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Modelling the frequency and extent of waterlogging: a case study

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Abstract: Waterlogging in soils due to the formation of perched water tables is a significant issue within the Australian landscape, resulting in annual crop losses of $300M. The ability to predict the timing and extent of waterlogging enables the formulation of adaptation and mitigation strategies, including land forming, surface and sub-soil drainage, soil management, crop selection and management, genetic breeding and combinations thereof for enhanced waterlogging tolerance. Assessing these options to increase agricultural production under varying agroclimatic conditions requires the creation and application of a spatiotemporal modelling framework that accounts for the complex interactions between landscape hydrology, soil properties and plant dynamics.

To assess the frequency and duration of waterlogging, a pseudo three-dimensional modelling framework was developed that accounts for landscape position and hydrological connectivity whereby upslope management units connect to adjacent downslope units. The novel aspect of the framework is the integration of farming system models that simulate daily soil-water-crop interactions with a hydrologically connected surface element network, enabling application across varying scales, from farm to sub-catchment to basin.

The current study aimed to evaluate the impact of landscape position on the establishment of perched water tables and the influence of runoff and sub-surface lateral flow on crop function. To quantify this impact, several field sites were established in south-west Victoria, Australia, to measure water tables under a wheat crop. The experiment monitored climate, soil moisture and crop growth indicators in upslope, mid-slope and downslope plots. Simulations reasonably matched measured waterlogging dynamics given the broad scale soil and slope attribution with root mean square values ranging from 0.68 to 0.81 in contrast to values of less than 0.45 with no accounting for landscape connectivity.

The model was applied to evaluate the potential yield loss from waterlogging for the period 1990 to 2024 within a 5,536 ha catchment in south-west Victoria. Results suggest that waterlogging reduces crop yield by 20% in 7 out of 10 years at the focus sites depending on landscape position. Downstream infiltration of upstream runoff had a positive impact on crop yield during dry climate conditions and a negative impact during above-average rainfall, during the growing season.

A key finding from the study was the validation of the hydrologically connected biophysical model and the robustness of the terrain analysis underpinning the creation of the surface element network. The adopted modelling framework is generic and provides a foundation to assess the extent and duration of waterlogging on crop growth and yield losses. Currently the model is being used to identify the extent of waterlogging and cost-effective mitigation options (land forming, surface drains, sub-surface drains, cultivar and time of sowing) at the land management scale.

Keywords: *Hydrological connectivity, waterlogging, shallow water tables*

1. INTRODUCTION

Waterlogging is estimated to cost Australian grain growers $180M annually (Pang et al. 2004) with annual crop losses of $300M (Manik et al. 2019) and up to USA$3B globally by 2030 (Kaur et al. 2020). Within the high rainfall zone of Australia, it is estimated that 70% of soils are susceptible to waterlogging (MacEwan et al. 1992). To manage waterlogging in such environments, it is recognised that there is a need to improve our ability to assess the interactions between different management practices, soil type and severity of waterlogging (Manik et al. 2019). However, contemporary process-based farming system models typically used to predict such interactions are one-dimensional, poorly describing the yield loss from excessive rainfall and overestimating yield under wet conditions (Li et al. 2019). As these models are point-based, they are appropriate for temporal analyses but have limited scope for capturing spatial implications of waterlogging, particularly where soils are variable (Liu et al. 2023). To simulate water flow across different areas of the landscape requires the application of biophysical models that account for hydrological connectivity (Bracken and Croke 2007). One such model is the three-dimensional HYDRUS 3D (Šimůnek et al. 2018). An alternative approach is to disaggregate the landscape into units based on terrain analysis and solve daily water balance and vegetation dynamics within each unit sequentially. Such an approach relies on the creation of a contour-based surface element network and a physics-based soil-water-plant model that considers not only runoff but also runon and subsurface lateral inflows. The surface element network must be compiled in such a way that upslope landscape units are solved before solving downslope adjacent units.

This paper describes the development and application of a hydrologically connected suite of farming system models to quantify the amount and timing of soil waterlogging within the high rainfall zone of south-west Victoria. The approach to landscape disaggregation is based on concepts adopted by TOPOG (O'Loughlin 1986), where contours are intersected by orthogonal flowpaths to create varying size surface elements, and those concepts underpinning a wetness index (Beven and Kirkby 1979), terrain analysis (Beverly and Croton 2002), and flow accumulation analysis. The current study applied the developed framework to assess the impact of landscape position on perched water tables within a continuous winter wheat cropping system.

2. METHOD

2.1. Field sites

The study region focuses on waterlogging-prone, soil texture contrast soils (e.g., heavy clay duplex soils) in south-west Victoria with a mean annual rainfall of less than 800 mm/yr. In 2017 and 2018, three experimental sites were established. The sites were located at Glenthompson, Hamilton and Tatyoon (Figure 1) and all sites were sown to wheat. Within each site, three locations were selected to monitor soil water and crop response within representative upper, middle and lower parts of the respective catchments. For brevity, this paper will only report on the Glenthompson study.

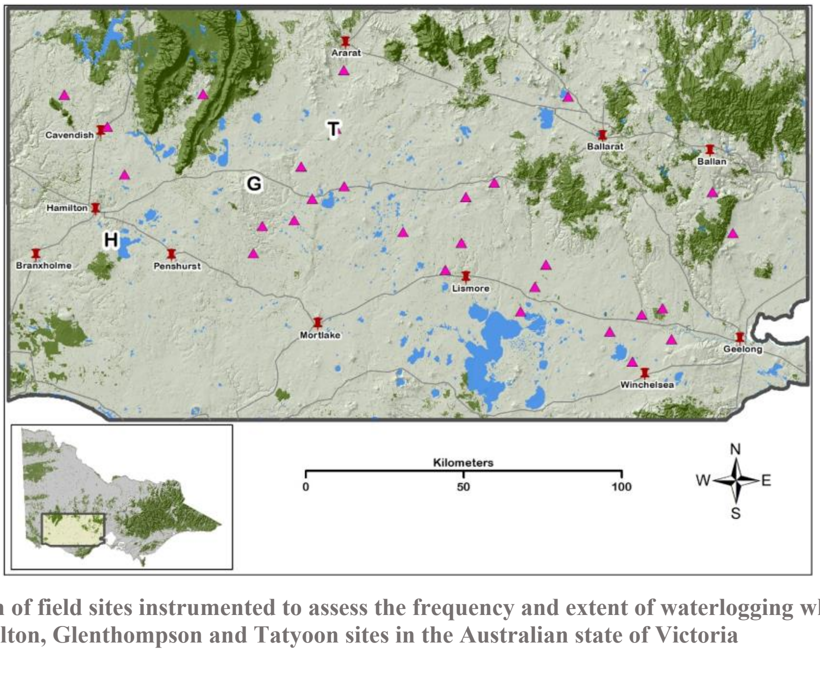

Figure 1 Location of field sites instrumented to assess the frequency and extent of waterlogging where H, G and T refer to the Hamilton, Glenthompson and Tatyoon sites in the Australian state of Victoria

2.2. Derivation of surface element network

To support and extrapolate findings from field monitoring, a hydrologically connected model was developed that relied on the creation of a surface element network using readily available terrain analysis tools. The hydrologically connected surface element network describes and assembles the ordering from upslope to downslope connected cells to enable the simulation of topographically derived water and nutrient transport processes. The topographical elements are further disaggregated by soil, climate and land use/management. The dominant soil type was sourced from the Australian Soil Resource Information System (ASRIS) http://www.asris.csiro.au/themes/Atlas.html and described using a Northcote (1979) classification, attributed using the 50th percentile predictions of soil properties described in McKenzie et. al (2000); historical climate was sourced from gridded 0.05° (~5km) SILO DataDrill (https://www.longpaddock.qld.gov.au/silo/about/).

The hydrologically connected network ensured continuous water flow through drainage basins by filling sinks in the DEM to create a depressionless surface. Slope and aspect rasters were generated to characterise terrain steepness and downhill direction. A flow direction raster was then produced using the D8 method, followed by flow accumulation to quantify the upstream contributing area for each cell. Using the flow direction and flow accumulation layers, hydrologically contained units, or drainage basins, were delineated to define the contributing area for each outlet point. The flow accumulation was subsequently log-transformed and banded to classify levels of landscape-water channelling. This final map product is a surrogate for contour-based surface elements such as those used by TOPOG (O'Loughlin 1986). Figure 2 shows an application of the approach when applied to the Glenthompson study region using a 10 metre DEM. Importantly, the workflow is dynamic, with the spatial resolution of the input DEM tailored to the analysis scale as the spatial resolution of the elevation data directly affects the unit size of the resultant surface element network: high-resolution DEMs for fine-scale assessments of landscape modifications (e.g., raised beds or levee banks), while coarser-resolution DEMs for broader-scale hydrological evaluations, such as regional waterlogging risk assessments.

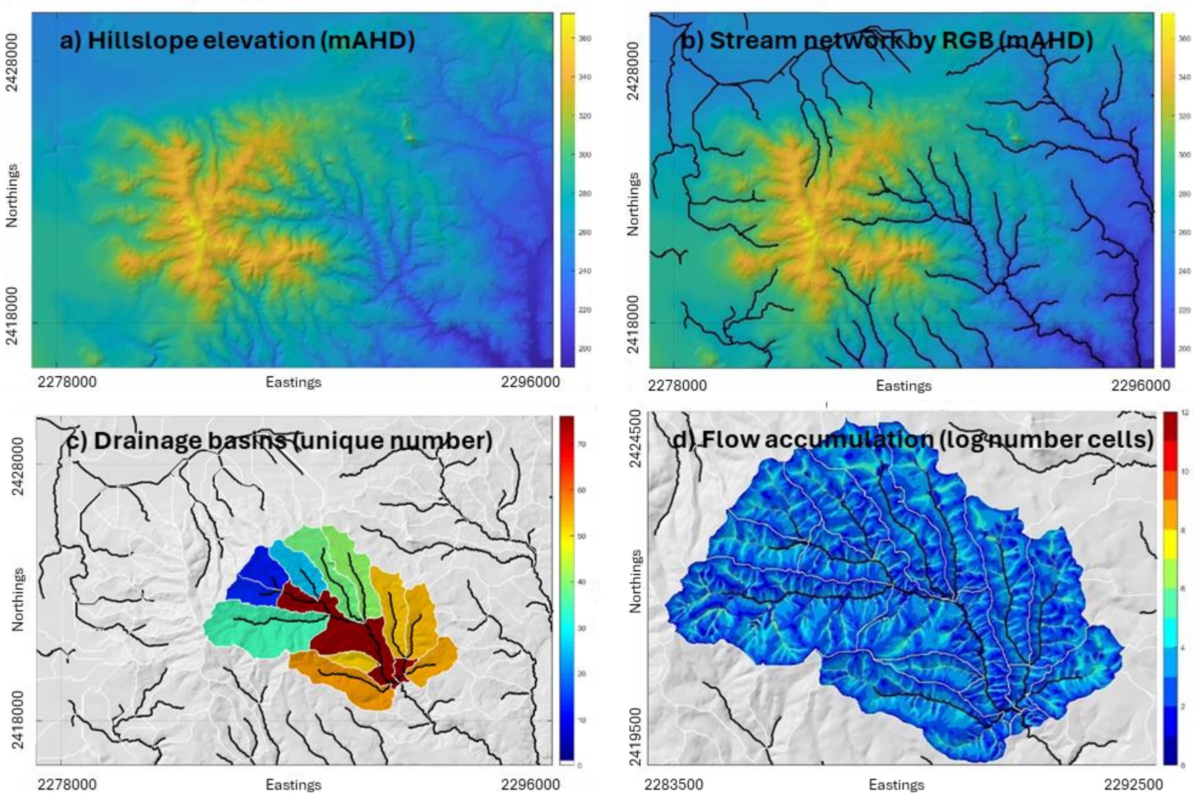

Figure 2 DEM, stream network, drainage basins and flow accumulation of the Glenthompson study region

2.3. Modelling the frequency and extent of waterlogging

The simulation of soil-water-plant-management was undertaken using the Catchment Analysis Tool (CAT), comprised of a range of farming system models of varying complexity, that account for water and nutrient transport between solution points (Beverly et al. 2005). Model simulation is performed on a daily timestep.

Daily plant growth is simulated using various vegetation growth models selected based on the spatially assigned land use, model complexity as nominated by the user, and data availability. All plant growth models predict plant phenology, leaf area and dry matter accumulation, and decay using functions of transpiration, transpiration efficiency, potential evaporation, radiation use efficiency, photosynthetically active radiation, leaf area index, daily temperature and photoperiod. Plant growth is modified by nutrients, water, and temperature stresses. In this study the wheat crop module was based on CropSyst (Stockle et al. 1994).

Soil water is updated daily by throughfall (rainfall less interception, soil evaporation and transpiration), irrigation and upslope runon and sub-surface lateral flows. Runoff from an upslope cell is calculated as a function of rainfall, water deficit, a retention parameter and a curve number (Knisel 1980) where the curve number accounts for surface roughness as a function of surface cover and crop cover. Daily runoff and sub-surface lateral flow from upslope cells are used as inputs to downslope cells.

Water redistribution within a soil column is calculated using a linear cascading technique where each modelled soil layer is represented as a bucket (Littleboy et al. 1992). Water moves from one layer to an adjacent lower soil layer when soil water exceeds field capacity at a rate based on saturated soil hydraulic conductivity. In the case of a soil layer with restricted drainage, the algorithm allows infiltration to be routed upwards towards the soil surface. Excess water at the soil surface (exfiltration) is added to runoff, whereas drainage of water from the lowest profile layer is assumed to be deep percolation. In this study, waterlogging was calculated as the sum of excess water in the top 30 cm (SEW_{30}) as defined by Sieben (1964) where excess water is soil water (mm) above drained upper limit.

2.4. Accounting for waterlogging impacts on crop yield at the catchment scale

Measured crop yields at all field sites were supplemented with results reported by Setter (2000) to derive a yield loss function describing the decline in crop yield with increasing levels of SEW_{30}. The fitted function assumed that wheat yield decline was not observed until the growing season SEW_{30} exceeded 280, after which declines of 50%, 70%, 80% and 93% were observed at SEW_{30} values (cm.days) of 920, 1400, 2000 and 2800 respectively. This function was used to estimate the level of crop yield loss within the study catchment under varying climates.

3. RESULTS

Model calibration was based on matching observed waterlogging for each measurement location at all three sites over two years.

Figure 3 shows the time-series comparison of observed and simulated water tables for the Glenthompson site, whereas Table 1 reports SEW_{30} results with and without landscape connectivity. Simulations reasonably matched measured waterlogging dynamics given the broad scale soil and slope attribution with root mean square (RMS) values of 0.81, 0.75, 0.72 for the upslope, mid-slope and downslope 2017 trial sites and 0.68, 0.72, 0.78 for the upslope, mid-slope and downslope 2018 trial sites. These results are an improvement on RMS values of less than 0.45 derived assuming no landscape connectivity.

To assess the frequency of waterlogging under varying climates at each focus site, simulations were undertaken for the period 2000 to 2024 using historical weather data. Results summarised in Figure 4 clearly show the impact of landscape position, with upslope sites having less waterlogging than downslope sites. Notably, crop limiting waterlogging did not occur in all years; however, 15 of the 20 years did record days with SEW_{30} values of greater than 600 cm.days.

To quantify the amount and timing of soil waterlogging at the catchment scale, the model was applied to the Glenthompson catchment within the high rainfall zone of south-west Victoria. The catchment area is 5,536 ha, includes 75 sub-catchments, and was disaggregated into 0.4 ha units. Simulations were undertaken for the period 2000 to 2024 using historical weather data and crop yields compiled for each growing season. Given that the biophysical wheat crop model does not account for waterlogging impacts on crop growth and recovery, the impacts of waterlogging were calculated by applying the derived fitted wheat yield decline function reported in Section 2.4 to the predicted crop yields. Simulations suggest that in 80% of years the catchment experiences a 13% yield loss due to waterlogging, and that yield losses of 60% occur in 12% of years (Figure 5).

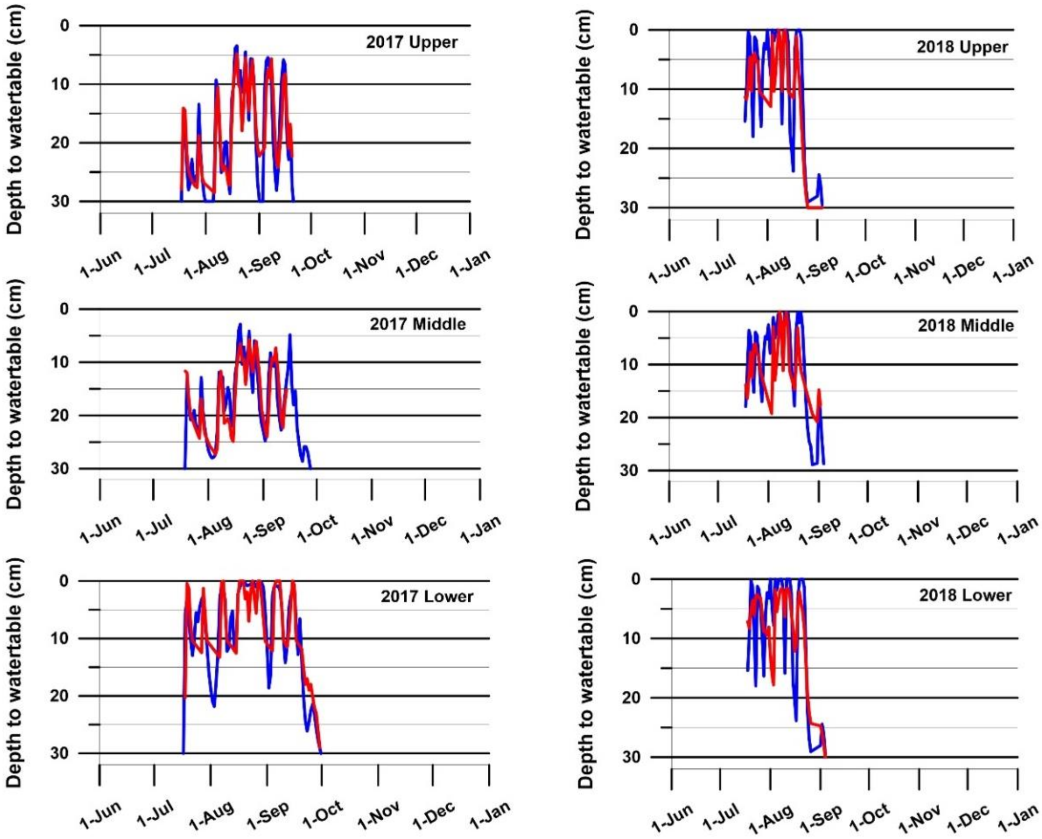

Figure 3 Depth to water table comparison between measured (blue line) and simulated (red line) for the upslope (upper), mid-slope (middle) and down slope (lower) locations for the two years of measurement at the Glenthompson site

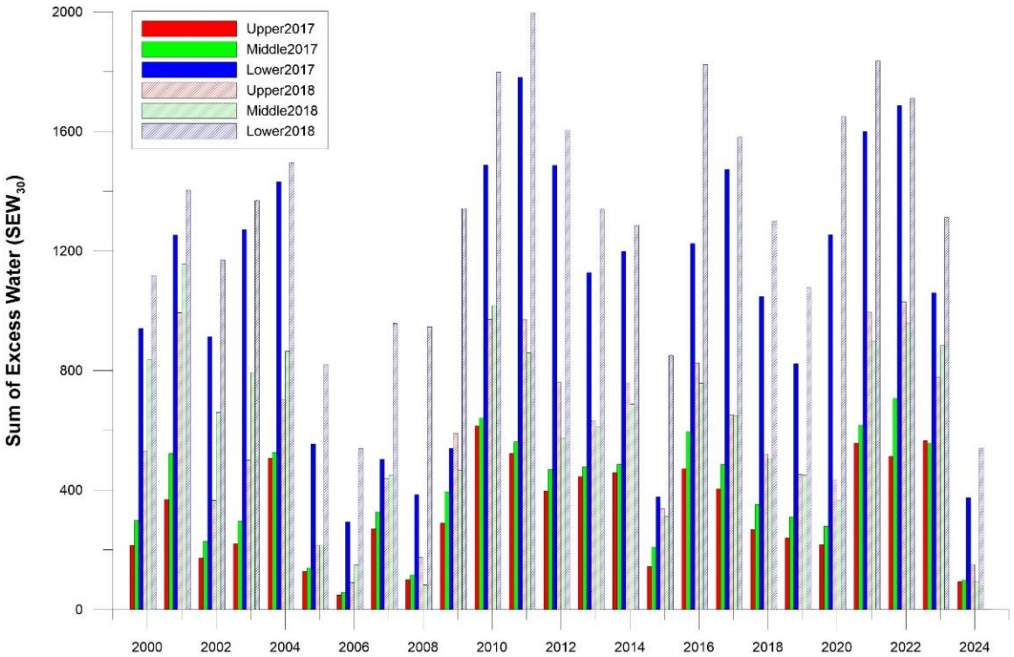

Figure 4 Sum of excess water (cm/yr) for years 2000 to 2024 at Glenthompson field plots

Table 1 Comparison of measured and simulated sum of excess water (cm) in the top 30 cm (SEW_{30}) over each season

Location	2017			2018		
	Measured	Simulated (without connectivity	Simulated (with connectivity)	Measured	Simulated (without connectivity	Simulated (with connectivity)
Upper	742	542	726	921	659	884
Middle	880	673	901	941	743	968
Lower	1583	1221	1592	1402	934	1152

4. DISCUSSION AND CONCLUSIONS

Results from this study demonstrate that the developed modelling framework can predict the impact and frequency of waterlogging at scales ranging from paddock to catchment. Because the framework is based on a connected surface element network, it could be generically adapted to any location with readily available spatial data and topographic tools.

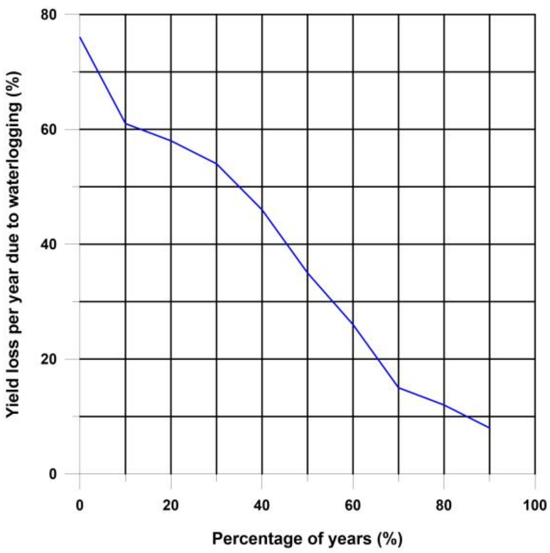

Figure 5 Yield loss as a function of years for the Glenthompson catchment

The yield loss function reported in Section 2.4 is drawn from previous field trials supplemented with measured data from this study. It is acknowledged that prediction results are sensitive to this function. To better account for cultivar and environment, enhanced process descriptors are required for inclusion into physics-based models to simulate the impact of reduced soil aeration on root performance, root architecture, crop growth rate and phenology, nutrient uptake dynamics and radiation use efficiency. These enhancements would negate the need to apply the derived fitted wheat yield decline function that accounts for waterlogging condition (Section 2.4). Future experimental design aimed at addressing this knowledge gap would need to evaluate the degree of plant damage resulting from the timing and duration of waterlogging during plant phenostages (Setter 2000; Setter and Waters 2003; Marti et al. 2015), the depth of waterlogging and the redox status of the soil (Patrick et al. 1985; Setter 2000).

Prediction reliability is sensitive to soil hydraulic characteristics and slope. Whereas the derivation of slope at the landscape scale can be improved through the use of LIDAR and other high resolution topographic data sets, accurate soil hydraulic characterisation through depth can be problematic. The causes of the differences in RMS between observed and modelled water table depth is attributed primarily to the spatial variability in soil hydraulic characteristics. Sensitivity analysis identified saturated soil hydraulic conductivity and available soil water above field capacity as being key soil parameters most impacting model predictions.

The impact of waterlogging on plant growth is complex. In cereals, grain production is greatly affected by the growth stage of the plant at the time of waterlogging and the ability of the plant to recover. The model presented in this paper is being used to identify the extent and timing of soil waterlogging across catchments at the land management scale. Coupled with estimates of intervention costs associated with land forming, installation of surface and sub-surface drains and crop management (including variety and time of sowing), model predictions are being used to guide where and when to undertake targeted management strategies to minimise crop yield losses.

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