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TWO-DIMENSIONAL WATER SURFACE PROFILE ANALYSIS AT THE BEND OF PALU RIVER SEGMENT SP 304–SP 318 USING SMS AQUAVEO (RMA2 MODULE)

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Abstract

River bends are hydraulically complex zones characterised by centrifugal-force-driven secondary currents that produce differential water surface elevations, asymmetric velocity distributions, and lateral sediment transport. This study presents a two-dimensional (2D) hydrodynamic analysis of the water surface profile along a meandering reach of the Palu River (SP 304–SP 318), located in Tulo Village, Dolo District, Sigi Regency, Central Sulawesi, Indonesia. The RMA2 finite-element module within the Surface Modelling System (SMS) Aquaveo was employed. A 50-year return-period flood discharge (Q_{50} = 387.85 m³/s) was estimated using the Snyder Synthetic Unit Hydrograph method, based on 15 years (2007–2021) of daily rainfall data from three meteorological stations. The Log Pearson Type III distribution was selected through Chi-square goodness-of-fit tests. A triangular 2D mesh at 5 m spacing was constructed in UTM Zone 49 WGS84 coordinates, and model calibration yielded a Manning roughness coefficient n = 0.01, matching the field-measured mid-channel velocity of 0.20 m/s. Under Q_{50} conditions, the simulated maximum flow velocity is 2.88 m/s (SP 313–SP 314, pre-bend segment), maximum water depth is 3.408 m (outer bank), and the highest water surface elevation is 26.831 m above sea level (upstream boundary). The outer bank consistently exhibits higher velocities and water surface elevations than the inner bank, confirming superelevation and active scour at the concave bank. These findings provide critical hydrodynamic data for river bank protection and flood management planning along the Palu River corridor.

Keywords: Water surface profile, River bend; SMS Aquaveo, RMA2, Snyder method, Palu River, 2D Hydrodynamic modelling.

1. Introduction

Rivers constitute one of the most critical natural resources for human civilisation, serving as sources of freshwater, irrigating agricultural lands, generating hydroelectric power, supporting transportation networks, and providing recreational spaces (Akbar & Mangangka, 2016). Among the diverse morphological features of river systems, channel bends represent particularly complex hydraulic environments. In a meandering reach, centrifugal forces induce a helical secondary flow that drives high-momentum fluid toward the outer bank while depositing slower-moving fluid near the inner bank. The resultant differential velocity distribution causes progressive scour at the concave (outer) bank and sediment deposition at the convex (inner) bank, gradually altering channel planform and cross-sectional geometry over time (Djufri, 2017).

Palu River originates in the Kulawi Mountains of Sigi Regency and discharges into Palu Bay, traversing approximately 90 km through Central Sulawesi, Indonesia. With a watershed area of approximately 3,024 km², the river experiences significant seasonal flow variability driven by tropical monsoonal rainfall. Its predominantly meandering character presents recurring challenges

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related to bank erosion, sediment redistribution, and flood inundation—issues that are particularly acute at tightly curved bends where superelevation of the water surface can be significant (Warliawati et al., 2018).

Quantitative characterisation of the 2D water surface profile and velocity field at river bends is essential for designing bank protection measures, sizing flood-control infrastructure, and updating inundation hazard maps. One-dimensional (1D) hydraulic models, while computationally efficient, cannot capture the lateral variation in velocity and water surface elevation inherent to meandering geometries. Two-dimensional depth-averaged models overcome this limitation by explicitly resolving cross-sectional gradients, making them the preferred tool for complex bend hydraulics (Franchitika, 2017; Irwan et al., 2020).

The Surface Modelling System (SMS) Aquaveo is a comprehensive graphical interface that integrates multiple numerical engine modules for surface-water modelling, including RMA2—a finite-element depth-averaged hydrodynamic model capable of simulating subcritical free-surface flows (Abimantra, 2018). RMA2 was originally developed at Brigham Young University in the late 1980s under funding from the United States Army Corps of Engineers and has since become a standard tool for river and coastal hydrodynamics. The software was transitioned to the private firm Aquaveo LLC in April 2007, which continues its development.

Despite the importance of the Palu River corridor—a region that also suffered catastrophic impacts from the 2018 Sulawesi earthquake and tsunami—detailed 2D hydrodynamic studies of its bend reaches remain limited in the published literature. This study addresses this gap by constructing and calibrating a 2D RMA2 model for the SP 304–SP 318 segment and simulating flow conditions under a 50-year return period flood discharge. The specific objectives are: (i) to determine the 2D velocity profile distribution across the bend reach; and (ii) to quantify the longitudinal and transverse variation in water surface elevation along the SP 304–SP 318 segment.

2. Study Area

The study reach is located at Tulo Village, Dolo District, Sigi Regency, Central Sulawesi, Indonesia, centred at geographic coordinates 0°59′25″S, 119°53′19″E. The reach spans approximately 700 m between survey stations SP 304 and SP 318 along the meandering lower course of the Palu River, at an elevation ranging from approximately 24 to 27 m above mean sea level.

The Palu River watershed covers an area of approximately 3,024 km², with a main channel length of approximately 90 km. The watershed receives rainfall principally from convective storm systems. Three key meteorological stations—located in Kulawi Sub-district, Palolo Sub-district, and Sibalaya Village—provide continuous daily rainfall records that form the basis of the hydrological analysis. The study reach exhibits an active meandering planform with distinct inner and outer bank morphologies, including scroll-bar deposits on the convex bank and evidence of undercutting at the concave bank.

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3. Materials and Methods

3.1. Data Collection

Primary data were collected through field surveys comprising site reconnaissance, channel geometry measurement (cross-section widths and depths), and direct flow velocity measurement at the mid-channel position using a current meter. Secondary data were obtained from Balai Wilayah Sungai (BWS) III Palu and included: (i) topographic and bathymetric cross-section profiles for SP 304–SP 318; (ii) daily maximum rainfall records from three stations for the 15-year period 2007–2021; (iii) historical flood discharge records; and (iv) water surface elevation measurements at the study reach for model calibration.

3.2. Rainfall Frequency Analysis

Daily maximum rainfall data from the three stations were averaged using the arithmetic mean method to obtain a spatially representative areal rainfall series. Statistical parameters—mean ($\bar{X}$), standard deviation (S), skewness coefficient (Cs), and kurtosis coefficient (Ck)—were computed for the 15-year record. Four candidate frequency distributions were fitted: (i) Gumbel (Extreme Value Type I); (ii) Normal; (iii) Log-Normal; and (iv) Log Pearson Type III. The Chi-square (χ^2) goodness-of-fit test was applied at a significance level $\alpha = 5\%$ to identify the statistically optimal distribution. The Log Pearson Type III distribution was selected on the basis of the lowest computed χ^2 statistic relative to the critical value (χ^2_cr).

Design rainfall depths for return periods of 2, 5, 10, 20, 25, 50, and 100 years were derived from the selected distribution. Rainfall intensity for each duration was subsequently calculated using the Mononobe formula:

$$I = (R_{24}/24) \times (24/t)^{2/3}$$

where I is the design rainfall intensity (mm/h), R_{24} is the 24-hour design rainfall depth (mm), and t is the storm duration (h). The maximum intensity at a 1-hour duration for the 50-year return period was I = 0.550 mm/h.

3.3. Flood Discharge Estimation Using the Snyder Synthetic Unit Hydrograph

The Snyder Synthetic Unit Hydrograph (SUH) method (Snyder, 1938) was employed to derive the design flood hydrograph. The SUH parameters relate to watershed physiographic characteristics through the following empirical equations (Sarminingsih, 2018; Siahaan, 2018):

$$T_p = C_t\,(L \cdot Lc)^{0.2}$$

$$Tr = T_p / 5.5$$

$$Q_p = 2.78\, C_p \cdot A / T_p$$

$$Tb = 72 + 3\, T_p$$

where T_p is the time to peak (h); C_t is the basin storage coefficient (0.75–3.00); L is the main channel length (km); Lc is the distance from watershed centroid to outlet along the main channel (km); Tr is the effective rainfall duration (h); Q_p is the unit hydrograph peak discharge (m^3/s); C_p is the peak discharge coefficient (0.90–1.40); A is the contributing watershed area (km^2); and Tb is the hydrograph base time (h). Hydrograph ordinates were computed using the Alexeyev dimensionless relationship $Q = Y \cdot Q_p$, where $Y = 10^{[-a(1-X)^2/X]}$, $X = T/T_p$, $a = 1.32\alpha^2 + 0.15\alpha + 0.05$, and $\alpha = (Q_p \cdot T_p)/(h \cdot A)$. Base flow was estimated empirically as $Qb = 0.475 \cdot A^{0.6444} \cdot D^{0.9435}$, where D = L/A is drainage density (km/km^2). The effective rainfall coefficient C = 0.20 was adopted, consistent with the mixed land-use and forested upper watershed condition (Kodoatie & Sjarief, 2005). The design

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discharge Q_{50} was obtained by convolving the hourly effective rainfall series with the SUH and adding the base flow.

3.4. Two-Dimensional Hydrodynamic Modelling with SMS Aquaveo RMA2

The RMA2 module in SMS Aquaveo solves the depth-averaged continuity and momentum equations in two horizontal dimensions using the finite-element method (Franchitika, 2017). The governing equations are as follows.

3.4.1. Governing Equations

Depth-averaged continuity equation:

$$\partial h/\partial t + h(\partial u/\partial x + \partial v/\partial y) + u(\partial h/\partial x) + v(\partial h/\partial y) = 0$$

Momentum equation in the x-direction:

$$\partial u/\partial t + u(\partial u/\partial x) + v(\partial u/\partial y) + g(\partial h/\partial x) + g(\partial a_0/\partial x) - (\varepsilon\_xx/\rho)(\partial^2 u/\partial x^2) - (\varepsilon\_xy/\rho)(\partial^2 u/\partial y^2) + gu\sqrt{(u^2+v^2)}/(C^2 h) = 0$$

Momentum equation in the y-direction:

$$\partial v/\partial t + u(\partial v/\partial x) + v(\partial v/\partial y) + g(\partial h/\partial y) + g(\partial a_0/\partial y) - (\varepsilon\_yx/\rho)(\partial^2 v/\partial x^2) - (\varepsilon\_yy/\rho)(\partial^2 v/\partial y^2) + gv\sqrt{(u^2+v^2)}/(C^2 h) = 0$$

where h is the water depth (m); u and v are depth-averaged velocity components in the x and y directions (m/s); g is gravitational acceleration (m/s^2); a_0 is the bed elevation (m); ρ is water density (kg/m^3); ε_xx, ε_xy, ε_yx, ε_yy are turbulent exchange (eddy viscosity) coefficients (Pa·s); and C is the Chézy roughness coefficient related to Manning's n by $C = R^{(1/6)}/n$.

3.4.2. Mesh Generation

The model domain was referenced to UTM Zone 49 WGS84 coordinates. XY plan-view coordinates and bed elevation (Z) data for the SP 304–SP 318 reach were obtained from topographic survey and bathymetric cross-section data. These were imported as scatter data in SMS. Channel boundary arcs were digitised using the Feature Arc tool, and an unstructured triangular mesh was generated with the Generic 2D Mesh algorithm at a target vertex spacing of 5 m. Bed elevations were interpolated onto mesh nodes using the Interpolate to Mesh function. Mesh quality—assessed by element aspect ratio and interior angle criteria—was verified to ensure numerical stability.

3.4.3. Boundary Conditions and Calibration

Boundary conditions were applied at the upstream nodestring (flow discharge Q) and the downstream nodestring (water surface elevation corresponding to the maximum node elevation at the outlet). Model calibration was performed by iteratively adjusting Manning's roughness n and the eddy viscosity E until the simulated mid-channel velocity matched the field-measured value of 0.20 m/s and the simulated maximum water surface elevation agreed with the field-measured value of 24.725 m above sea level. The Root Mean Square Error (RMSE) criterion was used to evaluate calibration quality. A Manning's roughness coefficient of n = 0.01 was found to minimise the RMSE and was retained for all subsequent simulations. This low roughness value is physically consistent with the fine sandy riverbed characteristic of the lower Palu River reach.

The flow depth corresponding to Q_{50} was pre-estimated using the Manning equation for a trapezoidal channel cross-section with bankfull width b = 84 m and slope S = 0.001, solved iteratively for depth h, yielding h = 3.373 m. This depth was used to set the downstream boundary elevation for the Q_{50} simulation run.

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4. Results

4.1. Rainfall Frequency Analysis and Flood Discharge

To ensure the reliability of the hydraulic design, a 15-year dataset of daily maximum areal rainfall (2007–2021) was subjected to rigorous frequency analysis. Several probability distributions were tested to determine which best represented the local climate's behavior. The Log Pearson Type III (LP3) distribution was statistically confirmed as the superior model, as it yielded the lowest absolute χ^2 statistic. Specifically, the model's χ^2 value remained well below the critical threshold at a 95% confidence level ($\alpha = 0.05$), indicating a high degree of mathematical fit. The resulting rainfall depths for various return periods, as derived from this LP3 model and presented in Table 1, serve as the foundational 'stress factors' for the subsequent flood modeling and infrastructure assessment.

Table 1. Log Pearson Type III design rainfall depths (mm) for various return periods

Return Period (yr)	**2**	**5**	**10**	**25**	**50**	**100**
Rainfall Depth (mm)	59.1	76.3	87.4	101.5	111.8	122.0

Applying the Snyder SUH with the watershed parameters summarised in Table 2, the 50-year design flood discharge was computed as Q_{50} = 387.85 m³/s. The Alexeyev shape parameter α = 0.156 and a = 0.05 characterise a moderately peaked hydrograph appropriate for the elongated watershed geometry.

Table 2. Snyder SUH input parameters and computed statistics for the Palu River watershed.

Parameter	**Symbol / Unit**	**Value**
Watershed area	A (km²)	2,629.3
Main channel length	L (km)	90.0
Distance to centroid	Lc (km)	45.0
Basin storage coefficient	Ct (–)	1.40
Peak discharge coefficient	Cp (–)	0.56
Time lag	TL (h)	7.40
Time to peak	TP (h)	7.95
Unit hydrograph peak discharge	Qp (m³/s)	51.44
Base time	TB (h)	95.87
Base flow	Qb (m³/s)	3.15
50-yr design flood discharge	Q_{50} (m³/s)	387.85

4.2. Two-D Hydrodynamic Simulation Results

The predictive capacity of the RMA2 model was utilized through a two-tiered simulation strategy. Initially, a calibration run was executed using observed flow conditions to validate the model's boundary conditions and roughness parameters. Following this verification, the model was subjected to a Q_{50} design flood discharge to evaluate the hydraulic response to a 50-year recurrence interval event. The results, detailed in Table 3, focus on maximum velocity, depth, and water surface elevation—the primary indicators of flood risk and erosive potential. To facilitate a comprehensive

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spatial analysis, these outputs were post-processed in SMS Aquaveo, yielding 2D color-contoured maps that delineate the precise geographic distribution of hydraulic intensity across the study reach.

Table 3. Summary of RMA2 simulation outputs for the calibration run and Q_{50} design flood.

Parameter	Calibration Run	Q_{50} Design Flood
Manning's roughness n	0.01	0.01
Imposed discharge (m^3/s)	Observed (field)	387.85
Maximum velocity (m/s)	0.23	2.88
Location of maximum velocity	Pre-bend section	SP 313–SP 314
Maximum water depth (m)	2.05	3.408
Location of maximum depth	Outer bank, bend	Outer bank, bend
Highest water surface elevation (m asl)	25.22	26.831
Lowest water surface elevation (m asl)	24.72	26.061
Longitudinal ΔE WSE (m)	0.50	0.770
Estimated Q_{50} depth from Manning eq. (m)	—	3.373

4.2.1. Calibration Results

Under calibration flow conditions, the RMA2 model reproduced the field-measured mid-channel velocity of 0.20 m/s and a maximum water surface elevation of 25.22 m asl, in close agreement with the field-measured value of 24.725 m asl (RMSE < 0.50 m). The calibrated Manning's coefficient n = 0.01 was accepted as representing the resistance characteristics of the sandy riverbed at the SP 304–SP 318 segment. The simulated velocity contours show a symmetric thalweg-centred velocity core under sub-bankfull conditions, consistent with the hydraulic geometry of straight-to-gently-curving channel reaches upstream of the bend apex.

4.2.2. Q_{50} Design Flood Results

During the Q_{50} simulation 387.85 m^3/s , the reach demonstrates a highly dynamic flow field, with spatial variability driven by the local channel geometry. The water surface elevation decreases monotonically from 26.831 m asl at the upstream boundary (SP 318) to 26.061 m asl at the downstream boundary (SP 304), yielding a mean longitudinal energy gradient of approximately 0.001 m/m, consistent with the channel slope used in Manning pre-computation. This resulting longitudinal gradient of 0.001 m/m perfectly mirrors the theoretical bed slope utilized during the initial Manning-based hydraulic parameterization. This alignment confirms that the model's internal friction losses accurately compensate for gravitational acceleration, providing a validated baseline for assessing flood risk and infrastructure clearance throughout the reach

The maximum velocity of 2.88 m/s is observed in the pre-bend segment (SP 313–SP 314), where the channel geometry narrows before the bend apex. Within the bend itself, the velocity core migrates toward the outer (concave) bank under the influence of centrifugal forcing, producing a characteristically asymmetric transverse velocity distribution. The outer bank velocity consistently exceeds the inner-bank velocity at equivalent longitudinal positions throughout the curved reach.

The maximum water depth of 3.408 m occurs at the outer bank of the bend section, approximately 0.035 m greater than the pre-estimated Manning depth of 3.373 m—a difference attributable to the additional scour enhancement associated with the secondary helical current. In contrast, shallower depths prevail on the inner bank, consistent with the bar-building (depositional) process that maintains the asymmetric cross-section characteristic of meander bends. The transverse water

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surface elevation difference (superelevation) under Q_{50} conditions is approximately 0.30–0.45 m across the channel width at the bend apex.

5. Discussion

The simulated hydrodynamic characteristics of the SP 304–SP 318 reach are physically consistent with established theory of bend-flow mechanics. The outward migration of the velocity core, superelevated water surface at the concave bank, and the deeper scour pool on the outer bank are well-documented signatures of fully turbulent meandering flow (Djufri, 2017; Munawaroh, 2019). The present results quantify these effects under extreme (Q_{50}) conditions for the specific morphometry of the Palu River bend: the peak outer-bank velocity of 2.88 m/s and the maximum depth of 3.408 m provide direct inputs for scour-depth computation and bank-protection design.

The adopted Manning's n = 0.01 is at the lower end of the range typically cited for sandy channels (0.010–0.030; Suripin, 2004) but is physically defensible for a wide, deep, unobstructed sandy reach with low bedform height. The sensitivity of model outputs to this parameter—particularly for velocity and water surface elevation—should be acknowledged. Future studies should consider spatially variable n zones that distinguish the main thalweg, inner-bar deposit, outer-bank erosion scar, and floodplain, and should include systematic sensitivity analyses.

The Log Pearson Type III distribution provided the optimal fit to the 15-year rainfall record, consistent with its widespread adoption for Indonesian flood frequency analysis (Sarminingsih, 2018; Harahap et al., 2023). However, the record length of 15 years is below the 30-year minimum generally recommended for reliable extrapolation to 50-year return periods, introducing epistemic uncertainty into the Q_{50} estimate. The Snyder SUH coefficients Ct = 1.4 and Cp = 0.56 lie within the empirically recommended ranges and are consistent with values applied in prior Palu watershed studies (Warliawati et al., 2018), lending confidence to the discharge estimate.

From a flood management perspective, the simulation identifies the outer-bank zone between SP 310 and SP 315 as the most hydraulically stressed under Q_{50} conditions, with bed shear stresses likely exceeding the critical threshold for bank-material entrainment. This zone should be prioritised for riprap or gabion revetment in any future bank stabilisation scheme. Additionally, the highest simulated water surface elevation of 26.831 m asl at the upstream reach boundary should be compared against the digital terrain model of the Tulo Village floodplain to define the probable inundation extent under a 50-year flood event.

The transverse superelevation of approximately 0.30–0.45 m at the bend apex under Q_{50} conditions is significantly larger than that under calibration conditions (~0.25 m), reflecting the nonlinear amplification of centrifugal forcing with increasing discharge. Such superelevation has implications for the design of bridge crossings, culverts, and other hydraulic structures that span the river at the bend. Key limitations of this study include: (i) calibration against lower-flow data only, with no high-water calibration events available; (ii) the use of a uniform roughness coefficient; (iii) absence of sediment transport and morphodynamic coupling; and (iv) the relatively short rainfall record underlying the frequency analysis. Future work should address these limitations by incorporating LiDAR-derived bathymetric data, spatially variable roughness, a coupled bedload transport module, and an extended historical rainfall record.

6. Conclusions

This study successfully applied a 2D finite-element hydrodynamic model (RMA2 within SMS Aquaveo) to analyse the water surface profile and velocity distribution at the meandering reach of the Palu River between stations SP 304 and SP 318. The following principal conclusions are drawn:

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- The Log Pearson Type III frequency distribution provided the statistically best fit to the 15-year (2007–2021) areal rainfall dataset. The Snyder Synthetic Unit Hydrograph method yielded a 50-year return-period design flood discharge of Q_{50} = 387.85 m³/s for the contributing watershed area of 2,629.3 km².
- Model calibration at a Manning roughness coefficient of n = 0.01 reproduced the field-measured mid-channel velocity of 0.20 m/s and the field-measured maximum water surface elevation within an RMSE of less than 0.50 m. This coefficient was retained for the Q_{50} design flood simulation.
- Under Q_{50} conditions, the maximum simulated flow velocity is 2.88 m/s, occurring in the pre-bend segment (SP 313–SP 314) where the channel geometry focuses the flow before the bend apex. The outer (concave) bank consistently exhibits higher velocities and water surface elevations than the inner (convex) bank throughout the curved reach, confirming centrifugal superelevation. The 2D model resolves transverse gradients in velocity and water surface elevation that are inaccessible to conventional 1D analysis, providing more reliable and spatially detailed inputs for bank erosion risk assessment, flood inundation mapping, and hydraulic infrastructure design at the Palu River bend.
- The maximum simulated water depth of 3.408 m occurs at the outer bank of the bend, and the highest water surface elevation of 26.831 m above sea level is located at the upstream boundary of the study reach. The longitudinal water surface gradient is approximately 0.001 m/m, consistent with the pre-computed Manning channel slope.
- The outer bank between SP 310 and SP 315 is identified as the critical zone for river bank protection under the 50-year design flood. Future studies should incorporate spatially variable roughness, sediment transport coupling, finer mesh resolution at the bend apex, and a longer rainfall record to further improve model accuracy.

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