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Enhancing Catchment Runoff Simulations using Soil Moisture Dependent Hydraulic Conductivity

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ABSTRACT

The estimation of unsaturated hydraulic conductivity in the vadose zone is crucial for the long-term continuous simulation of catchment runoff. A soil moisture dependent hydraulic function was built into the coupled surface/sub-surface water model of a fully 2D hydrodynamic solver (TUFLOW HPC), to better emulate the unsaturated soil hydraulic conductivity. Testing was carried out for the Springbrook Creek Catchment, QLD, for the period of November 2023 to January 2024, covering a dry period followed by an extremely wet period. The modelling results were compared against the water level at Little Nerang Dam, located at the catchment's exit, and with the soil moisture represented by the Bureau of Meteorology's AWRA-L model.

Models with fixed hydraulic conductivity tend to either overestimate the baseflow during the dry period or underestimate the baseflow immediately after the flood. The adopted hydraulic conductivity function improves soil moisture retention during the dry period, without compromising the baseflow during and after a wet period. Additionally, the "Log Law Roughness Length" bed friction approach produces a superior catchment response by applying a higher bed friction where the sheet flow depth is less than or comparable to the bed roughness.

With two soil layers, the model reasonably replicates the near surface soil moisture fluctuation predicted by the AWRA-L model. The multiple soil layers model did not significantly alter the surface runoff in this study, but the modelled topsoil moisture can be utilised in future studies to implement soil moisture dependent surface infiltration to address the infiltration rate difference during the dry and wet period.

INTRODUCTION

Direct rainfall hydraulic modelling (also referred to as rain on grid modelling) simulates rainfall runoff processes using a 2D hydraulic solver. Rainfall volume is applied at each model grid cell, and surface runoff is generated when the rainfall rate exceeds the infiltration rate (Hortonian overland flow), or when the soil layer is saturated (saturated overland flow). The surface runoff routing is simulated by the hydraulic solver, based on the adjacent cell geometry, bed friction and associated flows. The sub-surface water flow plays an important role in the catchment water balance: not only does it provide baseflow to creeks when it isn't raining, but it also drains the unsaturated zone so that infiltration occurs again at the next rain event, with associated attenuation of the catchment response. These catchment water flow processes are illustrated in Figure 1.

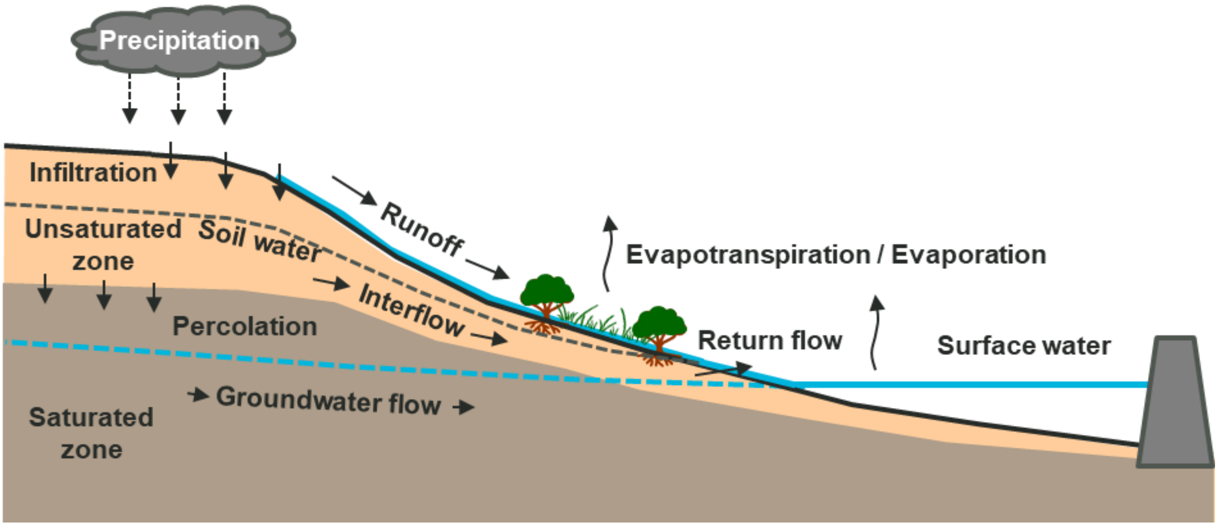

Figure 1. Illustration of the catchment runoff processes considered in this study.

The inclusion of unsaturated water advection in the vadose zone in a 2D hydraulic model has been shown to significantly improve the timing, the peak level/discharge, and the receding pattern of the catchment runoff hydrograph (Gao et al, 2023). The modelling approach adopted in Gao et al, 2023 utilised fixed horizontal hydraulic conductivities and only one soil layer with a constant thickness across the entire catchment. This resulted in higher-than-expected soil water movement during dry periods, while calibrated wet period horizontal hydraulic conductivities overestimated the baseflow during dry periods. This study enhances the sub-surface water flow model by applying soil moisture dependent hydraulic conductivity. Van Genuchten's (1980) function was adopted to predict unsaturated hydraulic conductivity based on the residual and saturated soil moistures.

This improved approach was applied to a 2D direct rainfall model of Springbrook Creek Catchment in Queensland, including both a dry period and extremely wet period before and after the 2024 January flood. The modelling results were calibrated against the water level at Little Nerang Dam, located at the catchment's exit, and soil moisture modelled by Bureau of Meteorology's AWRA-L model (Frost and Shokri, 2021). The impacts of other key factors, such as surface infiltration rate, bed friction and the application of multiple soil layers are also discussed.

METHODS

Modelling Unsaturated Water Advection

The 2D implementation of Darcy's law was initially adopted in the TUFLOW HPC solver (Collecutt and Syme 2017) to model the runoff attenuation by the saturated vadose-zone flow during flood events (Gao et al, 2023). This study enhances the model by applying van Genuchten (1980)'s soil moisture dependent hydraulic conductivity to simulate the unsaturated vadose-zone flow during dry periods. When the soil is unsaturated, the hydraulic conductivity is adjusted based on the residual and saturated soil moisture contents using:

$$K(S_e) = K_o S_e^L \left\{1 - \left[1 - S_e^{n/(n-1)}\right]^{1-1/n}\right\}^2 \quad (1)$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad (2)$$

where $K(S_e)$ is the unsaturated hydraulic conductivity (mm/hr). K_o is the matching point at saturation (mm/hr). K_o is similar to the saturated hydraulic conductivity K_s, but not necessarily equal to K_s. S_e is the relative saturation (-), L and n are the model parameters (-). θ is the soil water content by volume. θ_s is the saturated water content, i.e. the maximum amount of water a soil can hold. θ_r is the residual water content, which is the threshold where no further soil water can drain by gravity. The soil-class-averaged model parameters can be found from Rosetta's technical documentation (Schaap, 2002).

Note that Richard's equation is required to consider the impact of capillarity. This will be addressed in the future study for simulations with extended period, while this study focuses on the impact of soil moisture dependent conductivity only given the relatively short two-month simulation period.

Model Input

The model area is a sub-catchment of the Nerang River Catchment located in the southeast of Queensland, Australia. This includes the west and east branches of Little Nerang Creek, Little Nerang Dam, and the Springbrook Plateau, covering approximately 36 km^2 (Figure 2, left). The lower half of the catchment is predominately rainforest, while the Springbrook Plateau has both dense forest and some cleared grassland. The terrain is extremely steep with a change in ground elevation from 130 to 1000 mAHD, including substantial cliff faces along the edge of the plateau.

1 m resolution DEM data was collected from Elvis (https://elevation.fsdf.org.au/). Since the LiDAR data does not include the dam bathymetry, the 2D cell elevations at the dam were modified to match the model storage with the 'storage curve' documented in the "Emergency Action Plan of Little Nerang Dam" (SeqWater, 2023). For densely vegetated areas, the "Log Law / Roughness Length" approach was used to estimate the bed friction. Compared to the fixed manning's n approach, the log law approach, which varies the bed friction at very shallow depths (i.e. where the depth is smaller or comparable to the roughness height), produced superior results (Boyte, 2014). The modelling results using both approaches are presented for comparison.

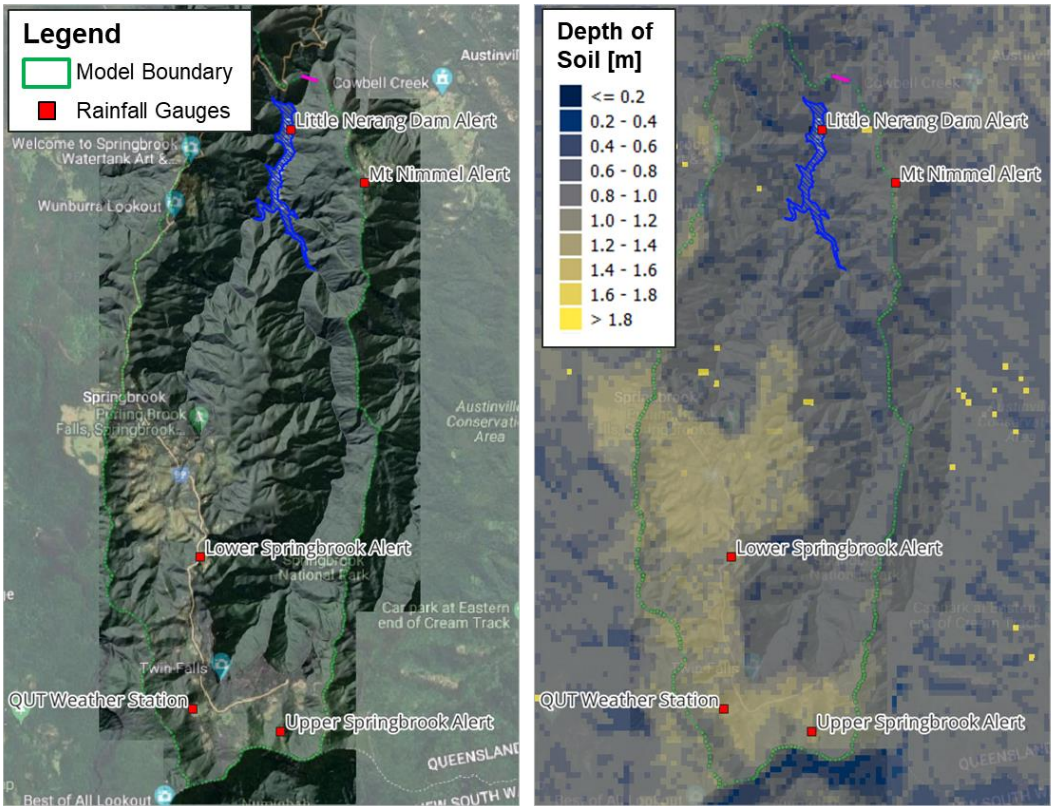

Figure 2. Model domain, rainfall gauges and depth of soil layer.

The soil layer thickness was determined based on the 'depth of soil' grid from Soil and Landscape Grid of Australia (https://esoil.io/TERNLandscapes/Public/Pages/SLGA/). This grid includes soil horizons A and B as presented in Figure 2 (right). The applied thickness is approximately 0.3~1.2m, with thicker soil layers in the upper catchment, and thinner soil layers in the lower catchment, which has steeper slopes. The two sections are separated by rocky cliffs where multiple waterfalls can be found. For the simplicity of the modelling, this study only investigated the sub-surface water movement in the vadose zone (top ~1.2m). The deeper groundwater layer, which may be influencing the baseflow during the two-month period, was considered to have a less influence due to a reasonably dry period prior to the study period. It is intended to investigate the effects of the deeper groundwater layer in future studies.

Historic rainfall data at multiple rainfall gauges was provided by QUT and sourced from the Bureau of Meteorology. The rainfall gauges are listed in Table 1 and the locations are presented in Figure 2. Voronoi polygons were created for each rainfall station as the rainfall input area. The simulation period was from 09/11/2023 to 14/01/2024 including a dry period before the rainfall event on 01/01/2024. The cumulative rainfalls at the stations are presented in Figure 3.

Table 1. List of rainfall gauges.

BoM Station ID	Name	Latitude	Longitude
N/A	QUT weather Station	-28.2283	153.2697
040848	Lower Springbrook Alert	-28.2069	153.2708
540353	Mt Nimmel Alert	-28.1542	153.2967
540054	Little Nerang Dam Alert	-28.1467	153.2850
540400	Upper Springbrook Alert	-28.2314	153.2836

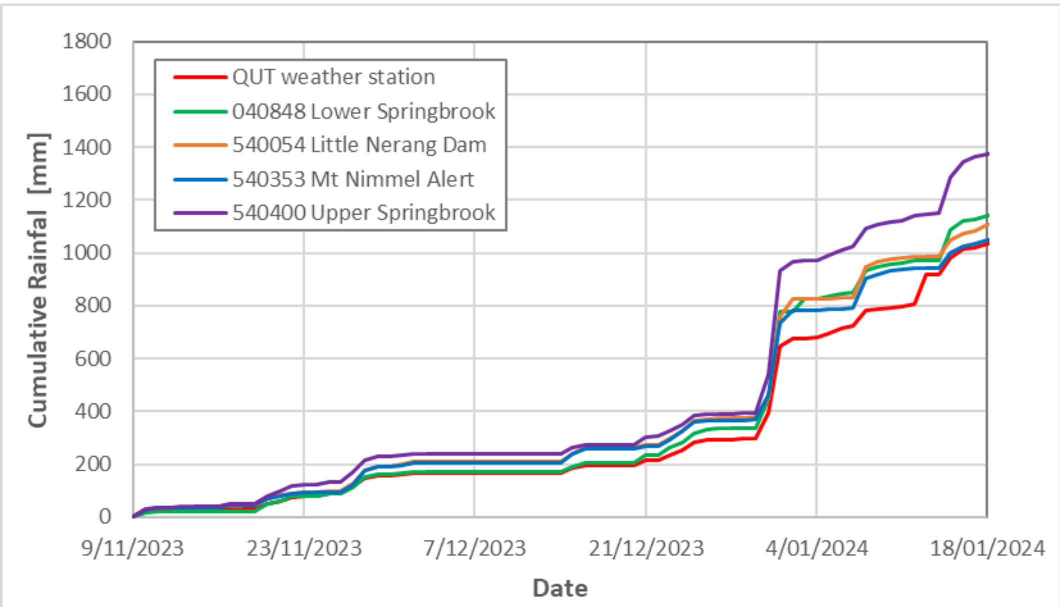

Figure 3. Cumulative Rainfall since 09/11/2023.

Uncertainty of Model Input

Catchment water balance and runoff process are affected by many factors that need to be approximated. Evapotranspiration contributes significantly to the drying of the soil between rainfall events. Changes in soil moisture affect the infiltration capacity for subsequent rainfall. Average monthly 'potential' evapotranspiration data was obtained from the Bureau of Meteorology (BOM, 2005) and was applied to the model. The evapotranspiration is applied to the surface water first. For cells with no surface water, but available sub-surface soil moisture, the soil moisture is reduced.

The ‘actual’ evapotranspiration rate depends not only on the availability of water, but also on the land use, vegetation type and density. Other factors, such as interception by trees, deep drainage, and dam releases to a water treatment plant also influence the dam water balance. Sensitivity tests were conducted to investigate the impacts of these factors. The tests showed the evapotranspiration, the interception by trees and the deep drainage have similar impact to the model outcome, therefore, these three factors were lumped together as one negative source for simplicity. A global calibration factor between 0.0 ~ 1.0 was applied to this negative source, and a factor of 0.5 was eventually adopted based on the sensitivity tests.

The dam releases data could not be obtained, so the impacts of the environmental release, the supply to a water plant, and the emergency release were tested based on the release rates documented in the “Nerang Water Supply Scheme Resource Operations Licence” (Department of Natural Resources and Mines, 2016). Based on the simulated impacts on the dam water level, it was concluded that the environmental release was insignificant, while the other 2 releases were not occurring (at least not during most of the simulation period). Therefore, the dam release was not included in the model.

Soil Parameters

Three types of hydraulic conductivity are required as model input in TUFLOW. The Green-Ampt infiltration rate (K_{GA}) sets the rate of infiltration at the soil when using the Green-Ampt infiltration approach. The horizontal hydraulic conductivity (K_h) defines the rate of soil water movement in horizontal direction, while the vertical hydraulic conductivity (K_v) sets the rate of soil water movement in vertical direction between multiple soil layers. These model parameters can be estimated from the saturated hydraulic conductivity (K_s). Based on CSIRO’s ‘Digital Atlas of Australian Soils’, the predominant soil type in the catchment is “porous earths” (Gn4.11 and Gn4.31) with high clay content, as well as high porosity and hydraulic conductivity (30~300 mm/hr) according to McKenzie et al (2000). However, both the ‘Digital Atlas of Australian Soils’ and QUT’s field measurements suggest the soil has high clay content, which usually leads to lower hydraulic conductivity, e.g. 0.3 mm/hr for clay and 1.0 mm/hr for clay loam in the Green-Ampt infiltration approach (Rawls et al, 1983).

The impact of K_{GA} and K_h have been studied and presented in Gao et al (2023). As the primary focus of this study is to investigate the impacts of fixed and soil moisture dependent horizontal hydraulic conductivity, the calibrations of K_h (both fixed and soil moisture dependent) are presented in detail, while K_{GA} was tested in a range from 0.3 to 100 mm/hr, with a final value of 5.5 mm/hr adopted (Table 2). Note that K_h tested in the model was typically two or more orders higher than the vertical conductivity to consider the impact of the soil anisotropy (see Barwell and Lee 1981).

Single and multiple soil layers were also trialled. With the single layer model, only one soil layer was used to cover the entire thickness of the ‘depth of soil’. The multi soil layer model used a 0.1 m upper layer with a deeper layer to cover the remaining ‘depth of soil’. The vertical hydraulic conductivity (K_v) between the two layers was set equal to K_{GA} for simplicity.

Table 2. Range of soil parameters tested in simulation.

Parameter	Symbol	Tested Range	Final value
Horizontal hydraulic conductivity	K_h	1 ~ 1,000 mm/hr	1,000 mm/hr
Green-Ampt hydraulic conductivity	K_{GA}	0.3 ~ 100 mm/hr	5.5 mm/hr
Vertical hydraulic conductivity (for multiple layers model)	K_v	0.3 ~ 100 mm/hr	5.5 mm/hr

Calibration Data

The water level record at Little Nerang Dam (146034A) was used to benchmark the model's runoff. The dam has an ungated spillway, thus the weir flow parameters in the 2D model were set based on the 'discharge curve' from the "Emergency Action Plan of Little Nerang Dam" (Seqwater, 2023). A water level slope boundary was applied further downstream the spillway as the 2D model outlet. But as the dam spillway acts as an upstream controlled structure, the downstream boundary had no influence on the results.

The "historical" soil moisture data modelled by AWRA-L (Frost and Shokri, 2021) was used (available from: https://awo.bom.gov.au/). Gridded outputs of daily soil moisture are modelled based on the historical near real-time climate data. The output grid is approximately 40 km by 40 km, so the total soil moisture from all 2D cells within the AWRA-L model grid was extracted and divided by the total soil storage capacity of the same 2D cells for comparison.

Model cell size convergency tests were conducted to check for any cell-size dependencies in the results, and the 20 m cell size is used for the results presented below. QUT conducted water level and soil moisture measurements within the upper catchment. However, the model presented in this study is not detailed enough to capture the depth/soil moisture at the specific measurement points due to the catchment scale of the modelling. A more detailed analysis is planned for the future to utilise these data.

RESULTS AND DISCUSSION

Fixed vs Soil Moisture Dependent Hydraulic Conductivity

Figure 4 presents the recorded and modelled water level at the Little Nerang Dam water level gauge (146034A). The modelling result with no soil layer is also presented (grey), in which the dam filled immediately after any rainfall (presented on the top axis as blue bars). By including a soil layer and a fixed K_h = 10 mm/hr (blue), the modelled dam water level increased more slowly due to the reduced/delayed runoff. With fixed K_h values of 100 mm/hr (green) and 1,000 mm/hr (yellow), the dam water level continued to increase between the rainfall events, caused by the baseflow to creeks from the soil layer. A small horizontal hydraulic conductivity of K_h = 10 mm/hr (blue) was required to retain the soil moisture and not to generate the baseflow or the seepage to the dam during the dry period. However, with this value the dam level dropped to the spillway level (168.02 m AHD) too early after the January 1st flood, suggesting the baseflow was too small during the wet period with such a small K_h. The model with a higher K_h of 1,000 mm/hr (yellow) produced better agreement with the dam water level after the flood. The soil moisture dependent horizontal hydraulic conductivity model was tested using the match point conductivity (K_o) of 10 ~ 1,000 mm/hr, and the model with K_o = 1,000 mm/hr is presented in Figure 4 as the red dotted line. Due to the reduction of horizontal hydraulic conductivity in the dry condition, this approach retained soil moisture well during the dry period without recharging the dam too early, while producing enough baseflow after the flood. Note that this K_o value is one order higher than the saturated hydraulic conductivity recommended by 'Digital Atlas of Australian Soils'. This can be attributed to the soil anisotropy (Barwell and Lee 1981), and/or the exclusion of the deeper soil layers. During wet periods, groundwater may rise up towards the ground surface and this process has not been included in the model yet.

Figure 5 compares the soil moisture simulated by this model and the top 1 m soil moisture output from the AWRA-L model. With high horizontal hydraulic conductivity of K_h = 1,000 mm/hr (yellow), the soil moisture reduces too quickly compared to the AWRA-L model. The lower K_h values (<100 mm/hr, blue and green) produce a better agreement during the dry period, however, the soil moisture remained flat after the flood. The soil moisture dependent model with K_o = 1000 mm/hr not only retained the soil moisture during the dry period, but also enabled release of soil moisture after the flood, which provided significant flow to the dam in the days following the flood. Note that grid sizes in this simulation and the AWRA-L model are drastically different (20m vs 40km), but the catchment wide trend in the soil moisture fluctuation after the rainfall events was captured well.

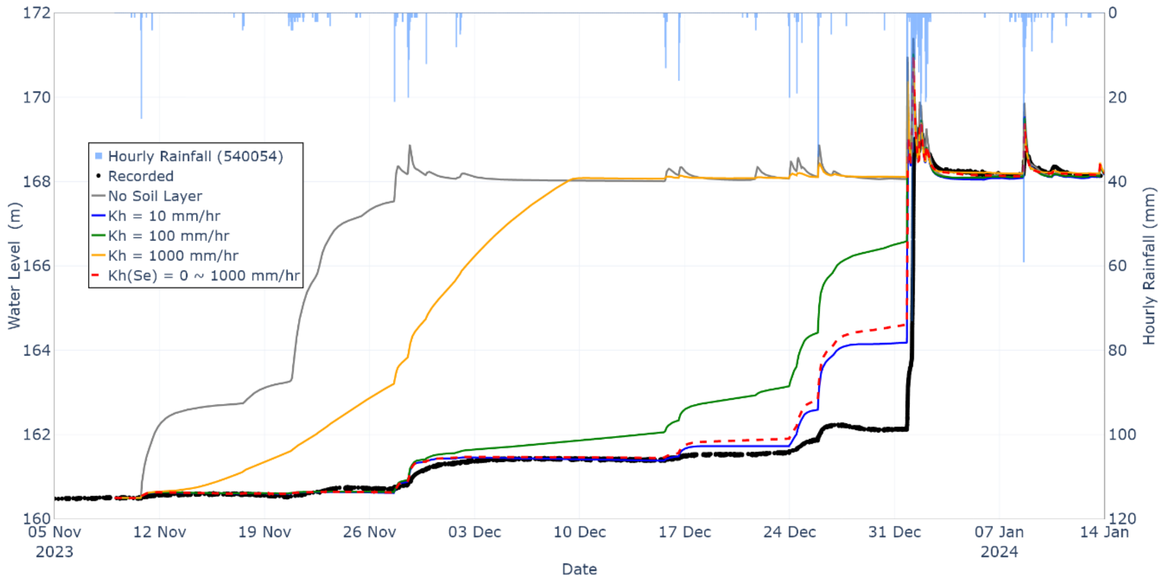

Figure 4. Recorded and modelled water level at the Little Nerang Dam (146034A) with fixed K_h.

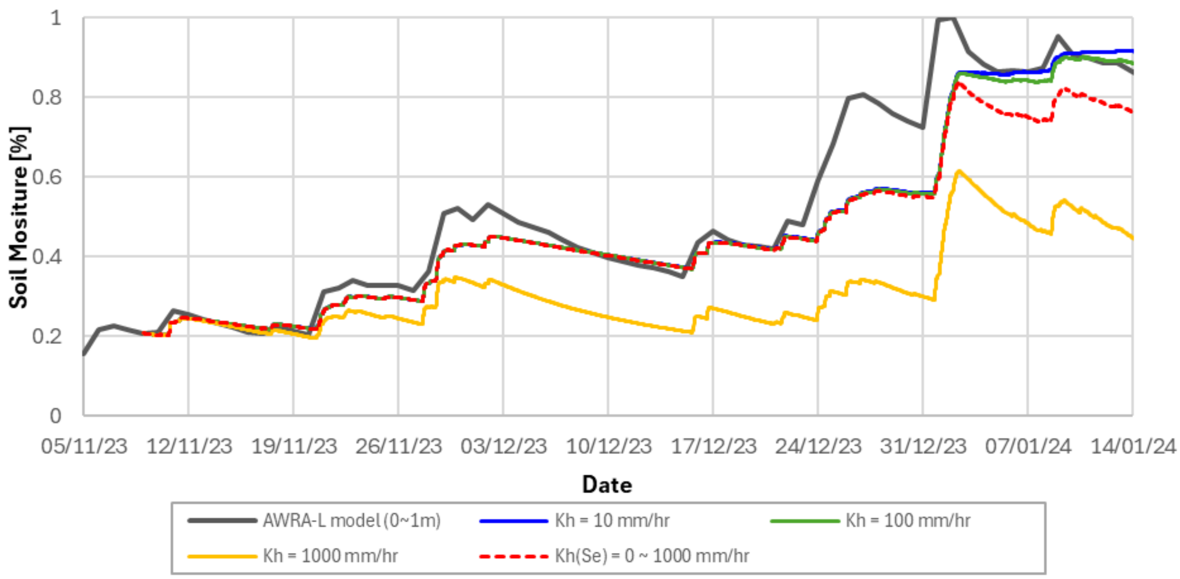

Figure 5. Comparison of simulated soil moisture with AWRA-L model (0~1m deep).

Infiltration Rate during the Flood Peak

The results presented above overestimated the peak water level during the January 1st flood. Multiple scenarios, such as including dam releases, changing soil layer thickness, interception by trees, etc, were simulated, and it was found that the soil surface infiltration rate is the most significant factor for reproducing the peak water level. Figure 6 presents the sensitivity test applying different Green-Ampt infiltration rates for a shorter simulation period around the January 1st flood. Note that the initial dam water level is reset as 162 m in these simulations. A higher Green-Ampt infiltration rate of 20~30 mm/hr was required to replicate the peak water level. This variance in the surface infiltration rate is most likely caused by the difference in the speed that the wetting front moves downward in the saturated and unsaturated soils. The standard Green-Ampt infiltration approach assumes the wetting front is always saturated, however, the unsaturated wetting front moves more slowly. Therefore, further investigation is required in the future to take into account the impact of soil saturation in the Green-Ampt infiltration approach (e.g. Smith et al, 1993).

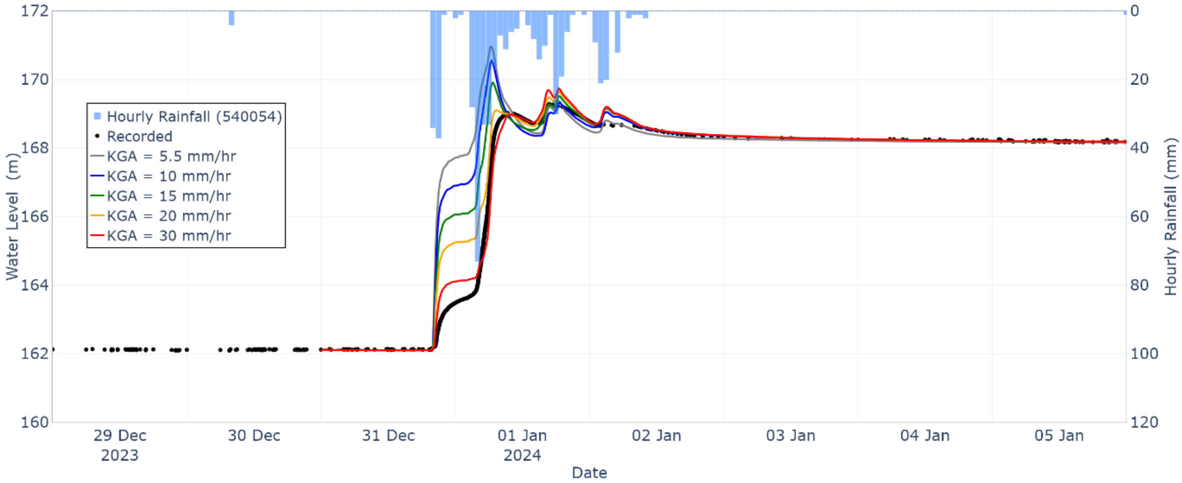

Figure 6. Sensitivity test of Green-Ampt infiltration rates for the flood peak.

Impact of Bed Friction

The bed friction model is a key factor for predicting realistic catchment responses in 2D direct rainfall models. The bed friction determines not only the velocity of surface water, but also the time available for the surface water to infiltrate before reaching the dam. The "Log Law / Roughness Length" approach (Boyte, 2014) was used in this study, and compared with the fixed Manning's *n* approach as shown in Figure 7. The typical Manning's *n* values are 0.035 for grass and 0.15 for very dense vegetation. However, even with a Manning's *n* of 0.20 (green) the modelled flood response was too rapid, as indicated by the sharp increases in water level after the minor rainfall events before January 1st. The log law approach is derived from theory based on a roughness height, and can be converted to equivalent Manning's *n* values for different depths when the depth is less than or comparable to the roughness height, at which point it transitions to the fixed Manning's *n* value. This approach produced a superior catchment response in this study (red), with smoother rises of water level in the dam after the minor rainfall events. The model with fixed Manning's *n* of 0.40 (yellow) produced a similar catchment response, however, the surface infiltration rate had to be almost doubled (K_{GA} = 10 mm/hr) to take into account the higher surface water velocities at the sheet flow cells modelled by the fixed Manning's *n* approach.

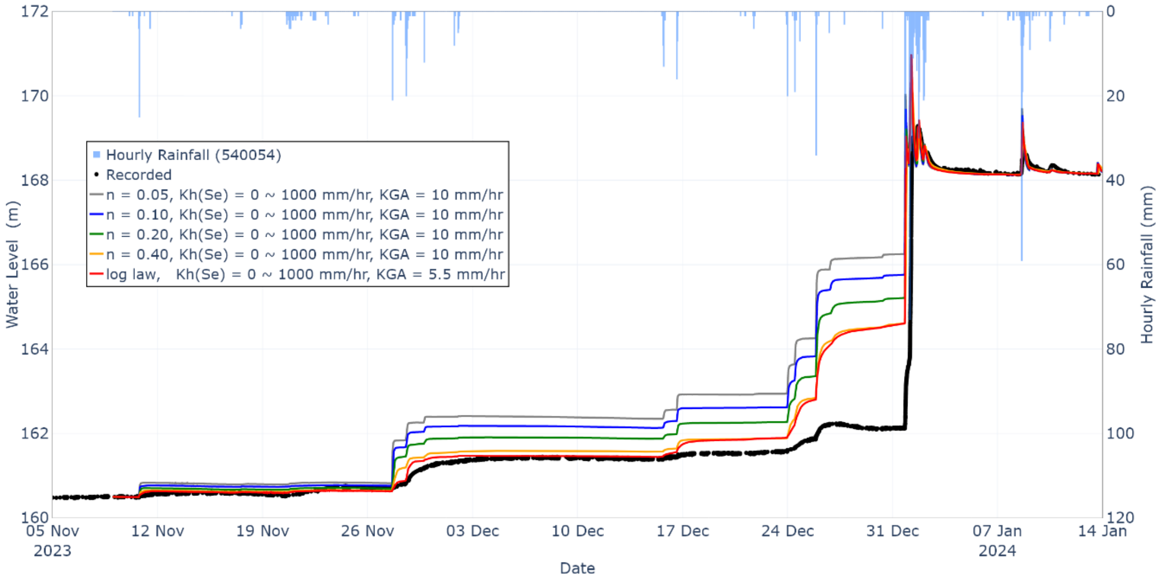

Figure 7. Comparison of log law bed friction approach and fixed Manning's *n* approach.

Multiple Soil Layers

Lastly, a model with two soil layers has been tested. The multi soil layer model has a 0.1m top layer and a second layer to cover the rest of the 'depth of soil'. The vertical hydraulic conductivity between the two layers was set to the same value as the Green-Ampt conductivity applied at the soil surface (i.e. $K_v = K_{GA}$) and the moisture dependent hydraulic function was applied. Figure 8 compares the upper layer soil moisture (0~0.1 m) and the total soil moisture (0~1 m) simulated by TUFLOW and AWRA-L models. It is worth mentioning at this point that the AWRA-L results are from a model, and not actual measurements. The top layer experiences higher fluctuation in the soil moisture compared to the soil moisture in the entire layer, and this trend was replicated well by the proposed TUFLOW model. The TUFLOW model underestimated the total soil moisture after 24th of December and overestimated the top layer moisture after the January 1st flood compared to the AWRA-L model. This suggests a higher vertical conductivity/surface infiltration rate may be needed during the wetter period. The multiple soil layers model did not significantly alter the surface runoff to the dam but showed potential that the soil moisture in the top layer can be used to adjust the vertical conductivity/surface infiltration rate.

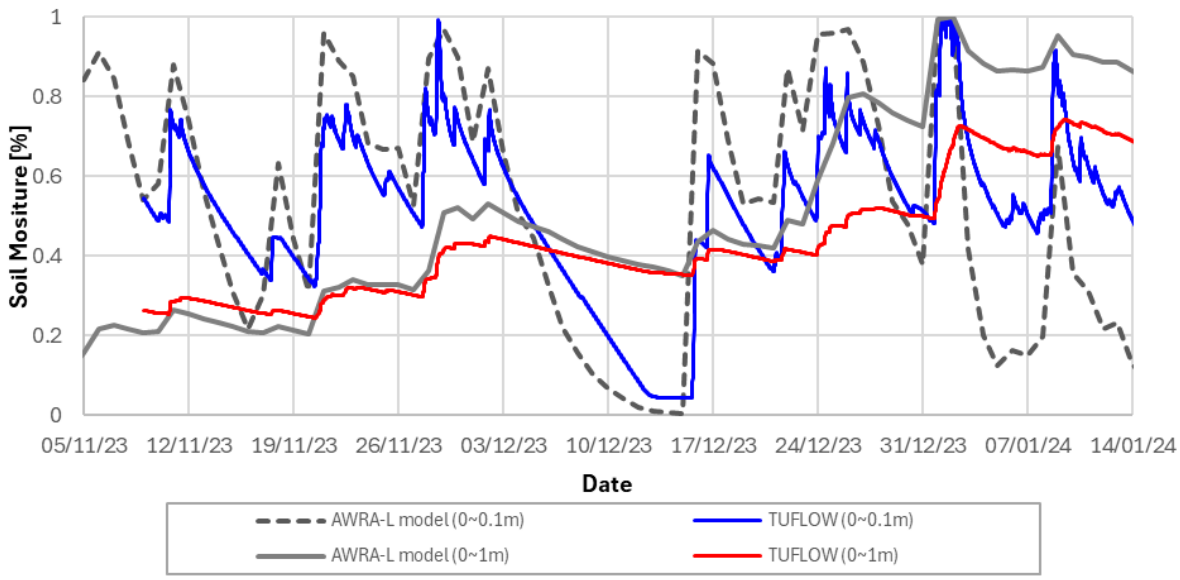

Figure 8. Comparison of simulated soil moisture with AWRA-L model for multi-layer model.

CONCLUSION

This study integrated a soil moisture dependent hydraulic conductivity model into the TUFLOW HPC 2D hydraulic solver to simulate the catchment runoff within the Springbrook Creek Catchment for both dry and wet periods. The model was calibrated against the Little Nerang Dam water level gauge and AWRA-L model's soil moisture outputs. General findings from the parameter testing include:

- Models using fixed hydraulic conductivity either overestimate the baseflow during the dry period or underestimate the baseflow after the flood.
- The added hydraulic conductivity function (van Genuchten, 1980) improves soil moisture retention during the dry period, without compromising the baseflow during and after the flood.
- The "Log Law / Roughness Length" bed friction approach produces superior catchment response by applying higher bed friction when the depth is less than or comparable to the bed roughness height.
- By including multiple soil layers, the model was able to replicate the soil moisture fluctuation near the surface (top 0.1 m), and the gradual changes in the deeper section (0~1.0 m).

- The surface infiltration rate during the flood (saturated) condition was estimated to be higher than that during the dry period. It is possible that surface infiltration models could be improved with the availability of multi-layer soil moisture information.

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BIOGRAPHY

Shuang Gao graduated from Tokyo Institute of Technology with a PhD degree in Environmental Hydraulic Engineering. He joined the TUFLOW software development team in 2017 and has been involved in varieties of R&D projects, flood and coastal modelling, technical support, and training. His main interests lie in the development of cutting-edge modelling methods applied to real-world engineering problems.

Lucy Reading is an associate professor, who has been teaching environmental science (water quality and hydrology) and groundwater science at the Queensland University of Technology since 2015. She has over 20 years' teaching, training, research and community engagement experience. Her current work is particularly focussed on: groundwater monitoring, groundwater resource assessments, groundwater-surface water interactions, groundwater quality assessments and water resource management.

Jakob Lowry is an undergraduate civil and environmental engineering student at QUT. He has been involved in research and data collection with QUT and the Gold Coast City Council at Springbrook Plateau. He is currently undertaking his thesis on modelling surface water flow in the Springbrook Creek Catchment using TUFLOW.

Greg Collecutt is the principal GPU software developer at TUFLOW. He has degrees in mechanical engineering and a PhD in theoretical physics and has spent most of the last twenty years working in computational fluid dynamics and flood modelling. In this role he is primarily involved with the implementation and benchmarking of new modelling features in the TUFLOW HPC 2D engine.

Phil Ryan is software development lead for the TUFLOW Classic and HPC hydraulic modelling software products. Phil has been actively involved in a range of consultancy projects over 15+ years. These include flood studies, floodplain management studies, flood impact assessments, storm tide studies, Monte Carlo analysis, wave modelling, coastal hydrodynamic and advection-dispersion modelling.

Bill Syme has 39 years' experience primarily in the flood hydraulics field. During this time, he successfully managed and led a wide range of studies in Australia and overseas. The widely used TUFLOW hydrodynamic modelling software was first developed by Bill starting in 1989. Today, Bill is BMT's Software Business Lead, managing TUFLOW's global operations, and continues to provide specialist hydraulic modelling and flood risk management advice. He was the Project Manager for the award-winning Brisbane River Flood Study Hydraulic Assessment, and in 2022, Bill was the recipient of the FMA Allan Ezzy Flood Risk Manager of the Year Award.

Errata

Page6, the grid size of the AWRA-L model is approximately 5km, not 40km.