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Hydrodynamic model development, implementation and validation for the Richmond River catchment in the Northern Rivers region, NSW, Australia

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30 June 2025

Report prepared for the National Emergency Management Agency (NEMA)

Australian Government
National Emergency Management Agency

Environment Research Unit, CSIRO

Citation

Vaze J, Mateo CM, Nguyen C, Marvanek S, Ticehurst C, Montazeri M, Teng J, Wang B, Austin J, Kim S, Lerat J, Yang A, Merrin L and Chilcott C (2025) Hydrodynamic model development, implementation and validation for the Richmond River catchment in the Northern Rivers region, NSW, Australia. CSIRO, Australia.

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Contents

Figures

Tables

Northern Rivers Resilience Initiative Project

The National Emergency Management Agency (NEMA) engaged CSIRO to undertake the Northern Rivers Resilience Initiative (NRRI).

The NRRI aims to understand the drivers behind the unprecedented flood events in February–March 2022 in the Northern Rivers region of NSW and develop community-supported solutions for flood mitigation and resilience investment. This initiative enables CSIRO to assess existing project proposals and identify further long-term options for reducing flood risk in the Northern Rivers region.

The NRRI consists of two phases:

1. Rapid review and assessment (Phase 1 – July to November 2022) – This phase identified and prioritised existing flood resilience/mitigation project proposals. It characterised the catchment and climate conditions that led to the 2022 floods and analysed the most effective intervention options for the allocation of the Australian Government's $150 million of funding. Residents and councils in each of the seven flood-affected Local Government Areas in the region (Ballina, Byron, Clarence Valley, Kyogle, Lismore, Richmond Valley and Tweed) were consulted to help identify and prioritise the most effective intervention options.

Outcome – This work, delivered in November 2022, informed investment of $150 million of Australian Government funding for flood mitigation and resilience projects in the Northern Rivers region in 2022–23, to support recovery and resilience efforts (https://www.nema.gov.au/our-work/resilience/the-northern-rivers-recovery-and-resilience-program). This also provided insights into the variability and severity of flooding across the Northern Rivers region during February-March 2022 floods.

2. Detailed modelling (Phase 2 – longer term) – This longer-term program of work has collected and generated high-resolution and high-accuracy Light Detection and Ranging – LiDAR data (a digital representation of the bare-earth's topographic surface). The data enables spatial analysis and supports hydrological/hydrodynamic modelling of water movement for the entire Northern Rivers region. The project also collected river bathymetry (continuous river cross sections) using boats for the Richmond and Tweed rivers and their main tributaries.

This high-quality data is used to underpin a detailed hydrodynamic model for the entire Richmond River catchment. The model will be used for examining and evaluating possible future events and scenarios, and predicting their outcomes while drawing on local knowledge and expertise on the catchment and flooding.

Outcome – CSIRO has generated high quality digital elevation datasets for the Northern Rivers region based on the collected LiDAR and bathymetry datasets. The datasets were made publicly available through the Geoscience Australia Elvis website on 28 June 2024 and can be used by regional councils, Australian and state government agencies, researchers and community members across the region. This data, along with other data, is used to develop a detailed hydrodynamic model for the entire Richmond River catchment. CSIRO will use this model to undertake scenario analysis to evaluate possible flood mitigation actions. The report for this work and the fully implemented model are due in June 2025 (this report). Scenario testing will take place in 2025–26, with the findings to be made available in a final report on 30 June 2026.

Acknowledgments

This work is carried out in CSIRO as part of the Northern Rivers Resilience Initiative (NRRI) project and is funded by the National Emergency Management Agency (NEMA). The authors thank the CSIRO sub-contractors Fugro Australia Pty Ltd and AAM/Woolpert for the LiDAR and bathymetry dataset collection respectively, and to Geoscience Australia for making the dataset publicly available, as well as the Bureau of Meteorology, WaterNSW and Manly Hydraulic Labs for providing rainfall and water level datasets. The authors also thank officials from the following organisations: Clarence Valley Council, Kyogle Council, Richmond Valley Council, Lismore City Council, Tweed Shire Council, Byron Shire Council, Ballina Shire Council, Rous County Council, NSW Reconstruction Authority, NSW Department of Primary Industries, NSW Department of Transport and NSW Public Works for useful discussions and data. The authors are thankful to the federal and state members of parliament from the region especially the Hon Kevin Hogan (Federal member for Page) and the Hon Janelle Saffin (State member for Lismore, Minister for Recovery; Small Business and for the North Coast), the Mayor's from the seven councils and the Northern Rivers Joint Organisation (NRJO), all the council staff, the project's Governance and Advisory panels, as well as CSIRO and NEMA management for continued support throughout this work. We are grateful and thankful for the enthusiastic and knowledgeable Northern Rivers local communities and local organisations for having faith in the team and providing on-ground datasets and expert knowledge. Those who provided substantial on-ground data and local understanding include: The Terania-Keerrong Flood Safety group, especially Annie Kia (for Channon and upstream of Lismore areas), Our Future Northern Rivers and Lismore Citizens Flood Review Group, especially Beth Trevan AM, Richard Trevan and Bill Moorhouse (for Lismore and some downstream areas and the drainage across Lismore CBD) and Jim McCormack, Bert Plenkovich OAM and Kevin Boyd for showing us around the catchments and providing important insights into the 2022 flooding around Coraki, Woodburn, Broadwater, Bagotville, Tuckean and, Evans Heads areas which was extremely useful for model validation. The team is grateful to Lismore City Council staff especially Eber Butron, Matt Potter, Thomas Lloyd, Garon Clough and others for helping with field reality checks and showing us the water infrastructure. Without your input we could not have done this work. We are also grateful to Rous County Council staff especially Phillip Rudd and Andrew Logan for data and on-ground checks. We are grateful to Ballina Council staff especially Paul Busmanis, Josh Wilde, Paul Crozier and others for useful discussions and taking us around showing the water infrastructure. Thanks to Michael Hutchinson from Australian National University for working with the team on generating detailed rainfall surfaces. The authors are grateful to and thank the three external reviewers (Dr Charles Perrin, INRAE France; Prof Dai Kamazaki, University of Tokyo, Japan and Prof Barry Croke, Australian National University, Australia) for their critical and detailed review. Finally, we thank the NEMA NRRI team directly involved in the work for their contributions and support.

Executive summary

The National Emergency Management Agency (NEMA) engaged CSIRO to undertake the Northern Rivers Resilience Initiative (NRRI). This report is for Phase 2 of NRRI, which is to develop and implement a detailed hydrodynamic model for the entire Richmond River catchment in the NSW Northern Rivers region to reproduce the past flooding history across the catchment and investigate flood mitigation scenarios. The Richmond River catchment has a large floodplain that floods frequently. This is the first time a detailed hydrodynamic model has been developed for the entire Richmond River catchment. This was developed to investigate the impacts of any flood mitigation interventions in the catchment on the overall catchment response (any intervention in the upper parts will have downstream impacts). Given the large area covered by the modelling domain and the very complex sections of steep and flat terrain, it was not possible to represent every small stream and channel as we tried to keep the total number of mesh elements within an acceptable limit. The model is set up to represent the entire modelling domain and is suitable for understanding the water level variations and floodplain dynamics at the scale of the modelling domain. The model is developed to get the overall river water levels at all gauges across the catchment as close as possible to the observed data, without focusing on any particular gauge or areas. Every attempt has been made to make sure that all important streams, levees, flow control structures such as bridges, culverts, and pipes, etc., across the entire catchment are explicitly represented in the model. The 2D hydrodynamic model (MIKE21 FM) implemented here covers the entire Richmond River catchment from headwaters to the ocean outlet and uses spatial rainfall as input (rain on grid) rather than the conventional way of using observed streamflow as inputs. The model generates spatial runoff on each grid at every time step and routes it through the catchment. This version of MIKE21 FM also accounts for spatial and temporal soil infiltration and soil moisture based on measured spatial soil properties and does not need any initial and continuing losses to be calibrated for each flood event. The model used here is the most appropriate tool to use when a substantial fraction of the total runoff and associated flooding is generated within the catchment landscape rather than just river inflows coming from upstream. This report briefly describes the model setup, implementation, and validation results of the MIKE21 FM model, and all the inputs and outputs for selected historical flood events. Five historical flood events are selected, and cover the entire range of floods (small – 1 in 7 years to the largest observed in history – February-March 2022) across the catchment. The developed hydrodynamic model can be used to evaluate how flood characteristics may change under future scenarios (flood mitigation measures and future climate change). The model setup includes model mesh and all related setup files, inputs include rainfall, potential evapotranspiration, LiDAR Digital Elevation Model (DEM), river and water storages bathymetry, satellite images for the flood events used for model validation, soil characteristics, vegetation characteristics and observed water level data at the internal validation gauges. The hydrodynamic model calculates results every 0.01 s to 30 s time step and outputs are saved at hourly intervals at selected point locations (i.e. it produces water level and depths time series) and at 3-hourly intervals for spatial data (e.g. flood depths, velocities, saturation) across the entire catchment. The implementation and validation results clearly show that the model can reproduce the water levels and flooding (timing, depth, velocities, etc.) across the Richmond River catchment at a fine spatial and temporal resolution for the complete range of flood events. Given the model simulated flows match the observed flows reasonably well at all key locations across the entire Richmond River catchment, these results provide confidence in the developed model and the outputs and shows that the model is representing the flows across the catchment and the match at any particular stream gauge is not due to compensating errors within the catchment. This provides confidence in the model and its use for flood mitigation scenario testing. The flood mitigation scenarios will be developed in consultations with NEMA, NSW Reconstruction Authority (NSWRA), local councils as well as other stakeholders and local communities in the Richmond River catchment.

1 Introduction

An exceptional flood event affected the Northern Rivers region in NSW between the end of February and the beginning of March 2022. The region was severely impacted, especially in some parts where the flood was unprecedented. In response, the Australian government, through NEMA engaged CSIRO to analyse what happened during this flood and investigate ways of mitigating such events in the future. There are several existing local area models mostly covering major towns across the Richmond River catchment developed over the last few decades to serve an intended purpose. However, to analyse and investigate flood mitigation options at the catchment scale, a full catchment-scale model was needed for the entire Richmond River catchment. Given the scale and complexity of the region, such a catchment model has not been attempted before. To enable this, CSIRO has chosen to use the 2D hydrodynamic model (MIKE21 FM) for this project. Rather than the conventional way of using observed streamflow at multiple point locations as forcing inputs and limit the model domain to floodplains, the model is driven by hourly spatial rainfall (i.e. rain on grid) that was generated for the region. The model generates spatial runoff on each grid at every time step and routes it through the catchment. The focus of the model is on reproducing larger flood event peaks (e.g. 2017, 2022) while also making sure that the final model setup (i.e. same setup for all events with the only change of event specific initial spatial soil moisture, rainfall, and evapotranspiration) can reproduce reliable inundation estimates at the Richmond River catchment scale for the complete range of floods. The developed and validated model will be used to reproduce past flooding history across the Richmond River catchment and to investigate the effectiveness of flood mitigation scenarios for possible large future flood event.

1.1 Background and Objectives

The Northern Rivers region of NSW has a history of flooding with minor to major floods occurring every few years. An exceptional flood event affected the Northern Rivers region in NSW between the end of February and the beginning of March 2022 (Lerat and Vaze, 2025). During this event, the rainfall totals and water levels exceeded historical records by a significant amount in many parts of the region. There was considerable damage in towns such as Lismore, Coraki, Woodburn and Ballina which triggered a range of actions by local communities, local government authorities, NSW state agencies, and Australian government to address emergency circumstances and formulate strategies to mitigate the impact of future floods in the region. In this context, NEMA commissioned CSIRO to initiate the ‘Northern Rivers Resilience Initiative’ project.

The project area covers the entire Northern Rivers region including the Clarence, Richmond, Tweed, and Brunswick River basins (and some of the coastal creeks which drain to the ocean) and seven Local Government Areas included in these catchments: Clarence Valley Council, Kyogle Council, Richmond Valley Council, Lismore City Council, Tweed Shire Council, Byron Shire Council, and Ballina Shire Council. The project area is presented in Figure 1.

The project has two Parts with Phase 1 of six months analysing the drivers of the 2022 flood (Lerat et al., 2022, https://www.nema.gov.au/sites/default/files/2024-08/Rapid%20Prioritisation%20for%20Flood%20Resilience%20in%20the%20Northern%20Rivers%20region.pdf), reviewing previous existing flood mitigation studies, and identifying and prioritising options for mitigating flood risks in the region (Weber et al., 2022, https://www.nema.gov.au/sites/default/files/2024-08/Characterisation%20of%20the%202022%20floods%20in%20the%20Northern%20Rivers%20region.pdf). Phase 2 of the project of work has collected high quality Light Detection and Ranging (LiDAR) data for the entire Northern Rivers area (~30,000 km^2) to provide spatial analysis and to underpin hydrological/hydrodynamic modelling of water movement for the Northern Rivers region. Detailed bathymetry for the Richmond and Tweed rivers, and their main tributaries has also been collected (~500 km). All this data has been quality assessed and made publicly available through the Geoscience Australia Elvis website on 28 June 2024 (fsdf.org.au).

This report describes Phase 2 of the project, where a detailed 2D hydrodynamic modelling is developed using MIKE21 FM to characterise flooding across the entire Richmond River catchment under historical flood events. The hydrodynamic model can be used to evaluate how flood characteristics may change under a full range of future interventions for flood mitigation and climate change scenarios.

Outputs from hydrodynamic modelling can be used to:

- identify areas susceptible to flooding under historical and current levels of infrastructure/development
- estimate changes in inundation under future interventions and climate change scenarios.

The hydrodynamic model developed here covers a large area, very complex terrain with very steep to low gradients and complex water regulation structures. The model is set up to represent the entire modelling domain and is suitable for understanding the floodplain dynamics at the scale of the modelling domain. The model is developed to get the overall river water levels at all gauges across the catchment as close as possible to the observed water levels without focusing on any particular gauge or areas.

1.2 Purpose of the Report and Outline

This report has been prepared to provide technical details of various aspects of the flood inundation modelling including data gathering and processing, methods and tools used for flood modelling, model setup, implementation and validation, and final model outputs. The report incorporates the following:

- the background, objectives, and outline of the report (this section)
- the study area and data collection and collation (Section 2)
- the methodology for inundation modelling and model setups (Section 3)
- results and discussion (Section 4)
- conclusions and recommendations (Section 5).

2 Study area and data collation

2.1 Floodplain inundation modelling area in the Northern Rivers region

The Richmond River catchment, located in NSW, Australia, is a significant geographic and ecological area that covers a substantial part of the Northern Rivers region. The catchment is situated in the northeastern part of New South Wales. It encompasses parts of the Northern Rivers region, extending from the Great Dividing Range in the west to the coastal plains in the east. The Richmond River catchment covers approximately 7,000 km^2 and the Northern Rivers region has a population of more than 300,000. The Richmond River is the primary watercourse within the catchment. It originates from the Great Dividing Range and flows generally eastward, emptying into the Tasman Sea at Ballina. There are other major tributaries including the Eden Creek, Iron Pot Creek, Leycester Creek, Wilson River, Bungawalbin Creek, Emigrant Creek, North Creek, etc., which drain different parts of the catchment into the Richmond River. The catchment experiences a subtropical climate with warm to hot summers and mild winters. Rainfall is generally plentiful, with the eastern parts receiving more rainfall than the western parts. The area features diverse vegetation, including subtropical rainforests, eucalypt forests, and riparian zones along the riverbanks. The eastern parts of the catchment, closer to the coast, are often lush with dense forest, while the western parts are more open with grassy woodlands. The catchment supports a rich array of flora and fauna. Notable species include various types of eucalyptus trees, as well as significant populations of birds, fish, and other wildlife. The region is also home to several threatened species and important habitats. The catchment contains valuable wetland areas and floodplains that provide critical habitat for wildlife and support biodiversity. The catchment is utilised for agricultural purposes, including grazing and crop production. The fertile floodplains and rich soils make it suitable for various types of farming. There are several towns and cities within the catchment, including Lismore, Casino, Kyogle and Ballina. These areas contribute to the regional economy and the annual economic contribution. The Northern Rivers region supports 123,320 jobs and has an annual economic output of $44.404 billion, 2.69% of $1.6 trillion for NSW (https://app.remplan.com.au/northernrivers/economy/summary). There are several national parks and reserves within the catchment that help protect important ecosystems and biodiversity. Various agencies and local groups are involved in managing and preserving the catchment's natural resources, addressing challenges such as flooding, drought, erosion, water quality, and habitat preservation. Overall, the Richmond River catchment is a diverse and ecologically significant area with a complex interplay of natural systems and human activities.

The boundary of the modelling area, which is about 7,000 km^2 covers the entire Richmond drainage basin. Figure 1 shows the Northern Rivers region (all areas except grey) and hydrodynamic modelling domain (light orange area).

As a numerical flood modelling exercise, representing flow behaviour on a floodplain of this size and complexity is a difficult and challenging exercise. While two-dimensional models such as MIKE21 FM are well-suited to apply to a floodplain of this type, the size, detail, and complexity of the floodplain necessarily require compromised decisions to be made by the modeller. Such decisions need to fit within the limitations and constraints of the modelling software and the computational capacity of the available computing hardware. After several discussions within the project team, and discussions and feedback from the community consultations, it was agreed to develop a detailed representation of the entire modelling domain (~7000 km^2) with about 10 million grids/mesh elements. The model has been setup using a flexible mesh approach of MIKE21 FM where higher resolution mesh is used for the key areas representing the streams, major infrastructure and floodplain, and the less flood-prone areas are represented by coarser mesh (Figure 13, Figure 14, Section 3.2). The entire modelling domain is divided into roughly five zones – major streams, minor streams, low-lying floodplain which often gets flooded, surrounding floodplain which usually gets flooded, and the rest of the floodplain which seldom gets flooded. All major infrastructure is also considered explicitly. The maximum floodplain inundation extent map derived from remote sensing imagery (by combining all 1 in 2, 1 in 5, 1 in 10 and 1 in 20 year events) was used to define the mesh resolution across the floodplains. Very detailed, high-resolution mesh is used for the major streams to represent the stream conveyance capacity accurately, with the mesh gradually coarsened across the other four zones. The main aim in setting up the mesh is to get the most accurate representation of the entire catchment, while ensuring that the total number of mesh elements is within the limits of what the model can handle, and the simulation times also remain realistic. These decisions have been taken as a compromise between the level of detail in the model (i.e. the number and size of model elements) and the model computation duration (i.e. model run time). This approach ensures the development of a fit-for-purpose model with spatial resolutions that are suitable to represent most of the important streams, floodplain channels, terrain characteristics, and other water infrastructure, in sufficient detail.

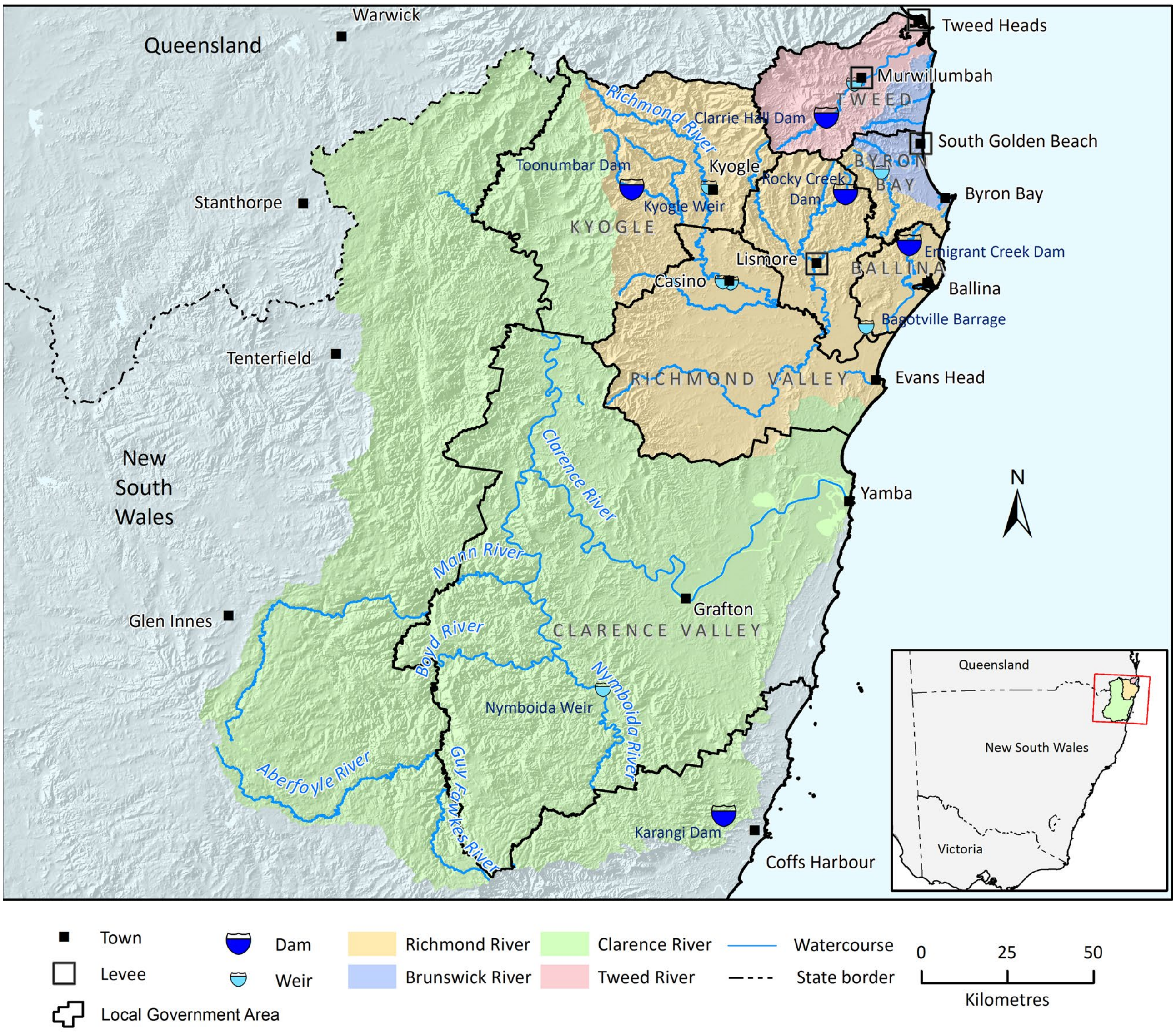


Figure 1 The spatial extent of the Northern Rivers region and the extent of the LiDAR data (all area except grey) and the Richmond River catchment and hydrodynamic modelling domains (light orange area).

2.2 Data collection and processing

2.2.1 Satellite imagery

Landsat and Sentinel-2 surface reflectance images were processed for the flood events to provide water extent using the modified Normalised Difference Water Index (mNDWI; Xu 2006; which is good for identifying open water) and the Tasseled Cap Wetness Index (TCW; Dunn et al. 2019; which can be useful for identifying flooded vegetation). The recent Landsat sensors include the Thematic Mapper (TM), Enhanced Thematic Mapper (ETM), Operational Land Imager (OLI) and Operational Land Imager 2 (OLI-2), which are advanced, multispectral, Earth resources sensors. Landsat data are collected in the optical to infrared wavelengths and provide reasonable information on inundation primarily due to its high spatial resolution (about 30 m x 30 m). The Sentinel-2 sensors collect data at similar wavelengths to Landsat but with a spatial resolution of 10 to 20 m. The Landsat sensors (operating for over 30 years) acquire data over the same area every 8–16 days (depending on the number of sensors in operation) and the Sentinel-2 sensors (operating since 2016) acquire data every 5 days. This temporal frequency reduces the probability of acquiring an image during peak flooding. Also, given the large floodplain areas for the modelling domain, it was difficult to find remote sensing images/scenes covering a majority of the modelling domain during the flood events. The Landsat and Sentinel-2 data archives are available through Digital Earth Australia (https://www.ga.gov.au/scientific-topics/dea) in an analysis-ready format. These images have been normalized for sun angle effects to be spatially and temporally consistent. All available Landsat and Sentinel-2 images collected during the flood periods within the Richmond River catchment were used to produce water maps. The Landsat and Sentinel-2 images come with a cloud/cloud shadow mask which is used to remove those pixels from further processing, however these masks do not always capture all cloud/cloud shadow. Each image was visually assessed for remnant cloud/cloud shadow and manually masked when required, however due to the extensive cloud cover in many scenes some small residual errors may remain. Significant cloud cover reduced the number of useable images (i.e. those that contained some visible flooding) within the Richmond River catchment to 4 for Landsat (in the southern lower catchment only) and 4 for Sentinel-2. The TCW is good at identifying flooded vegetation, however it can also misclassify cloud shadow and heavily vegetated areas as flooded. To reduce this error, additional masking was applied to the Landsat and Sentinel-2 water maps to remove areas unlikely to flood (i.e. upland and steep terrain) as well as areas where vegetation is too dense to detect flood water.

Sentinel-1 backscatter data were also processed to analysis-ready format (and filtered to reduce speckle effects) for the flood events. The Sentinel-1 Synthetic Aperture Radar sensors (operating since 2015) are not affected by cloud cover, since they use microwave wavelengths, and acquire data over the same area every 12 days. The Sentinel-1 data used here have a pixel size of 10 m x 10 m, although the visible detail in the imagery is somewhat reduced due to the speckle effects in radar imagery. A low backscatter threshold was used to identify surface water, and small ‘clumps’ of pixels misclassified as water bodies were removed. A total of 11 Sentinel-1 images, with partial or complete coverage of the Richmond River catchment, showed some evidence of flooding. This was mostly in the southern section of the lower catchment. Identifying flooded vegetation using Sentinel-1 data is challenging in complex environments like the Richmond River catchment, furthermore, flood water is difficult to identify in urban areas using Sentinel-1 due to the complex interaction of the radar signal with the varied building structures. Based on this, the Sentinel-1 water maps only identify large areas of open water. The quality of the processed Sentinel-1 images was found to be unreliable, and they are selectively used for flood extent comparisons only when no other Landsat or Sentinel-2 image was available. The European Space Agency also has a rapid mapping activity (Copernicus, only 1 image available) which provides flood maps using all available remote sensing data (including high resolution commercial satellite data) for populated areas. This included flood maps of the Lismore area near the flood’s peak at the end of March 2022.

All reasonable quality Landsat, Sentinel, and Copernicus images available (with some flooded area) for the period of historical simulations for the selected flood events for the Richmond River catchment were processed to produce water maps so that they can be used for validating the MIKE21 FM simulation results. But most of the 20 selected images are of poor quality and remote sensing images tend to underestimate flooded area especially for Sentinel-1. Table 1 provides the dates for which these remote sensing water maps were available for parts of the modelling domain.

Table 1 Remote sensing (Landsat, Sentinel and Copernicus) images processed for each flood event for comparison with MIKE21 FM simulation results for the historical flood events.

Flood event	Modelling domain	Image date	Source	Image quality
2008	No images available			
2009	Richmond	27/05/2009 09	Landsat	Poor
2013	No images available			
2017	Richmond	29/03/2017 06	Sentinel-1	Fair
2017	Richmond	3/04/2017 06	Sentinel-1	Fair
2017	Richmond	7/04/2017 09	Landsat	Poor
2017	Richmond	12/04/2017 09	Sentinel-2	Poor
2017	Richmond	15/04/2017 06	Sentinel-1	poor
2022	Richmond	24/02/2022 06	Sentinel-1	Poor
2022	Richmond	3/03/2022 06	Sentinel-1	Fair
2022	Richmond	8/03/2022 06	Sentinel-1	Fair
2022	Richmond	20/03/2022 06	Sentinel-1	Poor
2022	Richmond	20/03/2022 09	Landsat	Poor
2022	Richmond	22/03/2022 09	Sentinel-2	Poor
2022	Richmond	27/03/2022 06	Sentinel-1	Poor
2022	Richmond	31/03/2022 15	Copernicus	Fair
2022	Richmond	1/04/2022 06	Sentinel-1	Fair
2022	Richmond	1/04/2022 09	Sentinel-2	Fair
2022	Richmond	5/04/2022 09	Landsat	Fair
2022	Richmond	8/04/2022 06	Sentinel-1	Fair
2022	Richmond	11/04/2022 09	Sentinel-2	Fair
2022	Richmond	13/04/2022 06	Sentinel-1	Poor

2.2.2 LiDAR data

For detailed hydrodynamic modelling, especially in a complex region like the Richmond floodplain, a Digital Elevation Model (DEM) at fine grid resolution with high vertical and horizontal accuracy is necessary. The accuracy and reliability of the simulation results from the hydrodynamic modelling are a direct function of the quality of the input DEM. The NRRI project, with approval from NEMA, commissioned Fugro Australia Pty Ltd in mid-2022 to acquire a LiDAR DEM for the entire Northern Rivers region.

The acquisition area is located between Tweed Head and Coffs Harbour in the east and Warwick and Armidale in the west, comprising a survey area of approximately 31,020 km^2 (Lismore 8,643 km^2 and Clarence 22,377 km^2) as shown in Figure 2 (Orange and Blue outline). The LiDAR and imagery data were planned and flown with a LiDAR dual channel Riegl VQ-1560ii in a fixed wing, twin-engine Piper Navajo (PA-31) to achieve an average of 16 ppsm. A 150 Mpixel medium format camera (Phase1, RGB) was co-located for producing 10 cm orthoimagery. The flight altitude was ~4,900 feet above ground level, and the plane flew at an average of 160 kts. A pulse repetition of 1600 Khz per channel was selected. The LiDAR scanner was set to capture a full field of view (FOV) of 58.52 degrees and the camera at a 56-degree FOV. The coverage of LiDAR and imagery was achieved with a 25% side overlap of the camera footprint.

To achieve the operational requirements the field crew were based throughout northern NSW and southeast Queensland, and were able to fly from several aerodromes equipped with sealed airstrips and aviation fuel for the aircraft. The aircraft were operated from Gold Coast, Ballina, Coffs Harbour, Armidale, Warwick and Toowoomba.

The data acquisition area was divided into four capture areas of interest (AOIs): Kyogle, Murwillumbah, Casino, and Grafton. Fugro started flying for LiDAR collection in mid-2022, but after completing a small portion of the Lismore area, they had to stop due to unfavourable weather conditions. Due to continued poor weather, air traffic control and standing water in the landscape due to continued rain, the data collection was delayed by nearly 18 months and extra time was required to complete the aerial data capture. Some of the flight missions could not be captured to maximise the aircraft's endurance. This added additional ferrying between the airfield and the data capture area and consequently more engine hours, resulting in more aircraft maintenance and pilot duty times. The aircraft was active on the project for 252 days.

Survey control and check points were established across the Survey AOI as shown in Figure 2. A total of 297 ground control points (GCPs) were observed and surveyed in clusters of 9 points per location. The left side of Figure 2 shows the distribution of the GCPs across the AOI, while the top right is an example of the vertical control marked in red and the 8 check points marked in blue. The bottom right of Figure 2 shows the aerial target painted with a width of 0.2 m and arms of 1.5 m on a cross pattern. Figure 3 shows an example of 2 target locations. Survey observations were performed with a Leica GS18 GNSS receiver on a 2 m carbon fibre pole, measured daily to confirm receiver height, and stabilised with a bipod. Survey Control Information Management System (SCIMS) was used to locate and obtain details for suitable permanent marks (PMs) to provide an instrument and network quality assurance measurement within the vicinity of each established GCP, (i.e., the instrument measurement was verified to a state-issued PM before/post GCP observation). Due to a lack of suitable state PMs available in various areas, control of a lesser order was sometimes required. In addition, the PM provides a gross error check for instrument observation in these circumstances. The survey quality assurance checks were undertaken using the surrounding continuous reference stations: ARD2, BALN, COFF, COPS CSNO DORR, GFTN, GLIN, NMBN, SLTC, TNTR, TWED, WARW, WDBG, and YMBA, which are part of the state Geodetic Network (see the left panel in Figure 2, blue dots are the CORS stations).

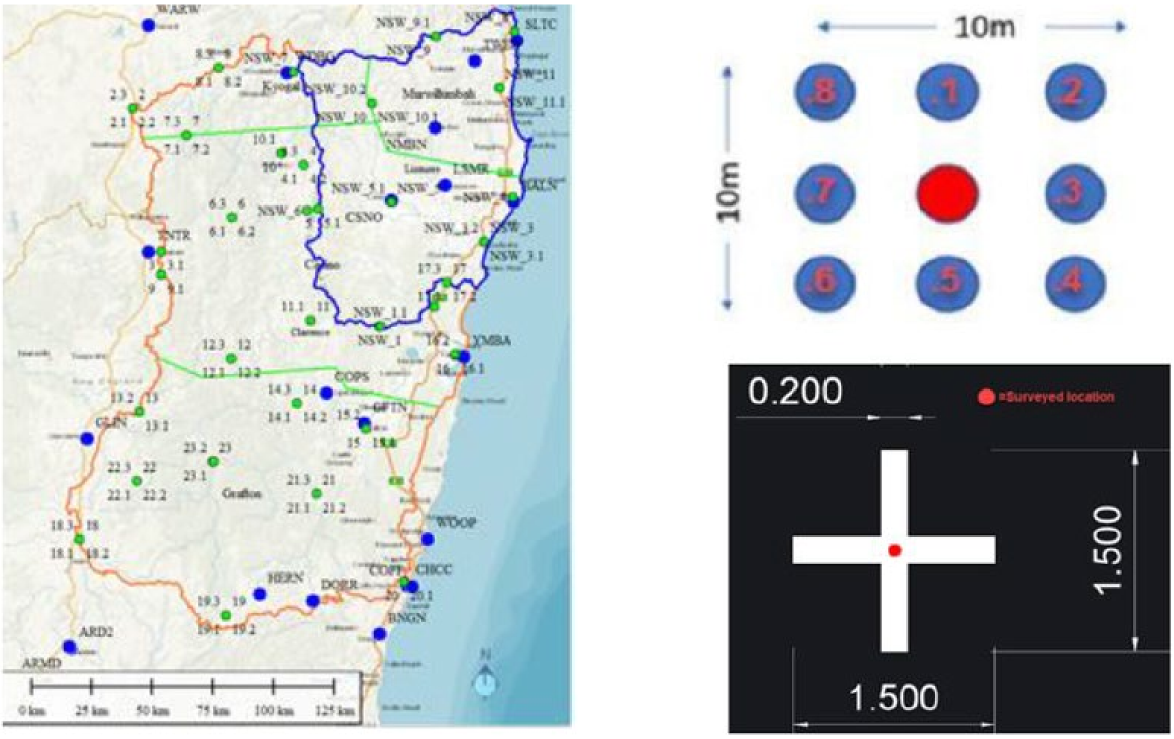


Figure 2 Digital Elevation Model acquisition area (orange and blue outline) and ground control points – Distribution, LiDAR vertical top right, imagery target bottom right (courtesy Fugro).

Figure 3 Example of ground control points installations –in Tenterfield (left) and Kyogle (right) (courtesy Fugro).

A LiDAR DEM for the entire Northern Rivers region was provided to CSIRO by Fugro Australia Pty Ltd in March 2024. The 1-m ground resolution LiDAR DEM was thoroughly reviewed by CSIRO researchers with expertise in hydrological landscape modelling and geospatial analysis to determine its suitability for detailed hydrodynamic modelling. The review was undertaken using several spatial analysis tools including ArcGIS. The point density of 16 ppsm was achieved with an average of 26 and std of 11. Vertical absolute accuracy meets the specifications with 68% (one standard deviation) of returns falling within the +/- 0.08 m range. The horizontal accuracy meets the specification of +/- 0.40 m for 68% of the returns. Based on all the checks, it was determined that the quality of the 1m LiDAR captured was suitable for detailed hydrodynamic modelling (Figure 4). The final DEM along with point cloud data for the entire Northern Rivers region was made available to the public on the 28th of June 2024 on the Geoscience Australia website (fsdf.org.au).

The Richmond River catchment has several large water storages and perennial rivers where the terrestrial LiDAR was unable to penetrate the standing water. Bathymetric data for these perennial rivers and storages were collected as part of the bathymetry survey (section 2.2.3) and was stitched with the 1-m LiDAR DEM for the Richmond River catchment to generate the final DEM to be used for hydrodynamic modelling.

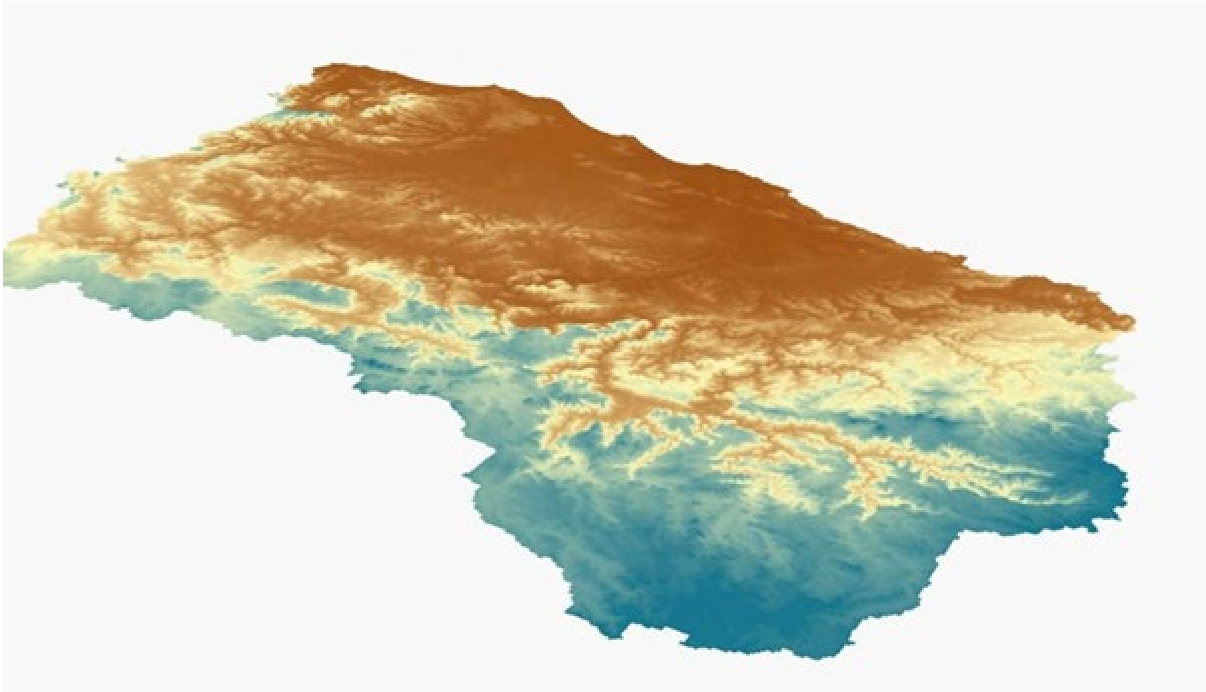


Figure 4 An aerial view of the LiDAR data across the Northern Rivers region. In this image the blue colour means high elevation and brown represents low-lying areas.

2.2.3 Bathymetry data

CSIRO engaged Woolpert Australia Pty Ltd to conduct bathymetric surveys of major perennial rivers, creeks and dams in the Northern Rivers region of NSW as part of the Northern Rivers Resilience Initiative. Some of the key rivers surveyed included the Richmond River, Tweed River, Evans River, as well as many of their tributaries.

Baseline bathymetric data, infill areas and a selection of cross sections in accessible areas were also collected to support the hydrodynamic modelling in the surveyed tributaries and assist in capturing features of interest in the riverbed, to better understand the natural hydrological flow of the regions river systems.

Woolpert utilised two vessels for accurate bathymetric capture. Most of the capture was undertaken with a staffed dinghy using the *Savage* system, while a smaller sample section was captured with a remote-controlled surface vessel, the *Otter* (Figure 5).

The *Savage* bathymetric system included an interferometric echosounder (PING DSP), a Side-Scan Sonar (SSS), which was fitted to a 3.85 m *Savage Extreme 375 Raptor* aluminium boat (tinnie/dinghy) with an outboard motor. This vessel was chosen such that it could survey both the larger river systems and upstream through to the smaller shallow creek sections. The PING system interfaced with a Reak time kinetic (RTK) GNSS positioning system and both were integrated with a survey navigation software, *QINSy*. Utilising a wide-angle scan, the PING DSP was determined to be the most suitable equipment for the project. It is a fully integrated positioning and motion sensor unit with an inbuilt inertial measurement unit (IMU) which produces a self-aligning heading solution. The PING DSP was fitted to the vessel via a side pole mount with the system interfaced with a RTK positioning system. This agile equipment allows continuous real-time efficient bathymetric scanning surveys to be accurately conducted in both large open rivers and smaller more shallow creeks upstream.

As a trial concept for a section of waterway near Casino, a remote-controlled boat (*Otter*) was used. This Unmanned Survey Vessel (USV) utilises the same instrumentation componentry as the manned boat, however, it is smaller and can be carried by two people for launch and retrieval from a riverbank. The *Otter* has a catamaran hull with dual propulsion and centre pole mounts to attach a high-resolution Side Scan Sonar (SSS). The *Otter* trial was only utilised in the Richmond River, near Greenridge and Irvington due to access issues and areas densely populated with tree branches and other obstructions.

Prior to the commencement of field capture, several calibration and verification checks were undertaken in the Richmond and Tweed rivers. These calibrations demonstrated that all on-board systems had been correctly interfaced and integrated into the online navigation software. They also confirmed that system configurations such as lever arm offsets measurements, sounding reductions, positioning corrections and online quality control had been established correctly prior to the commencement of survey. These processes included: Heading Verification; Position Verification; Patch Test Verification; Bar Check Verification and Sounding Position Verification.

Figure 5 Staffed bathymetric boat (left) and remote controlled bathymetric vessel (right) used for data collection (courtesy of Woolpert Australia Pty Ltd).

The final bathymetry data was quality assessed by CSIRO researchers with expertise in hydrological landscape modelling and geospatial analysis to determine its suitability for detailed hydrodynamic modelling. Based on all the checks, it was determined that the quality of the continuous bathymetry captured was suitable for detailed hydrodynamic modelling. The final quality assessed bathymetry data for the Northern Rivers region (~500 km, Figure 6, Figure 7) was made available to the public on 28 June 2024 along with the LiDAR data on the Geoscience Australia website (fsdf.org.au).

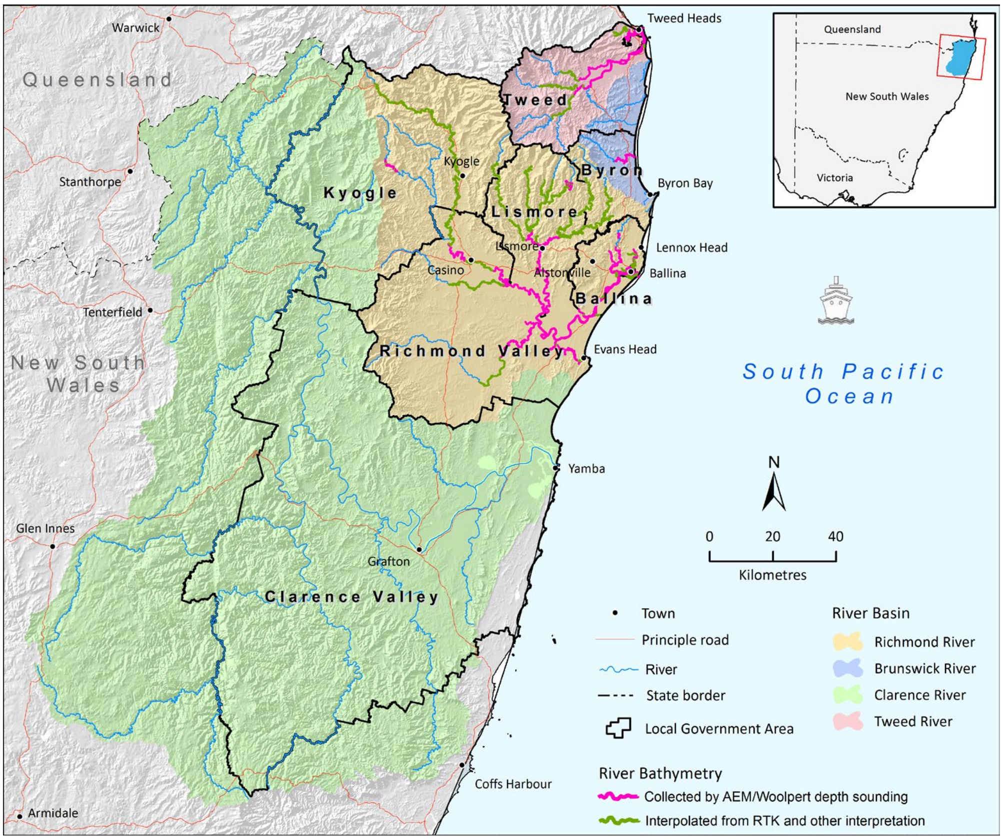


Figure 6 Bathymetry collected for the Northern Rivers region.

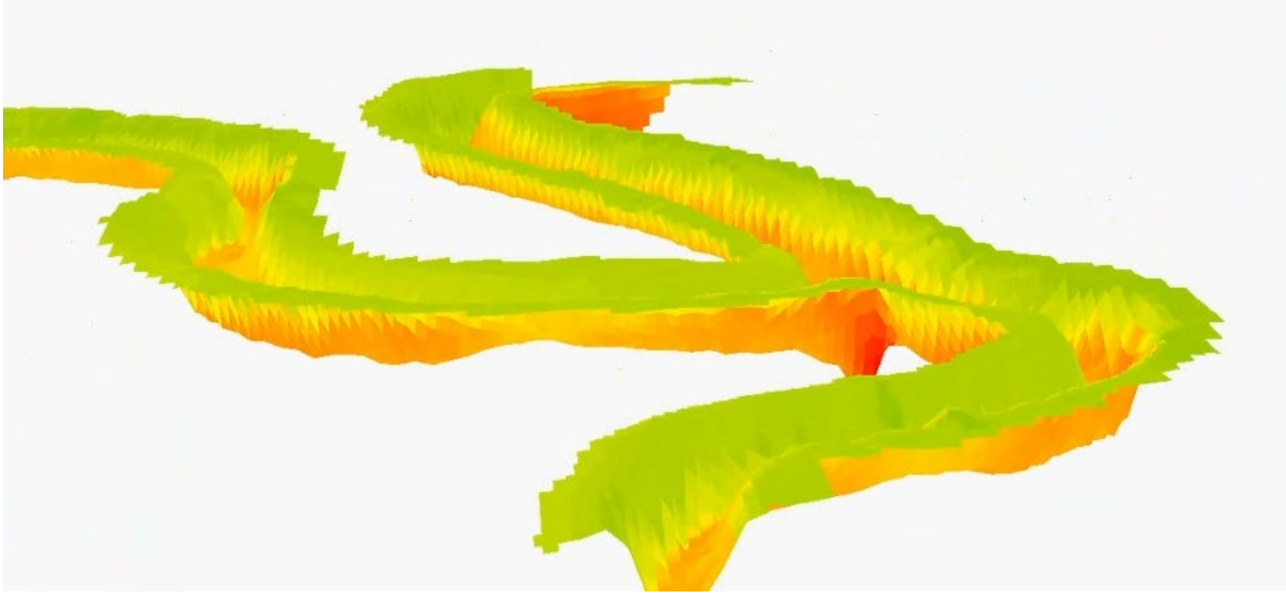


Figure 7 A zoomed in view of the bathymetry at the Wilson and Richmond river junction.

2.2.4 Blending LiDAR and bathymetry data for the Richmond River catchment

The hydro-flattened LiDAR DEM and the continuous bathymetry data collected for the Richmond River and its tributaries were merged to produce the final merged hydro-flattened DEM, including bathymetric data for input to the hydrodynamic model. The final merged DEM includes data from the LiDAR DEM, the hydro-flattened channel data (where bathymetry data was not collected), the bathymetric data, and small areas of smoothed elevations that sensibly link the DEM and bathymetric elevations along channel edges. The merged DEM has been created using the following steps (also see Figure 8):

- To incorporate the bathymetry into the DEM without creating an abrupt elevation change at the LiDAR/bathymetry interface, the continuous 1 m bathymetry raster data was converted to an array of points and combined with the LiDAR point cloud.
- This combined (LiDAR + bathymetry) point cloud then underwent the usual rasterisation process to produce the 1 m merged raster, but with bathymetry point data now informing elevations in what were previously data holes in the original LiDAR point cloud. Interpolation between the LiDAR points and bathymetry points rendered a smooth elevation transition across any gap between the coverage of the two input datasets. A consequence of this combined interpolation is that it creates bank-interpolated values across lakes and rivers where there is no bathymetry data to enforce the channel/lake bottom, thus creating triangular artefacts. DEM hydro-flattening is a post LiDAR DEM process whereby elevations occurring within a mask representing waterbodies, are subsequently “flattened” so that the lake/river is represented by a flat surface not exceeding the minimum bank elevation occurring on the periphery of the mask.
- For the final merged DEM, areas that underwent bank interpolation due to there being no bathymetry data (i.e. within the waterbody mask and outside the bathymetry coverage), were replaced with hydro-flattened values. While not representing the channel bottom, replacing bank interpolated values with hydro-flattened values ensured river/lake elevations remain below the toe of the bank.

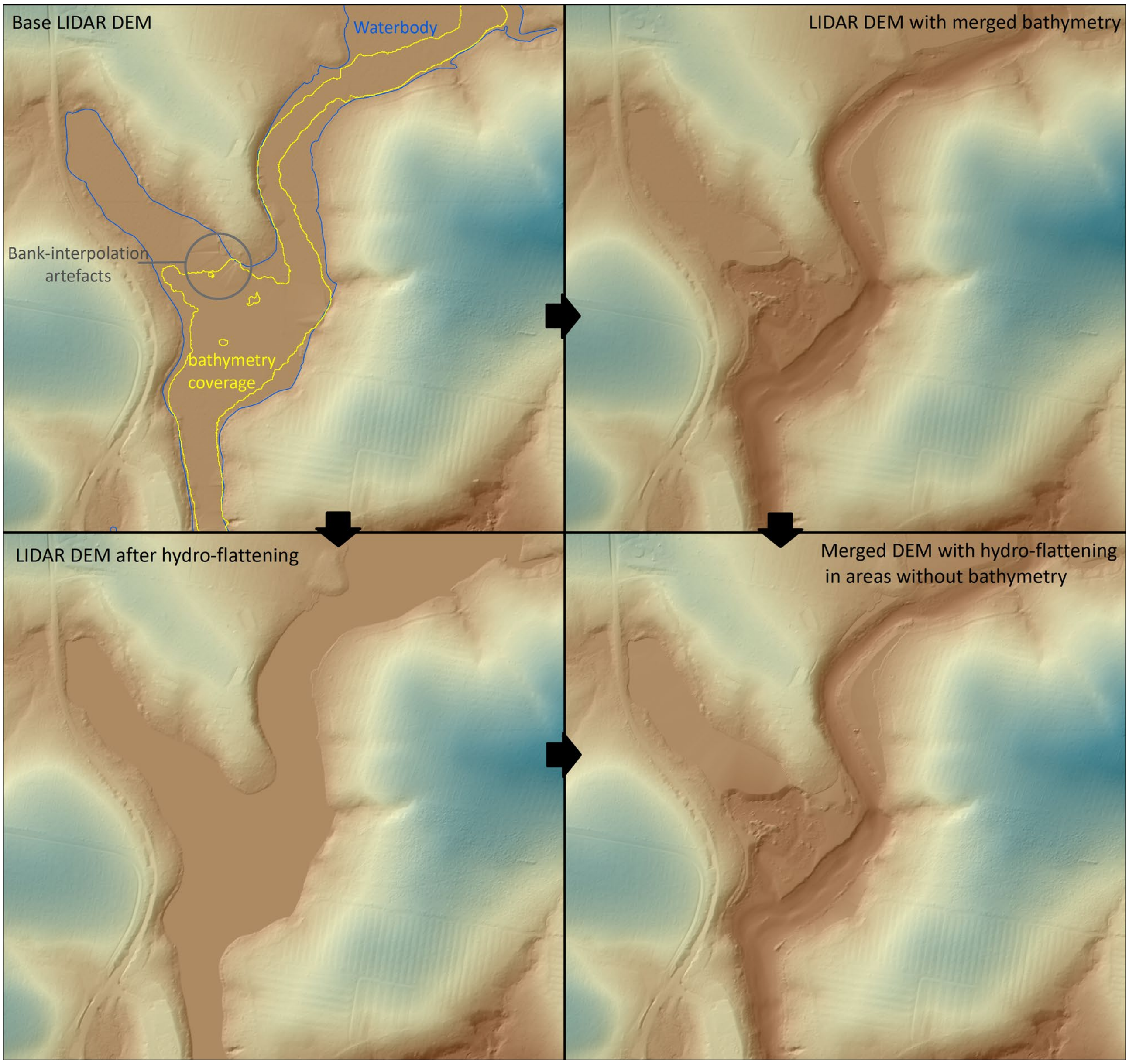


Figure 8 Steps for blending LiDAR and bathymetry data.

2.2.5 Flow control structures

When undertaking flood inundation modelling, it is important to process the DEM to maintain flow paths underneath structures such as bridges, culverts, and pipes, etc. The LiDAR data obtained from Fugro were Level 4 processed for bridges, which means the data were manually checked/edited to ensure they were correctly classified. However, culverts, on the other hand, are retained in the ground class as they are overlain with earth or soil and are therefore not removed from the DEM. Underground pipes are not detected by LiDAR, and are therefore neither used nor withheld in DEM creation. As DEM corresponds to the ground surface elevations, some underground water infrastructures such as culverts and pipes cannot be represented if the LiDAR-based DEM is directly used in the simulation. Using Google Earth, local field visits, and input from council technical staff, it was found that there are many culverts and pipes in the LiDAR domain. With the aid of Google Earth, and based on the information provided by local councils and collected during the field visit (multiple visits), those locations were identified. A DEM depression breaching tool from Whitebox Geospatial was also used to locate likely locations for culverts along the bigger roads and then the imagery captured with the LiDAR was used to decide whether those automated breaches were legitimate and located correctly. The LiDAR DEMs were manually edited to open the flow paths in those identified locations. All levee details were collected from the local councils and all data from the recent survey of the major levees undertaken after the 2022 floods (courtesy NSW Department of Public Works) are explicitly represented in the model mesh. The LiDAR collection started in July 2022 and was completed in late 2023. It provides an accurate representation of the Richmond River catchment landscape during this time. The Pacific Highway M1 development started in 2010 and continued incrementally until 2022. So, these time series of changes in the M1 infrastructure provided by Transport for NSW (courtesy Transport for NSW) is implemented in the model mesh. As such the model mesh structure in the vicinity of the M1 is slightly different for flood events in 2008 and 2009; 2013; 2017 and 2022 to correctly reflect M1 infrastructure in the model setups at the time of the flood events. The mesh elements for the model mesh for 2008, 2009, 2013, and 2017 are 10,192,388, and for 2022 there are 10,197,863 elements. The mesh for the first four events has exactly the same number of mesh elements and nodes, but has a slightly different placement of the nodes and varying elevation for those nodes along the M1.

2.2.6 Land use data

Land use map is used in inundation modelling to define surface roughness coefficients. The Land use of Australia 2020 (Figure 9), a product of the Australian Collaborative Land Use and Management Program (ACLUMP), was used to identify land use types within the modelling domains. ACLUMP is coordinated by ABARES (ABARES, 2021).

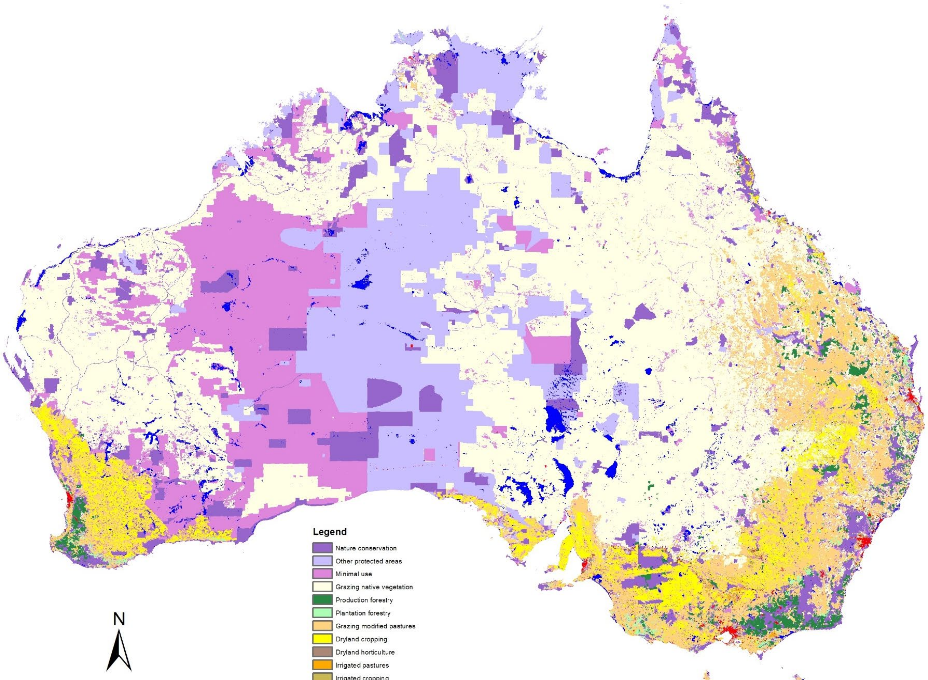


Figure 9 Land use of Australia 2020 ACLUMP (ABARES, 2021).

2.2.7 Soil characteristics data

There are a large number of soil physical property measurements across Australia, and various soil mapping studies have been undertaken to use the measurements, in order to estimate the soil types and produce maps of soil classifications. Soil maps for the Richmond River catchment are available from two main datasets, one from the NSW Department of Planning, Industry and Environment, and the other from the Terrestrial Ecosystem Research Network (TERN).

The NSW Department of Planning, Industry and Environment has developed a dataset that identifies the dominant soil types across NSW, which includes the entire Richmond River catchment, based on the Australian Soils Classification (Department of Planning, Industry and Environment, 2021). It uses available soil resource mapping coverage, incorporating over 55 different datasets of multiple scales across NSW.

Terrestrial Ecosystem Research Network (TERN) also has used Digital Soil Mapping (DSM) technologies combined with the real-time collations of soil attribute data, to produce a map of Australian Soil Classification soil order classes with quantified estimates of mapping reliability at a 90 m resolution (Searle, 2021).

As shown in Figure 10, the Richmond River catchment has a wide range of soil types including ferrosols in the northern reaches, kurosols in the west and south, and a mix of vertosols and dermosols throughout the mid reaches and hydrosol on the coastal plains around the town of Coraki (Beardmore et al., 2019).

CSIRO and the Australian Bureau of Meteorology have used a range of datasets including the TERN dataset, and implemented pedotransfer functions calibrated for Australian soils to estimate continental scale soil hydraulic properties (Dane and Puckett, 1994 for saturated hydraulic conductivity and Minasny et al.,1999 for available water content) (Vaze et al., 2018).

Figure 11 shows a data layer of saturated hydraulic conductivity obtained from this database for the Richmond River catchment at 1 km resolution. The estimated soil hydraulic properties were then modified using the land use layer to produce the infiltration layers to be incorporated as input data in the hydrodynamic model.

Figure 12 shows the modified land use data for Richmond River catchment that identifies urban areas (including roads), swamps, marshes, irrigated areas and permanent water bodies. This land use layer was used to modify the estimated soil hydraulic properties within the Richmond River catchment.

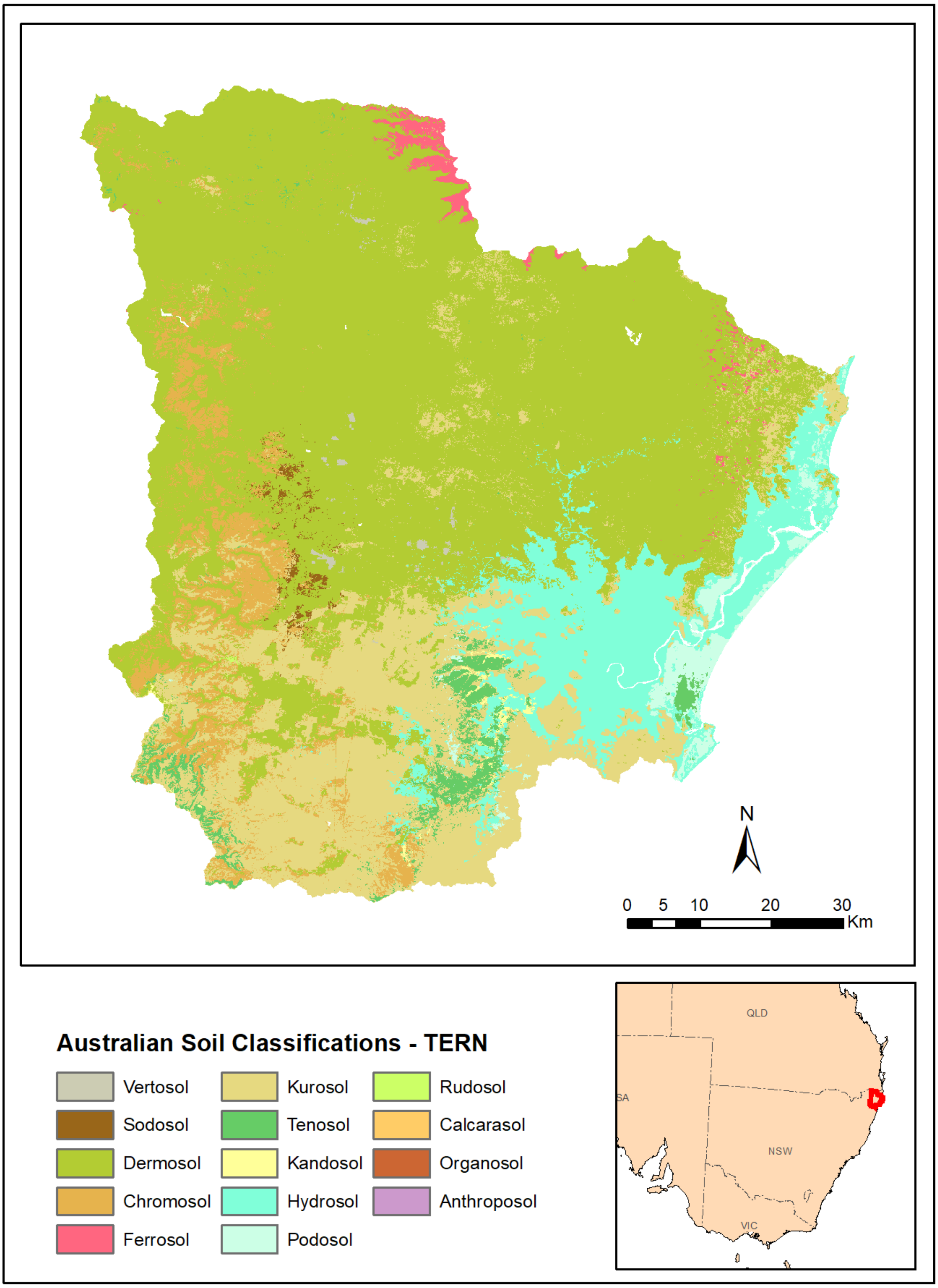


Figure 10 Soil map of the Richmond River catchment derived from TERN (Searle, 2021) showing the distribution of the various soil orders according to the Australian Soil Classification.

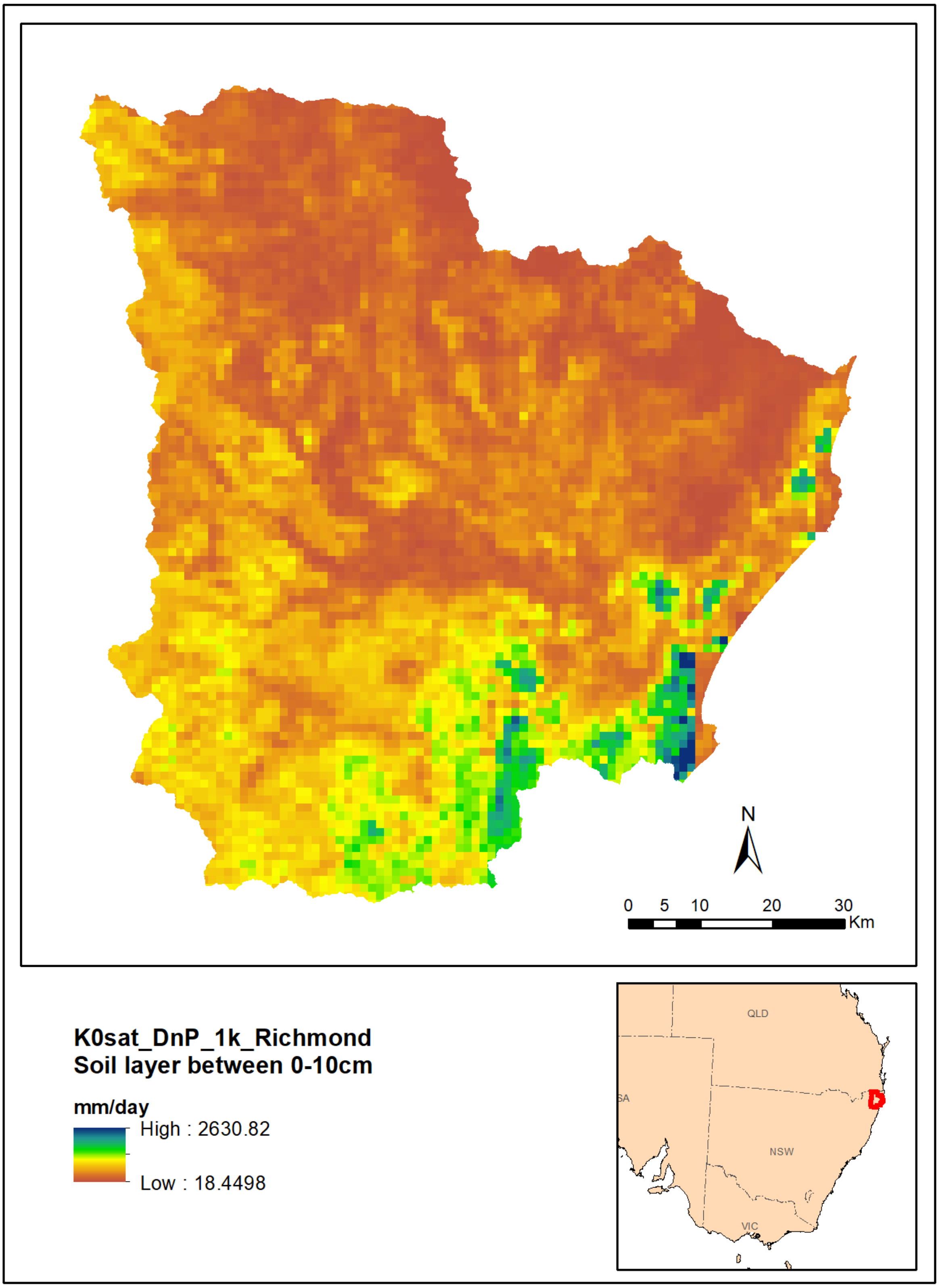


Figure 11 Saturated hydraulic connectivity of the soil layer between 0-10 cm within the Richmond River catchment.

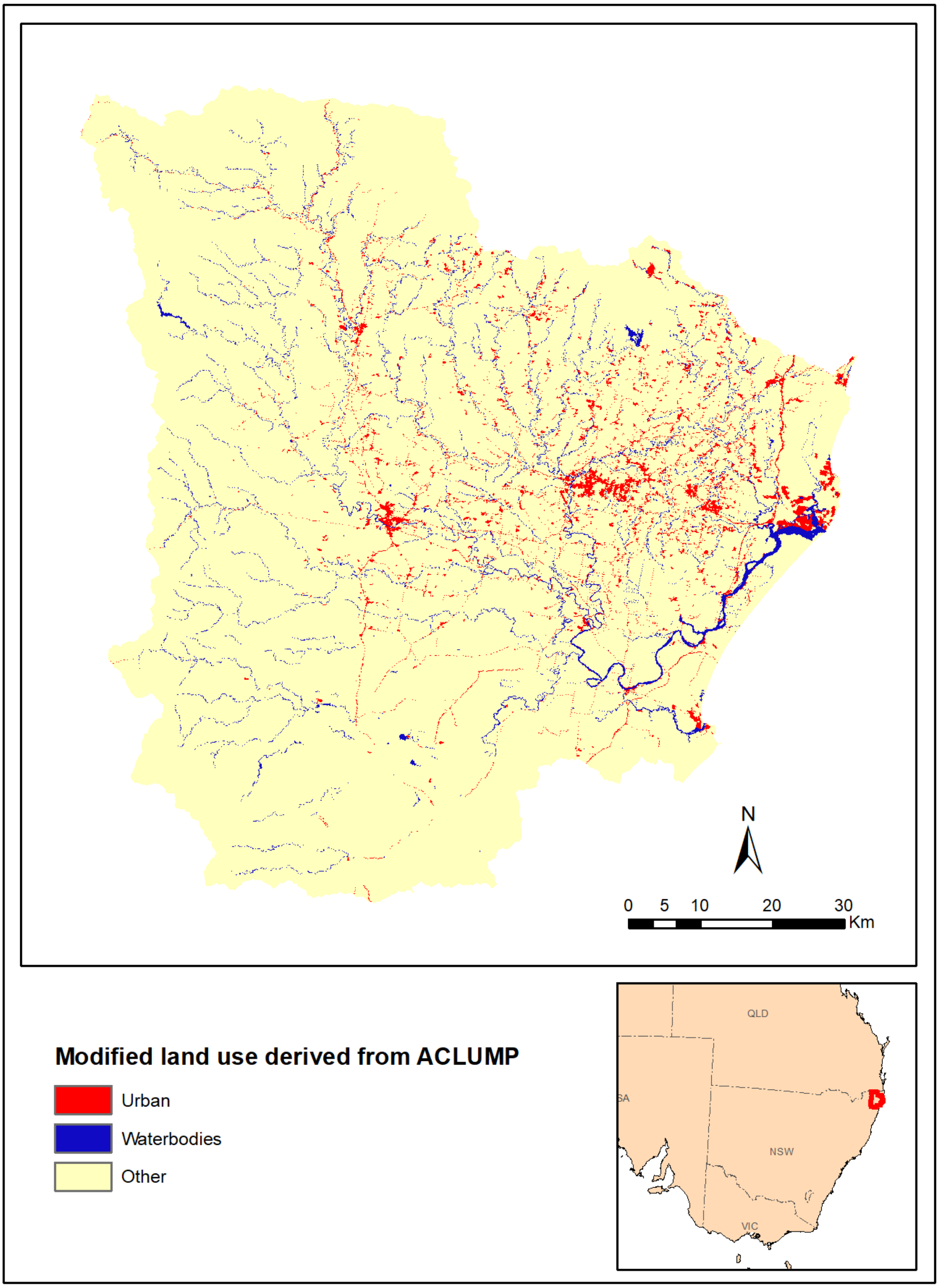


Figure 12 Modified land use of the Richmond River catchment, showing urban areas (including roads) and permanent water bodies.

2.2.8 Climate data

The climate data used as inputs for hydrodynamic modelling were spatial 1 km gridded hourly rainfall and daily potential evapotranspiration (PET). Due to the combination of the topographic and climate conditions, the Richmond River catchment is a rapid-response catchment prone to extreme and devastating floods. The annual rainfall in the Richmond River catchment can exceed 1800 mm per year, especially, with high rainfall intensities observed in the northeast and coastal areas (Lerat et al., 2022). There were 17 major flood events from 1945 to 2022, with a maximum daily rainfall of more than 60 mm per day (Lerat et al., 2022). The severe floods in 2017 (1 in 21 Annual Exceedance Probability (AEP) for Lismore) and 2022 (the largest observed flood event in the catchment on record) overtopped the levee in Lismore, causing loss of lives and serious damage to businesses and properties. When the catchment receives an excessive amount of rainfall in a few minutes or several hours, sub-daily and even sub-hourly precipitation data are required to capture the disparity of rainfall precisely (Davis, 2001; Ficchi et al., 2016; Westra et al., 2012). A higher temporal and spatial resolution representation of the rainfall data in the Richmond River catchment is essential for reliable flood modelling and mitigation in the region.

For the landscape within the Richmond River catchment (~7000 km^2), the rainfall-runoff module within the MIKE21 flexible mesh model is used to estimate the runoff for each mesh element (grid cell) at each modelling timestep. After collating and undertaking the suitability analysis for the available rainfall (few rain gauges spread across the catchment from different providers or the ~5 km daily rainfall surfaces available from the Australian Gridded Climate Data (AGCD) and Scientific Information For Land Owners (SILO) Jeffrey, et al., 2001.) it was found that a better spatial and temporal representation of rainfall will provide better simulations and more confidence in the results. To address this issue, the project team generated hourly rainfall at ~1 km grided surfaces across the Richmond River catchment using the available hourly rain gauge data and disaggregated daily rainfall totals using nearby hourly gauges and radar images. The hourly and daily rainfall data and the radar images were sourced from the Australian Bureau of Meteorology. Data for some stations in the higher rainfall areas upstream of Lismore were also used (courtesy of Rous County Council). The rainfall surfaces were generated using the ANUSPLIN program at a finer temporal and spatial resolution from 2007 to 2022. Initial checks against the hourly rain gauge data, continuous radar images and coarser available rainfall surfaces provide confidence that the newly generated rainfall surfaces represent the rainfall pattern and amounts across the Richmond River catchment and is suitable for undertaking detailed hydrodynamic modelling. Note that this was required to ensure reliable spatial and temporal rainfall representation across the Richmond River catchment, which is a critical input to the hydrodynamic model to simulate reliable and robust results.

Further details of the rainfall generation process, including input data used, selection and fitting of the splines, and validation of the results, is described in a published technical journal (Nguyen et al., 2024).

2.2.9 Hydrological data

The key hydrological datasets required for reliable floodplain inundation modelling are streamflow discharge or water levels at different gauging locations across the modelling domain, to be used for model validation. As already mentioned, the latest version of the 2D hydrodynamic model

(MIKE21 FM) implemented here uses spatial rainfall as input (rain on grid) rather than the conventional way of using observed streamflow as inputs. The model generates spatial runoff on each grid at every time step and routes it through the catchment. Available hydrological gauge stations at key locations with reasonable data availability and quality were identified such that we have the validation gauges representing every part of the overall catchment. Two observed gauge data closest to the river mouths were used as boundary conditions for modelling purposes – the water level at Evans Head (H558048) and the water level at Ballina Breakwall (203425). Where data was missing, the water level data at Evans Head was filled with data correlated with Byrnes Point (also referred to as Burns Point) (203461) and that of Ballina Breakwall with Missingham Bridge station (203465). The gauges used for in-filling were chosen based on correlation statistics, proximity, and reliability of the gauge data. Table 2 shows the list of water level gauges that were used for validating results from the hydrodynamic model for the Richmond River catchment. Figure 13 shows the location of these eight gauges where the model simulated hourly water levels are compared with the observed water levels for the five selected historical flood events.

Table 2 Gauges used for validating the results from the hydrodynamic model for the Richmond River catchment.

Position	Gauge name	Gauge ID
Upstream of Lismore	Leycester Creek at Tuncester	203443
Upstream of Lismore	Wilson River at Woodlawn College	203402
At Lismore	Wilson River at Lismore	H058176
Downstream of Lismore	Wilson River at East Gundurimba	203427
At Casino	Richmond River at Casino	203004
At Coraki junction	Richmond River at Coraki	203403
At Wardell	Richmond River at Wardell	203468
At Byrnes Point Ballina	Richmond River at Byrnes Point	203461

The gauge at Leycester Creek (203443) is used to validate the correctness of the flow contributions from the northwest of Lismore, which include key areas such as the Terania Creek, The Channon, Nimbin, and Rock Valley. The gauge at Wilson River (203402) is useful for validating the flow contribution from the northeast of Lismore, which includes the areas of Upper Wilsons Creek, Upper Coopers Creek, Eureka, Eltham, Woodlawn, and Richmond Hill. The gauge at Lismore (H058176) is located close to the confluence of the Wilson River and Leycester Creek, and to the CBD of Lismore. The Lismore gauge is useful for validating the flows coming from North Lismore, Browns Creek, and Lismore CBD. The gauge located a bit further downstream of Lismore CBD (203427) is useful for validating the flows coming from the Lismore airport, and the flows into the Gundarimba Canal. The gauge at Casino (203004) validates the correctness of flows into most of the northwest of Richmond, which includes the areas of the Border Ranges, Kyogle, Iron Pot Creek, and the Casino town. The Coraki gauge (203403) is located in the town, downstream of the confluence of the Richmond River coming from Casino side and Wilson River coming from Lismore side which makes it useful for validating the combined flows from those rivers. The gauge at

Wardell (203468) is useful for validating flows coming from the Bungawalbin area, Woodburn, East Coraki, and the Tuckean area. The gauge at Byrnes Point (203461) is useful for validating flows coming from all the area downstream of Wardell until Byrnes Point and this gauge is the last reliable gauge with reasonable data most downstream in the Richmond River catchment. Most of the water level data has been collated from the WaterNSW, Bureau of Meteorology and Manly Hydraulic Laboratory data bases. The water level data at the Evans Heads and Ballina outflow was used to enforce the downstream boundary condition at the ocean outlet.

Figure 13 Location of the eight internal gauges where the model simulated hourly water levels are compared with the observed water levels for model validation.

3 Modelling method and model setups

3.1 Two-dimensional hydrodynamic model – MIKE21 FM

The hydrodynamic module of the MIKE21 Flow Model FM of MIKE ZERO 2024 for Linux (hereafter referred to as MIKE21 FM) is based on the numerical solution of the two-dimensional incompressible Reynolds averaged Navier-Stokes equations, assuming hydrostatic pressure. Primitive variable equations are discretised using an element-centred finite volume method. The spatial domain is discretised into non-overlapping elements, which can be either triangular or quadrilateral (DHI, 2024). The finite volume method sets up an Equivalent Riemann Problem (ERP) across each element interface and solves it to determine the variable fluxes between elements. The technique used in MIKE21 FM applies the HLLC scheme (approximate Riemann solver) by Toro et al (1994). This scheme significantly improves the results for the velocities in areas with steep gradients in the bathymetry, for example, along riverbanks and steep slopes near the hill-tops and shoreline. The approach treats the problem as one-dimensional in the direction perpendicular to each element interface (Guinot, 2003).

MIKE21 FM has two options for time integration accuracy, with these being a first-order explicit Euler method (referred to as the lower temporal order scheme), and a second-order Runge Kutta method (referred to as the higher temporal order scheme). There are also two options for spatial integration, with the second order (higher order) accuracy being achieved through a variable gradient reconstruction technique prior to the ERP formulation (DHI, 2024). In this assessment the latest version of the flexible mesh model (MIKE21 FM) with GPU support and for Linux application was used for modelling the entire Richmond River catchment for floodplain inundation modelling. The use of GPU and Linux applications allow for higher and faster computational capabilities which are necessary to run the model for the entire Richmond River catchment at high spatiotemporal resolutions. The model developed for this assessment uses spatial rainfall as input (rain on grid) rather than the conventional way of using observed streamflow as inputs. The model generates spatial runoff on each grid across the entire Richmond River catchment at every time step and routes it through the catchment. This version of the model also accounts for spatial and temporal soil infiltration and soil moisture based on measured spatial soil properties and does not need any initial and continuing losses to be calibrated for each flood event.

The flexible mesh model is preferable over the classic MIKE21 regular grid model when highly detailed elevation data (e.g. LiDAR) are available because the model allows the selection of very small mesh elements for the area of interest and the alignment of mesh nodes to relevant physical features (i.e. riverbanks and relevant structures such as weirs, levees, and elevated roads).

In this modelling exercise, the MIKE21 FM was set up for five historical flood events (1 in 8 year return period – 2008; 1 in 12 year return period – 2009; 1 in 7 year return period – 2013; 1 in 21 year return period – 2017; maximum observed and two peaks – 2022 respectively at Lismore). Although the focus of the project is on reproducing larger flood event peaks (e.g., 2017, 2022), a full range of flood events, from small to the maximum observed were selected to investigate and demonstrate the ability of the developed model to simulate flood behaviour across the entire

Richmond River catchment for the complete range of floods. Note that the model setups, as well as all physical parameters such as soils and surface roughness, are the same for all of these events. The only differences between the event model setups are the event rainfall, the initial soil wetness for the event, potential evapotranspiration, and slight modifications of the mesh (only along the M1 highway where structural and terrain changes were made from 2008 to 2022).

3.2 Setting up of MIKE21 FM hydrodynamic model

This is the first time a detailed hydrodynamic model has been developed for the entire Richmond River catchment. This is necessary to investigate the impacts of any flood mitigation interventions in the catchment on the overall catchment response (any intervention applied upstream will have downstream impacts). Given the large area covered by the modelling domain and the very complex sections of steep and flat terrain, it was not possible to represent all small streams and channels while keeping the total number of mesh elements to about 10 million (note that to keep the total number of mesh elements within this limit, the model has limited capability in representing very small streams especially in the very upstream areas). The model is set up to represent the entire modelling domain and is suitable for understanding the floodplain dynamics at the scale of the modelling domain. Every attempt has been made to make sure that all important streams, levees, flow control structures such as bridges, culverts, and pipes, etc. across the entire catchment are explicitly represented in the model.

As evaporation and infiltration processes were included in the MIKE21 FM hydrodynamic model, transmission losses along the rivers and losses due to infiltration and open water evaporation from the inundation areas are considered in the modelled flows and inundation extents. Hence, the simulation results represent the actual field observed water levels and inundation extent and can be compared with gauge observations and remote sensing images.

The 2D hydrodynamic model has been setup using a flexible mesh approach of the MIKE21 FM model. In this approach, finer resolution mesh is used for the key areas representing the streams and floodplain and the less flood-prone areas are represented by coarser mesh. The modelling domain is divided into roughly five zones – major streams, minor streams, low-lying floodplain which often gets flooded, surrounding floodplain which usually gets flooded, and the rest of the floodplain which seldom gets flooded. All major infrastructure is also considered explicitly. The maximum floodplain extent map derived from Landsat imagery (by combining all 1 in 2, 1 in 5, 1 in 10 and 1 in 20 year events) was used to define the mesh resolution across the floodplains. Very detailed high-resolution mesh is used for the major streams to represent the stream conveyance capacity accurately and the mesh is gradually coarsened across the other four zones. The main aim in setting up the model mesh is to get the most accurate representation of the floodplain as possible while making sure that the total number of mesh elements stays within the limits of what the model can handle, and the simulation times also remain realistic. These decisions have been taken to service a compromise between the level of detail in the model (i.e. the number and size of mesh elements) and the model computation duration (i.e. model run time). This approach ensures the development of a fit-for-purpose model with spatial resolutions that are suitable to represent most of the important streams, floodplain channels, terrain characteristics and other water infrastructure in sufficient detail.

A series of simulations were carried out for the model, iteratively refining the representation of flow pathways for smaller streams in the mesh to improve the match of simulated flood levels at the internal gauges and model simulated floodplain inundation extents with the remote sensing flood maps. The final mesh network for the entire domain for the Richmond model is shown in Figure 14. Figure 15 presents zoomed in snapshots which show the gradual coarsening of the mesh from very fine to coarser elements for key locations in the Richmond River catchment. The model has a total of 10,197,863 mesh elements and all key features on the landscape within the catchment are appropriately represented in the model mesh.

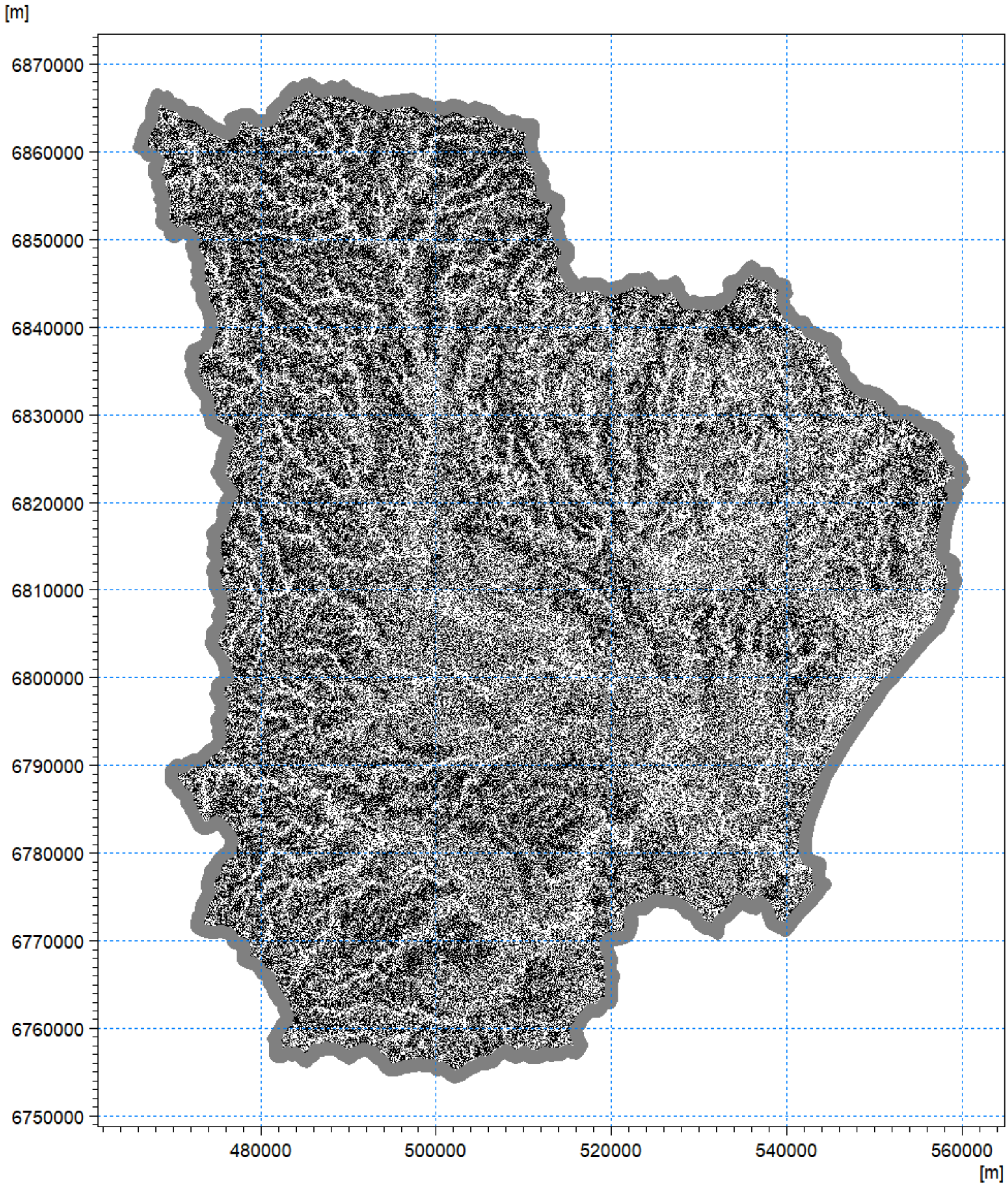
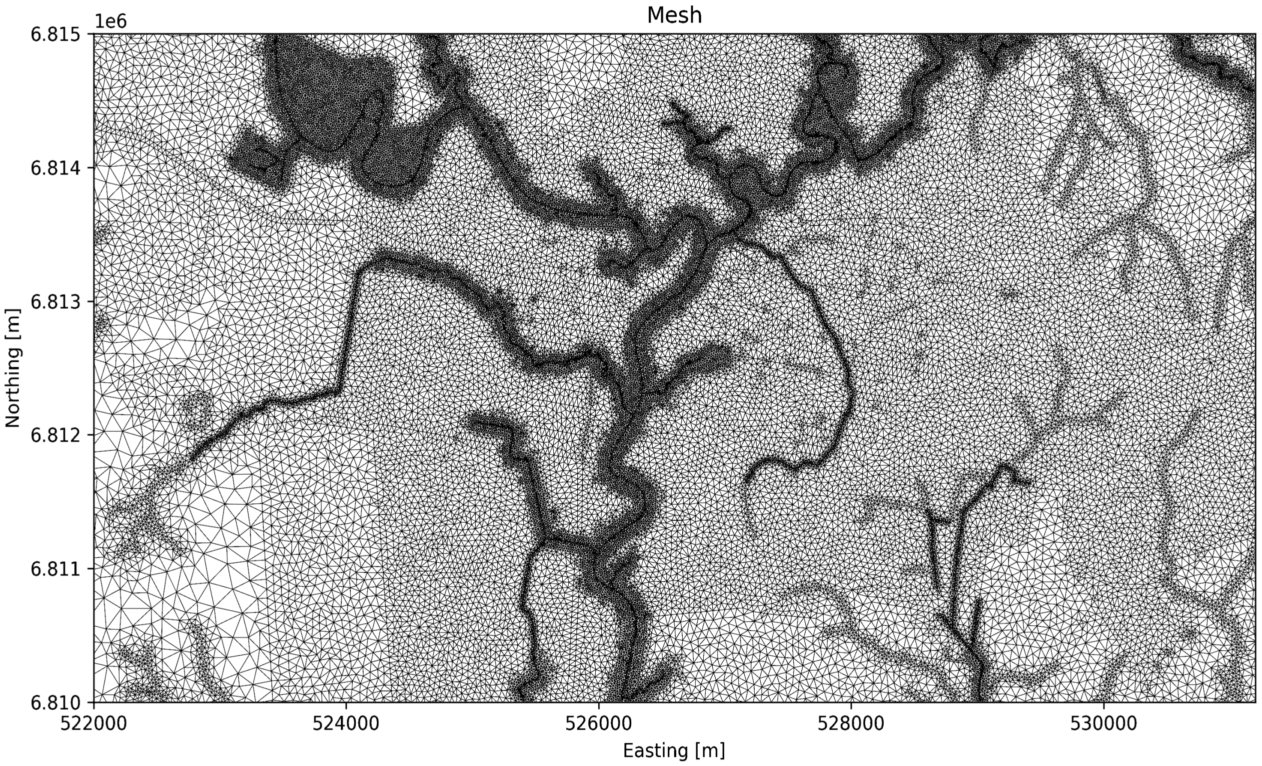
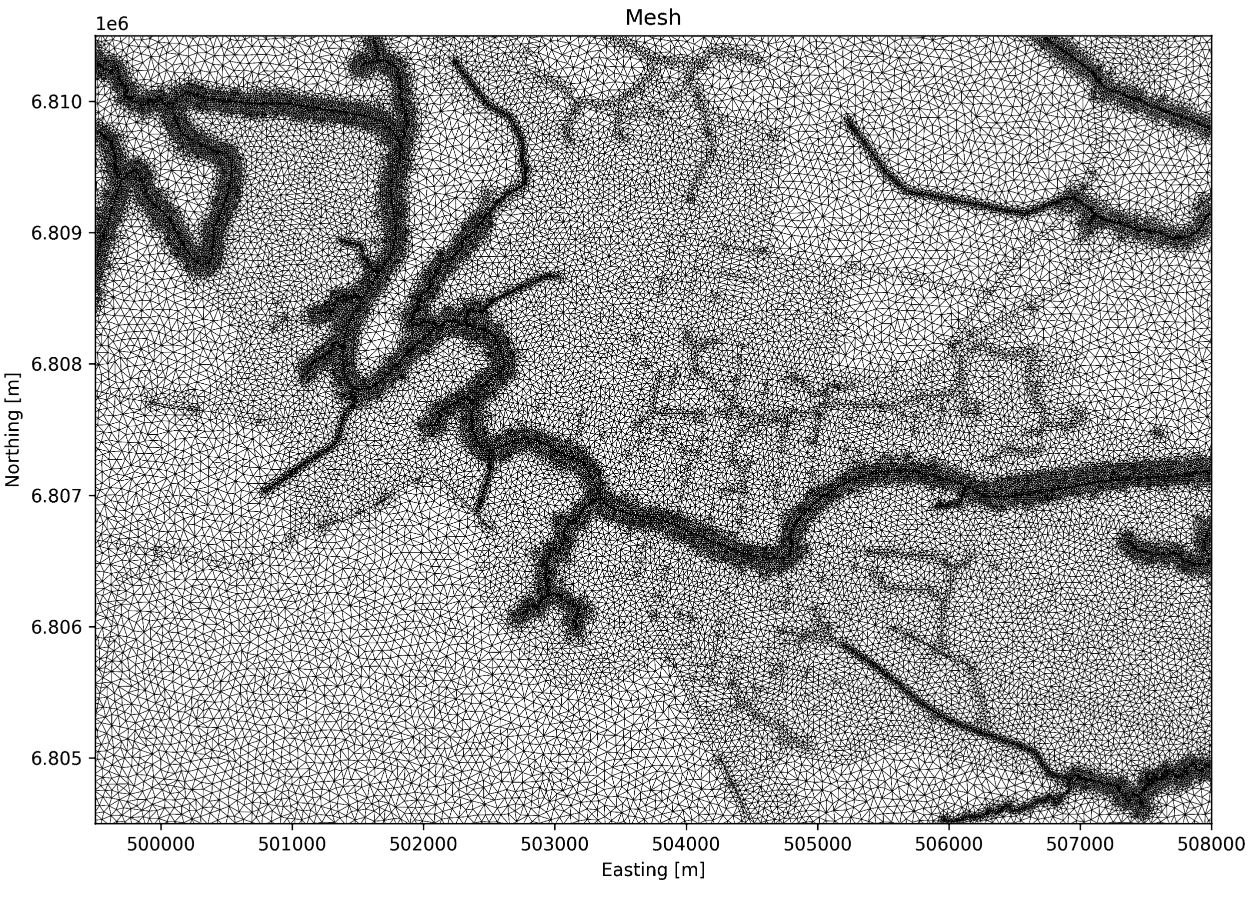


Figure 14 Final mesh network used in the MIKE21 FM model for the Richmond River catchment modelling domain, which has 10,197,863 mesh elements (darker colour means finer mesh).

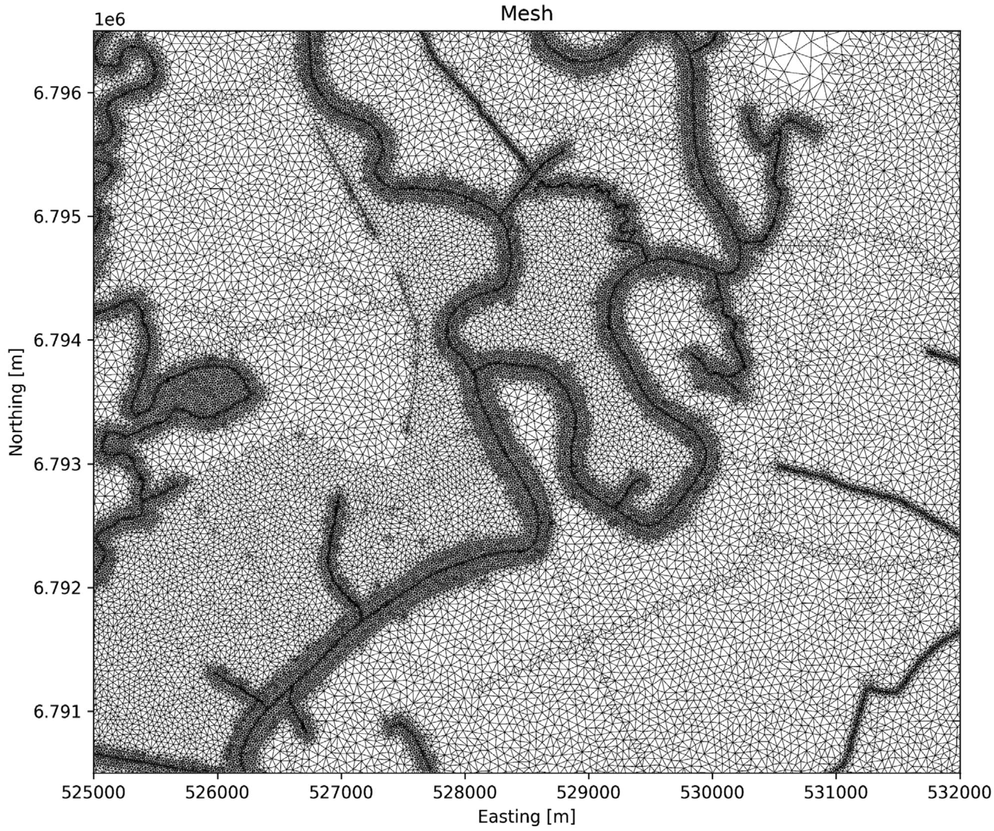
(a) Lismore junction



(b) Casino



(c) Coraki



(d) Ballina outlet

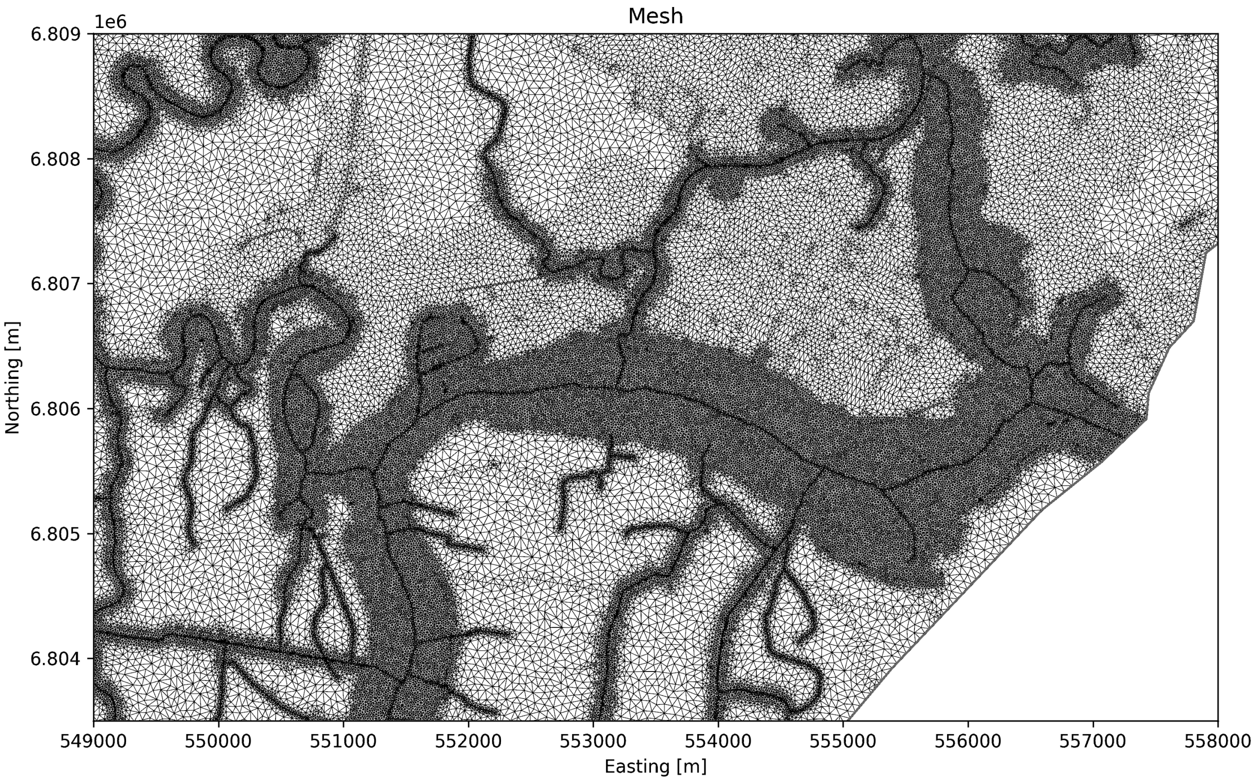


Figure 15 A zoomed in view of (a) Lismore junction, (b) Casino, (c) Coraki and (d) Ballina outlet mesh elements (gradual coarsening) of the MIKE21 FM model mesh (darker colour means finer mesh).

Hydrodynamic models are data intensive. A large amount of temporal and spatial data is required for setting up a hydrodynamic model for detailed and reliable floodplain inundation simulation. Data needed to setup this version of the MIKE21 FM model include:

i) Spatial rainfall data
ii) Topography data (LiDAR and bathymetry)
iii) Surface roughness data
iv) Initial surface water levels
v) Initial soil moisture across the catchment
vi) Infiltration layers (sourced from soils data, section 2.2.7)
vii) Evaporation (sourced from Bureau of Meteorology, section 2.2.8)
viii) Boundary conditions

The next subsections describe the first five data sets listed above. The last two data sets have been described in the previous sections.

3.2.1 Spatial rainfall data

Reliable spatial and temporal rainfall representation across the modelling domain is a critical input to the hydrodynamic model to simulate reliable and robust results. After collating and undertaking the suitability analysis for the available rainfall data for the catchment it was found that a better spatial and temporal representation of rainfall will provide better simulations and more confidence in the results. To address this issue, the project team generated hourly rainfall at ~1 km gridded surfaces across the Richmond River catchment using the available hourly rain gauge data and disaggregated daily rainfall totals using nearby hourly gauges and radar images. The hourly and daily rainfall data and the radar images were sourced from the Bureau of Meteorology. Data for some stations in the higher rainfall areas upstream of Lismore were also used (courtesy of Rous County Council). The rainfall surfaces are generated using the ANUCLIM techniques (Hutchinson and Xu, 2001) and at a fine temporal and spatial resolution from 2007 to 2022. This data was used to undertake detailed hydrodynamic modelling for the Richmond River catchment.

3.2.2 Topography data

LiDAR and bathymetry merged data was used in the modelling and the details of LiDAR and bathymetry data processing are explained in Chapter 2. The 1-m resolution merged LiDAR and bathymetry data was used to extract the node elevations for the flexible mesh for the modelling domain. In generating the flexible mesh, higher resolution mesh is used for the areas of the key rivers and low-lying floodplains identified from the maximum inundation water map by combining all of the relevant remote sensing images. As described earlier, multiple methods were used to identify and open the flow paths below culverts/pipes and bathymetry for several large permanent storages/waterholes and perennial stream sections where the LiDAR DEM was not able to penetrate the standing water was stitched with the 1-m LiDAR DEM to generate the final DEM to be used for hydrodynamic modelling.

3.2.3 Surface roughness data

Surface roughness is a tuning parameter in hydrodynamic modelling. The initial roughness values for the modelling zones within each domain were assigned based on the land cover map. Manning's roughness coefficients within the range of suggested values in existing reports were used for each land use type. Table 3 presents the initial values of the roughness coefficient used for different land cover types.

The surface roughness in streams was tuned such that the advancement of the in-stream flood and simulated overland flood extents reasonably matched the observations.

Table 3 Manning's roughness coefficients for different land cover types.

	Manning's roughness coefficient
Lakes	0.020
Grasses (closed)	0.040
Grasses (open)	0.05
Shrubs (closed)	0.055
Shrubs (open)	0.045
Shrubs/grasses (scattered)	0.040
Trees (closed)	0.085
Trees (open)	0.070
Trees (scattered/sparse)	0.060
Wetlands	0.045
Others	0.050

3.2.4 Initial surface water levels

The initial water surface along the river network and in the water storages/barrages used as the starting condition for the modelling domain were generated by adding the hydro-flattened DEM elevations to the dry LiDAR merged bathymetry. Remote sensing images which are available before the start of each event, were used to fine tune the initial water surface data used as inputs for each event. It is really important to get the initial conditions right, as some of the water storages have large storage capacity which greatly affects the flows across the river networks and floodplains. The initial water levels in the perennial streams were initialised as described above at the start of the warmup simulation (see next subsection below) and allowed to equilibrate over the warmup period.

3.2.5 Initial soil moisture across the catchment

It is important to get the initial spatial soil moisture status correct across the entire modelling domain for the version of MIKE21 FM used in this work. As mentioned earlier, the model uses spatial rainfall as input (rain on grid) and generates spatial runoff on each grid at every time step and routes it through the catchment. The model accounts for spatial and temporal soil infiltration and soil moisture based on measured spatial soil properties and does not need any initial and continuing losses to be calibrated for each flood event separately. We are using the 2-monthly accumulated spatially distributed rainfall to estimate the initial soil moisture and account for the antecedent conditions for each event. The spatial soil moisture estimates, along with other infiltration layers were used to run the model with at least a week of warmup period prior to the start of each event. The model estimates the spatial soil moisture for all mesh elements across the modelling domain to be used at the start of each flood event.

3.3 Selection of flood events for setup/validation of MIKE21 FM

Although the purpose of this modelling is to set up a Richmond scale detailed hydrodynamic model to focus on large floods, especially like the 2017 and 2022 floods in Lismore, we have selected a full range of historical floods ranging from 1 in 7 years (small) to the largest observed (2022). Also, the two separate 2022 events (end of February and end of March) were specifically modelled as one event to demonstrate the ability of the developed model to undertake continuous simulations. As described earlier, the same model physical setup is used for all flood events and the only difference will be the input climate and initial soil moisture. This is to demonstrate that the model can simulate the complete range of flood events across the catchment.

Timeseries of continuous daily observed water level data are available for a reasonable period at many gauging stations across the Richmond River catchment. It is advised to undertake flood frequency analysis using streamflow data but given most of the gauges in the region have tidal impact, and no streamflow data is available. So, water level data was used to get the rough estimates of return period. Most of the water level data has been collated from the WaterNSW, Bureau of Meteorology and Manly Hydraulic Laboratory data bases. Flood frequency analysis was undertaken to determine all the associated return periods (1 in 2 to the largest) for every flood event at these eight gauges for the period 1972 to 2022. Based on analysis of the historical data and consultations with the councils and community a total of five flood events were selected making sure we have the maximum possible observed data at the validation gauges for these events. The five events are 1 in 8 year return period/AEP – 2008; 1 in 12 year return period/AEP – 2009; 1 in 7 year return period/AEP – 2013; 1 in 21 year return period/AEP – 2017; maximum observed and two peaks – 2022 respectively at Lismore (Table 4).

Table 4 Flood events used for model setup and validation.

Flood event	Year	Flood frequency (Lismore)	Flood frequency (Ballina)	Flood frequency (Casino)	Peak flow (Lismore)	Period of inundation modelling
1	2008	1 in 8 years	1 in 5 years	1 in 48 years	6 Jan 2008	29/12/2007 to 20/01/2008
2	2009	1 in 12 years	1 in 12 years	1 in 10 years	22 May 2009	16/05/2009 to 08/06/2009
3	2013	1 in 7 years	1 in 6 years	1 in 3 years	30 Jan 2013	26/01/2013 to 11/02/2013
4	2017	1 in 21 years	1 in 8 years	1 in 7 years	31 Mar 2017	26/03/2017 to 15/04/2017
5	2022 (Two events) Feb 2022 March 2022	Maximum observed NA (no data)	1 in 113 years 1 in 19 years	1 in 159 years 1 in 4 years	28 Feb 2022 31 Mar 2022	20/02/2022 to 15/04/2022

As can be seen from the return periods and the shape of the hydrographs (section 4.1.1), the magnitudes and characteristics of the selected flood events vary significantly with flow ranging from low to moderate to very high flows with different rates of rise and fall. These contrasting events were specially selected to evaluate the performance of the model for different magnitude flood events with very different flood characteristics.

4 Results and Discussion

The simulation results from the hydrodynamic model for the five historical flood events are presented and discussed. Eight flow gauges at key locations representing all parts of the Richmond River catchment are selected for model validation. This is done to investigate the capability of the developed model to simulate flows that match the observed flows at all key locations across the entire Richmond River catchment, and to provide confidence in the implemented model and the outputs. This is also done to investigate that the model is representing the flows across the catchment and the match at any particular stream gauge is not due to compensating errors within the catchment for the complete range of flood events.

4.1 Results and discussion

There are three possible datasets which can be used for model validation, including water level measurements/observations at flow gauges, remote sensing derived flood inundation extents, and on-ground measurements by local agencies and community members. The water level measurements at river gauges are the most reliable data as it is measured. The remote sensing derived flood inundation extents are a derived/modelled product, and normally provides a reasonable understanding of the flood propagation and flooding patterns across the catchment but exact locations can be less accurate due to errors in the classification of water at the pixel level. The on-ground measurements are a useful dataset which provides insights into flooding at various locations within the catchment at certain time when the measurement was recorded, but is subject to discrepancies. All available datasets are used for model validation.

- Measured water level data at internal flow gauges spread across the catchment
- Remote sensing images
- On-ground validation with locals using community data

4.1.1 Validation at river gauges

The MIKE21 FM simulated water level at various validation gauges across the model domain are compared to observed water levels, where available for the five flood events. Table 5 presents the coefficient of determination (R^2) and Nash-Sutcliffe Efficiency (NSE) values for the simulated and observed hourly water levels for the five selected flood events at eight internal validation flow gauges. The time series of hourly model simulated and observed water levels are also plotted together for visual comparisons.

The R^2 and NSE values for the simulated and observed hourly water levels for the five selected flood events at all the eight internal validation flow gauges was calculated to determine how well the model can reproduce the observed water levels at an hourly time step. The statistics for those gauges and events where there is no observed data are presented as NaN. The Lismore gauge (H058176) has hardly any complete observed records and only the patchy data in 2017 can be used to undertake this analysis. As can be seen from Table 5, the model was able to reproduce both the magnitude and timing of all the selected events (from 1 in 7 years to the maximum observed at Lismore) quite accurately with hourly NSE values between 0.79 and 0.99. The 2022 flood has two peaks separated by nearly one month and the first peak represents the maximum observed flood at Lismore. It is a very complex event to simulate, especially when undertaking a continuous simulation but the R^2 and NSE values at all the gauges for 2022 multi-peak flood event clearly show that the model is robust and accurate and can reproduce observed water levels across the Richmond River catchment extremely well. The overall results show good agreement between the simulated and observed water level for all the flood events with both R^2 and NSE values always above 0.80 at most of the gauges.

Table 5 Statistics of comparison between the simulated and observed water levels at all gauges.

Flow Gauge	Flood event	2008		2009		2013		2017		2022	
	Evaluation metrics	R^2	NSE	R^2	NSE	R^2	NSE	R^2	NSE	R^2	NSE
203443		0.979	0.957	NaN	NaN	0.955	0.946	0.984	0.978	0.983	0.966
203402		0.983	0.955	0.971	0.962	0.942	0.937	0.989	0.979	0.983	0.962
H058176		NaN	NaN	NaN	NaN	NaN	NaN	0.991	0.984	0.974	0.955
203427		0.990	0.970	0.979	0.974	0.947	0.939	0.992	0.984	0.978	0.970
203004		0.925	0.902	0.985	0.981	0.952	0.942	0.948	0.935	0.971	0.940
203403		0.943	0.804	NaN	NaN	NaN	NaN	0.988	0.967	0.981	0.938
203468		0.976	0.939	0.938	0.928	0.883	0.851	0.975	0.966	0.959	0.953
203461		0.922	0.902	0.900	0.813	0.883	0.795	0.887	0.837	0.936	0.900

Figure 16, Figure 17, Figure 18, Figure 19, and Figure 20 show the hourly comparison between the simulated and observed water levels for the flood events in 2008, 2009, 2013, 2017, and the two flood events in 2022 at all eight internal gauges. The results show that the agreement between the simulated and observed water levels is good for all events at all gauges spread across the Richmond River catchment.

The 2008 flood event is a small event for Lismore (1 in 8 years) and other areas, but it is reasonably large for Casino (1 in 48 years). As described earlier, the 2-monthly accumulated spatially distributed rainfall was used to estimate the initial soil moisture and account for the antecedent conditions for the event. The spatial soil moisture estimates, along with other infiltration layers, were used to run the model with at least a week of warmup period prior to the start of the event. The model estimates of spatial soil moisture for all mesh elements across the modelling domain at the end of the warmup simulation were used at the start of the flood event. Figure 16 shows the comparison between the observed and simulated water levels at all eight internal flow gauges used for model validation. As can be seen from the plots, the model can reproduce the water levels at gauges 203443 and 203402 on the Leycester Creek and the Wilson

River upstream of Lismore junction quite accurately. There is no observed water level data available at the Lismore gauge (H058176) and the model simulated water levels match well with the observations at 203427 East Gundurimba for the available period. The match at 203004 Richmond River at Casino is a bit poorer and there is also slight difference in the flood peak arrival time between the two results (~ 4 hours). The results at 203403 Richmond River at Coraki are also good when observations are available. The model simulated water levels at 203468 Wardell and 203461 Byrnes Point match observed flows reasonably accurately. The overall results for 2008 flood event show that the model can reproduce observed water levels across the Richmond River catchment for a minor flood event quite well.

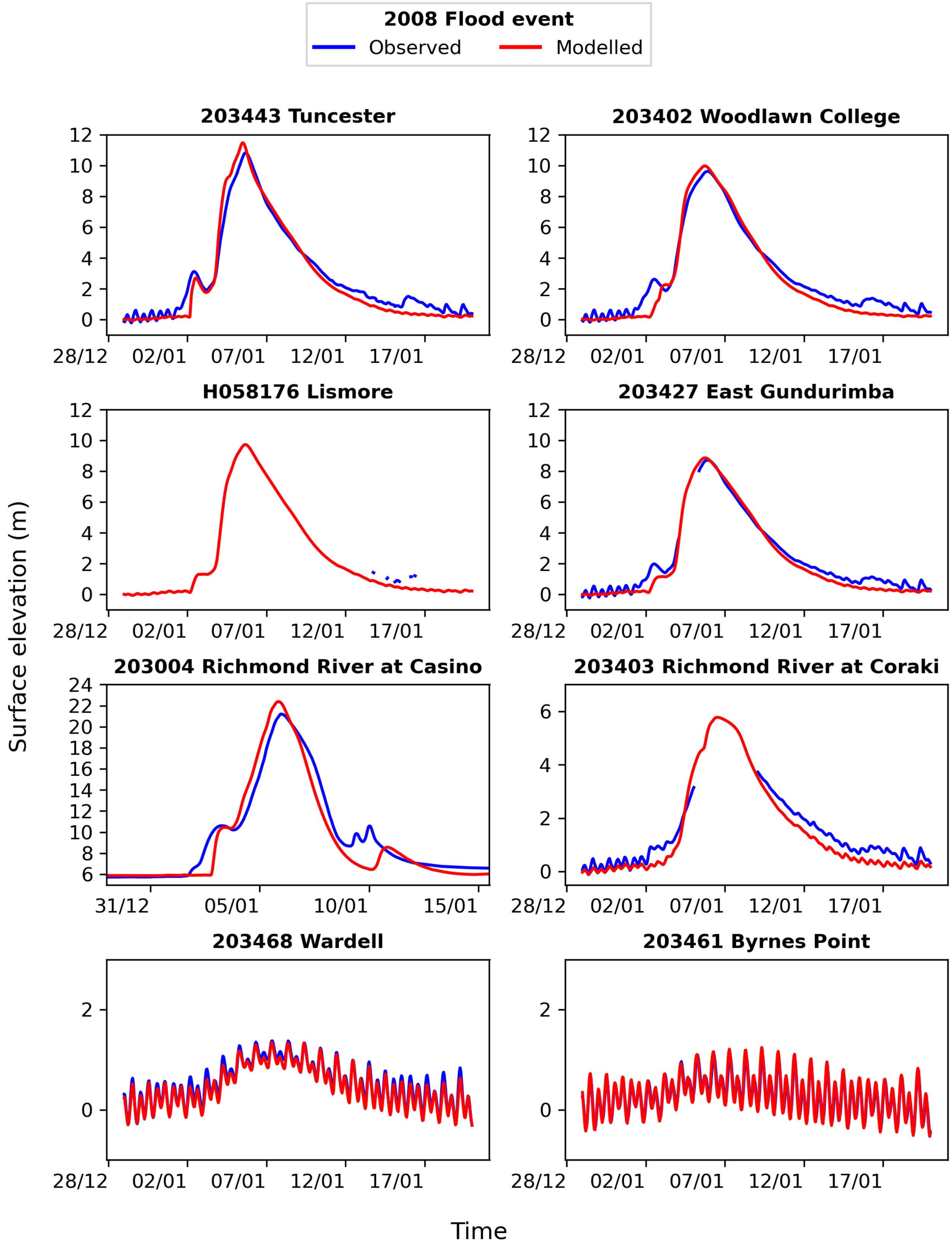


Figure 16 Comparison between the simulated water level and observed water level at all the selected gauges for the flood event of 2008.

The 2009 flood is a small to medium event for Lismore (1 in 12 years) and other areas (Casino 1 in 10 years and Ballina 1 in 12 years). Figure 17 show the comparison between the observed and model simulated water levels at all the eight internal validation gauges for the 2009 event. As can be seen from the plots, the model can reproduce the water level at gauge 203402 on Wilson River upstream of Lismore junction quite accurately. There is no observed water level data available at the Leycester Creek (203443) and Lismore gauge (H058176) and the model simulated water levels match very well with the observations at East Gundurimba (203427), as also indicated by the NSE value of 0.977. The match at 203004 Richmond River at Casino is very good for both the larger and smaller peaks and there is no observed water level data for Richmond River at Coraki (203403) for this event. The model simulated water levels at 203468 Wardell match the observations reasonably well and 203461 Byrnes Point water level is reproduced by the model accurately. The results for 2009 flood event again show that the model can reproduce observed water levels across the Richmond River catchment well.

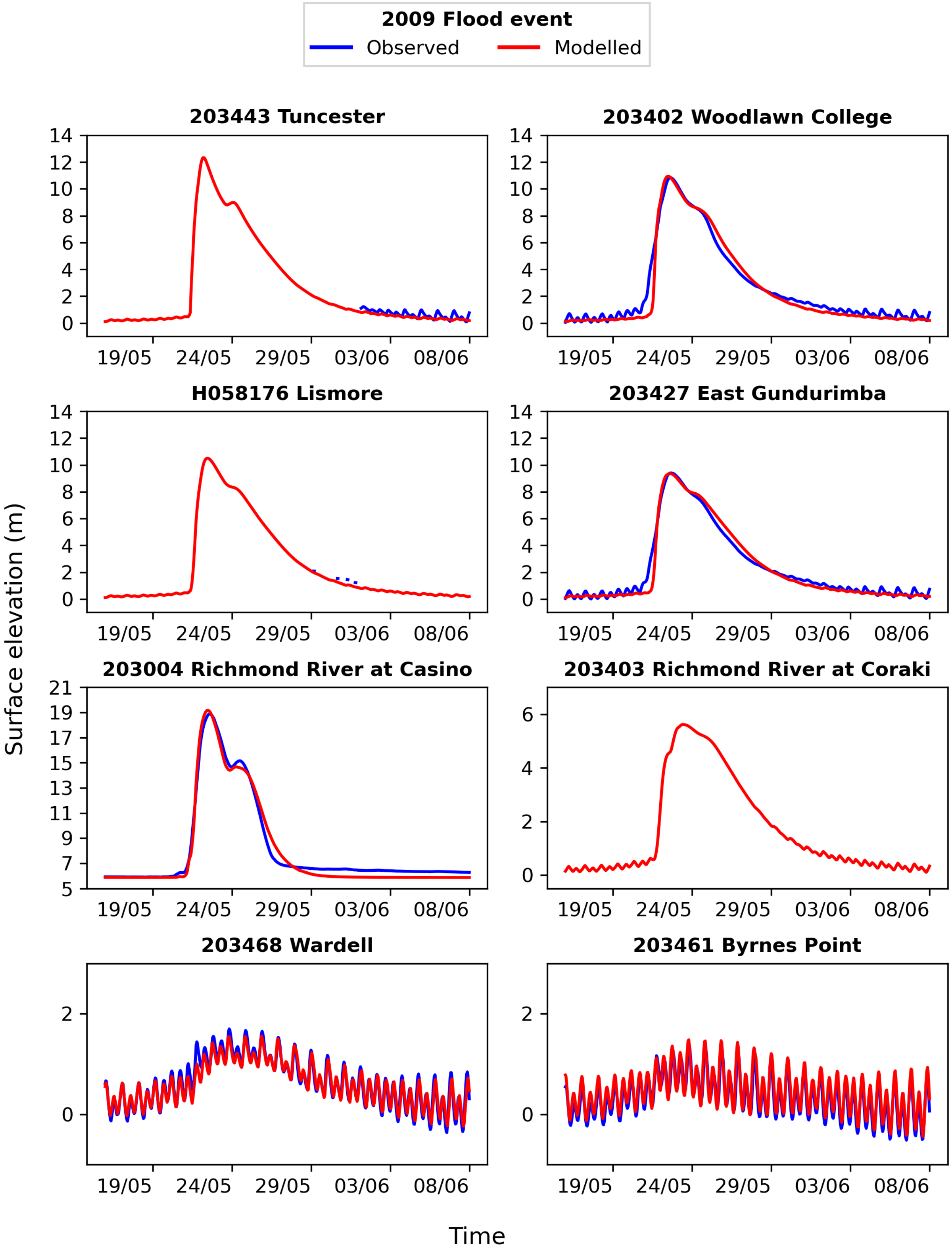


Figure 17 Comparison between the simulated water level and observed water level at all the selected gauges for the flood event of 2009.

The 2013 flood is the smallest event for Lismore out of the five selected events (1 in 7 years) and other areas (Casino 1 in 3 years and Ballina 1 in 6 years). As described earlier, the 2-monthly accumulated spatially distributed rainfall was used to estimate the initial soil moisture and account for the antecedent conditions for each event. The model estimates of spatial soil moisture for all mesh elements across the modelling domain at the end of this warmup simulation were used at the start of the flood event. The comparison between the observed and model simulated water levels for the 2013 flood event is shown in Figure 18. The model can reproduce the peak water level at gauges 203443 on Leycester Creek, 203402 on Wilson River upstream of Lismore junction, 203427 East Gundurimba, and 203004 Richmond River at Casino for this event quite accurately. For these gauges in Lismore and Casino, the match is poorer on the falling limb where the model is overestimating the water levels. There is no observed water level data available at the Lismore gauge (H058176) and Richmond River at Coraki (203403) for the 2013 flood event. The simulated water level at 203468 Wardell matches the observations reasonably well and 203461 Byrnes Point water level is reproduced by the model accurately. The results for the 2013 flood event prove that the model can reproduce observed water levels, especially the peak flows quite accurately across the Richmond River catchment, even for relatively minor floods.

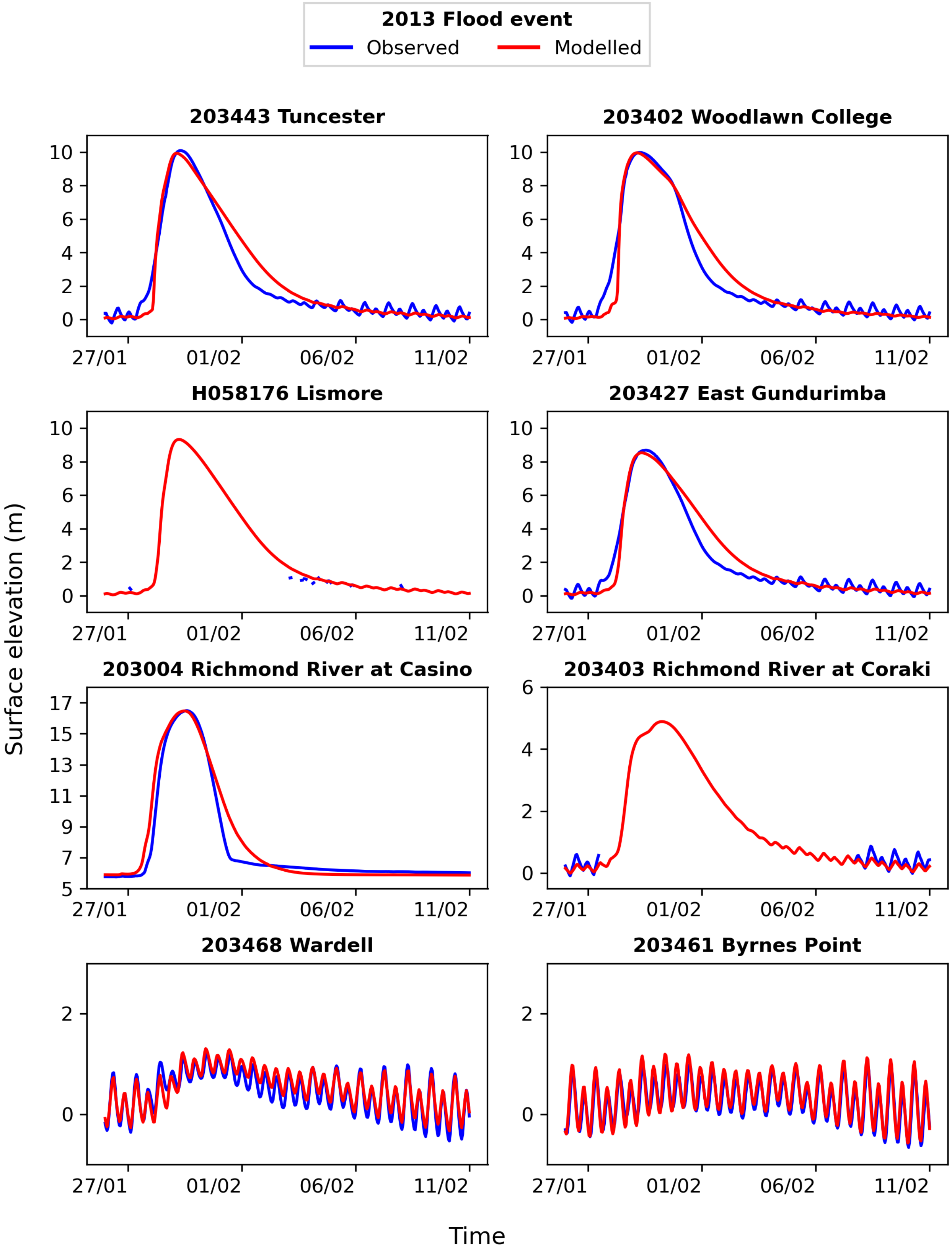


Figure 18 Comparison between the simulated water level and observed water level at all the selected gauges for the flood event of 2013.

The 2017 flood is a reasonably large event for Lismore (1 in 21 years) and medium to small for other areas (Casino 1 in 7 years and Ballina 1 in 8 years). Figure 19 shows the comparison between the observed and model simulated water levels at all eight internal validation gauges. As can be seen from the plots, the model can reproduce the flood peak and water levels at gauges 203443 and 203402 on Leycester Creek and Wilson River upstream of Lismore junction as well as H058176 Lismore gauge and 203427 East Gundurimba almost perfectly. There is some missing data for the Lismore gauge (H058176) but the match is close when there is data. The match at 203004 Richmond River at Casino are a bit poorer at the peak and the model is not able to simulate the peak correctly (over estimation). The rising and falling limbs match well but the match with the peak flow for the Casino gauge is much poorer than other events or other gauges. The match at 203403 Richmond River at Coraki are good and the model can simulate the peak correctly. The model simulated water levels at 203468 Wardell accurately represent the observations and 203461 Byrnes Point water level is reproduced by the model accurately. All attempts to work out the underlying issues for this mismatch of peak at Casino did not yield any results and it is a bit confusing as the model is overestimating the peak at the upstream gauge at Casino but reproducing the peak quite accurately at Coraki and Wardell downstream. With the model reproducing the water levels at all the downstream gauges well, we suspected that the flat peak at the Casino gauge shown in the observed data for this event could be the artifact from the measuring device operating during the high flow period, but this is just a guess. The overall results for 2017 show that the model can reproduce observed water levels across the Richmond River catchment at most gauges reasonably well.

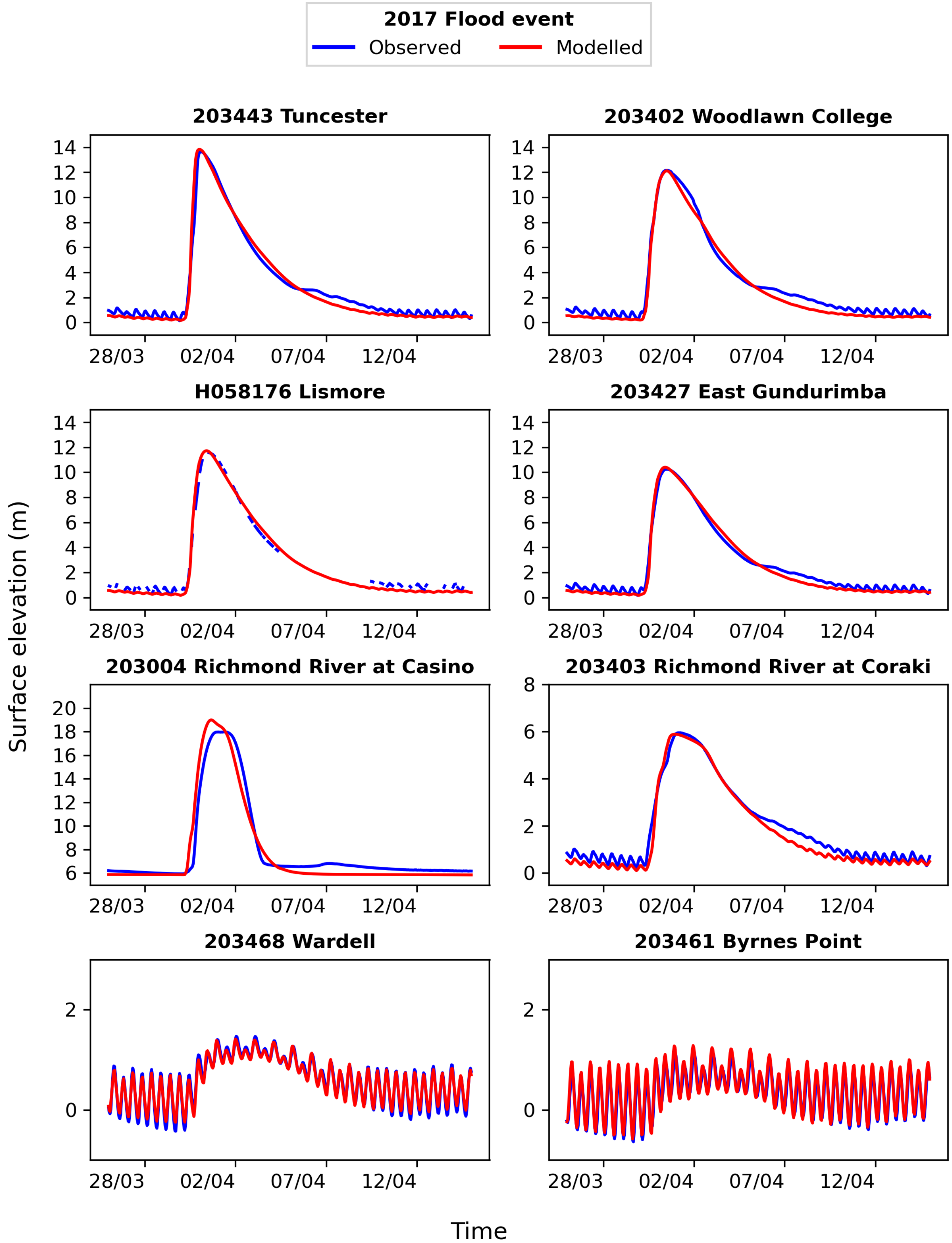


Figure 19 Comparison between the simulated water level and observed water level at all the selected gauges for the flood event of 2017.

The second peak of the first flood event in 2022 is the largest recorded flood event for Lismore (maximum observed) and all other gauges across the Richmond River catchment (1 in 159 years for Casino and 1 in 113 years for Ballina). For the 2022 flood event, the 3-monthly accumulated spatially distributed rainfall was used to estimate the initial soil moisture and account for the antecedent conditions for the event. The spatial soil moisture estimates, along with other infiltration layers were used to run the model with at least a week of warmup period prior to the start of the first peak of the actual event. The antecedent conditions prior to the first flood peak were extraordinary with large rainfall totals, so a longer accumulation period of three months was undertaken to account for the spatial soil moisture conditions across the catchment. Similar to other events, the model estimates of spatial soil moisture for all mesh elements across the modelling domain at the end of this warmup simulation were used at the start of the simulation for the first flood event. The model simulation was continued until the end of the second event and the entire comparison is shown in Figure 20. As can be seen from the plots, the model can reproduce the entire water level time series covering both flood events (rising limb, falling limb, both peaks as well as the low flows during the drier period between the two flood peaks) at gauges 203443 and 203402 on the Leycester Creek and the Wilson River upstream of Lismore junction very well. There is very patchy (majority missing) observed water level data available at the Lismore gauge (H058176) and East Gundurimba (203427). The match at 203004 Richmond River at Casino and 203403 Richmond River at Coraki are also good for the entire water level time series for both the peaks and the dry period between them (slight overestimation of the second flood peak at Casino and underestimation for the lower part of the falling limb for the Coraki gauge for the first flood peak). The simulated water levels at 203468 Wardell match the observations reasonably well for the first peak but there is a slight underestimation for the second peak and 203461 Byrnes Point water level is reproduced by the model accurately. The results for the 2022 multi-peak flood event show that the model is robust and accurate and can adequately reproduce observed water levels across the Richmond River catchment even for a very complex multi-peak flood event.

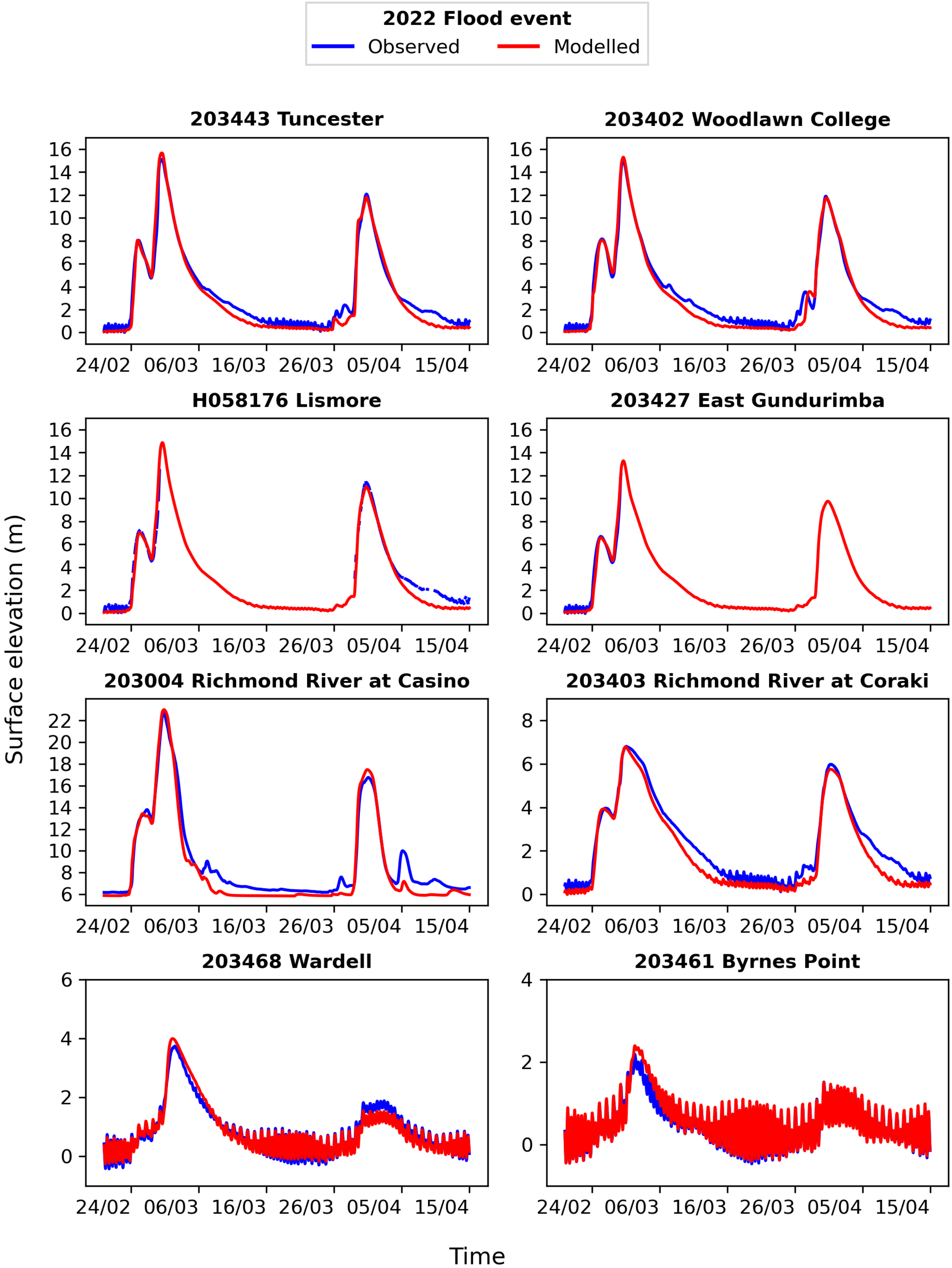


Figure 20 Comparison between the simulated water level and observed water level at all the selected gauges for the two flood events of 2022.

4.1.2 Remote sensing comparisons

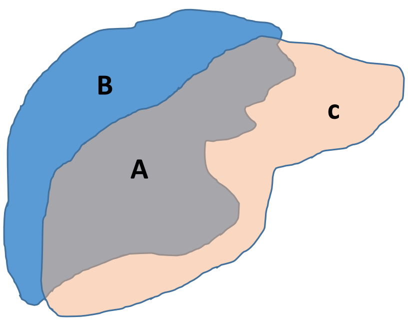
The MIKE21 FM simulated inundation extents for the five selected flood events were compared against the flood maps derived from remote sensing (when and where a reasonable quality Landsat or Sentinel and one Copernicus image was available) for different dates during the period of simulations. This comparison is undertaken to investigate whether the model can simulate the remote sensing derived flooding patterns at the entire catchment scale. The modelling domain for the Richmond River catchment model is relatively large (~7000 km^2) and multiple remote sensing scenes need to be put together to cover the entire domain. Only very few reasonable quality images were available during the selected flood events (see Table 1). All reasonable quality remote sensing images/scenes available (with some flooded area) for the period of selected flood events were processed and put together to produce water maps so that they can be used for validating the MIKE21 FM simulation results. A lot of effort was put into acquiring as much data as possible, but it was unfortunate that only a few reasonable quality images were available. All available data sources including Landsat, Sentinel-1 and Sentinel-2 and Copernicus were checked. This was partly expected as all these data sources are impacted by cloud cover and the Northern Rivers region normally has heavy cloud cover during and after any major flood event. There are no remote sensing images available for the 2008 and 2013 events and the 2009 event has one image. There are few images for the 2017 and 2022 events.

The cell-to-cell agreements between the simulated inundation extent and remote sensing inundation extents for the selected dates for the three flood events (no images available for 2008 and 2013 and only one image available for 2009) are presented in Table 6. It shows reasonable agreement between the simulated and remote sensing inundation extents. Although the visual comparisons between the remote sensing and model simulated flooding extents are also overall good (shown later), some of the comparison statistics is poorer than expected. This is partly caused by the poor quality of most of the remote sensing flood maps and also caused by the difference in resolution of the flood maps between the two flooding extends. Given that many of the streams are less than 30 m wide (remote sensing image resolution) in certain sections, the flow in the streams get represented in remote sensing maps as missing or disconnected fragments, whereas the model simulated outputs are continuous along all streams. This leads to poorer values of M2 and M3 statistics, although the model can reproduce the flood movement and extent reasonably okay across the catchment (as represented by M1 statistics in Table 6).

Table 6 Cell-to-cell agreements between the simulated and remote sensing based inundation extents for the Richmond River catchment.

Date and time	M1	M2	M3
2009-05-27 09am - Landsat	0.733	0.595	0.460
2017-04-03 06am - Sentinel-1	0.987	0.989	0.496
2017-04-07 09am - Landsat	0.826	0.540	0.536
2022-02-24 06am - Sentinel-1	0.884	8.794	0.090
2022-03-03 06am - Sentinel-1	0.992	0.639	0.605
2022-03-08 06am - Sentinel-1	0.989	1.608	0.379
2022-03-31 03pm - Copernicus	0.881	0.513	0.582
2022-04-01 09am - Sentinel-2	0.868	0.136	0.764
2022-04-05 09am - Landsat	0.839	0.304	0.644
2022-04-08 06am - Sentinel-1	0.948	1.907	0.326

Where



M1 = A/A+B
M2 = C/A+B
M3 = A/A+B+C

Where:
A + B = Landsat flooded area
A + C = Model estimated flooded area

Best outcome is when:
M1 is close to 1
M2 is close to 0
M3 is close to 1

For the visual comparisons between the remote sensing and model simulated flooding extents, remote sensing images were selected so that where possible we have images on the rising limb of the hydrograph, at or near the flood peak and also on the falling limb of the hydrograph. Figure 22 presents the comparison between the simulated inundation extent and the only Landsat image available for the 2009 flood event on 27/05/2009 at 09am for the 1 in 12 year flood event at Lismore gauge. This comparison in Figure 22 is for an image that is few days after the flood peak and about mid-way down the falling limb of the flow hydrograph (Figure 21). As can be seen from the comparison image where the remotely sensed and simulated inundation extent is overlapped with 50% transparency, the agreement between MIKE21 FM simulated and remote sensing flood map is okay for most of the areas except few areas. Sometimes wet vegetation does get picked as flooded areas in remote sensing water maps, but we are not sure about the exact cause. It can also be seen from the maps that all the small streams are picked up by the model, but the remote sensing maps are not able to capture those smaller water features. The comparison shows that model can reproduce the complex Richmond River catchment overland flooding reasonably.

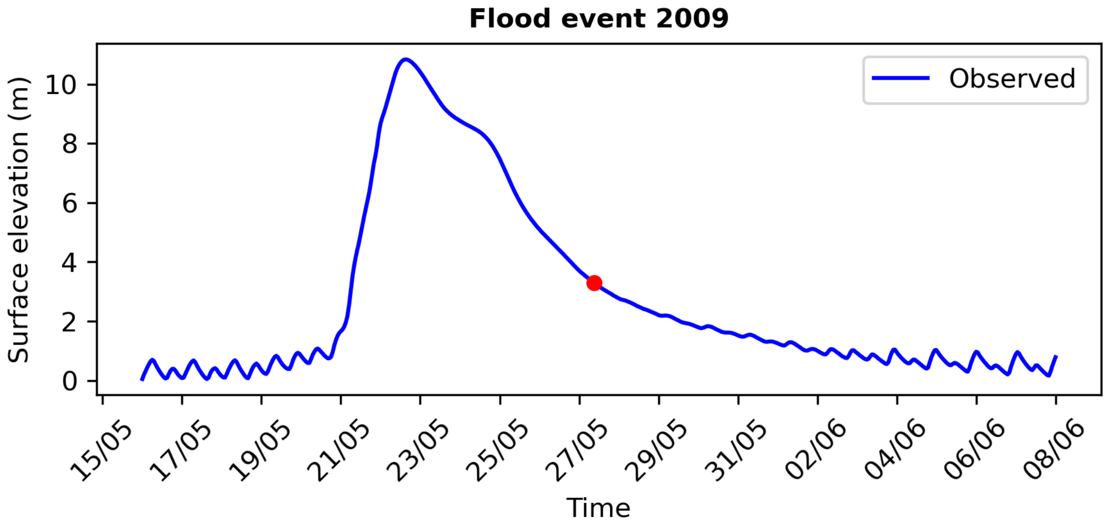


Figure 21 Observed water level at the 203402 gauge for the 2009 flood event and the date of the remote sensing flood map shown as red dot.

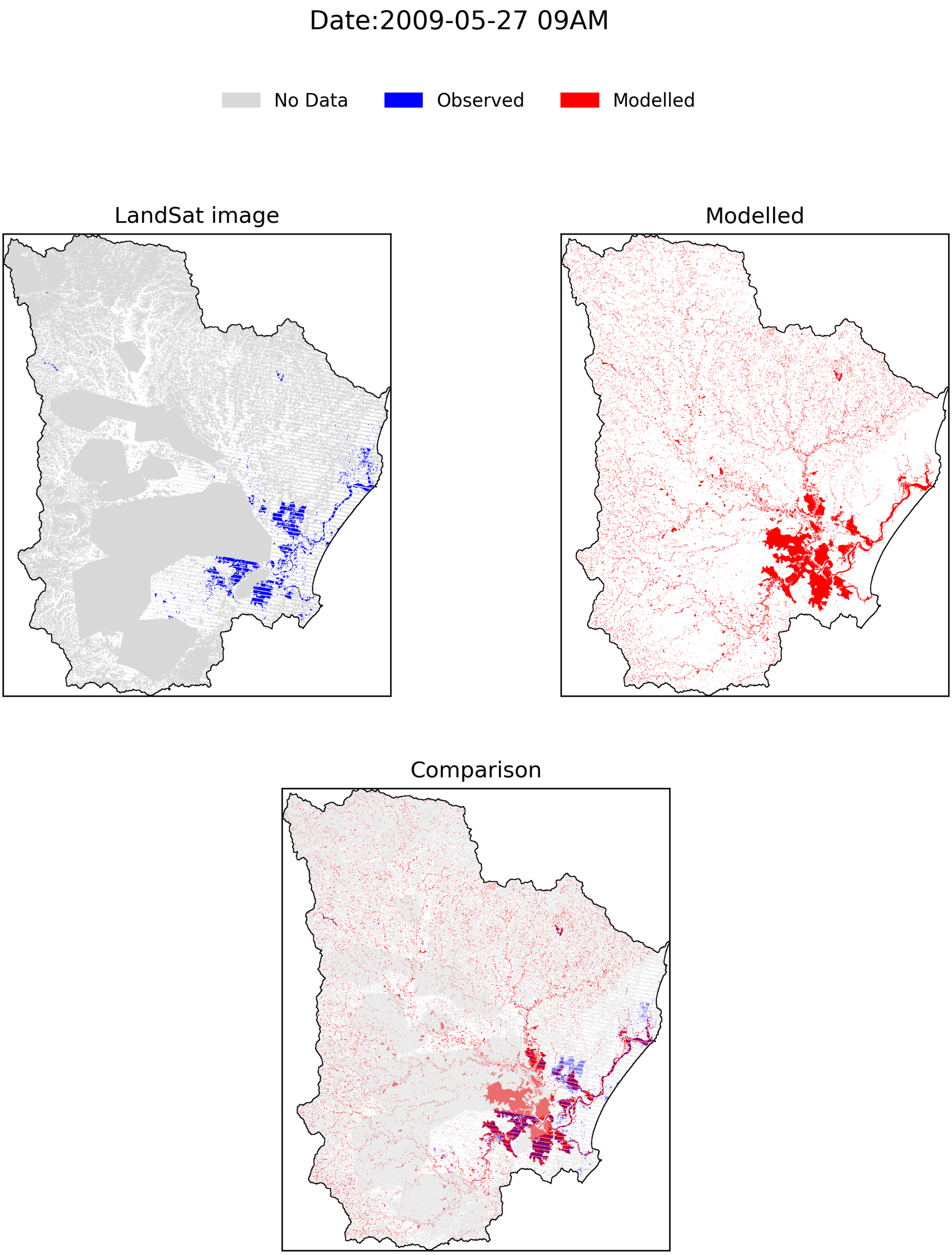


Figure 22 Comparison between the remote sensing flood map (dark blue), model simulated inundation extent (red), and comparison on 27/05/2009 (grey area represent missing remote sensing data due to cloud cover).

Figure 24, presents the comparison between model simulated and Sentinel-1 flood map for the for the 2017 flood on 03/04/2017 at 06 for the 1 in 21-year flood event at Lismore gauge. This comparison in Figure 24 is for an image that is few days after the flood peak (Figure 23). Figure 25 presents the comparison between model simulated and LandSat flood map for the 2017 flood on 07/04/2017 at 09 for the 1 in 21-year flood event at Lismore gauge. This comparison in Figure 25 is for an image that is about eight days after the flood peak and when right at the bottom end of the falling limb of the flow hydrograph (Figure 23). As can be seen from the comparison image where the remotely sensed and simulated inundation extent is overlapped with 50% transparency, the agreement between MIKE21 FM simulated and remote sensing flood map is okay for most of the areas. There are large areas masked by cloud cover and so the comparison can be done only in areas where we have remote sensing images. The model captures the spatial extent quite well but tend to overestimate the flooded area. But overall, it is able to reproduce the complex Richmond River catchment overland flooding reasonably well.

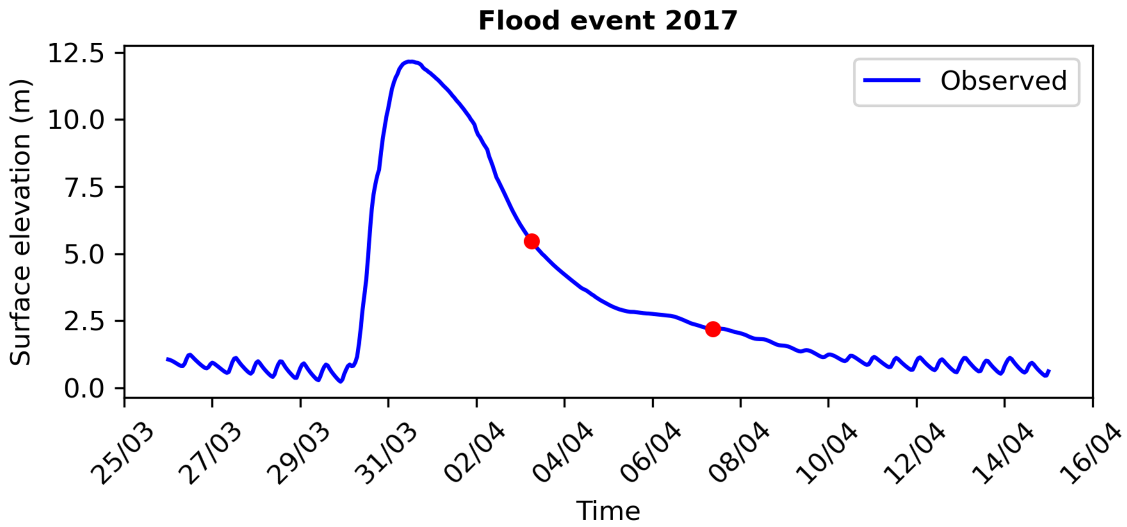


Figure 23 Observed water level at the 203402 gauge for the 2017 flood event and the dates of the remote sensing flood maps shown as red dots.

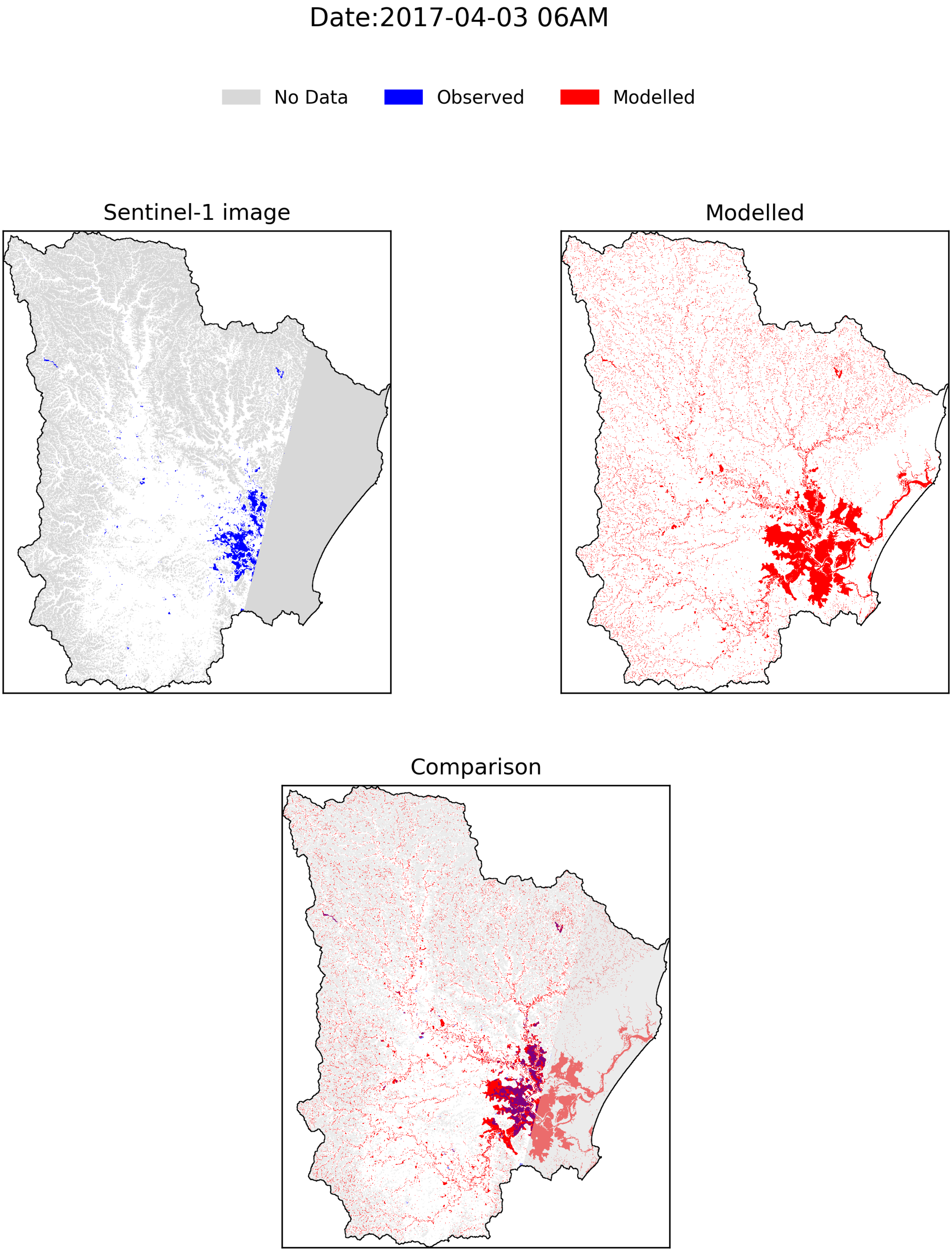


Figure 24 Comparison between the remote sensing flood map (dark blue), model simulated inundation extent (red), and comparison on 03/04/2017 (grey area represent missing remote sensing data due to cloud cover).

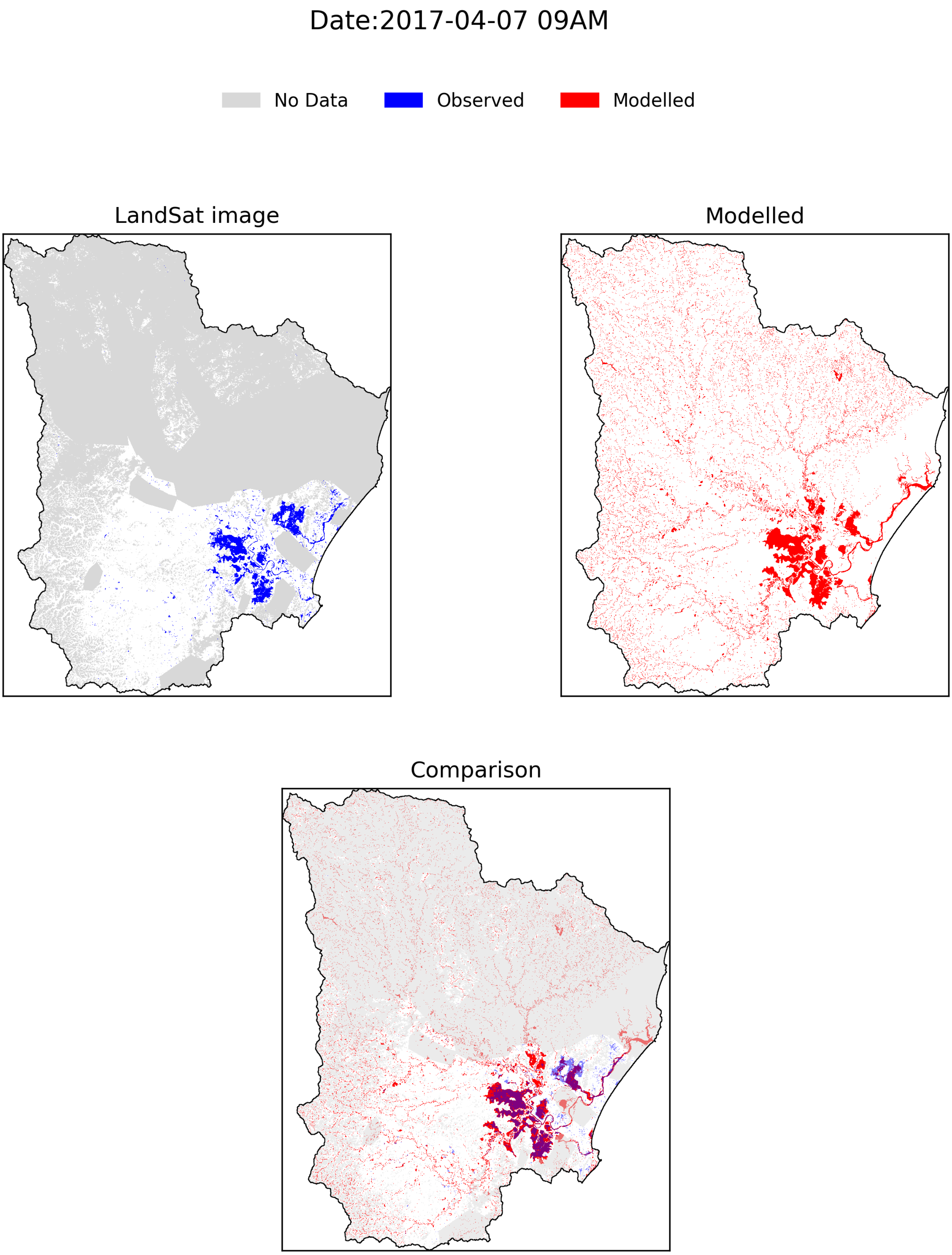


Figure 25 Comparison between the remote sensing flood map (dark blue), model simulated inundation extent (red), and comparison on 07/04/2017 (grey area represent missing remote sensing data due to cloud cover).

Figure 27, Figure 28, Figure 29 presents the comparison between model simulated and remote sensing flood maps for 24/02/2022, 03/03/2022, 08/03/2022 for the maximum flood peak observed at Lismore during the first event. The remote sensing images around both the flood peaks for 2022 are reasonably poor quality. The comparison in Figure 27 is for an image four days before the first large peak and one day before the first smaller peak on 25/02/2022, Figure 28 is for an image three days after the peak and Figure 29 presents the comparison for an image close to the bottom end of the falling limb of the flow hydrograph (Figure 26). As can be seen from the comparison image where the remotely sensed and simulated inundation extent is overlapped with 50% transparency, the agreement between MIKE21 FM simulated and remote sensing map is good for most of the areas. The model captures the spatial extent and flooding pattern reasonably well but tend to marginally overestimate the flooded area. But overall, it can reproduce the complex Richmond River catchment overland flooding reasonably accurately.

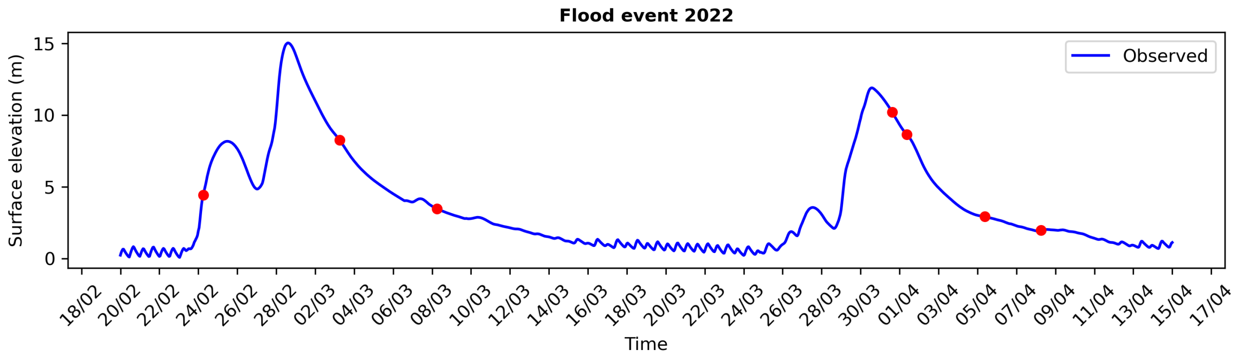


Figure 26 Observed water level at the 203402 gauge for the 2022 flood event and the dates of the remote sensing flood maps shown as red dots.

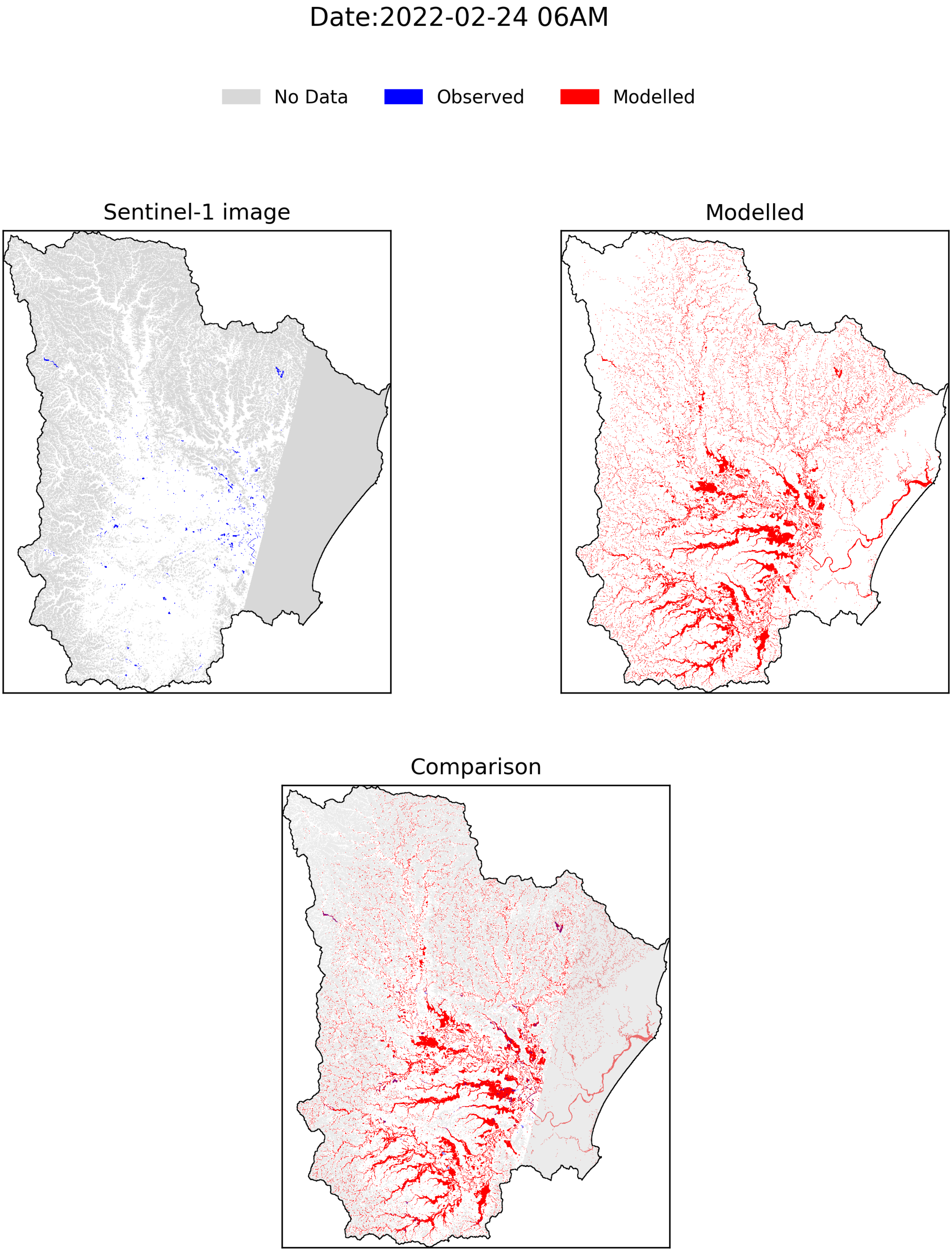


Figure 27 Comparison between the remote sensing flood map (dark blue), model simulated inundation extent (red), and comparison on 24/02/2022 (grey area represent missing remote sensing data due to cloud cover).

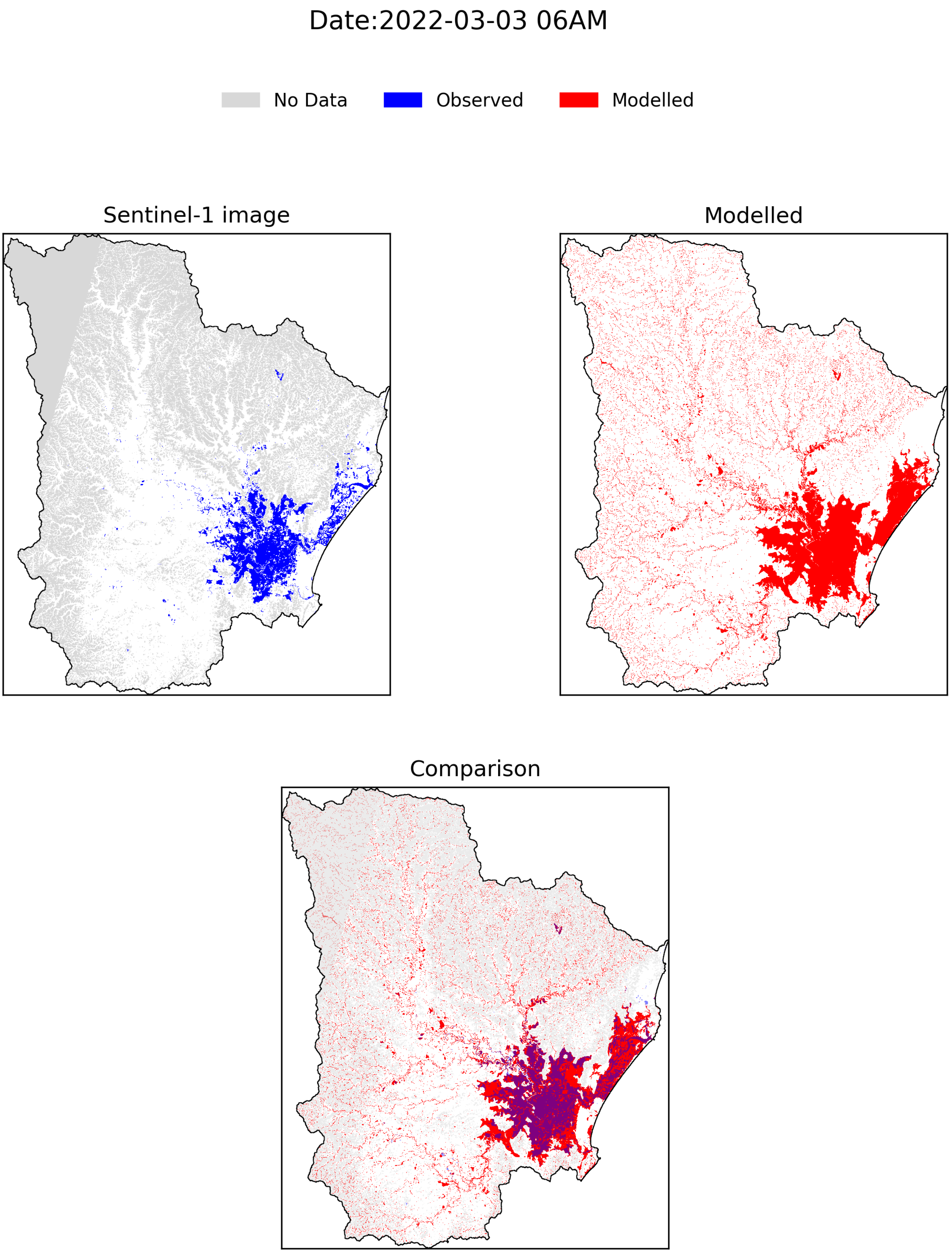


Figure 28 Comparison between the remote sensing flood map (dark blue), model simulated inundation extent (red), and comparison on 03/03/2022 (grey area represent missing remote sensing data due to cloud cover).

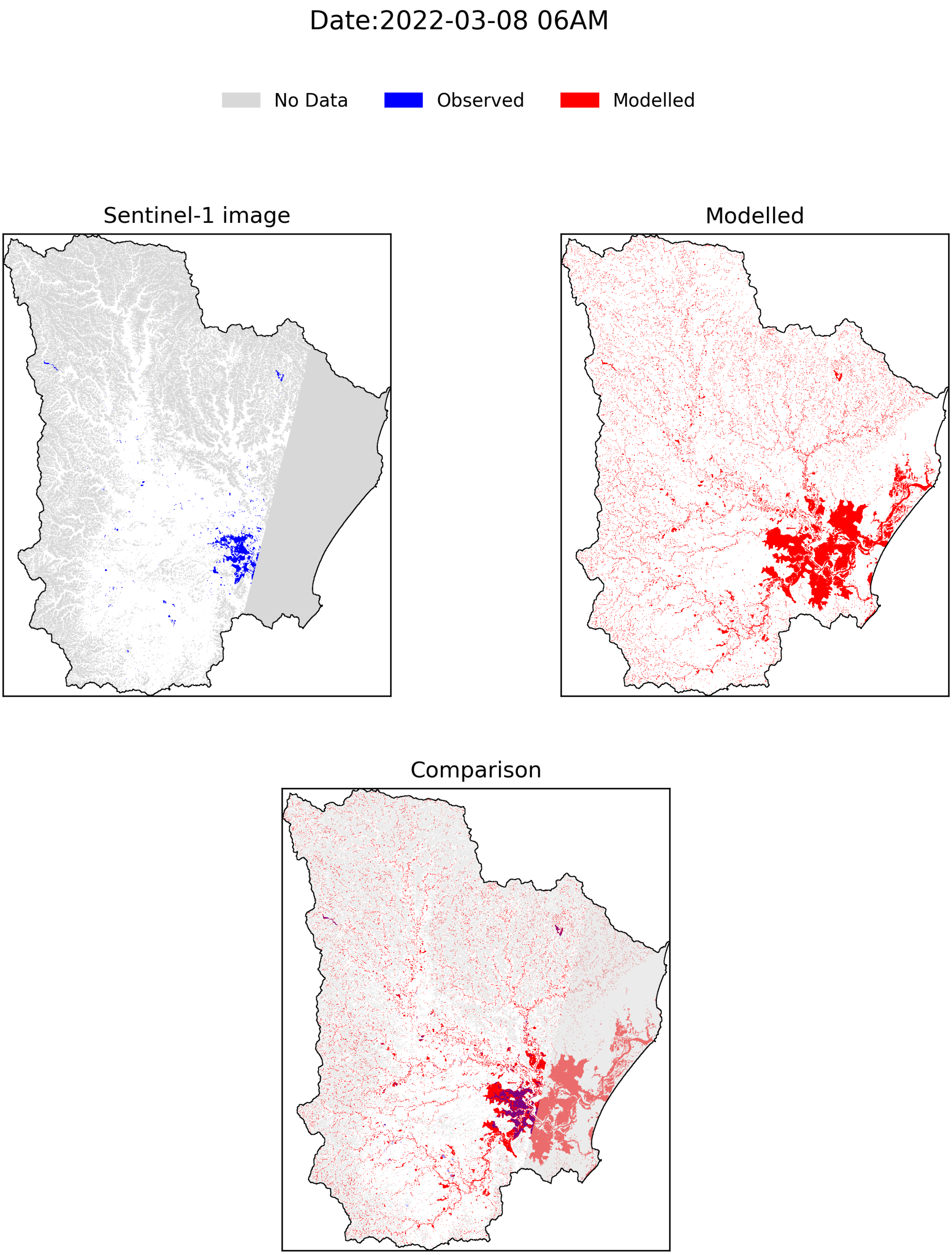


Figure 29 Comparison between the remote sensing flood map (dark blue), model simulated inundation extent (red), and comparison on 08/03/2022 (grey area represent missing remote sensing data due to cloud cover).

Figure 30, Figure 31, Figure 32 and Figure 33 presents the comparison between model simulated and remote sensing flood maps for 31/03/2022, 01/04/2022, 05/04/2022 and 08/04/2022 for the second observed flood peak at Lismore. The comparison in Figure 30 presents the comparison for an image on the day of the second peak, Figure 31 is for an image one day after the second peak, Figure 32 is for an image five days after the second peak and Figure 33 is for an image eight days after the second peak (Figure 26). As can be seen from the comparison image where the remotely sensed and simulated inundation extent is overlapped with 50% transparency, the agreement between MIKE21 FM simulated and remote sensing map is good for most of the areas (also evident from the M1 values). The model captures the spatial extent and flooding pattern reasonably well but tend to marginally overestimate the flooded area. But overall, it can reproduce the complex Richmond River catchment overland flooding reasonably well.

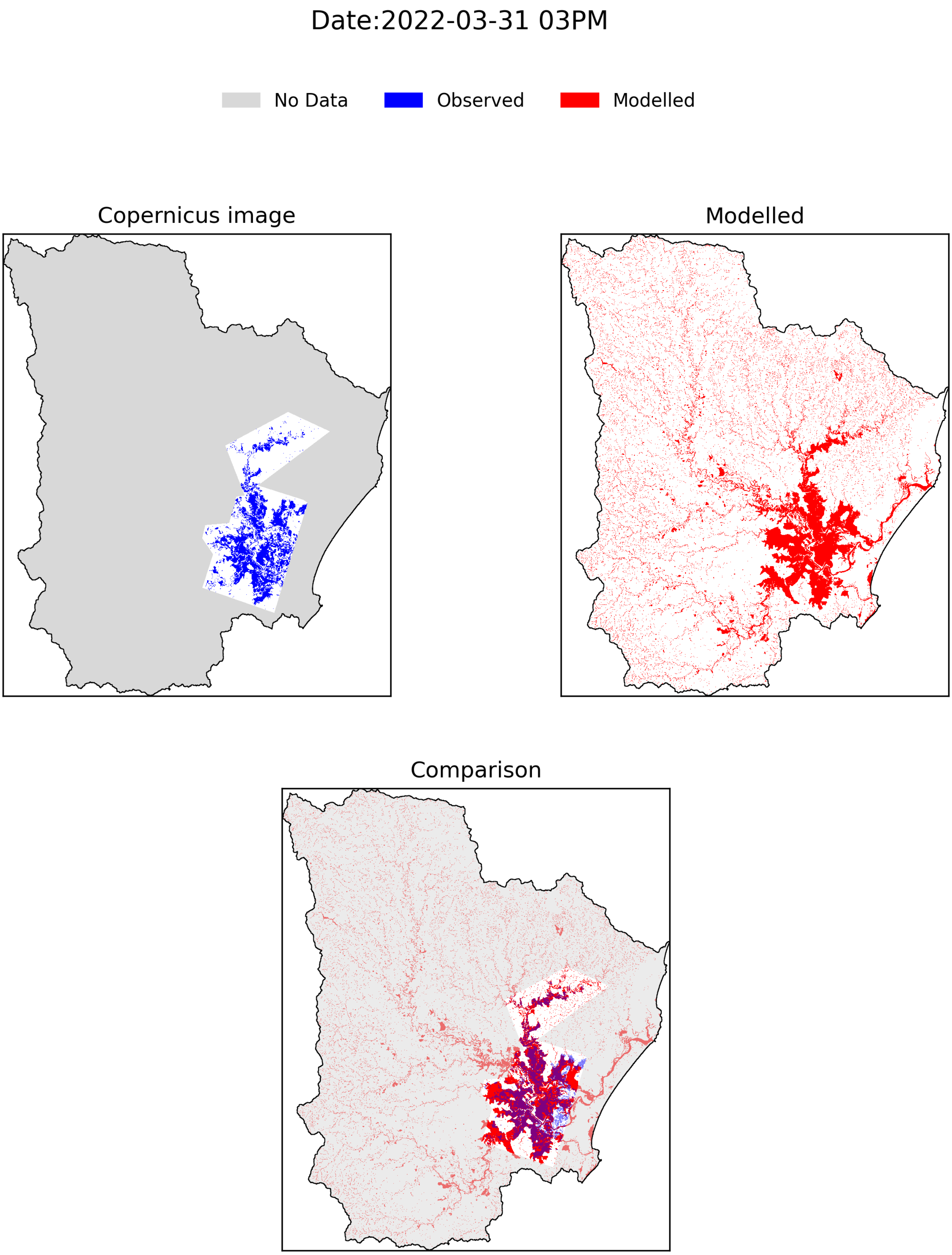


Figure 30 Comparison between the remote sensing (Copernicus) flood map (dark blue), model simulated inundation extent (red), and comparison on 31/03/2022 (grey area represent missing remote sensing data due to cloud cover).

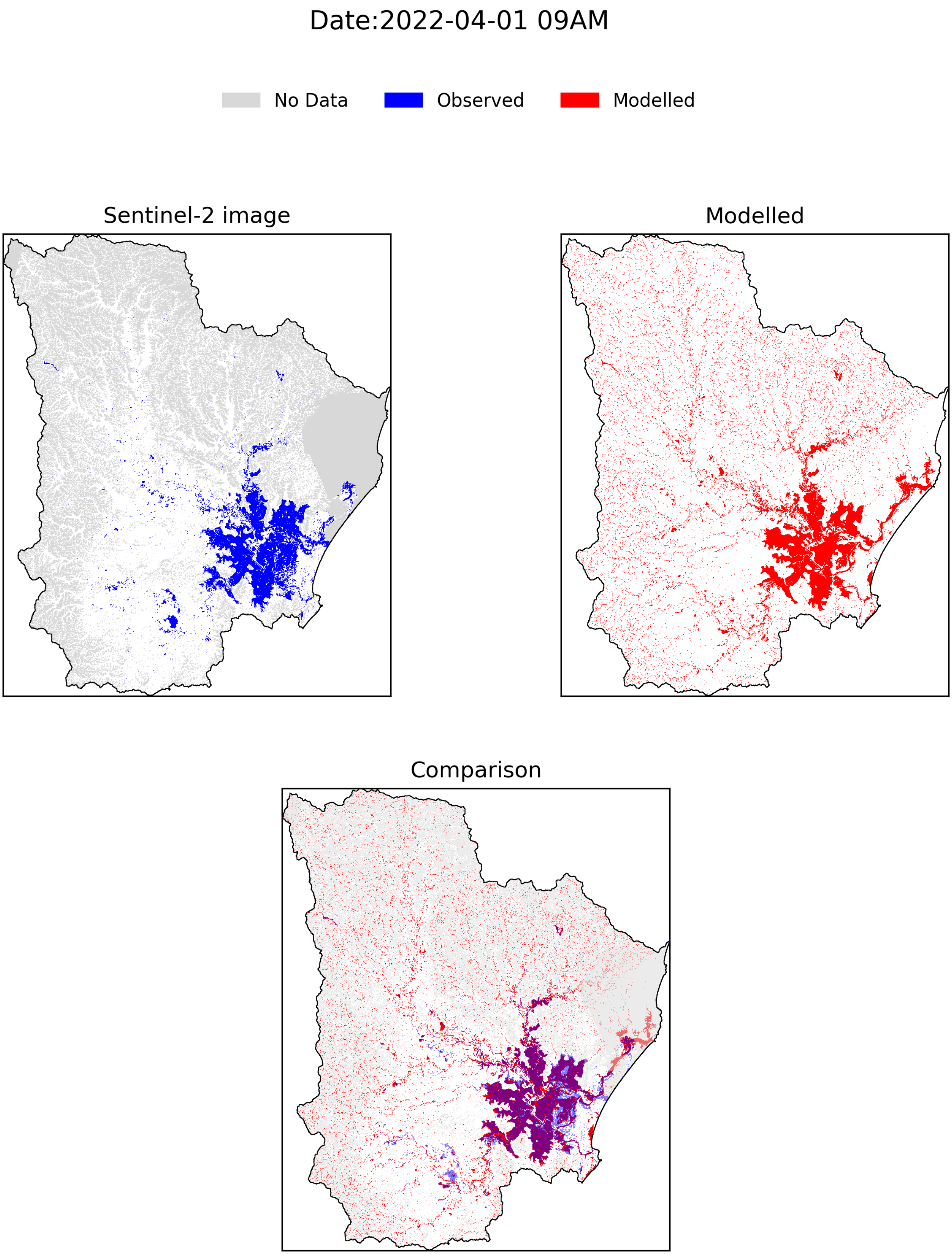


Figure 31 Comparison between the remote sensing flood map (dark blue), model simulated inundation extent (red), and comparison on 01/04/2022 (grey area represent missing remote sensing data due to cloud cover).

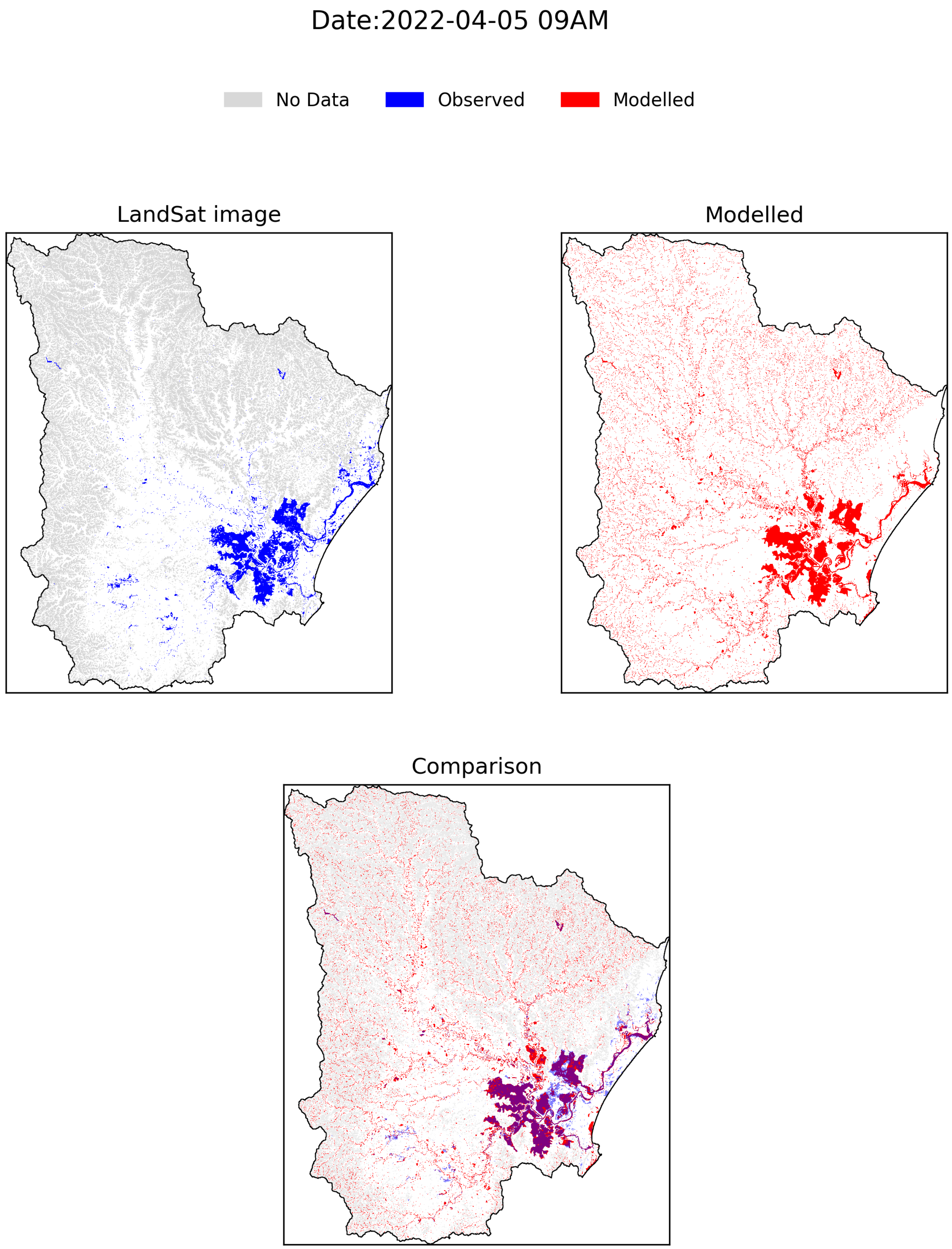


Figure 32 Comparison between the remote sensing flood map (dark blue), model simulated inundation extent (red), and comparison on 05/04/2022 (grey area represent missing remote sensing data due to cloud cover).

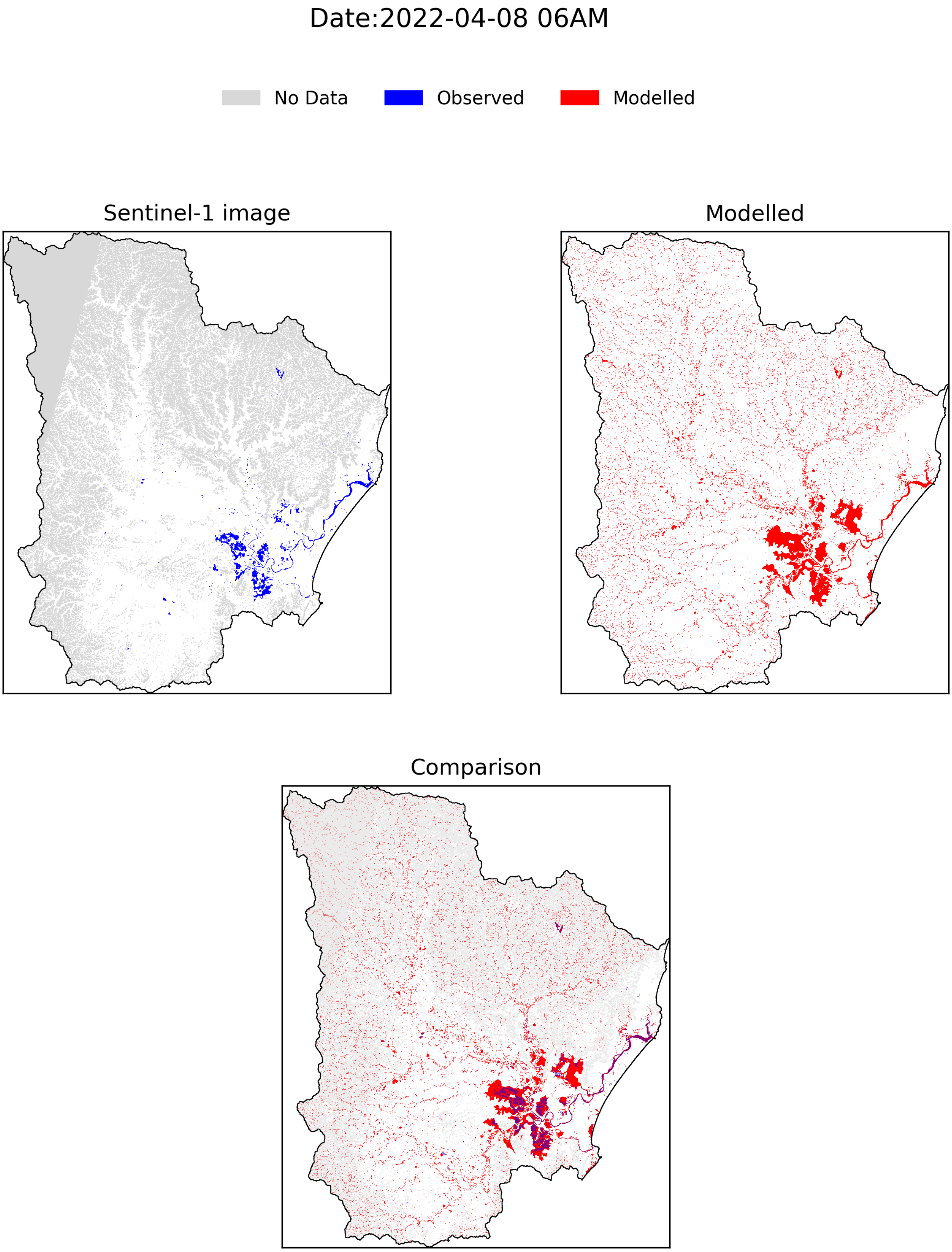


Figure 33 Comparison between the remote sensing flood map (dark blue), model simulated inundation extent (red), and comparison on 08/04/2022 (grey area represent missing remote sensing data due to cloud cover).

Based on the comparisons between the model simulated and remote sensing water maps for different dates of the flood events where reasonable quality remote sensing images are available, it can be said that the model has captured the complex flooding characteristics very well along the main streams and the floodplain at the catchment scale for the simulated events. This demonstrates the applicability of the developed model for the full range of historical and future flow scenarios for the Richmond River catchment.

4.1.3 On-ground validation with locals using community data

The simulated flood inundation water levels are compared with several on-ground data across large parts of the Richmond River catchment which were provided by the local Northern Rivers community members to the project team. On-ground validation other than the mainstream gauges is important in proving the robustness of the developed model to represent inundated water levels even in ungauged areas and in landmarks that matter to the community. It is also very important in building confidence among the local community and councils who will benefit from the developed model for flood mitigation options testing and any other use.

The on-ground data are available for the two most recent high-intensity flood events in 2022 and 2017 (fewer observations). Majority of the on-ground data were generously provided by all the community members mentioned in the acknowledgements at the start of the report and local council staff members. The on-ground comparison points cover the mountainous areas around Terania Creek as well as locations in the Channon, Goolmangar, Lismore CBD (quite a few locations including the flood mark at AZA Motel), south Lismore, Coraki, Woodburn, Tuckean, Evans Heads, and Broadwater. The project team acknowledge the dedication of these local community in collecting the data and providing it to us for model validation. This data is particularly important as it is in the landscape and away from the main rivers/streams.

A comparison of the flood height data collected by the community with the model simulated surface water levels is good in majority of the locations. Majority of the model simulated surface water levels are within about 0.30 m when compared with the community data. There is only one water level in Swan Bay area but all the other flood level information about the flooding in the surrounding areas was provided by the volunteers who were evacuating stranded people from those areas during the 2022 floods. The project team went around this area with the volunteers over a day to get these details. The model is simulating flood levels and timing in these areas very similar to what was explained to the project team during the trip. This is a good indication that the model is reproducing the observed flooding across the Richmond River catchment and simulating the overall behaviour of the flood events, even in an extremely complex terrain. The reasonably good comparison results provide extra confidence in the ability of the developed model to reproduce flood heights and flooding behaviour in the overall Richmond River catchment.

4.1.4 Discussion

As can be seen from the comparisons presented and discussed above, all the comparisons between model simulated and observed hourly water levels based on the R^2 and NSE values, the time series of hourly water level plots and the limited number of remote sensing images comparison as well as on-ground validation against data and insights provided by the local community clearly demonstrates that the hydrodynamic model developed and implemented in this project for the entire Richmond River catchment can reproduce the observed flows (both at the gauges and over landscape) across the entire modelling area for a full range of flood events reasonably accurately. The multiple lines of evidence used to validate the modelling results provide confidence in the applicability and suitability of the model for the intended purpose.

The 2D hydrodynamic model (MIKE21 FM) used here uses spatial rainfall as input (rain on grid) rather than the conventional way of using observed streamflow as inputs. The model generates spatial runoff on each grid at every time step and routes it through the catchment. This version of MIKE21 FM also accounts for spatial and temporal soil infiltration and soil moisture based on measured spatial soil properties and does not need any initial and continuing losses to be calibrated for each flood event. The model used here is the most appropriate tool to use when a substantial fraction of the total runoff and associated flooding is generated within the catchment landscape (which was the case for the 2022 floods) rather than just all river inflows coming from upstream and over-topping the stream banks.

As described earlier, the same model physical setup and parameters are used for all five flood events and the only difference between them is the input observed climate, evaporation and spatial soil moisture status at the start of the event. The model accounts for the Pacific Highway M1 with the M1 development starting in 2010 and continuing until 2022. So, these time series of changes in the M1 infrastructure provided by Transport for NSW (courtesy of Transport for NSW) is implemented in the model mesh. As such the model mesh structure in the vicinity of the M1 is slightly different for flood events in 2008 and 2009; 2013; 2017, and 2022 to correctly reflect M1 infrastructure in the model setups at the time of the flood events. The mesh elements for the model mesh for 2008, 2009, 2013 and 2017 are 10,192,388 and for 2022 there are 10,197,863 elements. The mesh for the first four events has the same number of mesh elements and nodes but have slightly different placement of the nodes and varying elevation for those nodes along the M1.

The results here clearly indicate that if any new infrastructure is correctly reflected in the model setups the model is capable of estimating changes in flows due to infrastructure development within the catchment. This provides confidence that the model is suitable for different biophysical interventions to test alternate flood mitigation scenarios. For modelling any climate/flow future scenario or any design flood event, the only thing that needs to change is the input climate. For any major infrastructure intervention for flood mitigation, the model mesh and setups need to be modified to reflect that change.

The 2022 flood is a combination of two large events with the first at the end of February (the maximum observed in history for Lismore) and the second at the end of March and the two flood peaks are separated by about one month. This is a very complex and difficult flood event to model but the results from the hydrodynamic model developed here clearly show that it can reproduce even such a complex double peak flood event accurately across the entire Richmond River catchment. These results demonstrate the continuous simulation capacity of the implemented model (and also demonstrate that the initial and continuing losses do not need to be calibrated for each flood event at all) for the two floods nearly one month apart.

The results from the comparison of the model simulated flood extents with the remote sensing images (although limited remote sensing images with partial coverage due to cloud cover and poor quality) show that the model has captured the complex flood characteristics reasonably well along the main streams and the floodplain for the simulated events. The reasonably good match between the model simulations and community and councils provided in-stream and overland water heights for the 2022 and 2017 flood events in areas spread across the Richmond River catchment further provides evidence of the suitability of the developed model.

The validation results clearly show that the model can reproduce the water levels and flooding (timing, depth, velocities (no observed data available for model validation), etc.) at the Richmond River catchment scale at fine spatial and temporal resolution for the complete range of flood events. Given the model simulated flows match the observed flows at all key locations across the entire Richmond River catchment, these results provide confidence in the model and the outputs and show that the model is representing the flows across the catchment and the match at any particular stream gauge is not due to compensating errors within the catchment. This provides confidence in the model and its use for flood mitigation scenario testing.

This modelling study is focused on accurately representing flood dynamics across the entire Richmond River catchment. Property scale assessments may require further analysis considering local minor drainage infrastructure. All efforts were made to collect and use consistent and accurate elevation data but areas of permanent water where bathymetry was not collected may be slightly under or overestimated by the dimensions used in the modelling.

5 Summary and recommendations

An exceptional flood event affected the Northern Rivers region in NSW between the end of February and the beginning of March 2022. The region was severely impacted especially some parts where the flood was unprecedented. The government wanted to analyse what happened during this flood and investigate possible ways of mitigating it in the future. There are several local area models mostly covering major towns across the Richmond River catchment developed over the last few decades but to analyse and investigate flood mitigation options at the catchment scale, a full catchment scale model was needed for the entire Richmond River catchment. NEMA engaged CSIRO to undertake the Northern Rivers Resilience Initiative. This report is for Phase 2 of NRRI which developed and implemented a detailed hydrodynamic model for the entire Richmond River catchment in the NSW Northern Rivers region to reproduce the past flooding history to investigate flood mitigation scenarios. The Richmond River catchment has a large floodplain that floods frequently. This is the first time a detailed hydrodynamic model is developed for the entire Richmond River catchment. This was needed to investigate the impacts of any flood mitigation interventions in the catchment on the overall catchment response (any intervention in upper parts will have downstream impacts).

The 2D hydrodynamic model (MIKE21 FM) used here uses spatial rainfall as input (rain on grid) rather than the conventional way of using observed streamflow as inputs. The model generates spatial runoff on each grid at every time step and routes it through the catchment. This version of MIKE21 FM also accounts for spatial and temporal soil infiltration and soil moisture based on measured spatial soil properties and does not need any initial and continuing losses to be calibrated for each flood event. The model version and setups used in this analysis is the most appropriate tool to use when a substantial fraction of the total runoff and associated flooding is generated within the catchment landscape rather than just all river inflows coming from upstream and causing overland flooding due to over topping of stream banks (which was surely the case for the 2022 floods). The hydrodynamic model simulations are validated against hourly observed water level at eight internal gauges, remote sensing imagery and other on-ground observations.

The validation results clearly show that the model can reproduce the water levels and flooding (timing, depth, etc.) across the Richmond River catchment at fine spatial and temporal resolution for the complete range of flood events. Given the model simulated flows match the observed flows at all key locations across the entire Richmond River catchment, these results provide confidence in the model and the outputs and shows that the model is representing the flows across the catchment and the match at any particular stream gauge is not due to compensating errors within the catchment. This provides confidence in the model and its use for flood mitigation scenario testing.

The hydrodynamic model developed here covers a large area and a very complex terrain with very steep to low gradients. The model are set up to represent the entire modelling domain and are suitable for understanding the water level variations and floodplain dynamics at the scale of the modelling domain. The model is developed to get the overall river water levels at all gauges across the catchment as close as possible to observed without focusing on any particular gauge or areas.

Recommendations: The hydrodynamic model validation results across a range of flood events (small 1 in 7 years to maximum observed at Lismore) across eight internal flow gauges and comparisons with remote sensing images and other on-ground observations clearly demonstrates that the developed model is capable of reproducing flows across the entire Richmond River catchment. The multiple lines of evidence used to validate the modelling results provides confidence in the applicability and suitability of the model. This provides confidence that the model is suitable for its intended purpose which is to undertake scenario analysis where any changes in flow control structures or climate can be tested to see the change in flow regime across the catchment. Flood mitigation scenarios (2 to 5) need to be developed/constructed in consultations and agreement with NEMA, local councils, stakeholders/community and NSWRA to investigate the suitability of any of the options to reduce the impacts of large future floods across the Richmond River catchment.

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