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TIME SERIES FORECASTING AND CLASSIFICATION OF POTENTIAL SAFETY RISKS OF STORING RADIOACTIVE WASTE NEAR SURFACE DISPOSAL

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Abstract
Long-term radioactive waste management, especially at Near Surface Disposal (NSD) facilities, requires a predictive approach and adaptive monitoring system to anticipate risks to groundwater quality. This research aims to develop a time series model to predict groundwater level parameters including depth, pH, and tds and integrate it with a rule-based ESG risk classification system and machine learning. The method used includes the Prophet time series model for predicting groundwater parameters in the next 50 years. The prediction results are classified using rule-based classification which is then evaluated using the Random Forest algorithm. The final application was developed web-based using Streamlit. The Prophet model provided the best prediction performance for depth MAE: 0.71; MAPE: 7.41% and pH MAE: 0.21; MAPE: 4.89%, but less accurate for TDS MAE: 12.16; MAPE: 31,62%. The Random Forest model produced classification accuracy of up to 98% and was able to replicate the rule-based classification system well. The integration of these models can produce a predictive system that supports decision making in sustainable radioactive waste management.

Keywords: Near Surface Disposal; Machine Learning; Time Series Forecasting; Classification.

Abstrak
Pengelolaan limbah radioaktif jangka panjang, khususnya pada fasilitas Near Surface Disposal (NSD), memerlukan pendekatan prediktif dan sistem pemantauan adaptif untuk mengantisipasi risiko terhadap kualitas air tanah. Penelitian ini bertujuan mengembangkan model deret waktu untuk memprediksi parameter muka air tanah meliputi kedalaman, pH, dan tds serta mengintegrasikannya dengan sistem klasifikasi risiko ESG berbasis aturan dan machine learning. Metode yang digunakan meliputi model deret waktu Prophet untuk prediksi parameter air tanah dalam 50 tahun ke depan. Hasil prediksi diklasifikasikan menggunakan rule-based classification yang kemudian dievaluasi menggunakan algoritma Random Forest. Aplikasi akhir dikembangkan berbasis web menggunakan Streamlit. Model Prophet memberikan performa prediksi terbaik untuk kedalaman MAE: 0,71; MAPE: 7,41% dan pH MAE: 0,21; MAPE: 4,89%, namun kurang akurat untuk TDS MAE: 12,16; MAPE: 31,62%. Model Random Forest menghasilkan akurasi klasifikasi hingga 98% dan mampu mereplikasi sistem klasifikasi berbasis aturan dengan baik. Integrasi model ini dapat menghasilkan sistem prediktif yang mendukung pengambilan keputusan dalam pengelolaan limbah radioaktif berkelanjutan.

Kata Kunci: Near Surface Disposal; Machine Learning; Peramalan Deret Waktu; Klasifikasi

INTRODUCTION

Radioactive waste management is a strategic issue that is directly related to environmental sustainability, human health, and national energy policy. This waste is generated from various activities such as nuclear power plants, medical facilities, research laboratories, and industry (Suhartawan et al., 2023). The characteristics of radioactive waste, which can retain its radioactivity over the long term, necessitate a safe, controlled, and sustainable storage system (Fariz Aditya et al., 2023).

Near surface disposal (NSD) is one of the approaches commonly used globally for low- to intermediate-level radioactive waste. Although NSD systems are designed with multiple natural and engineered barriers, the risk of contamination to the surrounding environment remains a significant concern, particularly in terms of

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groundwater and the stability of protective materials (Ojovan & Steinmetz, 2022; Pratiwi et al., 2022).

Concerns about the environmental risks of hazardous waste are increasing in line with shifts in energy policy and industrialization. In various countries, cases of groundwater contamination due to the movement of radionuclides from storage sites show that existing isolation systems still have vulnerabilities. Various international case studies confirm the migration of radioactive substances through underground layers, especially if barrier systems are not monitored predictively (Dizman & Mukhtarli, 2021; Jäger et al., 2025). This is even more complex in tropical regions such as Indonesia, where hydrogeological conditions, rainfall, and soil characteristics greatly influence the dynamics of groundwater quality. However, to date, there is no long-term predictive model capable of quantitatively and adaptively estimating changes in environmental parameters to support prevention policies (Tanaka et al., 2024).

In the last decade, information technology and machine learning approaches have begun to be widely used in the fields of environment and hazardous waste management. Machine learning-based approaches enable the prediction of environmental conditions based on complex historical data patterns without exclusive reliance on laboratory experiments. Models such as Long Short-Term Memory (LSTM), Prophet, and Exponential Smoothing State Space (ESSS) have been proven capable of accurately predicting time series variables in various fields, including hydrology, water quality, and environmental risk analysis (Alshara, 2022; Barooni et al., 2024; Chhabra et al., 2024; Masini et al., 2023; Pires & Martins, 2024; Shohan et al., 2022; Vu et al., 2022). This technique enables proactive monitoring and data-driven decision-making, especially in a long-term context. However, in the Indonesian context, there has been no application of predictive environmental models for radioactive waste storage facilities, either in relation to groundwater quality or risk classification.

Several previous studies serve as an important basis for identifying research opportunities and gaps. Studies conducted by (Adebisi et al., 2023) highlights the importance of integrating Environmental, Social, and Governance (ESG) frameworks into the management of waste from renewable energy sources. The study emphasizes that around 60–70% of renewable energy components contain toxic materials or heavy metals that require sustainable waste management strategies. The study also shows that ESG practices are not yet fully supported by long-term predictive data, so policies are still reactive rather than preventive. This highlights the urgency of a quantitative approach that not only supports monitoring but also future risk planning.

Another study by (Jiao et al., 2024) developing a machine learning-based ESG assessment system by combining Random Forest and K-Means Clustering. The study evaluated 71 solid waste management companies in China during the period 2013–2021 and found that only about 30% of companies were classified as having strong ESG performance. The disparity seen in the 2–8 range indicates that ESG implementation is not yet uniform, and long-term environmental data has not been used as part of the evaluation component. Other weaknesses lie in the limited indicators and the lack of integration of predictive risk models for hazardous waste types such as radioactive waste.

Meanwhile, research (Gholian-Jouybari et al., 2024) In Mexico, 32 domestic waste management facilities were evaluated using Data Envelopment Analysis (DEA) and Interpretive Structural Modeling (ISM). The results showed that only 9 of the 32 facilities, or about 28%, were technically efficient from an ESG perspective. This study developed four phases of strategic readiness, namely Groundwork, Structuring, Development and Growth, and Smart Maturity. However, the study has limitations because its scope only covers domestic waste and does not consider long-term dynamics or prediction-based environmental risks.

Research by (Hu & Pfingsten, 2023) presents the development of Data-Driven Machine Learning (DDML) for the management of high-level waste (HLW) in Deep Geological Repository (DGR) systems. The study identifies the use of Linear Regression, Principal Component Analysis, and Artificial Neural Network algorithms in long-term simulations. This research emphasizes that hybrid approaches and physics-informed models can improve accuracy, but there are no empirical field studies or applications for low/intermediate-level waste or NSD systems. Supporting environmental aspects such as groundwater quality have also not been a major focus.

Another study by (Kazaryan et al., 2022) highlights the application of neural networks for the subsurface analysis of waste storage facilities. Through subsurface image processing, this model is capable of detecting potential cracks and structural degradation that could trigger waste leaks. However, the study was limited to the physical aspects of the structure without linking environmental parameters such as fluid movement or changes in groundwater quality. In addition, the context of long-term radioactive storage has not been integrated into the analysis.

Machine learning-based prediction approaches have also proven effective in other waste management-related studies. For example, research by (Li et al., 2021) shows that the Gradient Boosting Regression Tree (GBRT) and Neural Network models can achieve up to 99.1% accuracy in predicting e-waste volume in the urban sub-sector. Although the topic is different, this study demonstrates the ability of machine learning to process historical data and build early detection systems. However, the research is limited to volume quantification and does not yet include risk classification or integration of ESG aspects.

Based on this review, it can be concluded that there are three main gaps that remain. First, there is no time series-based predictive model to monitor changes in environmental parameters at low- to intermediate-level radioactive waste storage facilities, particularly in NSD systems. Second, there is no approach that integrates prediction results with risk classification systems to support layered preventive decision-making. Third, the ESG aspect in the context of environmental prediction has not been widely developed, even though long-term data-based environmental management is a strategic component of waste management policy.

This study was conducted to address these gaps by developing a long-term time series-based prediction model to estimate changes in environmental parameters such as groundwater depth, pH, and Total Dissolved Solids (TDS) at near-surface radioactive waste storage sites. The models used include the Prophet, LSTM, and Exponential Smoothing State Space algorithms. In addition, the prediction results are used to classify potential risks using a clustering approach as a basis for mitigation. The final stage of this research is the creation of a web application as a decision support system that can be used by stakeholders in the nuclear and environmental sectors.

With this approach, the research not only contributes to the provision of technical predictive models, but also strengthens the integration of ESG principles in radioactive waste storage governance. In practical terms, the results of this research have the potential to support institutions such as BRIN, BAPETEN, and related agencies in implementing long-term data-driven strategies. Academically, this research expands the scope of machine learning studies in the field of the environment and high-risk waste management, while providing a foundation for the development of more proactive and sustainable policies.

RESEARCH METHODS

This research is quantitative research with a predictive approach based on time series or forecasting time series, rule-based classification, and web development or deployment. The following is a graph of the research flow:

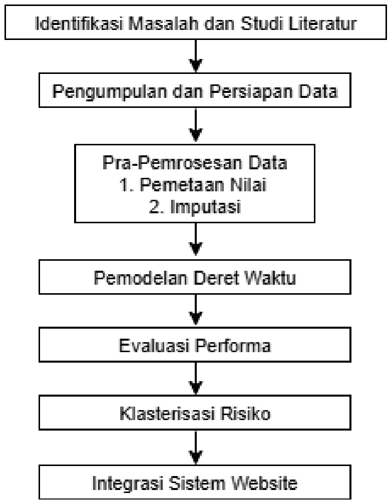

Figure 1. Graph of The Research Flow

The data used in this study is primary data obtained from BRIN RI, consisting of 1,529 data rows with 12 attributes from 2012 to 2019. This data is in the form of physical and chemical structure data on groundwater level parameters and forms the main basis for prediction and clustering analysis.

Problem Identification and Literature Review

This study began with the process of identifying problems, the potential for groundwater contamination due to the storage of radioactive waste in Near Surface Disposal (NSD) facilities. This stage also included a literature study on methods for predicting groundwater level parameters, time series modeling, clustering, and the ESG approach to hazardous waste management.

Data Collection and Preparation

This study uses historical data, which is secondary data in the form of groundwater level parameter values consisting of 12 data attributes. This stage aims to obtain data that can be used as a basis for analyzing groundwater level parameter predictions.

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Data Pre-processing

In this stage of the research, the data obtained will undergo data cleaning, including addressing missing values using a machine learning model. This stage aims to ensure good data quality for data analysis.

Time Series Modeling

This machine learning model is used to predict changes in depth, pH, and TDS parameters. This study uses the Prophet model, which is suitable for seasonal data and trends.

Performance Evaluation

At this stage, the three time series models will be evaluated using performance metrics, such as Mean Absolute Error (MAE), Root Mean Square Error (RMSE), and Mean Absolute Percentage Error (MAPE) to compare the accuracy levels of each machine learning model. The performance evaluation results are used to select the best model for producing groundwater level prediction analyses.

Risk Clustering

In this stage of the research, after the prediction analysis has been carried out, the results will be grouped into low, medium, and high-risk categories. This stage uses a rule-based classification approach by utilizing some knowledge about groundwater level parameters for radioactive waste storage.

Web System Integration

This stage involves developing the results of the groundwater level parameter prediction analysis and radioactive waste storage risk clustering into a web-based application system using Streamlit. This stage is carried out so that the research results can be utilized practically by relevant stakeholders.

RESULTS AND DISCUSSION

This study uses historical groundwater level data with a total of 1529 rows consisting of the date of sampling, location, groundwater depth, pH value, total dissolved solids (TDS), precipitation, water color, metal content such as Fe, K_2O, Ca^{2+}, Mg^{2+}, dan Mn/MnO_4, and electrical conductivity.

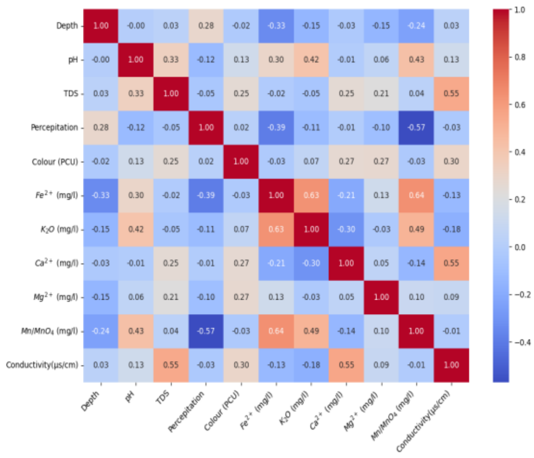

Figure 2. Heatmap Visualization

Figure 2 shows the correlation between parameters through heatmap visualization. Groundwater depth has a negative correlation with Fe^{2+} and Mn/MnO_4, indicating that the deeper the groundwater table, the lower the concentration of iron and manganese. This is related to the more limited dissolution of ions in deeper layers, making it important to predict the potential for contamination based on variations in depth. The pH parameter shows a strong positive correlation with TDS, Fe^{2+}, K_2O, and Mn/MnO_4. An increase in pH towards neutral or alkaline tends to be accompanied by an increase in dissolved solids content. The stability of minerals such as iron, potassium, and manganese is also higher at more neutral pH conditions, thus correlating directly with the concentration of these elements. In addition, TDS correlates positively with pH, conductivity, and water color. This indicates that an increase in dissolved substances, which generally originate from minerals such as magnesium and calcium, contributes to an increase in conductivity and water color intensity. TDS also serves as a potential indicator of radionuclide migration, so its monitoring can support early detection of the risk of contaminant release from storage sites.

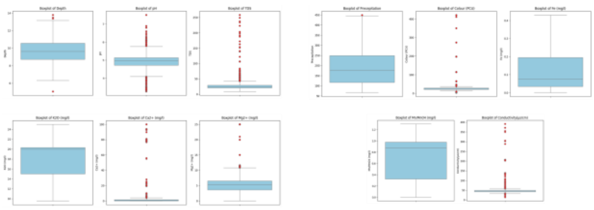

Figure 3. Boxplot Visualization

Figure 3 presents a boxplot visualization that identifies the presence of outliers in the data. The presence of extreme values in time series data does not automatically indicate an error, but may represent real conditions in the field. In this context, outliers are not removed because they are considered valid and informative, reflecting fluctuating environmental phenomena or special events. Furthermore, removing outliers has the potential to eliminate important characteristics that the model needs to learn the natural patterns of data variation. Therefore, all values are retained to maintain data integrity and support the accuracy of long-term predictions.

Table 1. Evaluation Matrix of Forecasting Time-Series

	Depth	pH	TDS
MAE	0.71	0.21	12.16
MSE	0.77	0.10	830.9
RMSE	0.88	0.32	28.82
MAPE	7.41%	4.89%	31.62 %

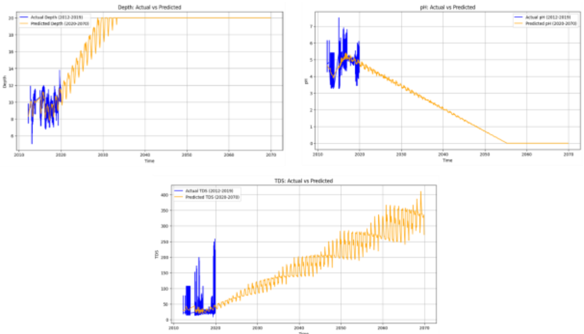

Figure 4. Result of Forecasting Time-Series

The evaluation results in Table 1 show that the Prophet model performs quite well in predicting depth parameters, with an MAE of 0.71 and a MAPE of 7.41%. These values indicate moderate accuracy and still leave room for improvement. For the pH parameter, the model consistently produces predictions that decline to a minimum value of 0 in the period 2054–2070. This occurs because Prophet captures the historical trend of annual decline. To prevent negative values, a lower limit of 0 is applied. The downward trend in pH can be linked to the potential increase in environmental pressure due to industrial and domestic activities and the use of chemicals in urban areas such as Serpong.

Nevertheless, the model's performance for pH is relatively good, as evidenced by the MAE of 0.21 and MAPE of 4.89% in Table 1, which indicate the consistency and reliability of the predictions. In contrast, Prophet's performance for the TDS parameter is much lower. The model only captures the general upward trend without being able to accurately represent actual fluctuations. MAE values of 12.64, RMSE of 28.82, and MAPE of 31.62% indicate a significant level of error and complex data patterns. These limitations are likely influenced by extreme variations in the data, the presence of outliers, and the characteristics of TDS, which are more difficult to model linearly. Overall, Prophet provides good prediction results for depth and pH, but is less capable of accurately modeling TDS due to the complexity of its parameter dynamics.

ESG risk classification was performed using a rule-based approach that refers to the threshold values of groundwater quality prediction parameters, namely groundwater depth, pH, and TDS. These classification rules were designed based on decision logic that represents the potential risk level of radioactive waste exposure in near-surface storage systems.

Table 2. Evaluation Matrix of Random Forest Model

	Precision	Recall	F-1 Score
Tinggi	1.00	1.00	1.00
Sedang	1.00	0.98	0.99
Rendah	0.99	1.00	0.99

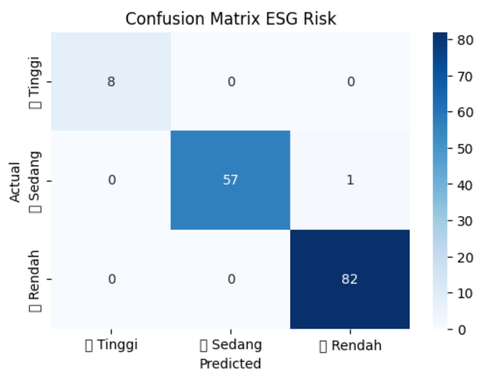

Figure 5. Confusion Matrix Random Forest

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The labeling results were then used as labels to train a supervised learning model with the Random Forest algorithm. Model performance evaluation based on accuracy, precision, recall, and F1-score in Table 2 and Figure 5 shows excellent results with a total accuracy of 98%. The "High" class achieved a precision, recall, and F1-score value of 1.00. The "Medium" class obtained a precision of 1.00, a recall of 0.98, and an F1-score of 0.99, while the "Low" class had a precision of 0.99, a recall of 1.00, and an F1-score of 0.99. These results demonstrate the model's ability to represent the classification structure consistently across all categories.
The confusion matrix supports these findings. The model successfully classified all samples in the "High" category correctly (8 samples), 57 of the 58 samples in the 'Medium' category, and all 82 samples in the "Low" category. The minimal classification errors indicate that the model is able to effectively mimic rule-based classification logic. These results confirm that the model does not simply memorize patterns, but is able to generalize rule-based decisions well.

Figure 6. Main Menu Website

Figure 7. Date Input for Processing Analysis

Figure 8. Result of Forecasting Time-Series and Rule-Based Classification

The prediction results from these three parameters are then used as input into the Random Forest model that has been trained previously to classify the level of Environmental, Social, and Governance (ESG) risk. The output of this system is a predictive parameter value and a risk label categorized into "Low," "Medium," or "High" classes. This system is also designed to display prediction results numerically and classification results clearly and easily understood by users. In addition to improving accessibility to the model, this approach also demonstrates how the integration of time-series forecasting and supervised classification can be operationalized in an applicable decision support system. Thus, this platform has the potential to be used by research institutions, policy makers, or radioactive waste managers in proactively monitoring and mitigating environmental risks.
The results of this study show a strong correlation with the principles of Environmental, Social, and Governance (ESG). From an environmental perspective, time series modeling of groundwater depth, pH, and TDS using Prophet provides long-term projections that can be used as an early detection system for potential pollution around radioactive waste storage facilities. The accuracy of the model for historical parameters reinforces its potential as a predictive and adaptive environmental monitoring tool.
In terms of Social, the application of rule-based and Random Forest risk classification produces accurate risk level categorization (low, medium, high). The dominance of classification at the medium risk level indicates that conditions are still under control, while the model's ability to identify

low risks reflects sensitivity to changes in environmental parameters. This information is relevant for risk communication, increased transparency, and strengthening public confidence in waste management.

From a governance perspective, the integration of scientific methods with digital technology through the development of a Streamlit-based system demonstrates support for data-driven risk management. Systematic model evaluation and interactive platform presentation of results enable stakeholders to directly access predictive information. Thus, this research not only provides technical contributions but also strengthens the implementation of a sustainability framework through synergy between environmental protection, social preparedness, and accountable governance.

CONCLUSIONS AND SUGGESTIONS

Conclusion

This study successfully achieved all of its objectives by integrating time series forecasting, risk classification, and ESG-based digital systems. The Prophet model was able to predict groundwater depth, pH, and TDS parameters for the next 50 years with high accuracy for the first two parameters. Depth and pH showed low MAE and MAPE values below 10%, while TDS still had a higher error rate with a MAPE value of 31.62%, requiring further development. The prediction results were then used in the classification of potential safety risks for storage facilities using a rule-based and Random Forest approach, which was able to systematically group risks into low, medium, and high categories. In addition, a web-based information system was successfully built using Streamlit to present prediction and classification results interactively, supporting transparency and utilization by stakeholders. Overall, this study also succeeded in integrating ESG principles, where environmental aspects are reflected in groundwater quality predictions, social aspects through ease of access to information, and governance aspects through the use of data as a basis for decision making.

Suggestion

Further research development is recommended to explore more adaptive predictive models, such as hybrid approaches or deep learning algorithms, in order to capture complex patterns, especially in parameters with high variability such as TDS. The information system that has been developed can also be improved by adding features such as automatic risk notifications, spatial visualization integration, and a more informative interface that can be accessed by various stakeholders, including the general public and regulatory agencies. Integration with sensor-based environmental data or field monitoring can also strengthen continuous model validation.

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