Hydrology & Water
Resources Symposium
12-15 November | Sydney

ENGINEERS
AUSTRALIA

National
Committee
on Water
Engineering

ISBN number for HWRS 2023 is 978-1-925627-81-7

Continuous Direct Rainfall Hydraulic Modelling with Coupled Surface / Ground Water Interaction: Real World Calibration within Oxley Creek Catchment

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ABSTRACT

Recent improvements to 2D hydraulic solvers and GPU computation continue to make direct rainfall hydraulic modelling a viable option for simulating long-term catchment wide rainfall-runoff hydrologic processes. For long-term simulations, the consideration of soil infiltration and groundwater dynamics is critical to accurately replicate the timing, magnitude, and the receding patterns of catchment runoff. This paper presents a coupled surface / ground water model using the TUFLOW HPC solver. Model validation was conducted by modelling year-long catchment runoff within the Oxley Creek Catchment, QLD, with multiple gauge recordings. The impacts of individual soil parameters on the model performance are presented in detail.

The soil thickness and porosity determine the total soil capacity, i.e., a thicker soil layer has a greater ability to attenuate surface runoff during floods and to produce larger base flow after the floods. The vertical hydraulic conductivity determines the rate of infiltration at the soil surface, while the horizontal hydraulic conductivity affects the horizontal movement of the groundwater and the recharge to the surface water. With higher horizontal hydraulic conductivity, the groundwater model can produce responsive base flow rates, which frees up soil capacity to attenuate the next flood event.

The proposed approach significantly improves the peak water level, and the receding pattern of the catchment runoff hydrograph compared to a surface water only model. The new approach may be equally applicable to short-term flood modelling and with continuous simulation of multiple flood events, as it does not require resetting the loss parameters between the rainfall events.

INTRODUCTION

There are numerous available approaches for modelling the hydrologic processes that generate catchment runoff flows from upstream rainfall. Australian Rainfall and Runoff (ARR) Book 4 (Ball et al., 2019) describes available approaches based on the spatial resolution as lumped, semi-distributed or distributed. Direct rainfall hydraulic modelling (also referred to as rain on grid modelling) is representative of a distributed assessment approach. Rainfall runoff processes are simulated using a hydraulic model for each model grid cell; based on the cell area, and the rainfall volume applied, subtracting soil infiltration losses and evapotranspiration. The surface runoff routes are generated based on the adjacent cell geometry and associated flows, groundwater infiltration (vertical) and horizontal convection.

Historically, the high computational demand associated with direct rainfall distributed modelling made the option unsuitable for long duration (multiple years) continuous simulation of a whole-catchment. GPU hardware and hydraulic modelling software advances in the past decade have dramatically improved simulation efficiency, increasing simulation speeds by over 1000 times compared to 2010 era modelling, which has alleviated the computational speed limitations. Challenges remain, in particular the modelling of soil moisture stores, the groundwater flows, and their interaction with the surface flows. The soil layer attenuates rainfall runoff by infiltrating the surface water, creating groundwater that may later recharge downstream channels, generating "base flow". A proportion of the groundwater may also infiltrate into deeper soil layers or can be removed from the soil layer via evapotranspiration, and subsequently not re-enter the surface streams at all. For long-term continuous catchment simulations, consideration of soil infiltration and groundwater movement is critical to accurately replicate the timing, magnitude, and rising and receding patterns of catchment runoff events.

This paper presents a coupled surface / ground water model using the TUFLOW HPC hydraulic solver. The surface runoff was calculated for the Oxley Creek catchment in Queensland, Australia, and the model validation was conducted with real-world gauge recordings. The modelling results affirmed the viability of the proposed modelling approach, and the impacts of individual soil parameters, such as soil layer thickness and hydraulic conductivity, on the model performance are presented in detail.

METHODS

Groundwater Model

The 2D implementation of Darcy's law has been adopted in the TUFLOW HPC solver to model groundwater movement. The vertical flux between the soil layers (Q^z) and the horizontal flux between sub-surface cells (Q^x and Q^y) are represented by the model using the equations below:

$$Q^z = -K_z \mathrm{A}, \;\; Q^x = -K_h h\theta \frac{de}{dx} dy, \;\; Q^y = -K_h h\theta \frac{de}{dy} dx \qquad (1)$$

where K_z is the vertical hydraulic conductivity (mm/hr), K_h is the horizontal hydraulic conductivity (mm/hr), A is the cell area (m^2), h is the depth of water in soil layers (m), θ is the porosity and e is the groundwater pressure elevation. For cells that are "unsaturated" the "groundwater pressure level" is exactly the groundwater elevation within that layer (see Figure 1). For cells that are fully saturated, the groundwater pressure level is that of the cell in the next layer above (or the water surface elevation if the next layer above is the surface layer). For cells that are "nearly saturated" the groundwater pressure level is transitioned between these two options. The threshold at which the transition begins is called the "groundwater blending threshold" ϕ:

$$\xi = \frac{h/dz - \phi}{1 - \phi}, \;\; e_i = (1 - \xi)(z_i - h_i) + \xi e_{i-1}, \;\; e_0 = WSE_{surface} \qquad (2)$$

where dz is the vertical thickness of the layer, z_i is the layer bottom elevation, and e_i the resulting groundwater pressure level for the layer. The surface water layer is indexed as "0", the interflow layer is "1", and any additional groundwater layers range from 2 to N, from top to bottom.

If the sum of flows into a layer cell causes it to exceed its soil capacity, the excess is pushed upwards to the next layer. If this happens for the top-most interflow layer, the excess is pushed into the surface water layer as a "return flow". This is to be expected in the creek beds but may also happen at the bottom of steep hills where the slope transitions from steep to shallow.

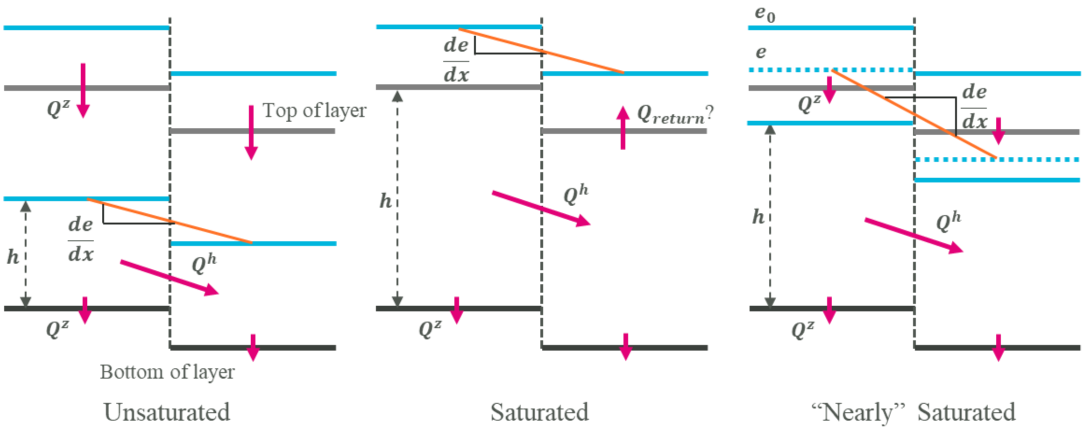

Figure 1. Groundwater fluxes and groundwater pressure gradient.

Model Input

The Oxley Creek catchment is located in the southeast of Queensland, Australia. The catchment covers an area of 260 km^2 with a mixture of rural and urban landuse. The upper catchment is predominately forest and farmland, while the lower catchment has medium density residential and industrial. The TUFLOW model files associated with the Oxley Creek Flood Study (Aurecon, 2014) has been provided by Brisbane City Council (BCC), and they have been used as the foundational dataset for the hydraulic model in this paper. Some key model updates include:

- The model extent has been expanded to include the whole Oxley Creek catchment (Figure 2).
- The model solver has been switched to the TUFLOW HPC Shallow Water Equation (SWE) solver (Collecutt and Syme 2017) and the simulations were executed using GPU hardware.
- The Sub-Grid Sampling (SGS) of terrain data was applied, as numerous research papers have been published highlighting the solution accuracy and simulation speed benefits associated with SGS (Kitts et al, 2020, Ryan et al, 2022, Huxley et al, 2022).
- The direct rainfall approach has been adopted with a coupled groundwater model.

Model Topography Data

The TUFLOW HPC catchment model has been updated using the latest available Council topography datasets. New Airborne Laser Survey (ALS) datasets added to the model include:

- 2014 Brisbane Council Digital Elevation Model (1 m resolution)
- 2017 Logan Council Digital Elevation Model (1 m resolution)
- 2019 Ipswich Council Digital Elevation Model (1 m resolution)

Bathymetry data was also updated between the Oxley Creek Mouth and Sherwood Road, based on creek cross-section survey data provided by BCC. A uniform grid size of 30 m was applied, and the sub-grid (SGS) elevations were sampled at the DEM resolution of 1 m.

Rainfall and Water Level Gauge Data

Historic rainfall and water level data at multiple gauges has been provided by BCC and the Bureau of Meteorology. The locations of these gauges are shown in Figure 2. The rainfall data was used to create the gridded rainfall input for the model. The water level record at the Oxley Creek Mouth (540274) was applied as the downstream tidal level boundary, while the rest of the water level gauges within the catchment were used for model calibration. These include 4 gauges along the main Oxley Creek channel and another 4 gauges along minor tributaries.

Three 12-month periods, 2019, 2020 and 2022, have been selected for rainfall/runoff calibration. These periods were selected based on their recency, data availability and variability of annual rainfall. 2022 is representative of an extremely wet period, while 2019 is representative of an extremely dry period. 2020 was a slightly below average year. Through calibration, the model was refined to a single, consistent set of parameters for all three periods, producing high quality calibration results at all gauge locations. However, due to the page length limitations associated with this publication, only the 2022 calibration result at 2 gauges are shown in this paper to demonstrate the impact of soil parameters. The full research is expected to be published at the end of 2023.

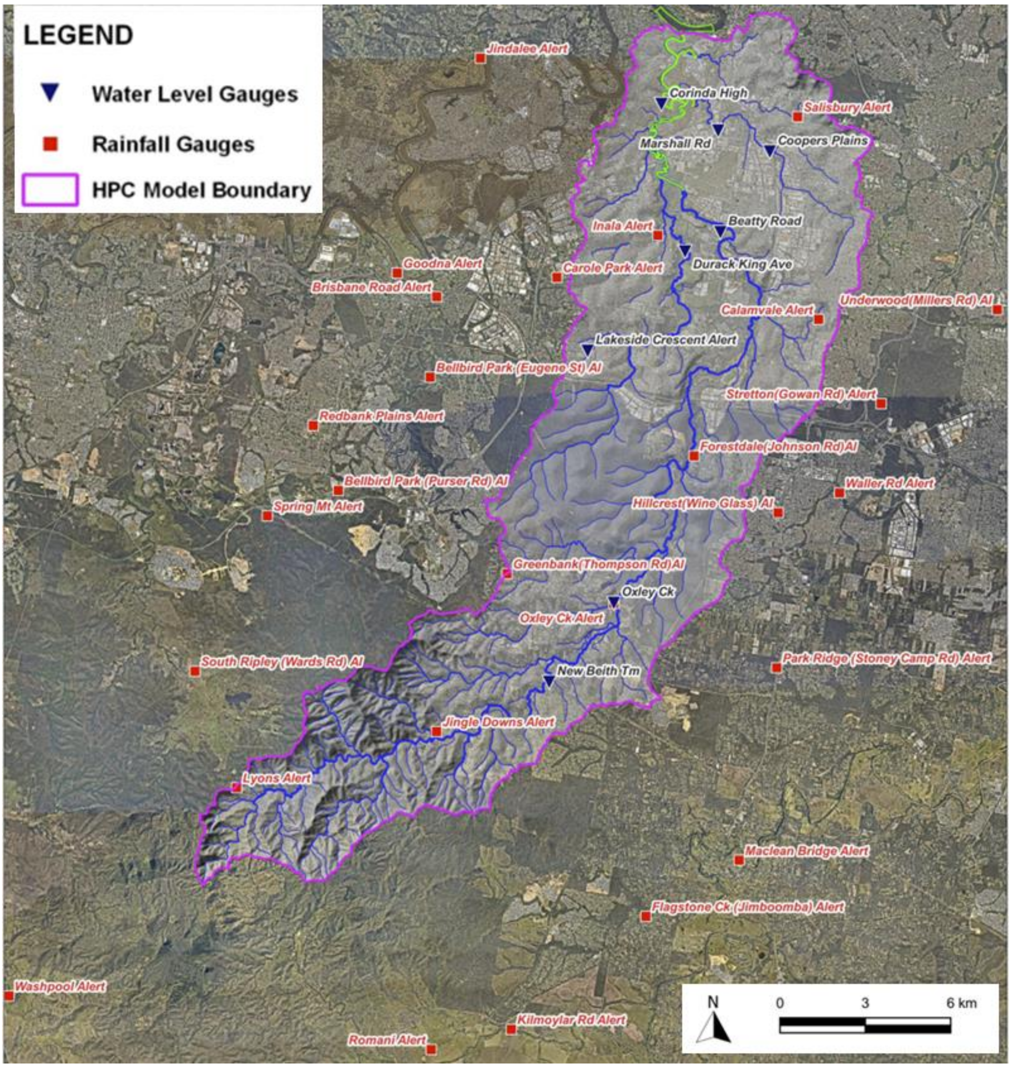

Figure 2. Rainfall and water level gauges inside and around the model domain.

Evapotranspiration

Evapotranspiration contributes to the drying of the soil between rainfall events. Changes in soil moisture affect the infiltration capacity for the subsequent rainfall event. Average monthly potential evapotranspiration data was obtained from the Bureau of Meteorology (`http://www.bom.gov.au/climate/maps/averages/evapotranspiration/?maptype=ap&period=an`) and was applied to the model, with the values ranging from 60 mm in winter months, increasing up to nearly 190 mm in summer months. In the model, when a cell is wet, the evapotranspiration applies to the surface water first. Once the cell surface becomes dry, the evapotranspiration applies to the groundwater, albeit at a lesser rate. Sensitivity testing during the model calibration found a soil evapotranspiration proportion of 20% produced model results that most reflected the recorded real-world behaviour.

Soil Paramerters

The model soil parameters were selected based on data obtained from the Australian Soil Atlas (`https://www.asris.csiro.au/themes/Atlas.html`). The predominate soil type in the catchment are hard acidic yellow (Dy3.41) and red (Dr3.41) mottled soils. The thickness of the Horizon A soil is from 0.1~0.6 m with a median value of 0.3 m (McKenzie et al, 2000). This can vary spatially, depending on many factors such as whether the 2D cell is located on the hilltop, at the bottom of the slope, or in the urbanised area. For the simplicity of the testing, one uniform thickness soil layer was applied in the model, and its thickness value was sensitivity tested.

The Green-Ampt method has been adopted as the surface water infiltration approach. Australian Soil Atlas indicates the texture of the Horizon A soil is categorized as "Sand", "Sandy Loam" or "Loam". Based on this, Green-Ampt soil porosity and suction representative of a "median texture" of "Sandy Loam" were used. The Green-Ampt hydraulic conductivity (K_{GA}) was set based on the saturated hydraulic conductivity for the Horizon A soil, which has a median value of 30 mm/hr. Sensitivity testing has been conducted assessing the model response to K_{GA} ranging from 0.3 to 100 mm/hr.

Horizontal hydraulic conductivity (K_h) in soils can be much larger than vertical, due to the soil anisotropy (Barwell and Lee 1981) and the formation of piping within the soil layer (Bell 2005). K_h sensitivity test was conducted over a wide range of 100 ~ 100,000 mm/hr. Note, numerically, the actual horizontal groundwater velocity is K_h multiplied by the groundwater slope (de/dx in equation 2), which is typically $\ll 1$.

Table 1. Range of soil parameters tested in simulation.

Parameter	Median	Tested Range
Soil thickness	0.3m	0.1 ~ 0.6 m
Green-Ampt hydraulic conductivities	30 mm/hr	0.3 ~ 100 mm/hr
Horizontal hydraulic conductivities	NA	100 ~ 100,000 mm/hr

The Australian Soil Atlas indicates the Horizon B soil type is clay, with minimal hydraulic conductivity. Considering this, Horizon B soil was neglected in the modelling. The initial soil moisture in the horizon A soil layer was set as zero and the first 30 days of the simulation was used as the "warm up period" to prime the soil layer. The rainfall-runoff processes considered in the model are illustrated conceptually in Figure 3.

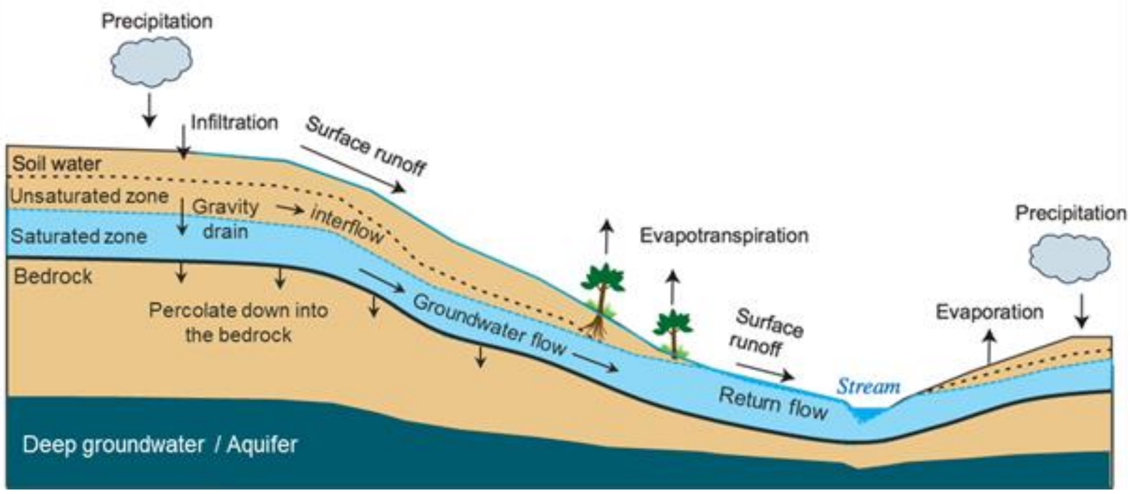

Figure 3. Illustration of the catchment runoff processes considered in this study.

RESULTS AND DISCUSSION

Horizontal Hydraulic Conductivity

Sensitivity testing of the horizontal hydraulic conductivity (K_h) was conducted using values in the range of 100 ~ 100,000 mm/hr, with the median soil thickness of 0.3 m and the Green-Ampt hydraulic conductivities K_{GA} of 30 mm/hr. Figure 4 presents the recorded and modelled water level at the New Beith water level gauge (540097). The result shows small K_h values (< 100 mm/hr) had minimal impact on the simulated hydrograph compared to the model with no soil layer. The horizontal movement of the groundwater is too slow to affect the surface runoff with such a small K_h. The impact of the groundwater parameter on surface water results becomes noticeable with K_h > 1,000 mm/hr, as demonstrated by different hydrograph receding limb patterns after the peak of the February flood. At the New Beith gauge (540097), K_h of 10,000 mm/hr produced the best replication of the recorded receding limb and base flow hydrograph characteristics. At an even higher K_h of 100,000 mm/hr, the amount of base flow reduces, and the peak water level increased during the second peak on 29th of March compared to the model with K_h of 10,000 mm/hr. Under this scenario the groundwater movement was most likely too responsive, and the soil layer was not able to retain sufficient water during the flood.

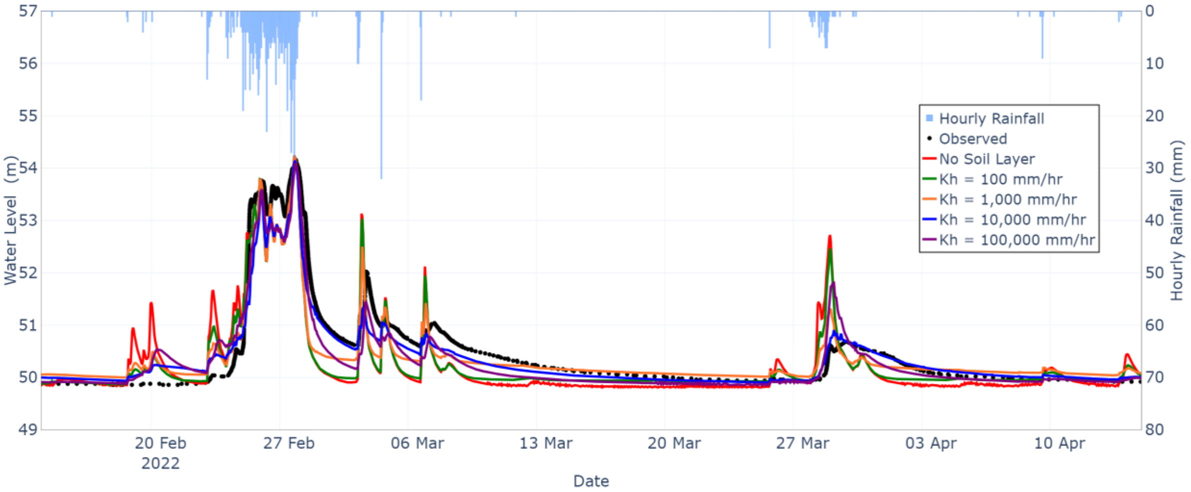

Figure 4. Recorded and modelled water level at the New Beith water level gauge (540097) with soil thickness = 0.3m, K_{GA} =30 mm/hr and K_h = 100 ~ 100,000 mm/hr.

Figure 5 presents the simulation result for the whole year of 2022. As can be seen, the peak water level and the receding limbs hydrograph shape associated with the subsequent rainfall events align well with the recorded behaviour with K_h of 10,000 mm/hr. With lower K_h or with no soil layer, the response of the simulated water level was too 'reactive' during the small to medium rainfall events. This clearly demonstrates the importance of groundwater modelling for long-term continuous simulations. The model run time was around 9.7 hours per year using an off the shelf NVIDIA GeForce RTX 4090 GPU card.

Figure 6 presents the simulation result at the Coopers Plain gauge (40791) for the same simulation period. This gauge is located on a tributary of the Oxley Creek, in an industrial/urbanised sub-catchment with the gauge located in a concrete channel. 'Rapid' water level response to the rainfall can be observed, compared to the New Beith gauge located in the upper rural catchment. The hydrograph produced with K_h of 10,000 mm/hr demonstrates too much attenuation for the small to medium rainfall events. For this sub-catchment, the model result using a smaller K_h of 100 mm/hr agreed better with the recorded results. This model behaviour was consistently observed at all rural and urbanised gauge locations. These result trends suggest the use of one soil type and thickness throughout the whole model is too simplistic, and instead separate soil parameters, including thickness and hydraulic conductivities, for urban and rural areas are necessary.

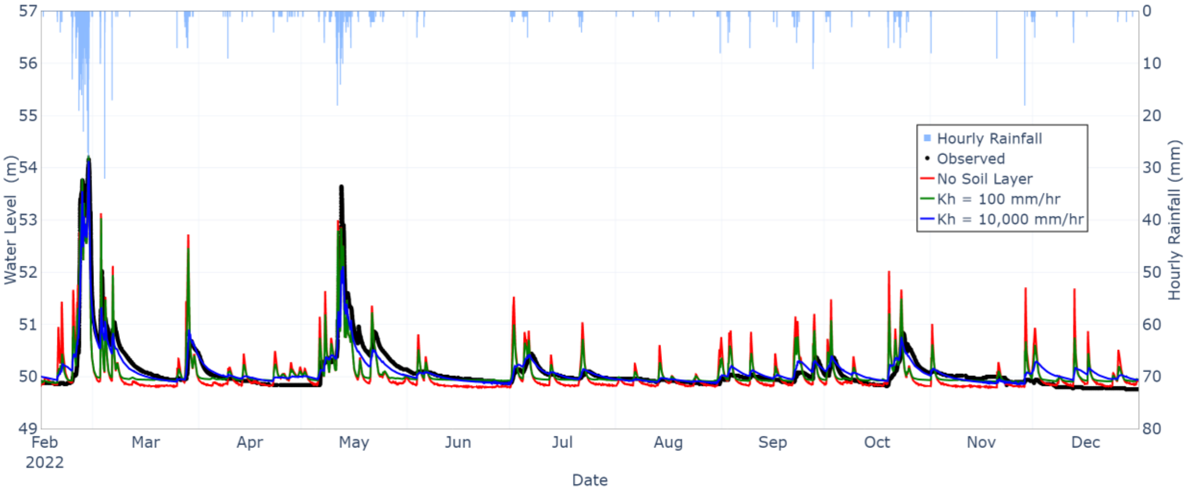

Figure 5. Recorded and modelled water level at the New Beith water level gauge (540097) for the year 2022, with soil thickness = 0.3m, K_{GA} =30 mm/hr and K_h = 100 ~ 100,000 mm/hr.

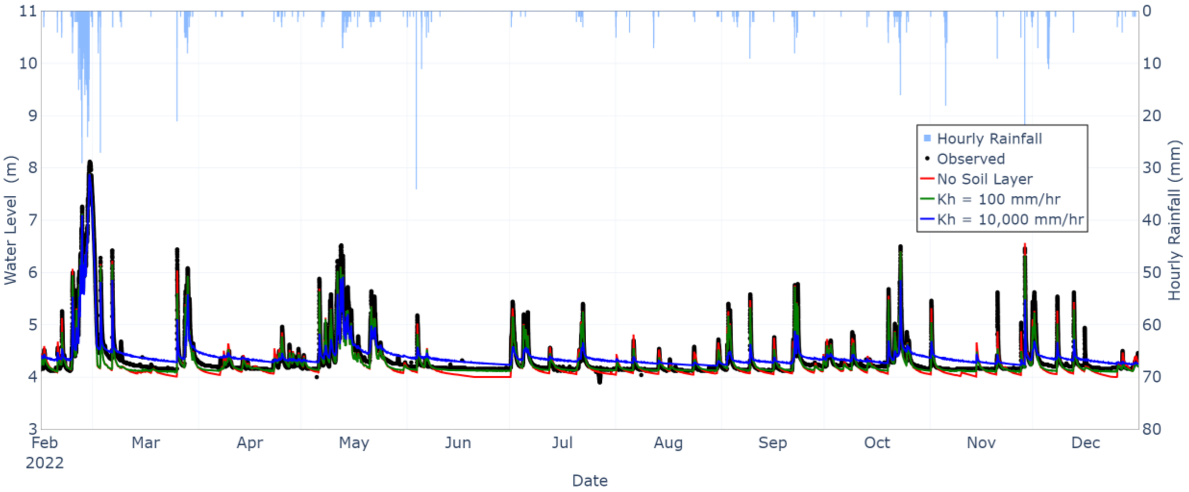

Figure 6. Recorded and modelled water level at the Coopers Plain water level gauge (40791) for the year 2022, with soil thickness = 0.3m, K_{GA} =30 mm/hr and K_h = 100 ~ 100,000 mm/hr.

Soil Thickness

In the second test, the Green-Ampt hydraulic conductivity of 30 mm/hr and the horizontal hydraulic conductivity of 10,000 mm/hr were adopted, while the soil thickness was varied from 0.1~0.6m. Figure 7 shows the recorded and modelled water level at the New Beith Water Level gauge (540097). The impact of the soil thickness on model results is as expected: a thicker soil layer offers larger soil moisture capacity to attenuate the surface runoff and to generate greater base flow volume. In general, the median soil thickness of 0.3m suggested by the Australian Soil Atlas was found to be a good estimation for setting the soil thickness parameter in this catchment.

Green-Ampt Hydraulic Conductivity

In the third test, the median soil thickness of 0.3 m and the horizontal hydraulic conductivity of 10,000 mm/hr were used, while the Green-Ampt hydraulic conductivity K_{GA} was tested between the values of 0.3 and 100 mm/hr. In the Green-Ampt infiltration method, K_{GA} decides the infiltration rate that can happen at the soil surface. As presented in Figure 8, more instantaneous surface runoff was generated when using a smaller K_{GA} during the small to medium size floods. Since the soil became saturated during the peak of 2022 February flood, the difference caused by K_{GA} is small for this large flood. Also, smaller K_{GA} produces less base flow and as such reduced flow attenuation, because of less water infiltrating into the soil layer. Under the modelled conditions, the results showed little difference when K_{GA} > 30 mm/hr, as the potential infiltration rate predicted by the Green-Ampt method exceeds the rainfall rate and the surface runoff is mainly caused by “saturation excess”.

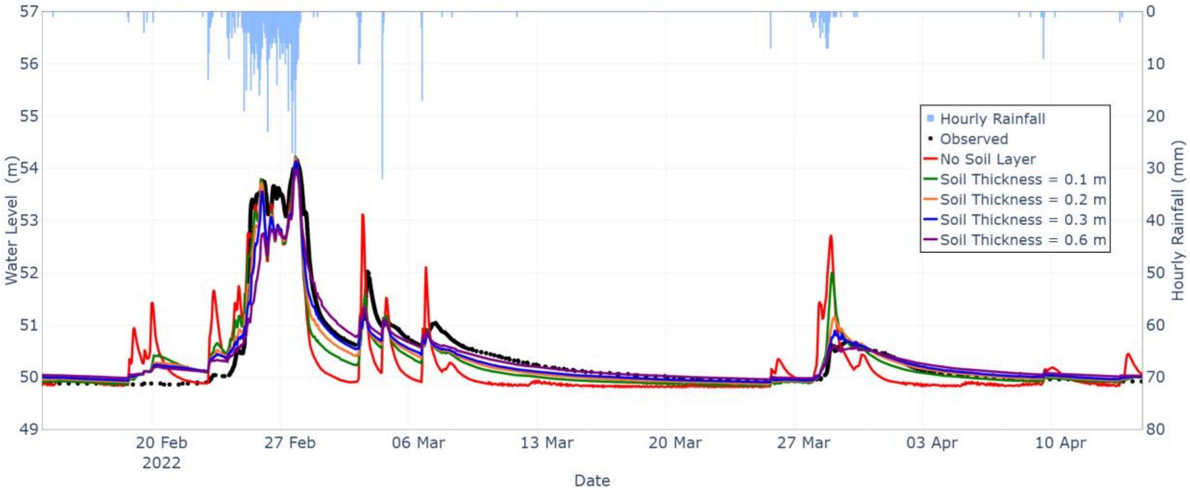

Figure 7. Recorded and modelled water level at the New Beith water level gauge (540097) with soil thickness = 0.1 ~ 0.6m, K_{GA} =30 mm/hr and K_h = 10,000 mm/hr.

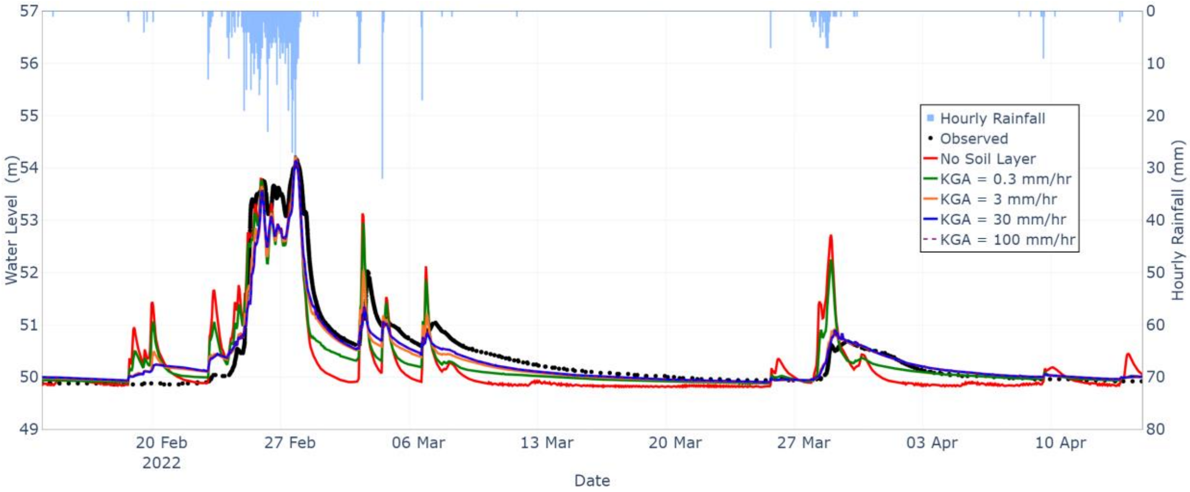

Figure 8. Recorded and modelled water level at the New Beith water level gauge (540097) for the year 2022, with soil thickness = 0.3m, K_{GA} = 0.3 ~ 100 mm/hr and K_h = 10,000 mm/hr.

CONCLUSION

This study integrated a groundwater and surface water model in the TUFLOW HPC solver to simulate the long-term catchment runoff within the Oxley Creek catchment. The model was calibrated to numerous water level gauge recordings. The impacts of individual soil layer parameters were investigated in detail during the model calibration. General findings from the parameter testing include:

- The soil thickness determines the total soil capacity. A thicker soil layer offers greater ability to attenuate surface runoff during floods and produce larger groundwater base flows after the floods. The soil thickness data sourced from the Australian Soil Atlas was found to be representative for the studied catchment.
- For the modelled catchment, the soil type has a relatively high surface infiltration rate, and it was found not to be the primary factor controlling the amount of water infiltrating into the

soil layer. The soil capacity was the primary factor controlling the quantity of water infiltrating into the soil layer.

- The horizontal hydraulic conductivity affects the horizontal movement of the groundwater and recharging of the surface water. With a higher horizontal hydraulic conductivity, the groundwater model can produce more responsive base flow rates, which subsequently frees up soil capacity to attenuate the next flood event. It also alters the receding limb shape of the surface water flow hydrograph.
- The use of one soil type and thickness throughout an entire catchment is most likely too simplistic. Separate soil parameters, including thickness and hydraulic conductivities, for urban and rural areas are needed to produce results that accurately reflect real world rainfall/runoff behaviour.

The proposed approach significantly improves the peak level/discharge, and the receding pattern of the catchment runoff hydrograph compared to the model without groundwater movement. The new approach may be equally applicable to short-term flood modelling with multiple flood events, as it does not require resetting the loss parameters between the rainfall events. It is envisaged the approach could provide valuable inputs to a wide variety of research, such as water quality and ecological modelling.

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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.

Abigail Lillo has recently joined the TUFLOW team, where she actively engages in flood modelling, provides technical support, and contributes to training. With a background in consulting, Abigail has been extensively involved in a diverse range of hydraulic and hydrologic modelling projects, including catchment-wide flood studies, site-based flood impact assessments and insurance hydrology investigations.

Chris is a Principal Engineer for BMT (TUFLOW) with over 18 years' experience in the field of flood / stormwater modelling and floodplain management. Chris is currently a senior member of the TUFLOW hydraulic modelling software development team and an Adjunct Lecturer at Central Queensland University where he teaches hydraulic modelling. Prior to his current role Chris worked in consulting and successfully completed a diverse range of projects in Australia and the USA addressing a wide range of topics: including stormwater management; infrastructure design; flood risk management; flood mitigation; land use development planning, approvals and emergency response planning.

Michael has over 25 years' experience working on environmental water quality assessments. During this time, he has successfully managed and led a wide range of environmental studies in Australia and overseas. Michael has also been actively involved in the exploitation of innovation more broadly across large organisations. Today, Michael leads water quality development within BMT Australia's Software Business. He also continues to provide advice related to innovation to the wider BMT team.

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 38 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.

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.

Blair is a Senior Flood Engineer at BMT and has experience working on large range of flood projects both nationally and internationally. He is known for his deep technical knowledge of flood hydrology and hydraulics. His skillset has led him to delivering quality work in regard to challenging catchment scale models, developing innovative hydrologic techniques, and supporting flood forecasting systems.