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Modelling the Hydrological Performance of Stormwater Ponds Using Observed Water Level Data

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Abstract
Stormwater modelling software operates on fundamental hydraulic and hydrological principles to predict and simulate the flow and movement of stormwater in large catchments. There are significant gaps in studies that use both modelling and field measurements to evaluate the water quantity control performance of stormwater management (SWM) ponds many years after construction. This study aims to provide new insights into the ability of design hydrologic models to predict the actual performance of aging SWM ponds. Models created during the design and planning stages of two SWM ponds in Vaughan, Canada were re-created in Visual OTTHYMO (VO), and modelled water levels were compared against observed pond depths for eight rainfall events at each pond. The results showed that 50% of the 16 modelled runs reasonably reflected the observed conditions, with 88% (14 of 16 events) achieving normalized root mean square error (RMSE) values below 0.5 and 50% attaining R^2 values greater than 0.7. A one-way sensitivity analysis showed that total impervious area (TIMP), modified curve number (CN*), and final infiltration rate (F_c) had a significant impact on the modelled peak runoff rates. To improve model performance, measuring the onsite discharge and re-creating the stage-storage-discharge relationship for as-built conditions is recommended.

Highlights
- Design hydrologic models reasonably predict observed stormwater management pond depth
- Estimations of impervious area and infiltration parameters can affect resulting peak flow rates
- Measuring the actual stage-storage-discharge relationship could improve model performance

Introduction
Stormwater infrastructure, such as stormwater management (SWM) ponds, is typically designed and sized using modelling software that applies hydraulic and hydrological principles to simulate the movement of stormwater within watersheds and across catchments. Today, practicing engineers and designers have access to a wide range of open-source and proprietary software for modelling the hydrologic and hydraulic processes in SWM ponds. Software options range broadly in complexity, targeted use, underlying hydrological and hydraulic processes and assumptions (Minnesota Pollution Control Agency, 2023). Visual OTTHYMO (VO) is the Graphical User Interface version of OTTHYMO, which is a modified version of the original HYMO hydrologic model engine developed by Dr. P.E. Wisner from the University of Ottawa in 1983 (Williams and Hann, 1972). VO is widely used in Ontario for watershed analysis, water balance analysis, and pond design by engineering consultants and municipalities. While modelling software can produce robust predictions of stormwater behaviour, the accuracy of modelled results largely depends on the quality of input data and the validity of the assumptions made about the hydrological processes (Sood and Smakhtin, 2015). A review of existing

literature reveals a significant gap in studies that use both modelling and field-based assessments to evaluate the water quantity control performance of SWM ponds many years after construction (Hancock et al., 2010; Fennessey et al., 2001). This paper aims to assess the effectiveness of two hydrologic models, developed during the design phase of the development site, in capturing the pond's water level responses to rainfall 14 and 19 years into their operation. Using measured water level data, the study provides new insights into the ability of the design model to predict the actual hydrologic and hydraulic behaviour of aging SWM ponds and demonstrates how real-time data can enhance ongoing monitoring efforts.

Methodology

VO Modelled Pond Depth

Models developed during the design and planning stage are re-created based on the output files of the post-development VO model included in functional servicing reports for the developments (EMC Group Ltd., 2001; Schaeffers Consulting Engineers, 2013). All watershed and infrastructure input parameters were retained, but the design storm hyetographs were replaced by real-time discrete rainfall events measured in the field from May 20th to October 31st, 2022, and May 1st to June 30th, 2023. These observed storms were used to generate model-predicted water levels within each pond. The simulated outflow hydrographs were converted to pond depths using the stage-storage-discharge relationship from the initial pond design. Estimated water levels were compared with observed water levels measured on site, as detailed by Gao (Gao, 2023).

Model Performance and Analysis

For each storm event, the normalized root mean square error (RMSE) and Pearson correlation coefficient (R^2) were used to compare simulated and measured pond depths. Hydrograph parameters, including the peak depth, time-to-peak depth, and drawdown time of the recession limb, were analyzed to evaluate how well the model replicated actual pond conditions. Since the design models rely heavily on default or program-recommended values for their parameters (e.g., Manning's number, total impervious area, infiltration parameters, etc.), a one-way sensitivity analysis was performed using the recorded rain events with the largest rainfall and longest duration.

Case study

The study area of this project is in Vaughan, a city in the Regional Municipality of York, in Ontario, Canada. The ponds chosen to assess the model quality of the original designs are Sir Stevens Pond (SSP) and Romina Pond (RP), wet detention ponds constructed in 2008 and 2003, respectively. Water level data from a partnership between the City of Vaughan and Ioticiti Networks is used to assess the water quantity control performance of the initial pond design many years into operation. Eight rainfall events for each pond were selected to conduct simulations in VO, and the one whose model output most closely represented the observed data (labelled "Strongest Match") and the one which had the least representative model output compared to the observed (labelled "Weakest Match") were selected for each pond for presentation (Figure 1). These were determined by comparing the RMSE and R^2 values and visual inspection of the hydrographs.

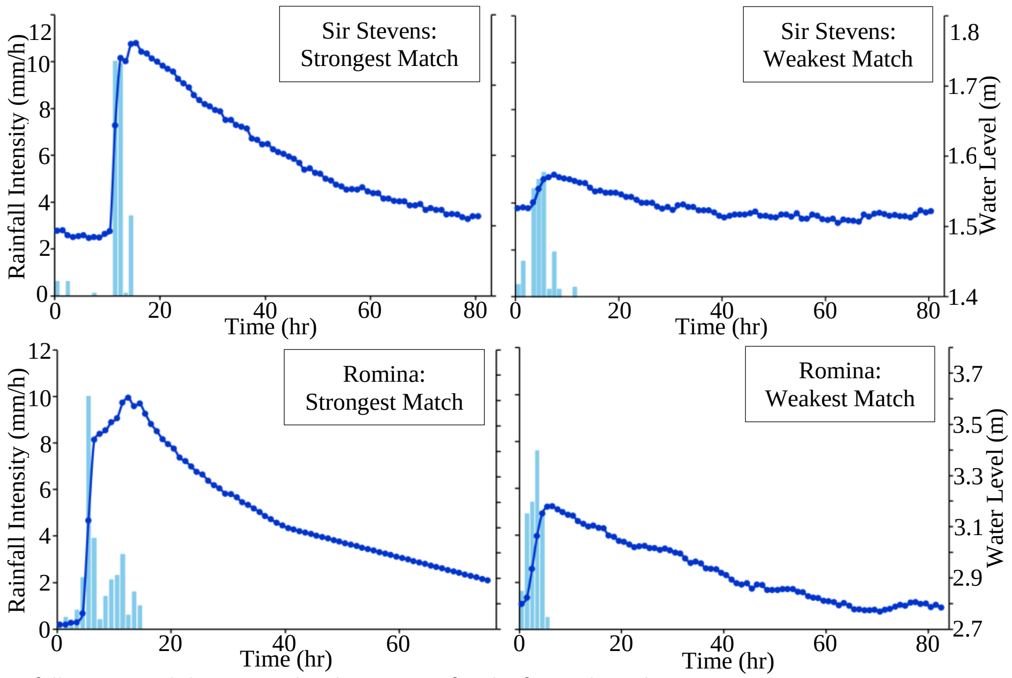

Figure 1: Rainfall events and their water level responses for the four selected cases.

Results and Discussion

Pond water levels for 50% of the selected storm events were reasonably simulated by the design models. Modelled water levels generally matched observed conditions, producing normalized RMSE values below 0.5 and R^2 values greater than 0.7. Figure 2 shows the modelled and observed depth for the strongest and weakest representations of observed data for each pond, as produced by VO.

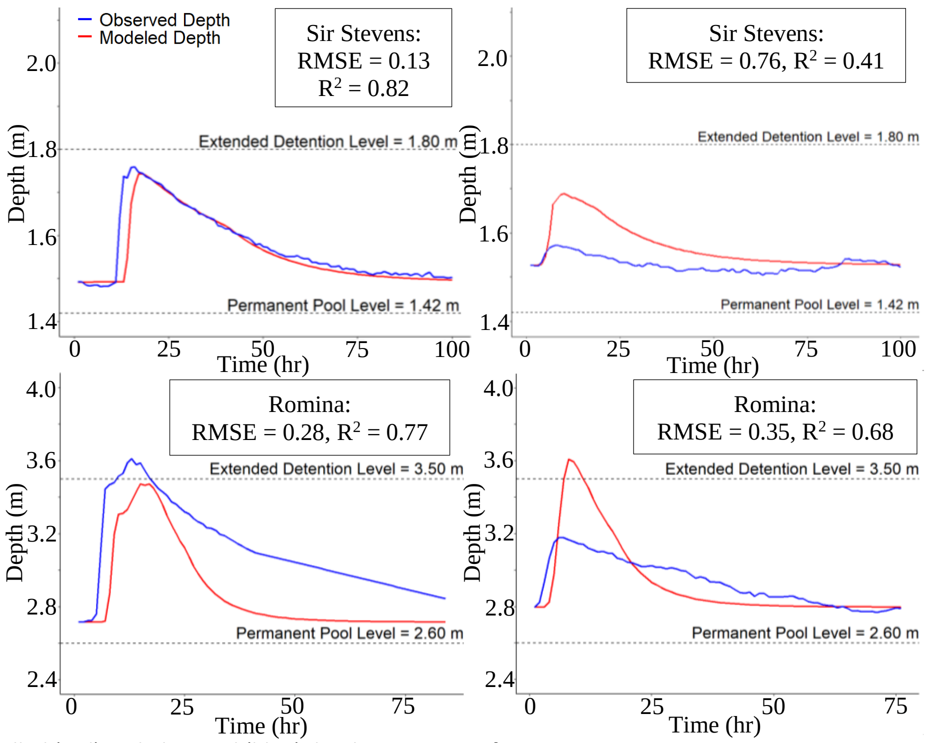

Figure 2: Modelled (red) and observed (blue) depth comparison for representative events.

Overall, most (14 of 16 events, 88%) simulated events had normalized RMSE values below 0.5 and half had R^2 values greater than 0.7 (Table 1). Modelled peak depth ranged from 13.9 cm below the observed peak depth to 42.9 cm above the observed, with average modelled peak depths 9.8 cm and

7.5 cm above the observed peak for SSP and RP, respectively. Modelled time-to-peak ranged from zero to five hours larger than the observed time-to-peak. For modelled drawdown time, SSP produced ranges of 2 hours shorter than observed drawdown time to 84 hours larger than observed, with an average of 46.5 hours greater than observed drawdown time. RP ranged from 169 hours quicker than the observed drawdown time to 26 hours longer, with an average of 38.6 hours less than observed drawdown time. This shows that the rising limb was more accurately captured than the falling limb.

Table 1: Summary of comparison results (average ± standard deviation) between modelled and observed depth.

Analysis Metric	SSP	RP
Normalized RMSE	0.42 ± 0.33	0.28 ± 0.09
R^2	0.75 ± 0.18	0.66 ± 0.07
Modelled Peak Depth (cm)*	+9.81 ± 14.05	+7.54 ± 18.08
Modelled Time-to-Peak (h)*	+2.13 ± 0.99	+2.88 ± 1.25
Modelled Drawdown Time (h)*^	+46.50 ± 32.05	-38.60 ± 82.56

*+/- means the model is overpredicting/underpredicting the magnitude of observed values.
^a new rain event started before full drawdown occurred, so values were calculated using the six events and five events for SSP and RP, respectively, that reached full drawdown.

The one-way sensitivity analysis revealed that total impervious area (TIMP), modified curve number (CN*) in the modified SCS curve method for infiltration, and final infiltration rate (F_c) in the Horton method for infiltration had a large impact on the peak runoff. When calculated at the lower bound of their parameter range, TIMP produced -35% of the modelled peak flow for SSP and -29% for RP, F_c for SP was +564%, and CN* for RP was -2%. At the upper bound, TIMP was +622% for SSP and +8% for RP, F_c was -3% for SSP, and CN* was +7% for RP. These parameters are connected to infiltration of the rainfall before it reaches the SWM ponds, with the most impactful being TIMP. This suggests that the impervious area have may have been overestimated during the subdivision design phases, leading to the model's overprediction of peak water depth. A smaller impervious area results in lower peak flow, thereby reducing modelled depth to be closer with the observed depth, which aligns with literature that has found that TIMP influences simulated runoff volume (Bell et al., 2016).

The VO model created to design and size the pond effectively captures the SWM ponds' actual water level responses as the pond fills with stormwater, but more errors were noted as the ponds drained. However, the prediction accuracy of the original VO model could still be improved, as the model overpredicted water depth in 12 of 16 events and the time to peak was larger in 15 of 16 events (it was equal in the 16th). Another explanation for the discrepancies between the modelled and observed depths could be the assumed stage-storage-discharge relationships. Since the model outputs flow data, it is converted to depth for comparison with the observed values. When the stage-storage relationship is adjusted by enlarging the storage volume, the modelled peak depth was closer to the observed depth. This suggests that the ponds' as-built shapes may be larger than intended. Since the function of the stage-to-storage change is based on the SWM ponds' shapes, storms of different storage volumes would be impacted differently when converted to depth. Overall, to eliminate inaccuracies in this conversion, measuring the discharge and creating the stage-storage-discharge relationship for as-built conditions would likely improve the model's prediction of depth.

Conclusions and Future work

This study re-created the original design models of two SWM ponds in Vaughan, Canada, in VO and compared the modelled water level to observed depths for 16 rain events. The main findings are:

- Modelled events reasonably reflected the observed water levels for eight of 16 rainfall events for two SWM ponds in Vaughan, Canada, but overpredicted peak depth in 12 events.
- To improve accuracy of the model, measuring discharge to create the as-built stage-storage-discharge relationship and experimenting with infiltration methods are recommended.

While overprediction is not a critical issue as the pond outflows did not exceed target discharge rates, the inability to accurately simulate hydraulic behaviour could lead to pond overdesign, increasing costs for both land developers and municipalities, underscoring the importance of improving design models.

Acknowledgement

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