Comparative analysis of fully 3D and hybrid 2D/3D simulations in Flow-3D: a case study of Springbank Off-Stream Reservoir, Canada

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COMPARATIVE ANALYSIS OF FULLY 3D AND HYBRID 2D/3D SIMULATIONS IN FLOW-3D: A CASE STUDY OF SPRINGBANK OFF-STREAM RESERVOIR, CANADA

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ABSTRACT

Computational Fluid Dynamics tools are increasingly used in the water sector, driven by computational advancements. However, the use of complex 3D models for large-scale hydrodynamics is limited by significant computational demands. A promising solution is hybrid 2D/3D modeling, which employs shallow water equations for less critical areas and 3D Navier-Stokes equations for regions requiring detailed flow analysis. This method offers a balance between computational efficiency and accuracy in crucial areas. The National Research Council Canada utilized physical modeling to assist in designing the Springbank Off-stream Reservoir's flood diversion structure on Elbow River, Canada. This involved assessing hydraulic performance through various flow scenarios and gate configurations essential for flood management. This study compares the hybrid 2D/3D modeling approach against fully 3D simulations using Flow-3D software for the Springbank project. By replicating laboratory-tested scenarios, the study evaluates the accuracy of hybrid model in predicting water levels and flow velocities. The results provide practical insights into the applicability of hybrid technique to large hydraulic projects, highlighting the impact of model configurations and parameters on performance. This study underscores the potential of hybrid model in optimizing computational resources while maintaining analytical precision in critical hydraulic analyses.

RÉSUMÉ

Les outils de Dynamique des Fluides Numérique sont de plus en plus utilisés dans le secteur de l'eau, stimulés par les avancées informatiques. Cependant, l'utilisation de modèles 3D complexes pour l'hydrodynamique à grande échelle est limitée par des exigences computationnelles significatives. Une solution prometteuse est la modélisation hybride 2D/3D, qui utilise les équations des eaux peu profondes pour les zones moins critiques et les équations de Navier-Stokes 3D pour les régions nécessitant une analyse détaillée des flux. Cette méthode offre un équilibre entre l'efficacité computationnelle et la précision dans les zones cruciales. Le Conseil National de Recherches Canada a utilisé la modélisation physique pour aider à la conception de la structure de dérivation des inondations du réservoir hors cours d'eau de Springbank sur la rivière Elbow, au Canada. Cela impliquait d'évaluer la performance hydraulique à travers divers scénarios de débit et configurations de vannes essentiels pour la gestion des inondations. Cette étude compare l'approche de modélisation hybride 2D/3D aux simulations entièrement 3D en utilisant le logiciel Flow-3D pour le projet Springbank. En répliquant des scénarios testés en laboratoire, l'étude évalue la précision du modèle hybride dans la prédiction des niveaux d'eau et des vitesses de flux. Les résultats fournissent des aperçus pratiques sur l'applicabilité de la technique hybride aux grands projets hydrauliques, soulignant l'impact des configurations et paramètres du modèle sur la performance. Cette étude souligne le potentiel du modèle hybride dans l'optimisation des ressources computationnelles tout en maintenant une précision analytique dans les analyses hydrauliques critiques.

1 INTRODUCTION

In 2013, the Elbow River, located west of Calgary, Alberta, underwent a significant flood event. Ordinarily, the natural capacity of the river is 180 m^3/s. However, during this particular incident, the flow of the river dramatically increased to 1,240 m^3/s. This substantial overflow led to extensive damage to both infrastructure and human lives, with costs exceeding $5 billion. The catastrophic impact of this flood served as a catalyst for the development of an off-stream storage system. This system was designed to mitigate future flood risks by temporarily storing excess flood waters in a reservoir. The project encompassed the creation of a diversion inlet, which would redirect water flow to the reservoir during flooding events, and subsequently release it back into the main river course in a controlled manner.

The Springbank Off-Stream Storage Project is designed to mitigate flood impact on the Elbow River (Government of Alberta 2016). This system includes a strategically placed diversion inlet that redirects floodwaters from the Elbow River into an adjacent off-stream reservoir via a diversion channel. In conjunction with this inlet, the project also incorporates a combination of a service spillway and a sluiceway situated on the main river. These structures are essential for providing operational control over the distribution of water between the main river and the diversion channel, enabling effective management of flow volumes. Figure 1 provides a comprehensive overview of the entire project.

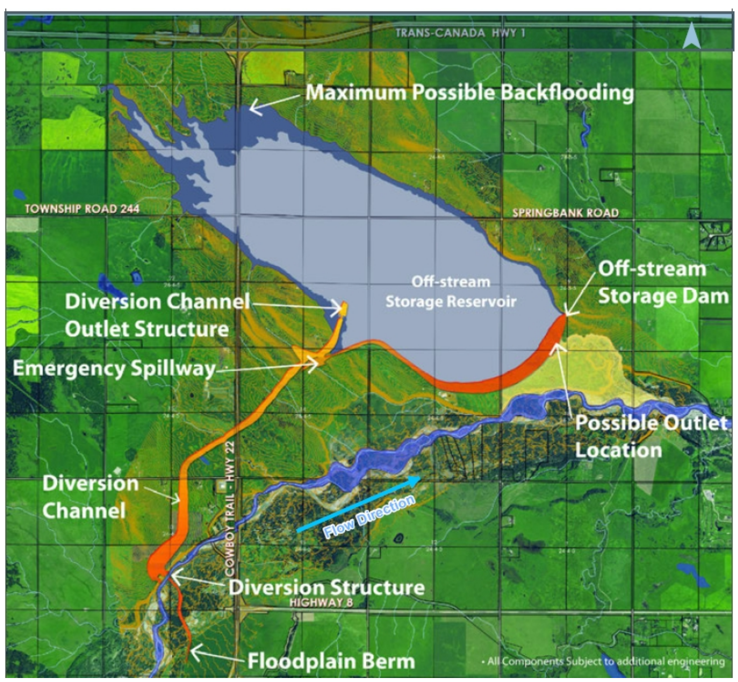


Figure 1: Overview of the Springbank off-storage project (Government of Alberta, 2016).

The National Research Council Canada (NRC) conducted a detailed physical simulation to facilitate the design of the diversion channel and the Springbank Off-Stream Storage System. This model, adhering to the principles of Froude similarity, was constructed at a geometric scale of 1:16. It encompassed an area surrounding the hydraulic structures as well as portions of both the diversion channel and the main river. Throughout this study, a comprehensive array of data, including water levels and flow velocities, was meticulously gathered using a variety of instruments. This extensive dataset played a crucial role in supporting and informing the design process of the project.

Simulating large-scale models with numerical tools is notably resource-intensive, particularly when detailed 3D hydrodynamic analysis is crucial, raising concerns about the simulation time. A potential strategy for reducing computational expenses is the implementation of hybrid 2D/3D models. In such an approach, areas of lesser importance are modeled in two dimensions using shallow water equations, while critical areas are rendered in three dimensions for greater detail and accuracy.

This study focuses on evaluating the efficacy of fully 3D simulations versus hybrid 2D/3D simulations using Flow-3D, a Computational Fluid Dynamics (CFD) tool. The Springbank Off-Stream Storage System serves as a case study for this purpose. The findings will be compared with data from the physical model developed by the NRC.

The remainder of this paper is organized as follows: Section 2 details the numerical simulations conducted in this study. Section 3**Error! Reference source not found.** presents the results obtained from these numerical models and compares them with the physical model data. This is followed by a discussion of these results in Section 4. The paper concludes in Section 5, summarizing the findings of the study and proposing avenues for future research in this domain.

2 METHODOLOGY

Flow-3D is a comprehensive software suite tailored for CFD applications. Primarily, it is utilized for simulating three-dimensional problems by solving the Reynolds-Averaged Navier-Stokes (RANS) equations, which govern fluid motion. Additionally, Flow-3D employs the Volume of Fluid (VOF) method (Hirt and Nichols 1981), to accurately capture free surface flows. A feature of the software is its module dedicated to solving shallow water equations for two-dimensional problems by employing a depth-averaged momentum equation under the assumption of hydrostatic pressure (Flow Science 2019).

A key strength of Flow-3D is its ability to address hybrid challenges, encompassing both shallow water and fully three-dimensional regions. This hybrid modeling capability is particularly useful for reducing the computational costs. It allows for the application of shallow water equations in suitable areas, such as rivers (modeled in two dimensions), while enabling more complex and detailed three-dimensional simulations in critical regions, such as around hydraulic structures.

In this project, the effectiveness of both fully 3D and hybrid 2D/3D simulations using Flow-3D was scrutinized. This software offers five turbulence models. For the purpose of this study, the standard k-ε model was employed.

2.1 Computational Domain and Nested Grids

The simulation parameters include a cubic domain with dimensions of 50.5 m in length (x-direction), 30 m in width (y-direction), and 5 m in height (z-direction), as depicted in Figure 2. Nine probes precisely positioned to correlate with the measurement instruments in the physical model were used to record the flow velocity and water surface elevation. Figure 3 illustrates the placement of these probes, along with the instrumentation layout of the physical model.

Two meshing properties were employed for both the fully 3D and hybrid 2D/3D models. The spatial resolution was chosen based on the available computational resources and adjusted to ensure comparability between the two models. Each model utilized two nested meshes: an inner, finer mesh surrounding the hydraulic structures to capture the more dynamic flow in this region, and an outer, coarser mesh. In hybrid models, it is imperative that the z-direction boundaries of the inner mesh remain within the outer 3D mesh. Table 1 summarizes the mesh characteristics utilized in this study (Flow Science 2019).

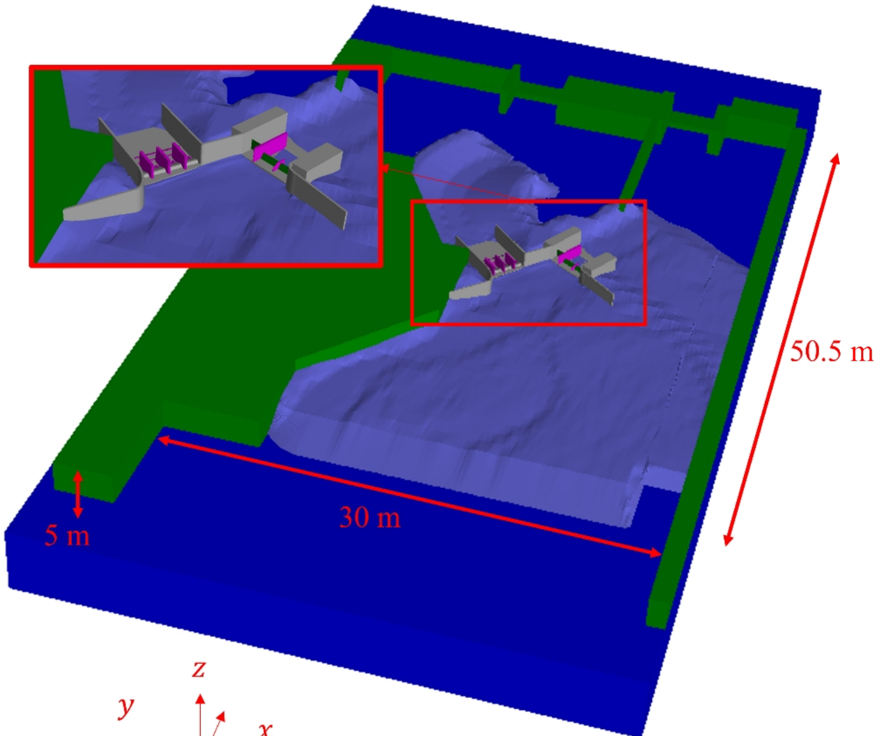
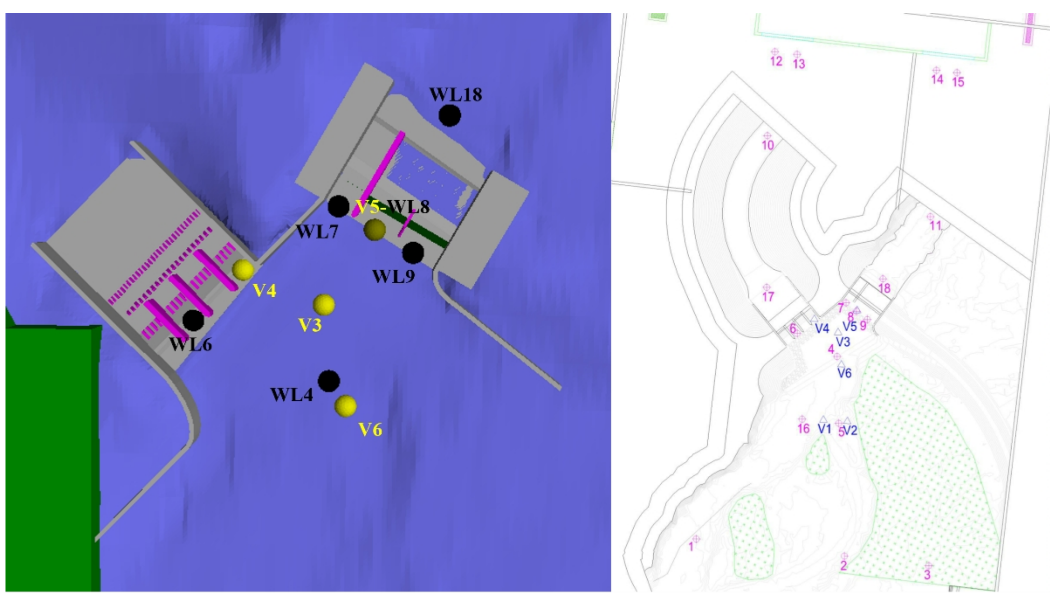


Figure 2: Sketch of the domain simulated in Flow-3D.



(a) (b)

Figure 3: (a) Location of the probes in the numerical model and (b) the instrumentation layout of the physical model (Knox et al. 2016).

Table 1: Summary of the mesh properties used in this study.

		3D	Hybrid 2D/3D
Mesh Properties	Inner mesh	3D, $\Delta x = \Delta y = \Delta z = 0.05$m	3D, $\Delta x = \Delta y = \Delta z = 0.05$ m
	Outer mesh	3D, $\Delta x = \Delta y = \Delta z = 0.2$ m	2D, $\Delta x = \Delta y = 0.2$ m

2.2 Boundary Conditions

In this study, two flow discharge scenarios from the physical model data were adopted. These scenarios reflect the scaled-down versions of real-world flow discharges adjusted to fit the model scale. This scaling was achieved using a Froude-scaling factor of $L^{5/2}$, where L represents the geometric scale factor. Consequently, the flow discharges for the scenarios were reduced to $Q_1 = 0.74219$ m^3/s and $Q_2 = 1.21094$ m^3/s, respectively and used as the upstream boundary conditions for the simulations.

A pressure boundary condition with zero pressure was implemented for the downstream boundary of the outer mesh. The zero-pressure boundary condition stipulates that the hydrostatic pressure at the designated boundary is consistently maintained at zero, implying that the flow depth at this boundary is null, thereby preventing the persistence of flow at this boundary. This methodology is utilized in Flow-3D to delineate the outflow and free-surface boundary conditions. Consequently, this approach was extended to the upper boundary of the outer mesh, thereby mirroring the intrinsic dynamics of water surfaces in real-world settings.

A summary of these boundary conditions is presented in Table 2. Figure 4 illustrates the precise location of each boundary within the simulation domain, providing a clear visual representation of the simulation setup and its corresponding boundary conditions. In this figure, the dark blue area shows the flow path, the light blue region shows the exact topography of the domain imported into the simulation as a Standard Tessellation Language (STL) file, and the green parts are presented to define the actual boundaries of the domain. Figure 5 also provides a closer view of the area around the hydraulic structures surrounded by the inner mesh.

Table 2: Summary of boundary conditions used in this study.

	X		Y		Z	
Mesh	Min	Max	Min	Max	Min	Max
Inner	Symmetry	Symmetry	Symmetry	Symmetry	Wall	Symmetry
Outer	Volume flow rate	Pressure	Wall	Wall	Wall	Pressure

3 RESULTS AND DISCUSSION

To evaluate the efficacy of the numerical model, comparisons were made between the simulated water levels and velocities and the measurements obtained at various strategic locations. Emphasis was placed on locations proximal to hydraulic structures, deemed the most critical within the domain, with comparisons confined to the probe locations illustrated in Figure 3-a. It is imperative to highlight that the presented measurements represented averages computed over a five-minute period subsequent to the attainment of a steady state, and that timeseries data were unavailable. Furthermore, reported velocities encompassed both the mean values calculated over a five-minute span and the accompanying standard deviations, measured at mid-water depth.

3.1 Water Level

To facilitate the comparison of water levels, the methodology employed mirrored that of the experimental analysis, wherein values were averaged over a five-minute interval and depicted on a 1:1 graph, with measured water levels positioned on the x-axis and simulated water levels on the y-axis. This comparative analysis encompassed both Q1 and Q2 scenarios. Figure 6 showcases the outcomes for the 3D and hybrid simulations corresponding to the Q1 scenario, illustrating the alignment between simulated and observed water levels.

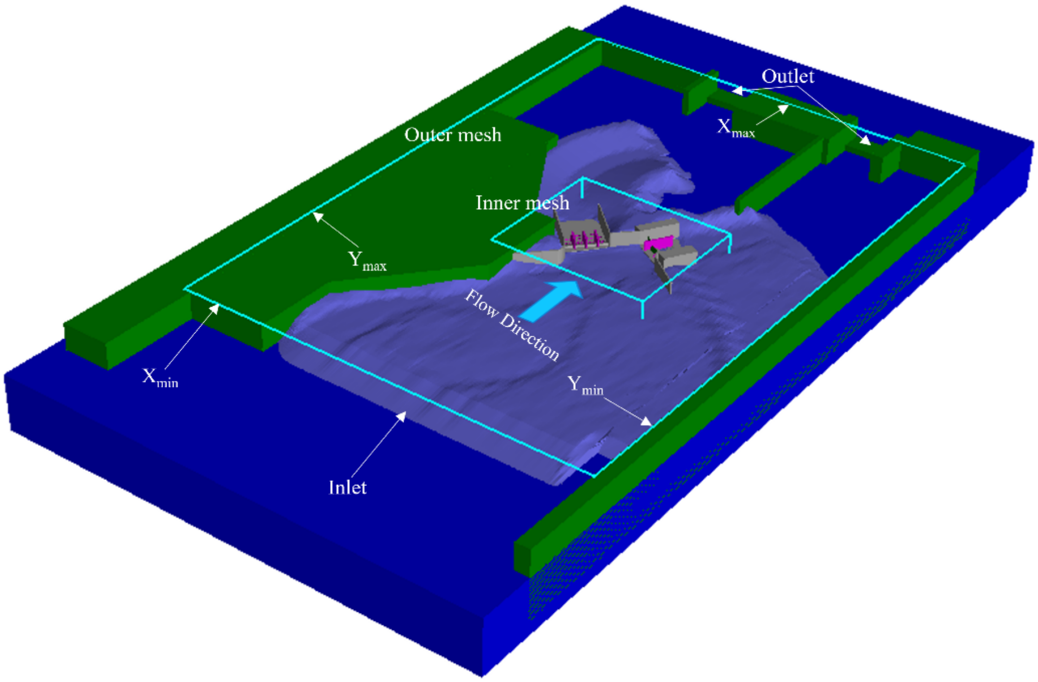


Figure 4: Location of the boundaries in the domain.

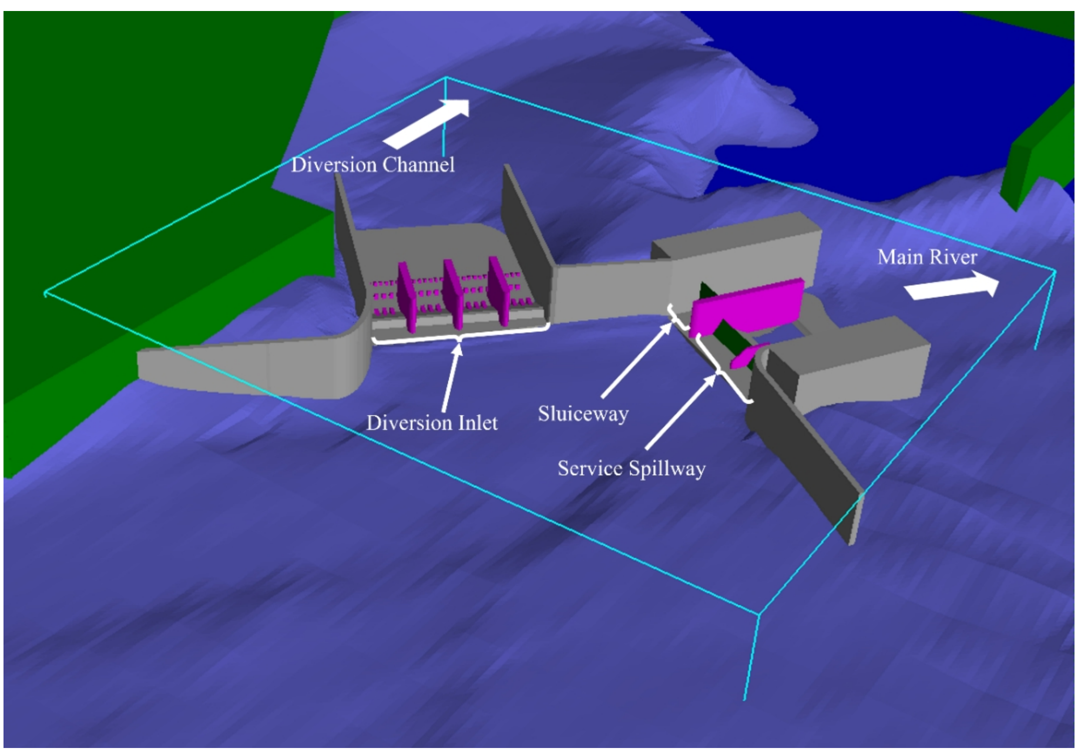
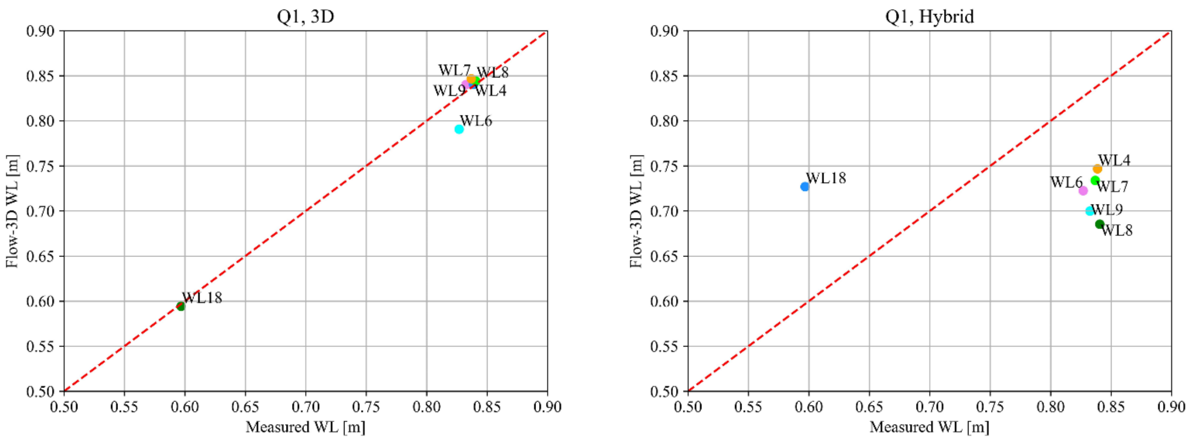


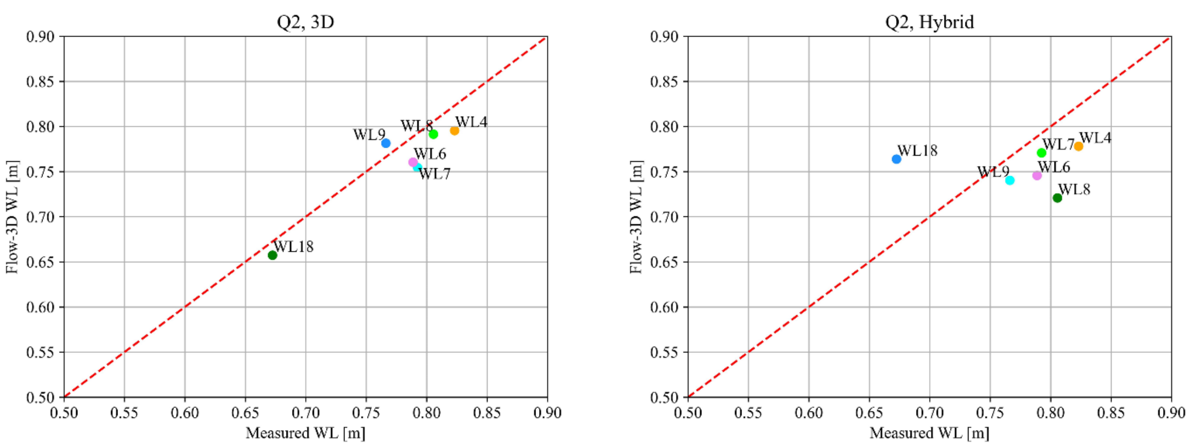
Figure 5: Close up of the inner mesh with the location of the hydraulic structures.



(a) (b)

Figure 6: The comparison of water level results for the Q1 scenario with (a) 3D and (b) hybrid 2D/3D mesh.

Figure 6 indicates that the 3D mesh produced results with greater accuracy when compared to the hybrid mesh. Specifically, for the hybrid mesh, water level readings at the WL 18 gauge, situated downstream of the service spillway, were significantly overestimated, whereas measurements at all other gauges consistently fell short of actual values. This trend was replicated in the Q2 scenario, which involved a higher discharge rate than Q1, as depicted in Figure 7. Nevertheless, it is noteworthy that the accuracy of the 3D mesh diminished in the Q2 scenario relative to Q1. Conversely, the performance of the hybrid 2D/3D mesh showed improvement in terms of accuracy under the conditions of the Q2 scenario.



(a) (b)

Figure 7: The comparison of water level results for the Q2 scenario with (a) 3D and (b) hybrid 2D/3D mesh.

Table 3 provides a comprehensive summary of the errors recorded at each water level gauge across all four scenarios, along with the mean error. The variance observed in the results can be attributed to the intricate nature of the flow at elevated discharge levels. In scenarios involving lower discharge rates (Q1), the flow dynamics are comparatively less complex, allowing the fully 3D mesh to delineate these simpler flow patterns more adeptly. Conversely, at higher discharge levels, the dynamics of surface flow become increasingly pronounced. In such instances, the 2D component of the hybrid mesh was better suited to accurately capturing these more dominant surface flow characteristics.

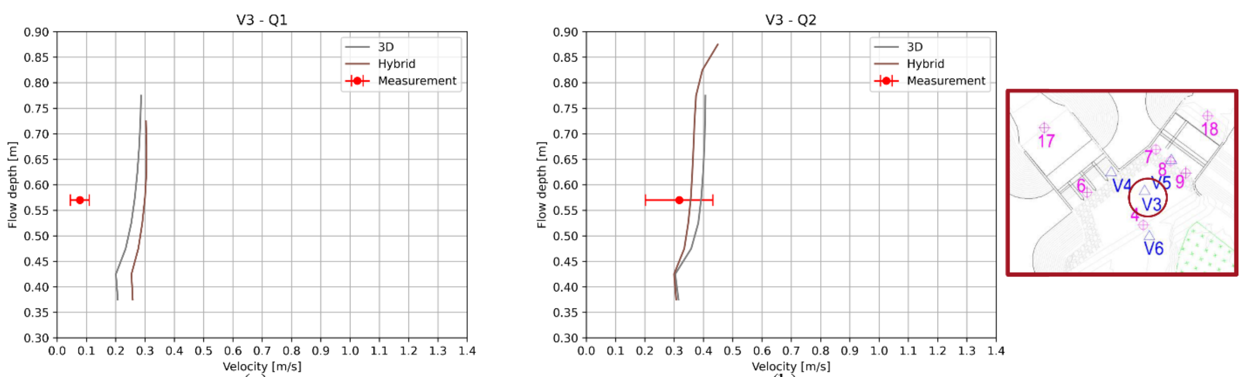
Table 3: Summary of the errors in water level for different scenarios.

Scenario		WL4	WL6	WL7	WL8	WL9	WL18	Mean Error
Q1	3D	0.20%	4.58%	1.15%	0.42%	0.91%	0.44%	1.28%
	Hybrid	12.32%	14.45%	14.04%	22.66%	18.94%	17.89%	16.72%
Q2	3D	3.48%	3.73%	5.05%	1.79%	1.94%	2.31%	3.05%
	Hybrid	5.80%	5.78%	2.82%	11.77%	3.50%	11.95%	6.94%

3.2 Flow Velocity

To facilitate the comparison of flow velocities at different locations, the mean vertical profiles of flow velocity, averaged over a five-minute span, were plotted at each probe site. These plots were accompanied by error bars representing the variability observed in the velocity measurements from experimental tests, as detailed in Figure 8 to Figure 11, which illustrate the findings at all velocity gauge locations.

Gauge V3, positioned at a distance from both the service spillway and the diversion inlet and located in a flat area adjacent to the hydraulic structures (as depicted in the topography shown in Figure 5), was subjected to relatively less complex flow dynamics. This less complex environment contributed to the model's ability to accurately compute flow velocities in the Q2 scenario, where higher discharge rates tend to produce flow patterns that are more uniform, enhancing model accuracy for Q2 compared to Q1.

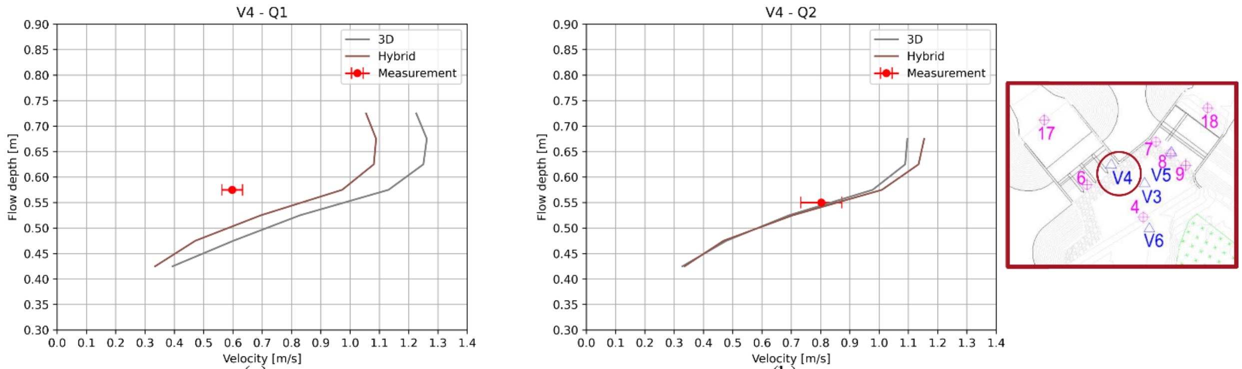


(a) (b)

Figure 8: Vertical profile of velocity for (a) Q1 and (b) Q2 at the location of V3 gauge.

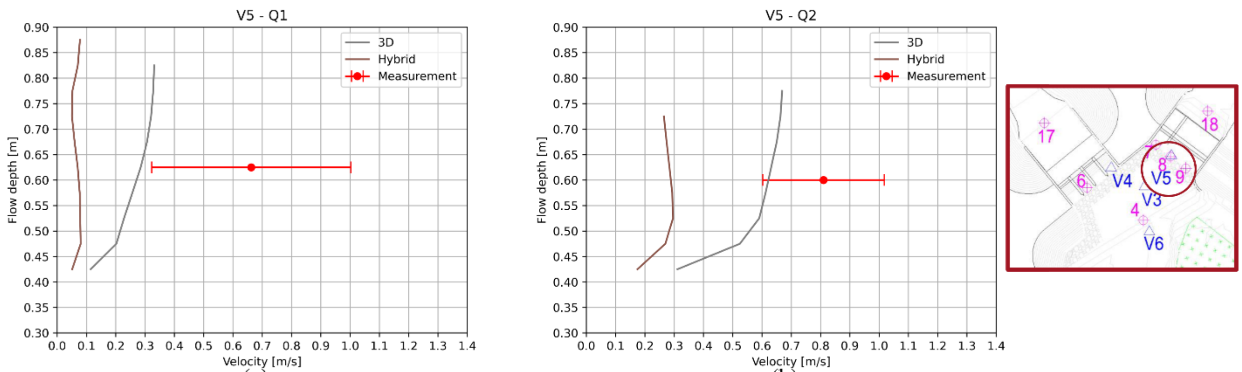
Gauge V4, situated directly upstream of the diversion inlet, was anticipated to encounter complex flow dynamics. Remarkably, the model adeptly captured this complexity, particularly in the Q2 scenario, demonstrating its effectiveness in modeling intricate flow patterns.

Located just upstream of the service spillway, gauge V5 was subjected to highly complex flow dynamics, further complicated by the presence of the gate at the service spillway entrance, which regulates the flow discharge into the main river. The complexity was exacerbated by the differing gate mechanisms— a vertical gate for the sluiceway (allowing flow underneath) and a rotating gate for the service spillway (permitting flow over the top). Experimental tests corroborated this complexity, indicating standard deviations in measured velocities of approximately 0.3 m/s for Q1 and 0.2 m/s for Q2. Despite these challenges, the 3D model achieved reasonable accuracy in capturing flow velocities at this location for both scenarios, albeit with slight underestimations. However, the hybrid 2D/3D model struggled to predict velocities accurately at this point, due to the intricate flow details involved.



(a) (b)

Figure 9: Vertical profile of velocity for (a) Q1 and (b) Q2 at the location of V4 gauge.



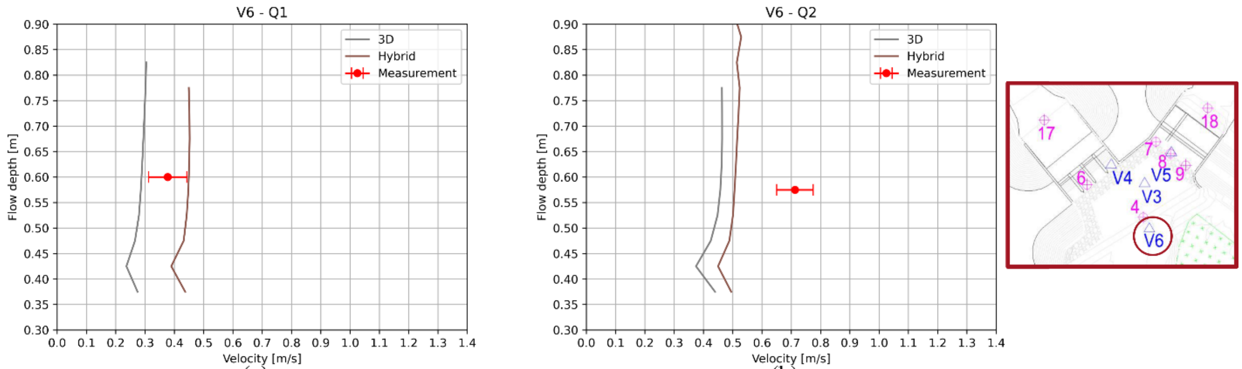
(a) (b)

Figure 10: Vertical profile of velocity for (a) Q1 and (b) Q2 at the location of V5 gauge.

Gauge V6 was situated downstream of the hydraulic structures, positioned within a region of complex topography, unlike the simpler terrain around gauge V3. Additionally, water depths at this location were observed to be lower in the Q2 scenario compared to Q1, as indicated by the water level data for gauge WL4 (located in proximity to V6) presented in Figures 6 and 7. The reduced water levels in Q2 led to diminished damping effects, resulting in a more turbulent flow pattern. However, during the Q1 scenario, despite close proximity of V6 to the transition zone between the 3D and hybrid 2D/3D meshes, suggesting a significant influence of the hybrid mesh on the flow dynamics, the hybrid mesh demonstrated commendable accuracy in predicting flow velocities. This performance highlights the capability of hybrid mesh to effectively model flow dynamics, even in areas where complex topography and varying water depths present significant challenges.

4 CONCLUSION

The findings elucidated in the preceding sections affirm that the Flow-3D model exhibits diminished precision when confronted with highly intricate flow scenarios, such as those observed at gauge V5. This indicates a requisite for meticulous fine-tuning of model parameters to ensure the derivation of robust outcomes. Despite this limitation, the hybrid 2D/3D models demonstrated commendable efficacy relative to their fully 3D counterparts, particularly in accurately estimating flow velocities, underscoring their utility in scenarios demanding precision in flow dynamics characterization.



(a) (b)

Figure 11: Vertical profile of velocity for (a) Q1 and (b) Q2 at the location of V6 gauge.

The primary objective of this study was to evaluate the viability of hybrid 2D/3D meshes in facilitating large-scale simulations while substantially mitigating computational costs. This was achieved by strategically applying shallow water equations within areas deemed less critical, thereby concentrating computational resources on regions of paramount importance. The results garnered from this study substantiate the potential of hybrid simulations as a viable alternative for addressing complex, large-scale hydrodynamic problems. Specifically, the adeptness of hybrid mesh in capturing the detailed flow dynamics in the vicinity of hydraulic structures, even under varying discharge conditions, highlights its applicability and effectiveness.

Moreover, the insights of study into the differential performance of the hybrid and fully 3D models under varying flow complexities and discharge scenarios underscored the importance of model selection and configuration in hydrodynamic simulations. The understanding of how topographical complexity and water depth variations influence model accuracy provided valuable guidance for future research and practical applications in hydraulic engineering. The ability of the hybrid model to yield accurate flow velocities in less complex terrains and under higher discharge scenarios, without compromising computational efficiency, suggested a promising approach for optimizing hydrodynamic modeling in large-scale environmental and engineering projects.

In conclusion, while acknowledging the inherent challenges posed by complex flow scenarios to modeling accuracy, this study demonstrated the considerable promise of hybrid 2D/3D mesh approaches in striking a balance between computational efficiency and the fidelity of flow representation. This balance is crucial for advancing the capabilities of hydrodynamic simulations in addressing the multifaceted challenges inherent in large-scale environmental and engineering applications.

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