# Where is Natural Flood Management (NFM) occurring in eastern NSW? Detecting signals to guide strategic on-ground rehabilitation

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**Key points**

- Readily available gauge-recorded hydrographs can be effectively used as a first-pass method to detect and map NFM signals across catchments without the need for full hydrodynamic modelling.
- Detectable NFM signals vary spatially and by flood magnitude, with contrasting patterns between the Hunter (stronger for overbank floods) and Richmond (stronger for in-channel freshes) catchments.
- The presence, absence, or emergence of NFM signals provides a practical evidence base for prioritising where to enhance or initiate nature-based rehabilitation efforts.
- Strong NFM signals are emerging in subcatchments and corridors where river recovery processes have been occurring for several decades, particularly where riparian and in-channel vegetation and structure has increased geomorphic and hydraulic roughness, either through active implementation of nature-based solutions (NbS), or passive enhancement of river recovery.
- Effective flood mitigation through NFM requires a multi-tool, multi-scalar approach, combining reach-scale interventions for smaller floods with catchment-scale land use and vegetation changes for major floods.

## Abstract

Natural Flood Management (NFM) represents a paradigm shift in flood risk mitigation, emphasising the rehabilitation and enhancement of natural hydrological and morphological processes across catchments - to deliver slower and lower floods – and reduce flood risk. Interest in NFM has grown rapidly, particularly in regions facing increasingly intense and destructive flooding under climate change, such as eastern NSW (including the mid-coast and Northern Rivers) since 2021. NFM works with natural processes either through active implementation of nature-based solutions (NbS), or passive enhancement of river recovery. Delivering NFM also provides environmental co-benefits beyond just flood mitigation, including healthier river ecosystems, improved water quality, enhanced habitat and biodiversity, and increased climate resilience.

Despite the expanding number of NFM projects, clear proof-of-concept remains limited in NSW and Australia. Many researchers and practitioners agree that robust monitoring is essential for building the evidence base required to mainstream NFM as a reliable flood mitigation approach. Detecting NFM signals in hydrological records across a full range of flood magnitudes from minor, to moderate and major, is critical and a required first step in the process. However, such monitoring frameworks are not yet available.

This paper utilises the full capacity of available gauge records to detect NFM signals in two key flood prone catchments; the Richmond and Hunter (the remaining eastern NSW catchments are under review in Fryirs et al., subm). We use both at-a-station and upstream-to-downstream metrics as our analysis and monitoring tools. At-a-station analysis examines temporal changes in hydrograph shape using kurtosis, rate of rise and skewness metrics. Upstream-to-downstream metrics include peak-to-peak travel time, flood-wave celerity and peak attenuation. Detecting NFM signals helps identify where in the landscape NFM is already occurring, emerging, not yet evident, or just not feasible.

With this understanding, practitioners can strategically enhance existing mitigation, initiate new rehabilitation, or redirect efforts.

**Keywords**

Flood mitigation, nature-based solutions, geomorphic and vegetative roughness, work with nature

## Introduction

Natural Flood Management (NFM) is defined as a nature-based solution (NbS) to flood mitigation that uses natural biophysical processes to slow floods down, reduce erosive power, and attenuate them downstream (Lane, 2017; Fryirs, 2026). NFM represents a paradigm shift in flood risk mitigation, focusing on the rehabilitation and enhancement of natural hydrological and geomorphic processes across catchments to deliver "slower and lower" floods (Lane, 2017; Wingfield et al., 2019). Rehabilitation and/or enhancement can occur via active and assisted means, or passive and unassisted means (Fryirs et al., 2018). Interest in NFM has grown rapidly among researchers, practitioners, and policymakers, driven by the need for more sustainable and cost-effective alternatives to traditional engineering approaches. This need is urgent in regions experiencing more frequent and intense flooding under climate change (Fryirs et al., 2023).

Despite expanding implementation and literature, the integration of NFM into mainstream flood management strategies remains inconsistent. A key limitation is the lack of robust, standardised methodologies for monitoring and evaluating NFM effectiveness (Bagheri-Gavkosh et al., 2025). There is growing consensus that monitoring is essential for establishing the evidence base required to support wider adoption of NFM. To do this monitoring requires that signals of NFM can be detected in the hydrological record and tracked over time. Identifying where such signals are already present, emerging, or absent enables practitioners to prioritise interventions, either by enhancing existing processes or initiating new mitigation efforts. However, foundation studies that identify where signals of NFM are occurring across regions and within (sub)catchments are extremely limited (Arash et al., 2023; Fryirs et al., 2023).

Hydrodynamic modelling of all flood-prone catchments is often impractical due to constraints in data, computational capacity, expertise, expense and time (Hill et al., 2023). Therefore, other methods are needed that can be used on readily available, non-synthetic hydrological data to provide a first snapshot of where a NFM signal may be occurring in the landscape. Gauge-recorded hydrographs provide a valuable, often Open Access resource for analysing hydrological change across multiple scales. Developing methods that utilise these data to detect NFM signals offers a practical means of assessment, enabling the triage of priority areas for on-ground action and guiding where detailed modelling efforts may be needed. The aims of this study are:

- Present a method and metrics that can be used on Open Access gauge-recorded hydrographs to detect changes in hydrology over time.
- Detect which rivers and subcatchments in the Hunter and Richmond catchments are showing a NFM signal for minor, moderate and major floods.
- Discuss how to use this analysis to aid prioritisation and implementation of on-ground NbS to deliver NFM.

## Methods and hypotheses

### *Gauge data and flood stage classification*

To assess temporal changes in flood hydrology, all available stage height data from 1950 to 2022 were extracted from the open-access Australian Bureau of Meteorology (BoM) and WaterNSW databases. Only gauges with sub-daily or hourly records were used. A total of 36 gauges in the Hunter and 13 in the Richmond were analysed (Figure 1). Gauges were excluded if located downstream of large dams, or draining areas smaller than 50 km$^2$. Sites in confined valleys or undisturbed national parks and state forests were also omitted, as these settings are not expected to produce a NFM signal (Fryirs et al., 2018; Zhang and Fryirs, 2023, 2024).

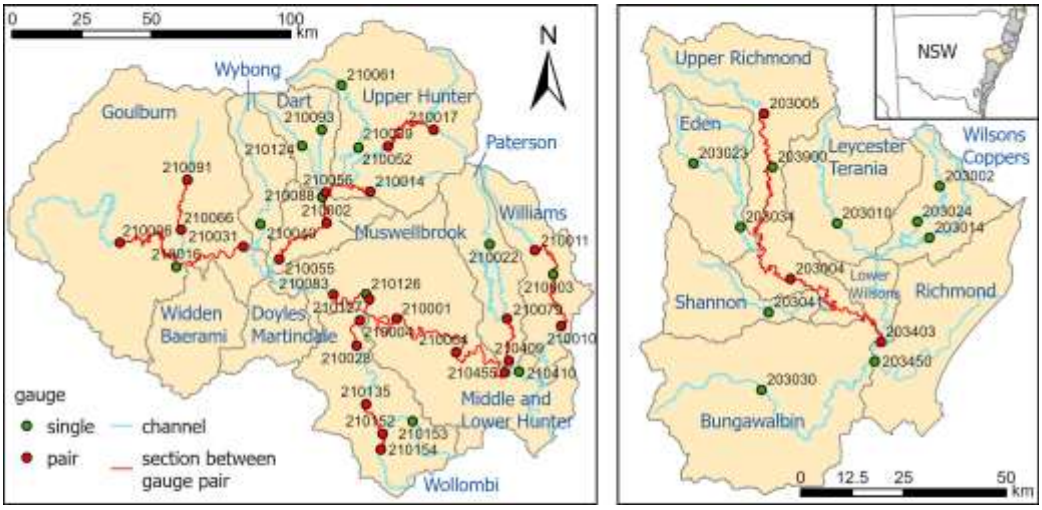


**Figure 1 Subcatchments and gauges used for the Hunter (left) and Richmond (right) analysis**

To enable consistent comparison across catchments, morphologically defined flow stages were derived for each gauge site by linking stage height records to macrochannel cross-sectional morphology. Three flow types are used; *in-channel fresh, high flow, and overbank flood* (Arash et al., 2023, 2024). An *in-channel fresh* is defined as a flow that inundates most instream geomorphic units and some vegetation, typically reaching approximately half-bankfull stage. These flows broadly correspond to BoM-defined minor floods, which may cause inconvenience and minor inundation of low-lying areas. A *high flow* is defined as between an in-channel fresh and a bankfull +5% threshold. These events inundate all geomorphic units, reach channel capacity, and may spill onto adjacent low-lying areas, broadly aligning with BoM moderate flood levels. An *overbank flood* is one that exceeds the high-flow threshold, inundating extensive floodplain areas. These correspond to BoM major floods that cause widespread inundation, infrastructure impacts, and potential evacuations.

### *Metrics used and hypotheses tested*

At-a-station analysis tracks changes in hydrograph shape at individual gauge sites over time. Three metrics are used; kurtosis (K), skewness (S) and rate-of-rise (RoR) (Figure 2). Upstream-to-downstream analysis tracks changes in flood dynamics along the channel/valley over time. Three metrics were used; flood wave celerity (C), the flood wave attenuation index (FWAI) and peak-to-peak travel time (tT) (Figure 2). FWAI is the normalised index of absolute flood peak attenuation (Ha) (normalised by catchment area at each gauge site). The equations used and the semi-automated workflow for running the calculations on hydrographs can be found in Arash et al. (2023, 2024). If NFM is occurring at-s-station it is hypothesized that K and S will increase, and RoR will decrease. If NFM is occurring upstream-to-downstream it is hypothesized that C will decrease, and $t_T$, Ha and FWAI (Figure 2).

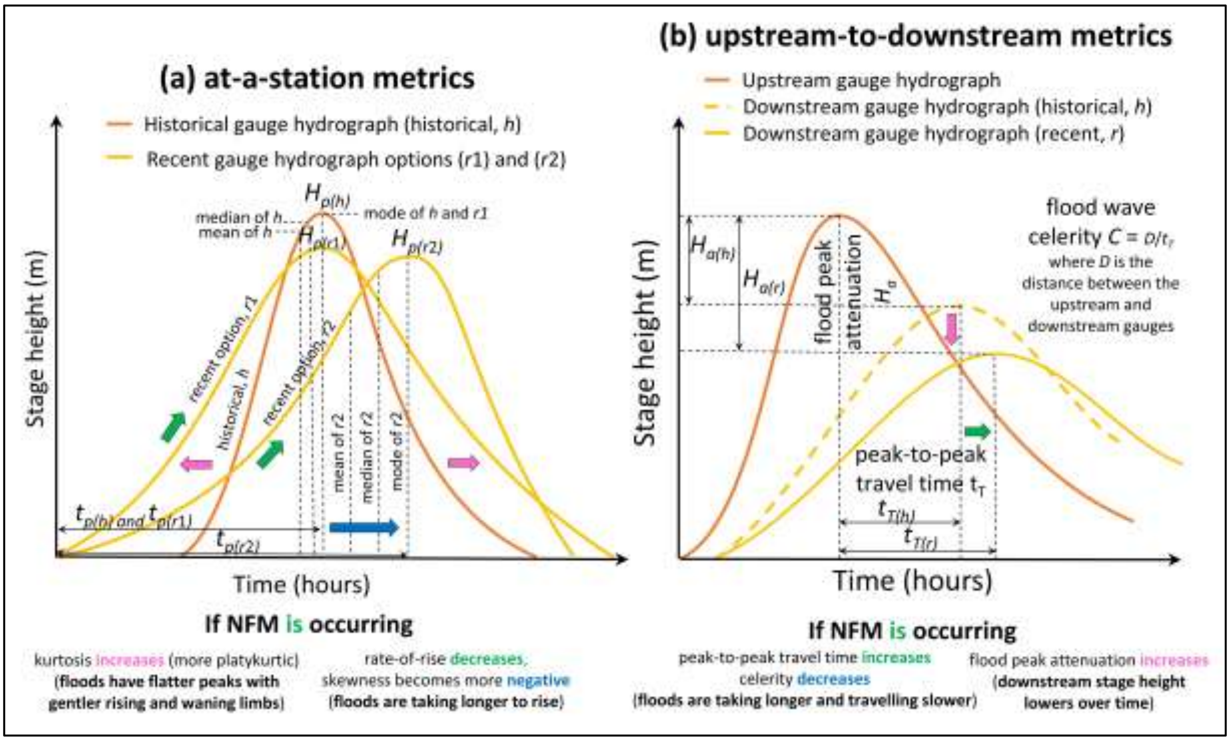


**Figure 2 Metrics used on stage height hydrographs to detect a NFM signal (a) at-a-station and (b) upstream-to-downstream. If NFM is occurring the metric must meet the hypothesized direction of change noted**

### *Detecting trends and directions of change in the data*

To detect change at the subcatchment scale, the at-a-station metrics are used. The reasoning is that any changes in hydrology recorded at-a-station will reflect catchment conditions draining to the point. To detect change along reaches, the upstream-to-downstream metrics were used as they are based on gauge pairs. The reasoning is that any changes in hydrology will in-part reflect altered conditions along that reach. The direction and strength of change was determined for each metric and flood type between each timeslice (TS1-TS2, TS2-TS3, TS1-TS3), by comparing the 0.25, 0.5, and 0.75 quantiles of the respective datasets creating 5 strength-direction categories: strong increase, weak increase, no change, weak decrease, and strong decrease. Then, the timing of the change was determined for each metric and flow type using a rule-based aggregation of change direction and strength between 3 timeslices that reflect phases of river degradation and recovery; 1950-1979 (TS1) the most degraded phase, 1980-1999 (TS2) the start of river recovery and 2000-present (TS3) river recovery underway (Fryirs et al., 2018; Agnew and Fryirs, 2022; Zhang and Fryirs, 2023, 2024).

### *NFM signal scoring system*

To determine whether a NFM signal is occurring, multiple metrics need to be changing as hypothesised. A scoring system was developed for this. Each metric is assigned a score relative whether it satisfies its hypothesis based on the overall change direction and strength for each metric derived as described above. Given the emphasis on detecting slower and lower floods, certain metrics were given a higher score if they met the hypothesis as they better reflect these characteristics in the hydrograph. Kurtosis, RoR, celerity and FWAI were therefore assigned scores of 2 if they strongly met the hypothesis, 1 if they weakly met the hypothesis and 0 if they do not meet the hypothesis or have experienced no change. For the skewness and peak-to-peak travel time metrics, scores were assigned as 1, 0.5 and 0 respectively. Each score was then summed to give a NFM signal strength, out of 5, and displayed on maps using a traffic lights colour system.

## Results: At-a-station changes in hydrology

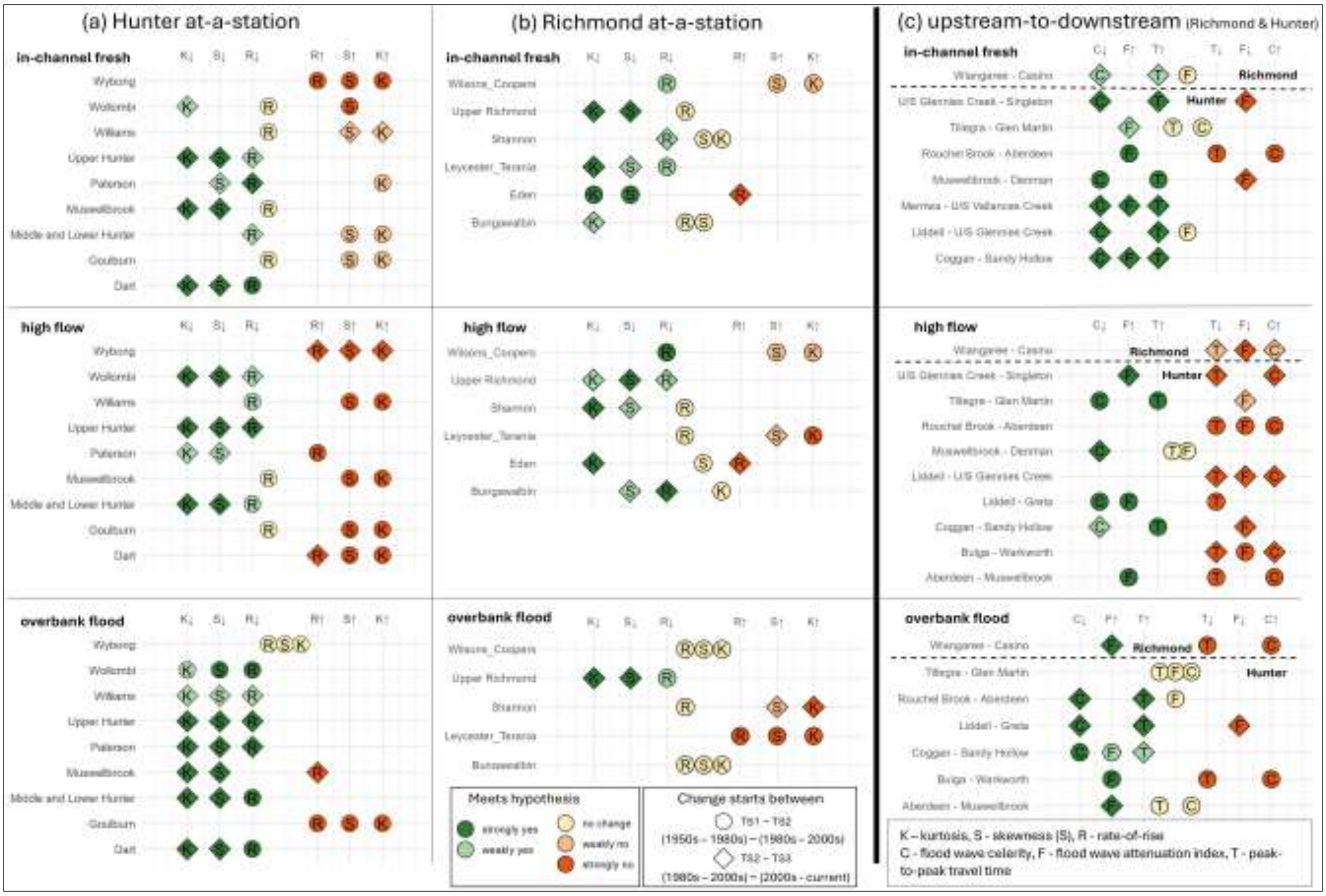


**Figure 3 (a), (b) at-a-station results for subcatchments in the Hunter and Richmond, (c) upstream-to-downstream results for both the Hunter and Richmond**

### *Hunter catchment*

Overall in the Hunter, changes in hydrology are occurring much more strongly for overbank floods with almost all subcatchments meeting the kurtosis, skewness and RoR hypotheses (except Goulburn and Wybong), and in most cases this is a strong result (Figure 3a). This is followed by in-channel freshes where there is a roughly even mix of subcatchments meeting or rejecting the hypotheses, with the bulk of the rejections being weak. High flows have the largest set of subcatchments where hydrology is not changing sufficiently to meet the hypotheses, and in all these cases this is a strong rejection of the hypotheses. In addition to Wybong and Dart have all three metrics showing a strong rejection and Williams, Muswellbrook and Goulburn showing strong rejections of two out of three at-a-station metrics for high flows.

Changes in hydrology are occurring across all but one of the subcatchments for some, if not all, the three flow types (Figure 3a). The exception is Wybong which has shown no change or a strong rejection of the hypotheses for all three flow types. What is clear from the distribution of green on the left and orange on the right is that the kurtosis and skewness of hydrographs has changed strongly in many places. RoR is also changing but has a higher proportion of weakly meets or no change results than kurtosis and skewness. The only subcatchment that consistently returns results that either strongly or weakly meet the hypotheses for all three metrics across all three flow types is the Upper Hunter. However, Wollombi, Middle and Lower Hunter, and Dart return results that either strongly or weakly meet the hypotheses for all three metrics for two out of three flow types.

Across the Hunter, where strong and weak changes meet the hypotheses (dark and light green diamonds), this has occurred between TS2-TS3 (Figure 3a). These changes are dominantly occurring to kurtosis and skewness of the hydrographs. Where changes to RoR meet the hypothesis, this has occurred much earlier between TS2-TS3 in some subcatchments (green circles). The exception is Wollombi where for overbank floods changes in hydrology across all three metrics was occurring much earlier between TS1-TS2 (green circles).

### *Richmond catchment*

Overall, the results show a patchy pattern of changes in hydrology in the Richmond (Figure 3b). Changes are occurring much more strongly for in-channel freshes and high flows and especially for kurtosis and skewness. This applies in the Upper Richmond, Leycester_Terania and Eden for in-channel freshes, and Shannon and Richmond for high flows. Where RoR meets the hypothesis it is weak. The remainder of the findings for these flow types are dominantly showing no change. Wilsons_Coopers shows a weak rejection of the hypotheses for these metrics (kurtosis and skewness) for both in-channel freshes and high flows. The hydrology of overbank floods across all but one subcatchment (the Upper Richmond) has not changed or does not meet hypotheses.

The only subcatchment that is consistently meeting hypotheses for at least two metrics for all three flow types is the Upper Richmond, and especially for kurtosis and skewness (Figure 3b). Many subcatchments are showing dominantly no change. This is especially evident for overbank floods. Only the Leycester_Terania subcatchment is showing a strong rejection of all three metric hypotheses for overbank floods. Elsewhere, isolated hypothesis rejections are occurring, most of which are weak.

Across the Richmond, where strong and weak changes meet the hypotheses (dark and light green diamonds), this has dominantly occurred more recently between TS2-TS3 and especially for kurtosis and skewness (Figure 3b). Some changes in RoR that have met the hypothesis (weak or strong) occurred earlier between TS1-TS2. or overbank floods, only the Richmond subcatchment has shown changes that meet the hypotheses for overbank floods, and this has occurred strongly more recently between TS2-TS3 for kurtosis and skewness, with RoR showing a weak earlier signal.

## Results: Upstream-to-downstream changes in hydrology

### *Hunter catchment*

Figure 3c shows the upstream-to-downstream results for the subcatchments in the Hunter. Overall, changes in flood wave celerity, flood wave attenuation and peak-to-peak travel time strongly meet the hypotheses much more widely for in-channel freshes than for high flow and overbank floods. There is no clear trend of whether celerity, attenuation or travel time are dominating the changes, however attenuation does appear more frequently as no change or weak/strong rejection of the hypotheses.

For in-channel freshes, all reaches except Tillegra-Glen Martin, and Rouchel Brook-Aberdeen show changes in hydrology for two or more of the upstream-to-downstream metrics, with all but one of these changes strongly meeting the hypotheses (Figure 3c). Only two reaches are showing a full set of changes to all three metrics (Merriwa-u/s Vallances Creek and Coggan-Sandy Hollow). Strong changes that meet the hypotheses have occurred more recently between TS2-TS3 (green diamonds). Muswellbrook-Denman is the only reach where an earlier change to celerity and travel time occurred between TS1-TS2 (green circles).

For high flows a dominant proportion of reaches show a strong rejection of the hypotheses for at least two out of three metrics (Figure 3c). This is particularly evident along Rouchel Brook-Aberdeen, Liddell-u/s Glennies Creek and Bulga-Warkworth reaches. Only two reaches show a strong or weakly meets hypotheses result for two metrics. These changes dominantly occurred earlier between TS1-TS2 (green circles). Five of the none reaches analysed showed a strong rejection of the hypotheses for two or more metrics.

For overbank floods, the bulk of reaches in the Hunter catchment are showing some changes that mees the hypotheses (Figure 3c). Three of the six reaches are showing strong or weak changes in celerity and travel time with most changes occurring more recently between TS2-TS3 (green diamonds). Additionally, two reaches show mostly no change over time. The reach with the strongest rejection of the hypotheses is Bulga-Warkworth, for celerity and travel time.

### *Richmond catchment*

Only one upstream-to-downstream pair of gauges met the eligibility requirements for our analysis (Wiangaree-Casino) (Figure 3c). For this reach only celerity and travel time are weakly meeting the hypotheses for in-channel freshes with this result emerging more recently between TS2-TS3. The only other hypothesis that was met for this reach was for attenuation for overbank floods which has also occurred more recently between TS2-TS3. All other metrics for all three flows reject the hypotheses or show no change.

## Discussion: Where are NFM signals occurring?

Figure 4 shows the NFM signal for each subcatchment of the Hunter and Richmond catchments. The colour of the subcatchment denotes the strength of the NFM signal for at-a-station metrics and the colour of the reach streamlines denotes strength of the NFM signal for upstream-to-downstream metrics between the gauge pairs. When the Hunter and Richmond subcatchments are compared an almost opposite trend occurs (Figure 4). In the Hunter the most widespread NFM signals are occurring for overbank floods, whereas in the Richmond the NFM signal is most widespread for in-channel freshes.

In the Hunter (Figure 4-left), for in-channel freshes, high strength NFM signals are only occurring in relatively small subcatchments in the north; Dart and Muswellbrook. Moderate and low signals dominate the downstream subcatchments with a large proportion of the Hunter catchment showing no signal of NFM for in-channel freshes. As flow stage increases, the NFM signal gets stronger over a greater proportion of subcatchments, with high strength expanding to almost all subcatchments in the eastern half of the Hunter and areas around Muswellbrook, Singleton, Maitland and Wollombi. The only subcatchments that show no signal for any flow type are the Goulburn and Wybong. In terms of upstream-to-downstream signals, in-channel freshes and overbank floods are showing the strongest NFM signal along significant lengths of stream, especially on the Hunter River trunk stream (in the Middle and Lower subcatchment). Contrary to the subcatchment signal, a portion of the Goulburn River trunk stream is also showing a strong NFM signal. The weakest upstream-to-downstream signals occur for high flows.

In the Richmond (Figure 4-right), for in-channel freshes, high strength NFM signals are widespread and occurring in most of the upstream subcatchments; Leycester-Terania, Upper Richmond and Eden, and the Lower Richmond downstream. Interestingly, every part of the Richmond is showing a NFM signal (albeit low in places) for in-channel freshes. However as flow stage increases into high flows and overbank floods, the strength of the NFM signal weakens dramatically with vast areas of the southern and northern subcatchments showing no signal for overbank floods; Wilsons-Coopers, Leycester-Terania, Shannon and Bungawalbin. In terms of upstream-to-downstream signals, the Richmond River trunk stream never reaches a strong NFM signal level. For high flows, Leycester-Terania stands out as having no NFM signal, and coupled with only a moderate signal for Wilsons-Coopers, means that Lismore remains at high risk.

These trends in hydrology in the Hunter and Richmond catchments are not surprising given the pattern of 'regreening' that has (or has not) occurred over the last 70 years, and especially since the 1980s (Cohen et al., 2022; Zhang and Fryirs, 2023). The change is most stark along the Hunter trunk stream where riparian woody vegetation coverage was as low as 6% in the 1950s. This had increased to 20-30% by 1987 and 45% by 2021 with the increase being evenly distributed between the riparian and in-channel zones. In areal terms, the amount of vegetated area along the Hunter River increased by almost an order of magnitude from 3.36 to 29.7 km$^2$ along the upper (upstream of Denman), middle (upstream and downstream of Singleton), and lower (downstream of Maitland) trunk stream (Zhang and Fryirs, 2023). In the Richmond catchment, the increase has been less stark. Catchment averaged riparian woody vegetation coverage was at around 40% in 1987 and only increased to around 50% by 1995. It has hovered around 50% ever since (Zhang and Fryirs, 2023). While these coeval regreening trends are encouraging, further research is needed to establish the extent to which riparian regreening is contributing to NFM signals relative to other geomorphic, climatic and anthropogenic controls that also play a key role in determining flood hydrology and routing in these catchments.

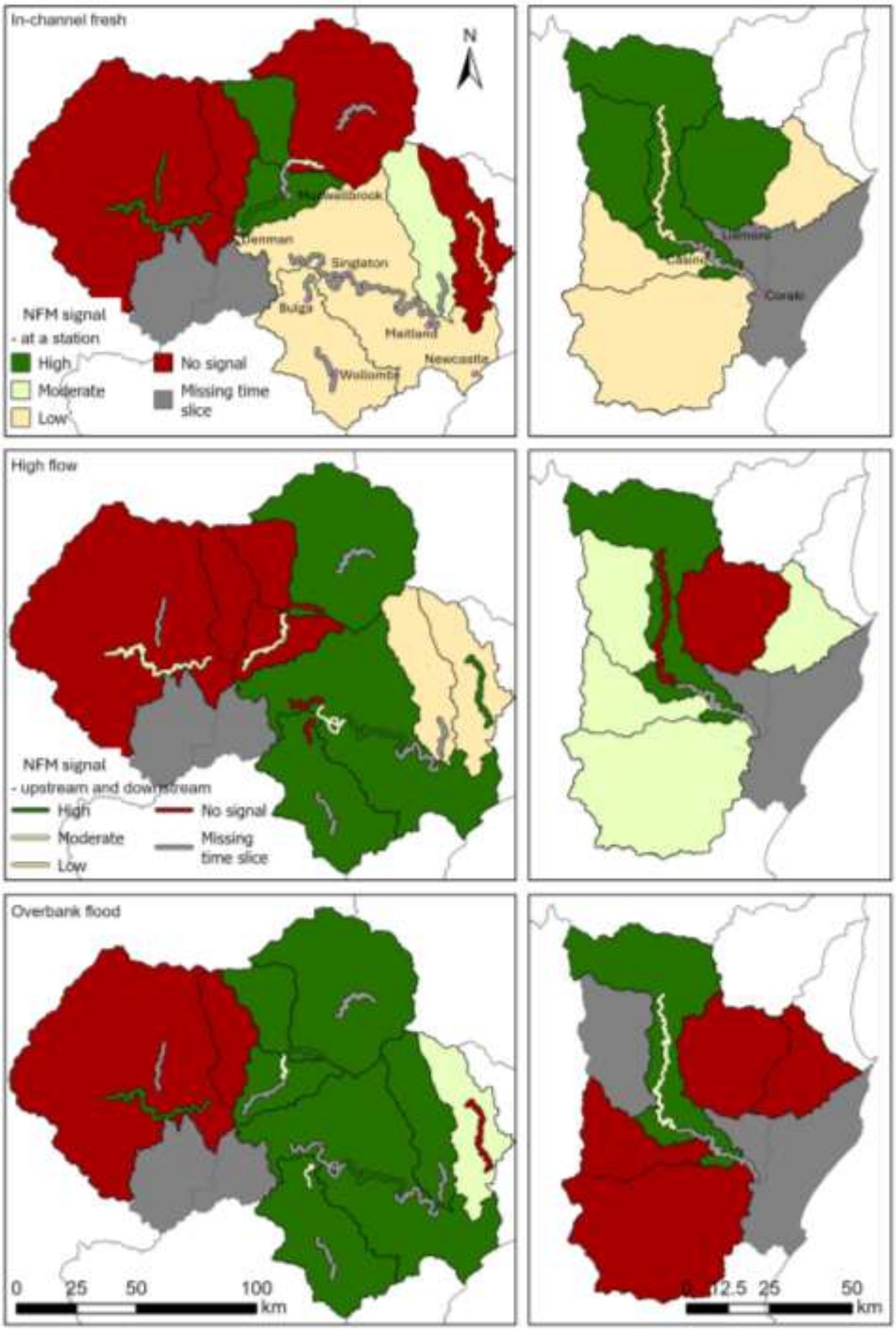


**Figure 4 NFM signal strength in the subcatchments and river reaches of the Hunter (left) and Richmond (right) for three flow stages; in-channel fresh (minor floods), high flow (moderate floods), and overbank flood (major floods).**

## Discussion: What does this mean for nature-based flood mitigation and river rehabilitation?

The findings provide a critical reality check for advancing nature-based flood mitigation. The NFM "traffic light" maps offer a practical prioritisation and decision-support tool, helping practitioners distinguish subcatchments with strong, emerging, or absent signals. Areas with strong to moderate signals present strategic opportunities for "value-add" interventions in systems already showing recovery and mitigation benefits (Agnew and Fryirs, 2022). These "value-adds" could utilise either/both active and assisted rehabilitation, or passive and unassisted approaches (Fryirs et al., 2018). In contrast, subcatchments with weak or no signals will require greater investment and longer timeframes (Agnew et al., 2024). This highlights the need for realistic expectations and alignment of resources with intervention scale. Strong-signal subcatchments can serve as benchmarks to guide rehabilitation design. Regardless of signal strength, effective NFM depends on multi-tool, multi-scalar approaches (Hartmann et al., 2019; Fryirs, 2026).

To mitigate minor and moderate floods (in-channel freshes and high flows) will require implementation of geomorphic and vegetative roughness tools along channels and riparian zones (Fryirs, 2026; Chauhan et al., 2026). Options include riparian replanting, installation of wood or leaky weirs, and the use of local runoff attenuation features (RAFs) to slow flows (Prinsley et al., 2025). Strategic reconnection of floodplains, wetlands, and palaeochannels can further enhance storage and attenuation capacity. However, achieving a noticeable effect on-the-ground will require a shift from isolated reach or site-scale actions towards corridor-based implementation (Agnew and Fryirs, 2022; Agnew et al., 2024).

To mitigate major floods (overbank floods) will require that focus shifts from opportunistic, small-scale interventions to initiatives at valley and (sub)catchment scales (Fryirs, 2026). Options include reforestation, agroforestry, soil health improvement, and wetland restoration, all of which reduce runoff generation, enhance landscape-scale water storage (Prinsley et al., 2025), and aid desynchronisation of tributary-trunk stream flood peaks. Such measures require long-term planning, coordination and sustained investment.

## Conclusions

Detecting NFM signals across (sub)catchments and along river reaches can be achieved using existing hydrological records. Marked spatial variability in signal strength across the Hunter and Richmond catchments highlights the importance of place-based prioritisation, with some subcatchments already exhibiting a signal while others show limited or no signal. Effective NFM requires a multi-tool, multi-scalar approach, coupled with long-term commitment and monitoring. By identifying where NFM is occurring, emerging, or absent, more strategic, targeted, and adaptive implementation of nature-based solutions can occur to deliver NFM.

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