



Flow structure in a local meander bend of a gravel-bed river

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Abstract: This study investigates the spatial variability of flow structure in a natural meandering bend of the Kheir-Abad River, a gravel-bed mountain stream in southwestern Iran, with emphasis on velocity distribution, boundary shear stress, and secondary circulation. Field measurements were conducted along a 270 m reach (arc angle 113°) across nineteen cross-sections, revealing a highly heterogeneous flow field characterized by a central high-velocity core and reduced velocities near the banks. Comparison with HEC-RAS simulations shows that the model captures the general spatial organization of velocity and shear stress, but produces a smoothed representation and underestimates localized variations, particularly in downstream sections where field data indicate pronounced acceleration and peak shear stress values (up to 84.1 Pa). The observed shear stress distribution deviates from classical outer-bank dominance, with maximum values frequently occurring in the central channel and downstream regions, reflecting the influence of coarse bed roughness, complex secondary flow structures, and thalweg-controlled momentum concentration. Analysis of the secondary flow coefficient (C) supports this interpretation, with peak values coinciding with zones of increased velocity and shear stress, indicating intensified momentum exchange and enhanced near-bed transport capacity. Overall, the results demonstrate that flow in gravel-bed meanders is governed by strongly non-uniform and three-dimensional processes that cannot be fully captured by simplified hydraulic assumptions, and that integrating field measurements with numerical modeling provides a robust framework for interpreting flow dynamics and their morphodynamic implications.

Keywords: Flow Structure; Meander bend; Gravel-bed river; Shear stress; Secondary flow.

1 INTRODUCTION

Meandering is a fundamental and ubiquitous feature of rivers, reflecting the dynamic interplay between hydrodynamics, sediment transport and channel morphology. This phenomenon has long been the subject of intensive research across theoretical, experimental and field domains (Afzalimehr and Singh, 2009; Blanckaert et al. 2009; Greenberg and Ganti, 2024). Flow through a curved channel involves not only the balance of gravitational and frictional forces but also the influence of centrifugal force, which elevates the water surface at the outer bank and depresses it at the inner bank (Abad and Garcia, 2009; Hooke 2023; Sohrabi et al. 2022). This pressure gradient sustains a transverse circulation that redistributes momentum throughout the cross-section. As a result, high-momentum surface water is deflected outward and downward, while low-momentum near-bed water is transported inward and upward (Hu and Yu, 2023; Najjari and Plesniak, 2018). Such interactions produce characteristic features including secondary circulation cells, helical flows, velocity redistribution and zones of flow separation at bend entrances and exits (Blanckaert et al. 2009; Dietrich and Smith, 1983; Hu and Yu, 2023). The complexity of these processes, coupled with channel topography and bank conditions, makes predicting flow structure in bends a persistent challenge (Kozarek et al. 2024; Van Balen et al. 2010).

Efforts to unravel bend hydraulics have historically relied on physical models and theoretical treatments that necessarily

simplify the real river environment. Experimental flumes, for instance, provide insights into secondary flows, shear stresses and turbulence structures under controlled conditions, but they often assume simplified geometries and neglect longitudinal depth variability (Blanckaert and de Vriend, 2003; Najjari and Plesniak, 2018). Theoretical approaches commonly model bend flow as a uniform open-channel flow scaled by bed shear stress (Rozovskii 1957; Van Balen et al. 2010). Yet, such assumptions have introduced significant uncertainty. For example, Rozovskii (1957) reported a von Karman constant ranging from 0.38 to 0.94, leading to a fourfold uncertainty in secondary flow predictions. Later studies revealed further discrepancies, including deviations between observed and predicted shear stress profiles and evidence that flow depth alone is an inadequate scaling parameter for turbulence in bends (Blanckaert et al. 2009; Jamieson et al. 2010; Kozarek et al. 2024). These inconsistencies highlight the limitations of laboratory and theoretical approaches and reinforce the necessity of detailed field studies in natural river environments.

Sediment transport processes further complicate bend hydraulics. Outer banks are typically subjected to elevated shear stresses that remove finer particles and leave behind coarser gravels, producing an armoring effect (Lamb and Venditti, 2016). Inner banks, by contrast, experience weaker stresses and favor deposition of finer sediments (Okhravi and Gohari, 2020). Helical flow patterns reinforce this sorting by directing coarse particles outward and fine particles inward, thereby establishing

cross-river grain-size gradients (Schleiss and Hersberger, 2001). Sorting intensity depends on curvature ratio, the ratio of bend radius to channel width, with tighter bends producing more pronounced segregation. Local slope variations also modify transport capacities, while flow velocity and Froude number influence the mobility of gravel and sand (Buffington and Montgomery, 1999; Nejat Dehkordi et al. 2022; Van Alphen et al. 1984). Thus, channel curvature, hydraulics and sedimentary processes interact to shape the evolving morphology of meanders.

Despite decades of research, field-based knowledge of three-dimensional flow structures in natural meanders remains limited. Many studies have focused on relatively small rivers (Engel and Rhoads, 2012; Finotello et al. 2024; Kasvi et al. 2015), while only a few have addressed larger rivers (Wilcock et al. 1996). Small rivers often introduce additional complexity due to bank failures, vegetation and large woody debris, further complicating scaling efforts (Alizadeh et al. 2025). Although the number of field investigations has increased in recent decades, much of this work remains descriptive rather than quantitative, offering limited guidance for upscaling laboratory and theoretical results to natural settings. As a result, uncertainties persist in predicting bend hydraulics and sediment transport under natural conditions.

Recent advances in numerical modeling have expanded opportunities to simulate meander hydraulics. Tools such as CCHE2D and HEC-RAS allow simulation of velocity field, shear stresses and secondary circulation under a variety of flow regimes. For instance, Patra et al. (2004) developed models to simulate longitudinal, transverse and vertical velocity variations in compound meanders, successfully validating them against experimental datasets. Njenga et al. (2012) used secondary flow theory to explore relationships between meander wavelength, velocity distribution and discharge, linking secondary circulation to meander growth and migration. Numerical experiments have also demonstrated how artificial deflectors can induce meandering flow patterns and alter velocity fields, with potential applications in river engineering (Zhan et al. 2024). Nevertheless, numerical models inevitably simplify natural bathymetry and boundary conditions, limiting their ability to capture the full three-dimensional variability observed in gravel-bed rivers.

This context underscores the importance of complementary field investigations. Natural gravel-bed rivers, with their irregular substrates and complex morphologies, present flow conditions that cannot be fully replicated in laboratory flumes or numerical models. Yet, such environments are often difficult to

study due to limitations in instrumentation and logistics. Advanced tools like three-dimensional acoustic doppler profilers provide detailed measurements but are not always feasible in remote or resource-limited contexts. Hence, there is a practical need for simple, reliable methods that can provide meaningful insights into flow velocity, shear stress and secondary circulation in natural meanders.

The present study contributes to this need by examining flow structure in a meander bend of the Kheir-Abad River, a gravel-bed mountain river in southwest Iran. Field measurements were conducted along a 270-m bend with a 113° arc, using a one-dimensional current meter to record velocity profiles at nineteen cross-sections. This low-cost, accessible methodology enables practical data collection in conditions where advanced instruments are unavailable or impractical. The specific objectives are to (i) quantify velocity distributions, shear stress patterns and secondary circulation within the meander bend, and (ii) demonstrate the utility of simple field methods for supporting river restoration and management in mountainous gravel-bed rivers. By combining empirical measurements with numerical modeling, this study aims to advance understanding of bend hydraulics and provide a practical framework applicable to similar mountainous gravel-bed rivers worldwide.

2 MATERIALS AND METHODS

2.1 Field studies

2.1.1 Study reach

Field measurements were conducted in the Kheir-Abad River in southwest Iran in Yasuj Province. The river begins in the Zagros Mountains downstream of the Kosar Dam and spans 92 km (Fig. 1a).

At the research location (the selected reach), the river bend features an arc angle of 113 degrees, a path length of 270 m, a wavelength of 298, and a sinuosity of 0.9 (see Fig. 1b and Fig. 2). It should be noted that this sinuosity refers to the local study reach and not to the overall river planform classification, the present study focuses on an individual local meander bend rather than a fully meandering river. The hydraulic and morphologic features of the flow and channel that are measured during the field campaign are outlined in Table 1 (See Appendix 1). Measurements were conducted in June 2024 with a moderate average flow discharge of 22.57 m³/s.

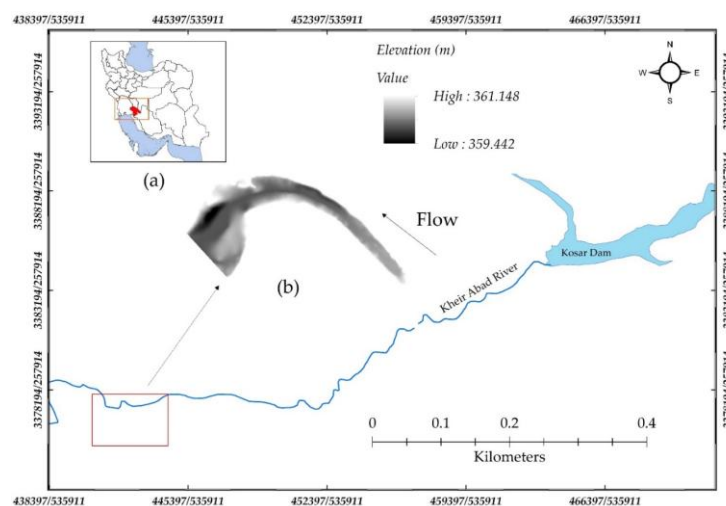


Fig. 1. Study area on the Kheir-Abad River, Yasuj Province, Iran (a); riverbed elevation contours (b).

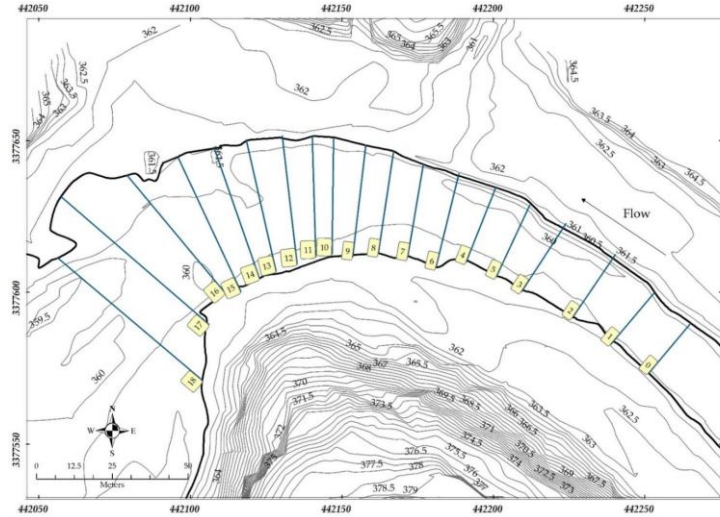


Fig. 2. 19 cross-sections with elevation contours cover the study area from upstream to downstream.

Table 1 defines B as the river width, H as the flow depth, U as the average flow velocity, Q as the flow discharge, U_* as shear velocity, Fr as the Froude number and Re as the flow Reynolds number. Based on the validated evaluation of the two-point velocity method in several mountainous gravel-bed rivers (Okhravi et al., 2023), U_* was calculated using Eq. 1, accounting for flow non-uniformity arising from significant variations in flow depth and bed irregularities.

$$\frac{U_{f2}-U_{f1}}{U_*} = \frac{1}{\kappa} (\ln y_2 - \ln y_1) \rightarrow U_* = \frac{\kappa(U_{f2}-U_{f1})}{\ln \frac{y_2}{y_1}} \quad (1)$$

where κ is the von Kármán coefficient ($\kappa \approx 0.4$), and U_{f2} and U_{f1} are local flow velocities measured at 20% and 80% of the flow depth from the water surface, respectively, with corresponding vertical distances y_1 and y_2 . The corresponding shear stress, τ , is then computed as ($\tau = \rho U_*^2$), where, ρ is the water density.

Flow discharge was calculated for each cross-section based on detailed water surface measurements. At each section, water level was measured at 1 m intervals, and three velocity profiles were recorded. Using the wetted cross-sectional area and the mean flow velocity, the section-averaged discharge was obtained (see Table 1 in Appendix 1). As expected, discharge varied between sections due to bed irregularities, upstream water withdrawals for agriculture and fish farms, and associated time delays. For the purposes of this study and subsequent numerical simulations, an average discharge of 22.57 m³/s was determined from all 19 cross-sections. Table 1 demonstrates that hydraulic parameters vary longitudinally along the reach, confirming the non-uniform nature of flow in the studied gravel-bed meander bend. The observed variations are consistent with expected flow behavior in curved natural channels, where geometry, bed topography and local disturbances control the spatial distribution of velocity, depth, and discharge.

The grading curve was drawn using the three sections at the beginning, middle and end of the studied bend. The Federal Highway Administration's (FHWA) toolbox was utilized to create the grading system. The median average diameter (D_{50}) of sediment particles in the bed is estimated to be 49.3 mm (Fig. 3).

The grain size distribution was analyzed at three representative sections along the bend: the upstream part of the bend (Section 9, average diameter 46 mm), the central bend region (Section 14, 54 mm), and the downstream part of the bend (Section 18, 47 mm). The results indicate that a decrease in the

curvature ratio from 2.33 (Section 9) to 1.42 (Section 18) is associated with an increase in average flow velocity, shear rate, and Froude number. Grain size became coarser from the beginning to the middle of the curve as the curvature ratio decreased, but finer from the middle to the end as the curvature ratio further decreased. In gravel-bed rivers, bed shear stress, reflected by shear velocity, is one of the key controls on the mobility of particles around the median grain size D_{50} . The flow must generate sufficient U_* to mobilize grains of size D_{50} . Hydraulic roughness and sediment supply modulate this relationship, often reducing effective shear stress and the observed D_{50} compared to theoretical predictions based solely on U_* .

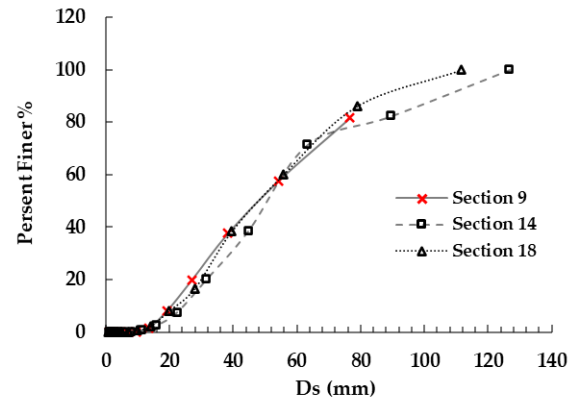


Fig. 3. Particle size distributions at sections 9, 14 and 18.

2.1.2 Equipment and measurements

In this study, a Survey Total Station was used to capture the topography of the riverbed along a 270 m stretch, employing a 30 × 30 cm grid to record height codes at each point. The topographic data was then imported into a GIS package to generate a Digital Elevation Model (DEM), as displayed in Fig. 1b. This model revealed a 1.7 m elevation difference between the highest and lowest points in elevation (see Fig. 2). The DEM indicated an average longitudinal slope (S) of 0.0022 across the area. The bed slope is influenced by sinuosity, sediment transport and channel adjustments, typically ranges from 0.1% (0.001) to 2% (0.02), varying with grain size, discharge, and tectonic/climatic factors. Steeper slopes (>1%) are common in

confined valleys, while lower slopes ($<0.5\%$) occur in meandering systems as reported by (Heitmuller et al. 2005; Rachelly et al. 2021).

The bed material samples were collected by acquiring 100 pieces from sections 9, 14 and 18, totaling 300 samples from different spots along the riverbed. These samples were photographed and analyzed utilizing the FHWA Hydraulic Toolbox Program to produce granulometry curves, illustrated in Fig. 3. For velocity measurements, a microcurrent meter with 0.1 m/s precision was utilized. Nineteen cross-sections, spaced about 14 m apart along the flow path, were chosen to collect velocity data on the right, middle and left sections of the riverbank. Depths of the river varied from 25 cm to 1.25 m, with an average upstream depth of around 57 cm. River width fluctuated between 20 m and 47 m. The field measurements were conducted to assess velocity distribution and secondary flows within the bend.

The major assumptions underlying this study are as follows: (i) no significant vegetation cover is present along the selected reach; (ii) the flow is considered quasi-steady during the measurement period, supported by the absence of noticeable short-term discharge variations and stable water levels, although minor temporal fluctuations due to turbulence and local disturbances may occur; and (iii) no boulders or major obstacles are present along the flow path within the study reach. While the one-dimensional current meter does not measure lateral and vertical velocity components explicitly, the combination of multi-sectional velocity profiles, shear velocity estimation, and secondary flow coefficient analysis enables indirect assessment of flow structure and momentum redistribution. Therefore, the results should be interpreted as a representation of dominant hydraulic patterns rather than a complete three-dimensional flow characterization.

The uncertainty associated with velocity measurements was estimated based on the precision of the microcurrent meter (± 0.1 m/s). Given that shear velocity (U_*) is derived from two-point velocity measurements, the propagated uncertainty in U_* is estimated to be on the order of ± 10 – 15% , depending on local velocity gradients. Consequently, the derived shear stress may exhibit an uncertainty of approximately ± 20 – 30% (Okhravi and Gohari, 2020). The secondary flow coefficient (C), which depends on both local velocity and shear velocity, is subject to a similar level of uncertainty. Despite these uncertainties, the magnitude of observed spatial variations in velocity, shear stress, and C across the bend is significantly larger than the estimated measurement error, indicating that the main hydraulic patterns and trends reported in this study remain robust.

3 RESULTS

3.1 Vertical velocity profile patterns

Table 2 presents the initial contact angle and the WDPT of the flow velocity profiles were recorded at 19 cross-sections (No. 0 upstream to No. 18 downstream) at the center, right, and left sides, resulting in 57 profiles. For clarity, only the 19 center channel velocity profiles are presented in Fig. 4. Vertical velocity (U) profiles in gravel-bed river bends exhibit distinct patterns influenced by curvature-induced flow dynamics and bed roughness. Experimental and field studies reveal these profiles are shaped by helical flow structures, turbulence interactions with gravel substrates, and morphological feedback mechanisms.

According to Fig. 2, the investigated reach is divided into 19 cross-sections from Section 0 to Section 18, following the downstream flow direction. It should be noted that Section 0

marks the upstream limit of the studied reach, not the beginning of the bend itself. Therefore, the sequence of sections captures not only the main bend but also the upstream approach flow and the downstream exit reach.

The results in Table 1, together with the normalized vertical velocity profiles (Fig. 4), show a clear downstream evolution of the flow structure across the bend. In general, the profiles indicate that velocity distribution is strongly non-uniform from section to section, which is consistent with the hydraulic complexity expected in a natural gravel-bed bend.

At the upstream approach zone (Sections 0–3), the velocity profiles are more scattered and less systematically developed than in the middle part of the bend. Section 0, located at the start of the investigated reach, shows relatively dispersed values with a concentration of lower normalized velocities in the lower part of the flow and a moderate increase toward the upper layers. Sections 1 and 2 still exhibit some scatter, but the vertical structure becomes more organized, indicating the beginning of adjustment of the incoming flow to the bend geometry. By Section 3, the profile becomes more coherent, with a clearer upward increase in normalized velocity, suggesting that the flow is already responding to curvature-induced redistribution.

This progressive adjustment is further reflected in the longitudinal redistribution of velocity along the reach. As the flow enters and develops within the bend, velocity becomes increasingly laterally non-uniform across the channel, with higher values concentrated along the main flow path and lower values near the margins. This redistribution is governed by centrifugal forces and cross-channel pressure gradients, which drive the flow toward the outer bank while inducing secondary circulation. The magnitude of this redistribution depends strongly on the bend geometry, the materials forming the bed (e.g. large gravels and cobbles) and local hydraulic conditions (Njenga et al. 2012; Sohrabi et al. 2022).

In the main bend zone (approximately Sections 4–10), the velocity profiles become more distinct and strongly curved. The profiles show a clear increase in normalized velocity with relative depth, indicating enhanced vertical differentiation of the flow. This behavior continues through Sections 6–10, where the upper part of the flow reaches the highest normalized velocities, while near-bed velocities remain comparatively small. Such profiles are characteristic of intensified momentum redistribution in curved channels.

Around the central and apex-related part of the bend (Sections 8–14), the profiles show the strongest organization and vertical gradients. The velocity increases rapidly from the lower to the upper flow region, indicating strong shear and energetic flow in the upper layers. Although some scatter remains due to natural bed irregularities and turbulence, this zone represents the hydraulically most active part of the bend. In addition, secondary flows and enhanced hydraulic resistance within the bend contribute to energy losses, which tend to reduce the average velocity within the bend compared to straighter upstream or downstream reaches. This behavior is consistent with observations in natural rivers, where energy dissipation within bends is influenced by roughness, curvature and discharge conditions (Pradhan et al. 2018).

In the downstream bend-exit and recovery zone (Sections 15–18), the velocity profiles remain well developed but indicate gradual downstream adjustment. The flow shows a relative increase in velocity compared to the bend interior, reflecting downstream acceleration and partial recovery of the flow structure. However, the profiles remain non-uniform, confirming that the hydraulic effects of the bend persist beyond the apex and into the downstream reach.

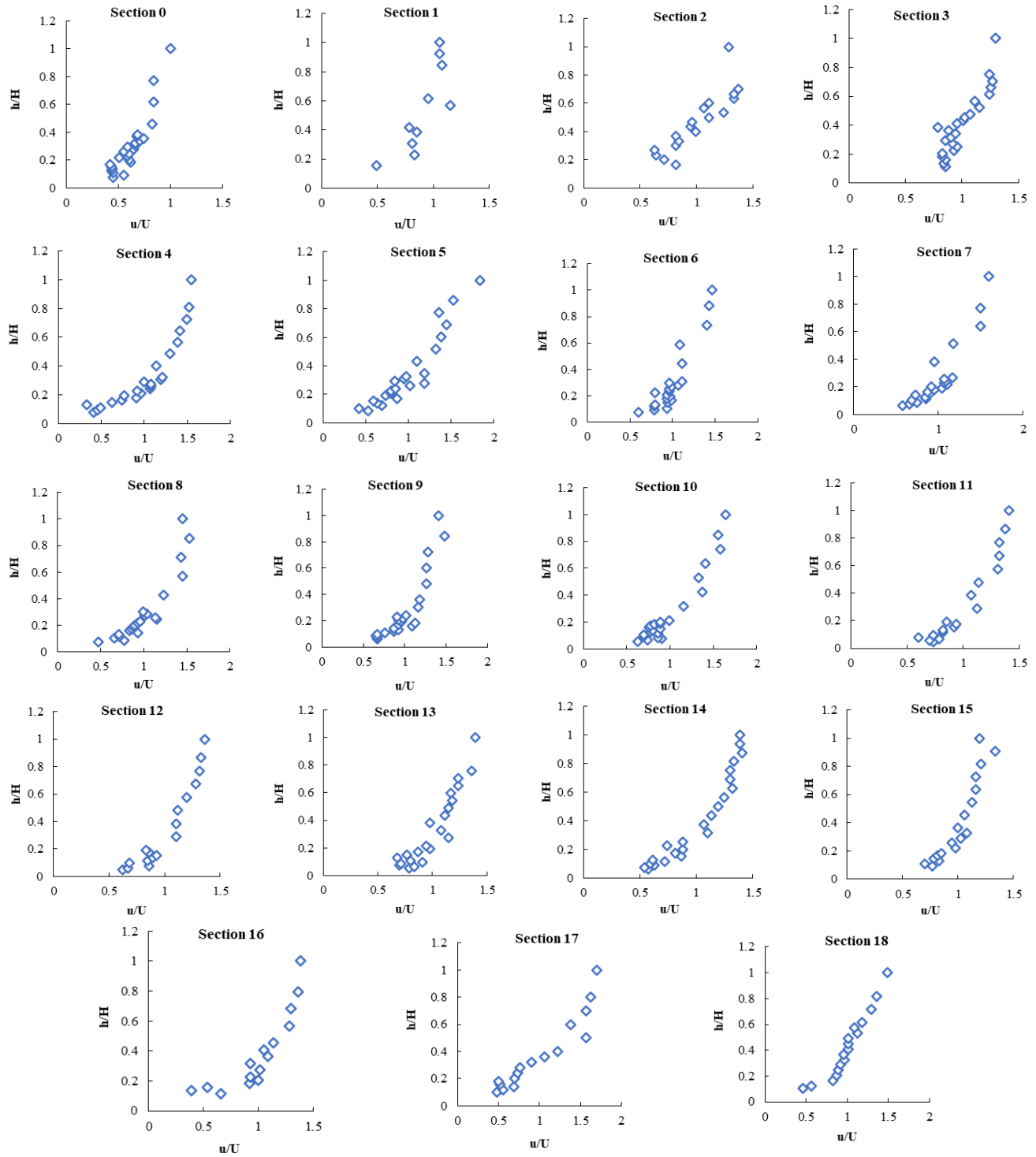


Fig. 4. Vertical velocity profiles, presented for each cross section, from upstream (Section 0) to downstream (Section 18). Here, h represents the depth of flow from the bed, H is the total flow depth, U is the average flow velocity.

In summary, the longitudinal sequence of velocity profiles confirms that the studied reach is hydraulically heterogeneous and that the bend exerts a strong control on the internal flow structure. The transition from the upstream entry condition to the central bend and finally to the downstream exit is reflected by the progressive change in profile shape, the increasing vertical velocity gradient in the middle sections, and the persistence of non-uniformity even at the end of the reach. These results support the interpretation from Table 1 that the flow is spatially non-uniform. They also demonstrate that the selected reach

captures a complete hydraulic transition from inflow adjustment, through bend-dominated flow, to partial downstream recovery.

3.2. Numerical analysis of flow velocity distribution

The free and open-source HEC-RAS 6.5 was employed to simulate subcritical flow at an average discharge of $22.57 \text{ m}^3/\text{s}$ to generate velocity contours and vectors. Normal depth boundary conditions were applied using upstream and downstream slopes of 0.01789 and 0.00031, respectively, based

on the measured bed gradients with imported detailed bed geometry at the local meander bend.

A constant Manning's roughness coefficient of $n = 0.025$ was adopted, initially estimated using the empirical Strickler relation ($n = 0.0132 \times D_{50}^{\frac{1}{5}}$). To improve reliability, a basic calibration was performed by testing Manning's n values within a typical range reported for gravel-bed rivers, and the selected value was found to provide the most physically consistent representation of the flow conditions. This approach provides a reasonable approximation of bed resistance in gravel-bed channels, where base roughness is primarily controlled by grain size (Okhravi et al., 2023).

It should be noted that the numerical model in this study is primarily used for qualitative visualization of flow patterns, rather than for detailed quantitative prediction. Therefore, the modeling results are intended to support the interpretation of flow structures within the meander, rather than to provide fully calibrated hydraulic outputs. Within this context, the adopted parameterization allows HEC-RAS to adequately reproduce the general velocity distribution and flow features relevant to the study objectives.

Fig. 5 presents the simulated velocity contours and corresponding velocity vectors within the studied meander bend. The results indicate that flow velocity reaches its maximum at the entrance of the bend and gradually decreases toward the downstream section. This longitudinal variation reflects energy redistribution along the bend, influenced by channel curvature and local flow resistance, which is consistent with observed velocity redistribution patterns in meandering channels (Blanckaert, 2010). Across individual cross-sections, higher velocities are consistently observed in the central (thalweg) region of the channel, while reduced velocities occur near the banks. This pattern highlights the influence of sidewall friction and bank resistance, where the sidewall effect diminishes with increasing distance from the banks (Franca et al., 2008). The velocity vectors further illustrate the alignment of flow with channel curvature, indicating the development of secondary circulation and lateral momentum exchange typical of meander bends.

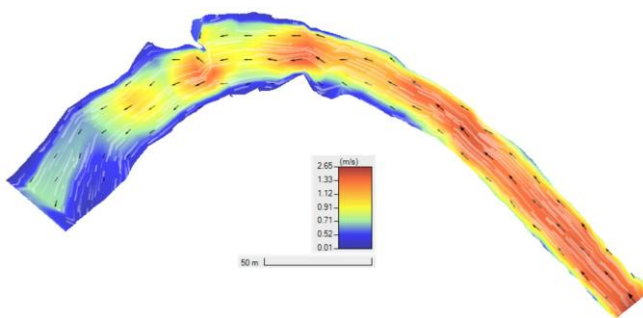


Fig. 5. Velocity distribution contour and velocity vectors within the bend (vectors highlighted in black).

The spatial distribution of velocity demonstrates a highly heterogeneous flow field, characteristic of gravel-bed rivers. This heterogeneity arises from the combined effects of bed roughness, grain-scale variability, and bedform geometry. Localized acceleration zones are associated with elevated bed features, whereas deceleration occurs in near-bank regions and sheltered zones. In addition, turbulent wakes generated downstream of coarse particles contribute to complex flow structures and enhanced momentum exchange (Nikora, 2007; Termini et al., 2022). Despite the simplifications inherent in the numerical approach, the model captures the primary hydraulic

features governing flow structure within the bend. It should be noted that flow in gravel-bed meanders is inherently three-dimensional and temporally variable due to ongoing sediment transport, bedform migration and turbulent fluctuations (Okhravi and Eslamian, 2022). Therefore, the presented results should be interpreted as a qualitative representation of dominant flow patterns rather than a fully resolved description of instantaneous flow dynamics.

3.2.1. Comparison between measured and simulated velocity distribution

This section presents a comparative analysis of the velocity distribution obtained from field measurements and numerical simulations to evaluate how well the model reproduces the observed spatial flow structure within the meander bend. The comparison is carried out in a qualitative, section-based manner, focusing on the overall patterns of velocity distribution, vertical profile development, and longitudinal evolution of the flow rather than point-by-point agreement. To provide a structured interpretation, the analysis considers the upstream approach, the central bend region, and the downstream sections, where different hydraulic controls govern the flow behavior.

In the upstream approach zone (Sections 0–3), field measurements indicate dispersed velocity profiles and incomplete vertical organization, whereas HEC-RAS predicts a more continuous and structured velocity core along the channel centerline. This discrepancy reflects the model's inability to capture the transitional adjustment of incoming flow to channel curvature and the associated turbulence-driven variability observed in the field.

In the central bend region (Sections 4–10), both field observations and numerical simulations consistently indicate the development of a well-defined high-velocity core along the thalweg, accompanied by reduced velocities near the banks. The measured vertical profiles show pronounced velocity gradients, which correspond closely with the simulated velocity contours and vector alignment, confirming that the model successfully reproduces the dominant curvature-controlled redistribution of momentum in this zone.

In the downstream sections (Sections 11–18), field measurements indicate a pronounced increase in velocity magnitude and vertical gradients, particularly in Sections 16–18, whereas the numerical model suggests a gradual reduction in velocity along the bend. This difference highlights the limitation of the model in capturing localized acceleration zones associated with flow contraction, bed irregularities, and secondary circulation effects, which are evident in the field data but smoothed in the simulation.

3.3. Shear stress distribution

Shear stress distribution in gravel-bed river bends is governed by the combined effects of channel curvature, secondary circulation, local bed morphology, and grain-scale roughness. In HEC-RAS, boundary shear stress is estimated using the tractive force relation, $\tau = \gamma RS$, where γ is the specific weight of water, R is the hydraulic radius, and S is the energy slope. This approach provides a cross-section-based hydraulic estimate of boundary stress derived from averaged flow properties and is most consistent with uniform or gradually varied flow assumptions. As a result, the HEC-RAS output represents a spatially smoothed distribution of shear stress along the bend rather than point-scale local stress variability (HEC-RAS Reference Manual, v. 6, 2024).

By contrast, the field-based shear stress values reported in Table 1 were derived from shear velocity obtained using the two-point velocity method. This method is more appropriate for non-uniform flow because it is based on measured vertical velocity structure at specific locations within each cross-section and therefore reflects local hydraulic variability more directly. In gravel-bed meanders, where flow is strongly affected by secondary flows, turbulence, bed irregularity and lateral momentum exchange, this local approach can capture pronounced differences between the left, center and right parts of the section that are not resolved by the section-averaged HEC-RAS formulation (Kironoto and Graf, 1995). A comparison of the measured and simulated shear stress patterns shows both agreement and expected differences. Both approaches consistently identify the central channel and the downstream sections (particularly Sections 16–18) as zones of elevated shear stress, confirming the presence of a dominant high-energy flow path along the bend. The field-derived values, however, reveal substantial lateral and longitudinal variability, with shear stress ranging from very low values (0.1–1.6 Pa) near the banks to pronounced peaks of 84.1 Pa at the channel center in Section 17, 44.1 Pa in Section 18, 40 Pa in Section 16, and 36.1 Pa in Section 5. These results indicate that the central part of the channel, especially in the downstream portion of the bend, experiences the highest hydraulic forcing, while near-bank regions remain comparatively less energetic.

In contrast, HEC-RAS reproduces the same overall spatial tendency of shear stress distribution and successfully identifies the main zones of elevated stress along the flow path. However, the simulated contours appear smoother and more continuous than the field-derived values, reflecting the model's reliance on cross-section-averaged hydraulic parameters rather than local near-bed velocity gradients. Consequently, the model does not capture the localized peaks and abrupt variations observed in the field. These localized intensifications are closely associated with high-velocity cores and secondary flow interactions, highlighting the influence of three-dimensional flow structures and bed roughness effects that are not explicitly resolved in the numerical simulation.

The discrepancy between the two approaches is therefore methodological rather than contradictory. The two-point velocity method reflects local, non-uniform flow conditions and is sensitive to small-scale turbulence and roughness effects, whereas HEC-RAS provides a reach-scale hydraulic approximation suitable for identifying the dominant pattern of stress redistribution along the bend. This distinction is particularly important in gravel-bed rivers, where local roughness elements, bedforms and three-dimensional flow structures generate strong point-to-point variability in shear stress (Rickenmann and Recking, 2011). Accordingly, the HEC-RAS results in this study should be interpreted primarily as a qualitative representation of the general shear stress field, while the field-based calculations provide more direct insight into local hydraulic conditions. The comparison also confirms that section-averaged numerical estimates alone cannot fully describe the hydraulic complexity of natural gravel-bed meanders, and that local velocity-based calculations remain essential for interpreting non-uniform flow behavior.

Although classical theory predicts maximum shear stress near the outer bank due to centrifugal acceleration and transverse water surface slope, the present results show that the highest shear stress values frequently occur in the central channel and downstream sections rather than being consistently confined to the outer bank. This deviation can be attributed to several interacting factors characteristic of natural gravel-bed rivers.

First, the coarse bed material enhances hydraulic roughness and promotes strong vertical momentum exchange, which redistributes shear stress away from the banks toward the main flow core. Second, the secondary flow structure in natural channels is often more complex than the idealized single helical cell, with multiple or shifting circulation patterns that modify the lateral distribution of velocity and shear stress. Third, the relatively wide channel geometry and the development of a dominant thalweg concentrate high velocities in the central region, particularly in the downstream sections where flow acceleration is observed. As a result, shear stress becomes more closely aligned with zones of maximum velocity rather than strictly with outer-bank position. Similar deviations from classical outer-bank dominance have been reported in field and experimental studies of gravel-bed and rough-bed meanders, where bed roughness, turbulence, and three-dimensional flow structures play a significant role in redistributing boundary shear stress (Blanckaert, 2010; Rickenmann and Recking, 2011; Stoesser et al., 2015).

3.4. Variation of the secondary flow coefficient

Secondary flow patterns play a fundamental role in the morphodynamics of gravel-bed rivers, as they control momentum redistribution, sediment transport and channel adjustment. In meander bends, flow curvature induces a transverse pressure gradient, with higher pressure near the outer (concave) bank and lower pressure toward the inner (convex) bank. Because the near-bed boundary layer cannot fully balance this gradient, a secondary circulation develops, typically characterized by outward-directed surface flow and inward-directed near-bed flow. However, in natural gravel-bed rivers, this structure is often modified by bed roughness, channel geometry and flow non-uniformity, leading to complex and sometimes multi-cellular flow patterns (Blanckaert, 2010; Hu and Yu, 2023). In contrast to straight channels, where velocity distribution is relatively uniform, the presence of curvature in bends distorts velocity profiles and redistributes both momentum and boundary shear stress. To quantify these effects, secondary flows along the bend were evaluated using the Bathurst relation (Bathurst et al., 1979) in Eq. 2.

$$C = \frac{\bar{U}}{\bar{U}_*} - \left(\frac{\bar{U}}{U_*} \right) \quad (2)$$

where $\bar{U}$ is the mean velocity at each cross-section, $\bar{U}_*$ is the average shear velocity at the cross-section, U is the local velocity, and U_* is the local shear velocity. Higher values of the coefficient C indicate stronger secondary circulation and greater deviation from uniform flow conditions. This parameter is particularly suitable for non-uniform flow, as it incorporates local velocity structure derived from field measurements.

Fig. 7 presents the longitudinal variation of the secondary flow coefficient C along the studied bend. The results reveal strong spatial variability in both magnitude and lateral distribution of secondary flows. At the upstream sections (S1–S2), very high values of C are observed, particularly along the left and right banks, indicating intense secondary circulation at the bend entrance. Moving downstream, the magnitude of C decreases and exhibits oscillatory behavior across the channel, with alternating peaks between the left bank, center, and right bank. This shifting pattern reflects the dynamic redistribution of momentum associated with curvature-induced flow, local bed irregularities and turbulence. In the entrance and downstream sections of the meander bend (approximately S6–S17), the

coefficient C shows moderate but persistent variability, with localized peaks in the central flow path and near-bank regions. Notably, strong secondary circulation is again observed in the downstream part of the bend (e.g., S16–S18), where higher values of C correspond to zones of increased velocity (Fig. 5) and elevated shear stress (Fig. 6). This correspondence confirms that secondary flows play a key role in redistributing flow energy and controlling the spatial patterns of velocity and shear stress within the bend.

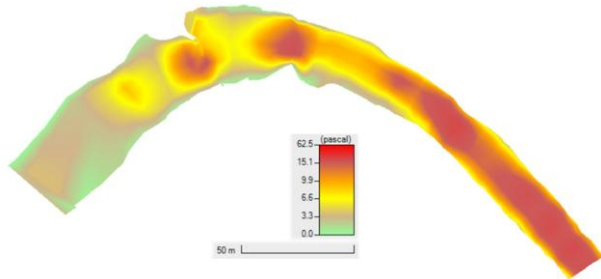


Fig. 6. Shear stress in Pascal (Pa) distribution contours.

Unlike an idealized single-cell structure, the observed patterns indicate that secondary flow in this gravel-bed meander is highly non-uniform and temporally variable. The alternation of maximum C between banks and the channel center suggests the presence of complex flow structures influenced by roughness elements, bedforms and three-dimensional turbulence. Similar behavior has been reported in natural and experimental studies, where secondary flows exhibit multiple cells and irregular spatial distribution under non-uniform flow conditions (Blanckaert, 2010; Stoesser et al., 2015).

From a morphodynamic perspective, these patterns have important implications. Zones of higher C correspond to regions of intensified momentum exchange and enhanced near-bed transport capacity, which can promote local scour and sediment mobilization. Conversely, areas with lower C are associated with reduced flow intensity and increased potential for deposition. The observed variability in secondary flow strength therefore contributes to the development of heterogeneous sediment sorting, bar formation and bank stability within the bend. Overall, the results demonstrate that secondary flows in gravel-bed meanders cannot be described by simplified, symmetric models. Instead, they reflect a complex interaction between curvature, roughness and non-uniform flow conditions. The use of the coefficient C , derived from local velocity measurements, provides a robust framework for capturing this complexity and complements the qualitative insights obtained from the numerical modeling of velocity and shear stress.

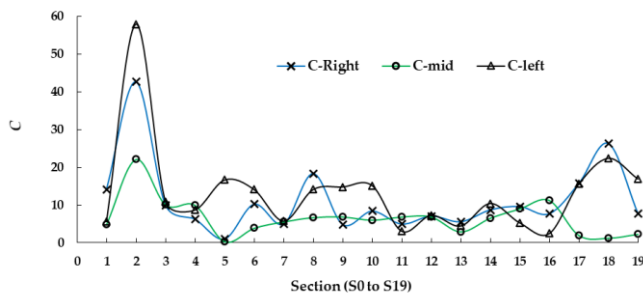


Fig. 7. Secondary flow coefficient variations along the bend.

Although the present study is based on a single natural meander bend, the observed hydraulic patterns are consistent with fundamental processes reported in gravel-bed rivers,

including curvature-induced secondary flow, roughness-controlled resistance and non-uniform velocity distribution (Rickenmann and Recking, 2011). However, the magnitude and spatial distribution of velocity, shear stress and secondary circulation are expected to vary with channel curvature, slope, discharge and bed material characteristics. Therefore, the results should be interpreted as representative of gravel-bed meanders with similar hydraulic and morphological conditions, while caution is required when extending the findings to systems with significantly different curvature or energy gradients.

The comparison between measured and simulated results reveals a consistent spatial correspondence between velocity magnitude, shear stress, and the secondary flow coefficient C . In particular, downstream sections (S16–S18) exhibit simultaneous peaks in velocity, shear stress, and C , indicating intensified momentum exchange and strong secondary circulation. While the numerical model captures the general location of these high-energy zones, it underestimates their intensity and spatial variability, confirming that secondary flow effects play a dominant role in controlling local hydraulic conditions in the bend.

4. CONCLUSION

This study advances understanding of flow structure in gravel-bed meander bends by combining field measurements with numerical interpretation to examine interactions among velocity distribution, boundary shear stress and secondary circulation. The results confirm that hydraulic behavior in such systems is strongly non-uniform and controlled by the combined effects of channel curvature, bed roughness and three-dimensional flow processes. Notably, strong secondary circulation is observed in the downstream part of the bend, where higher values of secondary flow coefficient C coincide with zones of increased velocity and elevated shear stress. This correspondence demonstrates that secondary flows actively redistribute flow energy within the bend and directly control the spatial organization of hydraulic forces.

In these regions, elevated values of C correspond to intensified momentum exchange and enhanced near-bed transport capacity, indicating a clear link between secondary circulation and sediment dynamics. These conditions promote local scour and sediment mobilization, highlighting the role of secondary flow structures in shaping bed morphology and driving erosion-deposition patterns in gravel-bed channels. Furthermore, the results show that secondary flow structures in natural meander bends deviate from simplified conceptual models, instead exhibiting spatially variable and dynamically shifting patterns influenced by local morphology and turbulence.

While the applied HEC-RAS framework provides a useful qualitative representation of the overall flow field, field-based estimates reveal pronounced local hydraulic variability that section-averaged model outputs cannot fully resolve. This reinforces the importance of integrating numerical modeling with targeted field observations when interpreting complex river hydraulics. Overall, the study demonstrates that reliable assessment of gravel-bed river dynamics requires approaches that explicitly capture non-uniform and three-dimensional flow behavior. While the quasi-steady assumption is suitable for capturing spatial flow structure, future work should incorporate time-resolved measurements, unsteady numerical simulations, and high-resolution three-dimensional modeling to better resolve transient dynamics and improve predictive capability for river management and engineering applications.

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Appendix 1.

Table 1. Field measurement characteristics over 19 cross-sections depicted on Fig. 2.

Section	<i>B</i> (m)	Location	<i>H</i> (m)	<i>U</i> (m/s)	<i>Q</i> (m ³ /s)	<i>U</i> [*] (m/s)	Fr	τ (Pa)	Re
0	21.29	left	0.37	0.48	14.25	0.07	0.25	4.9	179173.34
		center	0.65	1.03		0.15	0.41	22.5	669360.90
		right	0.69	0.87		0.06	0.33	3.6	599129.76
1	22.29	left	0.66	0.88	11.51	0.01	0.34	0.1	578635.20
		center	0.46	1.12		0.14	0.53	19.6	516407.50
		right	0.67	0.85		0.02	0.33	0.4	568606.67
2	23.7	left	0.64	0.67	6.40	0.06	0.27	3.6	426024.00
		center	0.30	0.90		0.10	0.53	10	270160.83
		right	0.66	0.74		0.07	0.29	4.9	485769.90
3	25	left	0.54	0.87	10.12	0.08	0.38	6.4	470304.36
		center	0.44	0.92		0.08	0.44	6.4	404995.25
		right	0.59	0.81		0.09	0.34	8.1	480729.32
4	25	left	1.06	0.57	10.46	0.03	0.18	0.9	603837.45
		center	0.62	0.67		0.12	0.27	14.4	418411.94
		right	0.58	0.46		0.07	0.19	4.9	268059.19
5	26.3	left	0.68	0.85	13.17	0.08	0.33	6.4	578130.09
		center	0.58	0.86		0.19	0.36	36.1	500737.96
		right	0.60	0.71		0.06	0.29	3.6	428267.73
6	29.8	left	0.71	0.75	19.39	0.08	0.29	6.4	535217.36
		center	0.68	0.96		0.13	0.37	16.9	650797.09
		right	0.84	0.79		0.11	0.28	12.1	665174.09
7	31	left	0.78	0.67	20.74	0.05	0.24	2.5	523179.68
		center	0.78	0.86		0.13	0.31	16.9	669108.82
		right	0.93	0.87		0.05	0.29	2.5	808224.59
8	34	left	0.73	0.50	19.88	0.03	0.19	0.9	368111.19
		center	0.70	0.84		0.15	0.32	22.5	584582.73
		right	0.74	0.73		0.08	0.27	6.4	542408.74
9	37	left	0.30	0.49	21.81	0.05	0.28	2.5	146331.67
		center	0.83	0.71		0.08	0.25	6.4	589395.63
		right	1.28	0.52		0.07	0.15	4.9	663623.11
10	38.4	left	0.59	0.46	22.50	0.06	0.19	3.6	270544.50
		center	0.94	0.62		0.09	0.21	8.1	585818.22
		right	0.77	0.54		0.075	0.20	5.625	428181.36
11	41	left	0.61	0.53	33.38	0.06	0.22	3.6	323622.66
		center	1.04	0.78		0.07	0.25	4.9	814233.33
		right	0.83	0.66		0.065	0.23	4.225	568928.00

12	42.5	left	0.70	0.52	36.30	0.07	0.20	4.9	361092.50
		center	1.04	0.82		0.08	0.26	6.4	854188.71
		right	1.18	0.45		0.07	0.13	4.9	534623.58
13	44	left	0.57	0.54	30.51	0.04	0.23	1.6	308220.38
		center	0.92	0.75		0.09	0.25	8.1	693521.09
		right	0.65	0.69		0.07	0.27	4.9	450203.00
14	45.8	left	0.25	0.51	26.69	0.06	0.33	3.6	128061.46
		center	0.80	0.73		0.09	0.26	8.1	582728.70
		right	0.47	0.65		0.08	0.30	6.4	307453.44
15	47.6	left	0.70	0.58	21.07	0.09	0.22	8.1	405671.00
		center	0.55	0.80		0.06	0.35	3.6	442658.33
		right	0.55	0.42		0.04	0.18	1.6	230906.81
16	50.38	left	0.31	1.35	32.92	0.10	0.78	10	419038.92
		center	0.44	1.49		0.20	0.72	40	653455.73
		right	0.26	1.10		0.18	0.69	32.4	286469.08
17	64.3	left	0.29	0.95	42.80	0.04	0.56	1.6	274372.35
		center	0.50	1.33		0.29	0.60	84.1	665690.63
		right	0.27	0.75		0.03	0.46	0.9	202215.38
18	62.35	left	0.35	1.09	35.00	0.10	0.59	10	382727.50
		center	0.49	1.15		0.21	0.52	44.1	561267.62
		right	0.46	1.15		0.09	0.54	8.1	526904.29