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Hybrid Integration of Computational Fluid Dynamics and Artificial Neural Networks for Enhanced Predictive Modelling in Hydraulic Engineering

Ir. Nur Azwa Binti Muhamad Bashar (UiTM & USM), Assoc. Prof. Dr. Mohd Remy Rozaini Bin Mohd Arif Zainol (USM),
Dr. Intan Shafeenar Binti Ahmad Mohtar (UiTM) and
Ir. Gs. Ts. Dr. Mohd Rashid Bin Mohd Radzi (TNB Power Generation Sdn. Bhd)

In recent years, the accurate prediction of fluid flow and the hydraulic properties of flow have become increasingly important for the management of underground and surface water systems and hydraulic structures. Computational Fluid Dynamics (CFD) has proven to be one of the most influential simulation techniques in the analysis of complex flow interactions in canals, spillways, reservoirs and other hydraulic systems. Despite its proven reliability and accuracy, CFD is still computationally intensive, particularly for real-time monitoring or large-scale water collection and storage systems. To overcome these limitations, researchers have explored the potential of Artificial Neural Networks (ANNs), which subdivide the ability of this method to approximate nonlinear functions based on input-output relationships. The integration of CFD with ANN represents a promising solution that combines the physical reliability of numerical models with the speed and adaptability of data-driven approaches.

The increasing number of complex flow solutions such as air-water interphase, air entrapment, bubble formation in a high-velocity flow, hydraulic jump, turbulent flow and cavitation problems, especially in flood events, require advanced simulation approaches such as CFD to solve the problem from the fundamental aspects to the application for engineering decision-making processes (Chanson, 2022; Chanson et al., 2021; Chanson & Shi, 2022). This selection was made due to the excellent simulation capabilities, reliability and realistic solutions of CFD for fluid dynamic problems (Mozaffari et al., 2022; Sharifi, 2025). However, its application is often limited by high computational costs and the requirement for expertise in setting up the system and validating the model (collected data from the physical inspection on site or the constructed, scaled-down physical model). This therefore represents a significant obstacle to the development of early warning systems, as this model offers a time-dependent approach. These limitations are particularly restricted to real-time predictions or decision support systems for managing hydraulic infrastructures. Conversely, ANN can provide fast approximations of system behaviour if the system is properly trained and sufficient data is available (Jabbari and Bae, 2018; Spiridonov et al. 2020). However, individual ANN models often have problems with reliability and accuracy when exposed to complex flow scenarios without physical laws embedded in the numerical models (Frnda et al., 2022). An urgent challenge is therefore to develop hybrid methods that integrate CFD with ANNs to capitalise on the strengths of both data-driven and physics-based approaches.

Despite the growing interest in the integration of CFD and ANN, some limitations have been emphasised. These include that most hybrid models are domain-specific and have limited ability to adapt to different hydraulic conditions or geometries, such as spillway capacity during flooding, unsymmetrical structure and capacity of the incoming stilling basin with baffle structure to control hydraulic jump, and erosion and sedimentation issues. Secondly, the quantification of uncertainties in ANN predictions remains underexplored, which is particularly important for high-risk applications such as dam failure analysis or modelling extreme weather conditions under the influence of climate change. Third, the training of ANN models often requires extensive and high-quality CFD data sets, which are costly and time-consuming to generate. Finally, the unstable nature of ANN models poses a challenge in terms of data interpretation and reliability, especially for engineers who need clear and accurate results to support the engineering decision-making process.

To address these gaps, future research should prioritise the development of general hybrid modelling frameworks which capable of learning from multiple hydraulic scenarios and geometries. The use of transfer learning could reduce data requirements and enable faster distribution across related domains. Research should also explore inexplicable artificial intelligence techniques to enhance the transparency of ANN outputs, allowing users to understand and validate model behaviour. Finally, collaborative efforts to create open-source benchmark datasets and modelling platforms would support reproducibility and encourage broader adoption of hybrid approaches.

In conclusion, the integration of CFD and ANN is a forward-looking strategy in fluid and hydraulic engineering that has the potential to deliver faster, effective and reliable predictions. By addressing current methodological challenges and advancing interdisciplinary research, this hybrid approach can contribute to resilient, intelligent and sustainable water infrastructure systems. Therefore, the positive integration of CFD and ANN today offers a trade-off effect, especially in the face of increasing environmental uncertainties and infrastructure requirements.

References:

Chanson, H. (2022). On air entrapment onset and surface velocity in high-speed turbulent prototype flows. *Flow Measurement and Instrumentation*, *83*, 102122. https://doi.org/https://doi.org/10.1016/j.flowmeasinst.2022.102122

Chanson, H., Leng, X., & Wang, H. (2021). Challenging hydraulic structures of the twenty-first century – from bubbles, transient turbulence to fish passage. *Journal of Hydraulic Research*, *59*(1), 21-35. https://doi.org/10.1080/00221686.2020.1871429

Chanson, H., & Shi, R. (2022). Optical measurements in dam spillways during major flood events: a down-to-earth review of pros and cons. Hydrology & Water Resources Symposium 2022 (HWRS 2022): The Past, the Present, the Future: The Past, the Present, the Future,

Frnda, J., Durica, M., Rozhon, J., Vojtekova, M., Nedoma, J., & Martinek, R. (2022). ECMWF short-term prediction accuracy improvement by deep learning. Scientific Reports, 12(1), 1-11.

Jabbari, A., & Bae, D. H. (2018). Application of Artificial Neural Networks for accuracy enhancements of real-time flood forecasting in the Imjin basin. Water, 10(11), 1626.

Mozaffari, S., Amini, E., Mehdipour, H., & Neshat, M. (2022). Flow Discharge Prediction Study Using a CFD-Based Numerical Model and Gene Expression Programming. *Water*, *14*(4), 650. https://doi.org/10.3390/w14040650

Sharifi, S. N. (2025). Enhancing performance of stepped spillways: CFD analysis of shaped step surfaces for improved flow dynamic. *Results in Engineering*, *25*, 103704. https://doi.org/https://doi.org/10.1016/j.rineng.2024.103704

Spiridonov, V., Baez, J., Telenta, B., & Jakimovski, B. (2020). Prediction of extreme convective rainfall intensities using a free-running 3-D sub-km-scale cloud model initialized from WRF km-scale NWP forecasts. Journal of Atmospheric and Solar-Terrestrial Physics, 209, 105401.