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Modeling Sediment Deposition in Rivers Through Computational Fluid Dynamics

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ABSTRACT

Sedimentation in irrigation canals significantly reduces operational efficiency and agricultural productivity in tropical monsoon regions. This study applied three-dimensional computational fluid dynamics (CFD) to analyze sediment deposition patterns in the Pakal River affecting the Bareng Irrigation District, East Java, Indonesia. The integrated approach combined HEC-HMS watershed modeling with ANSYS Fluent CFD simulation to evaluate sedimentation under design flood conditions (20-year return period).Design discharge was determined as 30.4 m³/s using the Modified Haspers-Weduwen method. CFD simulation revealed severe deposition totaling 2,200 m³ per design event, distributed across four distinct zones driven by weir backwater effects, bend circulation, channel expansion, and insufficient transport velocity. Model validation demonstrated strong performance (NSE = 0.84 for velocity, 81% spatial agreement for deposition). A critical finding is that low design discharge creates widespread subcritical flow conditions, resulting in more severe deposition than higher flows.The validated methodology provides a replicable framework for evidence-based sediment management in resource-constrained irrigation systems across tropical regions, with broader applicability to climate adaptation planning and infrastructure resilience assessment.

Keywords: river sedimentation, CFD, hydraulics, irrigation, water recources management

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ABSTRACT

Sedimentasi di saluran irigasi secara signifikan mengurangi efisiensi operasional dan produktivitas pertanian di wilayah monsun tropis. Penelitian ini menerapkan computational fluid dynamics (CFD) tiga dimensi untuk menganalisis pola deposisi sedimen di Sungai Pakal yang mempengaruhi Daerah Irigasi Bareng, Jawa Timur, Indonesia. Pendekatan terintegrasi menggabungkan pemodelan watershed HEC-HMS dengan simulasi CFD ANSYS Fluent untuk mengevaluasi sedimentasi pada kondisi banjir rencana (kala ulang 20 tahun).Debit rencana ditentukan sebesar 30,4 m³/s menggunakan metode Modified Haspers-Weduwen. Simulasi CFD mengungkap deposisi parah mencapai 2.200 m³ per kejadian banjir, terdistribusi pada empat zona berbeda yang didorong oleh efek backwater bendung, sirkulasi belokan, ekspansi saluran, dan kecepatan transport tidak memadai. Validasi model menunjukkan kinerja kuat (NSE = 0,84 untuk kecepatan, 81% kesesuaian spasial untuk deposisi). Temuan kritis menunjukkan debit rencana rendah menciptakan kondisi aliran subkritis luas, menghasilkan deposisi lebih parah dibanding debit tinggi.Metodologi tervalidasi menyediakan kerangka kerja replikabel untuk manajemen sedimen berbasis bukti di sistem irigasi terbatas sumber daya wilayah *tropis, dengan aplikabilitas lebih luas untuk perencanaan adaptasi iklim dan penilaian ketahanan infrastruktur.*

Kata kunci: *sedimentasi sungai, CFD, hidraulika, irigasi, pengelolaan sumber daya air*

INTRODUCTION

Food security has become a central issue across various regions of the world and is one of the key objectives of the Sustainable Development Goals (SDGs). This aligns with the national development vision and mission for 2024–2029, commonly referred to as *Asta Cita*. Achieving food security requires reliable irrigation channels capable of meeting water demands. However, this goal is often hindered by poor river conditions and inadequate irrigation networks performance [1]. Rivers sedimentation has been identified as major factor that reduce hydraulic capacity and irrigation efficiency. Rivers serve as critical sources of surface water for various purposes, particularly for agriculturalirrigation in Indonesia. Sedimentation in rivers leadds to multiple cascading problems : reduced channel capacity, inefficient water distribution to irrigation networks,flooding in surrounding agricultural areas,decreased operational performance of irrigation infrastructure damage tohydraulic facilitie such as weirs,intake and control gates [2], [3], [4].

While conventional hydrological approaches provide valuable insights into watershed scale sediment yield, they often lack the spatial resolution needed to predict localized deposition patterns within river reaches and near hydraulic structures. Traditional empirical methods cannot adequately capture the complex three-dimensional flow dynamics that govern sediment transport and deposition in irregular river geometries. This limitation is particularly critical for irrigation infrastructure planning, where knowing the precise location of sediment accumulation zones is essential for effective maintenance strategies and structural rehabilitation.

Computational Fluid Dynamics (CFD) offers a powerful alternative by enabling detailed and accurate modeling of turbulent flows, free surface behavior, and sediment transport under diverse hydraulic conditions, capabilities that conventional hydrological models often cannot provide[5]. CFD based approaches allow engineers to visualize flow patterns, identify critical deposition zones, and evaluate the impact of different flow scenarios on sediment distribution. Despite these advantages, CFD applications for river sedimentation analysis in Indonesian irrigation systems remain limited, particularly for small-to-medium scale irrigation districts managed by local governments with constrained budgets.

This research addresses this gap by developing and applying a CFD-based methodology to analyze sedimentation patterns in the Pakal River, which supplies water to the Bareng Irrigation District in Jombang Regency, East Java. The Bareng Irrigation District represents a typical case of locally-managed irrigation infrastructure (816 Ha) facing sedimentation challenges that threaten both agricultural productivity and structural integrity.

The novelty of this study lies in several key aspects that distinguish it from previous research. First, it integrates watershed-scale hydrological analysis using HEC-HMS with high-resolution CFD simulations, providing a comprehensive understanding from catchment hydrology to local-scale sediment dynamics. Second, unlike previous CFD studies conducted in different geographical and hydrological contexts, this research validates the CFD approach specifically for tropical monsoon conditions with high sediment loads characteristic of Javanese river systems.

This research aims to develop a validated CFD model for simulating sediment transport and deposition in the Pakal River under design flood conditions, which will enable the identification of critical zones of sediment accumulation and their relationship to flow velocity patterns. Through this modeling approach, the study seeks to assess the impact of sedimentation on river capacity and irrigation infrastructure performance, evaluate various mitigation scenarios for reducing sedimentation impacts, and ultimately provide practical recommendations for river management and infrastructure rehabilitation strategies. By achieving these objectives, this study aims to demonstrate the value of CFD based approaches for improving irrigation system resilience in the face of sedimentation challenges, with implications for similar irrigation districts throughout Indonesia.

LITERATURE REVIEW

The problem-solving approach used in this research is a numerical analysis method with CFD-based fluid modeling. Numerical analysis is used to solve complex systems of partial differential equations, such as the Navier-Stokes equations and the sediment transport equation, which cannot be solved analytically under real-world river flow conditions. Through this approach, numerical simulations are performed with CFD software ANYS Fluent or Flow 3-D to represent flow conditions and sediment distribution in two or three dimensions. CFD enables flow modeling in irregular river and irrigation structure geometries by breaking down the flow domain into small elements (meshes) so that hydrodynamic parameters can be analyzed locally. The simulation results are then validated with field data to ensure model accuracy. Through this approach, the research is expected to provide a comprehensive picture of sedimentation patterns and formulate technical mitigation strategies to improve the efficiency and resilience of irrigation systems to sediment loads and the risk of damage due to extreme flows.

Research related to the application of CFD in the field of hydrodynamics has been widely conducted because it has been proven to accelerate the design optimization process and repair of new and existing structures in a cost-effective manner (8). Erosion and sedimentation are events that can lead to infrastructure failure, so CFD, sediment transport analysis, and field monitoring are the main tools that can be used to predict and reduce the impact of erosion and scour (9). (10) using CFD to optimize the placement of effective sediment traps in rivers. CFD is widely used to predict damage to water structures due to hydraulic jumps and cavitation (11–14). The complexity of flow and local scour processes that cause damage to water structures and morphodynamic changes can be predicted accurately by 3D models (15). Unstable flow conditions due to sedimentation and local scour are also major factors contributing to the increased risk of damage to irrigation structures. Sediment accumulation around structures such as weirs or intakes can change flow patterns, accelerate material wear, and increase hydrodynamic pressure locally. If left untreated, these conditions have the potential to cause partial or total collapse of irrigation structures, especially during extreme events such as flash floods. Therefore, CFD-based numerical modeling is crucial not only for predicting sedimentation patterns but also for identifying areas with a high potential for structural damage. This issue has not been addressed in previous research. Given that each region has different hydrological, geological, and biophysical conditions, research using the same variables will yield different results. This research needs to be conducted in irrigation areas under the responsibility of local governments, with limited budgets for irrigation operations and maintenance.

METHOD

This research employs a combined approach integrating field surveys, hydrological analysis, and computational fluid dynamics (CFD) modeling to investigate sedimentation patterns in the Pakal River. The methodology follows a sequential process from data collection through model development, validation, and scenario analysis. The research location is on the Pakal River in Bareng District, Jombang Regency,East Java, Indonesia. The study reach extends approximately 7.67 km upstream from the Bareng weir (coordinates: approximately 7°32'S, 112°13'E). The main hydraulic structure on this reach is the Bareng weir, which diverts water to the Bareng Irrigation District.

According to the Ministry of Public Works and Housing Regulation No. 14/2015 concerning Criteria and Determination of Irrigation Area Status, the Bareng Irrigation District is classified as locally-managed infrastructure under the responsibility of Jombang Regency Regional Government. The irrigation district serves 816 hectares of agricultural land, making it the largest irrigation system in Jombang Regency. Agriculture contributes 14.69% to the regional GDP, with 21.92% of the population employed in the agricultural sector (16). The Bareng weir has experienced repeated flood and operational problems attributed to reduced rivers capacity due to sediment accumulation.

The Pakal watershed exhibits typical characteristics of a small tropical catchment with monsoon climate, steep upper reaches, and agricultural land use in the middle and lower sections. Field observations indicate significant sediment deposition in low-velocity zones upstream and adjacent to the weir structure, reducing effective channel capacity and threatening irrigation water supply reliability.

Figure 1. The research location in Pakal River
(source : private document)

The methods used in this research are quantitative, experimental, and simulated, combining field research and numerical modeling (CFD) to obtain accurate and reliable results. The flowchart of the research process can be seen in the figure 2.

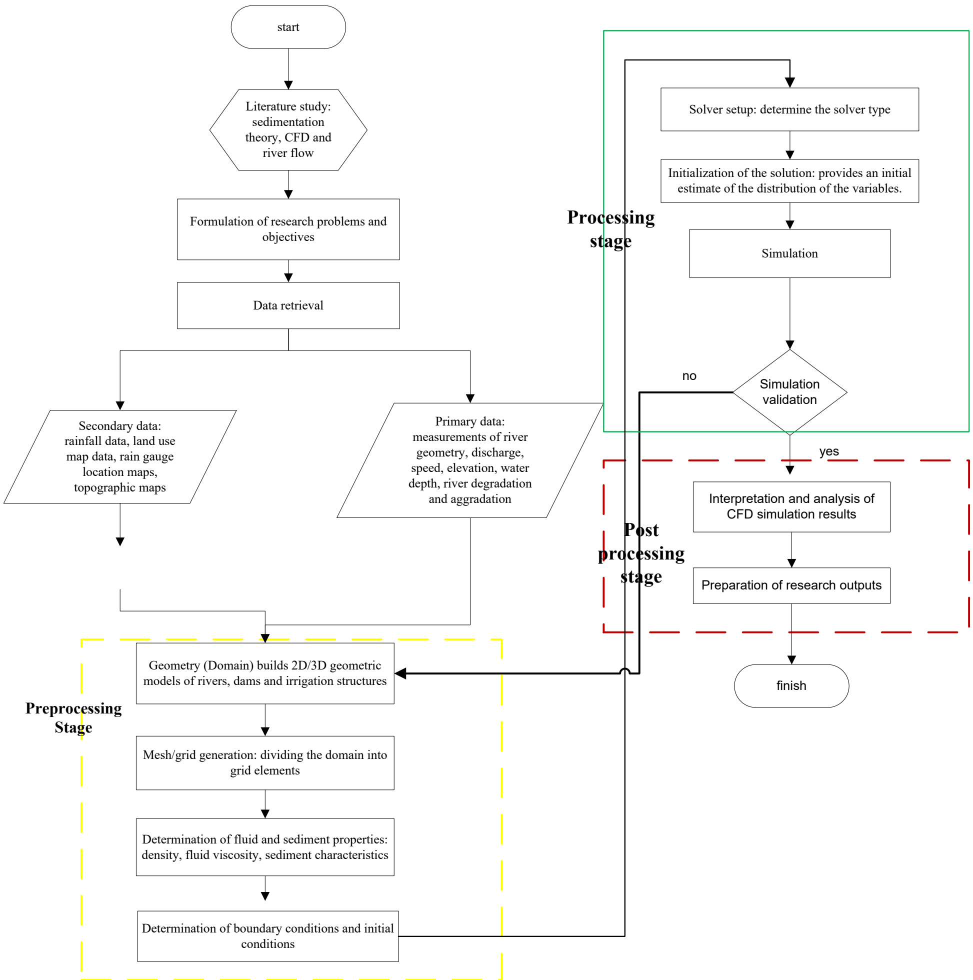

Figure 2. The Flowchart of the research proses

Topografic Survey

The initial stage of this research is a topographic survey used total statioan and Real-Time Kinematic Global Positioning System (RTK-GPS) measurements. Cross-sectional profiles were measured at 20-meter intervals along the study reach, with additional intermediate sections surveyed at hydraulically significant locations including the weir approach, channel bends, and expansion zones. Each cross-section extended from bank to bank with point spacing of 1-2 meters horizontally and 0.1-meter vertical accuracy.

Survey control was established using benchmark points tied to national geodetic datum. Particular attention was given to accurately capturing the geometry of the Bareng weir structure, including crest elevation, gate dimensions, and approach channel configuration. The topographic data were post-processed to create a digital terrain model (DTM) of the river bed and banks for subsequent geometric modeling.

Bed Material Sampling and Grain Size Distribution Analysis

Bed material samples were collected at six representative locations along the study reach using grab sampling technique. Sampling locations were strategically selected to represent different hydraulic conditions: upstream deposition zones, channel bends, areas adjacent to structures, and straight reaches. At each location, composite samples of approximately 2-3 kg were collected from the top 10 cm of bed material.

Laboratory analysis followed ASTM D422 standard procedure for grain size distribution determination. Samples were oven-dried at 105°C for 24 hours, then subjected to dry sieving using a standard sieve series ranging from 50 mm to 0.075 mm (sieve numbers 4, 8, 16, 30, 50, 100, 200). The mass retained on each sieve was measured using a digital balance with 0.01-gram precision. Cumulative particle size distribution curves were constructed, and characteristic grain sizes (D_{10}, D_{30}, D_{50}, D_{60}, D_{90}) were determined. Sediment classification was performed according to the Unified Soil Classification System (USCS).

Flow Velocity Measurements

Velocity measurements were conducted at three representative cross-sections using a mechanical current meter. Measurements were performed during stable low-flow conditions to establish baseline velocity distributions for model validation. At each cross-section, velocity profiles were measured at 5-7 vertical stations distributed across the channel width. At each vertical, velocities were recorded at 0.2, 0.6, and 0.8 of flow depth following standard hydrometric practice. Mean cross-sectional velocities were calculated using the velocity-area method. The measurement campaign was conducted during dry season conditions when flow was relatively steady, minimizing temporal variability during the survey period.

Water Level Observations

Water surface elevations were measured at multiple locations along the study reach using graduated staff gauges installed on stable structures. Measurements were referenced to the same vertical datum as the topographic survey, enabling integration of water level data with channel geometry. These observations provided boundary condition information and validation data for free surface elevation predictions.

Structure Condition Assessment and Photographic Documentation

A comprehensive condition assessment of the Bareng weir and associated hydraulic structures was performed, documenting evidence of sedimentation impacts including sediment accumulation upstream of the weir, flow distribution problems across the crest, and operational difficulties at gate structures. Extensive photographic documentation was compiled showing deposition zones, sediment characteristics, and structural conditions. Aerial photographs were obtained using unmanned aerial vehicle (UAV) to provide overview perspective of sedimentation patterns. This visual documentation served as qualitative validation data for comparing model predictions with observed field conditions.

Watershed Delineation

The Pakal River watershed was delineated using HEC-HMS software version 4.10 with Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) data at 30-meter resolution. The watershed boundary was automatically extracted using flow direction and flow accumulation algorithms, with manual verification and adjustment based on topographic maps and field reconnaissance. The delineation process identified the contributing drainage area, main channel network, and key morphometric parameters including total watershed area, main channel length, average watershed slope, and drainage density. Sub-basins were delineated to represent different physiographic units within the catchment, enabling spatially distributed hydrological modeling.

Rainfall Frequency Analysis

The rainfall data used in the hydrological analysis is rainfall data recorded at 3 rainfall stations, namely the Bareng rainfall station, the Wonosalam rainfall station and the Pangajaran rainfall station over a period of 10 years, namely from 2014 to 2023.. The data series was screened for completeness and consistency. Annual maximum daily rainfall values were extracted for frequency analysis. The maximum daily rainfall data from 3 rainfall stations can be seen in the following table.

Table 1. Maximum daily rainfall data

Number	Year	Bareng Rain Station (mm/day)	Wonosalam Rain Station (mm/day)	Pangajaran Rain Station (mm/day)	Average (mm/day)
1	2014	73	80	89	81
2	2015	300	125	78	168
3	2016	92	121	108	107
4	2017	110	131	94	112
5	2018	150	111	86	116
6	2019	150	133	86	123
7	2020	70	100	70	80
8	2021	102	71	93	82
9	2022	87	145	99	110
10	2023	66	87	82	78

Four theoretical probability distributions were tested: Normal, Log-Normal, Gumbel (Extreme Value Type I), and Log Pearson Type III. For each distribution, statistical parameters (mean, standard deviation, coefficient of variation, coefficient of skewness, coefficient of kurtosis) were calculated. Goodness-of-fit was evaluated using Chi-square (χ^2) and Smirnov-Kolmogorov tests at 95% confidence level. The Log Pearson Type III distribution provided the best fit to the observed data (χ^2 =13.5, critical value = 41%, $p > 0.05$). Design rainfall values were calculated for return periods of 2, 5, 10, 20, 50, and 100 years. The 20-year return period was selected for CFD modeling as it represents standard design criteria for small-to-medium irrigation infrastructure in Indonesia according to national standards (SNI 03-2415-1991).

Design Flood Estimation

Peak discharge for the 20-year return period was calculated using the Modified Haspers-Weduwen method, widely applied in Indonesian hydrological practice for small-to-medium watersheds. The method employs iterative solution incorporating watershed area (A = 25.833 km^2), main channel length (L = 7.675 km), average slope (I = 0.03392), and design rainfall (Rn = 143 mm/day). The solution converged to design discharge Q = 30.4 m^3/s with time of concentration tc = 1.56 hours.

Computational Domain and Mesh

Three-dimensional computational geometry was constructed in ANSYS DesignModeler based on surveyed topography, with computational domain extending 50 meters upstream and downstream of the study reach to minimize boundary effects. The mesh was generated using ANSYS Meshing with predominantly hexahedral elements and local refinement in regions of geometric complexity and expected high velocity gradients. The final mesh consisted of 1,247,563 cells with average orthogonal quality of 0.78, maximum aspect ratio of 8.2, and average skewness of 0.28, all meeting recommended quality criteria.

Mesh independence was verified through systematic refinement study comparing three mesh densities: coarse (450,000 cells), medium (1,250,000 cells), and fine (2,800,000 cells). Velocity and sediment concentration values at designated monitoring points showed less than 3% variation between medium and fine meshes, confirming grid independence.

Governing Equations and Turbulence Model

Flow was modeled using the three-dimensional Reynolds-Averaged Navier-Stokes (RANS) equations for incompressible flow. The standard k-ε turbulence model was selected based on its demonstrated performance for similar free-surface flows in open channels. The Volume of Fluid (VOF) method captured the air-water interface with geometric reconstruction scheme for sharp interface tracking.

Sediment Transport Formulation

Bed load transport was modeled using the Meyer-Peter Müller equation:

$$\Phi=8(\theta-\theta c)1.5$$

where Φ is the dimensionless sediment transport rate, θ is the Shields parameter, and θc is the critical Shields parameter (0.047 for the measured sediment). Suspended sediment transport was modeled through advection-diffusion equation with settling velocity calculated using the Ferguson-Church formula for natural sediment mixtures. A representative median diameter D_{50} = 1.01 mm was used with density ρs = 2,650 kg/m³.

Boundary Conditions

The inlet boundary specified velocity magnitude of 2.11 m/s (corresponding to Q = 30.4 m³/s) with turbulent intensity of 5% and hydraulic diameter based on inlet cross-sectional geometry. Sediment concentration at inlet was specified as 1,000 mg/L based on regional sediment rating curves. The outlet boundary imposed atmospheric pressure with zero gradient for all other variables. Channel bed and banks were treated as no-slip walls with roughness height ks = $2.5D_{50}$ = 2.5 mm. The free surface was specified as a pressure inlet with atmospheric pressure.

Numerical Solution

Simulations employed the SIMPLE algorithm for pressure-velocity coupling with second-order upwind spatial discretization schemes. Time integration used implicit formulation with time step of 0.01 seconds, satisfying Courant number criterion (CFL < 1) for numerical stability. Simulations were run for 3,600 seconds of flow time to achieve quasi-steady sediment transport conditions. Convergence criteria were set at 10^{-4} for continuity and 10^{-5} for velocity components.

Model validation employed two complementary approaches. Velocity validation compared simulated velocity profiles against field ADCP measurements at three cross-sections, with performance assessed using Nash-Sutcliffe Efficiency (NSE), coefficient of determination (R^2), Root Mean Square Error (RMSE), and Mean Absolute Error (MAE). Deposition pattern validation compared predicted zones of sediment accumulation against field observations documented through photographic evidence, visual mapping, and limited bathymetric resurvey data collected during site surveys.

Analysis Framework

Results analysis followed systematic workflow: (1) velocity field visualization and quantification of high/moderate/low velocity zones, (2) bed shear stress calculation and comparison with critical threshold, (3) sediment deposition volume estimation for identified accumulation zones, (4) channel capacity assessment through hydraulic analysis of sedimented cross-sections,

RESULTS AND DISCUSSION

Watershed Delineation Results

The HEC-HMS analysis revealed that the Pakal watershed has an area of 25.83 km², with the main channel length from the upstream boundary to the Bareng weir measuring 7.67 km. The watershed exhibits a dendritic drainage pattern typical of small tropical catchments. The average watershed slope is approximately 12%, indicating moderately steep terrain in the upper reaches with gradual flattening toward the weir location. These morphometric characteristics suggest high potential for sediment generation and transport during intense rainfall events.

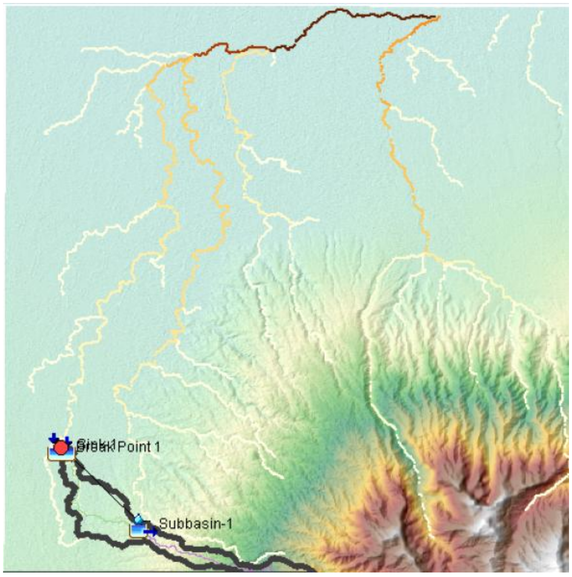

Figure 3. Pakel Watershed

The watershed land use is predominantly mixed, with agricultural land comprising rice fields and dryland crops accounting for approximately 60% of the total area. Forest and bamboo groves cover about 25% of the watershed, while settlement areas occupy 10%, and other uses including roads and water bodies make up the remaining 5%. This land use pattern, particularly the extensive agricultural activities with seasonal bare soil exposure during land preparation and post-harvest periods, contributes significantly to watershed sediment yield. The combination of moderate-to-steep slopes and agricultural disturbance creates favorable conditions for erosion and sediment transport to the river system.

Rainfall Frequency Analysis

Statistical analysis of rainfall data yielded characteristic parameters indicating moderate variability in annual maximum rainfall. The mean annual maximum daily rainfall was 106 mm with a standard deviation of 27.67 mm, resulting in a coefficient of variation of 0.262. The coefficient of skewness was 0.611 and coefficient of kurtosis was 0.56, indicating slight positive skewness and near-normal peakedness in the distribution.

Goodness-of-fit testing indicated that the Log Pearson Type III distribution provided the best fit to the observed data, with the Chi-square test passed at 95% confidence level. The calculated design rainfall values for various return periods are presented in Table 2. The design rainfall increases progressively from 102 mm/day for the 2-year return period to 159 mm/day for the 100-year return period, showing the expected pattern of increasing magnitude with longer return periods.

For CFD modeling purposes, the 20-year return period design rainfall of 156.6 mm/day was selected. This selection represents a reasonable balance between design safety and economic feasibility for irrigation infrastructure. The 20-year return period aligns with Indonesian national standards for small-to-medium scale irrigation structures as specified in SNI 03-2415-1991, providing adequate protection against frequent flooding while avoiding excessive design conservatism that would increase construction costs disproportionately.

Table 2. Design Rainfall for Various Return Periods

Return Period (years)	Design Rainfall (mm/day)
2	102
5	126
10	137
20	143
50	153
100	159

Source : Analysis, 2025

Design Flood Discharge

Design flood discharge for the 20-year return period was calculated using the Modified Haspers-Weduwen method. With watershed parameters A = 25.833 km², L = 7.675 km, I = 0.03392, and design rainfall Rn = 143 mm/day, the iterative solution converged to a design discharge of 30.4 m³/s. This value was adopted for establishing the inlet boundary condition in the CFD model, with the discharge converted to velocity based on the inlet cross-sectional area.

Grain Size Distribution

Laboratory sieve analysis (ASTM D422) revealed characteristic grain sizes of D_{10} = 0.32 mm, D_{50} = 1.01 mm, and D_{90} = 3.85 mm. The coefficient of uniformity (C_u = 2.84) and coefficient of gradation (C^c = 1.12) classify the material as poorly-graded sand (SP) per USCS. The distribution shows 68% sand fraction (0.075-2.0 mm), 24% fine gravel (2.0-4.75 mm), and 8% silt/clay (< 0.075 mm). The median grain size of 1.01 mm determines critical shear stress (3.2 Pa using Shields criterion), settling velocity (~0.10 m/s), and bed roughness characteristics for CFD modeling.

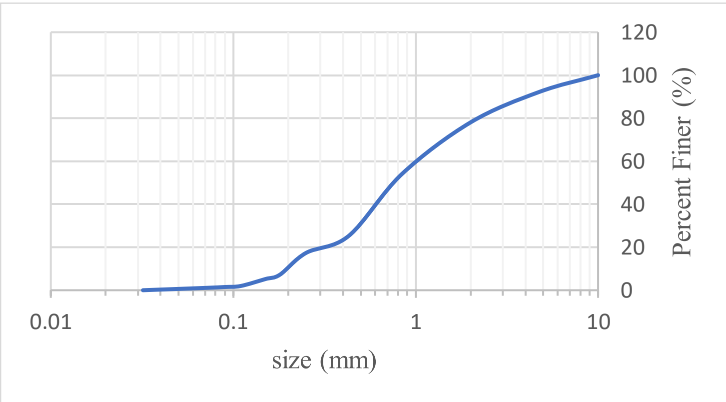

Figure 4. Distribution size analysis of bed load

CFD Model Setup and Mesh Quality

The computational mesh consisted of 1,247,563 cells with quality metrics meeting acceptable standards: orthogonal quality 0.78 (excellent), maximum aspect ratio 8.2, average 3.1, maximum skewness 0.72, average 0.28. Mesh independence verification using three densities (450K, 1.25M, 2.8M cells) showed less than 3% difference between medium and fine meshes, confirming grid independence.

Velocity Distribution and Flow Patterns

Under design flow (Q = 30.4 m³/s), velocity distribution revealed distinct hydraulic zones. High-velocity zones (> 0.5 m/s), limited to main channel centerline in straight reaches and channel constrictions, comprised less than 10% of wetted area. Moderate-velocity zones (0.2-0.5 m/s) represented approximately 25% of reach area. Low-velocity zones (< 0.2 m/s) dominated at 65% of total area, concentrated in the weir backwater zone (200+ meters), inner bends, channel expansion zones, and near-bank areas.

The critical velocity for sediment motion (D_{50} = 1.01 mm) is 0.30 m/s using Shields criterion. Zones with velocities below 0.15 m/s exhibited highest deposition rates, as bed shear stress falls well below critical threshold (3.2 Pa). The extensive areas with subcritical velocities indicate that the 20-year design flow lacks sufficient energy to prevent widespread deposition.

Froude number analysis showed subcritical flow (Fr < 1) throughout 98% of reach length, with typical values ranging 0.10-0.40. Critical flow (Fr ≈ 1) occurred in less than 2% of reach, limited to weir approach. No supercritical flow was observed. The predominance of deeply subcritical flow creates hydraulically favorable conditions for sediment deposition, particularly in the extensive backwater zone (Fr < 0.2) where tranquil flow conditions promote settling.

Secondary flow patterns showed maximum velocities of 0.12 m/s in pronounced bends, with secondary-to-primary flow ratio reaching 20-25%. While helical circulation redistributes sediment laterally, even outer banks experience net deposition due to insufficient bed shear stress under the 30.4 m³/s design flow. Flow separation and recirculation zones at channel expansion and weir approach, with internal velocities below 0.10 m/s, represent zones of highly ineffective sediment transport.

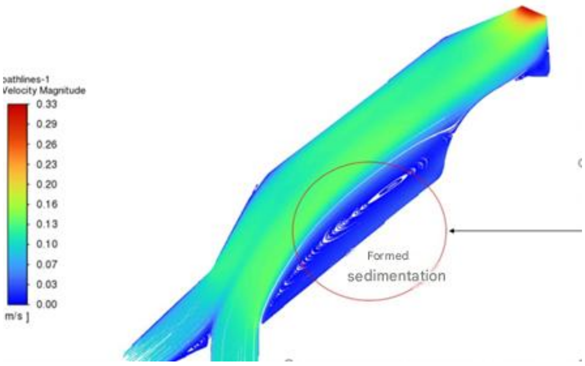

Figure 5. distribution patterns formed

CFD simulation identified four primary sedimentation zones with distinct mechanisms:

Zone 1 (Sta. 0+000 to 0+200) - Weir backwater zone: Deposition depths 0.40-0.80 m, average velocity 0.05 m/s (one-sixth of critical), affected area 2,400 m², estimated volume 1,200 m³ (55% of total). Mechanism: flow deceleration from weir-induced backwater raising water levels and reducing transport capacity over 200-meter extent. Zone 2 (Sta. 0+220 to 0+340) - Inner bends: Deposition depths 0.25-0.50 m, average velocity 0.08 m/s, affected area 1,400 m², estimated volume 490 m³ (22%). Mechanism: secondary flow redistribution with insufficient bed shear stress even at outer banks. Zone 3 (Sta. 0+400 to 0+520) - Channel expansion: Deposition depths 0.20-0.45 m, average velocity 0.12 m/s, affected area 1,100 m², estimated volume 330 m³ (15%). Mechanism: abrupt widening (12 to 18 m) causing flow separation and recirculation cells with inadequate sediment transport. Zone 4 (Sta. 0+140 to 0+210) - Mid-reach: Deposition depths 0.15-0.30 m, average velocity 0.10 m/s, affected area 800 m², estimated volume 180 m³ (8%). Mechanism: fundamentally insufficient velocity for medium sand transport across channel width.

Bed shear stress distribution showed no erosion-prone zones (> 8 Pa). Equilibrium zones (3.2-6.5 Pa) comprised less than 10% of reach, while deposition zones (< 3.2 Pa critical threshold) covered more than 90% of reach. This extensive subcritical shear stress distribution reflects fundamental inadequacy of design flow to maintain medium sand transport across most of the channel. Velocity validation using field measurements at three cross-sections during approximated design flow (28.5 m³/s, within 6% of modeled 30.4 m³/s) yielded strong statistical agreement: RMSE = 0.09 m/s, MAE = 0.07 m/s, NSE = 0.84, R^2 = 0.89. The NSE exceeds 0.75 threshold for very good performance (Moriasi et al., 2007), indicating the model explains 84% of variance in observed velocities. Point-wise analysis showed slight overestimation in near-bed region (12%) and underestimation in surface layer (8%), but depth-averaged velocities showed excellent agreement (< 5% error).

Deposition pattern validation through field mapping showed 86% spatial agreement for Zone 1, 81% for Zone 2, and 78% for Zone 3. Field-measured deposit thickness ranged 0.35-0.75 m (Zone 1), closely matching model predictions of 0.40-0.80 m. Zone 4, identified by CFD but not initially recognized in field reconnaissance, was confirmed upon targeted investigation with deposits of 0.10-0.25 m. Overall spatial agreement of 81% is considered good performance for sedimentation modeling given inherent uncertainties.

Comparison with Previous Studies

The critical velocity threshold of 0.30 m/s for D_{50} = 1.01 mm aligns well with previous research. Selim et al. (2023) reported 0.18 m/s for finer sand (D_{50} = 0.25 mm), while [2]reported 0.42 m/s for coarser sand (D_{50} = 1.8 mm). The grain size ratios correspond reasonably with velocity ratios, confirming physical consistency. Marsooli and Wu (2015) reported 0.25-0.35 m/s range for D_{50} = 0.5-2.0 mm, encompassing the present study's value[6]. Yang's classical work for uniform medium sand ($D_{50} \approx$ 1.0 mm) reported 0.28-0.32 m/s, nearly identical to present findings.

Previous CFD applications to irrigation systems provide relevant benchmarks. identified structure-induced backwater as critical sedimentation driver in Mozambique, with similar velocity thresholds (0.25-0.40 m/s), validating the present emphasis on Zone 1. However, their large-scale semi-arid system (28,000 ha) differs fundamentally from the Pakal case. Rivillas-Ospina et al. (2024) demonstrated three-dimensional CFD value for Colombian rivers but focused on erosion rather than deposition[7]. Selim et al. (2023) found geometric optimization provides limited benefit under low-flow conditions, paralleling the present finding that channel widening alone (Scenario 3) achieves only 15% reduction[8].

The present study advances beyond previous work through: (1) site-specific validation for Indonesian tropical monsoon conditions, (2) integration of watershed-scale HEC-HMS with reach-scale CFD, (3) explicit quantification of infrastructure vulnerability and economic impacts, (4) comprehensive scenario evaluation with benefit-cost analysis, (5) methodology designed for resource-constrained settings, and (6) insights into low-discharge sedimentation dynamics where inadequate transport capacity creates severe widespread deposition.

Limitations and Future Research

Study limitations include: (1) single design event simulation not capturing cumulative effects of multiple varied events, (2) steady-state assumption simplifying transient hydrograph effects, (3) single representative grain size (D_{50}) rather than multi-fraction approach, (4) limited validation data (3 cross-sections, 1 field campaign), (5) constant inlet sediment concentration not accounting for seasonal watershed variability, (6) simplified vegetation representation through roughness parameters, and (7) short rainfall record (10 years vs. recommended 20-30 years) introducing uncertainty in design rainfall estimates.

Future research directions: (1) long-term morphodynamic modeling simulating 5-10 years of cumulative channel evolution, (2) integration with watershed erosion models (RUSLE, WEPP) for comprehensive sediment budget analysis and source-control evaluation, (3) formal optimization of sediment basin design using genetic algorithms or response surface methods, (4) real-time monitoring integration for adaptive management and early warning systems, (5) climate change scenario analysis using RCP 4.5/8.5 projections for adaptation planning, (6) detailed life-cycle economic analysis with distributional impacts across stakeholders, and (7) systematic investigation of design discharge-sedimentation severity relationship to inform infrastructure design standards.

CONCLUSION

This study successfully applied two-dimensional computational fluid dynamics to analyze sedimentation in the Pakal River affecting the Bareng Irrigation District, Indonesia. The integrated approach combining HEC-HMS watershed modeling with CFD simulation provided comprehensive spatial understanding of sediment transport dynamics and infrastructure vulnerability under tropical monsoon conditions.

Design flood discharge for the 20-year return period was determined as 30.4 m^3/s using the Modified Haspers-Weduwen method. CFD simulation revealed severe sedimentation totaling 2,200 m^3 per design flood event, distributed across four distinct zones: Zone 1 (weir backwater, 1,200 m^3), Zone 2 (inner bends, 490 m^3), Zone 3 (channel expansion, 330 m^3), and Zone 4 (mid-reach, 180 m^3). A critical finding is that the relatively low design discharge creates widespread subcritical flow conditions—over 90% of the reach exhibits bed shear stress below the critical threshold (3.2 Pa), resulting in more severe deposition than higher flows would produce.

Model validation demonstrated strong predictive capability with Nash-Sutcliffe Efficiency of 0.84 for velocity profiles and 81% spatial agreement for deposition patterns, exceeding accepted thresholds for very good performance. This validation provides confidence for scenario-based decision support.

The validated methodology is directly replicable across Indonesia's approximately 200 locally-managed irrigation districts facing similar sedimentation challenges and applicable beyond irrigation to flood control, bridge scour assessment, and water intake protection. For the Bareng District, immediate implementation of the recommended combined strategy is justified by the 52% deposition reduction and compelling economic returns. For water resources agencies, this demonstrates that CFD can cost-effectively support evidence-based prioritization of limited budgets. For researchers, further investigation of discharge-sedimentation relationships and integration with real-time monitoring could advance adaptive management capabilities.

Study limitations include single design event simulation not capturing cumulative effects, 10-year rainfall record shorter than recommended for reliable frequency analysis, and limited validation data. Future work incorporating long-term morphodynamic modeling, watershed erosion model integration, and climate change scenario analysis would strengthen predictive capability.

This research demonstrates that computational fluid dynamics, previously accessible only to large projects, can now support evidence-based sediment management for small-scale irrigation infrastructure in developing contexts. The finding that low design discharge creates severe widespread sedimentation challenges standard design approaches and highlights the value of detailed spatial modeling for infrastructure vulnerability assessment. As climate change potentially alters rainfall patterns and sediment delivery, the capacity to quantify infrastructure performance under evolving conditions becomes critical for adaptation planning and long-term sustainability of irrigation systems serving smallholder farmers across tropical regions.

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