Rain-on-grid modelling of flood peak desynchronisation and attenuation to inform tributary roughness rehabilitation for Natural Flood Management (NFM)

Mehran Khan[1], Kirstie Fryirs[1] and Lucy Marshall[1,2]

1 School of Natural Sciences, Macquarie University, Wallumattagal campus, North Ryde, NSW, 2109. Email: mehran.khan1@hdr.mq.edu.au

2 The University of Sydney, Camperdown, NSW, 2050, Australia

Key points

- Increasing tributary channel roughness through riparian vegetation rehabilitation reduces peak flood depth at tributary–trunk confluences in the Hunter River catchment.
- Targeting roughness adjustment in certain upstream tributaries achieves greater flood attenuation (7.9% peak reduction) than treating all tributaries uniformly (3.9%), demonstrating that the spatial position of intervention matters.
- Rain-on-grid 2D hydraulic modelling is an effective tool for evaluating Natural Flood Management (NFM) scenarios at large catchment scales.
- Flood peak desynchronisation through tributary roughness manipulation may be achievable, but its magnitude is event-dependent and requires catchment-scale implementation.

Abstract

Natural Flood Management (NFM) through catchment roughness rehabilitation offers a nature-based approach to reducing flood peaks by desynchronising tributary and trunk stream flow contributions. This study investigates the potential of manipulating tributary roughness to achieve flood peak desynchronization and/or attenuation in the Hunter River catchment, New South Wales, Australia. A two-dimensional (2D) rain-on-grid hydraulic model was developed in HEC-RAS 7.0 using observed gridded rainfall data from the March 2022 major flood event (observed peak water level 13.16 m at the Singleton gauge). The model was calibrated primarily to replicate peak flood stage height, which is the most commonly used metric for flood warnings and flood hazard assessment in large catchments. The calibrated model reproduced the observed peak of 13.16 m with a 7.1% error (simulated peak 12.23 m) and a Nash-Sutcliffe Efficiency of 0.611. Two NFM scenarios were simulated by adjusting riparian vegetation roughness: (1) a scenario where the Manning's n roughness of all tributaries was increased from the calibrated base n = 0.060 to n = 0.100, representing more uniform riparian revegetation strategy; and (2) a more targeted scenario where roughness was only increased in tributaries upstream of Denman to n = 0.180, representing more dense riparian revegetation strategy. Results show that the targeted scenario (2), which treated fewer tributaries more densely, achieved a 7.9% peak water level reduction at the Wollombi Brook–Hunter River confluence, compared with 3.9% for the more uniform scenario (1). The uniform scenario also produced a 3-hour delay in peak timing, indicating the possibility of flood peak desynchronisation. These findings demonstrate that the spatial positioning of NFM interventions within a catchment is a critical determinant of effect downstream, with upper catchment roughness rehabilitation providing disproportionately greater flood attenuation per unit of intervention.

Keywords

Natural flood management; flood desynchronisation; attenuation; HEC-RAS; rain-on-grid; Hunter River; riparian vegetation; tributary-trunk confluence

Introduction

Flooding is one of the most destructive natural hazards in Australia, causing significant economic losses and social disruption. The Hunter River catchment in New South Wales has experienced repeated major flood events, including the March 2022 event, which reached 13.16 m at the Singleton gauge (Fryirs et al., 2023). Traditional flood mitigation approaches have focused on hard-engineering solutions such as levees and detention basins. However, there is growing recognition among catchment managers and policy makers that nature-based approaches can be used to achieve Natural Flood Management (NFM), and provide complementary and more sustainable reductions in flood risk by modifying catchment hydrological processes (Burgess-Gamble et al., 2017).

NFM strategies that increase channel and floodplain roughness, through riparian vegetation rehabilitation, large woody placement, and leaky barriers, can be used to slow the movement of water through catchments (Prinsley et al., 2025). This can desynchronise flood peaks from different tributaries as they arrive at trunk stream confluences (Lane, 2017). When tributary peaks arrive at different times rather than simultaneously, the combined downstream flood peak is lowered (attenuated), a process termed flood peak desynchronisation (Metcalfe et al., 2018; Wilkes et al., 2019). In practical terms, this means that well-positioned roughness treatments can reduce the stage height during a major flood, thereby reducing the area that becomes inundated.

While NFM principles are well established, their application at large catchment scales (greater than 1,000 km^2) remains poorly quantified (Dadson et al., 2017). The Hunter River catchment, at approximately 22,000 km^2, presents both a significant management challenge and an opportunity to test whether catchment-scale roughness rehabilitation can be modelled and provide an option to meaningfully influence large flood events. A critical but understudied question at large catchment scales is whether the spatial position of upstream interventions, versus distributed interventions, affect the magnitude of flood attenuation. .

This study tests this question using a calibrated 2D rain-on-grid hydraulic model of the Hunter River catchment. Two NFM scenarios with contrasting spatial configurations of tributary riparian roughness rehabilitation are evaluated against a calibrated baseline. Changes in flood peak stage height and timing at the Wollombi Brook–Hunter River confluence upstream of Singleton are assessed. The results provide guidance on where roughness rehabilitation could potentially deliver the greatest benefit for flood peak attenuation.

Study area and 2022 flood in the Hunter catchment

The Hunter River catchment drains approximately 22,000 km^2 of eastern New South Wales, Australia, as shown in Figure 1. The main Hunter River rises in the Great Dividing Range and flows approximately 470 km to its tidal limit near Maitland before entering the sea at Newcastle. Major tributaries include the Goulburn River, Pages River, Wybong Creek, and Wollombi Brook, each draining sub-catchments of varying size and land use. Decades of land clearing, stream channelisation, and removal of in-stream wood have caused riparian and floodplain degradation that has significantly reduced natural channel roughness compared to pre-European conditions (Fryirs et al., 2018).

The March 2022 flood event, which forms the basis for model calibration and scenario testing, was one of the most significant on record at the Singleton gauge. Sustained rainfall from 2–16 March 2022 produced catchment-average totals exceeding 200 mm across much of the upper catchment. The Hunter River at Singleton reached a peak water level of 13.16 m at 18:00 AEST on 9 March 2022, well above the major flood level. The event caused extensive inundation of agricultural land and significant damage to infrastructure across the lower Hunter Valley.

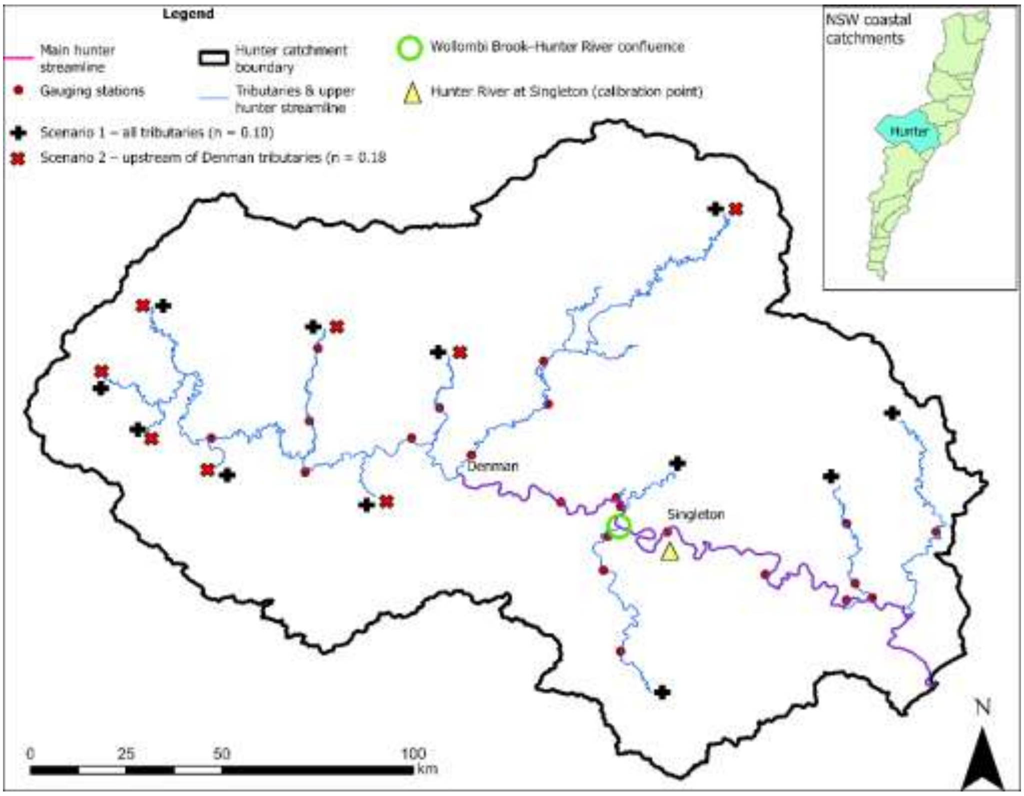

Figure 1 Location of the Hunter River catchment and scenario tributaries

Methods

2D rain-on-grid hydraulic model

A 2D unsteady flow hydraulic model was developed in HEC-RAS 7.0 (U.S. Army Corps of Engineers, 2026) using the rain-on-grid approach, whereby spatially distributed gridded rainfall is applied directly to the 2D computational domain as shown in Figure 2. The model domain encompasses the full Hunter River catchment, discretised at a 500 m computational mesh resolution. The terrain was derived from the 5 m resolution Digital Elevation Model (DEM) sourced from NSW Spatial Services (https://www.data.nsw.gov.au).

Gridded hourly rainfall data for the March 2022 flood event were derived from the Bureau of Meteorology (BOM) (http://www.bom.gov.au) for 17 gauges located within the Hunter River catchment (Figure 1). A Python-based inverse distance weighting (IDW) algorithm was applied to spatially interpolate the 17-gauge point rainfall observations onto a continuous precipitation grid at 500 m spatial resolution, matching the HEC-RAS computational mesh extent and cell size. The interpolated rainfall fields were first exported in NetCDF format. Subsequently, they were converted to HEC-DSS (Data Storage System) format before being imported into HEC-RAS 7.0 as the precipitation boundary condition for rain-on-grid modelling.

Manning's roughness coefficients were assigned spatially to the 2D computational mesh by intersecting land cover classes downloaded from the Sharing and Enabling Environmental Data in NSW (SEED) portal (https://www.seed.nsw.gov.au). Each land cover class was assigned a Manning's n value based on the (Te Chow, 1959) lookup table. The calibrated main channel roughness was n = 0.055, and the tributary roughness was n = 0.060, consistent with natural winding channels with moderate bank vegetation (Te Chow, 1959).

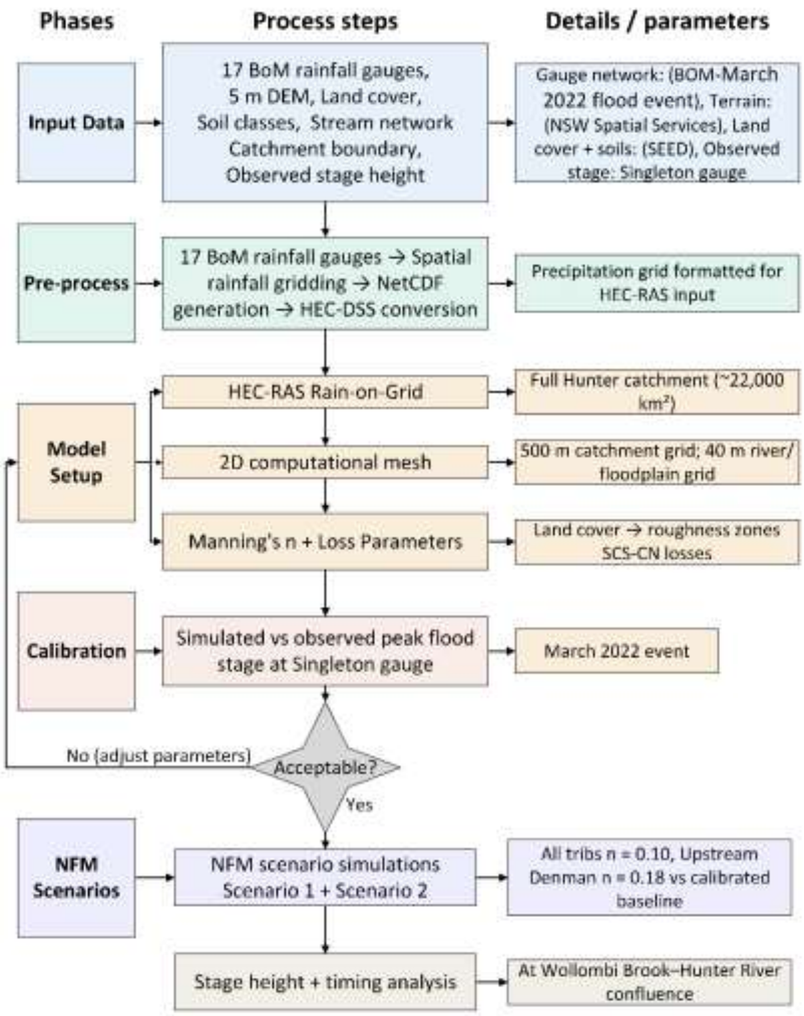

Figure 2 Methodology flowchart for the HEC-RAS 2D rain-on-grid NFM modelling

Rainfall loss parameters were defined using the SCS Curve Number (CN) method. Spatially distributed CN values were derived by overlaying the land cover classification with the Hydrologic Soil Group (HSG) layer, also obtained from the SEED portal, and assigning CN values using the standard lookup table from the NRCS National Engineering Handbook (M Robinson et al., 2007). An Initial Abstraction ratio of 0.05 was applied, reflecting pre-saturated Antecedent Moisture Condition III conditions following six days of antecedent rainfall before the event (Ball et al., 2016). Minimum infiltration rates were assigned based on HSG classification as recommended in the HEC-RAS 2D User's Manual (U.S. Army Corps of Engineers, 2026), ranging from 7.6 mm/hr for Group A soils (high infiltration capacity) to 2.3 mm/hr for Group B soils, 0.8 mm/hr for Group C soils, and 0.5 mm/hr for Group D soils (very slow infiltration capacity).

Model calibration

The model was calibrated against the observed stage height hydrograph at the Hunter River Singleton gauge for the March 2022 event (2–16 March 2022), focusing on peak flood stage replication rather than full hydrograph shape matching, as peak stage is the dominant control on BOM flood warnings and hazard assessment in large catchments (Bates et al., 2010). The calibrated model reproduced the observed peak of 13.16 m within 7.1% error (simulated peak 12.23 m), with an NSE of 0.611 and a peak timing error of 12 hours (Table 1). The residual underestimation is attributed to the temporal resolution of the gauge-interpolated rainfall grid, a well-documented limitation for large catchments (Ball et al., 2016), but is sufficient for the comparative scenario analysis, where the key metric is the relative change in peak stage height between scenarios.

Table 1 Model calibration performance metrics for the March 2022 flood event at the Hunter River Singleton gauge

Calibration Metric	Value
Observed Peak Stage Height (m)	13.16 m
Simulated Peak Stage Height (m)	12.23 m
Peak Stage Error (m)	−0.93 m
Peak Stage Error (%)	7.1%
Nash–Sutcliffe Efficiency (NSE)	0.611
Peak Timing Error	12 hours
Calibration Period	2–16 March 2022
Calibration Gauge	Hunter River at Singleton

NFM scenario design

Two NFM roughness scenarios were tested (Figure 2). Scenario 1 (Low NFM: All tributaries) tests a uniform increase in riparian vegetation roughness (defined here as a 30 m buffer on either side of the channel bank) across all tributaries. For this scenario, Manning's n roughness was increased from n = 0.060 to n = 0.1. Scenario 2 (Targeted NFM: Upstream of Denman) is a more targeted strategy whereby the increase in riparian vegetation roughness was applied only in tributaries upstream of Denman and for a higher level of roughness. Manning's n roughness was increased to n = 0.180. All other parameters were held at baseline values for both scenarios. Model outputs were extracted at the Wollombi Brook–Hunter River confluence (Figure 1) to assess changes in peak stage height and timing relative to the calibrated 2022 flood baseline.

Results

Baseline model performance

The baseline model produces a stage height of 5.04 m at the Wollombi Brook–Hunter River confluence on 9 March 2022 at 01:00 AEST (Figure 3). The hydrograph shows a gradual rise from 2 March, a secondary peak of approximately 1.9 m associated with the 4–5 March rainfall, recession through 6 March, a renewed rise through 7–8 March, and the primary flood peak on 9 March. This multi-pulse behaviour is consistent with the successive rainfall events over the 14-day simulation period, reflecting the progressive accumulation of catchment moisture and the multi-tributary nature of flood generation in the Hunter system.

Scenario 1: All tributary riparian vegetation rehabilitation

Increasing all tributary roughness to n = 0.1 produced a peak stage height of 4.85 m, a reduction of 0.19 m (3.9%) relative to the baseline of 5.04 m (Table 2). Critically, the peak timing shifted approximately 3 hours later, from 09 March 01:00 to 09 March 04:00. This timing shift could represent measurable flood peak desynchronisation, which is the increased tributary roughness slowing the translation of flow through tributary channels, causing tributary peaks to arrive at the confluence at slightly different times and reduce the combined peak magnitude. The recession limb in Figure 3 shows a slightly elevated stage height relative to baseline following the peak, reflecting the slower drainage of attenuated tributary flows through the treated channels.

Scenario 2: Targeting tributaries upstream of Denman only

Increasing roughness of the tributaries upstream of Denman, only to n = 0.180 produced a peak stage height of 4.65 m, representing a reduction of 0.39 m (7.9%) relative to baseline, more than double the reduction achieved by all tributaries Scenario 1 (Table 2). Unlike Scenario 1, the peak timing does not shift significantly; instead, the hydrograph shape changes throughout the rising limb from approximately 6 March onwards, with the entire hydrograph flattened and attenuated relative to the baseline (Figure 3). This pattern is characteristic of upstream flow attenuation, whereby increased resistance in upper catchment tributaries reduces the volume of water contributed to the main flood pulse, producing a lower and more extended hydrograph rather than a sharp peak.

Table 2 Summary of NFM scenario results for the March 2022 event at the Wollombi Brook–Hunter River confluence

Scenario	Tributaries, n	Peak Stage Height (m)	Reduction in Stage Height (m)	Timing Change
Baseline	0.060	5.04	—	09 Mar 01:00
Scenario 1: All Tributaries, n = 0.10	0.100	4.85	0.19 (3.9%)	09 Mar 04:00 (+3 h)
Scenario 2: Upstream Denman Tributaries, n = 0.18	0.180	4.65	0.39 (7.9%)	09 Mar 01:00 (no change)

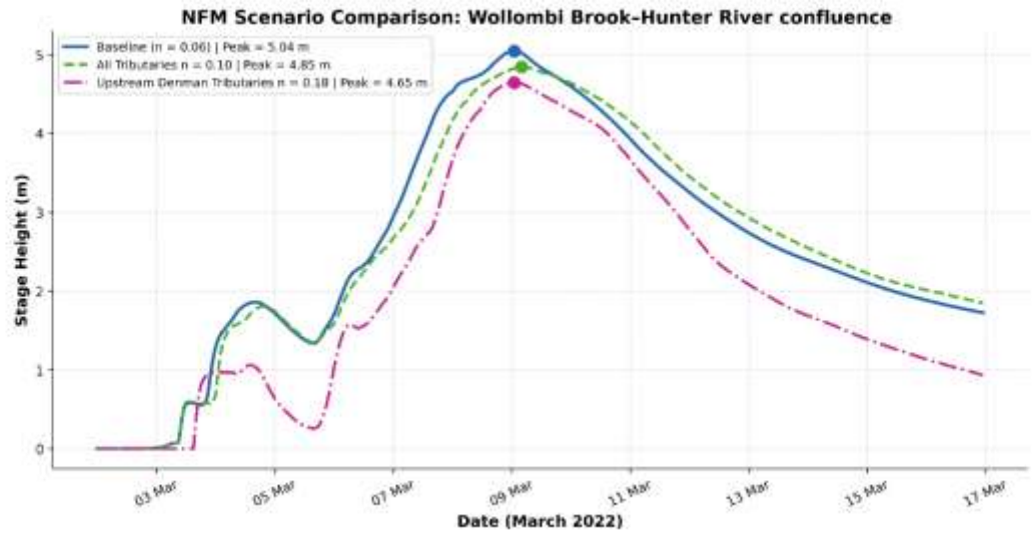

Figure 3 Simulated depth hydrographs at the Wollombi Brook–Hunter River confluence for the baseline (n = 0.06), Scenario 1 (all tributaries n = 0.10), and Scenario 2 (upstream Denman tributaries n = 0.18) for the March 2022 flood event

Discussion

The most significant finding of this study is that Scenario 2, which treated only upper catchment tributaries upstream of Denman, achieved more than twice the peak stage height reduction of Scenario 1, which increased roughness across all catchment tributaries to a lower level. Running such scenarios can provide important practical implications for catchment managers deciding where to invest in NFM.

In a large catchment such as the Hunter, upper-catchment tributaries have longer travel distances to the trunk-stream confluence. Increased roughness in these tributaries attenuates the flood wave over a longer routing distance before it reaches the main river, producing greater volume storage and peak reduction by the time flow arrives at the confluence. It may be that more downstream-located tributaries, even with increased roughness, may not have sufficient channel length to significantly attenuate the flood peak before it joins the main channel. This means that determining where in a catchment roughness rehabilitation provides proportionally more or less flood mitigation effect is important so that prioritisation and resourcing decisions can be made that will have the best mitigation effect.

These findings align with theoretical work on catchment network structure and flood generation (Benda et al., 2004), and with modelling results from Metcalfe et al. (2018) who found that NFM interventions in upper catchments provided disproportionately greater flood benefits relative to their spatial extent. The result also resonates with the concept of flood desynchronisation proposed by Awaad et al. (2025), whereby the spatial arrangement of tributaries relative to the trunk stream influences the extent to which tributary flood peaks synchronise and combine to generate major downstream flooding.

Further work is needed to determine if the modelled 3-hour delay in peak timing with moderate magnitude reduction in Scenario 1 is a result of desynchronisation or just the slowing of flow. Further runs are needed to test the effect of increasing roughness in each sub-catchment (or combination of). Scenario 2 produced primarily attenuation, a reduction in the overall stage height of the flood hydrograph without a significant timing shift. To confirm this response, further runs are needed for a wider range of Manning's n values. Both these mechanisms (desynchronisation, attenuation) provide mitigation effects, but their management implications will differ. Desynchronisation is most valuable when flooding results from the simultaneous arrival of multiple tributary peaks at a confluence, as a timing shift can prevent constructive peak superposition. Attenuation is most valuable when flood effects are primarily related to peak stage and inundation area, as it directly reduces the discharge contributing to the peak. In the Hunter River context, where major floods arise from sustained multi-day rainfall over the entire catchment, upstream attenuation through targeted riparian vegetation placement that increases roughness appears to offer greater flood risk reduction per unit of investment.

The contrast between Scenario 1 and Scenario 2 also indicates that system configuration, not just the magnitude of roughness change, strongly influences the outcome. More broadly, the effectiveness of tributary roughness rehabilitation is likely to depend on rainfall and flood characteristics together with broader landscape conditions, such as catchment shape, tributary drainage density and spatial arrangement, land use, and soil and geological characteristics (Herath et al., 2025; Thaler et al., 2023). Explicitly considering these landscape and configuration factors would help guide decisions on where this NFM approach is most likely to be effective.

Limitations and future work

This study presents an initial assessment based on a single historic flood event (March 2022) and the first calibration of a rain-on-grid model for this catchment. Further work is needed to improve model performance so a wide range of scenarios, both climate and on-ground rehabilitation, can be simulated. For example, in future, scenarios will be run that test the extent of NFM benefits that can be generated depending on the characteristics of rain events. It is possible that smaller, more localised events may exhibit greater percentage reductions because the intervention-affected area makes up a larger share of the flood-affected zone. Conversely, extreme events could surpass the flood mitigation capacity provided by roughness rehabilitation alone. The modelled roughness increases represent the hydraulic effect of NFM interventions without explicitly modelling the geomorphic and ecological processes that govern vegetation establishment over time. Longer-term catchment-scale modelling, incorporating multiple events, floodplain roughness changes, and climate change projections, is needed to fully characterise the benefits and limitations of tributary roughness rehabilitation in the Hunter River catchment. Future work will expand the scenario framework to include mixed spatial configurations and investigate threshold magnitudes beyond which the effectiveness of NFM diminishes.

Conclusions

This study demonstrates that riparian vegetation roughness rehabilitation in tributary systems of a large catchment (the Hunter) can achieve measurable reductions in flood peak arrival time and stage height at a downstream gauge. Targeted roughness rehabilitation of the riparian zones of tributaries upstream of Denman (n = 0.180) achieved a 7.9% reduction in peak flood stage height at the Wollombi Brook–Hunter River confluence for a flood event equivalent to the March 2022 flood event. In contrast, uniform riparian vegetation rehabilitation to a lower amount (n = 0.100) for all tributaries achieved a 3.9% reduction and a 3-hour delay in peak timing. The results indicate that the spatial position of NFM interventions is more important than their spatial extent, with upper catchment treatment providing greater flood-mitigation benefits despite involving fewer tributaries. These findings demonstrate that rain-on-grid 2D hydraulic modelling is an effective tool for evaluating large-scale NFM scenarios.

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