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Design Rainfall Analysis and SCS Synthetic Unit Hydrograph-Based Flood Discharge Estimation in the Karangnongko Dam, Bojonegoro

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A B S T R A C T

This study estimated design rainfall and flood hydrographs for the Karangnongko Dam Watershed, Bojonegoro, using the Soil Conservation Service Synthetic Unit Hydrograph (SCS-SUH) method. The analysis combined isohyetal rainfall estimation, frequency analysis and goodness-of-fit testing, Mononobe temporal distribution, and the Alternating Block Method. We converted effective rainfall into hydrographs to estimate peak discharge, time to peak, and runoff volume across rainfall return periods. Longer return periods produced higher design rainfall, peak discharges, and runoff volumes, while hydrograph shapes remained relatively consistent under unchanged watershed characteristics. The approach provides rainfall-based design flood estimates that can inform hydraulic structure planning, reservoir operation, and flood mitigation in data-limited watersheds

Contribution to Sustainable Development Goals (SDGs):
SDG 6: Clean Water and Sanitation
SDG 9: Industry, Innovation and Infrastructure
SDG 11: Sustainable Cities and Communities

1. INTRODUCTION

1.1. Research Background

Floods are among the most frequent natural disasters worldwide and continue to cause significant social, economic, and environmental impacts. The increasing occurrence of extreme rainfall events, combined with changes in land use and watershed characteristics, has intensified flood hazards in many river basins. Consequently, accurate flood discharge estimation has become essential for hydrological analysis, planning, design, and operation of hydraulic structures, including dams, spillways, and flood control facilities [1]. Reliable flood discharge estimation is required to ensure that water resources infrastructure can safely accommodate extreme hydrological events while maintaining operational efficiency.

Flood discharge estimation generally begins with determining design rainfall through statistical frequency analysis of historical rainfall records. The selected probability distribution is subsequently used to estimate rainfall magnitude for different return periods. Because rainfall data are commonly available only on a daily basis, temporal rainfall distribution methods such as the Mononobe method are often used to derive hourly rainfall intensity. Furthermore, rainfall excess must be determined before transforming rainfall into runoff hydrographs representing watershed response during storm events [2]. Therefore, every stage of hydrological analysis, from rainfall frequency analysis to hydrograph generation, plays an important role in determining the accuracy of flood discharge estimation.

Among rainfall–runoff transformation methods, the Soil Conservation Service Synthetic Unit Hydrograph (SCS-SUH) is widely used because of its simple procedure and reliable performance in ungauged or data-limited watersheds. The method utilizes watershed characteristics, including drainage area, land use, hydrologic soil group, and Curve Number (CN), to estimate runoff hydrographs, peak discharge, runoff volume, and time to peak [3]. Because of its practical implementation and moderate data requirements, the SCS-SUH method has been widely

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adopted in hydrological studies and engineering applications for flood analysis and water resources planning.

The Karangnongko Dam Watershed, located within the Bengawan Solo River Basin, plays a strategic role in supporting flood control, water supply, and regional water resources management. As one of Indonesia's national strategic water infrastructure projects, the watershed requires reliable hydrological information to understand its response under different rainfall return periods. Although numerous studies have implemented hydrological modeling for flood estimation, analyses focusing on the development of design rainfall and synthetic flood hydrographs using the SCS Synthetic Unit Hydrograph method in the Karangnongko Dam Watershed remain limited. This condition highlights the need for a comprehensive hydrological assessment based on local watershed characteristics and available rainfall records.

Therefore, this study aims to analyze design rainfall and estimate flood discharge using the SCS Synthetic Unit Hydrograph method in the Karangnongko Dam Watershed, Bojonegoro. The study covers areal rainfall estimation, statistical frequency analysis, probability distribution testing, temporal rainfall distribution using the Mononobe method, and developing synthetic flood hydrographs for selected return periods. The results are expected to improve the understanding of watershed hydrological response and provide valuable information for future flood assessment, water resources planning, and hydraulic infrastructure management in the study area.

1.2. Literature Review

Hydrological analysis plays an important role in estimating flood discharge for planning and managing water resources infrastructure. Reliable flood estimation depends on accurate rainfall analysis and an appropriate rainfall–runoff transformation method, as these determine the magnitude and characteristics of flood hydrographs. Errors in design rainfall estimation or runoff analysis may lead to inaccurate flood discharge predictions, affecting the safety and performance of hydraulic structures.

Determining design rainfall is a fundamental step in hydrological studies. Statistical frequency analysis is commonly used to estimate rainfall associated with selected return periods, while temporal rainfall distribution methods transform daily rainfall into hourly rainfall suitable for flood analysis. The resulting effective rainfall serves as the primary input for synthetic hydrograph development and strongly influences estimates of peak discharge, runoff volume, and watershed response.

Among rainfall–runoff transformation methods, the Soil Conservation Service Synthetic Unit Hydrograph (SCS-SUH) is widely used because it requires relatively limited hydrological data while providing reliable flood hydrograph estimates. The method incorporates watershed characteristics, including drainage area, land use, Hydrologic Soil Group (HSG), and Curve Number (CN), to simulate runoff response under different rainfall conditions. Consequently, the SCS-SUH method has been extensively adopted in flood estimation, watershed management, and hydraulic engineering applications.

This literature review discusses the theoretical concepts and previous studies related to design rainfall analysis, statistical frequency analysis, temporal rainfall distribution, and the application of the Soil Conservation Service Synthetic Unit Hydrograph (SCS-SUH) method for flood discharge estimation. These theories provide the scientific basis for evaluating the hydrological response of the Karangnongko Dam Watershed under various rainfall return periods.

1.2.1. Design Rainfall Analysis

Design rainfall analysis is a fundamental stage in hydrological studies because it provides the basis for estimating flood discharge associated with different return periods. The analysis is generally performed using historical rainfall records through statistical frequency analysis to estimate the probability of extreme rainfall events. Several probability distributions, including Normal, Log-Normal, Gumbel, and Log Pearson Type III, are commonly applied to determine design rainfall, while goodness-of-fit tests such as Chi-Square and Kolmogorov–Smirnov are employed to identify the most appropriate statistical distribution [1]. The resulting design rainfall serves as the primary input for rainfall–runoff transformation and significantly influences the accuracy of flood estimation.

1.2.2. Temporal Rainfall Distribution

Rainfall data are commonly available as daily observations, whereas hydrological modeling requires rainfall data with shorter temporal intervals. Consequently, temporal rainfall distribution methods convert daily rainfall into hourly rainfall intensity. One of the most widely used approaches is the Mononobe method, which distributes daily rainfall according to an empirical relationship between rainfall intensity and storm duration [4]. The generated hourly rainfall pattern is subsequently rearranged using the Alternating Block Method (ABM) to produce a realistic temporal rainfall distribution that represents storm events. This rainfall hyetograph becomes an essential input for estimating rainfall excess and generating flood hydrographs.

1.2.3. SCS Synthetic Unit Hydrograph

The Soil Conservation Service Synthetic Unit Hydrograph (SCS-SUH) is one of the most widely adopted rainfall–runoff transformation methods because it provides a practical approach for estimating flood hydrographs in watersheds with limited streamflow observations. The United States Department of Agriculture (USDA) developed the method based on the relationship between watershed characteristics and runoff response [5]. Unlike observed unit hydrographs that require continuous discharge measurements, the SCS-SUH estimates flood hydrographs using measurable watershed parameters such as drainage area, lag time, Curve Number (CN), and rainfall excess. The SCS-SUH method can estimate key hydrological characteristics, including peak discharge, time to peak, hydrograph shape, and runoff volume. Because of its relatively simple procedure, moderate data requirements, and satisfactory performance, the method has been widely applied in flood estimation, watershed management, reservoir planning, and hydraulic infrastructure design [6].

1.2.4. QGIS for Hydrological Analysis

QGIS is an open-source Geographic Information System (GIS) widely utilized for spatial and hydrological analysis due to its flexibility, accessibility, and integration with various geospatial processing tools. In hydrological studies, QGIS provides functionalities for DEM preprocessing, watershed delineation, stream network extraction, terrain analysis, and spatial data

visualization. The use of QGIS in hydrological modeling has increased significantly because it enables efficient processing of large spatial datasets while supporting reproducible and cost-effective watershed analysis. However, the accuracy of hydrological outputs generated in QGIS remains dependent on data quality, processing parameters, and the selected hydrological algorithms [7].

1.2.5. Previous Studies

Numerous studies have demonstrated the effectiveness of hydrological analysis for flood discharge estimation using rainfall–runoff approaches. Teshome et al. [8] applied the HEC-HMS model to simulate flood discharge in the Tikur Wuha River Basin, Ethiopia, and reported satisfactory agreement between simulated and observed hydrographs. Similarly, Yilmaz et al. [9] evaluated the performance of HEC-HMS in data-scarce watersheds and concluded that appropriate watershed parameterization significantly improves flood simulation accuracy. Recent studies have also emphasized the importance of watershed characteristics in determining hydrological response. Kumar et al. [9] highlighted that watershed morphology, land use, and soil properties strongly influence runoff generation and flood prediction accuracy. Furthermore, Ref. [10] demonstrated that integrating hydrological analysis with watershed characteristics provides reliable flood estimation for large catchments. Although previous studies have extensively investigated rainfall–runoff modeling and flood estimation, research focusing on the development of design rainfall and flood hydrographs using the SCS Synthetic Unit Hydrograph method in the Karangnongko Dam Watershed remains limited. Therefore, this study aims to analyze design rainfall and estimate flood discharge using the SCS-SUH method to improve the understanding of watershed hydrological response and provide supporting information for future water resources planning and flood management in the study area.

1.3. Research Objective

This study aims to analyze design rainfall and estimate flood discharge using the Soil Conservation Service Synthetic Unit Hydrograph (SCS-SUH) method in the Karangnongko Dam Watershed, Bojonegoro. The study includes areal rainfall estimation, rainfall frequency analysis, goodness-of-fit testing, temporal rainfall distribution, and development of synthetic flood hydrographs to determine the watershed's hydrological response under selected rainfall return periods.

2. MATERIALS AND METHODS

This study was conducted in the Karangnongko Dam Watershed, located in Bojonegoro Regency, East Java, Indonesia. The watershed is situated within the Bengawan Solo River Basin and serves as the primary catchment supplying inflow to the Karangnongko Dam. The study focused on estimating flood discharge through hydrological analysis using the Soil Conservation Service Synthetic Unit Hydrograph (SCS-SUH) method. The analysis investigated watershed response under various rainfall return periods based on historical rainfall records and watershed characteristics. The research employed a quantitative hydrological analysis approach. The study collected secondary data from relevant government agencies and previous project documents. The datasets consisted of daily rainfall records from rainfall stations surrounding the watershed, watershed boundary data, land use maps, Hydrologic Soil Group (HSG) data, and supporting hydrological information required for rainfall–runoff analysis. Areal rainfall was determined using the Thiessen Polygon method to represent the average rainfall over the watershed. The resulting areal rainfall data were subsequently used as the primary input for hydrological analysis.

Statistical frequency analysis was conducted to estimate design rainfall for selected return periods. Several probability distributions, including Normal, Log-Normal, Gumbel, and Log Pearson Type III, were evaluated to determine the most representative distribution of the historical rainfall data. We selected the distribution using Chi-Square and Kolmogorov–Smirnov goodness-of-fit tests. Design rainfall values were then calculated for the 2, 5, 10, 25, 50, and 100 year return periods. Since the available rainfall records consisted of daily observations, the Mononobe method was applied to convert daily design rainfall into hourly rainfall intensity. The generated hourly rainfall distribution was subsequently arranged using the Alternating Block Method (ABM) to produce a representative storm hyetograph. Effective rainfall was then determined to represent the portion of rainfall contributing directly to surface runoff after accounting for hydrological losses.

Flood hydrographs were developed manually using the Soil Conservation Service Synthetic Unit Hydrograph (SCS-SUH) method. Watershed characteristics, including drainage area, land use, Hydrologic Soil Group (HSG), and Curve Number (CN), were used to estimate rainfall losses and runoff response. The SCS-SUH method was applied to generate synthetic flood hydrographs and estimate the corresponding peak discharge, time to peak, and runoff volume for each rainfall return period. The generated flood hydrographs were analyzed to evaluate the hydrological response of the Karangnongko Dam Watershed under different rainfall scenarios. We compared the selected return periods to assess variations in peak discharge, hydrograph characteristics, runoff volume, and watershed response. The overall research workflow consisted of areal rainfall estimation, statistical frequency analysis, probability distribution testing, determination of design rainfall, temporal rainfall distribution using the Mononobe method, rainfall arrangement using the Alternating Block Method, effective rainfall estimation, development of the SCS Synthetic Unit Hydrograph, and flood discharge analysis. The research flowchart section presents a detailed illustration of the research procedure.

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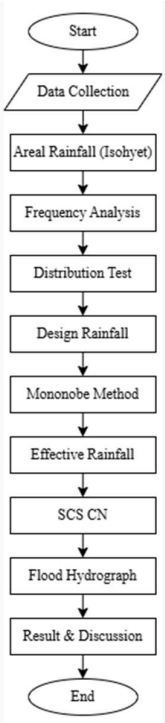


Fig 1. Research Flowchart for Design Rainfall Analysis and Flood Discharge Estimation Using the SCS Synthetic Unit Hydrograph Method.

3. RESULT AND DISCUSSION

3.1. Design Rainfall Analysis

The hydrological analysis was initiated by determining the areal rainfall of the Karangnongko Dam Watershed using the Isohyet method. Subsequently, statistical frequency analysis was performed to estimate design rainfall for selected return periods using several probability distributions. The most appropriate distribution was selected through Chi-Square and Kolmogorov–Smirnov goodness-of-fit tests. Similar statistical approaches have been widely adopted in recent hydrological studies to improve the reliability of design rainfall estimation [11], [12].

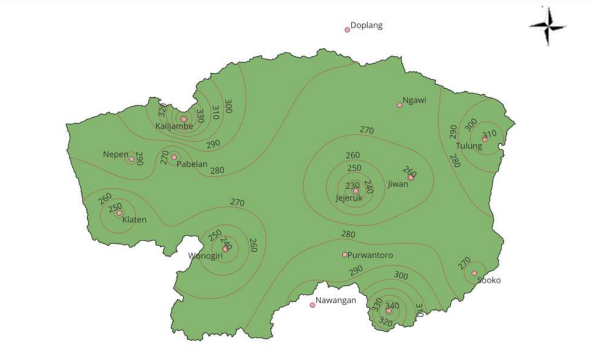


Fig. 2. Isohyet map of the Karangnongko Dam Watershed showing the spatial distribution of rainfall used for areal rainfall estimation

The estimated design rainfall increased progressively with increasing rainfall return periods, indicating a greater probability of extreme rainfall events producing larger runoff volumes. This tendency is consistent with recent studies reporting that rainfall magnitude is the dominant factor controlling peak flood discharge and watershed response [13], [14].

3.2. Temporal Rainfall Distribution

The calculated design rainfall was converted into hourly rainfall intensity using the Mononobe method and subsequently arranged into a temporal rainfall pattern using the Alternating Block Method (ABM). The Mononobe method transformed daily design rainfall into hourly rainfall intensities, enabling representation of the rainfall duration and intensity required for rainfall–runoff analysis. The ABM was then applied to distribute the calculated rainfall intensities over the storm duration by arranging rainfall blocks in an alternating sequence around the peak intensity, thereby producing a representative design storm hyetograph. The resulting storm hyetographs describe the temporal variation of rainfall intensity throughout the storm event and provide the effective rainfall input required for the development of the SCS Synthetic Unit Hydrograph (SCS-SUH). Appropriate temporal rainfall distribution is essential because it directly influences runoff concentration, peak discharge, time to peak, and the overall shape of the flood hydrograph. Consequently, combining the Mononobe method and ABM provides a systematic approach to generating realistic rainfall patterns for reliable flood discharge estimation under various rainfall return periods. Previous studies have demonstrated that appropriate temporal rainfall distribution significantly influences flood hydrograph characteristics and runoff concentration [15], [16].

3.3. Development of the SCS Synthetic Unit Hydrograph

The SCS Synthetic Unit Hydrograph (SCS-SUH) was developed based on several watershed characteristics, including drainage area, land use conditions, Hydrologic Soil Group (HSG), and Curve Number (CN). These parameters play an important role in representing the watershed's hydrological response to rainfall events. The drainage area influences the amount of runoff generated within the watershed, while land use and HSG determine infiltration capacity and surface runoff potential. In addition, the Curve Number (CN) parameter represents the combined effect of land cover, soil characteristics, and antecedent moisture conditions on rainfall losses and runoff generation. Therefore, the SCS-SUH method provides a practical framework for estimating effective rainfall, runoff response, peak discharge, time to peak, and runoff volume [17], [18]. The generated synthetic unit hydrograph illustrates the Karangnongko Dam Watershed's temporal response to effective rainfall. The hydrograph consists of three main components: the rising limb, peak discharge, and recession limb. The rising limb represents the initial increase in runoff discharge after rainfall excess begins to contribute to surface runoff. The peak discharge indicates the maximum runoff concentration reaching the watershed outlet, whereas the recession limb represents the gradual decrease in discharge after the peak flow has passed. These hydrograph components provide important information about runoff concentration processes and the watershed's storage characteristics [18].

Variations in watershed characteristics directly influence the shape and magnitude of the generated hydrograph. Watersheds with steeper slopes and shorter flow paths generally produce

faster runoff concentration and shorter time to peak. Conversely, watersheds with gentler slopes, longer flow paths, and higher infiltration capacity tend to delay runoff concentration and reduce peak discharge. Similarly, higher Curve Number values indicate lower infiltration potential, resulting in greater effective rainfall and larger runoff volumes. Consequently, differences in land use, soil characteristics, drainage area, and watershed morphology can significantly affect hydrograph shape, runoff concentration, peak discharge, and flood magnitude [19]. The SCS synthetic unit hydrograph provides an important basis for estimating flood discharge under different rainfall return periods. By combining effective rainfall with the watershed response represented by the unit hydrograph, the resulting flood hydrographs can be used to evaluate peak discharge, time to peak, runoff volume, and overall watershed hydrological response. These results provide valuable information for flood assessment, hydraulic structure planning, and water resources management within the Karangnongko Dam Watershed.

3.4. Flood Discharge Estimation

Flood hydrographs generated for different rainfall return periods indicate that higher rainfall magnitudes produce greater peak discharges and larger runoff volumes. As the rainfall return period increases, the hydrographs exhibit progressively higher peak flows while maintaining similar overall shapes because the physical characteristics of the watershed, including drainage area, basin slope, and flow path, remain unchanged throughout the simulations. The hydrograph comparison also shows steeper rising limbs and longer recession limbs for higher return periods, reflecting the increased volume of effective rainfall contributing to surface runoff. Consequently, the simulated flood hydrographs demonstrate a more pronounced watershed response under extreme rainfall events, resulting in greater flood magnitudes and higher potential flood risks. Previous studies report similar findings, indicating that design rainfall magnitude is a primary factor controlling peak discharge and hydrograph characteristics in synthetic unit hydrograph analyses [20].

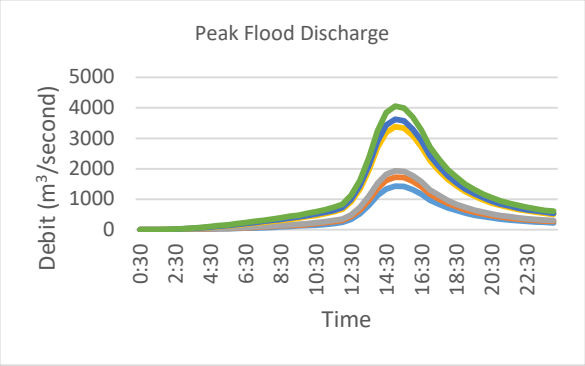


Fig. 3. Flood Hydrographs for Different Rainfall Return Periods Using the SCS Synthetic Unit Hydrograph Method.

The generated hydrographs provide a comprehensive representation of the rainfall–runoff response of the Karangnongko Dam Watershed under various design rainfall scenarios. The hydrograph characteristics, including peak discharge, time to peak, and runoff volume, provide valuable information for evaluating watershed behavior during flood events. These results can support the planning and design of hydraulic structures, reservoir operation strategies, and flood mitigation measures by providing quantitative estimates of flood magnitude under different rainfall return periods. Furthermore, the generated hydrographs may serve as a useful reference for future hydrological studies and water resources management in the Karangnongko Dam Watershed.

4. CONCLUSION

This study analyzed design rainfall and estimated flood discharge in the Karangnongko Dam Watershed, Bojonegoro, using the Soil Conservation Service Synthetic Unit Hydrograph (SCS-SUH) method. The hydrological analysis included areal rainfall estimation using the Thiessen Polygon method, statistical frequency analysis, probability distribution testing, temporal rainfall distribution using the Mononobe method, rainfall arrangement with the Alternating Block Method (ABM), and the development of synthetic flood hydrographs. The adopted methodology successfully generated flood hydrographs for the 2-, 5-, 10-, 25-, 50-, and 100-year rainfall return periods, providing estimates of peak discharge, time to peak, and runoff volume. The results indicate that design rainfall increases with increasing return periods, resulting in higher effective rainfall, greater peak discharge, and larger runoff volume. Although flood discharge varies with rainfall return period, the hydrograph shape remains consistent because watershed characteristics do not change throughout the analysis. These findings show that the SCS-SUH method provides a practical, reliable approach to estimating flood discharge with limited hydrological data and can support hydrological assessments in ungauged or data-scarce watersheds. Overall, the applied methodology provides useful hydrological information for understanding the runoff response of the Karangnongko Dam Watershed and may serve as a scientific reference for flood assessment, hydraulic structure planning, and water resources management. A limitation of this study is that the analysis used synthetic hydrological methods without comparison to observed discharge records. Therefore, future studies should validate the estimated flood hydrographs using observed rainfall–runoff data or numerical hydrological models to improve the reliability and accuracy of flood discharge estimates.

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