

Hydrodynamic Simulation of an Irregularly Meandering Gravel-Bed River: Comparison of MIKE 21 FM and Delft3D Flow models

Parna Parsapour-moghaddam¹, Colin D. Rennie¹, Jonathan Slaney²

¹Department of Civil Engineering, University of Ottawa, Ottawa, Canada

²Planning Engineering in the River Engineering Group - City of Calgary, Calgary, Canada

Abstract. This study aims at hydrodynamic modelling of Bow River, which passes through the City of Calgary, Canada. Bow River has a mobile gravel bed. Erosion and deposition processes were exacerbated by a catastrophic flood in 2013. Channel banks were eroded at various locations, and large gravel bars formed, which could lead to water level changes and accordingly more flooding. This study investigates the performance of Delft3D-Flow and MIKE 21 FM to simulate the hydrodynamics of the river during the 2013 flood. MIKE 21FM employs unstructured triangular mesh while Delft3D-Flow model uses curvilinear structured grids. Performance of each model was evaluated by the available historical water levels. The results of this study demonstrated that, with approximately the same averaged grid resolution, MIKE 21 FM resulted in more accurate results with a higher computational cost compared to the Delft3D-Flow model. It was shown that Delft3D-Flow model may require higher grid cell resolution to result in comparably same depth-averaged velocities throughout the study area. However, considering the balance between the computational cost and the accuracy of the results, both models were capable to adequately replicate the hydrodynamics of the river during the 2013 flood. Results of statistical KS and ANOVA test analysis showed that the model predictions were sensitive to the horizontal eddy viscosity and the Manning roughness. This confirms the necessity of an appropriate calibration of the generated numerical models. The findings of this study shed light on the Bow River flood modelling, which can guide flood management.

1. Introduction

Bow River is one of the major natural streams in Calgary, Canada that provides the local communities with valuable functions such as source for water supply, waste water receiving water, recreational purposes, etc. Bow River, however, at the same time can be hazardous to Calgary because of flooding and its consequences. Management of rivers such as Bow River, given the necessity and importance of their functions, can be a complex task. A good understanding of the hydrodynamic behaviour of rivers and their response to the flood events is a key factor in a proper river management that, in turn, minimizes the losses due to floods. In order to study rivers in flood events, the unsteady state flow conditions should be simulated to consider the flood hydrographs. To this end, the shallow water flow equations, which are governed by law of conservation of mass and momentum, should be solved. As, generally, there are no exact solutions available for these equations, approximate solutions can be obtained employing numerical methods with simplifying assumptions [1].

Considering the computational efficiency of the 2D models, they can be employed in a great range of applications in the river engineering. These models are based on the two-dimensional shallow water equations. Over the past few years, several 2D models have

been developed using various numerical methods such as finite difference (FD) [2], finite element (FE) [3], and finite volume methods (FV) [4]. DELFT3D and MIKE21 are among the widely used 2D numerical models can be used for river hydrodynamics simulations. [5, 6, 7, 8]. This study aims to evaluate the performance of Delft3D and MIKE21 FM (flexible mesh) as 2D river flow models. Particularly, the capability of these models in modelling extreme flood events in large rivers is sought. This also assesses the capability of the models in simulation of a flood hydrograph in an unsteady-state flow condition. Furthermore, it reveals the practicality and suitability of these models in river management. In the next section, we explain the area of interest. The methodology employed in this study is presented in Section 3. Results are shown in Section 4 followed by the conclusion in Section 5.

2. Study area

The study area is the portion of Bow River that passing through the downtown area of Calgary, ON, Canada with roughly $500 \text{ m}^3/\text{s}$ bank full discharge (Fig. 1). The Bow River is a 645-km long stream that passes through Calgary.

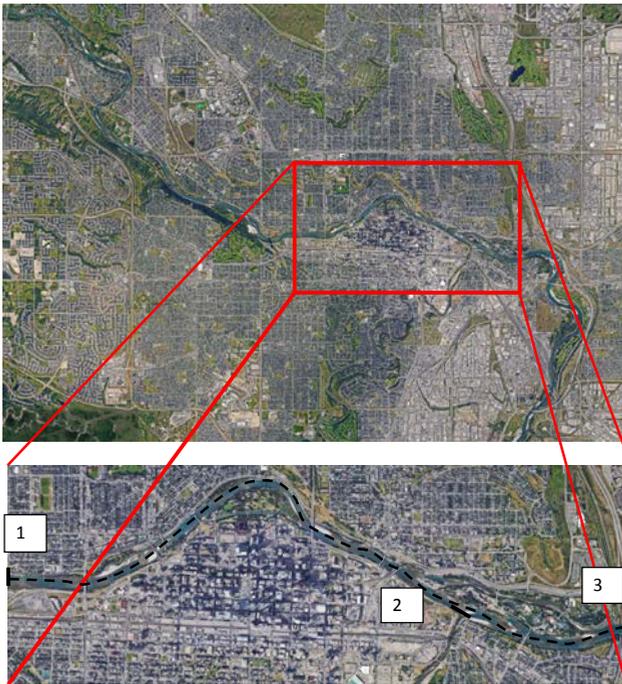


Fig. 1. Location of the study area in the City of Calgary, image adopted from Google earth. The model boundaries are shown with black lines. The numbers shown in the squares are corresponding to the boundary conditions which are defined in Section 3. Note that the centre line shown by the black dashed line would be used for the water level validation (Fig.5).

As almost 50 km of the river passing through the city extends, the city can be largely affected by the river flooding [9]. In 2013, the river experienced a large flood that is the focus of this study. Natural bank erosion and sedimentation throughout Calgary was enhanced during the 2013 flood. The 2013 flood was a 1:80 year event that impacted the City infrastructure [9]. The repair of these erosion sites came at a high financial and environmental cost. In addition, considerable amount of sediment movement resulted in

formation of large gravel bars in the river which may impact future water levels and therefore flooding (Fig.2b). Historically, the Bow River has not been showing a regular flooding pattern. While there were several major flooding events between 1879 to 1932, there was no large flood afterward until 2012. We explain the methodology used to simulate the hydrodynamic flood condition with in the study reach in the next section.



Fig. 2. (a) Aerial photo of the Bow River, near downtown Calgary, photo taken by the authors. Flow from west (right of the picture) to east (left of the picture). (b) Gravel bar formation in the study area.

3. Methodology

In this study, hydrodynamic condition of the study area was simulated during the 2013 flood. The flood boundary conditions data were obtained from the Calgary City's calibrated 1D hydraulic model (HECRAS) [10]. The boundary conditions were defined as:

- 1- Upstream flood discharge
- 2- Confluence flood discharge close to the downstream end of the study area
- 3- Downstream water level

The locations of these boundaries are shown by solid black lines in Fig.1. We evaluate the performance of MIKE21 FM and the 2D Delft3D-Flow model, which are among the widely used hydrodynamic models. Following equations were used to calculate different error statistics:

$$MAE = \sum_{i=1}^n \frac{|wl_{mod_i} - wl_{meas_i}|}{n} \tag{1}$$

$$RMSE = \sqrt{\sum_{i=1}^n \frac{(wl_{mod_i} - wl_{meas_i})^2}{n}} \tag{2}$$

where wl_{meas_i} and wl_{mod_i} indicate measured and simulated water level for i^{th} co-located point. *MAE* and *RMSE* stand for mean absolute error and root mean square error, respectively. The parameter *n* is total number of co-located points. These results are shown in Table 1. The 2D hydrodynamic solver of flow models provides numerical solutions of the 2D shallow water equations which are depth-integrated incompressible Reynolds averaged Navier-Stokes equations.

3.1. MIKE 21FM

MIKE 21 flow model, developed by DHI, simulates the 2D free surface flows. The numerical scheme employed in MIKE21 FM uses a cell-centered FV spatial discretization scheme. The spatial domain is discretized using triangular grid cells. MIKE21 FM employs

unstructured triangular grids for solving shallow water equations that provides geometric flexibility. The spatial scheme uses an approximate Riemann solver to compute the convective fluxes, which makes it possible to handle discontinuous solutions [11]. For the temporal terms integration an explicit scheme is used. It should be noted that both spatial discretization and time integration schemes are available in either lower and higher orders. In this study, in order to maximize the accuracy of the model, higher order schemes used. The authors refer the readers to [11] for more details on the MIKE 21 FM modelling.

3.2. Delft3D-Flow

Delft3D-Flow model is a modelling package developed by Deltares (formerly WL|Delft Hydraulics), which consists of several modules working around a mutual interface [12]. Delft3D-Flow simulates hydro-morphodynamic processes on a rectilinear or a curvilinear grid. This code solves the Navier-Stokes equations using shallow water assumptions and the Boussinesq approximation. In this paper, 2D hydrodynamic open source code Delft3D (version FLOW 4.01.01) was employed. Delft3D-flow solves the 2D shallow-water equations based on a finite difference method using staggered grid. Further details on the Delft3D modeling are available in [12, 13].

3.3. Model setup

Boundary meshes for the Mike21 FM and 2D Delft3D-Flow models were generated based on the available surveyed pre-flood bathymetric data [10]. Interpolated bathymetric data were assigned to the developed numerical grid. Averaged grid resolution of 300 m^2 and time step of 100s were used to maintain the stability condition. The number of grid cells was ~ 8000 and ~ 4400 in Delft3D-Flow model and MIKE 21FM, respectively. To keep the consistency between the models, all the model inputs such as initial water level as well as the calibration parameters including Manning roughness and horizontal eddy viscosity were set the same in both models. We employed spatially varying Manning roughness and constant horizontal eddy viscosity of $0.5\text{ m}^2/\text{s}$ which were obtained based on Delft3D calibration and then we applied the same parameters in the MIKE 21 FM. The unstructured triangular mesh generated by MIKE 21 FM is shown in Fig.3, while Fig. 4 illustrated generated Delft3D-Flow structured curvilinear mesh. Mesh quality was controlled in both models to avoid acute triangles in unstructured mesh and to maintain an acceptable aspect ratio and orthogonality of the curvilinear mesh.

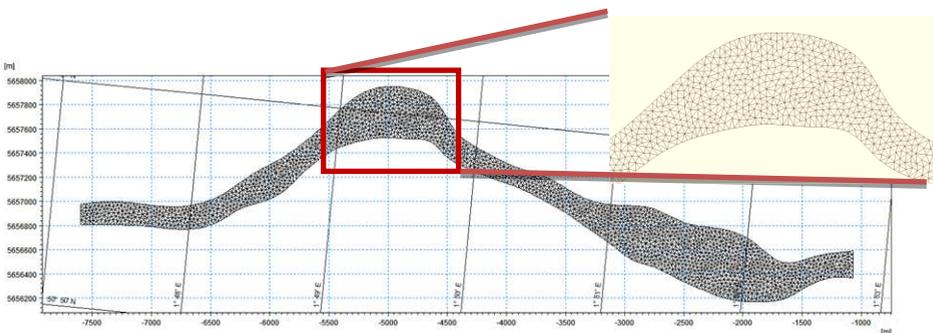


Fig. 3. Unstructured triangular grid cells generated with Mike21FM.

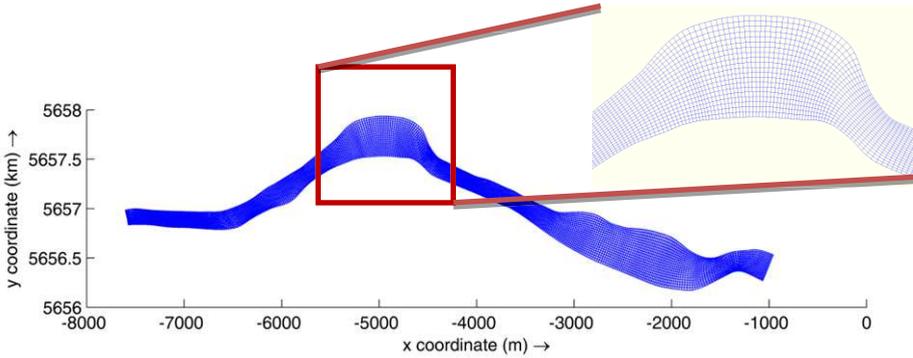


Fig. 4. Curvilinear structured grid cells generated with Delft3D

4. Results

In this section we assess the capability of the developed models to represent the hydrodynamics of the river flow across the study area at the Bow River. Both models were employed to simulate the 2013 flood event. The results of both models were compared against the available historical water level [10]. Fig. 5 compares the resulting water surface elevations along the centerline of the reach from each developed model against the historical water level.

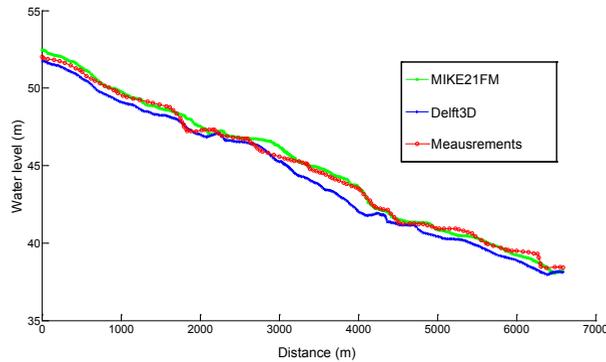


Fig. 5. Water elevation changes along the study area.

Table 1. Error metrics for water surface elevation across the reach centerline

Error Type	MAE	RMSE
MIKE21 FM	0.219	0.283
DELFT3D	0.511	0.589

As it can be seen, although both models show almost comparable water levels relative to the measured data, the results of MIKE21 FM seems to be closer to the measured water levels. Table 1 represents the error statistics for each model. As can be inferred, MIKE21 FM led to the lower amount of error statistics of the water level simulation. Fig. 6 shows the simulated depth-averaged velocities over the study reach for both models.

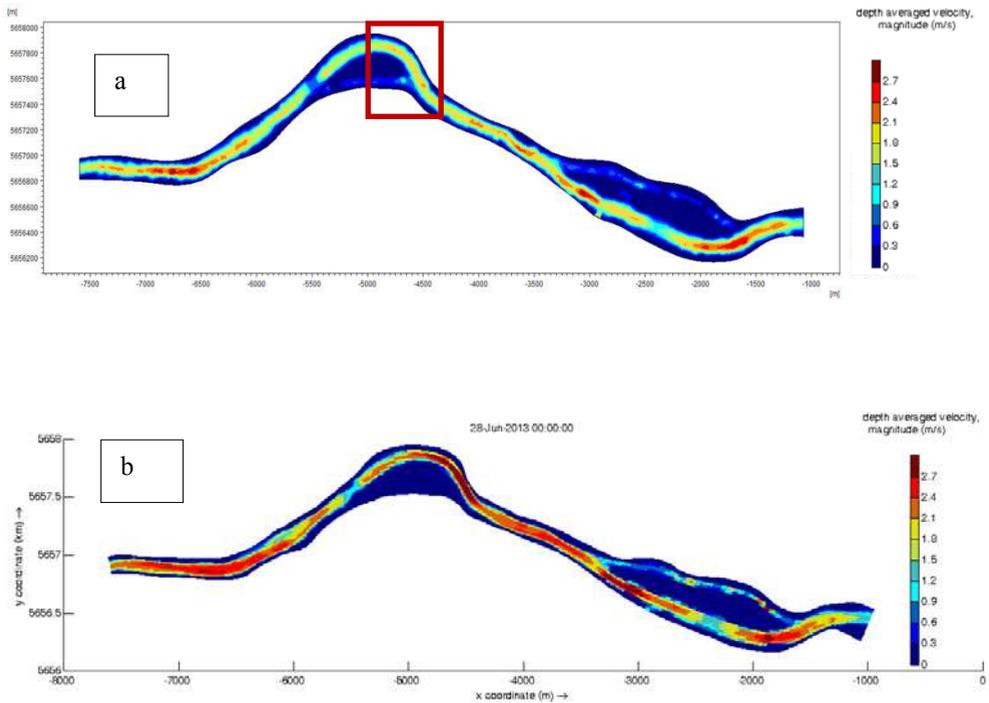


Fig. 6. Simulated post flood depth-averaged velocity using: (a) MIKE 21 FM (b) Delft3D-Flow model with coarse grid. The red square illustrates the meander location shown in Fig. 8.

Delft3D predicted higher velocities across the reach compared to the MIKE21 FM results. This can be due to the fact that the flow in Delft3D did not enter the secondary channel ($x \sim -5500\text{ m}$), while MIKE 21 FM was capable of simulating the secondary channel in this large meander. This can be also due the grid cell resolution. In order to further assess the impact of grid type, another Delft3D-Flow model was developed with the same model setup, however, using finer grid cells with an averaged resolution of 150 m^2 . The computed depth-averaged velocities are shown in Fig. 7. As it can be seen, the results are more comparable to those of MIKE21 FM. Fig. 8 shows the depth-averaged velocity vectors in the large meander of the study reach. As can be seen, unstructured grid cells employed by MIKE 21 FM yield a less smoothed predicted flow field.

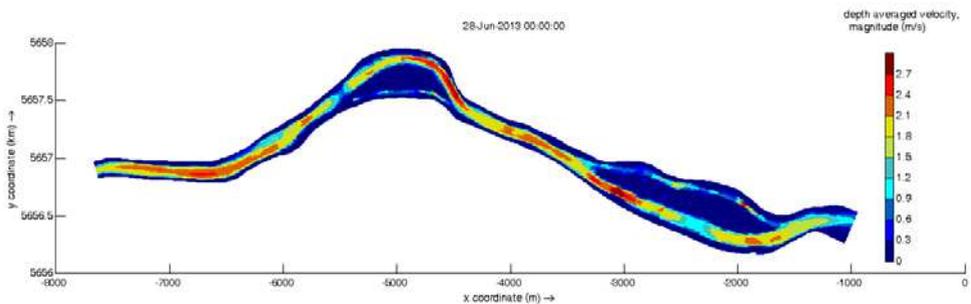


Fig. 7. Simulated post flood depth-averaged velocity using finer grid cells within Delft3D-Flow model.

Computational efficiency is another aspect of a numerical model that needs to be assessed, particularly for larger study areas with more complex features. MIKE 21 FM has the ability to run the model via multicores (Open Multi-Processing). However, DELFT3D can only use a single core. On the other hand, the natural characteristics of the unstructured triangular mesh increases the computational cost. For the study reach at the Bow River, running the 8-day long flood event takes approximately 90 and 30 minutes for MIKE21 FM (8 cores) and Delft3D (single core), respectively. It should be noted that for the Delft3D-Flow model with the finer grid cell (Fig. 7), we decreased the time step to maintain the stability condition (i.e., 10s in this case). Running the presented case study within this model setup takes approximately 4 hours.

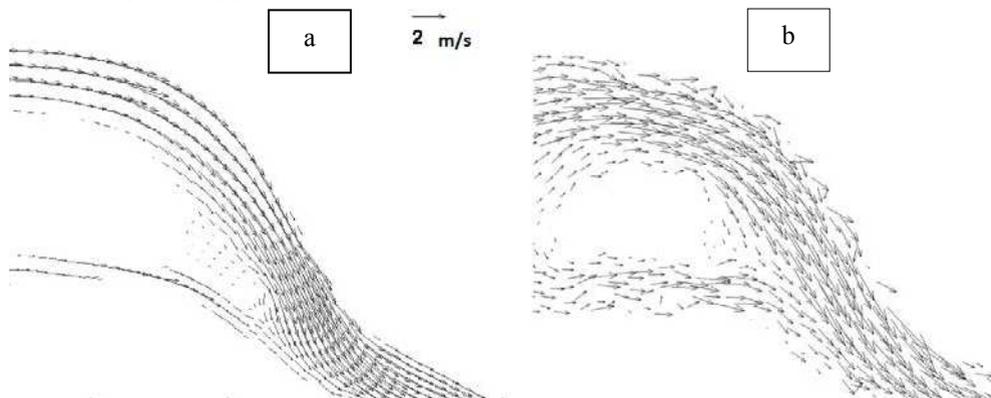


Fig. 8. Simulated depth-averaged velocity vectors based on the results of: (a) Delft3D-Flow (b) MIKE 21 FM. Refer to Fig. 6 for the location of the bend. Note that the depth-averaged velocity vectors of Delft3D-Flow are based on the finer grid resolution (Fig. 7).

Furthermore, in order to investigate the sensitivity of the calibration parameters (i.e., horizontal eddy viscosity and Manning roughness) on the model results, statistical two-sample Kolmogorov-Smirnov (KS) and multiway analysis of variance (ANOVA) tests were conducted. The Delft3D hydrodynamic numerical model was run under different modelling chain combinations of horizontal eddy viscosity (ranging from $0.05 \text{ m}^2/\text{s}$ to $1 \text{ m}^2/\text{s}$) and Manning roughness (ranging from 0.015 to 0.05). The results of all KS tests were rejected the null hypothesis that the depth-averaged velocity are from the same continuous distribution at the 5% significance level. Moreover, the resulting p -values in the ANOVA test analysis were $p \sim 0$ in all scenarios, showing that these factors were significant at 95% confidence level. Sensitivity of the generated hydrodynamic model to the horizontal eddy viscosity as well as the Manning roughness confirms the necessity of the proper model calibration for these parameters.

5. Conclusion

The 2013 flood event at the Bow River in the City of Calgary was simulated. We assessed the performance of MIKE21 FM and DELFT3D-Flow model as two widely-used 2D hydrodynamic simulation models. The results of both models were almost comparable, however, MIKE21 FM water level results agreed better with the measured data. It was shown that Delft3D-Flow model may necessitate higher grid cell resolution to obtain comparably same depth-averaged velocity magnitudes within the study reach. Finer grid resolution with cells averaging 150 m^2 was required to replicate detailed hydrodynamics in the Delft3D model. Considering the balance between the computational cost and the accuracy of the results, both models were capable to adequately replicate the

hydrodynamics of the river during the 2013 flood. It was shown that the unstructured grid cells employed by MIKE 21 FM could yield a less smoothed predicted flow field. Results of statistical KS and ANOVA test analyses showed that the model predictions were sensitive to the horizontal eddy viscosity and the Manning roughness which confirmed the necessity of a proper calibration of the generated numerical models. The results of this study could help finding the numerical model that best reproduce the hydrodynamic characteristics of an irregularly meandering gravel-bed rivers. This could be of essential importance in understanding the hydrodynamics of such rivers during the flood, and consequentially, the corresponding flood mitigation plans in the flood management.

References

1. Abbott, M. B. (1979). *Computational Hydraulics Elements of the Theory of Free Surface Flows*, vol. 1 of Monographs and Surveys in Water Resource Engineering.
2. Randall, D. A. (1994). Geostrophic adjustment and the finite-difference shallow-water equations. *Monthly Weather Review*, 122(6), 1371-1377.
3. Heniche, M., Secretan, Y., Boudreau, P., & Leclerc, M. (2000). A two-dimensional finite element drying-wetting shallow water model for rivers and estuaries. *Advances in Water Resources*, 23(4), 359-372.
4. Shirkhani, H., Mohammadian, A., Seidou, O., & Kurganov, A. (2016). A well-balanced positivity-preserving central-upwind scheme for shallow water equations on unstructured quadrilateral grids. *Computers & Fluids*, 126, 25-40.
5. Parsapour-Moghaddam, P., & Rennie, C. D. (2017). Hydrostatic versus nonhydrostatic hydrodynamic modelling of secondary flow in a tortuously meandering river: Application of Delft3D. *River Research and Applications*, 33(9), 1400-1410.
6. Parsapour-Moghaddam, P., & Rennie, C. D. (2014). Morphodynamic modelling of a tortuous meandering clay bed river using Delft3D: Stillwater Creek, Ottawa. *River flow*. In *International conference on fluvial hydraulics* (pp. 1163-117).
7. Warren, I. R., & Bach, H. (1992). MIKE 21: a modelling system for estuaries, coastal waters and seas. *Environmental Software*, 7(4), 229-240.
8. Patro, S., Chatterjee, C., Mohanty, S., Singh, R., & Raghuwanshi, N. S. (2009). Flood inundation modeling using MIKE FLOOD and remote sensing data. *Journal of the Indian Society of Remote Sensing*, 37(1), 107-118.
9. City of Calgary (Klohn Crippen Berger LTD), *Morphology summary report (draft)*, November 2016.
10. A. Melethil, *City of Calgary River Morphology Simulation Study (2015)*, Supported by City of Calgary, University of Calgary, Deltares, Report No: CofC-UofC-RMS (2015).
11. DHI. 2014 MIKE 21 Flow Model FM Hydrodynamic Modul, User Manual (2014)
12. Lesser, G. R., Roelvink, J. A., Van Kester, J. A. T. M., and Stelling, G. S. (2004). Development and validation of a three-dimensional morphological model. *Coastal engineering*, 51(8), 883-915.
13. Deltares, *Delft3D-FLOW users manual*. (2014). Simulation of multi-dimensional hydrodynamic flows and transport phenomena, including sediments.