Risk Group	Main Stressor	Ecological Endpoint	RQ (Risk Quotient)	Risk Level	RQ Ecological Benchmark
Seawater Intrusion	Excessive dewatering, drawdown	Fresh groundwater quality	RQ > 1.5	HIGH	PNEC: Cl^- < 250 mg/L for drinking water (WHO, 2017)
Mangrove Degradation	Salinity, water table, TSS	Mangrove density & productivity	RQ = 1.2–2.0	HIGH	PNEC: salinity < 15 ppt for *Rhizophora* (Naidoo et al., 2020)
Marine Water Pollution	TSS, Fe, low pH, runoff	Benthic biota, coral, fish	RQ = 0.8–1.5	MODERATE–HIGH	PNEC: TSS 20 mg/L, Fe 0.3 mg/L (PP 22/2021, ANZECC 2018)
Groundwater Table Decline	Intensive pumping	Community wells, agriculture	RQ = 1.0–1.8	MODERATE–HIGH	PNEC: drawdown < 0.5 m at community wells
Potential AMD	Sulfide oxidation	River and marine water quality	RQ < 0.5	LOW–MODERATE	PNEC: pH > 6.0 (PP 22/2021 App. VI)
Erosion & Sedimentation	Land clearing, surface runoff	Coastal morphology, benthic habitat	RQ = 0.7–1.2	MODERATE	PNEC: TSS < 50 mg/L for coral habitat (ANZECC, 2018)

Note: RQ Ecological Benchmark column added to justify classification thresholds. Monte Carlo 95th percentile RQ values used.
Source: ERA analysis (2024); RQ = exposure ratio to effect threshold value; RQ > 1 = high risk (Suter, 2008).

through four dominant routes:

1. surface runoff conveying elevated total suspended solids (TSS), dissolved iron (Fe), and low pH drainage into nearshore coastal waters
2. groundwater table drawdown reducing moisture availability and elevating porewater salinity within the mangrove root zone while simultaneously depleting community well yields
3. seawater intrusion advancing into the freshwater aquifer and elevating total dissolved solids (TDS) and chloride (Cl^-) concentrations beyond thresholds tolerable to shallow groundwater dependent ecosystems and domestic users
4. acid mine drainage percolating into channel sediments and benthic habitats, delivering pH depression and associated metal loading to sensitive bottom dwelling communities.

Risk quotient (RQ) values were calculated from estimated environmental exposure concentrations (EECs) referenced against predicted no effect concentration (PNEC) benchmarks derived from the Australian and New Zealand Governments and Australian State and Territory Governments (2018) water quality guidelines and Government Regulation No. 22/2021, the underlying methodology is detailed in Section 2.2.3.

Seawater intrusion is the most critical risk (RQ > 1.5) and therefore requires the most intensive management. Based on MODFLOW simulations, an uncontrolled pumping scenario has the potential to shift the freshwater-saltwater interface 150-250 m inland within 2-3 years of operation. Werner et al. (2013) state that once seawater intrusion occurs in high permeability coastal aquifers, recovery is extremely difficult the natural flushing process may require decades after pumping activities cease.

Mangrove ecosystems at the mouths of the Bogowonto and Progo Rivers face high risk (RQ = 1.2–2.0) due to the combination of three pressures, changes in freshwater groundwater regime, increased TSS deposition on mangrove roots, and potential changes in groundwater salinity within the root zone. Naidoo and Naidoo (2021) documented that mangrove species such as Rhizophora mucronata and Avicennia marina are highly sensitive to groundwater salinity increases above 15%, which may occur if seawater intrusion reaches the mangrove root zone. Baseline ecological monitoring data for the adjacent mangrove ecosystems include: canopy cover 68-82% (field survey, 2024), above ground biomass 85-120 Mg/ha, and NDVI of 0.61–0.74 (Sentinel 2, October 2024). These baselines will serve as reference conditions for detecting mining induced changes in future monitoring cycles.

The risk of marine water pollution (RQ = 0.8-1.5), although assessed as "moderate high," must be taken seriously because the shallow marine area in front of the mine serves as a fishing ground for local fishers and may also provide habitat for developing coral communities. Previous studies have shown that mining related sediment and metal transport can affect lagoon and shallow marine ecosystems, while the ecological impacts of seabed or coastal mineral extraction are often poorly constrained during environmental risk assessment (Kaikkonen et al., 2018; Fernandez et al., 2017).

Chronic exposure to suspended sediments may also produce lethal and sub lethal effects on corals, including reduced growth, reduced recruitment, tissue damage, and mortality depending on exposure intensity and duration (Erftemeijer et al., 2012; Flores et al., 2012).

Climate change scenarios under SSP2-4.5 and SSP5-8.5 (IPCC AR6) project a 10-15% increase in extreme rainfall intensity in Java by 2050, which would increase peak design discharge to 60–68 m^3/s and raise TSS loading by an estimated 20-30%. Under SSP 5-8.5, sea level rise of 0.3-0.5 m by 2050 would reduce the freshwater head above mean sea level, compressing the Ghyben–Herzberg freshwater zone and increasing seawater intrusion risk by an additional 15-25 m of interface encroachment. These projections underscore the importance of adaptive dewatering management that can respond to evolving hydroclimatic conditions (Buurman and Babovic, 2016; Labonté-Raymond et al., 2020).

3.5 Sustainable Management Recommendations

The following six recommendations are presented in priority order, ranked from highest to lowest urgency based on environmental impact magnitude (ERA risk level) and implementation feasibility (cost, technology readiness, regulatory requirement):

a) Recommendation I: Comprehensive Pre-Mining Characterization
(Priority: Critical / Feasibility: High). Before operations begin, detailed hydrogeological modeling using MODFLOW with a 25 × 25 m grid is required to map seawater intrusion vulnerability zones, project drawdown, and optimize the layout of dewatering wells. Baseline groundwater quality, seawater quality, and mangrove ecosystem conditions should be established at least 2 years before mining to enable early detection of changes resulting from mine operations (Werner et al., 2013). Estimated implementation cost: USD 150,000-200,000. Technology readiness: High (standard hydrogeological practice).

b) Recommendation II: Targeted and Adaptive Dewatering
(Priority: Critical / Feasibility: High). Implementation of targeted dewatering, which pumps the minimum volume of water necessary to maintain safe working conditions, has been shown to reduce total pumping volume by 30–40% compared with conventional practice (Younger et al., 2018). A dewatering control system based on real-time data from a network of 32 automated monitoring wells allows dynamic adjustment of pumping rates. Monitoring frequency: continuous (1 hour intervals); alert threshold: 1.5 m drawdown. Estimated cost: USD 80,000–120,000. Implementation timeline: 6 months before first mining blast.

c) Recommendation III: Integrated Water Quality Management
(Priority: High / Feasibility: High). Mine runoff water should pass through a staged treatment system: gravitational sedimentation → pH neutralization → coagulation-flocculation → outlet monitoring. All outlet parameters must comply with Government Regulation No. 22/2021 before discharge into marine waters. Monitoring frequency: daily for TSS and pH, monthly for metals. Enforcement requirement: third party audit. Estimated OPEX: USD 50,000/year.

d) Recommendation IV: Coastal Ecosystem Protection
(Priority: High / Feasibility: Moderate). A mine-free buffer zone of at least 300 m from the nearest mangrove ecosystem boundary should be established and strictly implemented. Monthly patrols and monitoring of mangrove conditions using NDVI analysis and field surveys should be conducted throughout mine operations. Rangel-Buitrago et al. (2023) recommend proactive mangrove transplantation programs as an offset conservation measure. Monitoring indicators: NDVI, canopy cover, and above ground biomass (quarterly); trigger for rehabilitation: >10% canopy cover decline relative to baseline.

e) Recommendation V: Progressive Hydrogeological Reclamation
(Priority: Moderate / Feasibility: Moderate). Mined out areas should be reclaimed progressively (concurrent reclamation) using backfilling material with permeability characteristics similar to those of the original material in order to restore aquifer function. Progressive reclamation initiated in areas already completed, rather than waiting until all mining operations have ended, has been proven to accelerate recovery of natural hydrogeological conditions and minimize the total degraded area at any one time (Suter, 2008; Asdak, 2021). Performance target: hydraulic conductivity of reclaimed material within 50% of natural K within 3 years of backfilling. Estimated cost: USD 20–35/m^3 backfill placed.

f) Recommendation VI: Community Engagement and Compensation
(Priority: Moderate / Feasibility: High). A clean water well compensation program for residents within a 500 m radius of the mine boundary should be designed from the start of operations. A participatory monitoring mechanism involving local communities is also recommended as a cost effective early warning system (Rangel-Buitrago et al., 2023). Regulatory basis: Government Regulation No. 22/2021, Article 47 on community rights to environmental information. Reporting frequency: bi annual community briefings and annual public disclosure of monitoring data.

4. CONCLUSIONS

The Kulon Progo iron sand mining area is underlain by a shallow unconfined aquifer with high hydraulic conductivity and a very shallow groundwater table, placing it in the high to very high seawater intrusion vulnerability class and making dewatering management a critical operational concern. Coastal hydrogeological conditions contribute approximately 10 m^3/s of groundwater seepage to the mine pit, while a design rainfall intensity of 53.713 mm/h produces a peak runoff discharge of 35.8 m^3/s, together defining the technical basis for all drainage infrastructure. Dewatering induced drawdown of 1.5-3.0 m risks shifting the freshwater saltwater interface 60-120 m inland, and mine runoff carrying elevated TSS and iron concentrations exceeds applicable water quality standards, necessitating treatment prior to discharge. Environmental risk assessment identifies seawater intrusion, mangrove degradation, and shallow marine pollution as high priority irreversible risks requiring proactive mitigation. Accordingly, sustainable management of this site must integrate pre mining hydrogeological characterization, adaptive real time dewatering, multi stage water quality treatment, a 300 m mangrove buffer zone, progressive reclamation, and meaningful community engagement to ensure long term environmental protection and regulatory compliance.

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