Flow and sediment transport in a sharp river bend using a 3D-RANS model

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Abstract. Flow dynamics and sediment transport in a river bend have recently been studied using experimental and numerical investigations. A three-dimensional numerical modeling model named NaysCUBE was used in this study to describe the flow pattern and process of sediment transport in a sharp river bend as a complement to the prior work of the physical hydraulic model. The model uses the RANS equation to simulate flow where a fully complex 3D flow is governed. Despite the limitations of the RANS model, NaysCUBE well reproduces the flow pattern and turbulence phenomena in a movable bed channel with sharp curvature. Compared with data from a prior experiment, the morphological adjustment is simulated sufficiently. The three-dimensional flow structures are useful for determining the appropriate countermeasures for local scouring and riverbank protection.

Keywords: sediment, river bend, turbulent, NaysCUBE, RANS

1. Introduction
Flow distribution in channel bends is important in hydraulic and environmental engineering. It is used to proportion river channel sections, optimize bank protection options, design ecological and environmental development methods, etc. Channel bends have quite distinct flow patterns and structures than straight channels. The water flow and sediment transport in a sharp river bend are of significant interest in river engineering. Whether there is a steady or unsteady flow, bed erosion occurs at a sharp river bend, causing significant damage to infrastructure along the rivers. [1,2,3].

River bends have a complex three-dimensional flow field. A strong main secondary current dominates the flow structure. It produces higher shear stress in the bottom and bank, resulting in erosion along the outer bank. An imbalance of inertial forces and transverse pressure gradients causes a helical flow to form. High-velocity flow is convected towards the outer bank and pushed into the river bed, resulting in high-shear stresses and erosion potential. The eroded sediments are transported across the river section and deposited on the inner bank as the flow is recirculated from the outer bank to the inner bank. [4].

As computer power has expanded, modeling turbulent flows in bends and meandering channels has become more common. The unsteady three-dimensional Navier-Stokes equations are not directly solved in existing current numerical models for flow in open channels and rivers. It is too expensive to apply direct numerical simulations (DNS) to actual water flows at high Reynolds numbers [4].
Reynolds-Averaged Navier-Stokes (RANS) equations are utilized in most models due to their computational efficiency and performance. Here, the Reynolds stress tensor must be represented using turbulence model equations [5,6]. The flow pattern of meandering rivers is highly complicated, having distinct characteristics at bends that are not seen along the straight channel. Such flow fields can be effectively predicted using a numerical model. Several isotropic RANS turbulence models, notably the kappa-epsilon model, play a prominent role in real applications. These models have all predicted flows in curved open channel flumes, natural river flows, and delta morphodynamics. RANS models often accurately represent the fundamental flow structure [7,8,9]. The good performance is likely because the flow topologies in those test examples are relatively basic, with only one major circulation in each cross-section. Despite their widespread use, the RANS models' capacity to forecast complex flow configurations has yet to be tested. In many occasions, RANS model predictions were proven to be inaccurate; nonetheless, numerous issues, such as influencing variables, inherent causes, and the level of inaccuracy under various circumstances, remain unsolved [10,11,12,13].

This paper describes the performance of applying the RANS model (NaysCUBE) to investigate flow behavior in sharp river bends. This result is complementary to prior physical hydraulic model experiments.

2. Material and Methods

2.1 Description of the study
A physical hydraulic model was developed in the laboratory to analyze the flow behavior in river bends with a moveable bed. A three-dimensional numerical model with non-linear-turbulent models is also used to describe the mechanism of developing and decaying turbulence in the flow.
Figure 2. Physical hydraulic model of an alluvial channel with a sharp bend ($r/B < 2.5$)

| Table 1. List of the experiment data used |
|------------------------------------------|
| **Data Type** | **Description** | **Prototype** | **Physical hydraulic model** |
| A sharp bend with a radius ($r$) of 75m with a length of 150m | Bottom width = 12m Top width = 35m Average slope 0.0025 Flow regime= subcritical Froude ~ 0.4 Averaged velocity = 1.4 m/s | Undistorted 1:20 |
| Hydrology data | $Q_{30}$ | 53.67 m$^3$/s | 30 l/s |
| Sediment data | uniform | $\rho_s = 2.680 \text{ ton/m}^3$ | $\rho_s = 1.538 \text{ ton/m}^3$ |
| | | $d_{50} = 0.15 \text{ mm}$ | $d_{90} = 0.55 \text{ mm}$ |
| | | $d_{90} = 0.30 \text{ mm}$ | $d_{90} = 2.25 \text{ mm}$ |
| Numerical Model | RANS - kappa epsilon model (NaysCUBE) with Meyer Peter Muller for bed sediment transport |

2.2. Numerical Simulation
The International River Interface Cooperative (IRIC) created the solver for Reynolds-Averaged Navier-Stokes (RANS) equations, freely available on the internet. We performed numerical computations using iRIC Software (NaysCUBE) for 3D flow analysis to investigate further the bed morphological changes and flow pattern as yielded by the experiment.

2.3. Summary of NaysCUBE
Professor Ichiro Kimura of Toyama University developed NaysCUBE, a fully unsteady three-dimensional solution for open channel flow and bed morphological changes [5,15]. The method solves the fundamental equations of three-dimensional flow while considering non-hydrostatic water pressure and high vertical accelerations and velocities. The following are the NaysCUBE formulas. In the Cartesian coordinate system, Formula (1) represents the equation of continuity. The equations of motion in three dimensions are shown in Formula (2). The kappa-epsilon equation is shown in formulas (3) and (4), respectively. The Formula is transformed into a generalized curvilinear coordinate system. NaysCUBE calculates the turbulent-flow field using diffusion terms, and the kappa-epsilon model was applied to the turbulent-flow field.
\begin{align}
\frac{\partial U^i}{\partial x^i} &= 0 \\
\frac{\partial U^i}{\partial x^j} + \frac{\partial U^j}{\partial x^i} &= G^i - \frac{1}{\rho} \frac{\partial \rho}{\partial x^i} + \frac{\partial \left( -u'u^j \right)}{\partial x^i} + \nu \frac{\partial^2 U^i}{\partial x^i \partial x^j} \\
\frac{\partial k}{\partial t} + \frac{\partial \left( k \right)}{\partial x^j} &= -u'u^j \frac{\partial U^i}{\partial x^j} - \varepsilon + \frac{\partial}{\partial x^i} \left( \frac{\nu}{\sigma_k^2} + \nu \right) \frac{\partial k}{\partial x^j} \\
\frac{\partial \varepsilon}{\partial t} + \frac{\partial \varepsilon}{\partial x^j} &= -C_{\varepsilon_1} \frac{\nu}{k} u'u^j \frac{\partial U^i}{\partial x^j} - C_{\varepsilon_2} \frac{\varepsilon^2}{k} + \frac{\partial}{\partial x^i} \left( \frac{\nu}{\sigma_\varepsilon} + \nu \right) \frac{\partial \varepsilon}{\partial x^j}
\end{align}

where $x'$: spatial coordinates; $t$: time; $U^i$: flow velocity; $p$: pressure; $u^i$: turbulent velocity; $\nu$: kinematic viscosity coefficient; $\rho$: fluid density; $k$: turbulent kinetic energy; $\varepsilon$: dissipation rate of turbulent kinetic energy; $\nu_k$: turbulent kinetic viscosity coefficient; $G'$: gravity acceleration; $u'u^j$: Reynolds stress tensor.

### 2.4. Other Conditions

The prototype river was replicated using a numeric model. The computational mesh was constructed at a 1.0-2.0 m grid size range, as illustrated in Figure 3 below. Following the experiment conducted in the physical hydraulic model, the flood hydrograph was used as the upstream boundary condition. In contrast, the water level was used as the downstream boundary condition. In both the upstream and downstream boundaries, there was no sand feeding. $n = 0.025 \text{ m}^{1/3}/\text{s}$ was chosen as the general roughness coefficient.

![Figure 3](image-url)

**Figure 3.** The perspective view of river bend in the study and its computational mesh with selected sections which observed in the physical model.
3. Result and Discussion
The numerical simulation was run for 3 hours of flood according to the hydrological data. With a few significant exceptions, the findings show that three-dimensional flow patterns match the conceptual model of flow across river bends (Figure 4). The summary of findings is as outlined below:

3.1 Velocity Patterns
The pattern of depth-averaged mean velocity vectors best represents a general summary of the velocity field in the meander bend. Figure 4 shows that the flow pattern at the entry is asymmetric and tilted toward the upstream bend's outer bank. The flow pattern at the entrance is asymmetric and inclined outwards, as seen in Figure 4. It progressively turns into a rather symmetrical pattern downstream from the apex. The most important outcome is the maximum velocity in horizontal and vertical locations, as seen in Figures 4 and 5.

![Figure 4](image)

Figure 4. Contour and flow velocity vector at the bottom, mid and surface channel, respectively.

3.2 Primary Flow Overview
Additionally, depth-averaged patterns gave data that showed flow field characteristics in the horizontal plane. In the vertical plane, the profile of flow velocity is depicted in Figure 5. The highest flow velocity is convergent and near the surface at the entrance. The flow velocity near the right bank is slowly lowered to virtually zero at the center of the flow in cross-section one and cross-section 2. It is due to the presence of a minor separation zone near the outer bank. Following the pattern of depth-averaged velocity vectors, the velocity converged to the center when approaching the curve and after the bend. According to Figure 5, CS 4, 5, and 6 show good agreements between measurement and simulation, but CS 1, 2, 3, the output model deviates slightly from measured data, particularly for the right bank.
velocities. Since the propeller velocity meter was used, there is limited to measuring the main velocity only at a certain depth. The development of secondary flow close to the right banks caused reverse flow (cross-section 1 to cross-section 3), which appears to be the reason for the incorrect reading in the measurements. Overall, the numerical results are also supported by observed values (red dots) from the experiment in the physical model.

![Figure 5](image)

**Figure 5.** Perspective views in three dimensions and profile cross-section plots with overlaid velocity for each section measured in the physical model.

### 3.3 Pattern of Secondary Flow

In meander bends, secondary flow is a unique feature of water flow. Velocity vectors show the patterns of secondary flow and how they develop over the meandering curve. (Figure 6). Flow patterns in cross-sections downstream from the bend apex also suggest the development of a secondary counter-rotating cell towards the outer bank. The counter-rotating cell is found in one-third of the water depth, with the greatest interaction with the main cell of the secondary flow towards the outer bank's bed. There were strong reverse flows in cross-section 1 to cross-section 3. Similarly, the minor one also expands along the inner bank before decaying downstream (fourth, fifth, and sixth cross-sections).
3.4 Pattern of Turbulence

Figure 7 depicts the distribution of turbulent kinetic energy (TKE in $m^2/s^2$) in the section featuring the turbulence structure. The convergence of the velocity vectors in the centre part corresponds to the area with high $k$, which intensifies turbulence as described in the previous paragraphs. TKE reaches its maximum value at the center of the flow depth, which varies with channel alignment. It steadily decreases beyond the bend apex. Figure 8 depicts the patterns of eddy viscosity coefficients in the river bend, which correspond to turbulent kinetic energy.

Figure 6. Selected cross-section plots measured in a physical model show the contour of velocity magnitudes with vertical velocity vectors.
3.5 Bed morphology and Sediment transport
The local scour developed downstream due to no sediment supply from upstream. During the early stages of the studies, scour was rapid, but it slowed when the local scour approached equilibrium. With increasing mixing and turbulence intensities, the length and width of the local scour grew. According to a physical hydraulic model and numerical results, a deep and centralized local scour progressively
formed towards the outer bend apex and downstream. The bed material was carried fast due to the substantial mixing activity downstream of the river bend. With no additional material, the local scour grew deeper and larger until stabilizing. The final bed adjustments are shown in Figure 9. In summary, the RANS model with a selected MPM transport formula gave smaller morphological changes compared with physical experiments in Figure 10.

**Figure 9.** Magnitude (contour) of bed shear stress and riverbed migration patterns (experiment and numerical)

**Figure 10.** Comparison bed changes between the RANS and the physical hydraulic models (CS 3 and CS 5).

### 4. Conclusions

Studying flow patterns and sediment transport in meandering channels is extremely useful in river engineering, river network, channel design, river mechanics, and stream evolution. The performance of the RANS model (NaysCUBE) for investigating flow dynamics at severe river bends is described in this
study. This finding might be valuable in conjunction with previous physical hydraulic model studies. The following are the findings:

- NaysCUBE well reproduces the flow pattern and turbulence phenomena in a movable bed channel with sharp curvature.
- Compared with data from a prior physical experiment, the morphological adjustment is insufficient to simulate the selected MPM transport formula. It is recommended to check another bed load formula and re-calibrate the sediment parameters in the model.
- The three-dimensional flow structure is useful for determining the appropriate countermeasures for local scouring and riverbank protection.

In order to get better morphological parameters, an experiment with a physical hydraulic model should be installed with proper equipment for detecting the motion of bed particles. An instantaneous three-dimensional velocities measurement device should be installed too.

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**References**

[1] Thorsten Stoesser, Nils Ruether, Nils Reidar Boe Olsen 2010 Calculation of primary and secondary flow and boundary shear stresses in a meandering channel *Advances in Water Resources* 33 158–170

[2] Sukhodolov, A. N. 2012 Structure of turbulent flow in a meander bend of a lowland river *Water Resour. Res.*, 48 W01516, doi:10.1029/2011WR010765.

[3] Jyotismita Taye, Jyotirmoy Barman, Mahesh Patel & Bimlesh Kumar 2019 Turbulent characteristics of sinuous river bend *J. Hydraulic Engineering*, DOI: 10.1080/09715010.2019.1629843

[4] Okamoto, Y. & Nishio, J. & Kanda, K. & Michioku, Kohji & Nakamura, F. & Kubo, H.. 2020 Study on riverbed variation management by groin at a river confluence associated with the barrage water *Proc. 10th Conference on Fluvial Hydraulics* 10.1201/b22619-92

[5] Taeun Kang, Ichiro Kimura and Yasuyuki Shimizu 2020 Numerical simulation of large wood deposition patterns and responses of bed morphology in a braided river using large wood dynamics model *Earth Surf. Process. Landforms* 45, 962–977 DOI: 10.1002/esp.4789

[6] Comp Mehrzad Shams, Goodarz Ahmadi, Duane H. Smith 2002 Computational modeling of flow and sediment transport and deposition in meandering rivers *Advances in Water Resources* 25 689–699.

[7] Jian-yin Zhou, Xue-jun Shao, Hong Wang, Dong-dong Jia 2017 Assessment of the predictive capability of RANS models in simulating meandering open channel flows *J. Hydrodynamics* 29(1):40-51 DOI: 10.1016/S1001-6058(16)60714-X

[8] Chang Geun Song, Il Won Seo, Young Do Kim 2012 Analysis of secondary current effect in the modeling of shallow flow in open channels *Advances in Water Resources* 41 29–48

[9] İnci Güneralp, Jorge D. Abad, Guido Zolezzi, Janet Hooke 2012 *Advances and challenges in meandering channels research*, *Geomorphology* 163–164 1–9

[10] W. Ottevanger, K. Blancaert, W.S.J. Uijtewaal, 2012 Processes governing the flow redistribution in sharp river bends *Geomorphology* 163–164 45–55

[11] Frank L. Engel, Bruce L. Rhoads 2012 Interaction among mean flow, turbulence, bed morphology, bank failures and channel planform in an evolving compound meander loop *Geomorphology* 163–164 70–83
[12] James D. Riley, Bruce L. Rhoads 2012 Flow structure and channel morphology at a natural confluent meander bend *Geomorphology* 163–164 84–98
[13] Jianchun HUANG, Blair P. GREIMANN, and Timothy J. RANDLE 2014 Modelling of meander migration in an incised channel *Int. J. Sediment Research* 29 441-453
[14] Thorsten Stoesser, Nils Ruether, Nils Reidar Boe Olsen 2010 Calculation of primary and secondary flow and boundary shear stresses in a meandering channel *Advances in Water Resources* 33 158–170
[15] Kimura, I 2020 NaysCUBE ver 3.1 Solver Manual iRIC Software