Griffith UNIVERSITY
Queensland, Australia

PRECISION EROSION &
SEDIMENT MANAGEMENT
RESEARCH GROUP

PrESM

FINAL REPORT

Sediment Pollution Sources to the Richmond River: Final report for the Richmond River Estuary Coastal Management Program: Stage 2.1 Strategic Prioritisation for on-ground works.

A report to ROUS County Council **November 2025**

FINAL REPORT

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Representation of the GIS reach panorama viewer which forms the basis of the ground truthing strategy across the catchment

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Executive Summary

Project Overview – Sediment Pollution Sources to the Richmond River

Background (from RFQ)

Rous County Council (Rous), Ballina Shire Council (BaSC), Lismore City Council (LCC) and Richmond Valley Council (RVC) are partnering with NSW Government to prepare a Coastal Management Program (CMP) for the Richmond River estuary in collaboration with Kyogle Council (KC), Byron Shire Council (BySC) and catchment stakeholders. The Stage 1 Scoping Study report identified the need for a whole-of-catchment approach to ensure inclusive and equitable governance, recognising the interests of the large number of stakeholders and the need to support and promote collaboration and effective communication. While governance barriers exist, stakeholders agree on the need to focus on whole-of-catchment protection and enhancement of these values. Collaboration relies on a shared catchment understanding of the whole-of-system needs. The Richmond River Coastal Management Program (CMP) will provide a whole-of-catchment perspective for the coastal management planning process which recognises the influence of the catchment issues and activities on the health of the coastal zone. The key ecosystem health challenges facing the Richmond River are linked to its physical characteristics including the large catchment area (6,850 km^2), large floodplain (> 1,000 km^2) and small estuary water surface area (19 km^2) relative to the catchment area, coupled with the significant catchment modifications that have occurred since European settlement. With this substantial catchment area and land use modifications, the management of the catchment has a significant impact on the health of the river, estuary and coastal zone. While there are a number of localised management plans and on-ground catchment management actions currently being implemented within the Richmond River catchment, there is no whole-of-catchment management plan or similar document integrating the diverse nature of catchment characteristics, linkages and current actions to comprehensively guide future management and investment in the region.

The key threats to the Richmond River ecosystem health identified in the CMP Stage 1 Scoping Study include:

- Acid sulphate soil (ASS) runoff and blackwater events as a result of hydrological modification of wetlands and floodplain drainage works, floodgate design, operation and maintenance.
- Diffuse source water pollution and pressure from agricultural practices, clearing of riparian and adjacent habitat, uncontrolled stock access to and grazing within the riparian zone.

It is important to note that whilst ASS and blackwater are recognised as significant threats to ecosystem health, based on the findings of the Richmond River CMP Scoping Study these issues are excluded from the scope of this project and will be incorporated in Stage 3 of the CMP.

Accurate and detailed information about risk and consequence is necessary to assist decision makers generate effective management strategies which identify and prioritise future actions and investment. Stakeholder consultation has identified limited support for further studies and significant support for on-ground works (improve soil health, revegetate and rehydrate landscapes and riparian zones, remove stock access to waterways, address bank erosion, improve management of floodplain infrastructure to reduce ASS and blackwater impacts and better manage stormwater and wastewater systems in urban areas). This document recognises that despite the preference for action some strategic planning is necessary to focus efforts and ensure the cost-effectiveness of actions. A key challenge going forward will be to identify and attract investment and implement targeted on-ground works at sufficient scale to significantly improve the health of the Richmond River.

Project Approach

In addressing the core objectives set out in the RFQ, we first set out to build a detailed understanding of the primary erosion sources to the Richmond Estuary, and then to develop a Geo-Economic prioritisation strategy that will enable us to develop a strategic prioritisation for on-ground riparian works to address the dominant sediment pollution sources in the most cost effective manner. The project focused on channel erosion as a dominant source of sediment to the Richmond estuary given that it has been shown in many rivers in sub-tropical eastern Australia that channel erosion is the dominant source of sediment to the end of river (Wallbrink, 2004, Hancock and Caitcheon, 2010, Olley et al., 2013b). As outlined below, we also investigate alternative sediment sources as a means of testing the hypothesis that the channel network is the dominant sediment source in this river system.

In addressing the core objectives of the project, we have for the first time compiled a series of high-resolution datasets for the Richmond channel network (3rd order streams and above) that represent the current (2023) state of the Richmond channels and associated riparian buffers. Given the key premise underpinning the analysis is that channel erosion is likely to be the dominant sediment source to the estuary, the key premise underpinning sediment management is that erosion is minimised when the in-channel/riparian zone woody vegetation density is maximised. The assumed endpoint of the rehabilitation strategy is to achieve a fully vegetated riparian zone. We recognise that this is a long-term goal, however it is essential to have this costed goal in place so that the most cost-effective reaches can be identified as interim steps towards achieving this long-term goal. We also present data to justify the central role played by woody riparian vegetation in minimising erosion at the catchment scale.

The new datasets developed for the project include:

- a geomorphically defined representation of the Richmond channel network for 1442 km of the 3rd order and above stream network, with a variable width riparian buffer that varies according to channel dimensions. This channel network was then divided into 2884 reaches of 500m length which are the management units for the prioritisation.
- channel erosion volume for each 500m river reach was then derived from multi-temporal lidar datasets spanning 6-13 years (between 2010 and 2023).
- detailed woody vegetation mapping of foliage projected cover (FPC) within the channel and riparian zone derived from the 2023 lidar coverage, represented as the percentage cover within the reach.
- the 35 year woody vegetation trend within the channel and riparian buffer derived from quarterly Landsat persistent green data. This enables us to determine whether the vegetation cover is naturally increasing, decreasing or is largely static over decadal timescales. The slope of the trend line is represented by the Delta Green metric (Pietsch et al., 2021).
- the extent of weeds as reflected by satellite mapping of camphor laurel as a key weed indicator species across the catchment.

The approach adopted includes a series of underlying assumptions, and we present data that addresses each of these in the report.

1) All other things being equal, channel erosion will be less for a similar river reach, the higher the woody vegetation FPC. This assumption justifies the focus on maximising woody riparian vegetation extent as the primary management focus.
2) The presence of camphor laurel - as mapped from satellite imagery, is an indicator of a broader suite of exotic species within that reach. Hence the extent of camphor laurel within a reach can be used to determine weed management requirements.

Decision Support Tool - Cost Effectiveness of Riparian Rehabilitation

These datasets form the basis for deriving a fully costed riparian zone rehabilitation strategy across the entire catchment, in which the most cost-effective reaches are prioritised. Cost effective management is defined as the investment required to achieve a riparian zone (channel + buffer) fully vegetated with native vegetation whilst targeting greatest amount of prior erosion in that reach at the lowest cost. Hence, the key metric for assessing cost-effectiveness is the \$ cost per m^3 of erosion within the reach. This provides the opportunity for the first time to consider the most cost-effective way to manage the entire Richmond River system. A Marxan modelling approach is used to derive the least-cost solutions.

Additional Sediment Sources

While the project is not developing a comprehensive catchment sediment budget (i.e. to quantify all other sources of erosion in the catchment, over and above channel erosion) we do provide some preliminary data on potential additional sediment sources within the catchment for comparative purposes. It must be stressed that these are first approximations only and much more detailed analysis is required to fully quantify each source. It is also acknowledged that this is not a comprehensive list of alternative sediment sources. Tthe accurate quantification of all other sources can only be determined through comprehensive empirically based sediment budget program, coupled with sediment tracing.

The additional sources investigated include:

- An assessment of sediment contributions from landslides (primarily from the upper Wilsons Catchment)
- Estimates of likely worst-case scenario sediment yields from macadamia farms
- Unsealed roads as a potential sediment source
- Channel erosion from within first and second order headwater streams.

Riparian Rehabilitation Optimisation using Marxan Modelling.

The Decision Support Tool that is at the heart of this project, utilises the well-known Marxan optimisation modelling tool, originally designed for conservation planning, to meet user-defined 'management targets' for the ‘minimum cost’. Targets are the amount of each feature that the model is instructed to select (e.g. 10% of Total Erosion volume). Marxan operates with three fundamental principles to optimise conservation priorities namely,

- meet a conservation or management percentage or integer targets for a species or ‘feature’ (in this case the attributes of a river reach).
- for minimum rehabilitation total cost
- with the most compact reserve design (Serra-Sogas et al., 2020).

In this project the Marxan modelling approach has been adapted and applied to 500m reaches of the Richmond catchment to address erosion and rehabilitation issues. In this case the primary management objectives targeted are erosion volume in 500m *reaches* and woody riparian vegetation deficit. In this case we are optimising a solution that will meet the following criteria:

- meet management rehabilitation percentage targets to address a specific management issue or 'feature' (e.g. Total Erosion)
- for minimum total rehabilitation cost
- with the most compact selection of reach area.

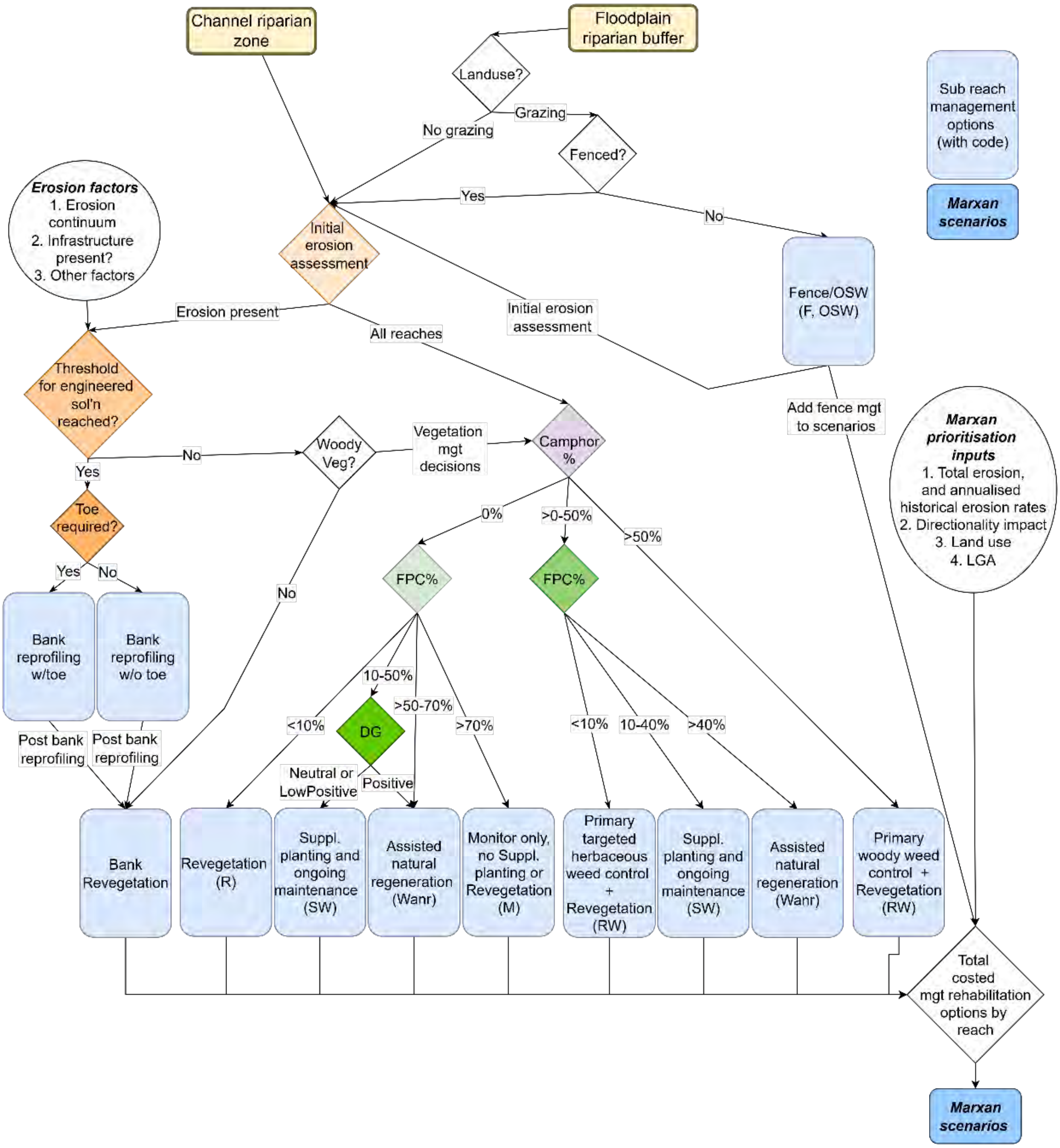

Figure 1. Marxan workflow decision tree showing how each of the management scenarios have been derived. These management scenarios are applied at the sub-reach planning unit scale and for the basis for the rehabilitation costs

Marxan Model Assumptions

1. As per Figure 1 total costs are the sum of the six different management scenarios that are calculated for each reach (F+M+R+RW+SW+Wanr). Note that more than one management strategy can be applied in a single reach on a pro-rata basis (by % of reach area).
2. Total Costs excluding Monitoring only reaches. Reaches (combined Channel and Buffer) where only Monitoring costs occur have been excluded from the Marxan analysis. Note monitoring only is applied in reaches with zero weeds and > 70% FPC (which are often in conservation land use)
3. Reach area (on which all costs, except Fencing cost, are calculated) excludes Watermask area within the channel zone, and roads which occur within the Channel and buffer zones). Fencing costs are calculated from length in m of Buffer zones classified as Grazing land use.

Project rehabilitation costings

The following project scale cost data has been derived from individual management costs applied to reaches and sub reaches based on the selection criteria and is summarised in Table 20 and Table 21.
The total cost of reestablishing a fully vegetated riparian zone across the 1442km of the 3rd order and greater stream network in the Richmond catchment is $336M.

Table 1. Summary of catchment-wide riparian statistics

Project Data	
Project Total Channel Erosion volume (m^3)	3,283,000
Project Annualised channel Erosion volume (m^3)	459,000
Project Annualised channel Erosion mass (t)(BD=1.6)	734,000
Project Non Woody Vegetation (NWV) area (ha)	6,500

Table 2. Summary of catchment wide scenario costs (R = revegetation; RW = primary woody weed control + revegetation; SW = supplementary planting + ongoing weed maintenance; Wanr = assisted natural regeneration; M = monitoring only; F= Fencing).

Project scale costs	$
Total Cost ($)	$ 336,052,481
Active Cost ($) (R+RW+SW+Wanr)	$ 298,777,423
Passive Cost ($) (M+F)	$ 37,275,057
R cost ($)	$3,276,187
RW cost ($)	$53,706,617
SW cost ($)	$117,057,633
Wanr Cost ($)	$124,736,986
M Cost ($)	$3,481,610
F Cost ($)	$33,793,447
70% Total Cost ($)	$283,840,349
70% R cost ($)	$2,293,331
70% RW cost ($)	$37,594,632
70% SW cost ($)	$81,940,343
Total Cost per hectare $/ha	$25,781
Total Cost/Total Erosion $/$m^3$	$102
Active Cost/Total Erosion $/$m^3$	$91
Passive Cost/Total Erosion $/$m^3$	$11
M Cost only (number of reaches)	184

Key Findings Summary:

Dominant Sediment Source

- Channel erosion is confirmed as a dominant sediment source to the Richmond River estuary – in line with evidence for comparable sub-tropical coastal rivers.
- High-resolution datasets (LiDAR, Landsat, woody vegetation mapping) show clear relationships between low riparian vegetation cover and elevated erosion rates.
- A fully vegetated riparian zone is the most effective long-term erosion mitigation strategy.

Scale of the Issue

- Total channel erosion volume detected (from multi-temporal LiDAR): 3.28 million m^3.
- Annualised channel erosion sediment yield: ~734,000 t/yr.
- Total non-woody riparian vegetation area requiring rehabilitation: ~6,500 ha.

Costed Catchment-Wide Rehabilitation Strategy

- Total cost to fully rehabilitate the 3rd-order+ channel/riparian zone network (1442 km): $336M.
- Cost effectiveness average metric: $102 per m^3 of erosion; active intervention costs dominate.
- Cost effectiveness for top 10% = $19.5 per m^3 of erosion
- Marxan optimisation identifies the least-cost groups of reaches for staged rehabilitation.

Rehabilitation Prioritisation (Marxan Decision Support Tool)

- Addressing 10% of total channel erosion requires treating only 6.1% of reaches at 1.9% of total cost.
- Addressing 20% requires 10% of reaches at 5.3% of cost.
- Addressing 50% requires 25.2% of reaches at 21.9% of cost.

Spatial Distribution of Priority Reaches

- Priority erosion-source reaches are concentrated in Kyogle and Richmond Valley LGAs.
- 80–90% of priority reaches lie outside the NSW-defined coastal zone → sediment sources are overwhelmingly upper catchment derived.
- Most priority reaches occur on private land, affecting funding pathways and feasibility.

Alternative Sediment Sources (Preliminary Estimates)

- Landslides (2022 flood event): 970,000 m^3 mobilised; ~710,000 t delivered to streams (predominantly during one off event – although delivered sediment continues to be reworked).
- Macadamia farming (likely worst-case estimate): up to 84,000 t/yr (upper bound of erosion only based on SCU data; not sediment delivered to stream network).
- Unsealed roads: ~17,500 t/yr potential erosion (based on SEQ monitoring data).
- First/second-order streams (initial estimates, unvalidated): potentially comparable to 3rd-order+ network – but detailed investigation required to confirm.

Ground-Truthing Insights

- Strong correlation (≈77%) between camphor laurel presence and other environmental weeds — validates remote-sensing weed proxy.
- Drone-based reach inspections confirm LiDAR-derived erosion mapping and panoramic provides a good communication tool.

Key Conclusions

- Riparian vegetation condition is the primary lever for reducing sediment delivery to the estuary.
- Woody vegetation above ~70% FPC greatly reduces maximum potential erosion.
- Most effective management: riparian revegetation + weed removal + stock exclusion where relevant.

- In light of the findings from this study, the Estuary Health Risk Assessment (EHRA) management prioritization approach needs to be evaluated (Figure 2).

Study Limitations

- The current study assesses total erosion and does not weight sources according to sediment particle size, geochemistry or particulate nutrient loads
- While the study focused on the most likely dominant sediment sources it is not possible to compare these data with all other potential sources. A full quantitative sediment budget is required to do this – which requires all sources are measured and the spatial and temporal variability of sources assessed. This would also require that sediment delivery ratios to the estuary for each source and sediment particle size fractions are also quantified.
- This study does not assess the fate of sediment and associated nutrients within the estuary and out to sea nor its ecological significance. A different study with these aims is required to answer these questions.
- All lidar DoD analyses have used a very conservative 2 sigma “Limit of Detection” (LoD) and all ground coverage with fewer than 1 ground pt per $3m^2$ have been removed from the analysis. Hence the erosion data are extremely conservative.
- The analysis does not include erosion below the standing water level at the time of lidar data capture – hence once again the channel erosion data should be regarded as minima.

Table 3. Catchment sediment sources and catchment and estuary sediment deposition findings, study years and references + data from this study.

	Lit Review Findings	Study years	Key References	This Study	
Catchment sediment sources				Study years	Sediment Yield
Landslide erosion	n/a	*	*	DoD 2017-2023 -primarily one off input from 2022 flood	966,000 m^3 total -with 473,000 m^3 (710,000 t) delivered to stream
Bank erosion	123,975 t/yr (dry year) 502,709 t/yr (wet year)	1994-1996	(Hossain, 1997)	DoD 2010/16/17-2023 - primarily from 2017 & 2022 floods	3,283,000 m^3 (total erosion) Annual 734,000 t/yr
Horticultural erosion - macadamia	~3.8 t/ha/yr	2007-2009	(Keen et al., 2010)		
	3.3-47,055 mg/m^2 (non-IOM) 0.5-474 mg/m^2 (IOM) ~7 t/ha/yr (IOM)	2023-2024	(Southern Cross University, 2024)	Potential upper level (based on highest SCU data) & 12,000 ha maccas	~ 84,000 t/yr
Agricultural erosion - sugarcane	<15 t/ha/yr (no tillage)	1980-1986	(Prove et al., 1995)		n/a
	16 t/ha	modelling	(Lu et al., 2003)		
	2-5 t/ha/yr	1999-2001	(Visser et al., 2007)		
	12 kg/ha/0.67hr	2006-2007	(Masters et al., 2008)		
	0.098 – 0.113 t/ha	2011, 2014, 2015	(Melland et al., 2022)		
Non-Horticultural Hillslope erosion	n/a	*	*		n/a
Gully erosion	n/a	*	*		n/a
Urban development	n/a	*	*		n/a
Channel incision	n/a	*	*		n/a
Road erosion	5.7 t/km vs 3.9 t/km (gravelled vs ungravelled road plots). Susp. solids contributed 86% of total sed loss from gravelled road, and 72% from ungravelled road over the 2 yrs	SEQ (2003 – 2005)	Forsyth et al. (2006)	Using Forsyth et al data unsealed road area (5750ha)	Est ~17.5 Kt/yr erosion
Total catchment	<1000 t/yr (1998 dry) to > 600,000 t/yr (1989 wet) ~106,000 t/yr (mean)	1989-1998	(McKee et al., 2002)		n/a
Catchment and estuary sediment deposition					
Estuary	12,800-17,400 t (1994-95 dry) 5,800-8,000 t (1995-96 wet)	1994-1996	(Hossain and Eyre, 2002)		n/a
Whole of Catchment Yield					
	28,788 t (1994-95 dry) 221,202 t (1995-96 wet)	1994-1996	(Hossain et al., 2001)		n/a
n/a = none available					

Recommendations

Implications for the Richmond CMP

1. This study demonstrates that sediment and associated particulate nutrients entering the Richmond River Estuary are primarily sourced from upstream channel networks beyond the Coastal Zone. While actions within the coastal zone remain important, the most cost-effective opportunities to reduce sediment entering the estuary come from outside the coastal zone and require a whole-of-catchment approach. .

2. Analysis shows that significant reductions in channel erosion can be achieved through targeted investment:
    - Addressing 10% of total erosion by rehabilitating 6.1% of reaches at ~1.9% of total cost ($6.6M).
    - Addressing 20% of erosion by focusing on 10% of reaches at ~5.3% of total cost ($20.2M).

    Recommend adopting the 20% erosion reduction target as a 10-year plan, with an indicative annual budget of $2M (2025 dollars). This would enable the 10% target to be achieved within the first 3–4 years Noting that Most priority reaches lie outside the CMZ, reinforcing the need for a whole-of-catchment approach.

3. There is a highly unequal spatial distribution of priority reaches around the catchment so there will be a need to pool council funds to establish a prioritised program of works that may well focus in other parts of the catchment that are outside of individual councils' operating area (or backyard). There may also be opportunities to foster community engagement through an 'adopt a reach' programs, where residents, Landcare groups, school groups or other community groups effectively adopt a high priority reach to help address this issue.

4. To support CMP implementation, establish and maintain a web-GIS platform housing all spatial data generated by this study, including detailed rehabilitation plans for 2,884 reaches.
    - Include a public interface for transparency and citizen science contributions (e.g., ground-truthing, weed mapping).
    - Estimated annual cost: $120K–$250K, covering licensing, administration, and updates.

    Once priority reaches are selected, undertake additional field investigations to refine site-specific plans. Drone-based surveys, similar to those used in this study, should be repeated, and all new data integrated into the web-GIS system. This will strengthen implementation planning and monitoring.

5. The results from this study generally conform with expectations from the highest level of River Styles reach classes, however, a significant departure is the fact that the prioritisation is somewhat reversed - i.e. River Styles places higher priority on reaches currently in good condition, whereas this study is specifically targeting the reaches contributing most sediment. The situation is more complex in the current study, however, because it incorporates an economic analysis which also targets some reaches currently in relatively good condition because they are the most cost-effective to

rehabilitate (see Appendix 11). Most of the bank erosion observed is in the form of major slumps that appear to be largely self-healing (i.e. they are colonised with vegetation – often becoming the focus for primary colonising species such as river oak (*Casuarina cunninghamiana*). For this reason an assumption is made across the catchment that revegetation alone (i.e. not engineering with revetments or pile fields) will be sufficient to achieve the long-term channel stabilisation objectives. Engineering solutions would only be required where infrastructure is under immediate threat (see Appendix 13).

6. Key areas for further research include:
   - Sediment yields from first- and second-order channels in representative sub-catchments ($200K–$300K).
   - Sediment tracing studies to validate findings and inform a comprehensive sediment budget:
     1. Pilot study ($73K)
     2. Full catchment study ($300K)
   - Analysis of sediment particle size and associated nutrient variability across geomorphic units
   - Given this study does not assess the fate of sediment and associated nutrients within the estuary and/or out to sea nor its ecological significance – a study should be instigated with the aims to better understand these issues. (NB it would make sense to link this work to the sediment tracing and channel boundary sediment particle size study).

Broader Implications of this Study

8. Findings suggest that sediment contributions from upstream channel networks may dominate in other NSW coastal catchments. Similar studies should be undertaken in priority catchments to confirm this pattern.

9. While this study highlights the critical role of channel erosion and riparian management, some components of the sediment and nutrient budget remain unquantified. Developing comprehensive sediment budgets for Richmond and other catchments will provide a robust basis for prioritising management actions. This aligns with best practice approaches used in GBR catchments, with modifications to address known limitations. Current estuary health risk assessment methods may no longer be fit for purpose in the Richmond catchment. Future investment frameworks should reflect whole-of-catchment dynamics rather than CMZ boundaries. Similar reviews should be undertaken in other catchments

10. As part of the sediment budget process, detailed sediment tracing studies should be undertaken in all priority catchments to provide an additional independent line of evidence as to the relative sediment sources within the catchment. The sediment tracing should include both spatial geochemical tracing and radionuclide tracing to distinguish the dominant erosion processes.

11. Given the likely importance of catchment sediment sources in other catchments, future decisions regarding the investment of resources designed to achieve the greatest benefit to NSW estuaries should not be limited by the artificial delineation between the CMZ and the upper catchment.

12. Based on the results from this study, it would appear that the current Estuary Health Risk Assessment approach that has been used in the past for prioritising investment, is no longer fit for purpose in the Richmond catchment given that it is completely dominated by hillslope erosion modelling that is highly sensitive to slope (see Figure 2, Appendix 12).

13. Similar studies need to be carried out in other catchments to test whether the same applies in these other catchments.

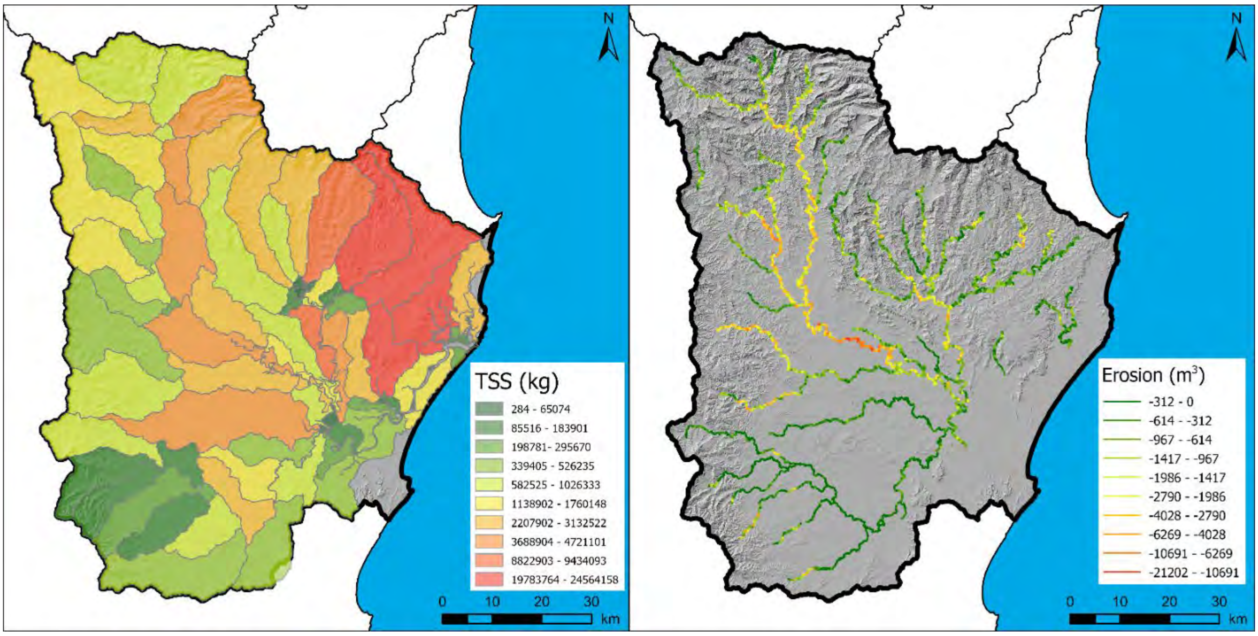

Figure 2. Comparison between the predictions from the EHRA sources of sediment in the Richmond catchment cf the distribution of channel erosion sources defined in this study. NB – The EHRA does not explicitly quantify channel erosion.

Key Datasets Underpinning Prioritisation

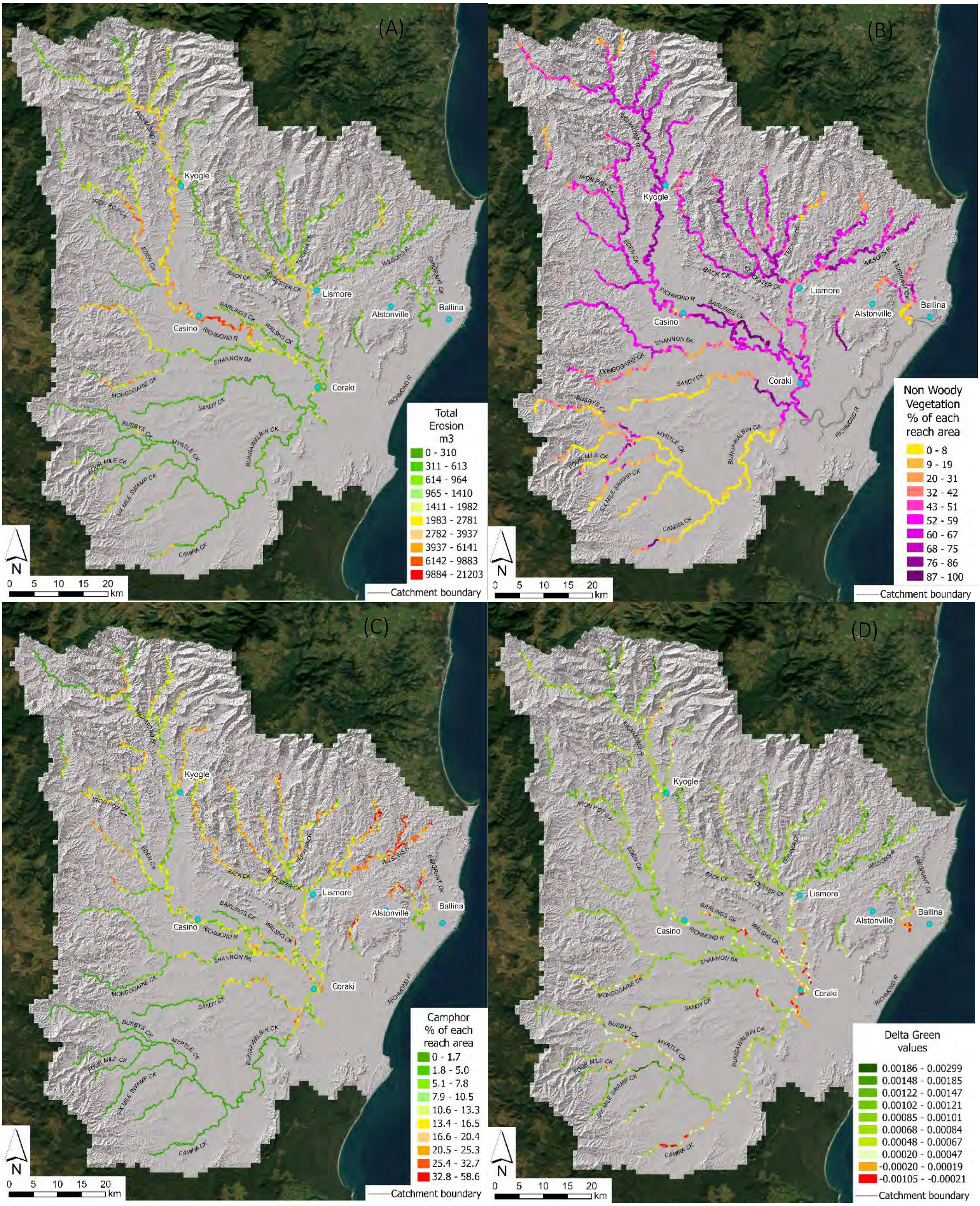

*Figure 3. Maps showing the spatial distribution of the 4 key new input data layers derived to underpin the rehabilitation costings and the rehabilitation prioritisation. A) Total reach erosion volume; B) Reach % non-woody vegetation area; C). Reach % camphor laurel; D) Woody vegetation cover trend over 35 years as relected by the Delta Green metric (See Pietsch et al., 2021). **(NB Full page versions of these maps can be found in the body of the main report).***

Key Findings: Further Detail

A Rationale for the Focus on Riparian Vegetation.

The central premise underpinning the management strategy which is the basis for the rehabilitation strategies that are being optimised in this study, is first that channel erosion is a dominant source of sediment in the Richmond catchment, and that the most effective way to minimise channel erosion is to maximise the extent of woody vegetation within the riparian, preferably with native vegetation. To test this underlying assumption the sequence of graphs shown in Figure 3 plot the relationship between total reach erosion and total reach FPC of the channel zone. For each population an upper and lower envelope curve is derived which shows that maximum reach erosion decreases significantly with increased woody vegetation FPC. Similarly at the lower end of the scale, when FPC drops below a certain threshold minimum erosion rates increase. Note that each tributary system has a distinctly different relationship, which gives an indication of the sensitivity of the different rivers. Note that Ironpot Creek and Shannon Brook have very steeply declining curves, reflecting the sandy nature of these catchments, whereas Bungawalbin Creek has a more gradually decreasing curve, with some anomalous outliers that have high FPC. These curves likely provide an indication of the potential erosion reductions that can be achieved once vegetation is increased, however, caution should be used extrapolating sediment yield reductions given that due to hysteresis, channel degradation and recovery are not linearly related. Furthermore, these relationships suggest that different maximum FPC targets could be identified for different parts of the catchment.

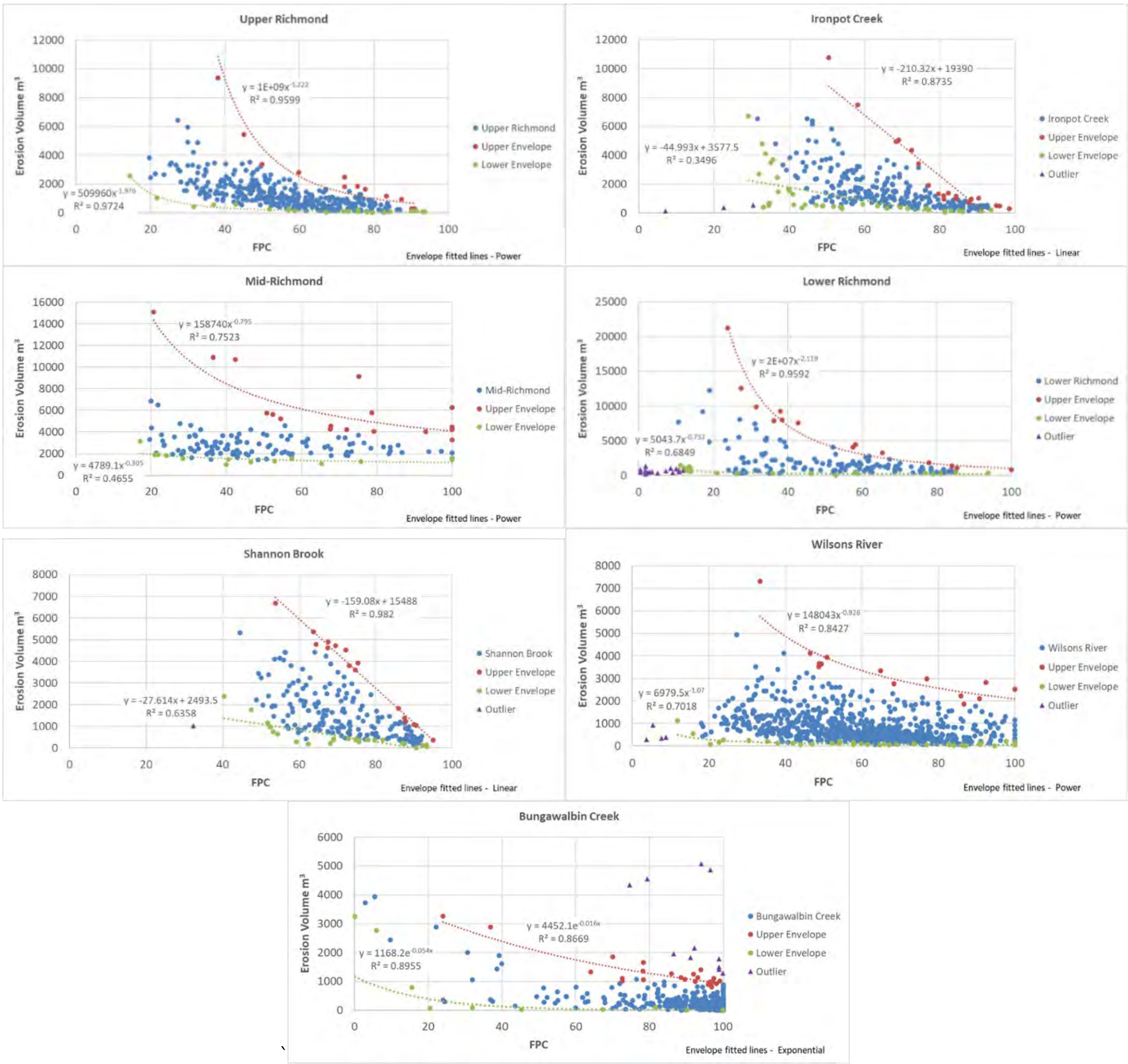

Figure 4. Plots showing the relationship between reach total erosion volume and reach % FPC. The curves show an upper envelope curve that provides an upper limit for reach erosion as a function of the extent of riparian vegetation within the reach. The noise within the relationships (between the upper and lower envelope curves) represents the myriad local controls on channel erosion, particularly channel boundary erodibility.

Where are the most effective reaches to target for channel erosion reduction

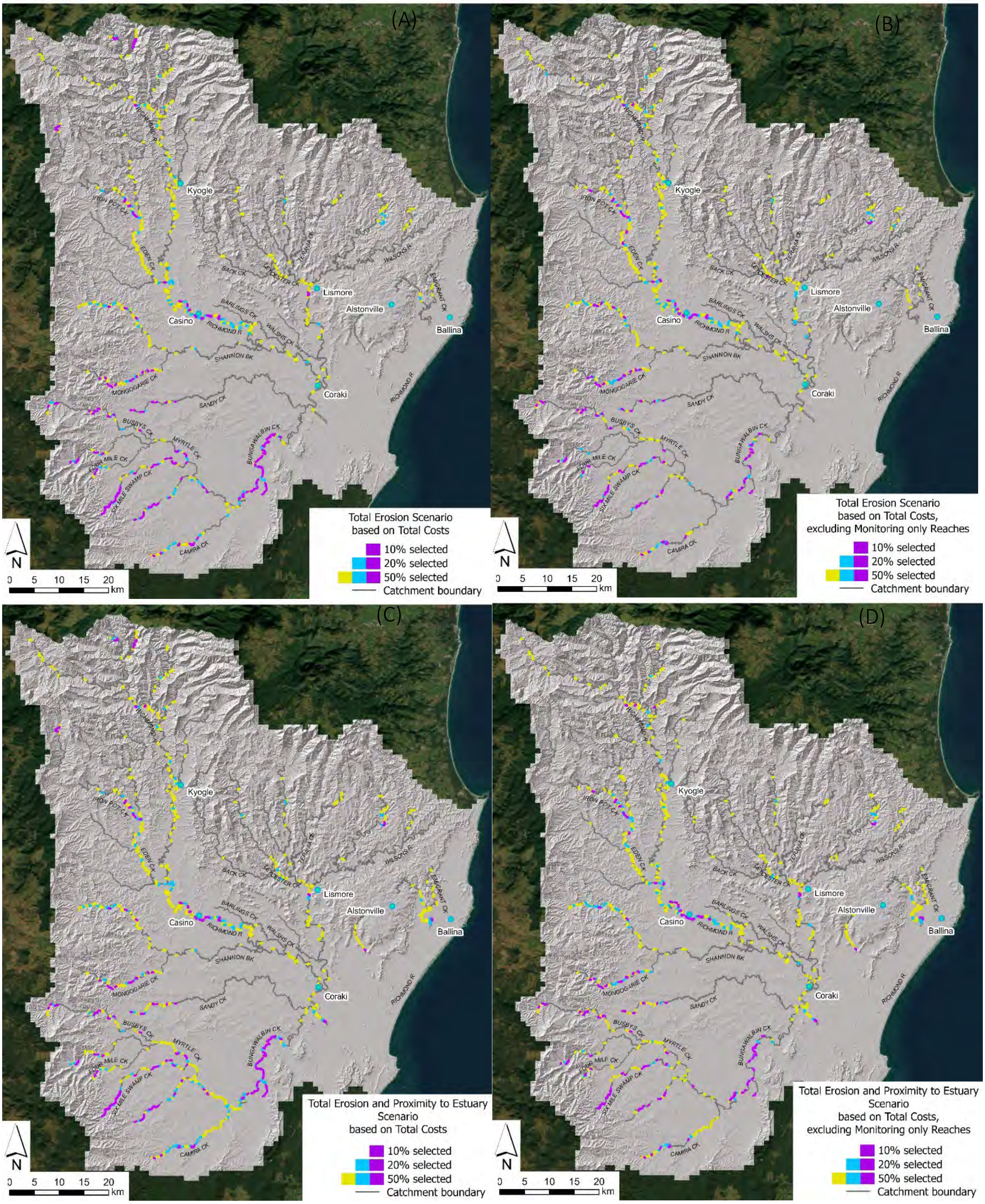

Figure 5. 4 prioritisation scenarios derived from the Marxan optimisation modelling. A) The distribution of prioritised reaches based on total cost alone for the 10%, 20% and 50% erosion scenarios; B) The distribution of prioritised reaches based on total cost excluding monitoring only reaches for the 10%, 20% and 50% erosion scenarios; C) The distribution of prioritised reaches based on total cost + proximity to estuary for the 10%, 20% and 50% erosion scenarios; D) The distribution of prioritised reaches based on total cost excluding monitoring only reaches + proximity to estuary for the 10%, 20% and 50% erosion scenarios ***(NB full page version of these maps are available in the main report)****.*

Marxan optimisation Modelling

- Scenario solutions show that selecting reaches contributing 10% of the Total Erosion volume can be addressed by targeting just 6.1% of the reaches in the catchment at just 1.9% of the Total Cost required to rehabilitate the entire catchment.
- Similarly targeting 20% of the erosion source areas can be addressed by focusing on 10% of the reaches at a total cost that is just 5.3% of the total cost. Whereas focusing on reaches contributing 50% of the channel erosion at the catchment scale can be addressed by focusing on 25.2% of reaches at 21.9% of the total catchment cost.
- Scenarios based on a single feature, Total Erosion, have a lower per hectare cost than combined scenarios, as the algorithm attempts to satisfy targets for two features, i.e. Total Erosion and Proximity to Estuary.
- Per hectare cost for the scenarios (ranging from $8,542 to $14,091 for the 10% scenarios) is significantly lower than the average for the Project Total Cost per hectare of $25,781.
- Per hectare cost increases as the percentage prioritised of Total Erosion volume increases. This is because the optimal solution at higher percentage scenarios must select increasingly more expensive reaches.

Breakdown of Prioritised Reaches According to their Local Government Area Location.

The graphs in Figure 5 show that for each of the different prioritisation scenarios (i.e. 10%, 20% and 50% of total erosion) the reaches requiring the most investment occur with the Kyogle and Richmond Valley Shires. The relative proportion of priority rehabilitation reaches increased for the Kyogle and Lismore Shires as greater proportions of the erosion problem are tackled.

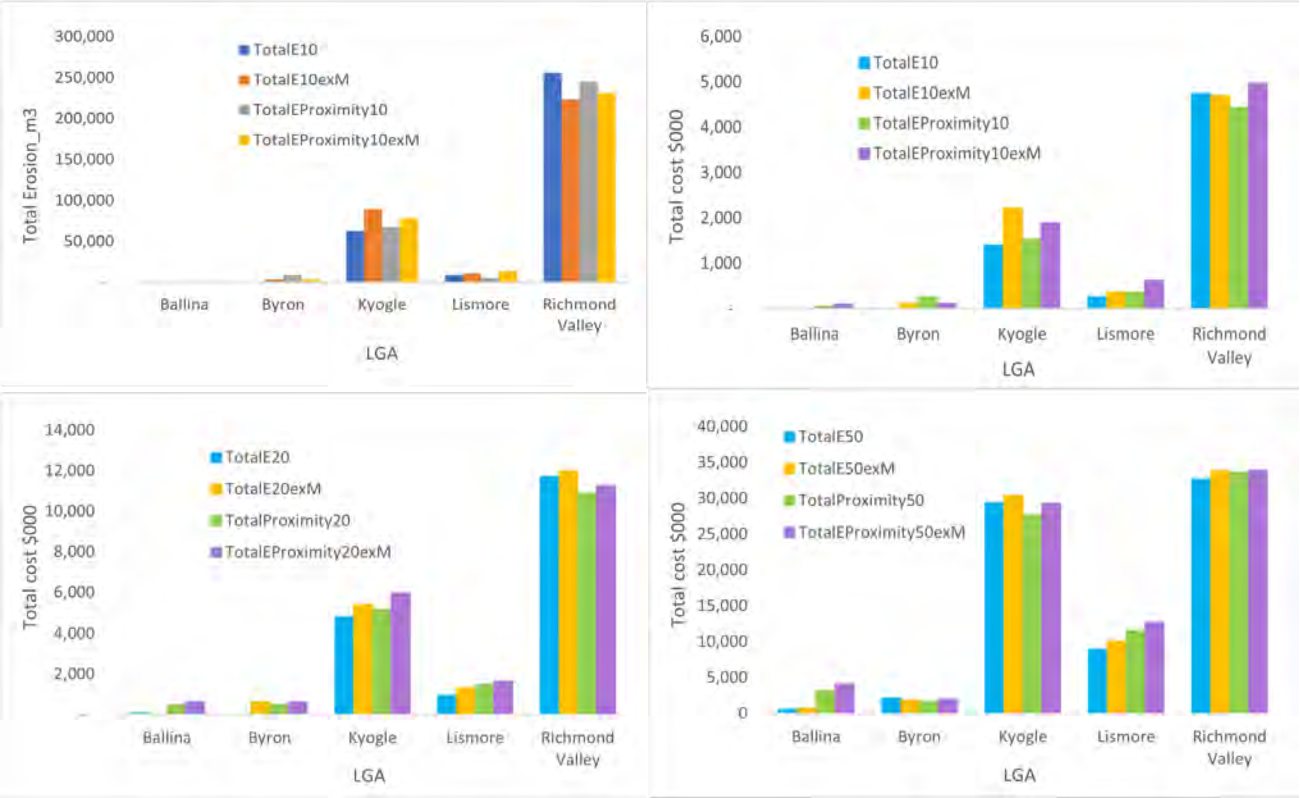

Figure 6. Graphs showing the relative concentration of prioritised rehabilitation reaches by LGA.

Table 4. Summary statistics for the 4 variants of the Scenarios targeting 10%, 20% and 50% of the erosion volume for the total catchment and then showing the breakdown into the 5 Local Government Aarea (LGAs) within the Richmond Catchment. For each scenario

Scenario and %	Details	Richmond catchment	Ballina	Byron	Kyogle	Lismore	Richmond Valley
TotalE10	*Scenario rehabilitation Tcost ($000)*	$6,406	$0	$0	$1,400	$258	$4,748
	Scenario Reach Area (excluding roads) selected (ha)	749.9	-	-	104.2	9.0	636.6
	Scenario # of reaches selected	176	-	-	21	2	153
TotalE10exM	*Scenario rehabilitation Tcost ($000)*	$7,389	$0	$108	$2,222	$361	$4,697
	Scenario Reach Area (excluding roads) selected (ha)	524.3	-	4.1	76.4	11.2	432.6
	Scenario # of reaches selected	117		1	14	2	100
TotalEProximity10	*Scenario rehabilitation Tcost ($000)*	$6,663	$50	$262	$1,538	$368	$4,444
	Scenario Reach Area (excluding roads) selected (ha)	716.7	2.2	9.3	95.3	12.5	597.4
	Scenario # of reaches selected	169	1	2	19	3	144
TotalEProximity10exM	*Scenario rehabilitation Tcost ($000)*	$7,713	$102	$108	$1,896	$630	$4,976
	Scenario Reach Area (excluding roads) selected (ha)	572.4	4.5	4.1	65.7	22.0	476.0
	Scenario # of reaches selected	132	2	1	12	5	112
TotalE20	*Scenario rehabilitation Tcost ($000)*	$17,931	$61	$0	$4,821	$939	$11,718
	Scenario Reach Area (excluding roads) selected (ha)	1,291.1	2.1	-	219.8	33.0	1,022.5
	Scenario # of reaches selected	286	1	-	42	7	233
TotalE20exM	*Scenario rehabilitation Tcost ($000)*	$19,381	$0	$636	$5,424	$1,324	$11,996
	Scenario Reach Area (excluding roads) selected (ha)	1,017.3	-	23.5	189.4	46.8	757.6
	Scenario # of reaches selected	215		5	36	10	164
TotalEProximity20	*Scenario rehabilitation Tcost ($000)*	$18,502	$464	$502	$5,183	$1,481	$10,872
	Scenario Reach Area (excluding roads) selected (ha)	1,364.2	19.0	17.9	226.6	50.4	1,050.3
	Scenario # of reaches selected	307	5	4	44	11	243
TotalEProximity20exM	*Scenario rehabilitation Tcost ($000)*	$20,164	$651	$625	$5,966	$1,649	$11,274
	Scenario Reach Area (excluding roads) selected (ha)	1,056.7	26.5	21.9	201.1	56.5	750.7
	Scenario # of reaches selected	229	8	5	38	12	166
TotalE50	*Scenario rehabilitation Tcost ($000)*	$73,692	$577	$2,143	$29,392	$8,933	$32,648
	Scenario Reach Area (excluding roads) selected (ha)	3,461.1	19.4	78.9	1,076.2	308.6	1,978.0
	Scenario # of reaches selected	728	7	17	209	62	433
TotalE50exM	*Scenario rehabilitation Tcost ($000)*	$76,924	$693	$1,857	$30,421	$10,099	$33,853
	Scenario Reach Area (excluding roads) selected (ha)	3,092.1	24.8	69.8	1,011.2	344.4	1,641.8
	Scenario # of reaches selected	633	9	15	195	69	345
TotalEProximity50	*Scenario rehabilitation Tcost ($000)*	$77,670	$3,161	$1,620	$27,673	$11,572	$33,644
	Scenario Reach Area (excluding roads) selected (ha)	4,020.4	124.1	60.6	1,022.1	396.1	2,417.5
	Scenario # of reaches selected	892	42	13	198	82	557
TotalEProximityexM50	*Scenario rehabilitation Tcost ($000)*	$81,923	$4,079	$1,968	$29,269	$12,744	$33,863
	Scenario Reach Area (excluding roads) selected (ha)	3,438.8	154.2	74.0	963.0	417.8	1,829.9
	Scenario # of reaches selected	751	51	16	187	89	408

Breakdown of Prioritised Reaches According to their location in the designated Coastal Zone or not.

The graphs in Figure 7 show that for each of the different prioritisation scenarios (i.e. 10%, 20% and 50% of total erosion) the vast majority (80%-90%) of investment is required in the non-coastal zone (as defined by NSW Govt) portion of the catchment. The proportion increases marginally to just over 20% to achieve the 50% erosion target. Either way, it is very clear that the dominant sediment sources to the Richmond Estuary are located in the catchment upstream of the designated Coastal Zone.

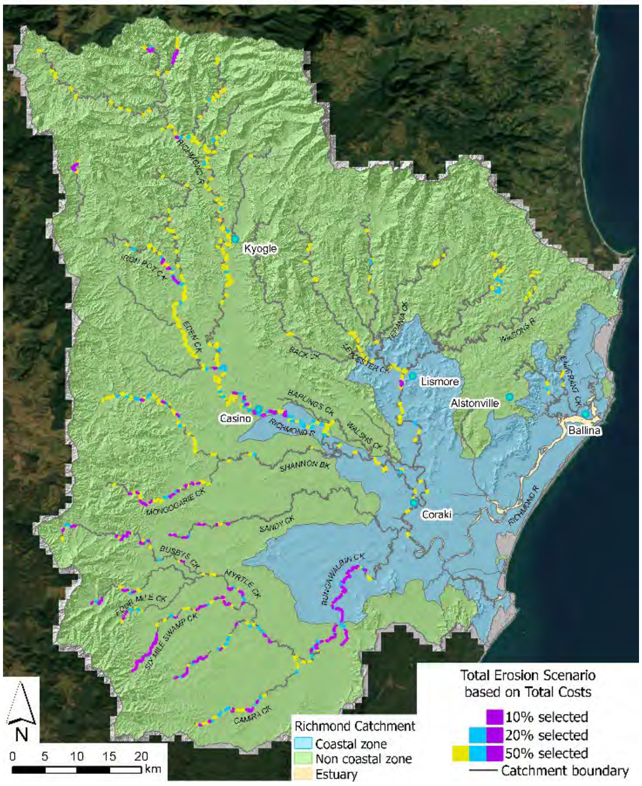

Figure 7. Map showing the proportion of the catchment designated as "coastal zone" with the prioritised reaches overlaid.

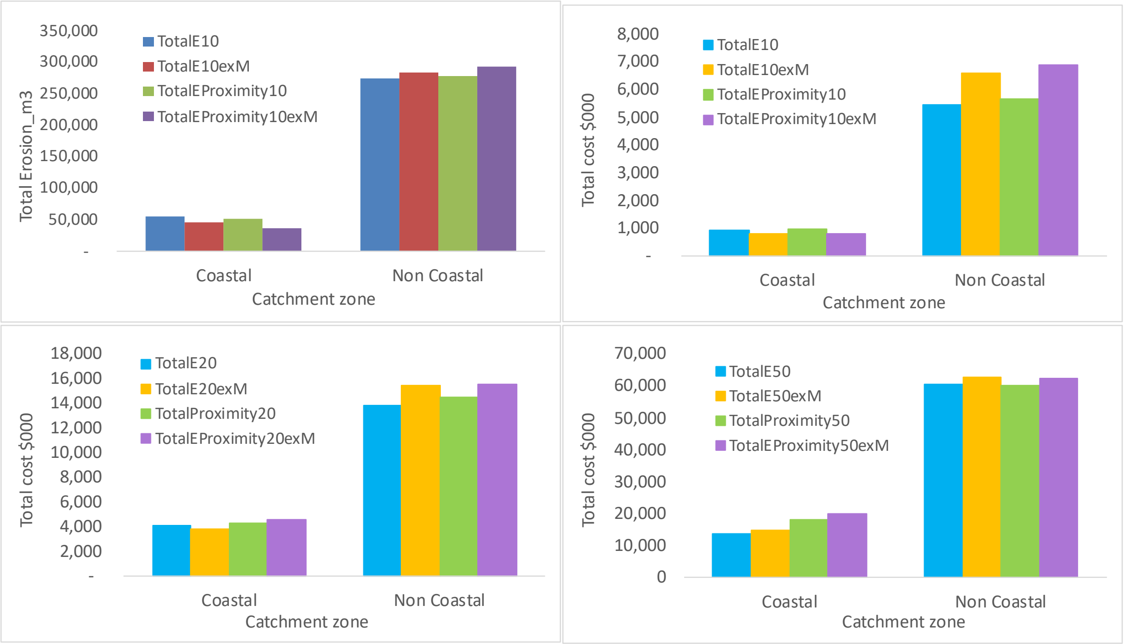

Figure 8. Plots for the 10%, 20% and 50% prioritisation scenario showing the relative proportion of rehabilitation reaches in the coastal zone or in the catchment.

Public vs Private Land

The nature of land tenure within the areas that have been prioritised for management will have a bearing on both the capacity of the land holder to host rehabilitation works on their property and the potential sources of funds that can be used to carry out works on this land. As can be seen in Figure 8 the vast majority of the prioritised reaches occur on private land.

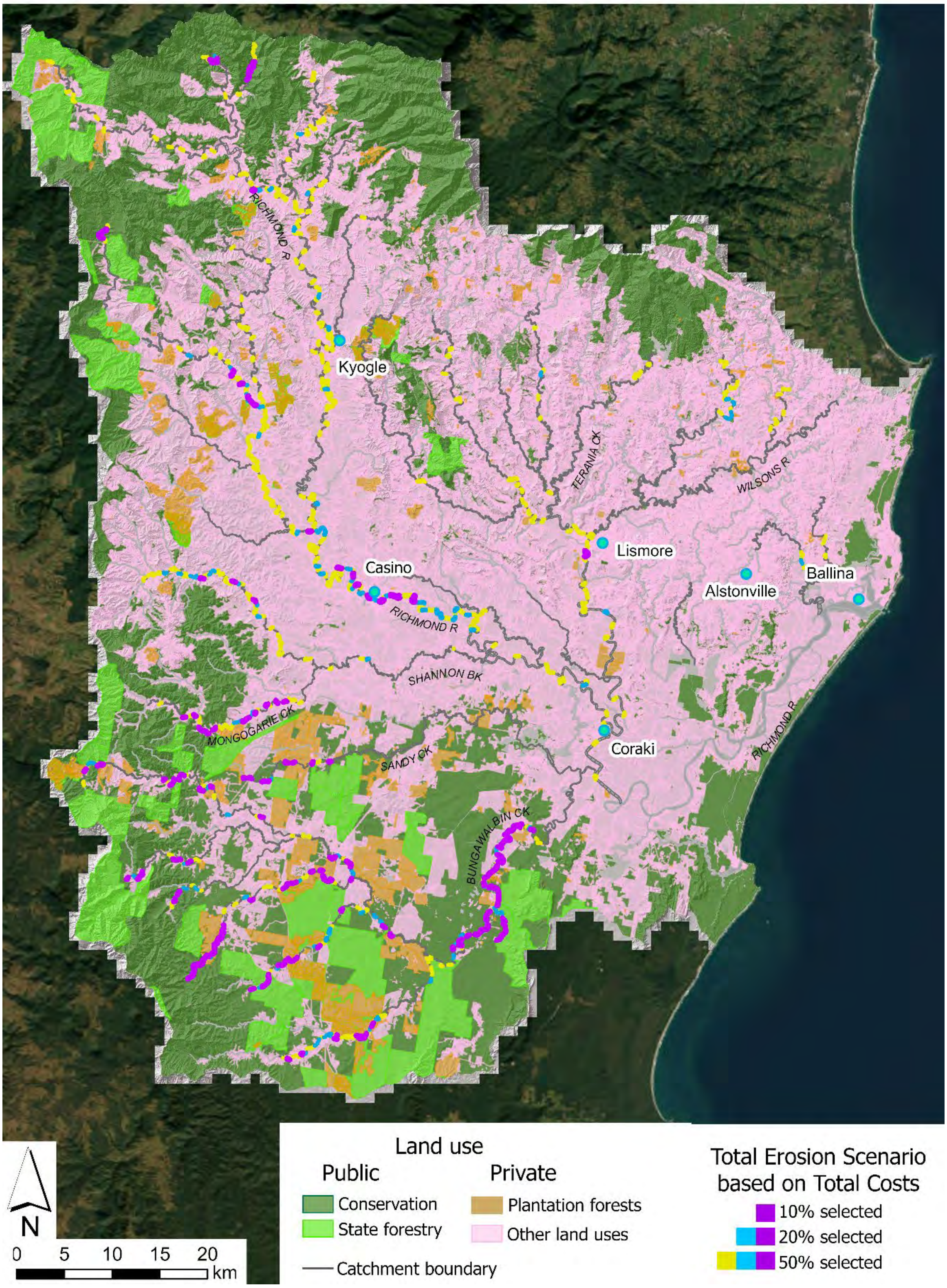

Figure 9. Map showing the distribution of public vs private land in the Richmond catchment and the association between reaches that have been prioritised for management.

Preliminary Data on Alternative Sediment Sources

Landslides

Our analysis shows that the total volume of soil and sediment mobilised by landsliding in the 2022 flood event was in the order of 970,000 m^3 of sediment from 1630 mapped landslides. We estimate that around half of this, or ~ 710,000 tonnes of sediment was delivered to the channel network. Ground observations from several of the larger landslides visited during the study, suggests that these features have largely stabilised and are not currently active sediment sources. This is not to say that they may not be remobilised in similar rainfall to that experienced in 2022. It is likely that a significant volume of sediment delivered by landsliding into the channel network still resides within the channel network and may be remobilised in subsequent flood events.

Macadamia Farms

A very rough estimate of the potential sediment yield from Macadamia farms has been made through the application of observed sediment yields from a study undertaken by Keen et al., (2010) and Southern Cross University (2024). If we assume that all ~12,000 hectares of macadamias (in the Richmond are subject to the worst case-scenario erosion rates measured by Southern Cross University, this would result in an annual sediment yield of around 84,000 t/yr. This, however, likely represents an upper limit to erosion from macadamias and does not represent the quantum of sediment delivered to the channel network due to sediment delivery ratios being less than 100%.

Unsealed Roads

Based on the Forestry NSW roads dataset, there are 11,038 km of roads within the Richmond River catchment. Roads are categorised by surface – sealed, wet weather gravel, major gravel, intermediate gravel, natural surfaces, 4WD tracks and other/not constructed. Based on the average widths of the various roads (Table 4) this equates to ~ 5750 ha of unsealed road surface. To get an initial estimate of the potential sediment yield from unsealed roads around the Richmond catchment have drawn on measured sediment yields from forestry roads in Southeast Queensland and applied these specific yields to the road surface area in the Richmond as shown in Table 4. From these data we can roughly estimate the potential sediment runoff from roads as being in the order of 17.5Kt/yr. This represents a very small fraction of the sediment sourced from the channel network.

Table 5. Potential sediment yield from unsealed roads based on observed yields from forestry roads in South East Queensland (Forsyth et al., 2006)

Forsyth et al 2006						Richmond catchment				
Road class	**Road description**	**Road width**	**Sediment loss reported by Forsyth (over 2 yrs)**	**Sediment loss adjusted for road width (over 2 yrs)**	**Sediment loss adjusted for road width (over 1 yr)**	**Road area (ha) by type and sub-catchment**	**Road width**	**Road Length (km)**	**Road area**	**Potential sediment yield (based on Forsyth etal**
		m	**T/km**	**T/ha**	**T/ha/yr**		**m**		**ha**	**T/ha/yr**
..	..	..	..	..	..	Sealed	11.7	2669	3,112	..
A	gravelled	10	5.7	5.7	2.85	Wet Weather Gravel	9.2	1783	1,635	4,659
A	gravelled	10	5.7	5.7	2.85	Major Gravel	9.1	199	181	515
A	gravelled	10	5.7	5.7	2.85	Intermediate Gravel	8.2	9	8	22
C	ungravelled	6	3.9	6.5	3.25	Natural Surface	6.4	3938	2,516	8,178
C	ungravelled	6	3.9	6.5	3.25	4WD Track	5.8	2232	1,288	4,186
..	..	..	..	..	..	Other/Not constructed	5.8	208	120	..
						Total		**11,038**	**8,859.6**	**17,560**

First and Second order Tributaries

An initial analysis of low order channels (first and second order) in the Upper Richmond catchment indicated that there are potentially very high sediment yields from the channels within these low order catchments. If the initial estimates are accurate (and they have not been ground truthed, so should be considered with great caution) there is potentially a similar order of magnitude of sediment load sourced from this part of the channel network as the third order and larger channel network.

Comparison Between estuary sediment yields from this study and the NEAP study (Fruition, 2025).

A comparison between the erosion estimates in the estuary in this study and that undertaken for NEAP by Fruition (2025) shows good agreement between the two datasets. A full description of the comparison can be found in the results section. In summary a comparison between the NEAP high erosion sites and GU analysis (this report) are 98,722 m^3 and 100,932 m^3 respectively. Further, the volume of erosion from the entire coastal zone within the current study is 532,835 m^3, which represents about 17.5% of the erosion from the total channel network assessed in this study. It was also apparent from the NEAP study, which looked at the entire lower estuary as well, that the majority of the erosion in the estuary was from what were described as the fluvial reaches of the upper estuary.

Key Results from Ground Truthing Analysis

Association between Camphor Laurel and other key Weeds

The data summarised in Figure 9 shows the direct association between Camphor and any other weeds, which validates the notion that by mapping Camphor laurel from satellite imagery that we are indeed capturing the association of a broad range of key environmental weeds. Table 9 demonstrates that on average there is an association of around 77% between Camphor laurel and other key weed species. The spatial distribution of camphor laurel and associated weeds (of any type) shown in Figure 10 also confirms the assumption that Camphor laurel is a good indicator of weeds in general. Only around 20% of sites had other weeds present with no Camphor, while only around 4% of sites had Camphor and no other woody weeds or vine weeds.

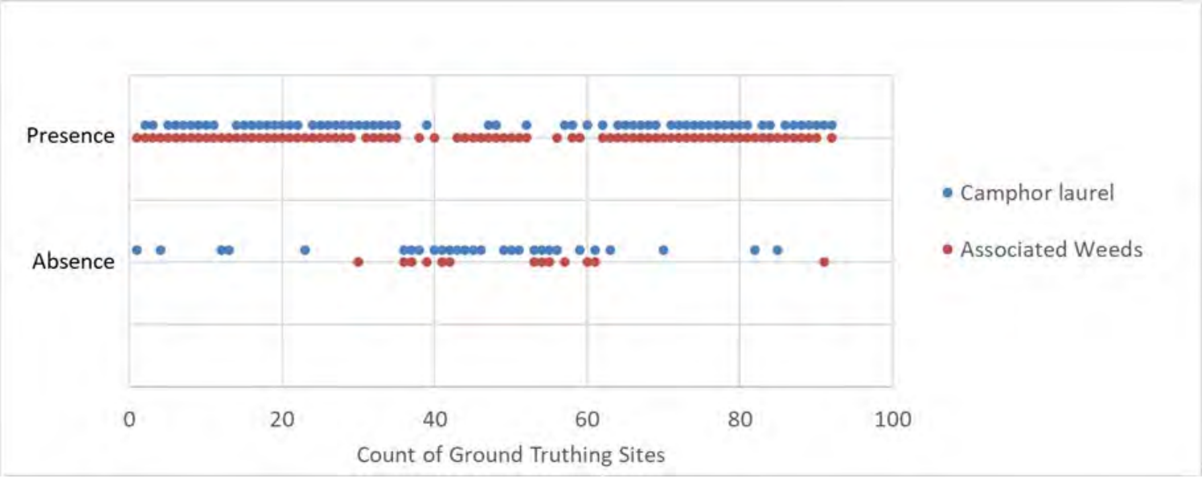

Figure 10. Graphical representation of the association between Camphor Laurel and other key environmental weeds.

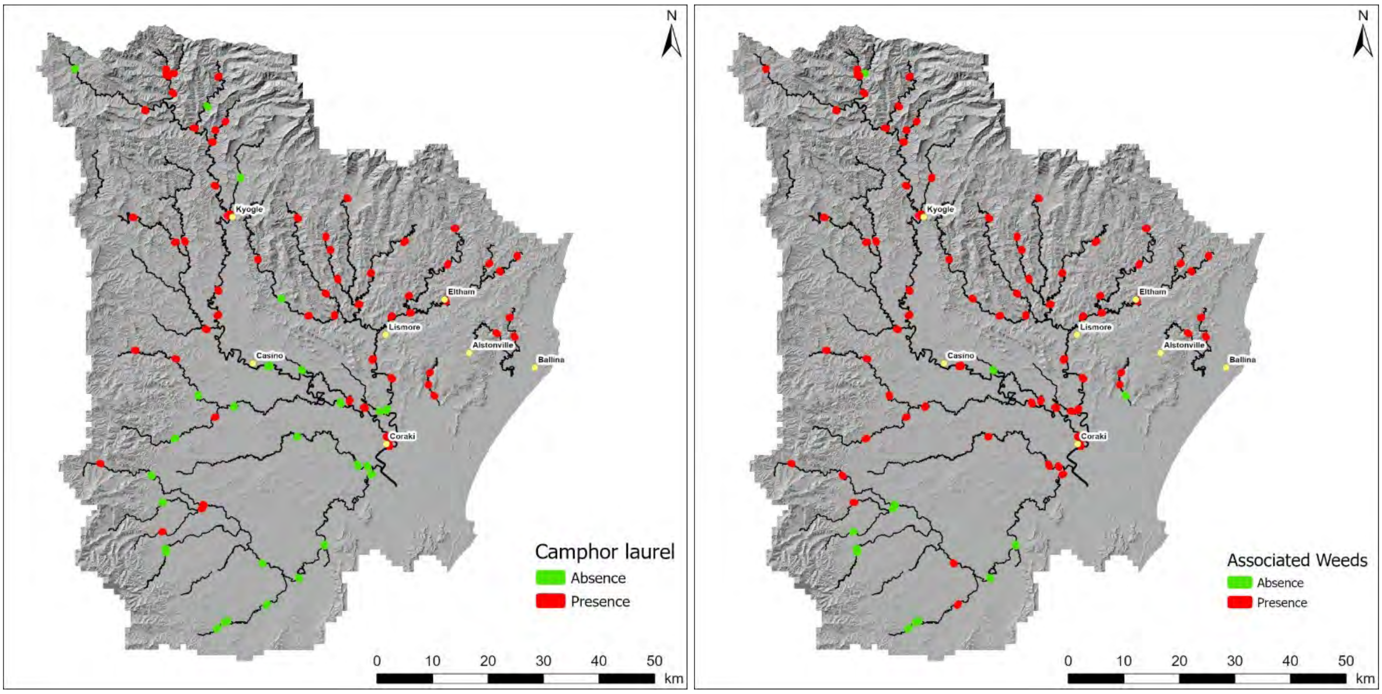

Figure 11. Spatial distribution of Camphor laurel at ground truthing sites (left) and the presence/absence of associated weeds (of any species).

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Introduction

Background

Rous County Council (Rous), Ballina Shire Council (BaSC), Lismore City Council (LCC) and Richmond Valley Council (RVC) are partnering with NSW Government to prepare a Coastal Management Program (CMP) for the Richmond River estuary in collaboration with Kyogle Council (KC), Byron Shire Council (BySC) and catchment stakeholders. The Stage 1 Scoping Study report identified the need for a whole-of-catchment approach to ensure inclusive and equitable governance, recognising the interests of the large number of stakeholders and the need to support and promote collaboration and effective communication. While governance barriers exist, stakeholders agree on the need to focus on whole-of-catchment protection and enhancement of these values. Collaboration relies on a shared catchment understanding of the whole-of-system needs. The Richmond River Coastal Management Program (CMP) will provide a whole-of-catchment perspective for the coastal management planning process which recognises the influence of the catchment issues and activities on the health of the coastal zone. The key ecosystem health challenges facing the Richmond River are linked to its physical characteristics including the large catchment area (6,850 km^2), large floodplain (> 1,000 km^2) and small estuary water surface area (19 km^2) relative to the catchment area, coupled with the significant catchment modifications that have occurred since European settlement. With this substantial catchment area and land use modifications, the management of the catchment has a significant impact on the health of the river, estuary and coastal zone. While there are a number of localised management plans and on-ground catchment management actions currently being implemented within the Richmond River catchment, there is no whole-of-catchment management plan or similar document integrating the diverse nature of catchment characteristics, linkages and current actions to comprehensively guide future management and investment in the region.

The key threats to the Richmond River ecosystem health identified in the CMP Stage 1 Scoping Study include:

- Acid sulphate soil (ASS) runoff and blackwater events as a result of hydrological modification of wetlands and floodplain drainage works, floodgate design, operation and maintenance.
- Diffuse source water pollution and pressure from agricultural practices, clearing of riparian and adjacent habitat, uncontrolled stock access to and grazing within the riparian zone.

It is important to note that whilst ASS and blackwater are recognised as significant threats to ecosystem health, based on the findings of the Richmond River CMP Scoping Study these issues are excluded from the scope of this project and will be incorporated in Stage 3 of the CMP.

Accurate and detailed information about risk and consequence is necessary to assist decision makers generate effective management strategies which identify and prioritise future actions and investment. Stakeholder consultation has identified limited support for further studies and significant support for on-ground works (improve soil health, revegetate and rehydrate landscapes and riparian zones, remove stock access to waterways, address bank erosion, improve management of floodplain infrastructure to reduce ASS and blackwater impacts and better manage stormwater and wastewater systems in urban areas). This document recognises that despite the preference for action some strategic planning is necessary to focus efforts and ensure the cost-effectiveness of actions. A key challenge going forward will be to identify and attract investment and implement targeted on-ground works at sufficient scale to significantly improve the health of the Richmond River.

Project Objectives as per RFQ

i. Improve understanding of key drivers of ecosystem health within the Richmond River and how these vary across the catchment.
ii. Understand and map spatially the nature and extent of threats to Richmond River ecosystem health across catchment. This should focus on quantitative and/or semi-quantitative techniques that systematically evaluate nutrient and sediment sources and transport across the catchment.
iii. Quantify the magnitude of on-ground actions necessary to measurably impact ecosystem health for the Richmond River.
iv. Establish a decision support tool that defines and prioritises the key actions (at the project site scale – this may be at a property or reach scale) to manage the threats including establishing the relative contribution of each action to the threat reduction. It would be desirable for this tool to be suitable to use on an ongoing basis as new funding opportunities emerge that often need refined criteria (e.g. nature-based flood risk reduction, or specific threatened species, or climate change resilience factors) and as ecosystem health conditions evolve.
v. Develop concept designs/plans for the priority actions – whether this be at site specific or at reach-scale.

Project Deliverables

(i) Comprehensive understanding of the scale of the issues facing the catchment and estuary and the ability to effect positive change: We are seeking to obtain a scientifically-robust appreciation of the geomorphological character, functioning and condition of waterways throughout the system, key sources of sediment and nutrient contamination, and a strategic blueprint for responding to these key water quality threats. This should embrace an understanding of the impacts of the 2022 floods.
(ii) Decision support tool: Capable of responding to changing circumstances and emerging funding opportunities: a high-resolution catchment model based on the Risk-Based Framework to assess the risk of impact of nutrients and sediment on the estuary. Include consideration of practical factors (e.g. landholder willingness, relationship to other on- ground works, funding opportunities, regulatory requirements etc.).

Project Approach

In addressing the core objectives set out in the RFQ, we first set out to build a detailed understanding of the primary erosion sources to the Richmond Estuary, and then to develop a Geo-Economic prioritisation strategy that will enable us to develop a strategic prioritisation for on-ground riparian works to address the dominant sediment pollution sources in the most cost effective manner. The project focused on channel erosion as a dominant source of sediment to the Richmond estuary given that it has been shown in many rivers up the east coast of Australia that channel erosion is the dominant source of sediment to the end of river (Walling et al., 2004, Hancock and Caitcheon, 2010, Olley et al., 2013b). As outlined below, we also investigate alternative sediment sources as a means of testing the hypothesis that the channel network is the dominant sediment source in this river system.

In addressing the core objectives of the project, we have for the first time compiled a series of high-resolution datasets for the Richmond channel network (3rd order streams and above) that represent the current (2023) state of the Richmond channels and associated riparian buffers. Given the key premise underpinning the analysis is that channel erosion is likely to be the dominant sediment source to the estuary, the key premise underpinning sediment management is that erosion is minimised when the in-channel/riparian zone woody vegetation density is maximised. The assumed endpoint of the rehabilitation strategy is to achieve a fully vegetated riparian zone. We recognise that this is a long-term goal, however it is essential to have this costed goal in place so that the most cost-effective reaches can be identified as interim steps towards achieving this long-term goal. We also present data to justify the central role played by woody riparian vegetation in minimising erosion at the catchment scale.

The new datasets developed for the project include:

- a geomorphically defined representation of the Richmond channel network for 1442 km of the 3rd order and above stream network, with a variable width riparian buffer that varies according to channel dimensions. This channel network was then divided into 2884 reaches of 500m length which are the management units for the prioritisation.
- channel erosion volume for each 500m river reach was then derived from multi-temporal lidar datasets spanning 6-13 years (between 2010 and 2023).
- detailed woody vegetation mapping of foliage projected cover (FPC) within the channel and riparian zone derived from the 2023 lidar coverage, represented as the percentage cover within the reach.
- the 35 year woody vegetation trend within the channel and riparian buffer derived from quarterly Landsat persistent green data. This enables us to determine whether the vegetation cover is naturally increasing, decreasing or is largely static over decadal timescales. The slope of the trend line is represented by the Delta Green metric (Pietsch et al., 2021).
- the extent of weeds as reflected by satellite mapping of camphor laurel as a key weed indicator species across the catchment.

The approach adopted includes a series of underlying assumptions, and we present data that addresses each of these in the report.

3) All other things being equal, channel erosion will be less for a similar river reach, the higher the woody vegetation FPC. This assumption justifies the focus on maximising woody riparian vegetation extent as the primary management focus.
4) The presence of camphor laurel - as mapped from satellite imagery, is an indicator of a broader suite of exotic species within that reach. Hence the extent of camphor laurel within a reach can be used to determine weed management requirements.

Cost Effectiveness

These datasets form the basis for deriving a fully costed riparian zone rehabilitation strategy across the entire catchment, in which the most cost-effective reaches are prioritised. Cost effective management is defined as the investment required to achieve a riparian zone (channel + variable buffer width – explained below) fully vegetated with native vegetation whilst targeting the greatest amount of prior erosion in that reach at the lowest cost. Hence, the key metric for assessing cost-effectiveness is the $ cost per m^3 of erosion within the reach. This provides the opportunity for the first time to consider the most effective way to manage the entire Richmond River system.

Additional Sediment Sources

While the project is not developing a comprehensive catchment sediment budget (i.e. to quantify all other sources of erosion in the catchment, over and above channel erosion) we do provide some preliminary data on potential additional sediment sources within the catchment for comparative purposes. It must be stressed that these are first approximations only and much more detailed analysis is required to fully quantify each source and to assess the extent to which they are a problem in this catchment. It is also acknowledged that this is not a comprehensive list of alternative sediment sources. However, the accurate quantification of all other sources can only be determined through comprehensive empirically based sediment budget program, coupled with sediment tracing.

The additional sources investigated include:

- An assessment of sediment contributions from landslides (primarily from the upper Wilsons Catchment)
- Estimates of worst-case scenario sediment yields from macadamia farms
- Unsealed roads as a potential sediment source
- Channel erosion from within first and second order headwater streams.

Riparian Rehabilitation Optimisation using Marxan Modelling.

Marxan optimisation modelling is a tool developed for conservation planning that addresses the general problem of how to meet user-defined 'management targets' for the ‘minimum cost’. Targets are the amount of each feature that the model is instructed to select (e.g. 10% of Total Erosion volume). Marxan operates with three fundamental principles to optimise conservation priorities namely,

- meet a conservation or management percentage or integer targets for a species or ‘feature’ (in this case the attributes of a river reach).
- for minimum rehabilitation total cost
- with the most compact reserve design (Serra-Sogas et al., 2020).

In this project the Marxan modelling approach has been adapted and applied to 500m reaches of the Richmond catchment to address erosion and rehabilitation issues. In this case the primary management objectives targeted are erosion volume in a 500m *reaches* and woody riparian vegetation deficit. In this case we are optimising a solution that will meet the following criteria:

- meet management rehabilitation percentage targets to address a specific management issue or ‘feature’ (e.g. Total Erosion)
- for minimum total rehabilitation cost
- with the most compact selection of reach area.

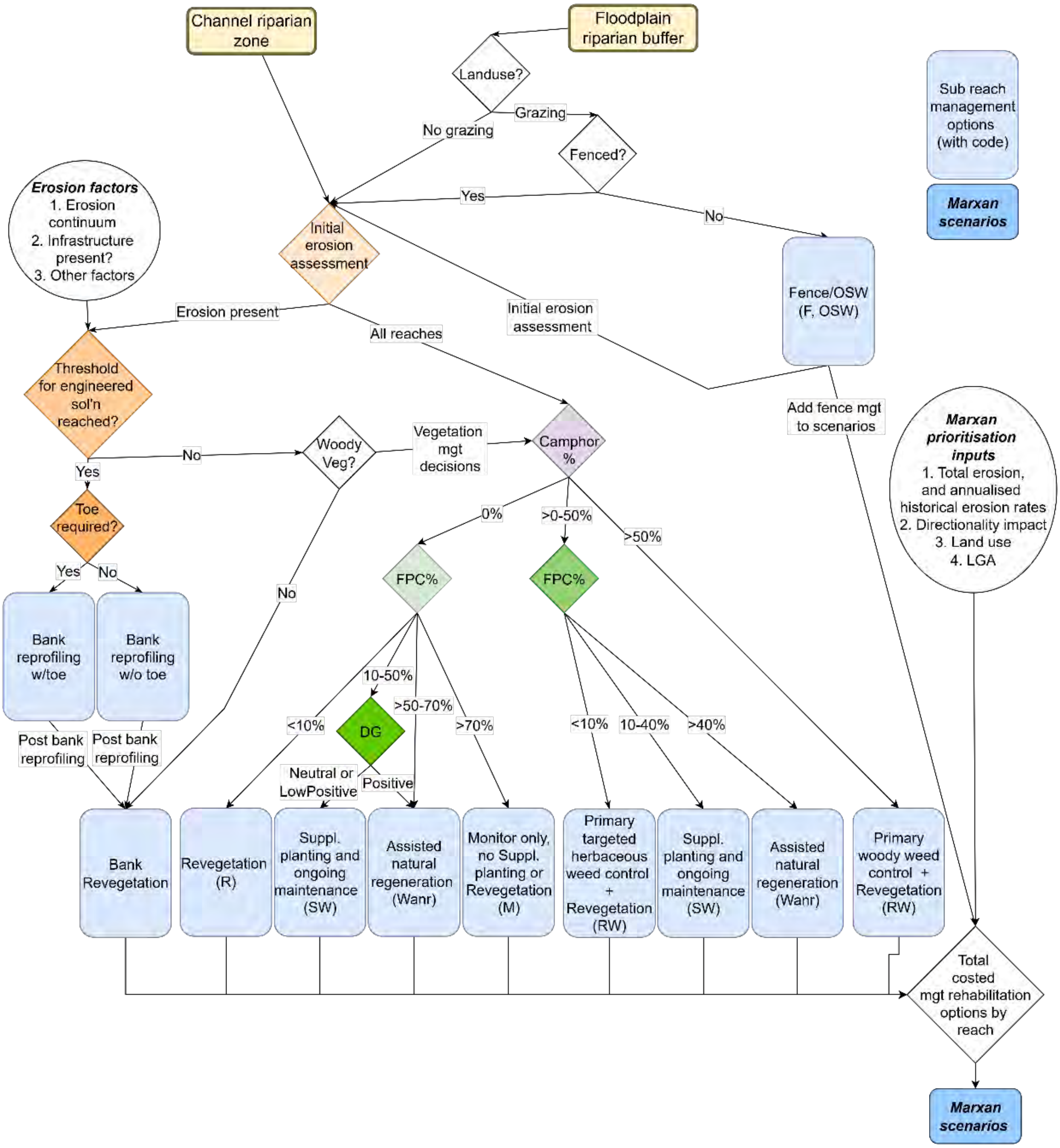

Figure 12. Marxan workflow decision tree showing how each of the management scenarios have been derived. These management scenarios are applied at the sub-reach planning unit scale and for the basis for the rehabilitation costs

Marxan Model Assumptions

1. As per Figure 1 total costs are the sum of the six different management scenarios that are calculated for each reach (F+M+R+RW+SW+Wanr). Note that more than one management strategy can be applied in a single reach on a pro-rata basis (by % of reach area).

2. Total Costs excluding Monitoring only reaches. Reaches (combined Channel and Buffer) where only Monitoring costs occur have been excluded from the Marxan analysis. Note monitoring only is applied in reaches with zero weeds and > 70% FPC (which are often in conservation land use)
3. Reach area (on which all costs, except Fencing cost, are calculated) excludes Watermask area within the channel zone, and roads which occur within the Channel and buffer zones). Fencing costs are calculated from length in m of Buffer zones classified as Grazing land use. Note the buffer zone width is determined for each reach as a function of the channel dimensions – but typically varies from ~ 20 – 40 m on each side of the channel).

Inputs to modelling

The following maps show the distribution of each of the key input datasets that underpin the rehabilitation scenarios and the associated costings.

Channel erosion

Figure 13 shows the distribution of total erosion by planning unit reach (i.e. 500m reaches) across the longest available time period between lidar datasets as shown in Figure 60 and Figure 61. The annualised reach erosion data is shown in Figure 14 using the timeslice between the oldest available lidar (varying from 2010 – 2017 depending on availability) compared to the 2023 lidar dataset captured across the whole catchment.

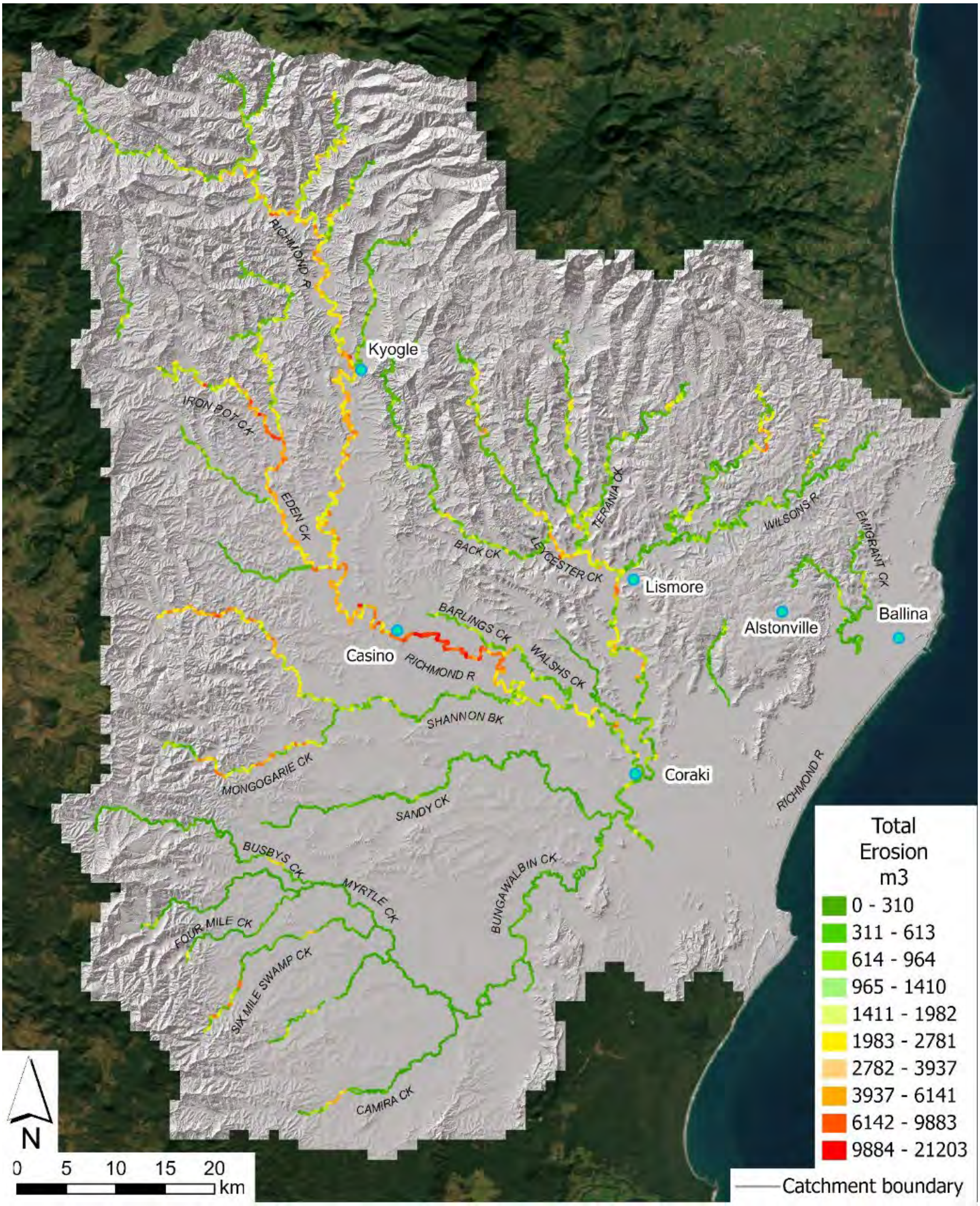

Figure 13. Distribution of total erosion volume per reach (i.e. the total volume of erosion observed through DoD analysis between the oldest lidar epoch at a given reach and the most recent - 2023) data.

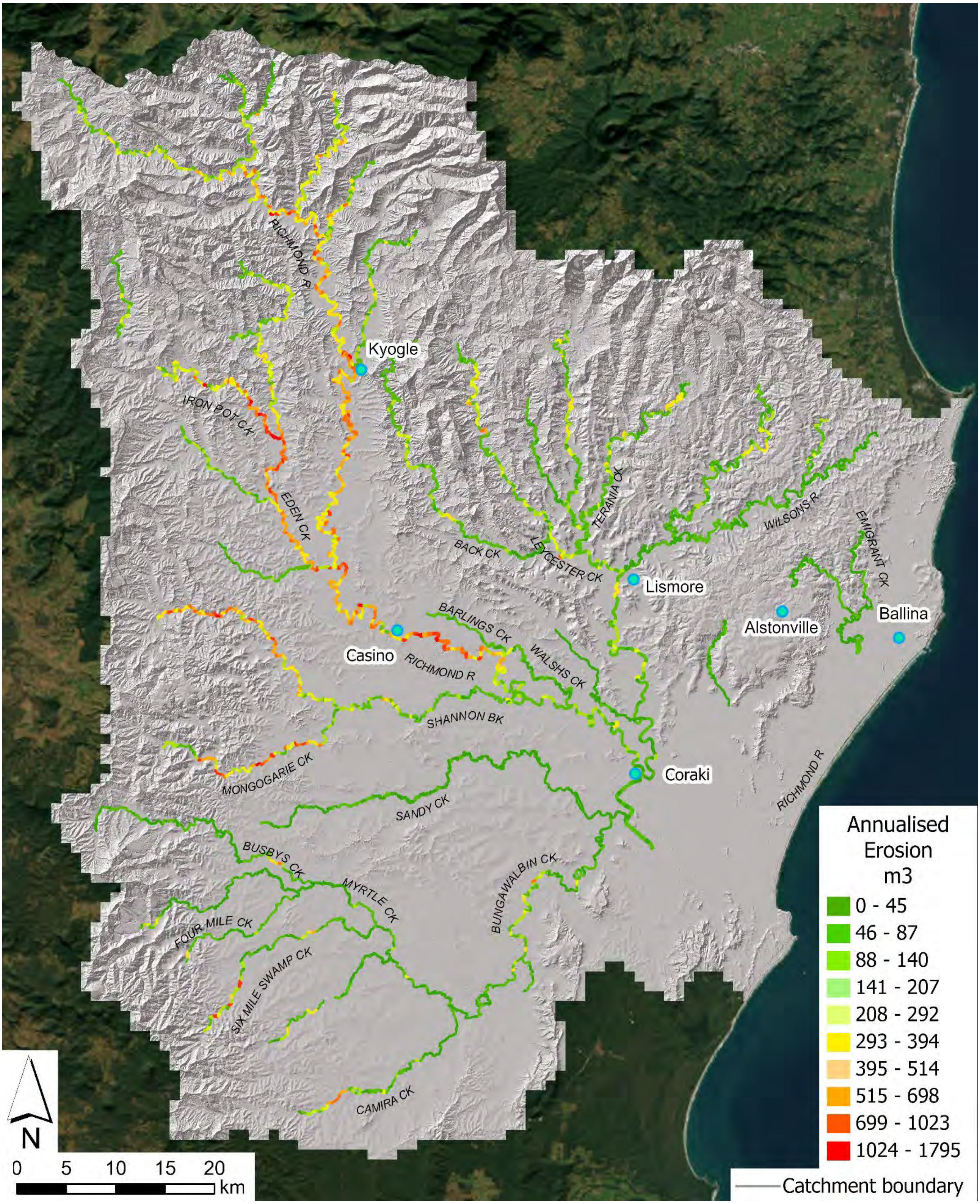

Figure 14. Distribution of annualised erosion per reach over the longest available timeslice for the available lidar DoD data (see Figure 60 and Figure 61).

Vegetation

The catchment-wide distribution of the riparian woody vegetation deficit (i.e. reach area of non-woody vegetation) is shown in Figure 15 and Figure 16. Figure 17 and Figure 18 show the distribution of the Delta Green metric per reach, which provides a measure of the trajectory of riparian vegetation change across the last ~ 35 years. This metric is used in the management scenario decision tree to differentiate whether supplementary planting is required – or whether just assisted natural regeneration is required. Figure 19 shows the distribution of mapped camphor laurel (original catchment-wide camphor distribution data courtesy Dr Pat Norman – Griffith University).

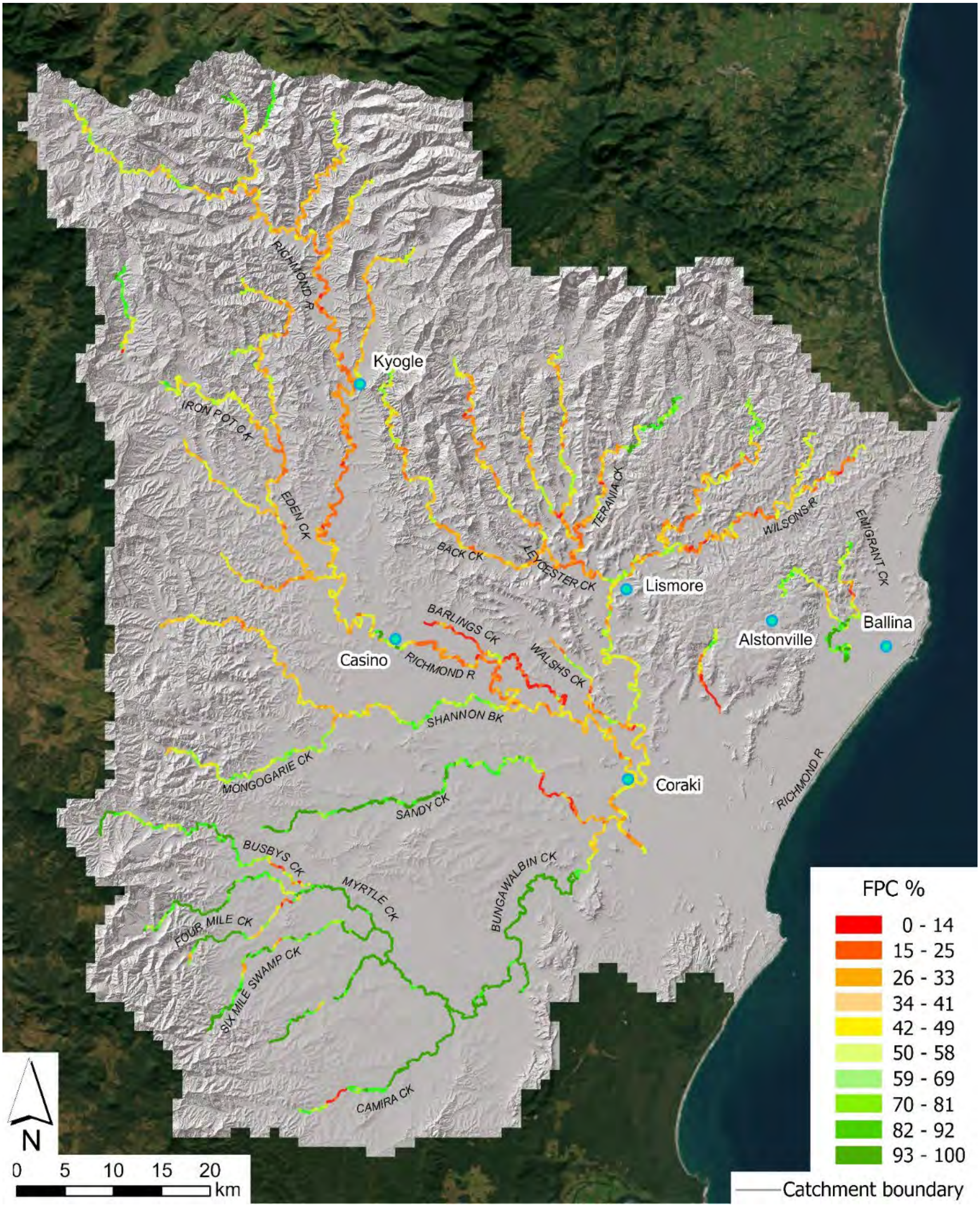

Figure 15. Distribution of reach area without woody vegetation(represented as woody vegetation Foliage Projected Cover (FPC) - where woody vegetation is defined as vegetation >3m in height. This is represented as a percentage of the non-wetted reach surface area – a number between 0 -100%)

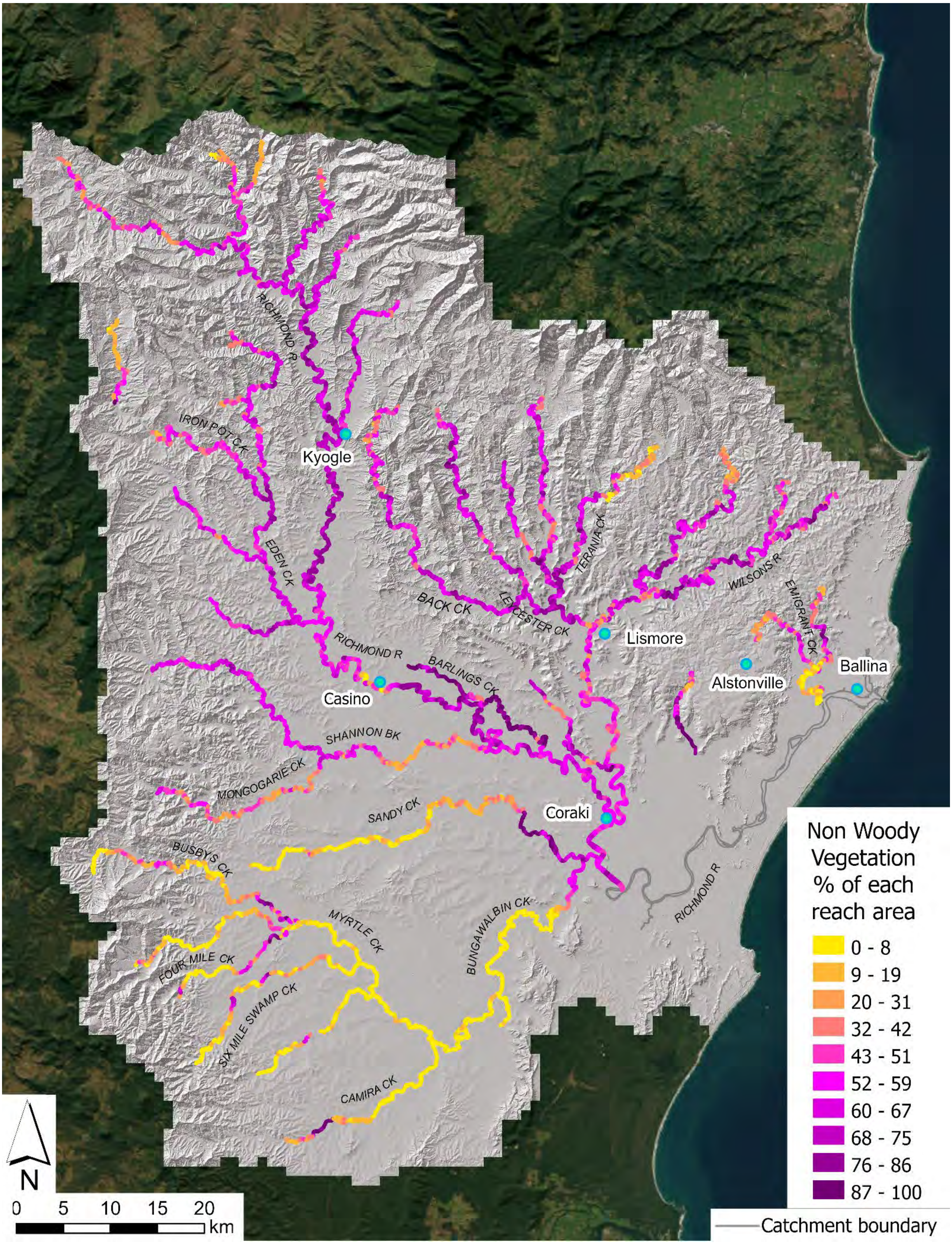

Figure 16. Distribution of reaches without woody vegetation represented as a percentage of the full reach area (i.e. channel + buffer).

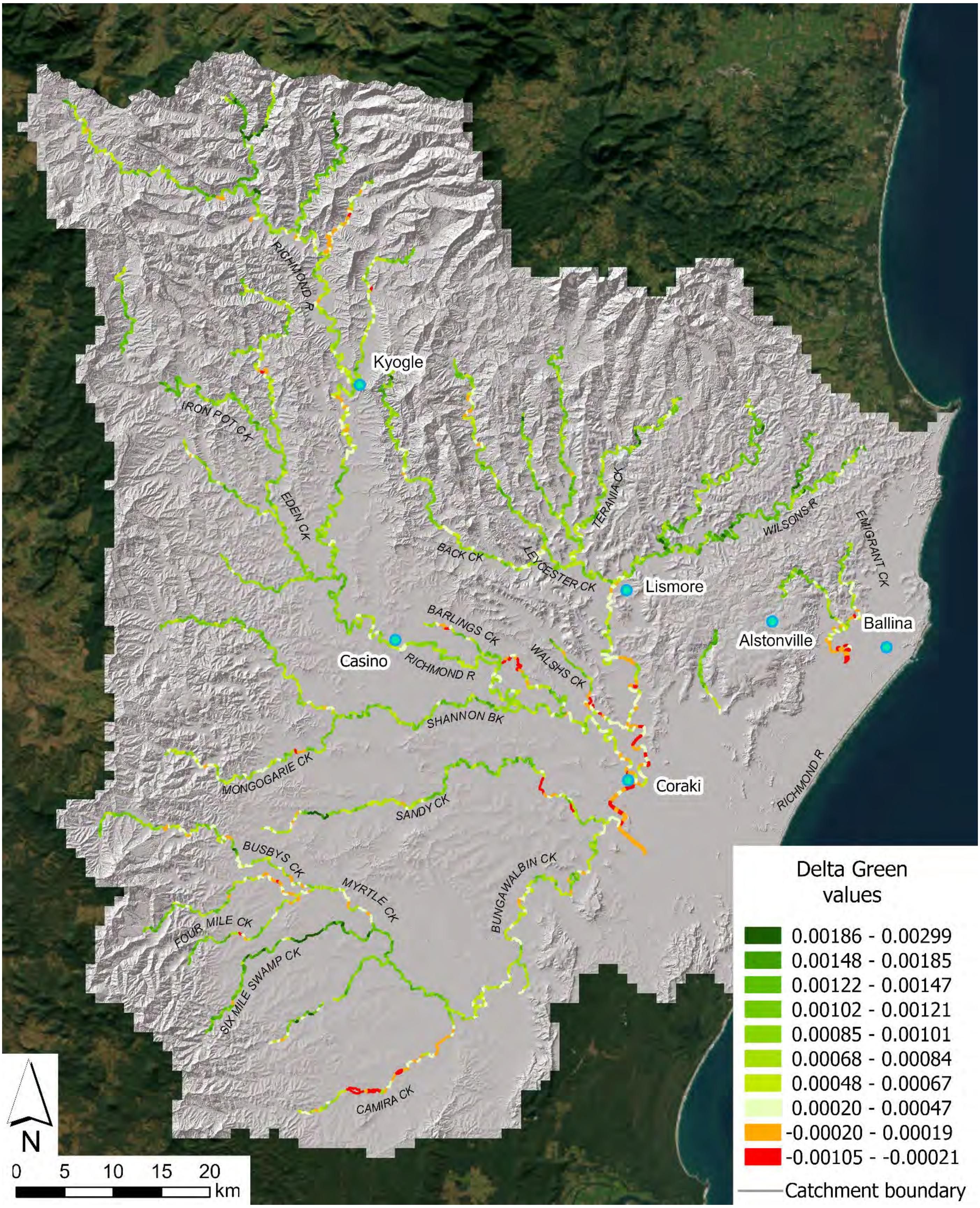

Figure 17. Map showing the spatial distribution of the Delta Green metric across the catchment. Values above zero (cold colours) represent reaches in which woody vegetation has increased over the last three decades, whereas those that have decreased are represented by warm colours.

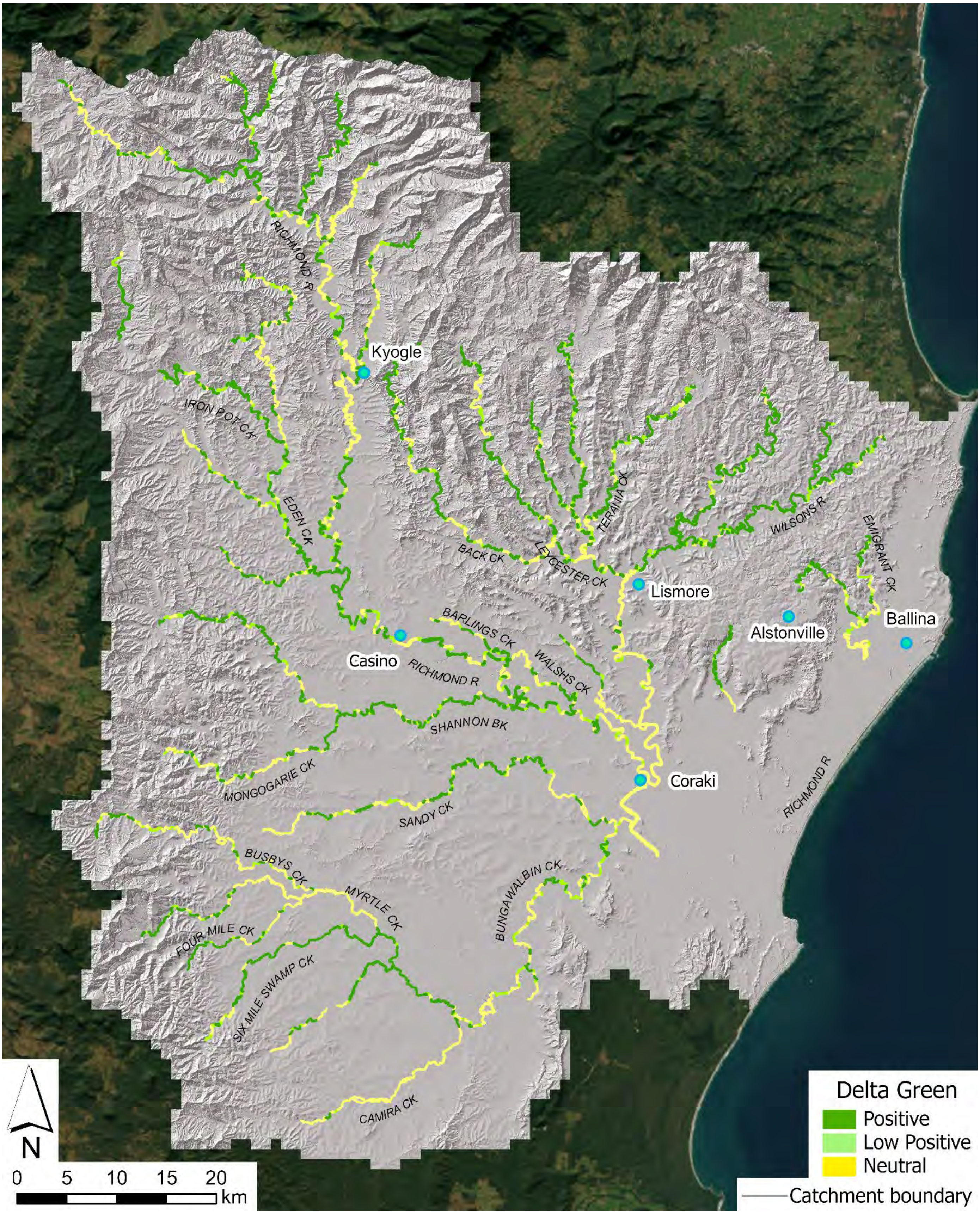

Figure 18. Map showing the spatial distribution of the Delta Green metric across the catchment simplified into 3 classes. Positive values are reaches with a clear signal in which woody vegetation has increased over the last three decades, whereas those with Low positive are those with a weak positive slope and/or high variability (low signal/noise ratio). Neutral trend indicates a low probably of increase or decrease in woody riparian cover over the 35-year period (i.e. includes reaches that could have a minor decrease). Note reaches with a neutral change could include reaches with 100%, 50% or 0% woody vegetation cover.

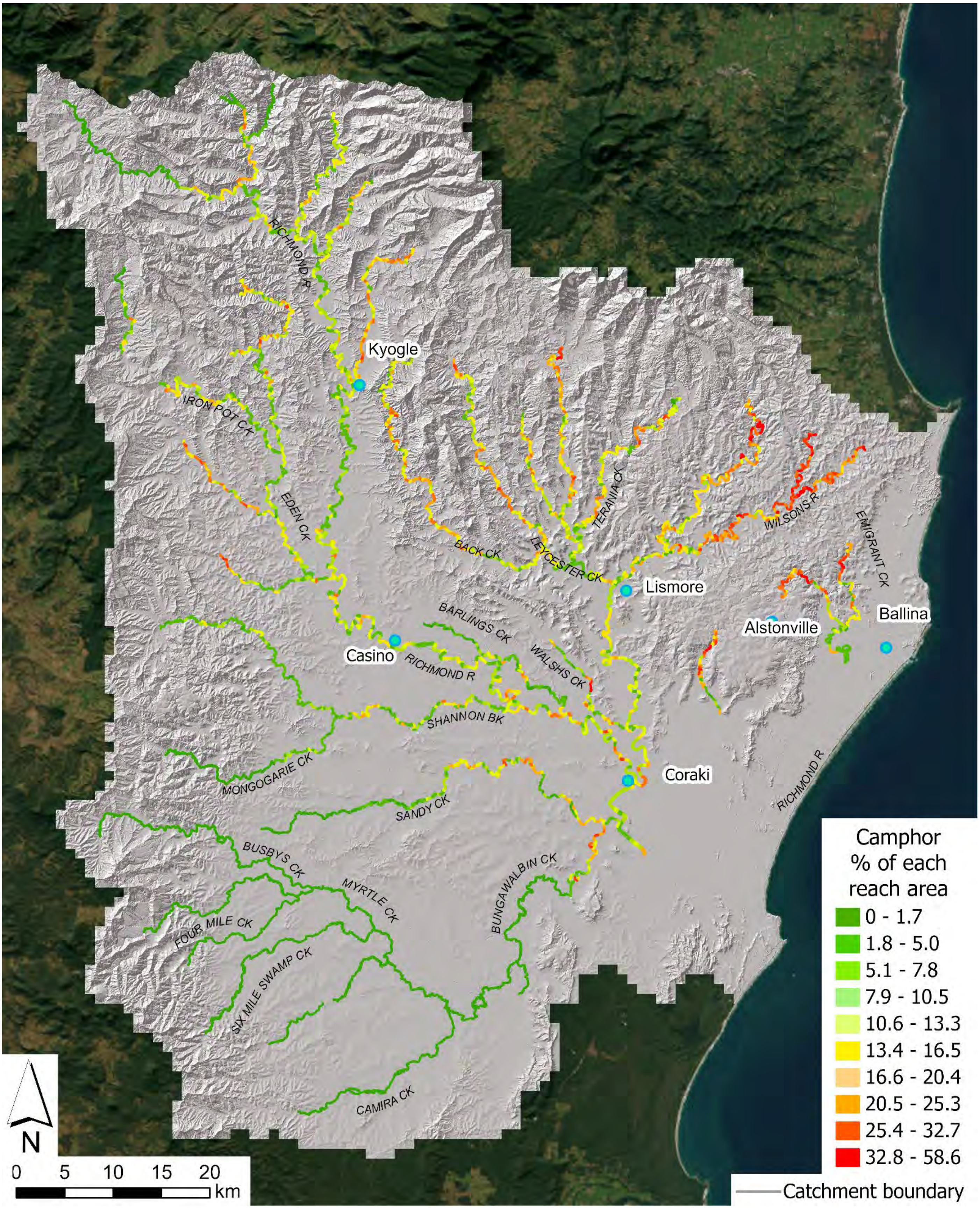

Figure 19. Map showing the distribution of mapped camphor laurel (original catchment-wide camphor distribution data courtesy Dr Pat Norman)

Land use

Key land uses are shown in Figure 20 which form the basis for determining the requirements for stock exclusion particular in the prioritisation decision tree.

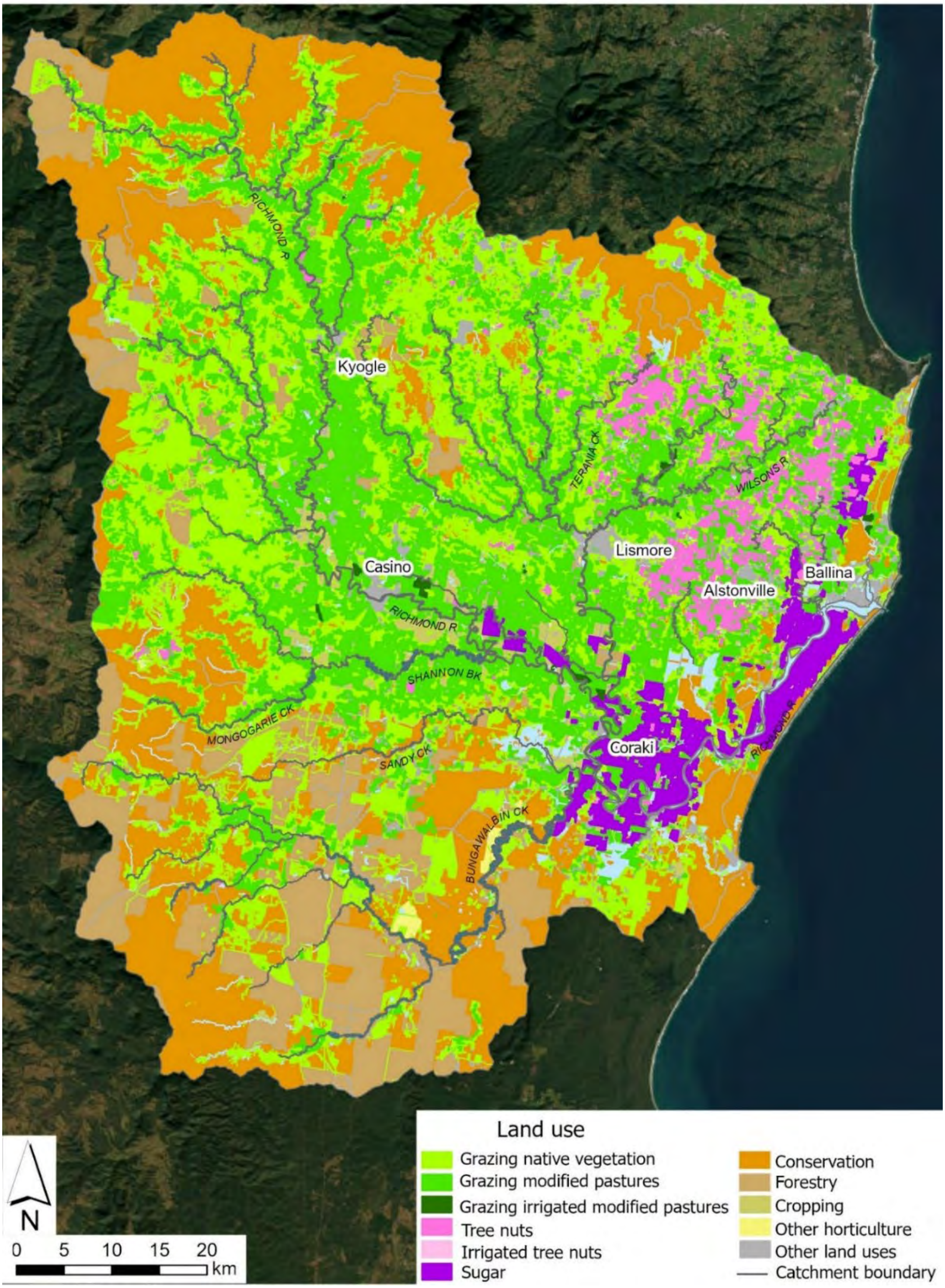

Figure 20. Map showing the distribution of key land-uses in the Richmond catchment

Relationship between Erosion and Reach FPC for the Major Tributary Systems

A Rationale for the Focus on Riparian Vegetation

The central premise underpinning the management strategy that is the basis for the rehabilitation strategies that are being optimised in this study, is first that channel erosion is a dominant source of sediment in the Richmond catchment, and second, that the most effective way to address this issue is to maximise the extent of woody vegetation within the riparian, preferably with native vegetation. To test this underlying assumption between channel erosion and woody vegetation cover in different tributaries (Figure 21) the sequence of graphs shown in Figure 22 plot the relationship between total reach erosion and total reach Foliage Projected Cover (FPC) of the channel zone. For each population an upper and lower envelope curve is derived which shows that maximum reach erosion decreases significantly with increased woody vegetation FPC. Similarly at the lower end of the scale, when FPC drops below a certain threshold minimum erosion rates increase. Note that each tributary system has a distinctly different relationship, which gives an indication of the sensitivity of the different rivers. Note that Ironpot Creek and Shannon Brook have very steeply declining curves, reflecting the sandy nature of these catchments, whereas Bungawalbin Creek has a more gradually decreasing curve, with some anomalous outliers that have high FPC. These curves likely provide an indication of the potential erosion reductions that can be achieved once vegetation is increased (Table 6), however, caution should be used extrapolating sediment yield reductions from comparisons between vegetated and de-vegetated reaches given that due to hysteresis, channel degradation and recovery are not linearly related (*sensu*,Brooks and Brierley, 2004, Brooks et al., 2006).

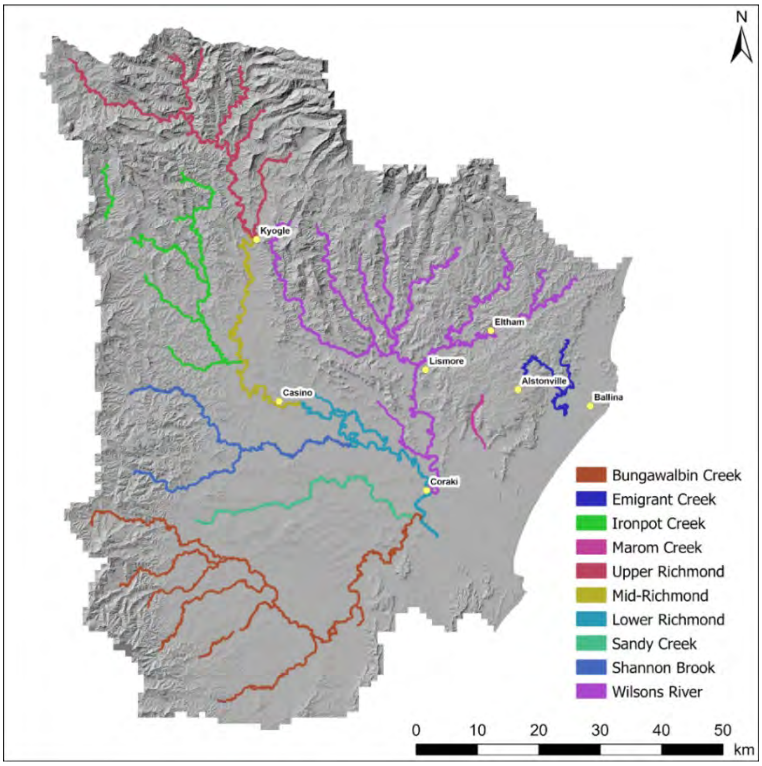

Figure 21. Map of the different sub-catchments and reaches that have been used to derive distinct relationships between total reach erosion and reach average FPC.

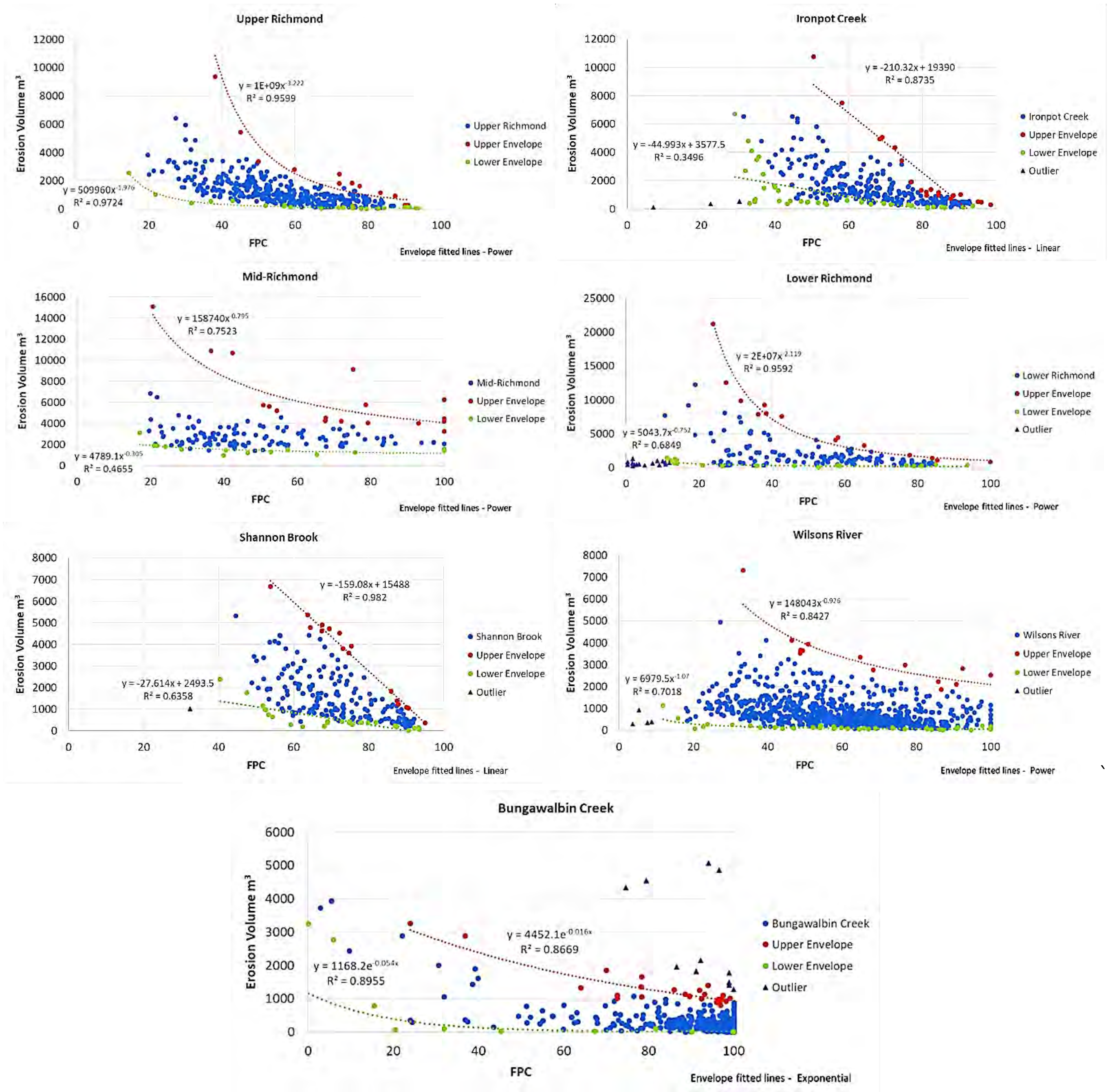

Figure 22. Plots showing the relationship between reach total erosion volume and reach % FPC. The curves show an upper envelope curve that provides an upper limit for reach erosion as a function of the extent of riparian vegetation within the reach. The noise within the relationships (between the upper and lower envelope curves) represents the myriad local controls on channel erosion, particularly channel boundary erodibility.

Erosion Reduction/Increase as a function of Reach FPC

Using the tributary specific upper envelope curves (Figure 22) we can get a sense of the maximum potential sediment reduction that can could be achieved once a mature woody riparian vegetation community is reestablished in a given reach (Table 6). Using the fitted envelope curves, Table 6 shows the difference in channel erosion in the different tributaries/reaches by looking at the difference between FPC 30% yield and the FPC 70% yield as well as the difference between the FPC 30% the FPC 100% yield. Noting the caveats above, this exercise shows that in some systems a 70% target FPC may be sufficient to limit erosion to acceptable levels, whereas in other systems (e.g. sand dominated Shannon Brook and Ironpot Creek that have very steep curves), 100% FPC may be required to achieve acceptable erosion rates. It should be noted, however, that these fairly crude analyses take no account of the sediment particle size composition of the eroded sediments. The sediment size fractions eroded will determine how likely this sediment source is to negatively impact the Richmond estuary, given that the finer suspended sediment fractions will tend to have a greater impact on turbidity and tend to transport higher nutrient loads adsorbed to the sediments.

Table 6 The predicted maximum erosion volumes per reach for a given FPC in different tributaries/reaches

Upper Envelope Curves by Tributary (reach FPC vs erosion Volume m^3)

FPC (%)	Wilsons River	Shannon Bk	Lwr Richmond	Mid Richmond	Upr Richmond	Ironpot Ck	Bungawalbin
10	17554	13897	152065	25450	599791	17287	3794
20	9239	12306	35006	14668	64281	15184	3233
30	6347	10716	14826	10626	17407	13080	2755
40	4863	9125	8059	8454	6889	10977	2348
50	3955	7534	5022	7080	3357	8874	2000
60	3341	5943	3413	6124	1866	6771	1705
70	2896	4352	2462	5418	1135	4668	1453
80	2559	2762	1855	4872	738	2564	1238
90	2295	1171	1445	4437	505	461	1055
100	2082	0	1156	4080	360	0	899
30%-70%	**3451**	**6363**	**12364**	**5208**	**16271**	**8413**	**1302**
30%-100%	**4266**	**10716**	**13669**	**6546**	**17047**	**13080**	**1856**

Final prioritisation

Marxan scenarios and results

Marxan scenarios have been developed to prioritise reaches with high volumes of erosion for rehabilitation, and also incorporate proximity to the estuary. Two categories of scenarios have been developed in Marxan.

1. Total Erosion scenarios (Figure 23 - Figure 24). In these scenarios, Total Erosion volume in a specific reach is selected for prioritisation based on the Total Cost of rehabilitating that specific reach in order to achieve 100% woody vegetation cover.

2. Combined scenarios of Total Erosion and Proximity to the Estuary (Figure 25 - Figure 26). This prioritisation combines the reaches contributing the largest volumes of sediment and their proximity (in terms of number of reaches) to the estuary. In combined scenarios, each ‘feature’ can be independently scaled to determine the relative importance of meeting its representation target. This

can be thought of as way of distinguishing the relative importance of different features and how important it is to get them fully represented. In these combined scenarios, Total Erosion has been prioritised over Proximity to the Estuary.

In Marxan, the scenarios have been further refined by adjusting various parameters. Reaches containing only Monitoring costs (184 reaches) have been excluded from the solution (Figure 24). The rationale here is that given Marxan will select these reaches as they are lowest cost, their prioritisation will not address sediment delivery and erosion mitigation through vegetative rehabilitation.

For each scenario, three levels of rehabilitation have been developed. In the Total Erosion scenarios, rehabilitation of 10%, 20% and 50% of Total Erosion volume have been developed. Likewise, in the combined Total Erosion and Proximity to the Estuary scenarios, rehabilitation of 10%, 20% and 50% of Total Erosion Volume and inclusion of Proximity to the Estuary have been developed. In the figures, distribution of the 10% scenario is shown in purple, the 20% scenario is represented by the combined purple and blue reaches, and the 50% scenario is represented by the combined purple, blue and yellow reaches.

In summary, four Marxan scenarios have been run as follows:

1. Scenario Total Erosion, based on Total Costs, with 10%, 20% and 50% solutions (Figure 23)
2. Scenario Total Erosion, based on Total Costs (excluding Monitoring only reaches), with 10%, 20% and 50% solutions (Figure 24)
3. Scenario Total Erosion with Proximity to Estuary (combined), based on Total Costs, with 10%, 20% and 50% solutions (Figure 25)
4. Scenario Total Erosion with proximity to Estuary (combined), based on Total Costs (excluding Monitoring only reaches), with 10%, 20% and 50% solutions (Figure 26)

Summary statistics showing a range of metrics associated with each scenario are shown in Table 7.

Key Qualifications of Marxan Analysis

1. The modelled scenarios do not currently account for variable implementation costs associated with the remoteness of a site
2. The scenarios do not take into account landholder willingness to participate in a catchment wide stream rehabilitation program

Scenario Total Erosion, based on Total Costs

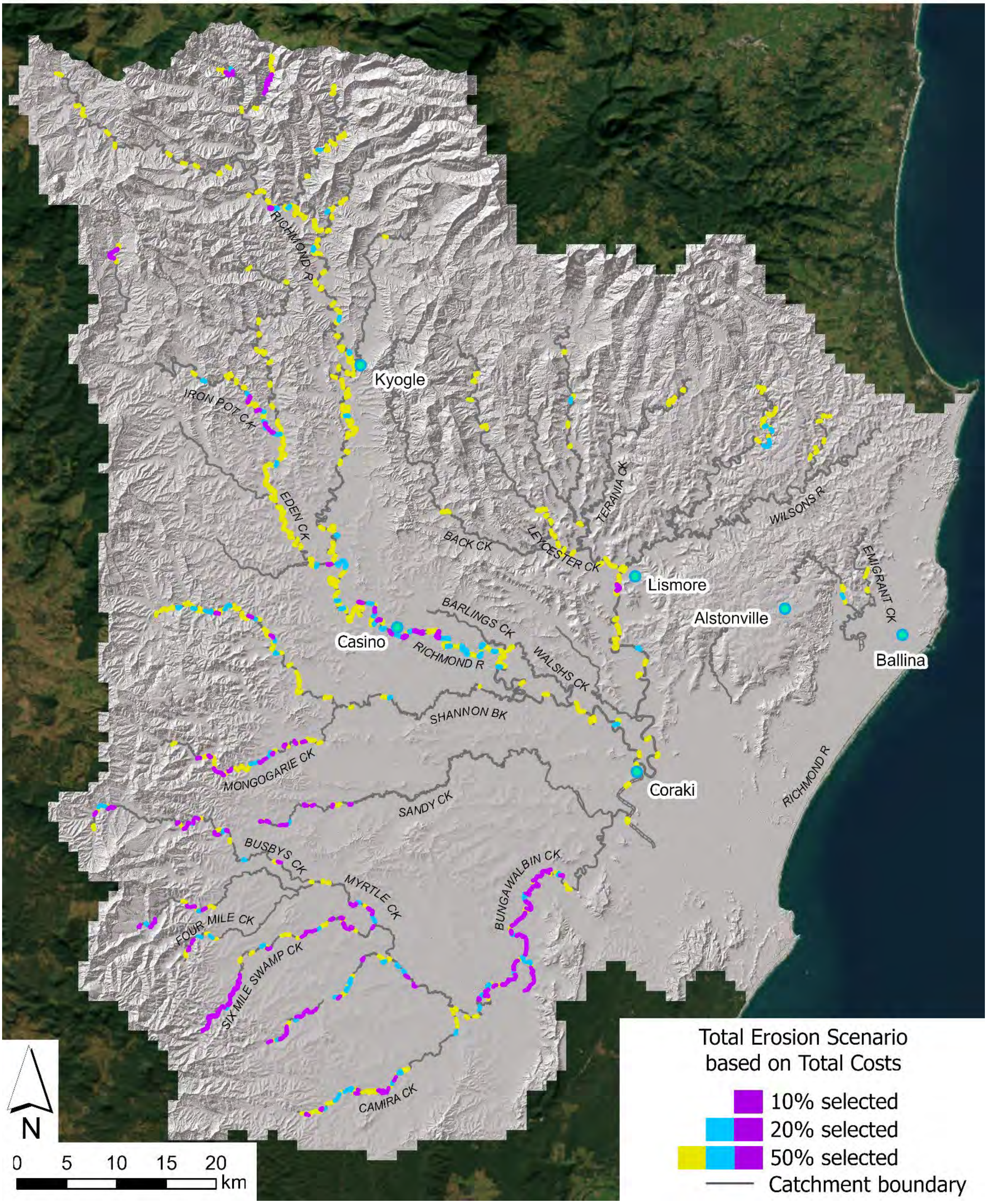

Figure 23. Marxan scenario prioritising reaches comprising top 10%, 20% and 50% of the total erosion volume optimised according to Total cost.

Scenario Total Erosion, based on Total Costs (excluding Monitoring only reaches)

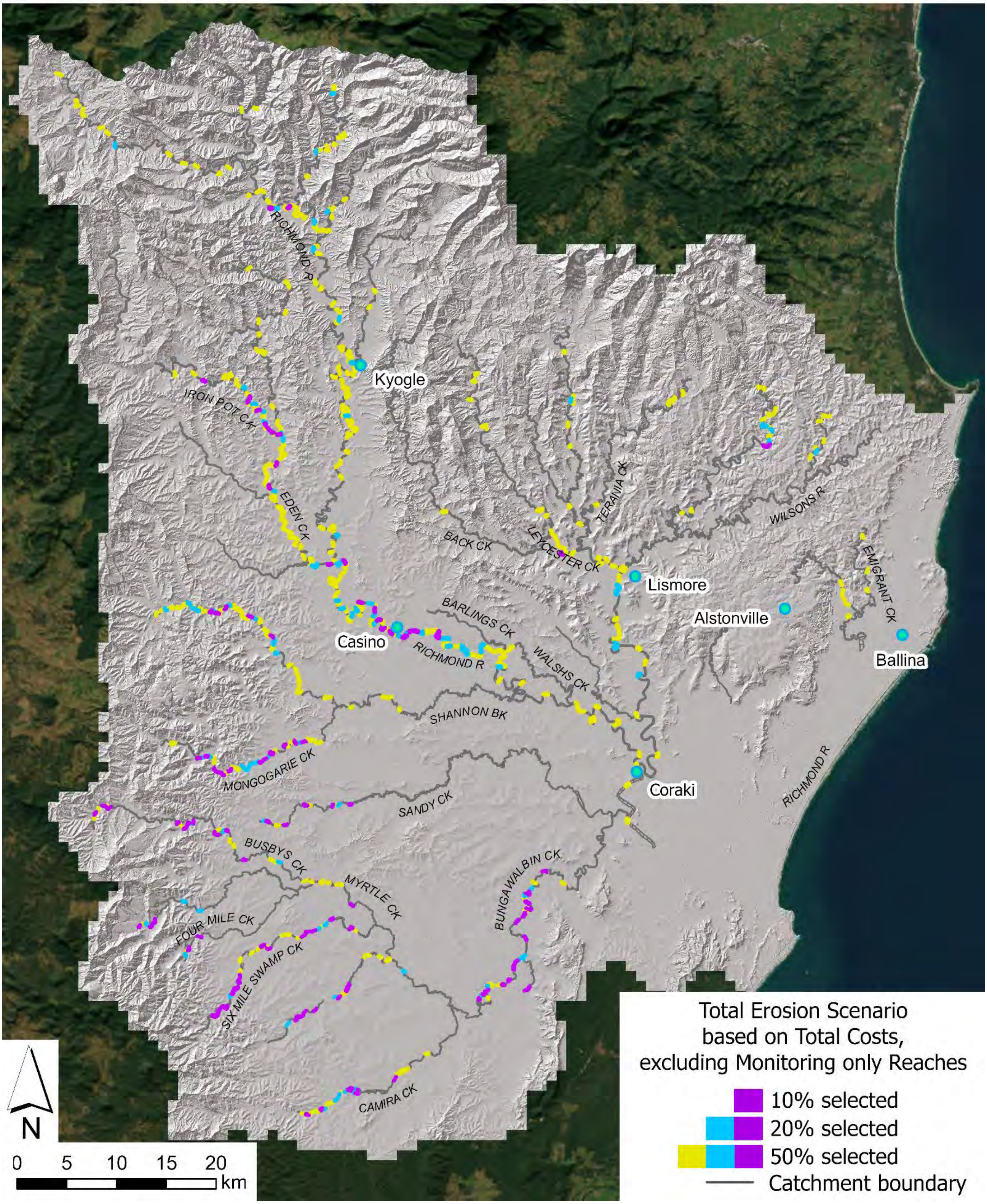

Figure 24. Marxan scenario prioritising reaches comprising top 10%, 20% and 50% of the total erosion volume optimised according to Total cost with monitoring only reaches excluded.

Scenario Total Erosion with Proximity to Estuary (combined), based on Total Costs

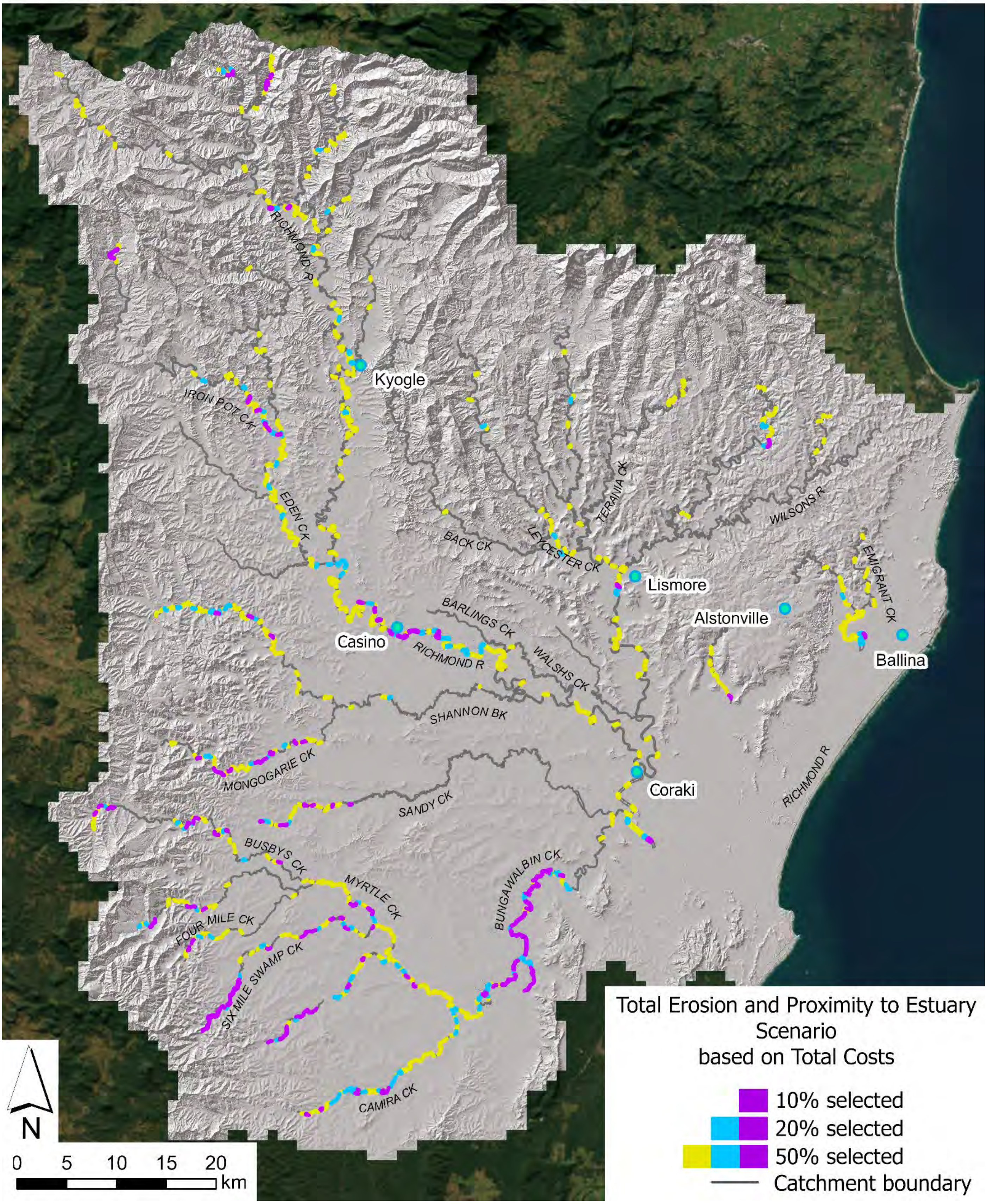

Figure 25. Marxan scenario prioritising reaches comprising top 10%, 20% and 50% of the total erosion volume and proximity to the estuary optimised according to Total cost.

Scenario Total Erosion with proximity to Estuary (combined), based on Total Costs (excluding Monitoring only reaches)

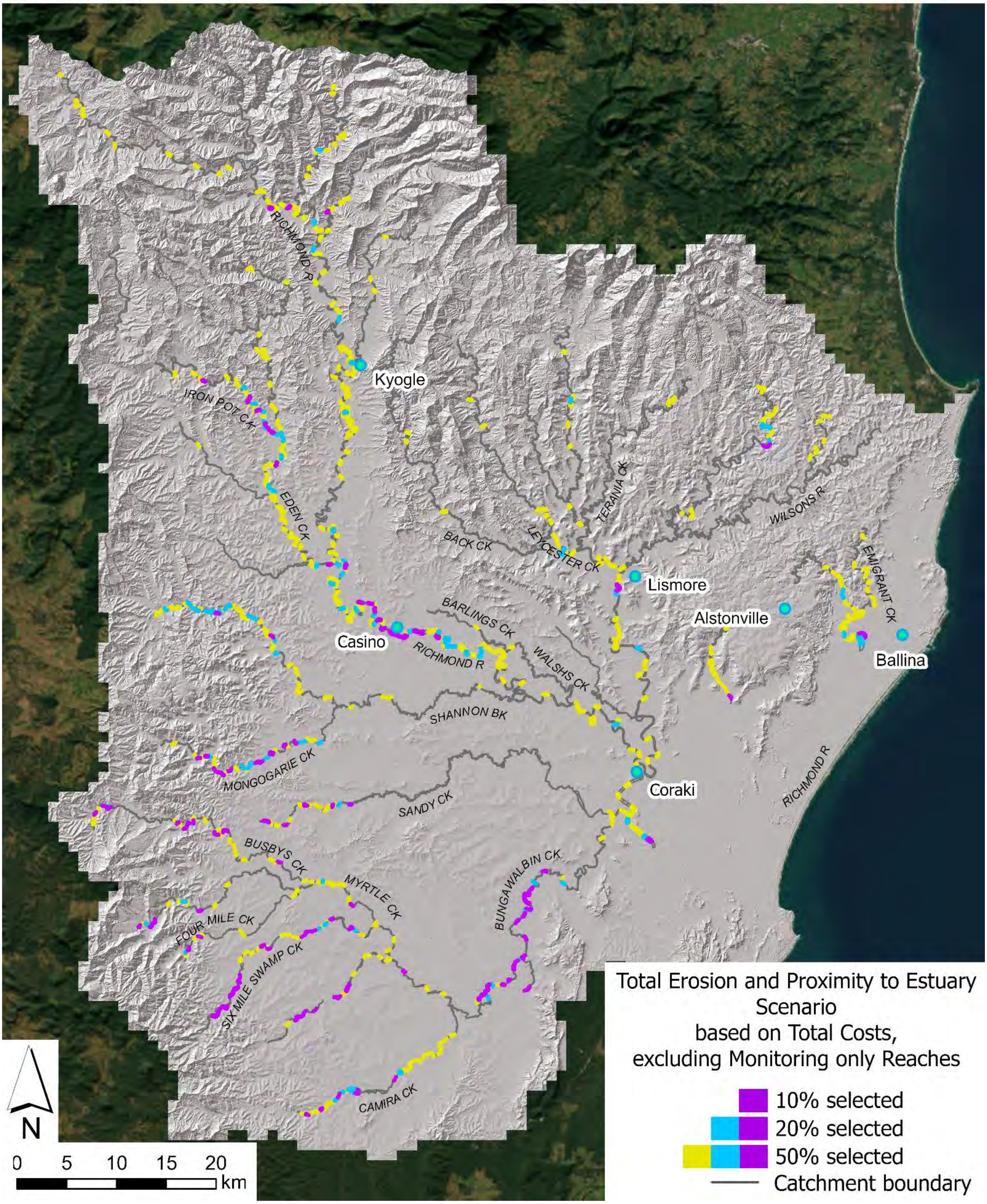

Figure 26. Marxan scenario prioritising reaches comprising top 10%, 20% and 50% of the total erosion volume and proximity to the estuary optimised according to Total cost (excluding Monitoring only reaches).

Scenario Summary Statistics.

Table 7. Total Erosion scenarios

Scenario Total Erosion, based on Total Costs			
	TotalE 10	TotalE 20	TotalE 50
Total Erosion selected (m^3)	328,299	656,574	1,641,487
% selected of project total TotalE volume (m^3)	10.000	19.999	50.000
Scenario rehabilitation Tcost ($)	$6,405,822	$17,931,053	$73,692,027
% selected of project rehabilitation Tcost ($)	1.9	5.3	21.9
Scenario Reach Area (excluding roads) selected (ha)	749.9	1291.1	3461.1
% selected of project Reach Area (excluding roads)	5.8	9.9	26.6
$ cost per hectare	$8,542	$13,888	$21,292
Scenario # of reaches selected	176	286	728
% of project total # of reaches selected	6.1	9.9	25.2
Scenario Total Erosion, based on Total Costs (excluding Monitoring only costs)			
	TotalE 10exM	TotalE 20exM	TotalE 50exM
Total Erosion selected (m^3)	328,322	656,588	1,641,478
% selected of project total TotalE volume (m^3)	10.001	20.000	50.000
Scenario rehabilitation Tcost ($)	$7,388,629	$19,381,167	$76,923,882
% selected of project rehabilitation Tcost ($)	2.2	5.8	22.9
Scenario Reach Area (excluding roads) selected (ha)	524.3	1017.3	3092.1
% selected of project Reach Area (excluding roads)	4.0	7.8	23.7
$ cost per hectare	$14,091	$19,051	$24,878
Scenario # of reaches selected	117	215	633
% of project total # of reaches selected	4.1	7.5	21.9
Scenario Total Erosion and Proximity to Estuary, based on Total Costs			
	TotalEProximity 10	TotalEProximity 20	TotalEProximity 50
Total Erosion selected (m^3)	328,286	656,571	1,641,452
% selected of project total TotalE volume (m^3)	10.000	19.999	49.999
Scenario rehabilitation Tcost ($)	$6,662,851	$18,502,355	$77,669,968
% selected of project rehabilitation Tcost ($)	2.0	5.5	23.1
Scenario Reach Area (excluding roads) selected (ha)	716.7	1364.2	4020.4
% selected of project Reach Area (excluding roads)	5.5	10.5	30.8
$ cost per hectare	$9,297	$13,563	$19,319
Scenario # of reaches selected	169	307	892
% of project total # of reaches selected	5.9	10.6	30.9
Scenario Total Erosion and Proximity to Estuary, based on Total Costs (excluding Monitoring only costs)			
	TotalEProximity 10exM	TotalEProximity 20exM	TotalEProximity 50exM
Total Erosion selected (m^3)	328,236	656,567	1,641,480
% selected of project total TotalE volume (m^3)	9.998	19.999	50.000
Scenario rehabilitation Tcost ($)	$7,712,805	$20,164,258	$81,922,697
% selected of project rehabilitation Tcost ($)	2.3	6.0	24.4
Scenario Reach Area (excluding roads) selected (ha)	572.4	1056.7	3438.8
% selected of project Reach Area (excluding roads)	4.4	8.1	26.4
$ cost per hectare	$13,475	$19,082	$23,823
Scenario # of reaches selected	132	229	751
% of project total # of reaches selected	4.6	7.9	26.0

Scenarios reported by LGA.

The graphs in Figure 27 - Figure 30 show that for each of the different prioritisation scenarios (i.e. 10%, 20% and 50% of total erosion) the reaches requiring the most investment occur with the Kyogle and Richmond Valley Shires. The relative proportion of priority rehabilitation reaches increased for the Kyogle and Lismore Shires as greater proportions of the erosion problem are tackled.

It should be stressed that the primary reason for this asymmetric distribution is primarily due to the underlying geomorphic controls on the channels within these different regions, along with the cumulative history of development and land use in these areas that are a function of the underlying geology and the long-term landform evolution that has given rise to the distribution of soil landscapes in these different regions.

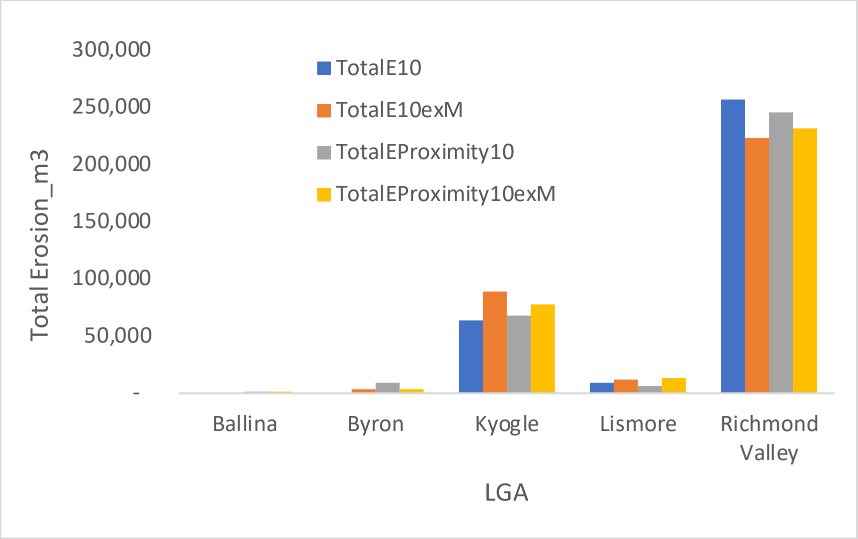

Figure 27. Breakdown of the distribution of optimal treatment reaches for 10% of the total erosion volume optimised according to Total cost for the 4 scenarios shown above.

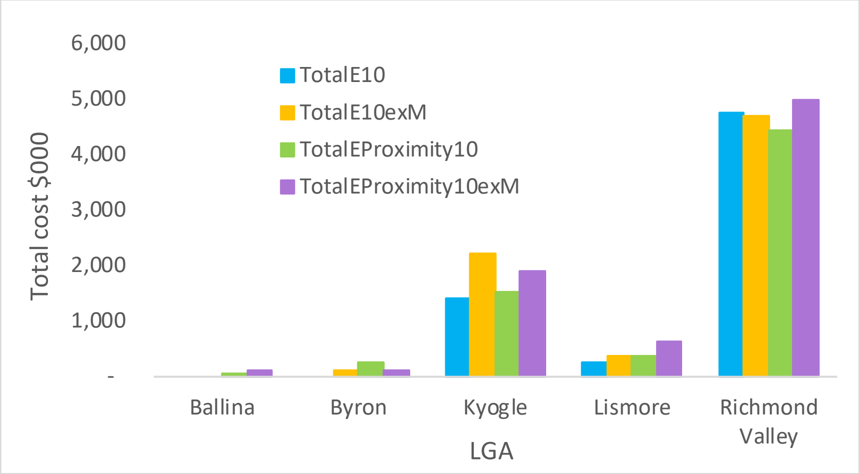

Figure 28. Total cost breakdown by LGA classification of Marxan scenario prioritising reaches comprising top 10% of optimised treatment reaches

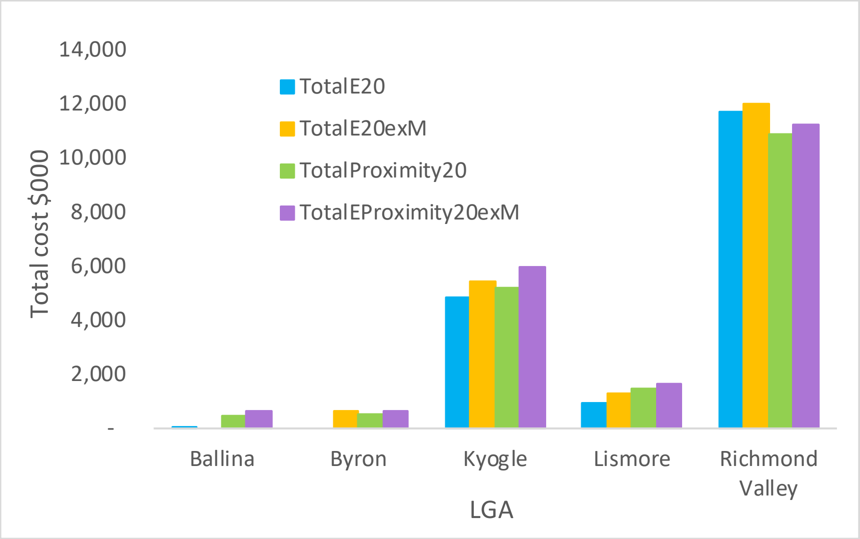

Figure 29. Total cost breakdown by LGA classification of Marxan scenario prioritising reaches comprising top 20% of optimised treatment reaches

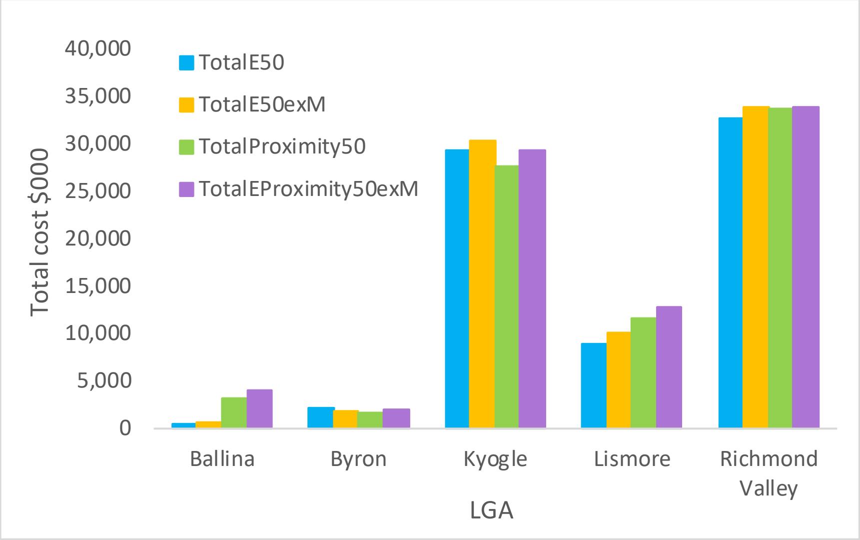

Figure 30. Total cost breakdown by LGA classification of Marxan scenario prioritising reaches comprising top 50% of optimised treatment reaches

Total Erosion scenario compared to Public and Private land use

An initial assessment of the extent to which prioritised rehabilitation reaches occur on private or public land can be seen in Figure 31. Not surprisingly it is apparent that the majority of the prioritised reaches for rehabilitation are located on private property. Whilst a full prioritisation for rehabilitation on private property alone was not within the scope of this study, such an analysis could be undertaken. Clearly this is an important qualification for prioritising on-ground works as the nature of land tenure will have a bearing on both the capacity of the land holder to host rehabilitation works on their property and the potential sources of funds that can be used to carry out works on this land.

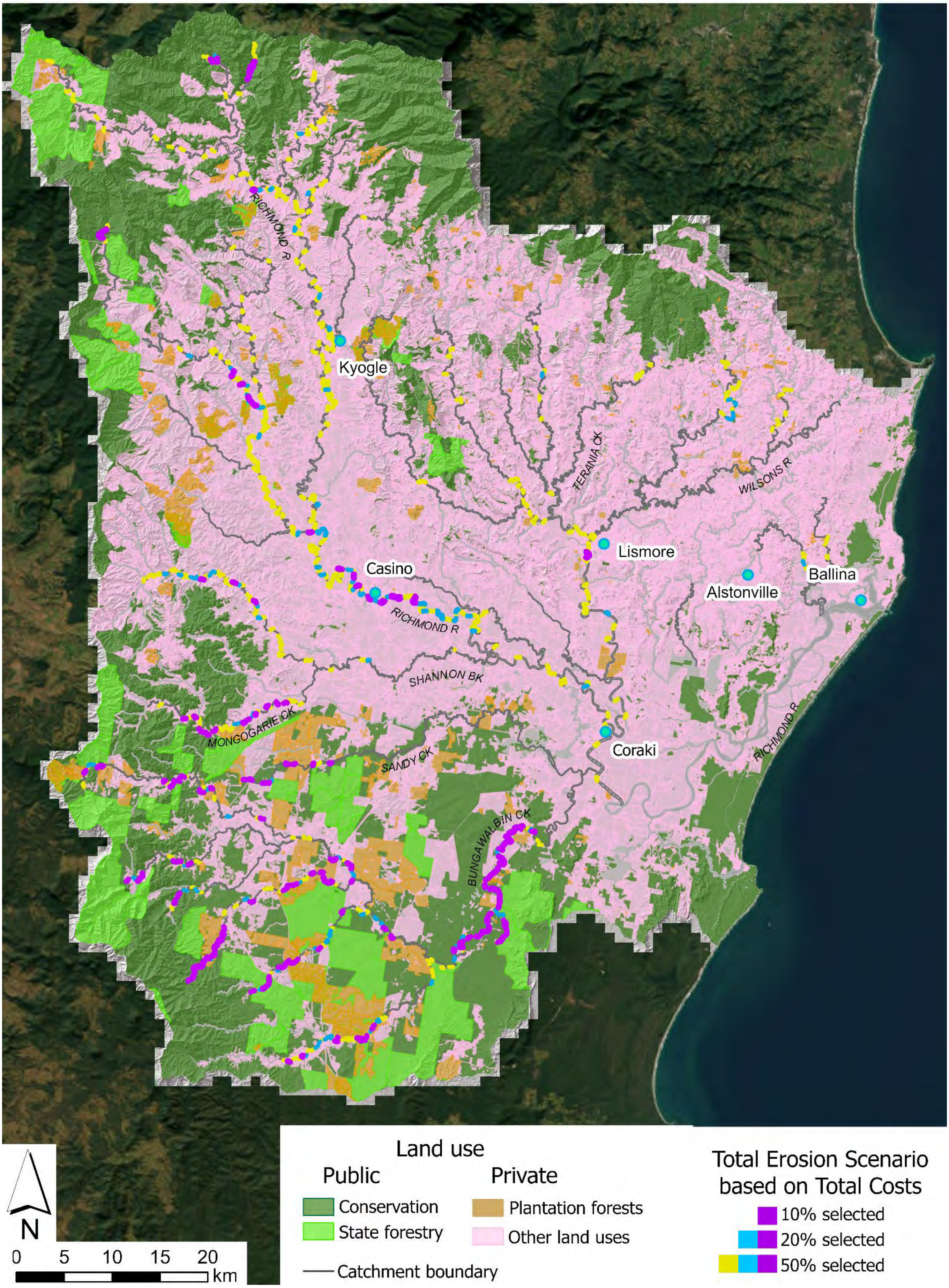

Figure 31. Total Erosion scenario compared to Public and Private land use

Comparison between Erosion Estimates from this Study *cf* Fruition NEAP Estuary Study

This section compares the estuary catchment erosion estimates from the Griffith University (GU) assessment (this study) with those from the recently completed NEAP Bank Erosion and Vegetation Condition Assessment (Fruition Environmental, 2025). Given the similarity in timing and scope of the two studies, this comparison provides a valuable review of the results, helping to confirm the robustness of the derived erosion volumes and to interpret any apparent differences in the derived estimates.

Both assessments draw on the same underlying lidar datasets but were undertaken at different spatial scales and for different purposes. The NEAP assessment was primarily designed to validate field-mapped categories of high erosion severity at a limited number of selected sites. Volumes were extrapolated to other banks identified as high erosion, providing an indicative ("first-cut") estimate of estuarine sediment yield. In contrast, the GU analysis was conducted at a broader spatial scale to generate consistent reach-based erosion volumes across the entire catchment and a substantial proportion of the estuary.

Both analyses cover overlapping portions of the Richmond River estuary and its tributaries, though neither extends across the entire system (Figure 32a).

The NEAP assessment extends to Tatham on the Richmond River, near Yarringully State Conservation Area on Bungawalbin Creek, to Teven on Maguires Creek, and to Koellner Road in Cumbalum on Emigrant Creek. The GU assessment extends from the top of the estuary in each tributary downstream to Swan Bay on the Richmond River and includes the entirety of the Emigrant Creek estuary, though the lower Richmond estuary was not assessed.

This partial overlap provides sufficient common ground to test the consistency of volumetric results, while also highlighting differences in coverage and purpose.

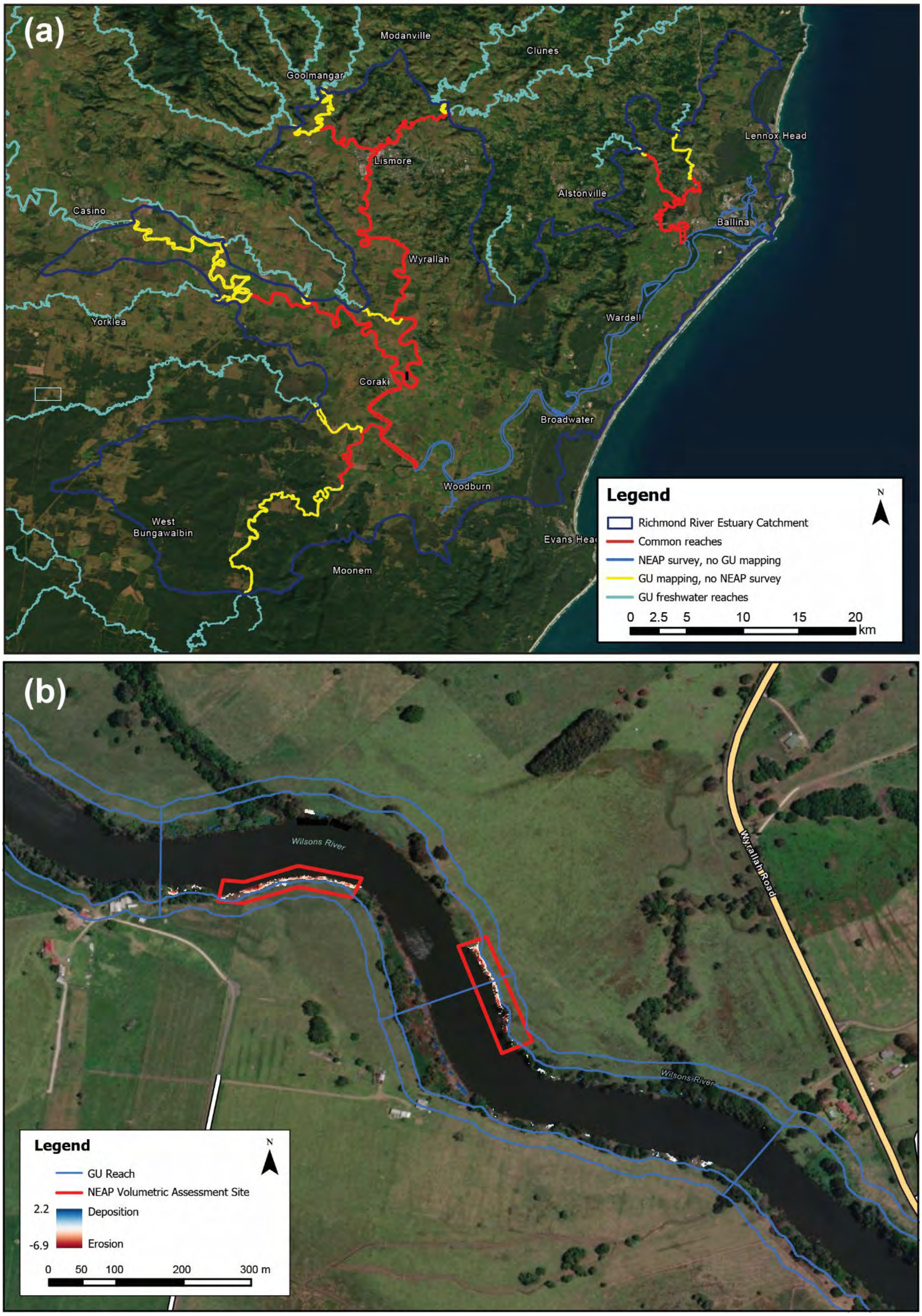

Figure 32. (a) Study area of the Richmond River estuary showing the overlapping extent of the GU and NEAP assessments. (b) Example of volumetric analysis areas for the GU assessment and NEAP assessment at Reaches 593 and 594 along the Wilson River near Wyrallah. The sites highlight that the NEAP analysis areas identified the most significant erosion source in these reaches, although there is also additional erosion outside of the areas.

Methodological Differences

A detailed description of the NEAP analysis has been presented by Fruition Environmental (2025). The GU method (this study) is described in this report. Although both assessments employed volumetric change analysis based on the same data, there are several methodological distinctions between the analyses. In large part, the distinct methods relate to overcoming the limitations of lidar data and reducing uncertainty. The solutions for overcoming such limitations are different when considering a site-scale analysis to a catchment-wide analysis. It is worth noting that despite the distinctions, both methods are scientifically robust and adopt conservative estimates of erosion. Briefly summarised, these distinctions include:

1. Input data:
- The NEAP analysis used publicly available DEMs available on ELVIS, manually clipped to site-specific areas with reliable elevation data.
- The GU analysis instead recreated DEMs directly from lidar point data, excluding all cells below a ground-point threshold to ensure consistent reliability in data quality across the catchment.
2. Limit of Detection (LoD):
- The NEAP assessment applied a single LoD of 0.315 m using a published method based on propagated error from DEMs and nearby survey markers. This method is suitable for a site-scale analysis.
- GU applied a locally variable LoD, based on a 2-sigma standard deviation approach (excluding 95% of elevation data as noise). Across the 15 detailed comparison sites, the average LoD was 0.357 m, but varied from 0.12 – 0.75 m. While typically more conservative, this method provided a more appropriate and flexible measure of uncertainty for catchment-scale analysis.
3. Timing and coverage:
- The NEAP results represent a snapshot of current condition, focused on banks classified as High severity at the time of the 2025 survey. Sites with lower erosion severity were not included. Accordingly, the NEAP results represent a minimum estimate of annual sediment contribution, providing a conservative snapshot of contemporary conditions rather than a comprehensive historical record.
- The GU analysis captures all detectable erosion between 2010 and 2023, including the impacts of five major floods. It therefore reflects cumulative change rather than recent erosion alone.

These differences mean the two analyses are not directly comparable in a numerical sense, representing different scales, timeframes, and analytical purposes. But they remain complementary perspectives on the same erosion processes.

Site-Scale Comparison

Erosion volumes were compared at 15 detailed sites common to both assessments. The GU analysis used standardised 500 m reaches covering both banks, while NEAP delineated smaller, field-based areas along individual banks. Figure 32b highlights the discrepancy between the spatial scales of the two assessments. Total erosion volumes across these sites were 29,231 m³ (NEAP) and 24,571 m³ (GU). Visual inspection of the spatial datasets confirmed that both methods identified the same actively eroding areas. Site-scale volumes showed strong correlation ($R^2 = 0.84$), indicating a consistent relationship despite differing spatial definitions. The GU volumes were typically lower than the NEAP volumes, with some exceptions (Figure 33).

This is expected given that some sites had a considerably lower LoD and the relationship between this threshold and identified erosion. The primary variations in the derived volumes for individual reaches were explained by:

- Misalignment between NEAP site boundaries and GU reach extents (Figure 32b).
- Differences in LoD thresholds, where lower thresholds captured greater volumes.
- Inclusion of additional eroding areas in GU reaches not mapped as discrete NEAP sites.

The differences in the derived values are consistent with these methodological expectations rather than analytical differences. Nonetheless, despite these differences the results are closely aligned, and overall yields are relatively similar. Comparisons of the derived DoDs from both analyses show the two datasets consistently identify the same primary erosion sources within the identified reaches (Figure 32a). In effect, both datasets capture the same erosion signals at slightly different resolutions.

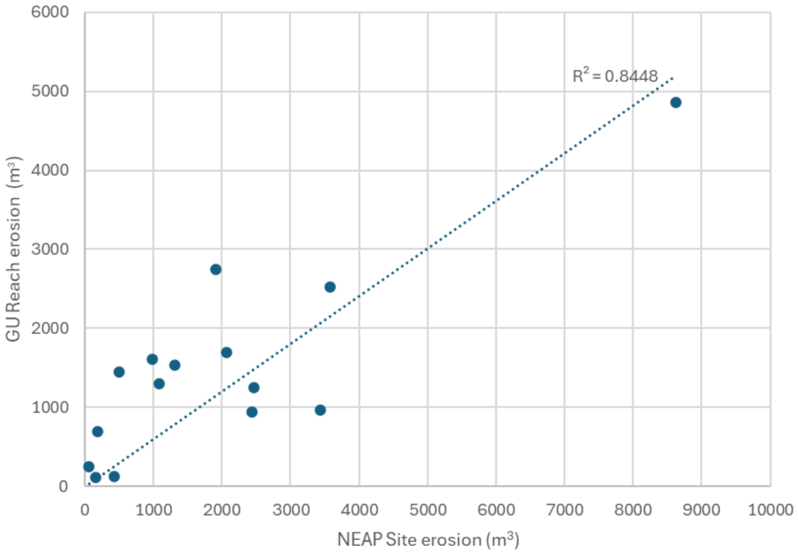

Figure 33. Comparison of site-reach erosion volumes for the 15 comparison sites in the Richmond River estuary.

Broad Scale Comparison

At the broader scale, comparison across the common reaches of the Richmond River estuary revealed larger numerical discrepancies but strong interpretive agreement.

The extent of the common reaches includes almost all of the estimated NEAP volume (89% of the estimated total). The NEAP assessment estimated a total of 113,300 m^3 throughout the study area. This finding suggests that only a small proportion of the estuary catchment total erosion from the lower estuary may have been missed by the GU assessment. While other erosion issues may be occurring in that area, it is unlikely to be a significant source of contemporary sediment pollution.

However, common reaches only capture 43% of the estimated 532,835 m^3 of estuarine channel erosion from the GU assessment. Further inspection of the data indicates that this is primarily due to the upper Richmond River estuary being a significant source of erosion and sediment over the 2010 – 2023 period.

Fruition Environmental assessed that the majority of erosion in the estuary occurs in the fluvial-dominated process zones of the upper estuary, related to flood impacts. The finding is reinforced by the results of the GU assessment.

In the common area extent, the NEAP assessment estimated 100,932 m³ of subaerial erosion, while GU derived 237,846 m³ (Figure 34). While the GU estimate is more than double that of the NEAP estimate, it is expected due to its greater spatial and temporal coverage. When a comparable subset of GU reaches is selected that intersect with the NEAP high erosion criteria, the GU volume for those reaches is 98,722 m³, an approximate 2.2% difference from the NEAP yield. This strong agreement demonstrates that, when analysed on equivalent terms, both approaches produce highly consistent results (Figure 34). It is also worth noting when NEAP's sub-aqueous component is considered (totalling 213,746 m³), the overall magnitude converges more closely to the GU estimate.

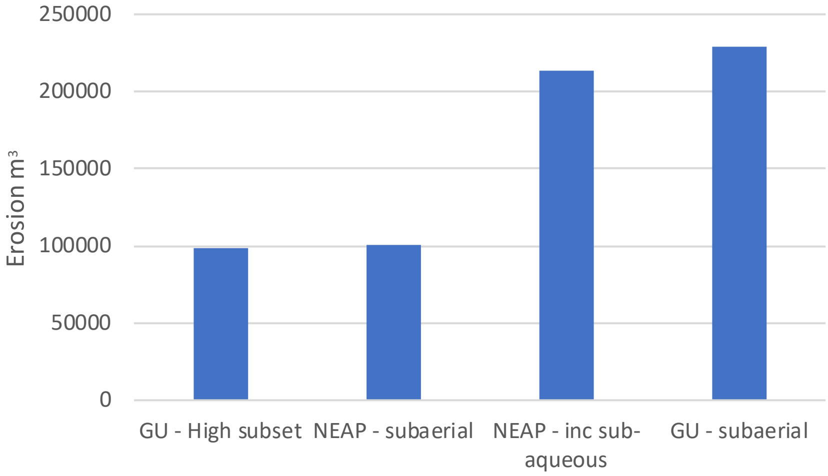

Figure 34. Comparison catchment erosion volumes in common reaches. The GU high subset represent reaches which intersect NEAP extrapolation sites, identified using the same criteria as the NEAP assessment.

The difference between the two erosion estimates is primarily explained by the extent and purpose of the assessments. The GU analysis covers the period from 2010 to 2023 for the whole channel network, a period encompassing five major floods. Each flood produced distinct erosion throughout the estuary. The GU volumetric estimate therefore represents the cumulative geomorphic change from all five floods over 13 years, rather than current rates of activity.

In contrast, the NEAP analysis provides a snapshot of present condition, focusing only on sites with High or Extreme erosion observed in the 2025 survey. It excluded Moderate and Low severity sites due to higher uncertainty in extrapolating from those classes and limited field data. As such, the NEAP result represents a minimum estimate of contemporary erosion, reflecting only recent or ongoing failures. The report acknowledges that the total estuary sediment load is likely to be substantially higher if cumulative sediment losses from lower severity classes are accounted for. The broader results of the GU assessment effectively demonstrate this assumption.

Both assessments reveal a predominance of bank slumping during flood events, rather than gradual channel migration or scour. These slumps typically represent discrete mass-failure events. Visual inspection of reaches identified in the GU analysis as having experienced substantial erosion confirms that historical slumps have since stabilised through vegetation recovery, colonised by a mix of herbaceous and woody weeds as well as some native recruitment (Figure 35). While historically some reaches have yielded high volumes of sediment (up to several thousand cubic metres) and former slumps remain visible along the bank (Figure 35d), NEAP field surveys indicate they are currently not active sediment sources. Many areas currently exhibit negligible to moderate severity erosion. Comparison of the two datasets demonstrates the episodic, flood-driven nature of upper estuary bank failures.

The consistency between field observations and geomorphic analysis indicates that apparent discrepancies in erosion volumes primarily reflect recovery of older bank failures rather than analytical inconsistency, reinforcing the validity and complementarity of both assessments.

Collectively, the two assessments provide a coherent understanding of estuarine bank erosion and have implications for bank erosion management. Despite their methodological differences and variation in the reported absolute values, the two assessments produce results of similar magnitude and direction, indicating strong internal consistency. The NEAP results provide a minimum estimate of current, active erosion, while the GU result presents a more comprehensive assessment total morphological change. Taken together, the consistency and alignment of the two assessments strengthen confidence in the reliability of the derived sediment yield estimates.

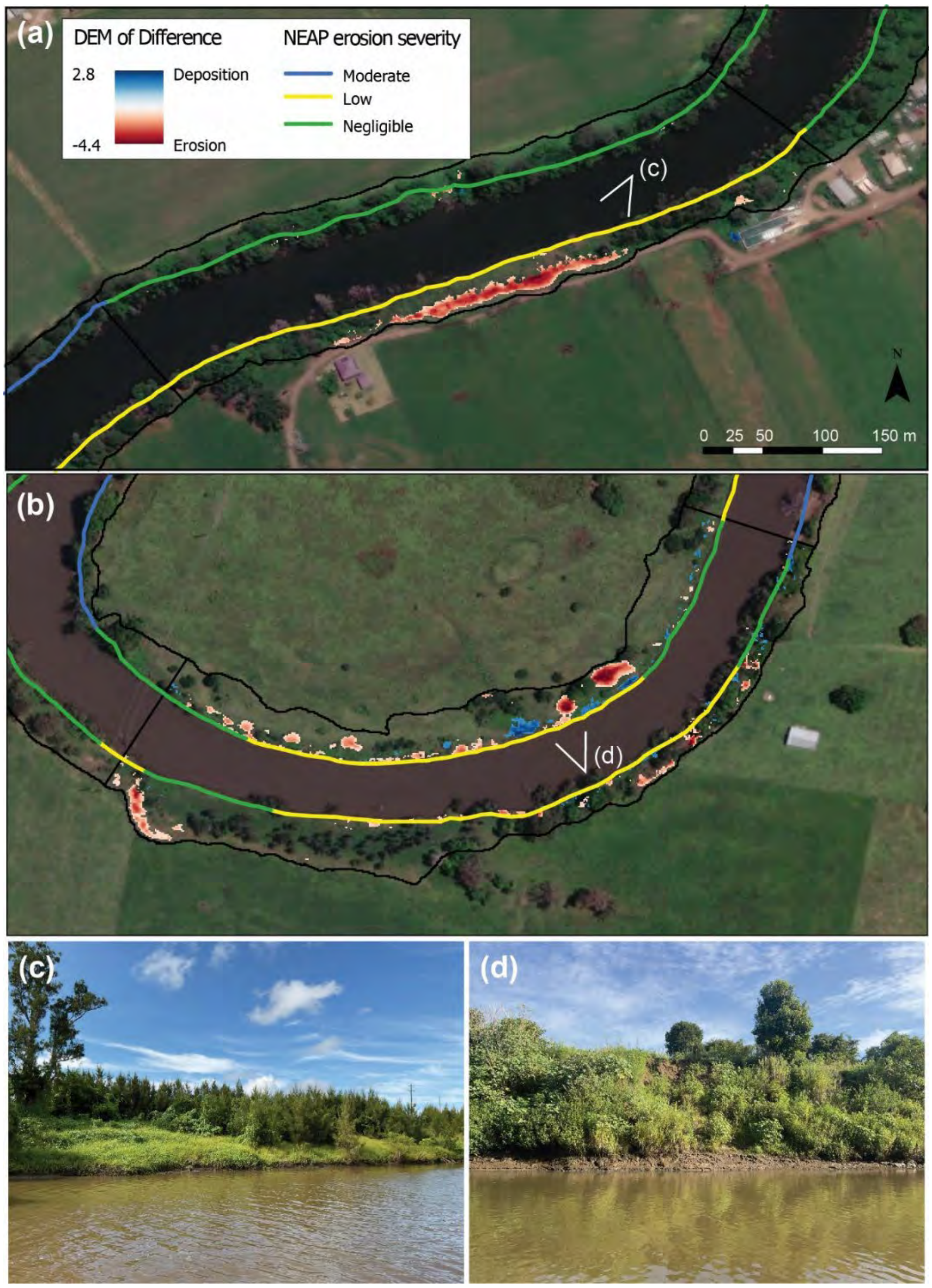

Figure 35. Examples of GU DoD mapping showing historical erosion compared with current NEAP field survey data. The white triangle shows the photo point location for c-d. (a) Reach 398 on the upper Richmond River with extensive slumping on upper bank but currently limited active erosion. (b) Reach 2371 along Leycester Creek shows multiple small-scale slumps over the analysis period, but currently Low severity erosion. (c-d) Vegetation recruitment in former slumps of Casuarina spp., Erythrina crista-galli and other weeds (source: Fruition Environmental, 2025).

Ground Truthing Protocol

Site selection

A total of 92 sites were selected for on-ground investigation at representative sites throughout all tributaries. As shown in Figure 36, reaches have been selected to sample the geomorphic diversity of river reaches as well as channel scales, as well reach conditions and riparian vegetation cover across the catchment. Ease of access to the sites was also an important consideration.

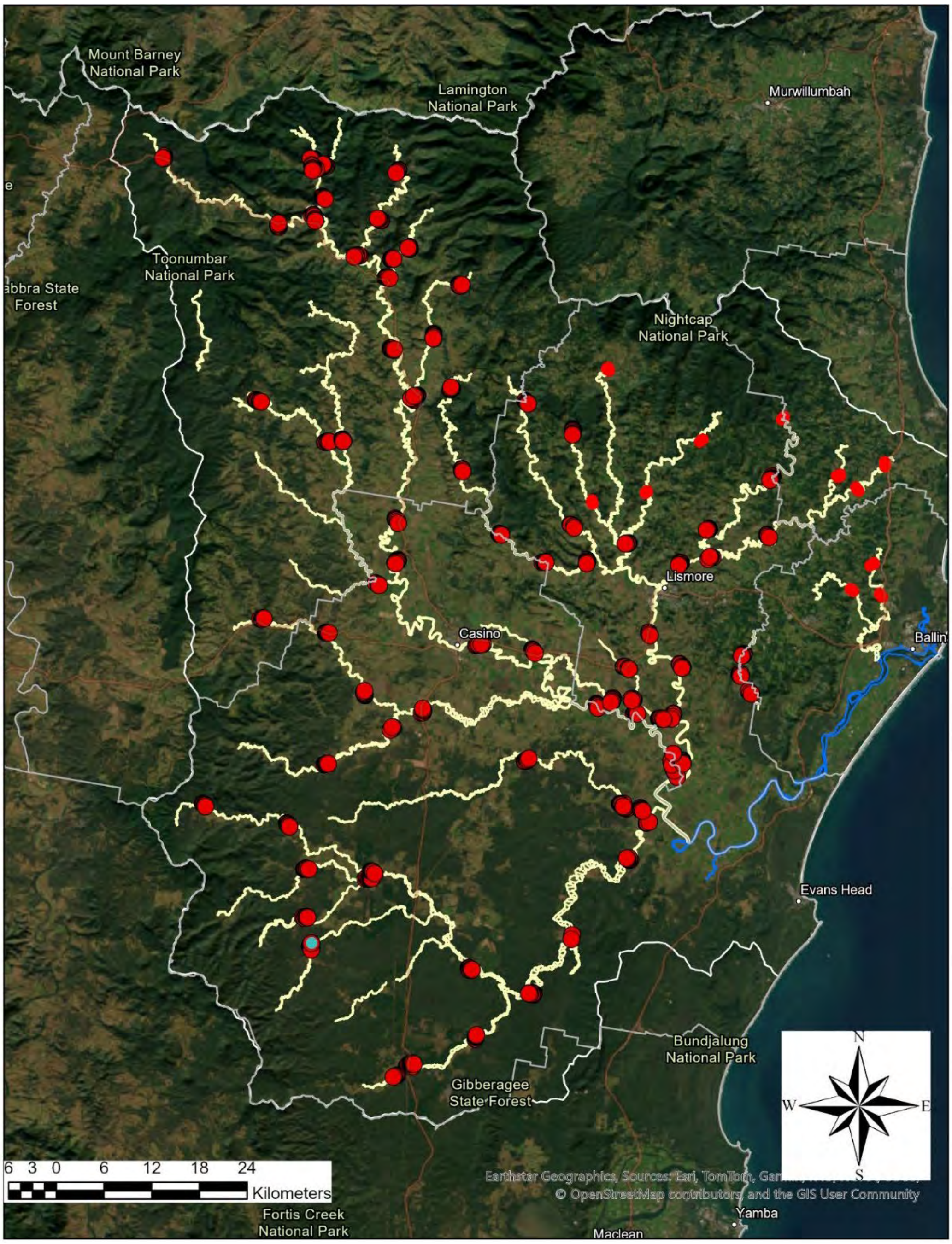

Figure 36. Example of a subset of the reach planning units with the ground verification reaches highlighted in light blue.

Ground Truthing Objectives

In broad terms the ground surveys are intended to verify the key attributes that are used to determine the management scenarios (Figure 82). The attributes that are the focus for the ground truthing are as follows:

1) Does the adjacent land use involve grazing?
2) If so, is the riparian zone currently fenced?
3) Extent of woody vegetation cover in-channel and within buffer
4) Extent of exotic trees – including overall proportion of exotic vs native
5) Extent of weed vines impacting trees
6) Other notable weeds
7) Extent of erosion

Ground Truthing Approach

The approach undertaken relies on gaining oversight of the entire 500m reach by collecting a series of panoramic images at different elevations at approximately 100m intervals along the reach. Additional oblique video footage was also captured at low elevation of each bank to enable better visibility of bank erosion and to enable weed species identification. The data sheet shown in Table 8 is populated through a combination of analysis of the drone reach panoramic images (Figure 37, Figure 38), oblique images and on-ground observations.

Table 8. Richmond CMP Ground Truthing Field sheet that are designed to target the key decision points in the Marxan model decision tree

Richmond CMP Ground Truthing Template	Date					
Name of Observer	Reach ID					
	LB	RB				
Does the reach have grazing adjacent to the riparian zone? Y/N						
Is a fence required? Y/N						
woody vegetation extent	<10%	10-50%	50-70%	>70%	% Native/Weed	
LB Buffer						
LB in-channel						
RB in-channel						
RB Buffer						
Woody Weed Extent (specify if LB & RB signf different)	<10%	10-40%	40-50%	>50%		
Camphor laurel						
Cockspur coral						
Privet						
other (specify)						
weed vine extent (specify if LB & RB signf different)	<10%	10-40%	40-50%	>50%		
catsclaw						
asparagus						
balloon vine						
morning glory						
singapore daisy						
other (specify)						
	Left Bank			Right Bank		
Erosion extent	<10%	10-30%	>30%	<10%	10-30%	>30%
fluvial scour						
major undercutting/collapse						
mass failure slumps						
other notable weeds (specify if LB & RB signf different)	<10%	10-40%	40-50%	>50%		
arundo						
large tropical grasses (e.g. paragrass)						
lantana						
castor oil						
tobacco						
other (specify)						

Ground Truthing Results

Datasheets for the 92 ground truthing reaches were compiled into a spatial database and analyses performed to test a number of assumptions that underpin the reach rehabilitation costings and spatial datasets. The following assumptions were tested:

1) That the presence of Camphor Laurel is a good indicator of the presence of a number of other key environmental weeds.
2) The presence/absence of key weed species as shown in Table 9.
3) Whether the adjacent land is grazed and whether there is a fence keeping cattle from the riparian zone

Table 9. Key environmental weed species that can be observed from the drone imagery

Camphor laurel
Cockspur Coral
Privet
Other Woody Weed
Catsclaw
Asparagus
Balloon Vine
Singapore Daisy
Other Weed Vine
Arundo
Lantana
Castor Oil
Tobacco
Other notable weeds.

Results

Figure 37. Example of panoramic imagery viewed in Arc-Pro. The arc shown in the image on the left moves as the image on the right is panned and zoomed so that the viewer can keep track of where they are looking withing the designed reach.

Figure 38. Another example of panoramic imagery viewed in Arc-Pro of the same reach but looking in a different direction and slightly zoomed in. Note the arc shown in the image on the left is now oriented in a different direction with the smaller arc reflecting the fact that the image on the right is panned and zoomed compared to the previous location above.

The images shown in Figure 37 and Figure 38 demonstrate the GIS interface for viewing the high-resolution panoramic images. This interface, which can be made public, provides a mechanism for gaining detailed views of the reach from above that allows for zooming and panning in all directions to gain an appreciation of the key attributes of interest for the prioritisation modelling.

Association between Camphor Laurel and other key Weeds

The data summarised in Figure 39 shows the direct association between Camphor and any other weeds, which validates the notion that by mapping Camphor laurel from satellite imagery that we are indeed capturing the association of a broad range of key environmental weeds. Table 10. Percentage association between Camphor and key environmental weeds, demonstrating and average association of around 77%. Also shown in Figure 40 to Figure 42 are the spatial distribution based on presence/absence observations from ground truthing reaches of a number of key weed species. The spatial distribution of camphor laurel and associated weeds (of any type) shown in Figure 40 confirms the assumption that Camphor laurel is a good indicator of weeds in general. Only around 20% of sites had other weeds present with no Camphor, while only around 4% of sites had Camphor and no other woody weeds or vine weeds.

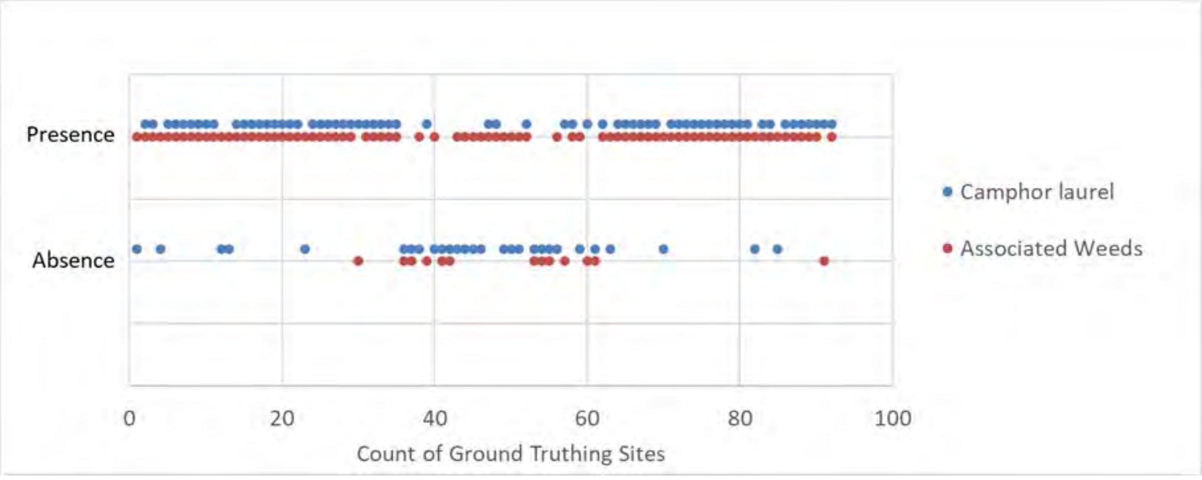

Figure 39. Graphical representation of the association between Camphor Laurel and other key environmental weeds.

Table 10. Percentage association between Camphor and key environmental weeds

Weed Category	Number of presence within all ground truthing sites	Number of Camphor co-presence	Percentage co-presence
Cockspur Coral	14	8	57.1%
Privet	40	32	80.0%
Other Woody Weed	8	5	62.5%
Catsclaw	51	36	70.6%
Asparagus vine	6	4	66.7%
Balloon Vine	38	32	84.2%
Lantana	22	17	77.3%
Castor Oil	26	20	76.9%
Tobacco	40	29	72.5%
Other notable weeds.	35	32	91.4%
Summed	280	215	76.8%

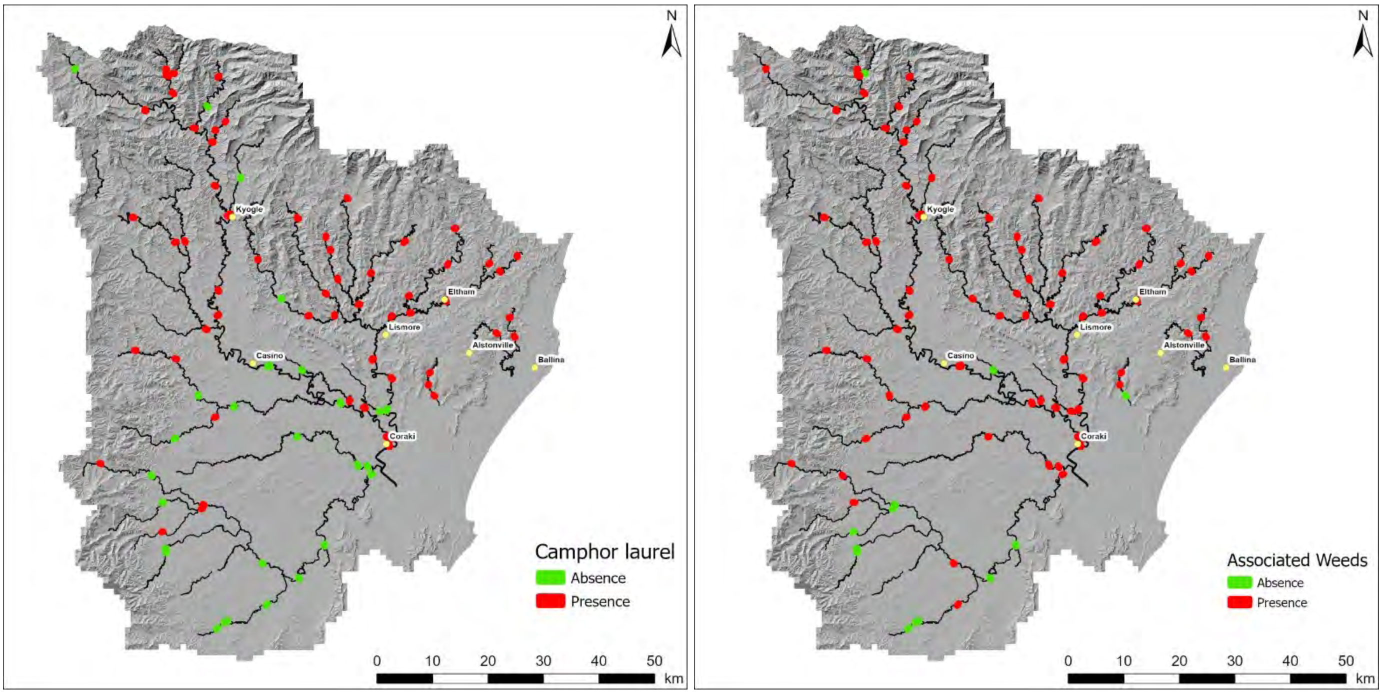

Figure 40. Spatial distribution of Camphor laurel at ground truthing sites (left) and the presence/absence of associated weeds (of any species).

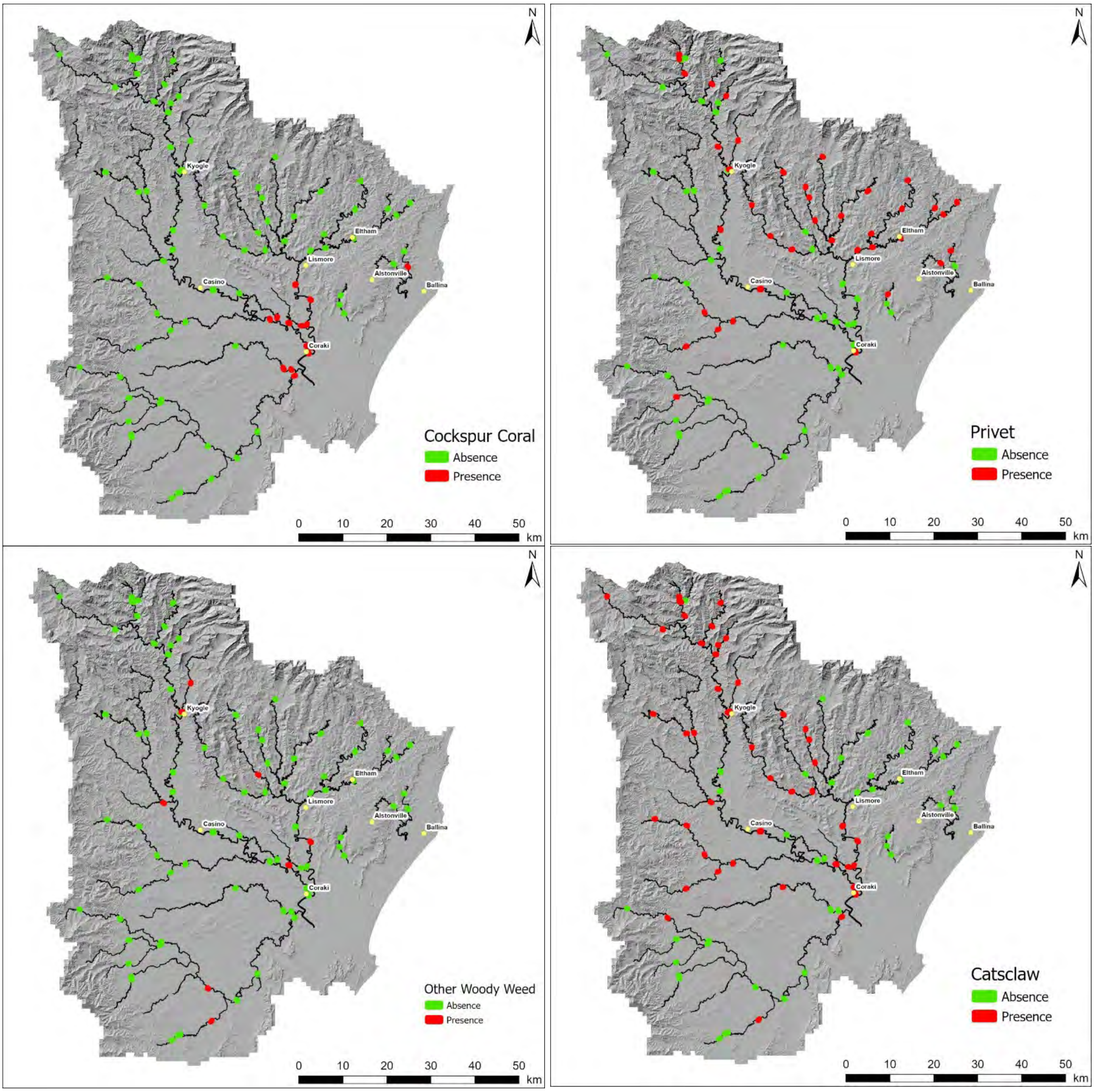

Figure 41. Spatial distribution of presence/absence of key weeds at ground truthing sites (Cockspur coral, Privet, Catslaw vine, misc other woody weeds.

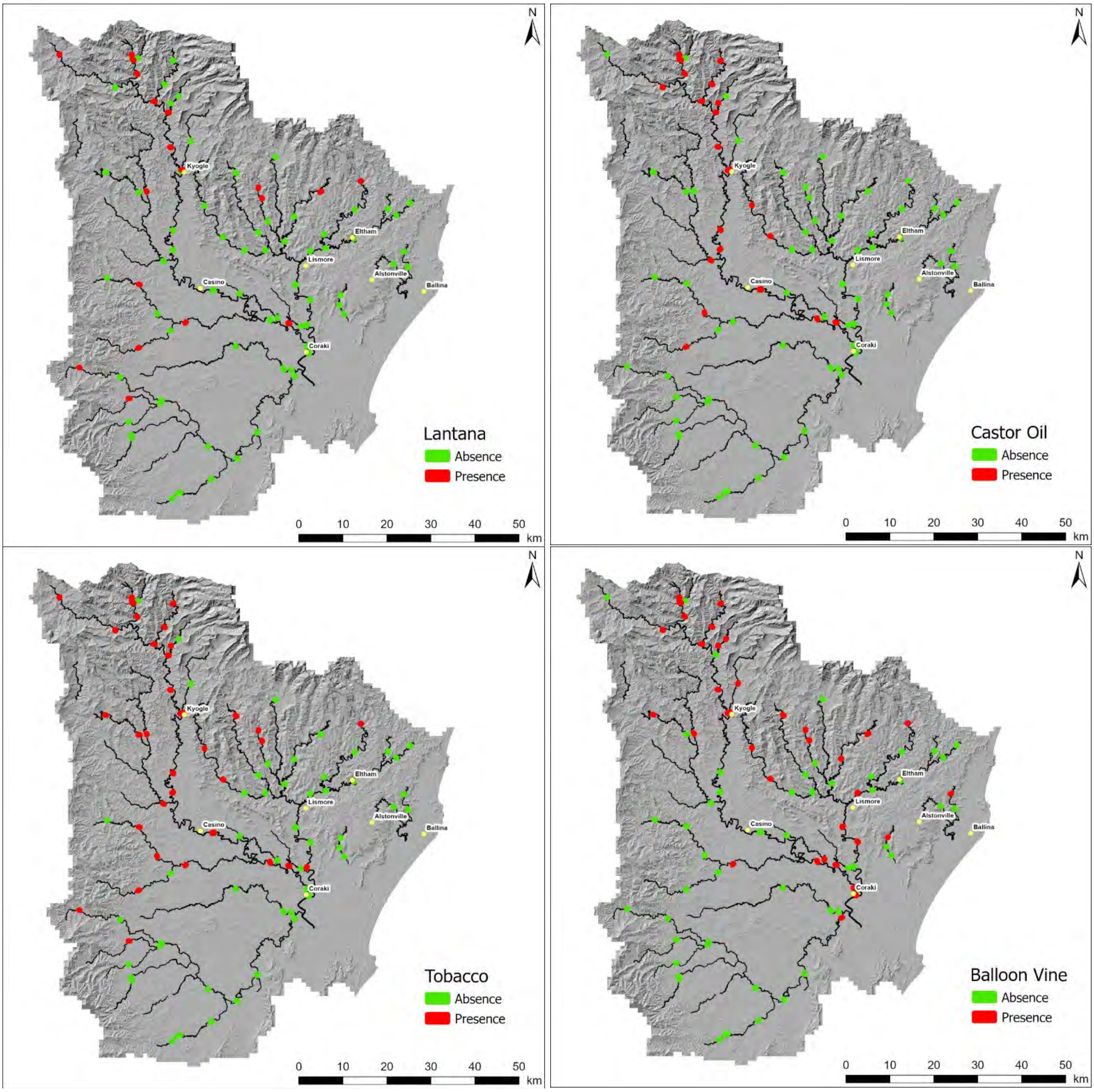

Figure 42. Spatial distribution of presence/absence of key weeds at ground truthing sites (Lantana, Privet, Castor Oil plant, balloon vine, tobacco.

Appendices

Appendix 1: Literature Review

Regional setting – Richmond catchment

The Richmond River is located in the subtropical zone of coastal northern New South Wales. The river drains a catchment area of 7006 km^2, receiving major flows from its two main tributaries Wilsons River and Bungawalbin Creek, in addition to the flows from the primary Richmond catchment (Figure 75). The northern part of the catchment is comprised of basalt geology which produces rugged hilly country with steep escarpment topography. Volcanic plateaux occur in the northeast. The southern part of the catchment is comprised of sandstone which underlies the basalt in the headwaters and produces rolling hillslopes and valleys with gentle topography, and extensive floodplains to the south and southeast (Khan and Fryirs, 2020). Due to the extensive flat floodplain topography, there is a pronounced tidal influence up to 100 km inland (Lerat et al., 2022) as indicated by the extensive estuarine reaches shown in Figure 43. Mean annual temperature is 18-21°C. Rivers in the Richmond catchment have undergone significant geomorphic adjustment since European colonisation (Khan and Fryirs, 2020). Catchment land use ranges from horticulture (1.7% of land use, mainly macadamia and tropical fruit on the basalt plateau), cropping (3.6%, mainly sugarcane production on the floodplains), dairying (0.4%), and beef production (48.4%) and forestry (41.2%) in the western areas (McKee et al., 2001). Urban areas with high residential and tourism populations occur predominantly on the lowland floodplains and coastal fringe.

Figure 43. Richmond catchment showing estuarine extent, major towns and waterways, and location of studies included in this report

Some of the highest rainfall in NSW occurs in this catchment, particularly within the upper reaches of the Wilson River sub-catchment. There is significant variability within the mean annual rainfall from the drier climate of the western headwaters (< 900 mm/yr) to the wet conditions characterising the northern and coastal parts of the catchment (> 1800 mm/yr) (Lerat et al., 2022). Seasonal variability has lowest rainfall occurring in August-September along with the lowest number of high intensity rainfall days (> 50mm). Highest rainfall occurs between December and March, with streamflow during this period categorised as 'extreme late summer flows' (Finlayson and McMahon, 1988; Lerat et al., 2022). Figure 44. shows the annual rainfall at Lismore from 1884 to 2024. Readings from 1884 to 2002 are from Lismore Centre (Station 58037 - closed in 2004), and readings from 2003 to 2024 are from Lismore Airport (Station 58214), except for gaps in the record due to missing valid daily observations. In these years (2006, 2016, 2017, 2019, 2022, and 2024), rainfall totals from Macleans Ridge (Station 58023), the closest station to Lismore with records for the missing daily observations (11.7 km from Lismore), have been used.

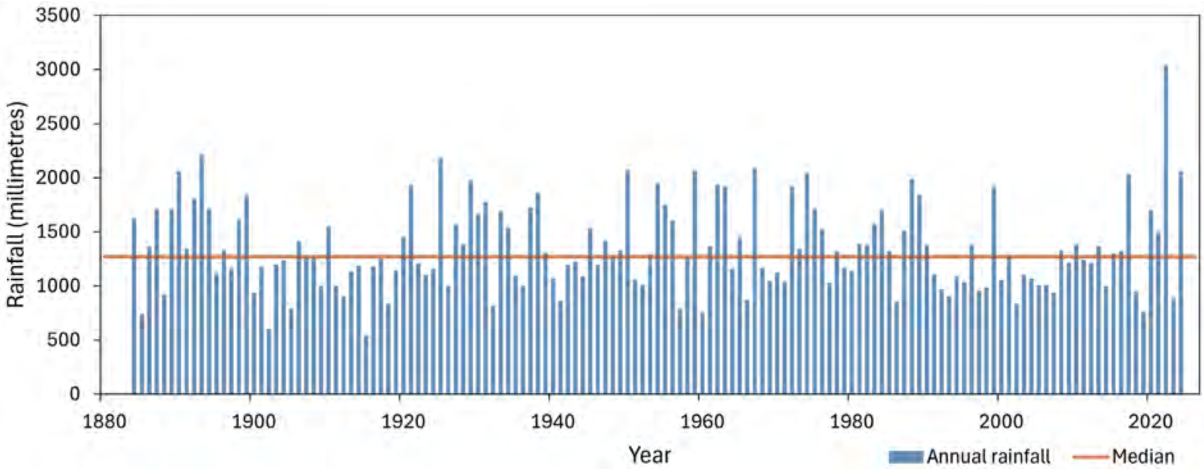

Figure 44. Annual rainfall at Lismore from 1884 to 2024. Source: BOM

Flood records extend back to 1857; some of the largest floods on record occurred in 1861, 1945, 1954, 1974, 2017 and 2022 (Figure 45). The three highest major flood events in the Richmond River catchment were in 2022, 1954 and 2017, with maximum daily basin rainfall during the event of 296, 232, and 210 mm/day, respectively. The Northern Rivers region is characterised by floods with significantly different peak flows as a result of the combination of differing initial conditions and rainfall patterns, namely prevailing soil moisture, groundwater levels, significant impact of tidal fluctuations on large floodplains, and storm surges (Lerat et al., 2022).

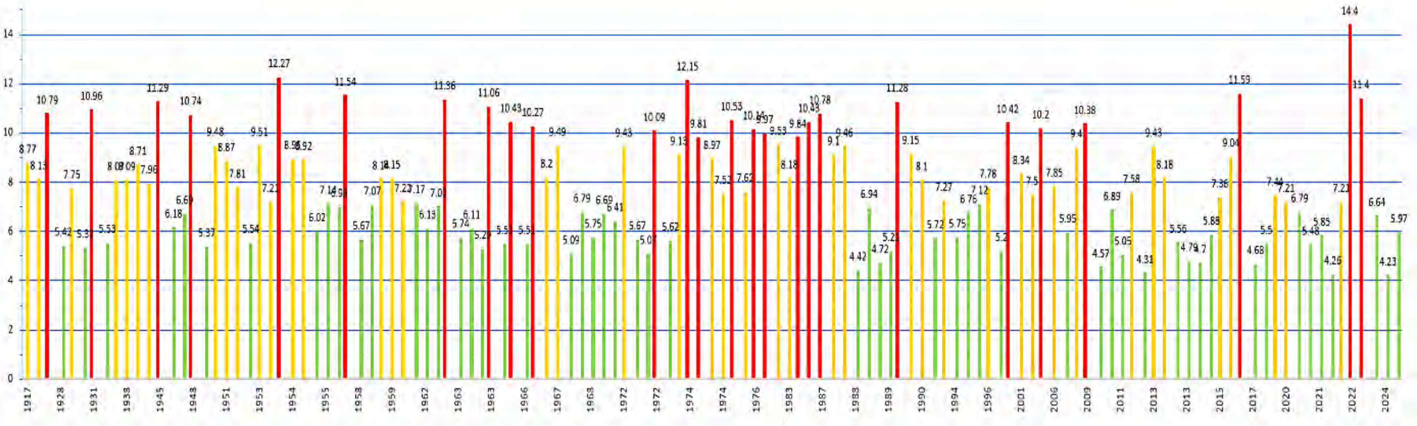

Figure 45. Wilsons River flood heights (1917-2024) at Lismore (metres AHD). Flood levels: green = minor > 4.2 m, orange = moderate > 7.2 m, red = major > 9.7 m. Sources: BOM, Lerat et al. (2022), https://australianseverweather.com/floods/index.html

Background - Richmond catchment

It is widely understood based on the findings from at least 26 studies and reports over the last 30 years (Landos, 2024) that water quality in the Richmond is significantly compromised, and that management intervention is required to rectify the situation (Ryder et al., 2014). Declining water quality is a result of a multiplicity of pressures within the catchment that have compounded through the period since European settlement (Ryder et al., 2014; Landos, 2024). Sediment yields as a result of all land use changes have been estimated to represent a 4.6 fold increase over pre-European rates (Hossain, 1997). Factors contributing to the deterioration of water quality through the catchment include:

- Logging/Land clearing and the conversion of forest to grazing and farming land,
- Dredging and desnagging of river channels leading to accelerated channel erosion,
- Grazing pressure, particularly within riparian zones,
- Urban development,
- Intensive farming,
- Horticulture - notably macadamia, banana and avocado farms, within which ground cover is suppressed below dense tree crops giving rise to accelerated surface erosion,
- Floodplain drainage,
- Unsealed road runoff, and road drainage from sealed and unsealed roads,
- Loss of oyster reefs within the estuary (caused by over harvesting, declining water quality, which further contributes to declining water quality due to the loss of the filtration service that oysters contribute),
- Camphor laurel infestations within former dairy country that have given rise to dense monocultures with very little ground cover leading to elevated surface erosion.

Study Focus

The focus for this review is on the sources of sediment contributing to declining water quality in the stream network and ultimately the extensive estuary system within the lower Richmond River. Having a sound understanding of the relative contributions from all erosion processes and sources in the catchment, their spatial distribution within the catchment and potential to contribute under different flow magnitude and frequency conditions, is a necessary precursor to being able to formulate a management prioritisation schema for the catchment. Geomorphologists have used sediment budgets as the basis for quantitatively understanding sediment sources and sinks in catchments for many decades, and they have become accepted as the primary tool for understanding catchment sediment fluxes and their management (Slaymaker, 2003; Walling and Collins, 2008).

The role of sediment budgets as a framework for understanding sediment sources and sinks

So what is a Sediment Budget? In effect a sediment budget is an accounting tool for quantifying sediment source, transfer and depositional conditions of a catchment (Walling and Webb, 1983). It accounts for various erosion processes, defined here as river channel/bank, gully, landslide and hillslope erosion, and their *net* input into the stream network (i.e. erosion minus deposition between the point of sediment detachment and the stream). Sediment budgets can be applied at different hierarchical scales within a catchment, and there are different types of sediment budgets (Fryirs and Brierley, 2012). To understand the net sediment yield, the quantification of sediment deposition (or sediment storage) within a catchment is equally as important as quantifying the source inputs and the pathways along which sediment is transported. The net sediment yield then becomes the result of all inputs minus the deposition (sinks) at a defined point within the catchment. There are also different sediment budgets for different sediment particle size fractions. The sediment budget for the coarse bedload sediment fraction (typically defined as particles > 63µm) might be completely different to the budget for the fine suspended sediment load (typically defined as particles < 63µm) within a catchment, depending on the nature of the geology, and the particle size distribution of the regolith and soils produced by the different geologies (Walling, 1983; Collins and Walling, 2004; Walling, 2005).

A sediment budget can also be applied at the scale of a single hillslope, a single gully or landslide, a single reach of channel, a sub-catchment or the entire catchment (Slaymaker, 2003). At each of these scales there will be a different sediment delivery ratio (SDR) (see Figure 46), and it is important to understand how the SDR can influence the management prioritisation of different sediment inputs and stores, depending on the specific management objective (Walling and Collins, 2008). For example, if you are primarily interested in the fine sediment yield at the end of the catchment, relatively small sediment inputs from bank erosion in the estuary (which have a very high SDR), may be more important than very high yielding sources in upstream parts of the catchment, but which have a low SDR. If on the other hand, the focus is on the sources of turbidity for a local stream, those high yielding sources close to the site of interest will be the highest priority. Sediment budget models, when properly parameterised with empirical data from all key erosion processes can be a very powerful tool for helping to prioritize management resources to the most cost-effective solutions that target the sediment source most relevant to the problem that is the focus for management (Nyssen et al., 2008; Walling and Collins, 2008).

The following review has focused on compiling the available empirical data that has quantified different erosion sources within the Richmond catchment. These help us to identify the major data gaps and show how the data collection that is being conducted through the current study will fill some of the known gaps in the sediment budget. Similarly, they also show that regardless of the detailed data collected in the current study on channel and landslide sources, there still remain some significant gaps in the sediment budget, particularly associated with the quantification of the sediment sinks and understanding how the internal dynamics of the sediment budget operate under different magnitude-frequency conditions (Nyssen et al., 2008).

The sediment budget is complex as different sediment sources and sinks are available in catchments with different residence times and are active over different spatial and temporal scales. Each catchment is different. One way to make sense of this complexity is via the concept of sediment (dis)connectivity which is widely used to understand the internal dynamics of catchment and the operation of the sediment budget under different magnitude-frequency conditions.

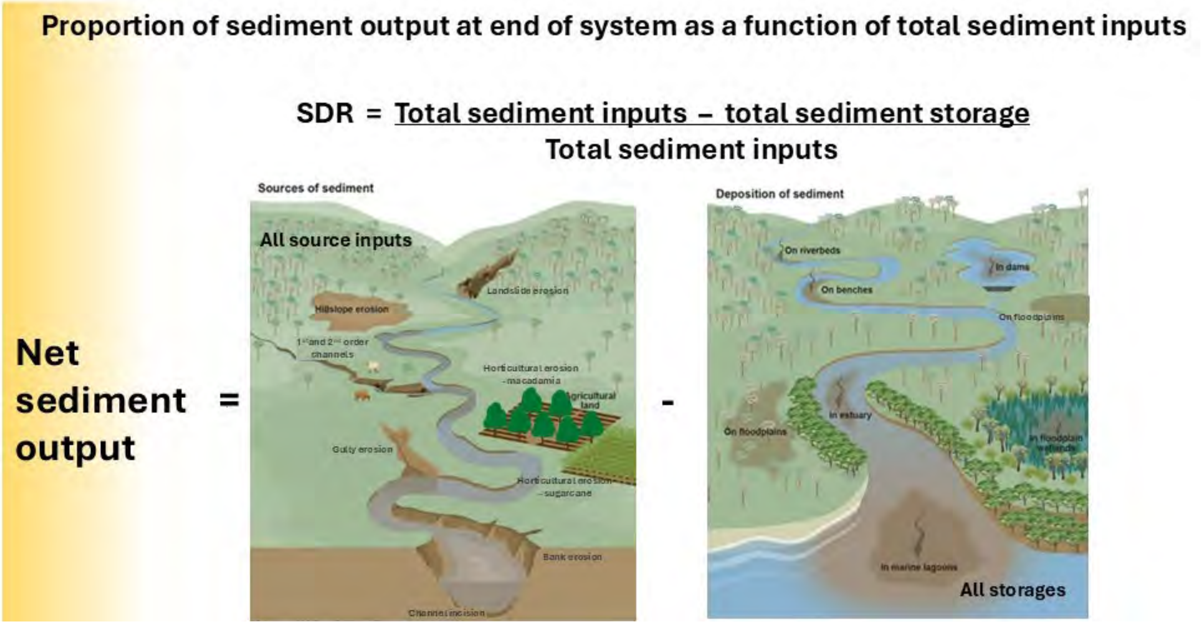

Figure 46. Conceptual model of a sediment budget, illustrating how the net yield at the end of catchment is a function of the inputs minus the storages

Sediment sources and their quantification in the Richmond catchment

To date only limited attempts have been made to quantify the sources of fine sediment within the greater Richmond River catchment. A simple sediment budget for the catchment was developed by Hossain (1997) and Hossain and Eyre (2002), in which catchment sediment sources were divided into "upland" surface erosion, modelled with the Universal Soil Loss Equation (USLE), and river bank erosion. The USLE is an empirical model designed for estimating erosion from agricultural field plots and has been shown to overestimate sediment yields by up to four orders of magnitude when applied over larger areas in landscapes for which it was not designed (i.e. non-agricultural catchment scale) (Brooks et al., 2014b; Fernández and Vega, 2016). The river bank erosion component of the sediment budget was quantified using a very crude empirical method of measuring bank top retreat rates at selected sites using the distance between stakes set back from the bank top as a method for calculating annual bank retreat rates. From these data Hossain (1997) determined that the mean annual bank erosion rate throughout the catchment was around 0.150 m per year, which then appears to have been applied to all channels throughout the catchment. The fluvial sediment budget determined total bank erosion varied from 123,975 t/yr (1994-95 dry year) and 502,709 t/yr (1995-96 wet year). Neither of the methods employed in the Hossain study would be considered to represent acceptable approaches to developing a sediment budget today.

An extension of this work by McKee et al. (2002) provides a more robust estimate of the annual variability of suspended sediment loads at the catchment scale based on measured suspended sediment concentration (SSC) data at gauging stations. Annual catchment suspended sediment loads were empirically modelled from continuous turbidity and discharge data between 1986 and 1999 in the Richmond River near Casino, with the turbidity calibrated to measured SSC data. This study shows that the annual loads vary widely as a function of annual discharge, ranging from <1000 t/yr in dry years (1998) to > 600,000 t/yr in wet years (1989). While this study provides reasonable estimates of the suspended sediment load delivered from one of the major sub-catchments in the greater Richmond catchment (i.e. the Richmond above Casino), the study provides no insights into the specific sources of sediment with the catchment, and hence provides no basis for targeting rehabilitation works. Furthermore, the studies by Hossain (1997) and McKee et al. (2002) provide no breakdown of the particle size distribution within the suspended sediment load, and how particle size distribution varies with floods of different magnitude. Such data would provide an important additional line of evidence to help targeting source areas that have higher contributions of these critical sediment particle size fractions.

Concurrently with the work by Hossain (1997), nitrogen and phosphorus budgets for the Richmond catchment were developed by McKee and Eyre (2000). Budgets incorporated both particulate and solute measures, including riverine and precipitation loads, fertiliser, manure and sewage inputs, bedrock phosphorus weathering, and atmospheric nitrogen fixation. Total loadings for nitrogen and phosphorus ranged from 12-57 kg/ha/yr and 0.25-6.6 kg/ha/yr respectively, and varied due to topography, runoff variation, rainfall distribution, land use and population density. Nitrogen and phosphorus nutrient fluxes (i.e. transfer) and storage were similar to catchments with mixed land use and relatively low nutrient catchment loadings, as found elsewhere globally (Jaworski et al., 1992; McMahon and Woodside, 1997).

Ecos Environmental Consulting (2009) modelled suspended solids (SS) generation for the Wilsons River catchment, deriving event mean concentration (EMC) values for various land uses, including, horticulture (12.7 mg/l) and grazing (5.8 mg/l). The study used a long-term turbidity dataset from Eltham gauging station, low in the Wilsons catchment. The study’s modelling was based on a turbidity-SS relationship for the Richmond River derived by Letcher et al. (1999). Letcher’s turbidity-SS relationship was based on daily turbidity monitoring data for the period July 1995 to July 1996, a 12-month period of below-average rainfall, collected 3 km upstream of Casino by Casino Shire Council.

There are two limitations to the data contained in the Ecos Environmental Consulting (2009) study for the purposes of developing a suspended sediment budget for the Richmond catchment. Firstly, the study categorised EMC data based on land use, rather than on erosion processes within a geomorphic landscape context. Land use categories are not always relevant when attempting to quantify sediment delivery given that they don’t explicitly account for the landscape context (Yang et al., 2024). This is despite the fact that certain land uses have been responsible for accelerating some erosion processes. Land use categorisation also lumps a suite of erosion processes together, and the relative distribution of these processes may vary within the same broad land-use category but in different geomorphic landscape units (Poff et al., 2006; McIlroy et al., 2008). It is more useful to categorise according to erosion processes, for example, bank erosion or gully erosion, in different parts of the catchment. Secondly, EMC modelling assumes a linear relationship between concentration and discharge, and takes no account of event hysteresis in which the different plots demonstrate non-linear variation in the relationship between SS concentration and discharge during flood events (see Hossain et al., 2002, Figure 47). Depending on the nature of a flood event, high concentrations may occur earlier or later in the event as different erosion processes deliver sediment to the streamflow at different times during the event(Williams, 1989; Malutta et al., 2020; Haddadchi and Hicks, 2021). For example, high surface erosion tends to be delivered early in the event as part of the elevated “first flush” of suspended sediment delivery, while bank erosion often does not get triggered until later in the event as flood waters are waning, delivering higher sediment concentration at the tail end of a flood hydrograph (Williams, 1989; Asselman, 1999; Haddadchi and Hicks, 2020).

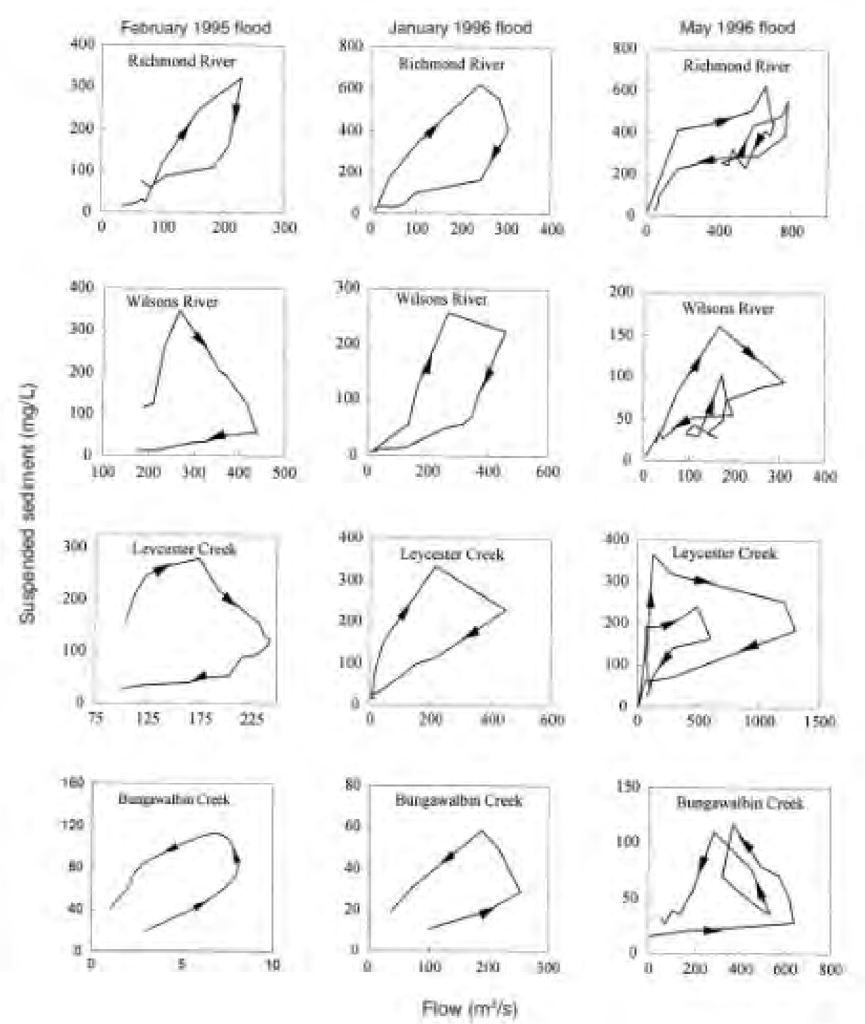

Figure 47. Example of different hysteresis relationships at different locations through the Richmond catchment. These hysteresis curves highlight that there is a non-linear relationship between discharge and sediment concentration during a flood event. Source: Hossain et al. (2002).

Bedload Transport

A study by Khan et al. (2021b) provides insight into the bedload sediment transport dynamics through the major tributaries within the broader Richmond catchment. Bedload sediment flux is an important control on local channel morphology and can determine the local availability of critical pool habitat (Pasternack et al., 2008). While the bedload sediment fraction is not a major direct driver of the elevated suspended loads outlined above, it can be an indirect driver as excessive bedload accumulation can drive increased channel erosion (Brooks et al., 2014a). This can occur by increasing lateral channel migration as the bed-material load accumulates in point bars contributing to increased shear stress on the outer banks. Typically management prioritization strategies that are focused on downstream water quality (i.e. SSC) are not framed around the coarse bedload sources in catchments, given that they will often be derived from different sources to the fine sediment fractions.

Reach scale behavioural sensitivity was assessed for the Richmond River by Khan and Fryirs (2020) and Khan et al. (2021a). These studies determined the ease with which geomorphic units and associated sediment, water and vegetation interactions adjusted over time and the extent to which each reach in the catchment is likely to adjust in the future. The coarse sediment (dis)connectivity dynamics of the Richmond catchment were also modelled (using the CASCADE model), providing insight into the internal dynamics of the coarse sediment budget and how a reach's sensitivity controls potential changes in the sediment regime of the catchment. While these analyses are focused on coarse sediment dynamics, the geomorphic units that are the focus for analysis all have varying proportions of fine sediment, and as such with some additional field sampling this analysis could be reframed to provide insights into fine sediment contributions to suspended sediment supply and dynamics.

Erosion Risk (MCAS) Modelling

The NSW Estuary Health Risk Assessment has undertaken a simple "first pass" catchment risk assessment modelling exercise. These data are further analysed in the Richmond MCAS-S modelling (Barrett, 2018). This approach uses a simple catchment hydrologic modelling approach within the national Geofabric sub-catchments (Stein et al., 2014) coupled with pollutant EMC data assigned to different land use categories within the sub-catchments (see above the issues around using this land use/EMC based modelling approach). Additional risk parameters, such as the extent of riparian vegetation are also included as distinct attributes in the risk assessment. River bank erosion is only assessed qualitatively as a function of the River Styles fragility index and riparian vegetation derived from 5m Spot satellite imagery within a 100m buffer along all stream lines. Such an approach, like all models, is only as good as the specific data layers (see discussion below regarding the use of standardised riparian buffers) and EMC values used to populate the model.

This approach does not yet account for variable sediment delivery from different sources areas, nor does it explain how sediment delivery varies during different magnitude or sequences of floods. Furthermore, in addition to the shortcomings in identifying source processes (e.g. various types of bank erosion, gully, hillslope erosion), the resolution of the analysis means that the dataset as currently formulated is of limited value for prioritizing *site scale riparian* remediation activities given that it is based on sub-catchment scale data. On the upside, the framework is highly flexible and can be updated as new higher resolution data becomes available, as was demonstrated in the model for the Manning Catchment (Swanson, 2019). In the Manning case study, high resolution riparian vegetation mapping undertaken by Pietsch et al. (2019) was used to quantify erosion risk as a function of the woody vegetation cover within the geomorphically defined channel zone, coupled with the trajectory of change in that riparian vegetation extent through time. The work of Zhang and Fryirs (2023) built on this work and analysed the historical trends in woody riparian vegetation cover, including trends across the North Coast of NSW. These works provide a template for the way in which the Richmond catchment Estuary Health Risk Assessment can be updated with similar high-resolution datasets. Ground truthing of the riparian vegetation (delta green) dataset derived by Pietsch et al. (2019) for the Manning Estuary Risk Assessment, found it to be a reliable indicator of riparian vegetation extent (i.e. a narrow definition of vegetation condition that does not distinguish between native and exotic vegetation).

Remote sensing has enabled characterisation of the complex vertical structure of riparian vegetation and effects on roughness and therefore on flow dynamics, sediment transport and channel geomorphology (Corenblit et al., 2024; Gurnell and Bertoldi, 2024). Riparian vegetation as broadly defined to include the in-channel vegetation as well as vegetation on the banks and proximal floodplain, influences channel size and shape through controls on bank shear strength and the available energy (shear stress) to do work on the channel boundary (McMahon et al., 2017; Sharpe et al., 2023). When the role of in-stream wood is also included, depending on the scale of the channel and the relative wood load, channel roughness and therefore total hydraulic resistance can be even more profound, increasing energy loss and further reducing sediment erosion and transport (Brooks and Brierley, 2002; Brooks et al., 2003; Fryirs and Brierley, 2012).

The focus for the approach taken by Pietsch et al. (2019) in the Manning catchment was based on the premise that the primary management lever available to river managers today is in maximizing the extent of riparian vegetation throughout the river corridor, given that this delivers the multiple objectives of reducing channel erosion, potentially facilitating increased sediment deposition and slowing flood wave propagation, and maximizing biodiversity and carbon co-benefits (Cunningham et al., 2015). Development of spatial datasets (DEM, Canopy Height model and Water layer) from high resolution Lidar data and comparison with the LANDSAT derived Persistent Green dataset (Pietsch et al., 2021), then enables the development of appropriate prioritization strategies to be developed, along the lines of the approaches outlined in Agnew and Fryirs (2022) and Daley et al. (2024). Different strategies can be employed depending on the reach sensitivity and other geomorphic controls, and whether the riparian vegetation is on a declining or recovering trajectory. When vegetative and geomorphological characteristics and adjustments are coupled with the current vegetation extent, the level of investment required to develop the optimal outcome (a continuous riparian corridor in which the woody vegetation cover exceeds 70% - Figure 48), or other strategic objectives, can then be determined.

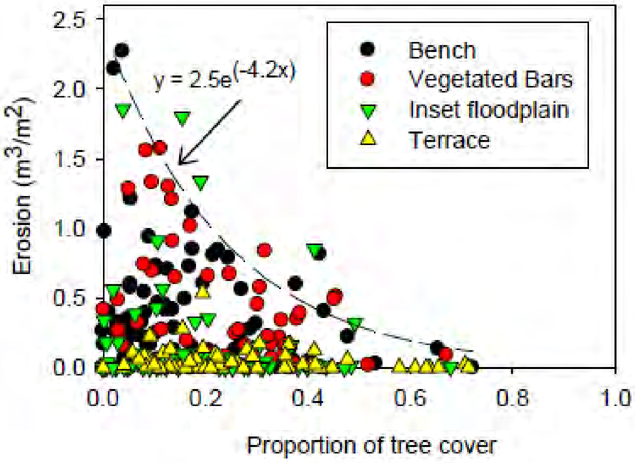

Figure 48. The relationship between observed erosion within the Brisbane River across a 90km reach over a 10-year period as a function of woody riparian vegetation cover. Note the differences in erosion within different geomorphic units. Unit erosion is minimised, regardless of the underlying sedimentology (associated with different geomorphic units) as woody vegetation cover exceeds 70%. Source: Daley et al. (2024).

Horticultural sediment sources

Erosion rates and sediment delivery to the catchment mouth do vary as a function of land use (Dunne, 1979). An important land use in the Richmond catchment is associated with horticultural activities. Soil erosion in macadamia orchards is a major issue due to fact that the orchards tend to be on steep basalt soils and the density of the orchard canopies typically is such that it suppresses ground cover under the trees (Firth et al., 2002; Reid, 2002) Erosion on these bare orchard floors is also exacerbated by stemflow down macadamia trunks (Keen et al., 2010). A pilot study by Reid (2002) determined the establishment of shade tolerant ground covers could reduce soil loss from traditional macadamia plantations by 99%. However, Ecos Environmental Consulting (2009) argued this is unlikely to equate to a corresponding reduction in sediment export (measured in t/ha/yr), suggesting a more realistic reduction in annual sediment yield is likely to be ~75% of suspended solids once sediment delivery is taken into account. Keen et al. (2010) measured stemflow volumes monthly over a 16-month period, with soil movement away from the base of trees averaging 6.5 mm/m^2/yr, highly correlated to rainfall volume. With associated surface rilling and root exposure, Keen estimated soil movement could be ~3.8 t/ha/yr from typical macadamia orchards. A study by Southern Cross University (2024) compared integrated orchard management (IOM) and non-IOM practices (i.e. business as usual) at a macadamia orchard located at the Centre for Tropical Horticulture, Alstonville, NSW. The study determined that IOM practices, in which every second row of trees is removed to allow for light penetration and hence improved ground cover development, reduced soil and nutrient loss from rain events by a significant ~95% and ~70% respectively. Non-IOM soil loss range was 3.3-47,055 mg/m^2 compared to IOM loss of 0.5-474 mg/m^{2,} with modelled IOM practices retaining ~7 t/ha/yr (Figure 49). The results are considered conservative due to the low number of high (>20mm) rainfall events sampled, however these benefits are only just beginning to be realised in working macadamia orchards as these practices begin to be rolled out by some early adopters. Whilst these erosion levels do not necessarily equate to sediment delivery, due to the nature of the topography and/or buffers between orchards and drainage lines, it does provide some insight into the impacts of IOM practice. Further analysis is required to quantify sediment delivery at the sub-catchment scale to fully explain the extent to which this land use is a primary contributor for fine sediment to the channel network and therefore the catchment estuary. The Richmond catchment hosts ~12,000 hectares of macadamia orchards (Southern Cross University, 2024) across varying topography. A reduction in sediment delivery, and consequential improvements in water quality from introducing IOM practices across macadamia orchards could be substantial. However, these data can now form the basis for comparison with sediment sources from other erosion processes. As an example, if we took as a worst-case scenario the figure of 7t/ha/yr as representing the sediment yield from all macadamia farms in an average year, the total annual sediment yield (i.e. delivered to the stream network) from all macadamia farms would be 84,000 t/yr. For comparison, a single landslide of 1 ha in area that eroded an average of 2m deep in which all the sediment was delivered to the stream, and assuming a soil density of 1.5 t/m^3, would deliver 30,000 t of sediment to the stream. Sediment budget analysis allows for these types of comparisons to be made, and thereby assess the efficacy of different management strategies and where they should be focussed.

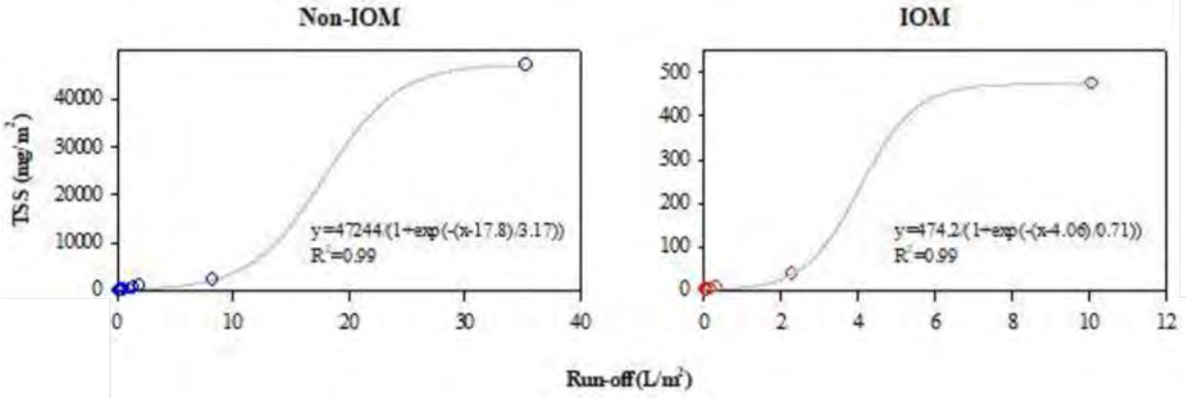

Figure 49. Relationship between TSS and run-off in non-IOM and IOM practices. Note the difference in scale between non-IOM and IOM. Source: Southern Cross University (2024)

Sediment delivery to the catchment mouth is also sourced from runoff from sugarcane cultivation albeit with most available data coming from studies in the Queensland wet tropics. Prove et al. (1995) compared soil erosion under different management practices on several Innisfail Qld sugarcane plantations situated on sloping (5-18%) land from 1980-1986. Conventional cultivation resulted in erosion ranging from 47-505 t/ha/yr due to variable annual and episodic rainfall, with average annual losses of 148 t/ha/yr. No-tillage management practices reduced this significantly to <15 t/ha/yr, with no-tillage effects greater than the use of trash harvested groundcovers. Modelling by Lu et al. (2003) estimated average erosion rates under sugarcane of 16 t/ha, using the revised USLE, and remotely sensed imagery and daily rainfall time series data to incorporate the effects of seasonally variable groundcover and rainfall intensity. In Visser et al. (2007) sediment exports from floodplain sugarcane plantations in the Herbert River, in Qld's Wet Tropics, varied between 2 to 5 t/ha/yr. Comparison of further refinements and precision in no-tillage sugarcane cultivation near Mackay Qld were undertaken in a field-based rainfall simulation study by Masters et al. (2008). Total sediment loss was 12 kg/ha for controlled traffic farming (dual sugarcane rows 0.8 m apart, in 2 m wide beds) and 21 kg/ha for (then) standard practice (1.5m wide beds, single sugarcane row), representing a 44% reduction (67 mm simulated rainfall at 100 mm/hr event). However, both measures resulted in negligible erosion compared to conventional practices. Another simulated rainfall and runoff study on a Herbert River sugarcane plot determined total suspended solids (TSS) runoff ranging from 0.39 – 12.16 g/l under green cane trash blanketing with varying fertiliser applications, with a mean load range of 0.098 – 0.113 t/ha (Melland et al., 2022). It is worth noting that sugarcane cultivation in the Richmond catchment generally occurs on flat floodplains where soil erosion rates are lower than sloping land that is sometimes cultivated in the wet tropics.

An important distinguishing feature of these macadamia and sugarcane studies is that the macadamia (and some sugarcane) studies only considered one component of catchment sediment sources, i.e. erosion from runoff from horticultural cultivation, and none of the deposition components. In contrast, Visser et al. (2007) developed a sediment budget to quantify net sediment production from a sugarcane plantation, based on the different landscapes affecting the plantation, quantifying all source and deposition components (Figure 50). Total sediment exported from the cane farm when accounting for the complete farm scale sediment budget were in the order of 2-5 t/ha/yr. This type of study provides an exemplar of the sort of studies required to properly quantify sediment yields from different land use scenarios. With further work on the pathways of supply and the (dis)connectivity of them, a fuller understanding of the contributions from these land uses could be made. This could be undertaken using a variety of radionuclide or geochemical, sediment tracing methods. See for example (Walling, 2005; Olley et al., 2013b; Haddadchi et al., 2015).

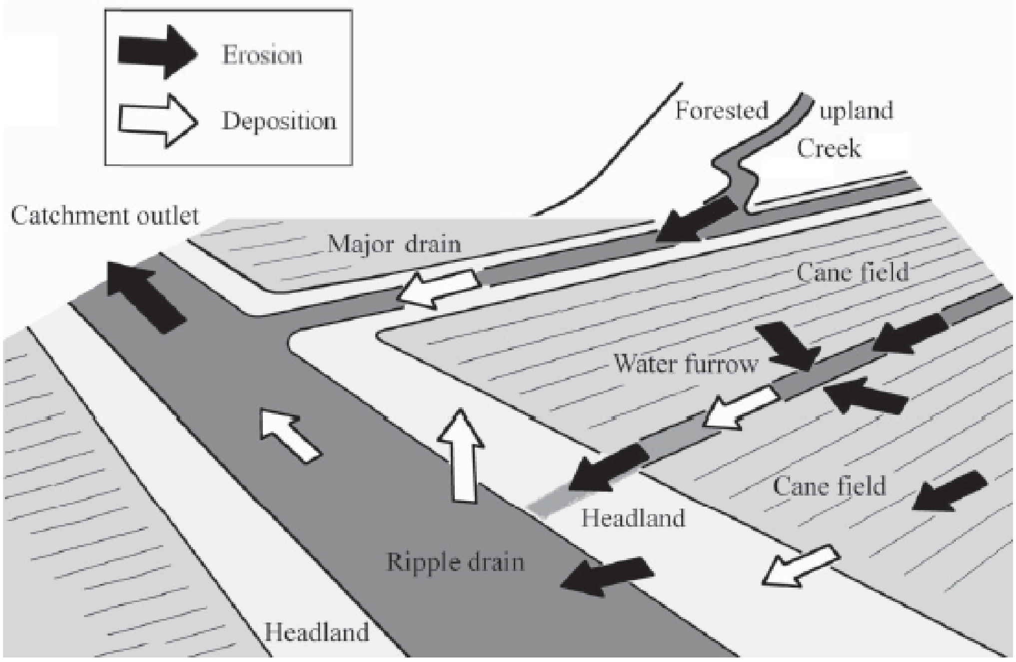

Figure 50. Schematic of Herbert River sugarcane plantation illustrating typical landscape erosional and depositional units quantified to develop a sediment budget. Source: Visser et al. (2007)

Water Quality Monitoring: SSC, TSS and turbidity

Rous County Council has a network of water quality monitoring stations currently operating, primarily within the estuarine reaches, to deliver real time turbidity, pH, salinity, conductivity, dissolved oxygen and temperature data. Historical data was also collected continuously from 2016 to June 2020 collecting a similar suite of water quality parameters. By adopting a similar approach to that used by McKee et al. (2002) these data, could provide a basis for determining catchment sediment loads, providing the turbidity data can be calibrate to SSC data. However, even with SSC calibration, these data cannot be used in isolation for catchment management prioritisation given that they do not tell us where in the catchment the sediment is coming from. Such data, do however, provide an important basis for calibrating the total sediment load at that point in the catchment.

Reports available for Richmond catchment have mostly quantified total suspended sediment loads as total suspended solids (TSS). Whilst some data is available across the catchment, other reports are highly localised. A PhD study by Oeding (2019) (and associated peer reviewed articles) focused on developing a diatom index, measuring water quality, including TSS, Total Phosphorus (TP), Total Nitrogen (TN) and turbidity, at 48 sites in the Richmond River multiple times from 2014 to 2016. Oeding (2019) found that, in general, TSS increases from upper to lower catchment but peaks in the mid catchment (0.5 to 139.3 mg/l). A study into sewerage upgrades for three villages in Kyogle LGA reported TSS at Richmond River sites ranging from 0.07 to 973 mg/l during the period 2001 to 2021 (Public Works Advisory, 2022). A study of the effects of exotic fish on water quality by Akhurst et al. (2012) found higher TSS (from 12 to 72 mg/l), TP, TN and turbidity (18-53 NTU) levels associated with the presence of exotic fish compared to native fish in experimental enclosures in Emigrant Creek Dam. Native planktivorous fish (e.g., Australian bass) likely recycle existing water column nutrients, whereas exotic fish species (e.g. benthivorous carp), potentially increase TP and TN by resuspending sediments and nutrient excretion (Akhurst et al., 2012).

A Richmond River catchment wide study was undertaken by the State Pollution Control Commission (1987) as part of an investigation into water quality across several Northern Rivers catchments. Data was collected from 1983 to 1986 at 40 sites (11 freshwater and 29 estuary). The study reported elevated turbidity mid catchment, and concluded volatile suspended solids (i.e. undissolved organic matter obtained from the loss on ignition of TSS) originated in the central catchment downstream of Casino and Lismore during high flow conditions, peaking at 71 mg/l, likely due to both urban and agricultural runoff. The study also reported mean loads of TSS (previously called non-filtrable residue NFR) in high flow conditions for the Wilsons River at Wyrallah and the Richmond River at Codrington (both just within the estuary zone) of 201,000 and 64,600 kg/day respectively.

Turbidity was measured in several studies, sometimes as a major study component, and on other occasions the turbidity data was ancillary to the main purpose of the study. Much of this data is temporally or spatially restricted, such as in the Emigrant Creek Dam exotic fish study by (Akhurst et al., 2012) or the water quality monitoring review by Australian Wetland Consulting (2024). In most cases, turbidity measures indicated poor water quality. Taken as a group, these studies indicate ongoing water quality issues in the Richmond River. ANZECC/ARMCANZ guidelines are site specific, but typically 6-50 NTU for lowland rivers, and 1-20 NTU for lakes and reservoirs (ANZECC ARMCANZ, 2000). Turbidity measures were taken at seven sites in 1997-1999 and 2003, as part of a macroinvertebrate community composition study (McCulloch, 2009) in two creeks in the Terania Creek subcatchment. There were significant seasonal variations in turbidity, and levels were higher, often above trigger values in Goolmangar Creek (range 0-374 NTU), compared to the less agriculturally oriented Terania Creek (range 0-65 NTU). Water quality was regularly monitored during the Pacific Highway upgrade 2019-2023 (. Turbidity measures were taken up and downstream of construction sites at regular intervals. Whilst most monitoring sites were within the estuary management zone, several were in freshwater locations. Upstream turbidity was generally within ANZECC/ARMCANZ guidelines. There were numerous studies investigating river reach condition, for which turbidity measurements are available. A river reach assessment in 2022 of the Eltham to Boatharbour section of the Wilsons River by Hydrobiology (2023) determined turbidity levels did not vary by sub-reach or season, and were found to be within water quality guidelines (DECCW, 2006), similar to data recorded at Boat Harbour Nature Reserve in 2013 (Ryder et al., 2014). Hydrobiology (2023) also undertook a qualitative geomorphological assessment (e.g. bank erosion severity rankings) and determined the study area as a sediment transfer zone, supplied by sediment delivered from upstream/gullies/tributaries, and bank/bed erosion processes occurring within the study reaches.

Other qualitative reports have been prepared, however most provide minimal insights into sediment dynamics, water quality or riparian vegetation condition assessment, examples include a broadbrush water quality, vegetative and erosion riparian survey commissioned by Rous (2014), and biodiversity plan by

Woodroffe et al. (2010), and earlier State of the Environment Reports prepared for regional councils. The Regional State of the Environment Report 2016 (North Coast Region State of the Environment Report Working Group, 2016) is a qualitative report, and reports a decline in water quality and river health from a variety of measures including turbidity, TN, TP, dissolved oxygen and Chlorophyll-a, riparian vegetation, riverbank health, and ecosystem health assessments, but the data quality is low to medium (as with the corresponding 2012 report). Key issues for the Richmond catchment are consistently high phosphorus and nitrogen nutrients, poor riparian vegetation condition, and poor riverbank stability linked to livestock access to the river. A river reach assessment of ~10km of eastern Emigrant Creek by Australian Wetlands Consulting (2022) provided qualitative geomorphological and vegetation assessments. Instream sediment was inferred to be largely sourced from macadamia orchards, and stock access to riparian zones in both the main channel and tributaries. Vegetation was significantly degraded due to limited riparian extent, vegetation canopy cover, invasive weeds, and lack of native species diversity. A compilation of water quality data by Hydrosphere consulting (Hydrosphere, 2016), suggested that the Pacific Highway construction through the Emigrant Creek catchment between 2012 – 2015 was responsible for increased turbidity over that period.

Riparian vegetation condition and assessment

Riparian vegetation assessment and condition reporting in the Richmond catchment has been generally qualitative in nature. A qualitative study by Lymburner et al. (2006) found successful removal of camphor laurel and recruitment of native pioneer species in riparian zones, using soil disturbance to trigger seed bank recruitment. A qualitative riparian geomorphic and vegetation assessment of the mid Wilsons River (~16 km) (NRCMA, 2011) was undertaken using a Northern Rivers Catchment Management Authority (NRCMA) developed, rapid assessment method, focussed on grazing stock impacts on bank erosion, riparian width, vegetation extent, density, and diversity to identify and prioritise rehabilitation at the reach scale. Less than 3% of the riparian zone was found to be in relatively good condition, with weed control, bank stabilisation, stock access and revegetation being the main rehabilitation activities proposed. A program of riparian restoration prioritisation and education was conducted by Landmark Ecological Services (2013). GIS mapping identified areas of stream bank currently eroding or at risk of erosion, to be prioritised for revegetation. However, prioritisation categories did not take into consideration the ecological health of the riparian zones, high priority areas required ground truthing, and the report recommended further refinement of the GIS layers to establish a catchment scale dataset. A GIS-based qualitative rapid assessment of riparian vegetation condition methodology developed by O'Hobbs (2017), was used to assess riparian vegetation condition and inform prioritisation for the Richmond catchment. Results showed the majority of the catchment’s riparian zones required rehabilitation, with highest priority areas found in the middle parts of the catchment, where grazing and agriculture dominates the land use. The 1996 Office of Environment and Heritage multi-attribute dataset (DCCEEW, 2000), measuring slope, vegetation, erosion and land use was used in the O’Hobbs study. Limitations of this study included lack of access to sites for ground truthing, and that riparian zone width measurements were taken from midstream using a standardised buffer, resulting in the riparian zone being under-represented or excluded from wide channels and potentially over-represented in small channels. Standard buffers can introduce errors into the analysis by, for example, picking up adjacent irrigated pastures, which can provide misleading persistent green signatures in the satellite imagery that are not related to riparian vegetation condition.

Sediment yield from road runoff

Decreases in forest canopy through land clearing and forestry activities, is a critical component of land degradation, facilitating sediment delivery to surrounding streams. Unsealed roads are acknowledged as the major source of sediment pollution in forested catchments. Sediment delivery can be sourced directly from forestry activities or via runoff from the often high density road networks associated with these activities The composition of roads varies as well, ranging from unsurfaced roads on erodible subsoils to high quality all weather gravel surface roads (Sheridan and Noske, 2007). There are number of factors which can affect sediment delivery to streams:

Road composition. A survey (over 1 yr) was undertaken of sediment delivery for ten 100-200 m sections of forest management activity roads in Victoria. Total annual sediment load (normalized for slope) varied about 25-fold, from 216 mg/m2/ml of rain for a high-quality gravel surfaced road with minimal traffic to 5373 mg/m2/ml of rain for an unsurfaced road on an erodible subsoil with moderate light-vehicle traffic (Sheridan and Noske, 2007). Runoff, sediment loss and water quality from gravelled and ungravelled forest roads in a SE Qld Pine plantation was monitored for 2 years. Total sediment loss over the 2-year period was greatest from the gravelled road plot at 5.7 t/km compared to the ungravelled road plot with 3.9 t/km. Suspended solids contributed 86% of total sediment loss from gravelled road, and 72% from ungravelled road over the 2 years (Forsyth et al., 2006). Sediment tracing and modelling was undertaken in the East Tarago catchment, Victoria, an agricultural, grazing and forested catchment (no forestry operations). The relative contributions of suspended sediment from gravel vs ungravelled roads, and different land uses, found that the highest contributions were from gravelled surfaced roads (Motha et al., 2004). Rainfall simulations demonstrated that compacted, disturbed surfaces such as gravel roads are the dominant sources of sediment in forested areas (Croke et al., 1999b). A rainfall simulation (CREAMS model) and overland flow study by Costantini et al. (1999) demonstrated very low concentration of fine particles from gravel road surfaces, and higher proportion from ungravelled (i.e. dirt) road surfaces. However, there was an increase in fine sediment particles eroded under rain simulations, with concentrations up to 8 g/L of <0.02 mm diameter particles.

Rainfall volume and intensity. Webb and Hanson (2013), working in State forests in coastal catchments, mid-north coast NSW, undertook surveys to determine connectivity between gravel roads and streams via channelised and diffuse pathways under a range of rainfall intensities. The study showed that preventing or reducing road-to-stream drainage connectivity was essential for reducing the impacts of roads on water quality. No sediment yield data (Webb and Hanson, 2013). During lower intensity storms with average recurrence intervals of 10 years or less, less than 20% of drains were connected to streams via overland flow paths. However, the degree of diffuse connectivity increased with increasing rainfall intensity. Croke et al. (1999a) field observations of simulated rainfall suggested that flow paths continued for distances up to 15±20 m down hillslopes during extreme simulated rain intensities. These distances were recorded when the hillslope was not receiving natural rainfall and were likely to underestimate the maximum potential path length under extreme rainfall conditions.

Road to stream connectivity and thresholds for gully formation. Road to stream connectivity via gullied pathways can contribute significant fine sediment inputs to streams. The Webb and Hanson (2013) study showed that preventing or reducing road-to-stream connectivity was essential for reducing water quality impacts. Field surveys in a SE NSW forest road network were undertaken by Croke and Mockler (2001) to examine two types of connectivity, namely direct connectivity via gullied pathways, and diffuse connectivity via dispersive pathways. The study found that a reduction of road-to-stream connectivity can be achieved by planning a road network in areas where runoff can be dispersed on relatively gentle hillslopes. In Croke et al. (2005), modelling demonstrated the greatest contributor of runoff occurs at a stream crossing where a road segment discharges directly into the stream. Three road categories were modelled: major access (MA), feeder access (FA), and dump access (DA). Mean sediment concentration, the majority silt and clay, in runoff plumes downslope from MA and FA roads were significantly different, 7.18±0.66 g/L and 1.85±0.80 g/L, respectively (Croke et al., 2005). A Monte Carlo simulation was undertaken by the Victorian Corangamite Catchment Mgt Authority to assess long-term annual sediment production from unsealed forest roads at stream crossing scale. Mean total sediment load ranged from 2-34 MT/yr. For each site, runoff coefficient was almost always the single most important variable followed by the bank angle (Jha et al., 2006). As shown in Croke and Hairsine (2006), the range of potential road-stream connectivity pathways comprises fully connected segments drained by a gully that has become part of the stream network; partially connected segments drained by a gully that stops prior to joining the stream network, direct connectivity occurs at a bridge or ford where there is no hillslope between the road and the stream network. Where no gully or channel exists below a road drainage feature then the overland flow may be partly or fully dispersed, thus limiting or eliminating the connectivity (Figure 52).

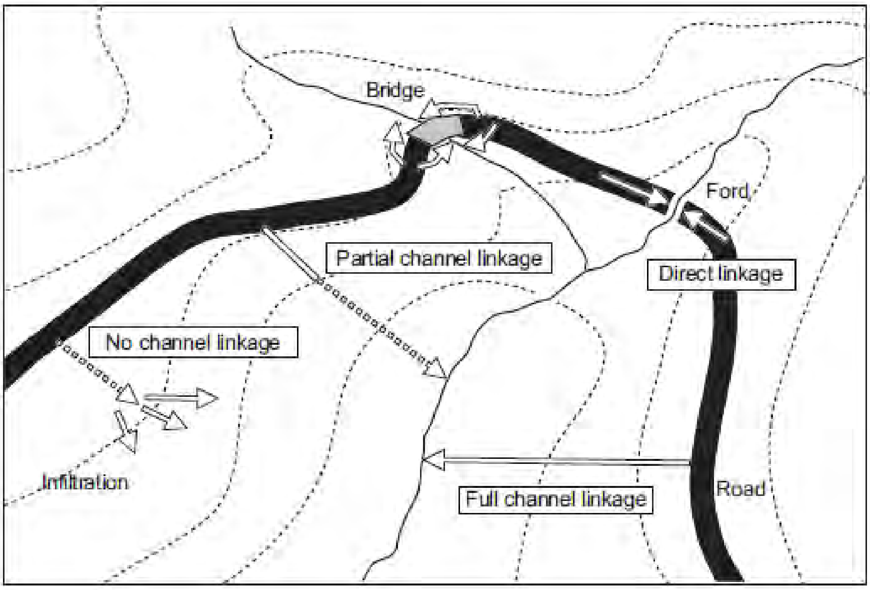

Figure 51. The range of potential road-stream connectivity categories. Source Croke and Hairsine (2006).

Sediment particle size. Croke et al. (2005) found the majority (>50%) of sediment in runoff from road outlets consisted of silt and clay sized material, but sediment concentrations in runoff plumes from MA roads had about 3.5 times higher concentrations of <63 µm material than those from FA roads. A simulation by Croke et al. (1999b) found that the delivery rate of the fine fraction per metre length of hillslope also increased with increasing surface flow velocities (Figure 53).

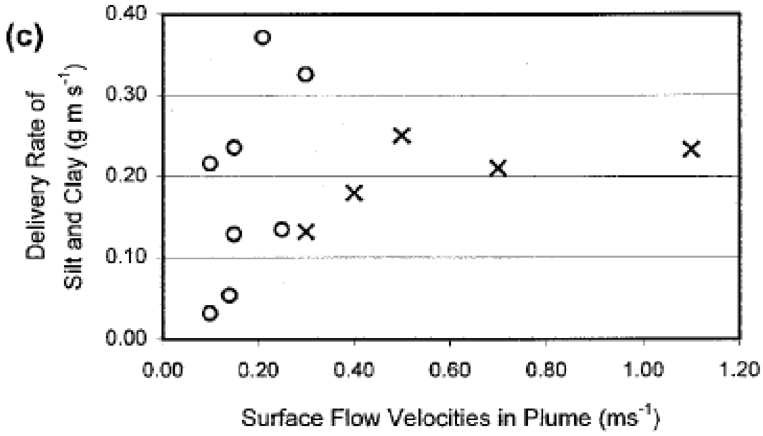

Figure 52. The relationship between delivery of silt and clay material with surface flow velocities for all sites. Open circles are coarse-grained granites (>63 µm) and crosses are fine-grained metasediment (<63 µm). Source (Croke et al., 1999b).

Volume and frequency of heavy vehicles on gravel roads. A survey in Victoria demonstrated that suspended sediment concentration under low truck-traffic conditions (<9 return truck passes prior to a storm) was 269 mg/l, increasing 2-7-fold to a median of 725 mg/l under high truck-traffic conditions (>= 9 return truck passes prior to a storm). These concentrations, and increases due to traffic, were substantially less than most previously reported values (Sheridan et al., 2006). Figure 54 shows the relationship for three road segments between traffic and suspended sediment concentration of runoff (Sheridan et al., 2006).

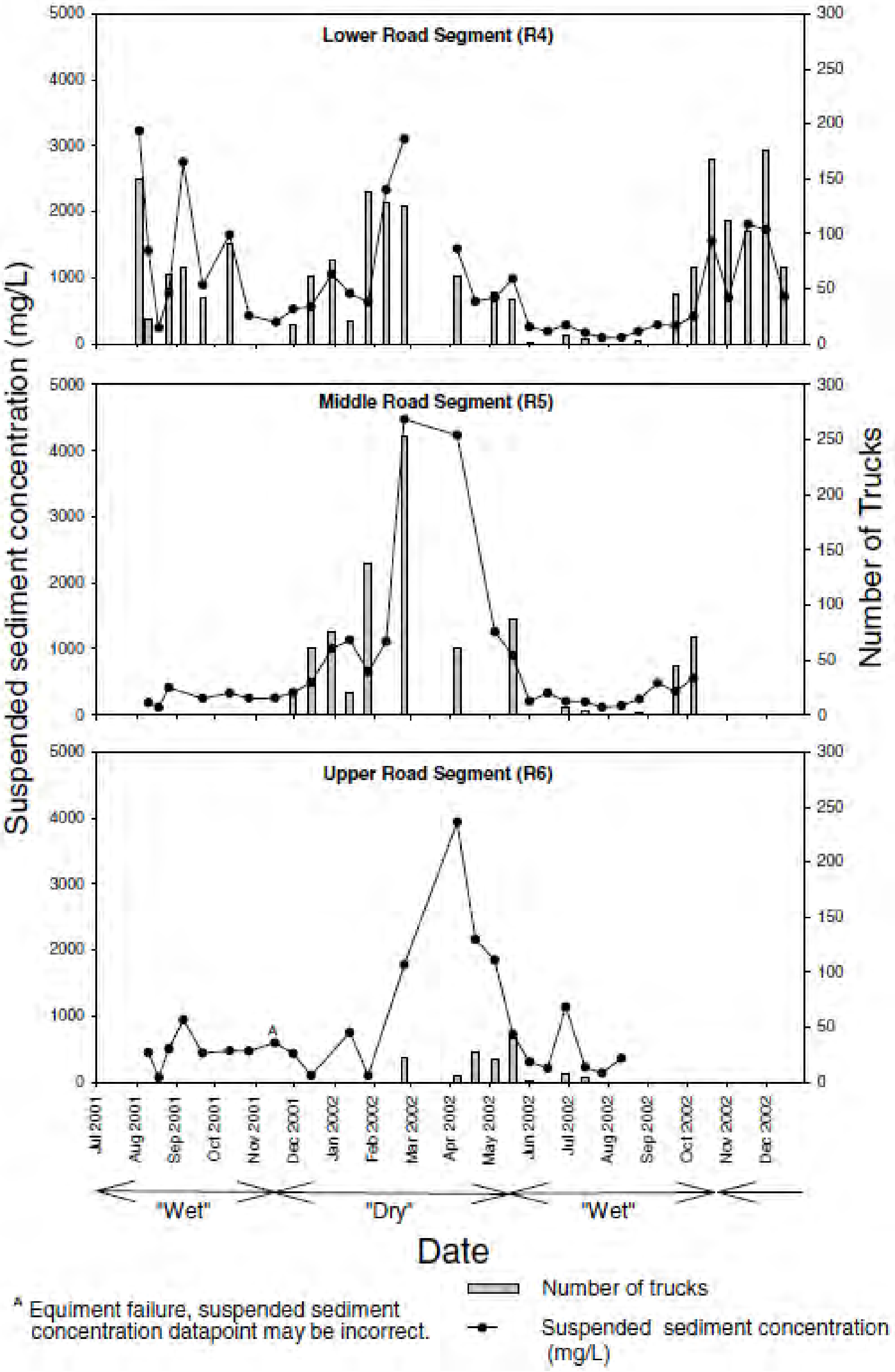

Figure 53. Relationship for the three instrumented road segments between traffic and the suspended sediment concentration of runoff. Source: Sheridan et al. (2006).

Sheridan and Noske (2007) show the relationship between traffic level and annualised sediment delivery rates for gravel surfaced roads (Figure 55).

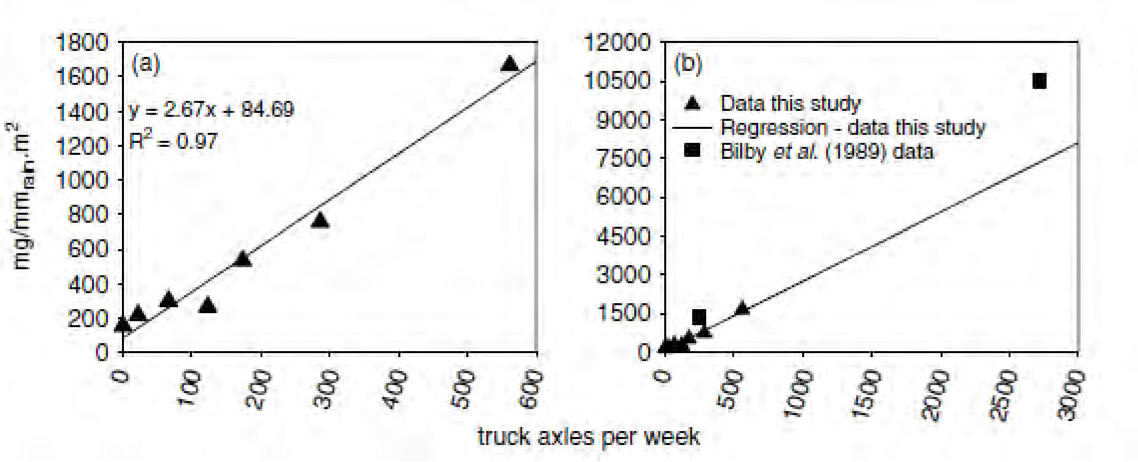

Figure 54. Relationship between traffic level and annualised sediment delivery rates for gravel surfaced forest roads a) from Sheridan and Noske (2007) study and b) comparison with Bilby et al. (1989) data over a greater range of traffic values.

Timing of timber harvesting (and associated vehicle movements) compared to rainfall volume and intensity. A study of sediment dynamics was undertaken in ephemeral headwater channels and in 10 -metre buffer strips in timber production forests in Broonam State Forest, Batemans Bay, NSW. Harvesting increased runoff and sediment levels but not mean sediment concentration, and sediment levels dissipated over 18 months where there was no harvesting in stream buffer zones (Walsh, 2017).

The use or lack of use of timber harvesting best management practices. The NSW Forestry Corporation monitors water quality in native forests and plantations, across various intensities of harvesting and road activities, and across soil types, to investigate the potential impacts of forest activities on stream sediment and downstream water quality. A replicated catchment experiment in native eucalypt forest in Kangaroo River State Forest, near Coffs Harbour, showed that selective harvesting using best management practices did not affect suspended sediment yields in two of three treated catchments. Overall suspended sediment yields remained low with monthly yields ranging from 0 kg/ha during cease-to-flow conditions in all catchments to a high of 116.1 kg/ha during Feb 2009 in one catchment. In the third catchment, an increase in event sediment loads and concentration, at the time of selective harvesting, was limited to a few post-harvest flow events, and had subsided within 12 months of the cessation of harvesting (Webb et al., 2012) (Figure 56).

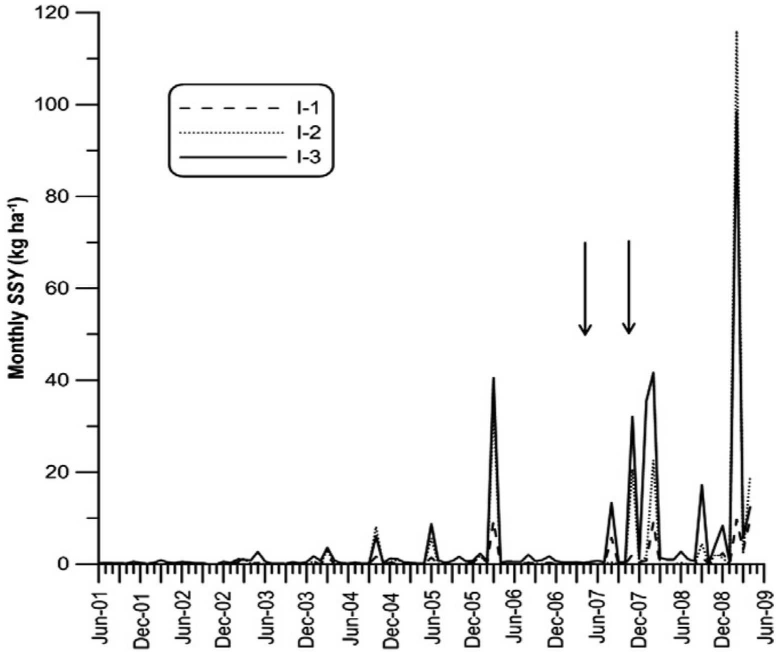

Figure 55. Time series of monthly suspended sediment yields in the harvested catchments. The arrows denote the onset and cessation of harvesting. Source: Webb et al. (2012).

Post-fire debris flows. Analysis of the 2009 Victorian bushfires demonstrates that post-fire debris flows are major sources of fine suspended sediment, and a risk to water quality in forest catchments, as sediment flow rates can be 2–3 orders of magnitude higher than annual background erosion rates (Nyman et al., 2011; Cawson et al., 2013; Sheridan et al., 2015). The effects of prescribed burning on surface runoff, erosion and water quality, however, were shown to be minimal and to last only for a short period (3 months to 1 year) (Cawson et al., 2013), due to the general low fire intensity and burn patchiness. The most significant runoff, erosion and water quality impacts of prescribed burns occurred when these were followed by an intense storm.

International studies, focused on the forestry industry, particularly in the Pacific Northwest USA and Canada, have studied sediment dynamics in forested catchments. Arismendi et al. (2017) found road to stream suspended sediment transport in forestry operations in Oregon, USA, ranged from road pre-construction of 634-2,317 mg/L, to road post-construction of 2,631-12,834 mg/L, and post-construction with harvesting/hauling of 159-18,874 mg/L. Rainfall simulation experiments on unsealed roads in British Columbia, Canada, resulted in a spatially variable peak sediment concentration range 0.6-15.0 g/L, with a steady state concentration range of 0.1-4.1 g/L (van Meerveld et al., 2014). Rainfall intensity was the dominant control on sediment quantity generated from the road surface; the total sediment mass increasing linearly with rainfall intensity. The number of passages of loaded logging trucks during an experiment was the second most dominant control on the total amount of sediment generated from the road surface. A study of monitored plots in Oregon, Pacific Northwest USA demonstrated sediment production was 9 times higher from gravelled silty clay loam road vs gravelly loam roads (Luce and Black, 1999). Additionally, road segments where vegetation was cleared from the cutslope and ditch produced about 7 times as much sediment as road segments where vegetation was retained, demonstrating the positive impact of vegetation cover. Reid and Dunne (1984) found heavily used road segments contributed 130 times as much sediment as abandoned roads in forested catchments, Washington State, Pacific Northwest USA. Average sediment yields ranged from 0.51 - 500 t/km/yr, for abandoned to heavy-use roads, respectively.

Summary of findings from Literature Review

A literature search revealed 36 Richmond River peer reviewed, government and grey literature reports focused on the sediment budget characteristics and health of the river system, excluding estuary reports. Of these, 28 reports contained quantitative data, 3 with qualitative data, and 5 contained both quantitative and qualitative data. In contrast, the literature search revealed a total of 54 reports focussed on the Richmond River Estuary zone, which are not the subject of this report. However, we have included Hossain and Eyres (2002) and Hossain et al. (2001), as they are effectively whole of catchment studies which include the estuary.

The literature review reveals that there are significant gaps in data available for the different erosion and deposition processes occurring across the Richmond catchment. Whilst the data contained in these reports provides some insights into catchment sediment dynamics, much of the data is not suitable for developing a catchment sediment budget. Data was available for only some sediment sources, and very little data was available for sediment deposition or the dynamics of the sediment budget under different flow magnitude and frequency conditions. The exception for deposition being the estimates derived by Hossain and Eyre (2002) for the estuary based on a mass-balance analysis. Overall, available data is variable, both spatially and temporally, with the relevant findings summarised in Table 11 and Figure 56.

Table 11. Catchment sediment sources and catchment and estuary sediment deposition findings, study years and references.

	Findings	Study years	References
Catchment sediment sources			
Landslide erosion	n/a	*	*
Bank erosion	123,975 t/yr (dry year) 502,709 t/yr (wet year)	1994-1996	(Hossain, 1997)
Horticultural erosion - macadamia	~3.8 t/ha/yr	2007-2009	(Keen et al., 2010)
	3.3-47,055 mg/m^2 (non-IOM) 0.5-474 mg/m^2 (IOM) ~7 t/ha/yr (IOM)	2023-2024	(Southern Cross University, 2024)
Agricultural erosion - sugarcane	<15 t/ha/yr (no tillage)	1980-1986	(Prove et al., 1995)
	16 t/ha	modelling	(Lu et al., 2003)
	2-5 t/ha/yr	1999-2001	(Visser et al., 2007)
	12 kg/ha/0.67hr	2006-2007	(Masters et al., 2008)
	0.098 – 0.113 t/ha	2011, 2014, 2015	(Melland et al., 2022)
Non-Horticultural Hillslope erosion	n/a	*	*
Gully erosion	n/a	*	*
Urban erosion	n/a	*	*
Channel incision	n/a	*	*
Road erosion	5.7 t/km vs 3.9 t/km (gravelled vs ungravelled road plots). Susp. solids contributed 86% of total sed loss from gravelled road, and 72% from ungravelled road over the 2 yrs	SEQ (2003 – 2005)	Forsyth et al. (2006)
Total catchment	<1000 t/yr (1998 dry) to > 600,000 t/yr (1989 wet) ~106,000 t/yr (mean)	1989-1998	(McKee et al., 2002)
Catchment and estuary sediment deposition			
Estuary	12,800-17,400 t (1994-95 dry) 5,800-8,000 t (1995-96 wet)	1994-1996	(Hossain and Eyre, 2002)
Whole of Catchment Yield			
	28,788 t (1994-95 dry) 221,202 t (1995-96 wet)	1994-1996	(Hossain et al., 2001)
n/a = none available			

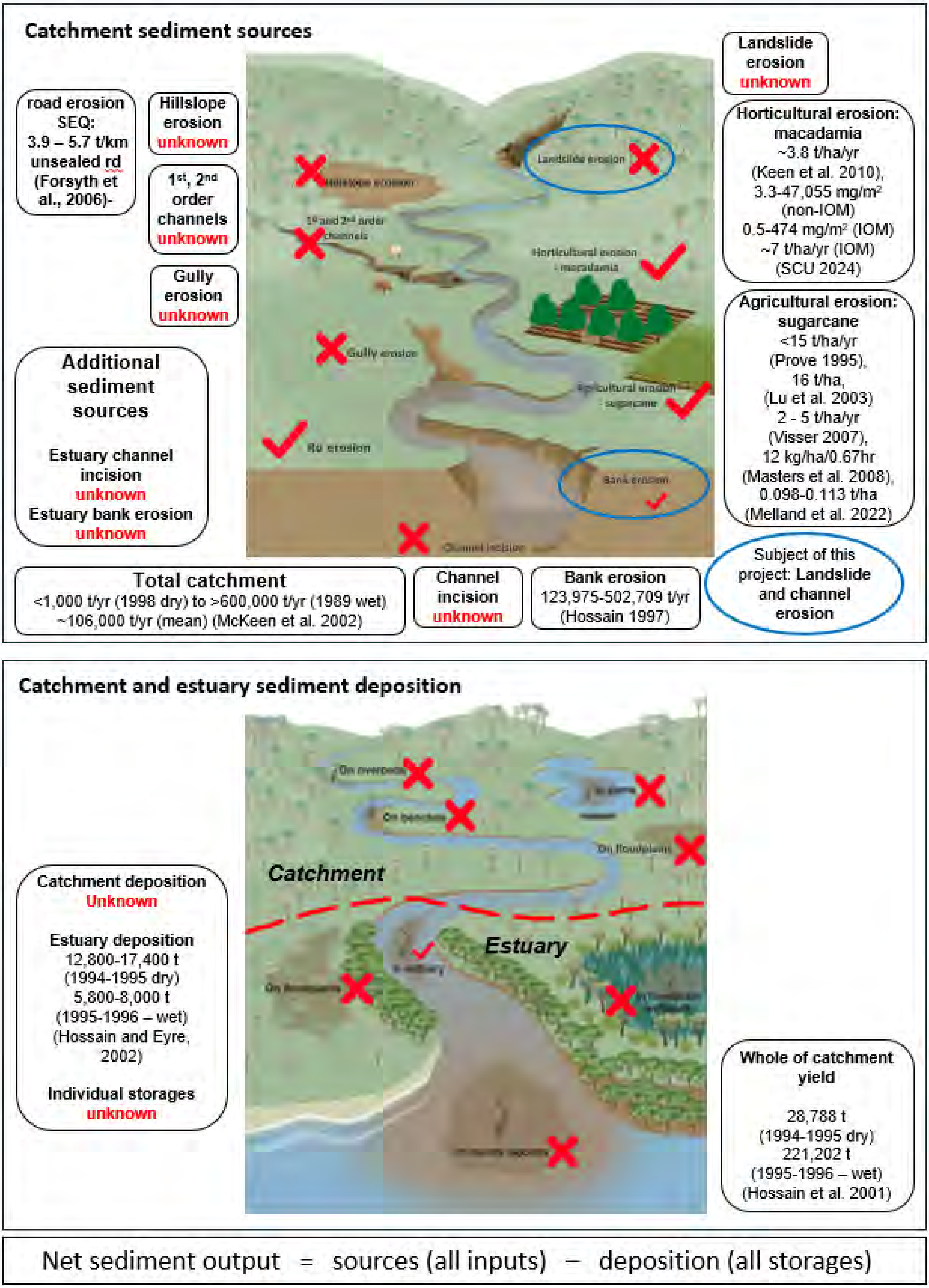

Figure 56. Conceptual diagram showing catchment sediment sources and deposition. Note landslide and bank erosion are the subject of this project (blue ellipses). Adapted from (Prosser et al., 2001)

Based on all this information it is apparent that there are significant gaps in the data required to develop a catchment sediment budget. For sediment sources, data from landslide, hillslope, and gully erosion, channel incision and erosion from 1st and 2nd order channels is not available. Data is available on horticultural erosion from macadamia (Keen et al., 2010; Southern Cross University, 2024) and sugarcane cultivation, albeit for studies from the Queensland wet tropics (Prove et al., 1995; Lu et al., 2003; Visser et al., 2007; Masters et al., 2008; Melland et al., 2022). There is some insight into total catchment load based on the work done by Hossain (1997) and Hossain and Eyre (2002) and this is the closest approximation of what is trying to be achieved in terms of a catchment sediment budget. However, this sediment budget model it is now over 20 years old, very coarse resolution, has many missing sources and as such is of very little use for identification and comparison of sediment sources at a practical management scale. The bank erosion data from Hossain (1997) is limited in both its spatial and temporal scope, and would not be considered to be a robust dataset today. Hossain (1997) measured linear bank-top retreat rates at a small number of sites, but does not consider the different types of bank erosion processes which have significantly different sediment yields. In contrast, in large scale LiDAR analysis of Qld’s 2011 Lockyer Valley, Grove et al. (2013) identified and quantified different types of erosion processes which occurred such as wet flow failures and rotational failures. Wet flow failures exhibit a well-defined scarp (steep) wall and absence of failed blocks at the toe (base) of the failure, whereas rotational failures have curved failure scars, slippage of intact bank failure blocks, and a curved bank line behind the failure mass (Grove et al., 2013). For the same flood event, Thompson et al. (2016) identified a complicated pattern of varying bank erosion and deposition estimates depending on reach scale expansion or contraction characteristics. It is this type of data that is required for sediment budget analysis, and hence for management prioritisation. Long term turbidity data monitoring data from Eltham gauging station used in the Ecos Environmental Consulting (2009) study may be useful for calibrating an end-of-sub-catchment sediment budget, but on its own this type of data cannot provide a basis for a prioritisation strategy that is required for high resolution planning.

On the depositional side of the budget, there is no direct data available on the locations of depositional zones or on depositional rates. McKee et al. (2002) found that 90% of suspended sediment load was transported through the estuary only 2.3% of the time. Annual Suspended sediment loads were shown to vary by a factor of 910 times over a 14-year period from 1985-1999 (range <1000 to >600,000 t/yr, averaging 105,620 t/yr) with an average delivery of 87%. This implies an average that only 13% of the suspended sediment load delivered to the estuarine reaches is captured within the system, however there is no analysis to suggest where this deposition occurs within the estuary channel or estuary floodplains. Finally, very little work has been undertaken to analyse the (dis)connectivity patterns and the internal operation of the sediment budget and how this occurs for different sediment fractions and under difference flow and flood magnitude-frequency conditions. Such work is needed to provide the bespoke detail needed to prioritise which sediment sources to target, where to target them and under what conditions will mitigation be effective.

This project is investigating catchment sediment processes, and not estuary sediment processes. Estuary sediment sources (i.e. estuary bank erosion and estuary channel incision) are being considered as part of the Fruition Environmental study that is being undertaken in parallel with this catchment study.

Discussion & Implications for Further Work

From the review outlined above it is apparent that a key missing element in the datasets available for the Richmond catchment is an understanding of the spatial and temporal variability of channel erosion sources and riparian vegetation condition within the non-tidal reaches of the stream network, at a resolution suitable for underpinning rehabilitation prioritisation. To date there has been no quantitative analysis of the relative proportion of sediment contribution from each of the main sediment sources, particularly the contributions between surface hillslope erosion, channel erosion and landslides (Olley et al., 2013a; Olley et al., 2013b). Having a good empirical understanding of the relative importance of different erosion processes in different parts of the catchment is critical for decision support analyses that weigh up the relative cost/benefit ratio of rehabilitation investments. Economic assessments can be highly misleading if the appropriate physical process data is not at the heart of the analysis.

Hence a major component of the next phase of this project will focus on the development of new high-resolution datasets that can provide the basis for a robust reach scale prioritisation, focusing particularly on some of the main missing components of the sediment budget (Figure 56.). In particular we will focus on the quantification of the current riparian vegetation extent within the geomorphically determined riparian zone, as well as the distribution of channel and landslide erosion throughout the catchment. Accurate mapping of the channel and riparian zone forms the foundation for the subsequent analyses. Geomorphic change detection (DEM of Difference analysis) will then be undertaken throughout the channel network, with particular attention focused on the relative contribution of erosion from the different parts of the channel network (River Styles), but importantly from different in-channel geomorphic units. The reason for this being that not all channel erosion is equal, and not all erosion is bad (e.g. erosion and scour is needed to maintain pool habitats and the heterogeneity of habitats that support a wide range of aquatic floor and fauna). Whether the erosion is of the bed, bars, benches, inset floodplains or the primary floodplain material, determines its geomorphic and ecological consequences. Knowing which types of erosion to treat and which to allow is critical.

Each different geomorphic unit will contribute a different quantum of fine (contributing to SSC) and coarse (bedload) sediment. Hence it is important to be able to stratify the various sediment sources according to the geomorphic unit, which will each have distinctly different sediment particle size distribution. At this point it is beyond the scope of the project to apportion different sediment size fractions to different source geomorphic units (given that this would require a significant field sampling campaign), but the delineation of these different channel source zones in the characterisation of the channel morphology at the outset, provides the opportunity for retro-fitting the sediment budget with these data at a later date.
Once the channel/riparian template is accurately established, the focus will then shift to the quantification of the extant vegetation and the trajectory of change in that vegetation through time (last 3 decades). This will be achieved through the quantification of the current extent of woody vegetation from the 2023 lidar dataset that is now available for the entire catchment. The vegetation change trajectory will be quantified form the Landsat persistent green metric used to calculate the Delta Green and decadal percentage change metric, as outlined in Pietsch et al. (2019), Pietsch et al. (2021) and Daley et al. (2024).

In parallel to the channel geomorphic mapping and the riparian vegetation mapping, landslide mapping will be undertaken to quantify the volume of sediment mobilized into the upper reaches of the stream network in the 2022 floods. This will primarily be focused in the Wilsons River sub-catchment which was the focus for the most intense rainfall on the steeper parts of the catchment, where most landsliding occurred. Landslides will be characterized according to their connectivity to the channel network, the volume of sediment delivered and their propensity to continue delivering both fine and coarse sediment into these channels into the future. This component of the project will provide an important new input dataset that has not been accounted for in any previous river health assessment.

These data will then collectively form the basis for the prioritisation strategy which will ultimately contribute to the updating of the Estuary Health Risk assessment in a manner that reflects some of the profound changes wrought in this catchment with the 2022 floods. As an example, the existing River Styles reaches that were used in the previous catchment risk assessments, delineated the bedrock controlled reaches in the upper catchment as being stable with minimum active sediment sources (Alluvium, 2012; DCCEEW, 2023). However, some headwater catchments in the upper Wilsons River experienced dozens of large landslides that likely injected tens of thousands of tonnes of sediment into the stream network, impacting these streams and the channels downstream in ways that and not yet understood (Figure 57). Hence, river reaches that for many years have been considered to be stable bedrock channels with very low erosion rates, overnight potentially became the highest yielding reaches within the catchment. Many of these landslides remained active sources of some fine sediment for years after the 2022 event. Hence it is critical to understand the short, medium and longer term impacts of such sediment sources in the post 2022 flood river landscape. The prevalence of landslides in the 2022 flood was the impetus for quantifying the contribution that landslides have made to the Richmond catchment sediment budget.

Figure 57. Example of section of Tuntable Creek in the Wilsons River catchment, within which numerous landslides mobilised tens of thousands of tonnes of sediment often directly into the channel network during the 2022 flood. Source: DECCW

Appendix 2: Lidar and satellite data compilation and QA

Complete lidar data coverage is available for the Richmond catchment at different time intervals prior to 2018 (Figure 58) and at different resolutions (Figure 59). The western 2932 km^2 portion of the catchment has slightly lower 2m pixel resolution data than the eastern 4632 km^2 of the catchment which was captured at 1m resolution. The 2023 dataset is notionally all collected at 1m resolution, but initial analysis of the ground point density in the heavily forested portions of the catchment would suggest that this is overly optimistic. The QA/QC analysis of the lidar data revealed that within heavily forested areas, including riparian zones the lidar ground point density can drop to zero. A ground point density of zero means there is no elevation data for that location. A ground point density of zero does not occur in all cases heavily forested areas, but in many. Lidar penetration of dense vegetation is a factor that is managed during the lidar acquisition flight and is based on specified data collection purpose and cost-benefit considerations. Greater frequency of data acquisition, particularly in areas of dense vegetation, at different elevations and slower speeds can generate more lidar ground point data. In general, and observed with the available Richmond catchment lidar datasets, more recent lidar acquisitions have better delineation of the ground surface. This is due to ongoing development of the lidar technology, particularly the laser pulse rate, and adaptation and improvement of acquisition techniques. Figure 60 and Figure 61 show the pre-2108 lidar acquisition campaigns and dates.

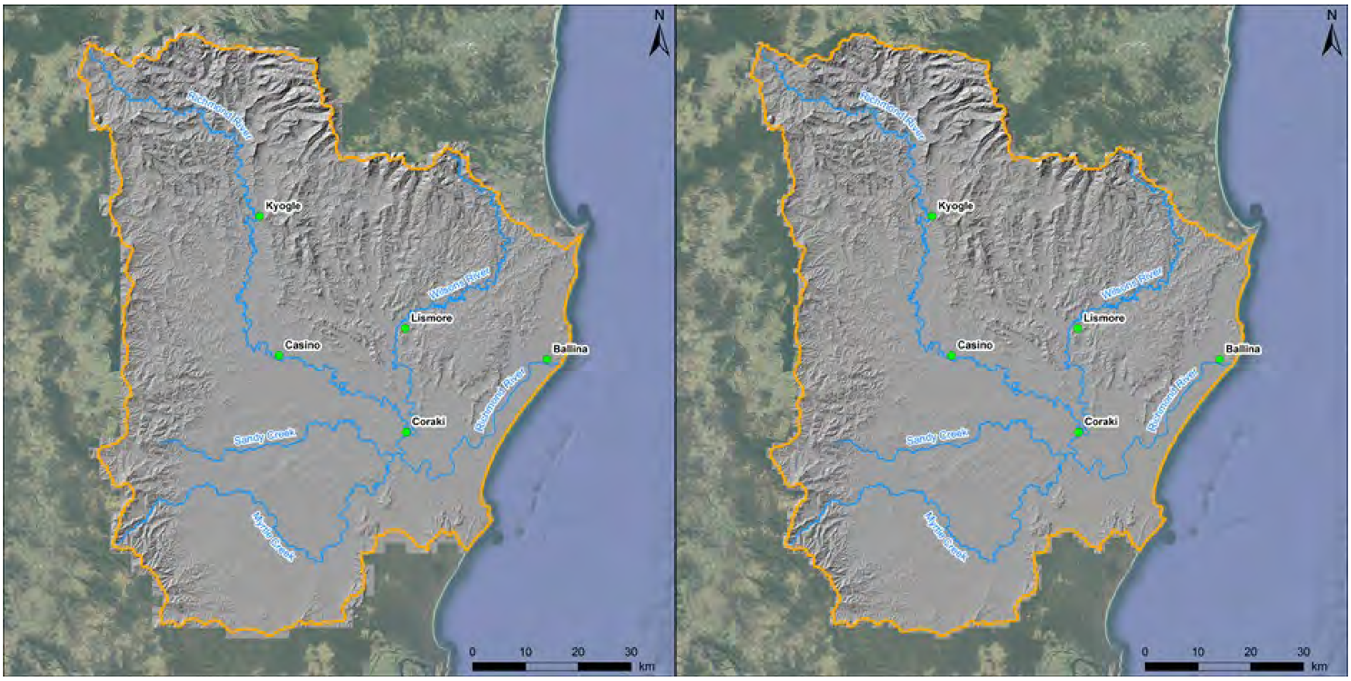

Figure 58. Lidar hillshade for the Richmond catchment pre 2018 (LHS), and 2023 data RHS. NB: at this resolution there is no discernible differences between the two datasets, but this is only revealed in site scale data analysis.

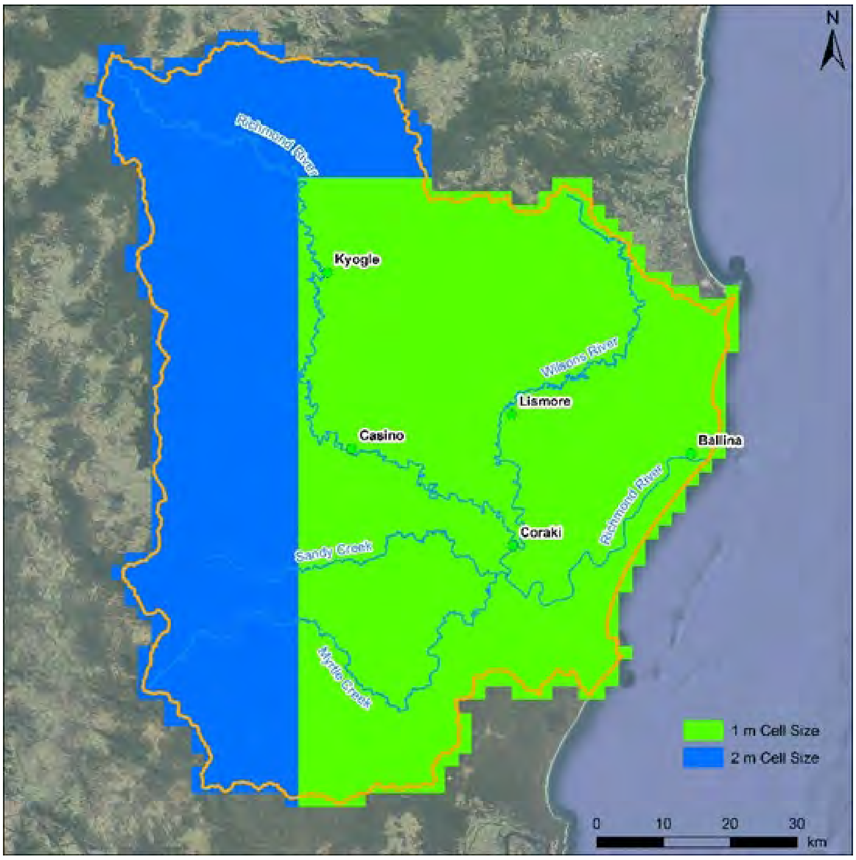

Figure 59. Lidar derived DEM resolution for the pre-2018 data.

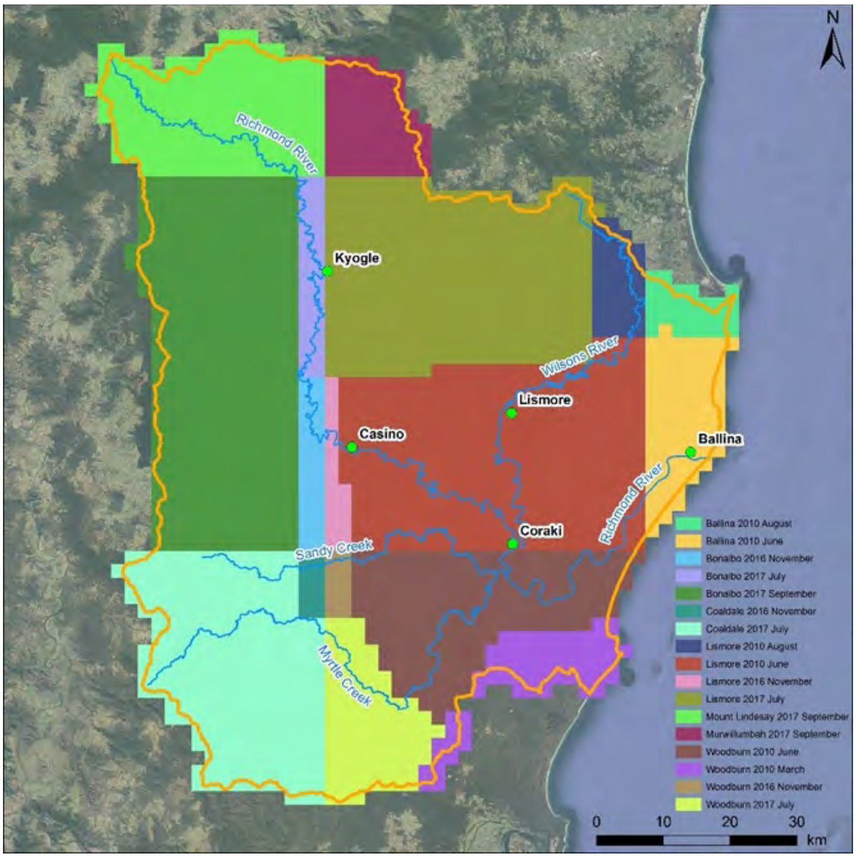

Figure 60. Pre-2018 lidar acquisition campaigns

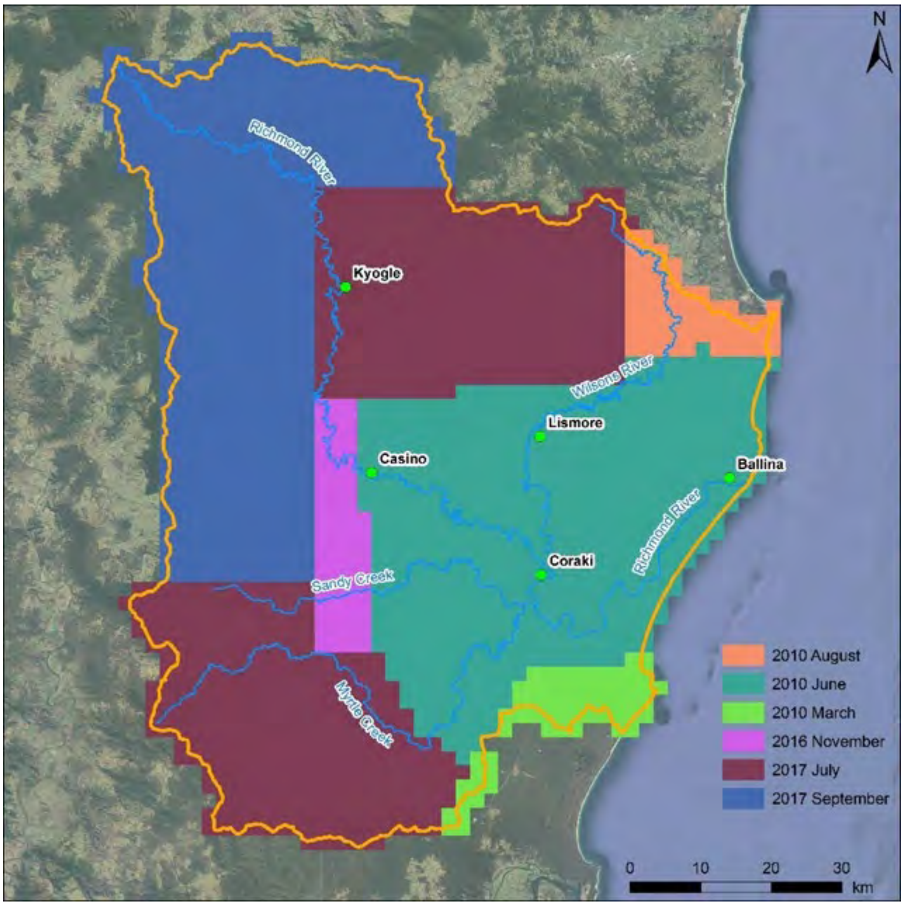

*Figure 61. **Pre-2018 lidar acquisition dates***

Satellite and other airborne data compilation & QA

Two different satellite datasets have been acquired and used in this study. These have all been compiled and QA undertaken. An overview of each of these datasets and how they are being used is provided below.

PlanetScope SuperDove

A license for PlanetScope SuperDove imagery was purchased for the project, which provides us access to the whole spatial data library since the sensor began acquiring data in 2017. With a spatial resolution of 3 meters these data were used for the water mask mapping, and the mapping of the distribution of camphor laurel throughout the catchment. An example of the imagery acquired is shown in Figure 62. These data are also being used in the landslide mapping. The planet scope data has the great benefit that we can access the imagery in near real time, provided cloud free conditions prevail. We also have the potential to use the data as a tool to validate the Landsat time series data for selected time slices.

Figure 62. Example of the Planetscope Superdove imagery acquired on consecutive days during the Cyclone Alfred floods.

Landsat Persistent Green time series

The Landsat persistent green time series product has been compiled for each quarter between 1992 and 2022. This provides the basis for the delta green analysis, which is effectively showing the rate of change in persistent green, which is assumed to be a proxy for tree cover, over the 30 year period. An example of the Persistent Green product compared with high resolution RGB imagery is shown in Figure 63.

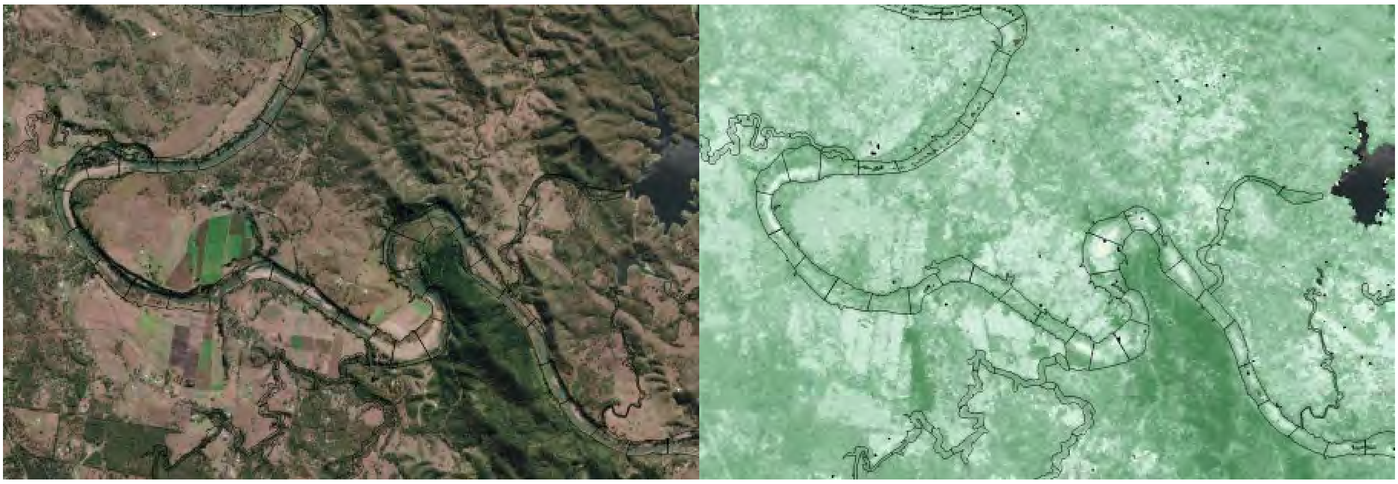

Figure 63. Example of Persistent Green product compared with high resolution RGB satellite imagery, highlighting the increased persistent green (darker shades) in areas with increased woody vegetation cover.

Appendix 3: Richmond River Channel and Riparian Zone Delineation Methods

Overview

As a basis for developing an objective river channel/riparian management prioritisation strategy for the whole Richmond Catchment (3rd order streams and above) we first needed to develop an accurate map of the river channel network along with an appropriately scaled riparian zone. The river channel boundary was geomorphically defined as the high bank of the active channel zone. Depending on the channel form (or River Style) in different locations around the catchment, this might be the high bank of a clearly identifiable simple channel, or it might be the high bank of a series of inset surfaces making up the active channel zone. Once the channel zone was defined, an additional riparian buffer was identified as an aspirational vegetation management zone for each reach, in accordance with the legislative requirements under the NSW Water Management Act (2000)[1] We have developed an objective method that assigns a buffer width as a function of mean reach width, all of which are slightly smaller than that required under the Water Act. It is recognised that it may or may not be practical to fully revegetate all of these riparian zones as part of future management strategies, but it was considered to represent an ideal scenario that would maximise root reinforcement of the high bank, as well as increasing hydraulic roughness such that it might have a beneficial impact on flood dynamics at the catchment scale.

For the purposes of this study, we will analyse the current extent of woody vegetation within these two zones (channel + riparian buffer) for each 500m segment of the 3rd order channels and above, as well as quantify the trajectory of change in woody vegetation cover within the 500m reach across the last 35 years. The following described how these zones were delineated across the 2884 reaches that are the focus for the Richmond Catchment prioritisation.

Channel Delineation

The channel boundary was delineated on the 2023 lidar data. Lidar is topographic data generated using aircraft-based laser scanning to collect ground elevation data for every 1 m^2 of the catchment. A hillshade representation of the ground surface is derived from the elevation data, examples of which can be seen in Figure 64 to Figure 67.

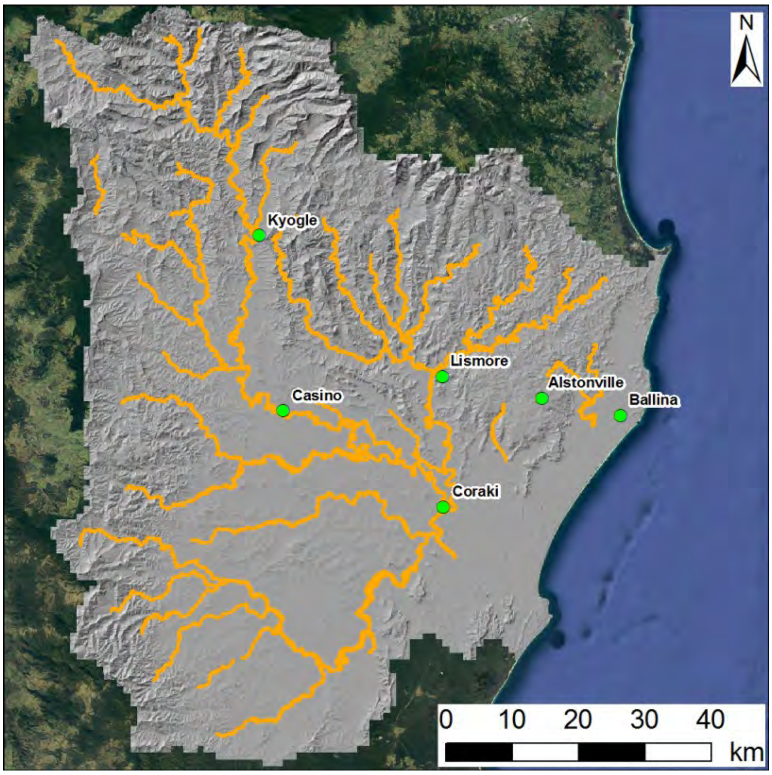

Figure 64. Richmond catchments showing the extent of the 3rd order + channel network within which channel/riparian boundaries have been delineated..

The channel boundary was delineated through a combined semi-automated approach with manual editing and digitisation. Figure 65 shows examples of the channel margin on the hillshade image. This was done for all 1442 km of channel that are the focus for this study (Figure 64). To ensure the channel/riparian mask closely matches the topographic data, the data was transformed to match the 1m raster data.

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[1] Under the NSW Water Act – the following minimum riparian buffer widths apply: 1st order – 10m; 2nd order – 20m; 3rd order – 30m; 4th order + - 40m

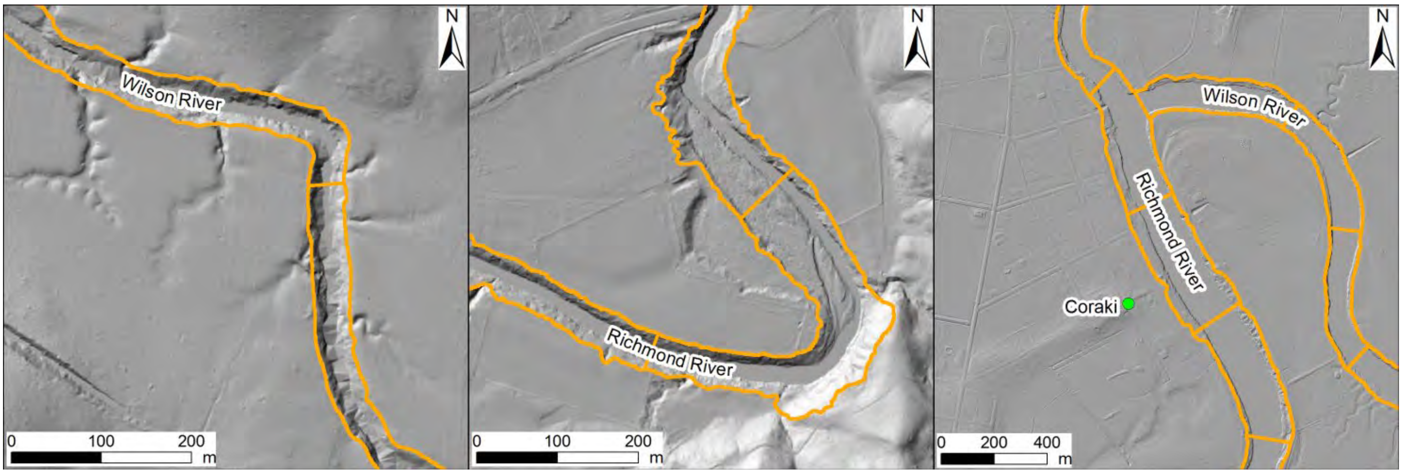

Figure 65. Three examples of channel boundary delineation.

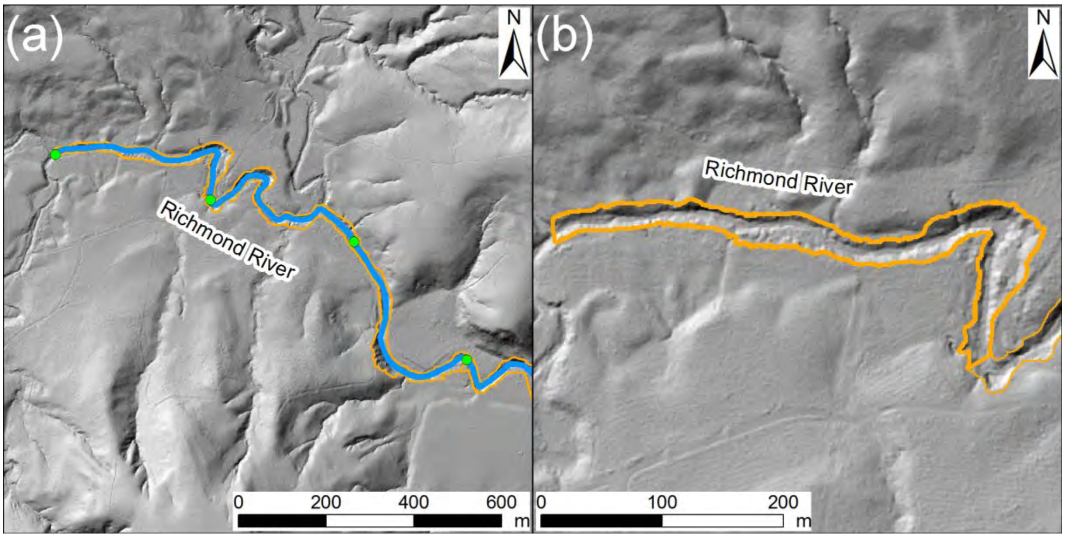

Figure 66. a) Channel centreline with 500m interval points. b) 500m reach example.

To produce the 500m channel analysis reaches, a channel centre line was delineated throughout the entire channel network, and was then segmented at an interval of 500m (see Figure 66). These 500m interval points along the channel centre line were used to derive a segment clipping masks that was used to cut the mapped channel into 500m reaches (Figure 65).

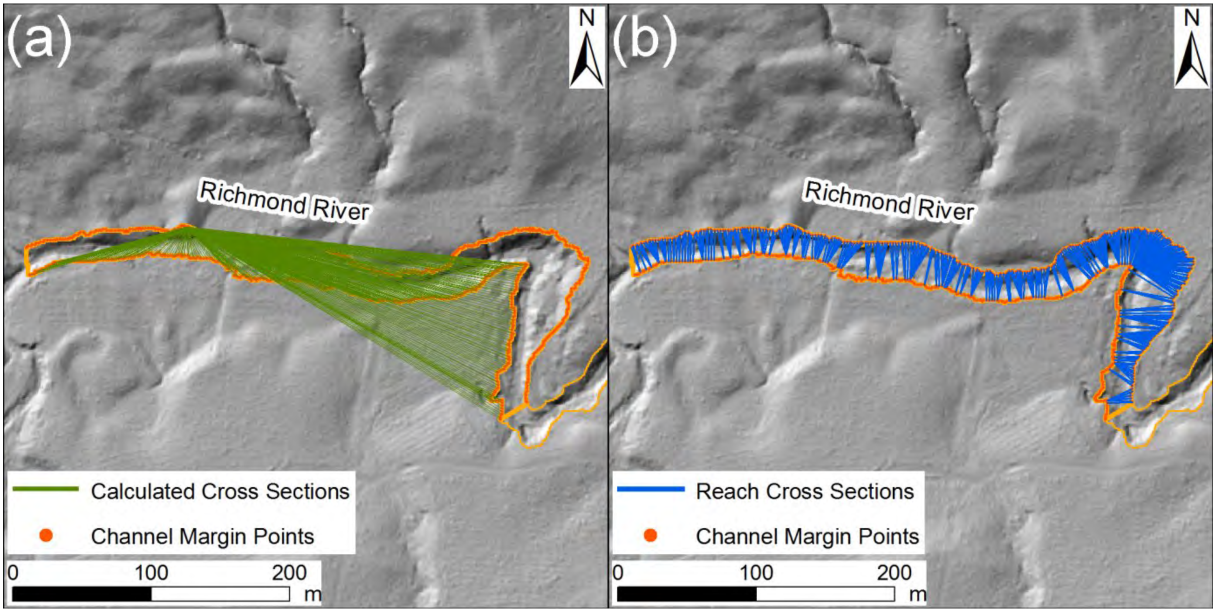

Figure 67. a) Calculated width between margin points for 1 point. b) Channel cross-sectional distance for each margin point having assessed which is the shortest of all possible cross section options.

Riparian Zone Delineation

A riparian buffer zone was objectively determined as a function of the mean reach channel width. For the larger active channels that are outliers in the dataset (Figure 68), the riparian zone width is delimited by the fitting of an exponential trend to the whole dataset. The average channel width was determined for each of the 2884 500m channel reaches. This process involved, firstly, calculating the width between every left side channel margin point in a reach compared with all the right side points (i.e. every 1m along the channel bank top). A representation of this approach can be seen in Figure 67a, which graphically shows the calculations for one left-of-channel point, compared with all the right-side points for this one 500m reach. The shortest of the calculated widths was then retained as the channel cross-sectional distance for that location of the channel. Having determined the minimum width for every point along the bank (i.e. every 1m), the average of these cross-sectional distances was calculated for each of the 500m reaches. Hence the reach average width is derived from 250,000 calculations.

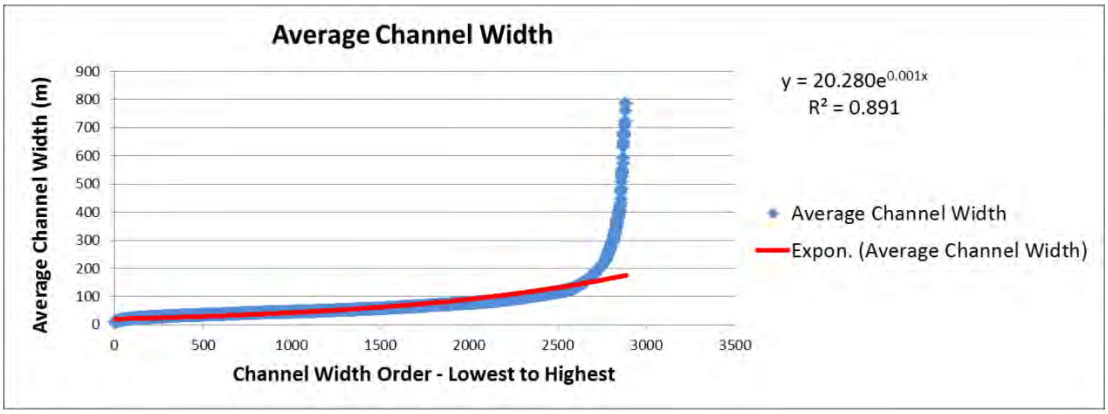

Figure 68. Average channel width plot for the 2884 reaches ordered from smallest to largest. The fitted exponential function shown in red has been used to derive a riparian buffer.

The riparian buffer was then determined as a function of the average channel widths for the entire Richmond dataset (Figure 68). The average channel width for all 2884 of the 500m reaches were sorted in order from lowest to highest and an exponential trend line fitted to the whole dataset (Figure 68). The channel width was highly correlated (R^2 = 0.89) to position in lowest to highest order when fitted with an exponential function. This exponential function was used to scale the buffer between approximately 20 and 40m, limiting the buffer at the upper end of the distribution. In the case of this dataset, using the exponential function with the average channel width was as the independent variable to calculate the buffer width (the dependent variable), produced a range of analysis buffer widths between 20 and 36.5m.

This method provides an objective method for deriving the riparian buffer beyond the top of the high bank. This is to accommodate a range of values that these minimum buffers can offer, including: allowing for ongoing channel erosion; providing root reinforcement to minimise ongoing bank erosion; providing hydraulic roughness to reduce shear stresses on the banks during floods; providing shade and terrestrial riparian habitat; providing sources of large woody debris and leaf litter. It should be stressed that while we have kept this buffer within that proposed under the Water Act – the buffer delineated here has no legislative force. It may be regarded by some as an aspirational planning boundary and others as a minimum. If circumstances on the ground allow, there is no reason why a larger riparian buffer cannot be revegetated/maintained. For the purposes of this study, the boundary we have delineated forms the basis for planning at the catchment scale (Figure 69). No allowance has been made in this analysis for existing infrastructure, so it is recognised that there may be some reaches where it will not be possible to achieve the revegetation of the entire buffer. Neither has allowance been made for existing land uses that may be incompatible with revegetation. These issues will be addressed in more detail in the ongoing study. The buffers outlined here are simply the basic building blocks for the ongoing study.

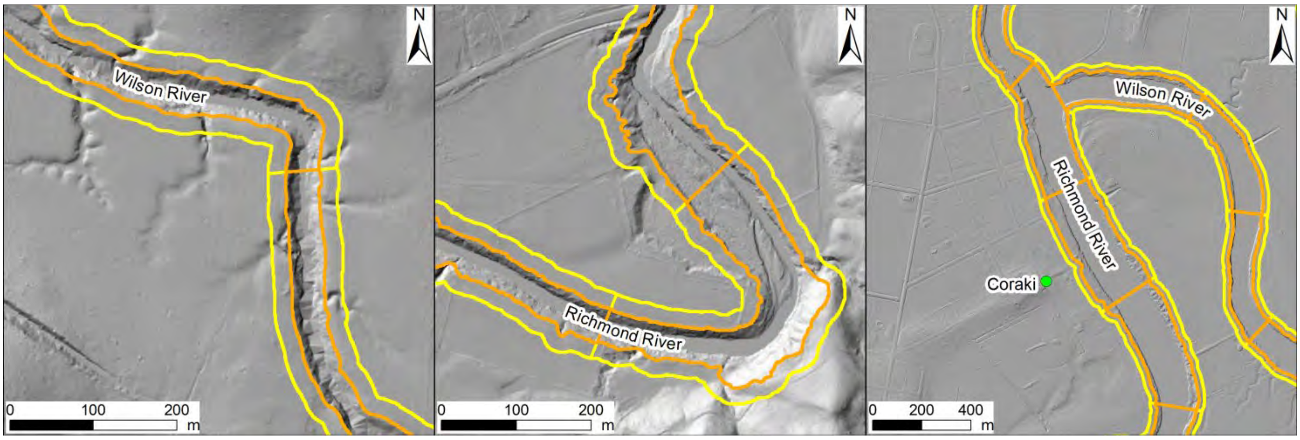

Figure 69. Three examples of channel margin and analysis buffer.

Appendix 4: Current woody riparian vegetation mapping

The lidar point cloud data (i.e. the entire raw lidar dataset) enables the non-ground data points that are excluded from the data in generating a ground surface DEM, to be used for classifying the vegetation into canopy height and foliage projected cover (FPC) metrics within each river reach. This type of analysis provides the most accurate representation of the current extent of the riparian vegetation throughout the catchment at the time the lidar data was captured in late 2023. An example of the woody riparian vegetation mapping is shown in Figure 70, while a map of the distribution of the reach scale FPC across the catchment can be seen in Figure 74.

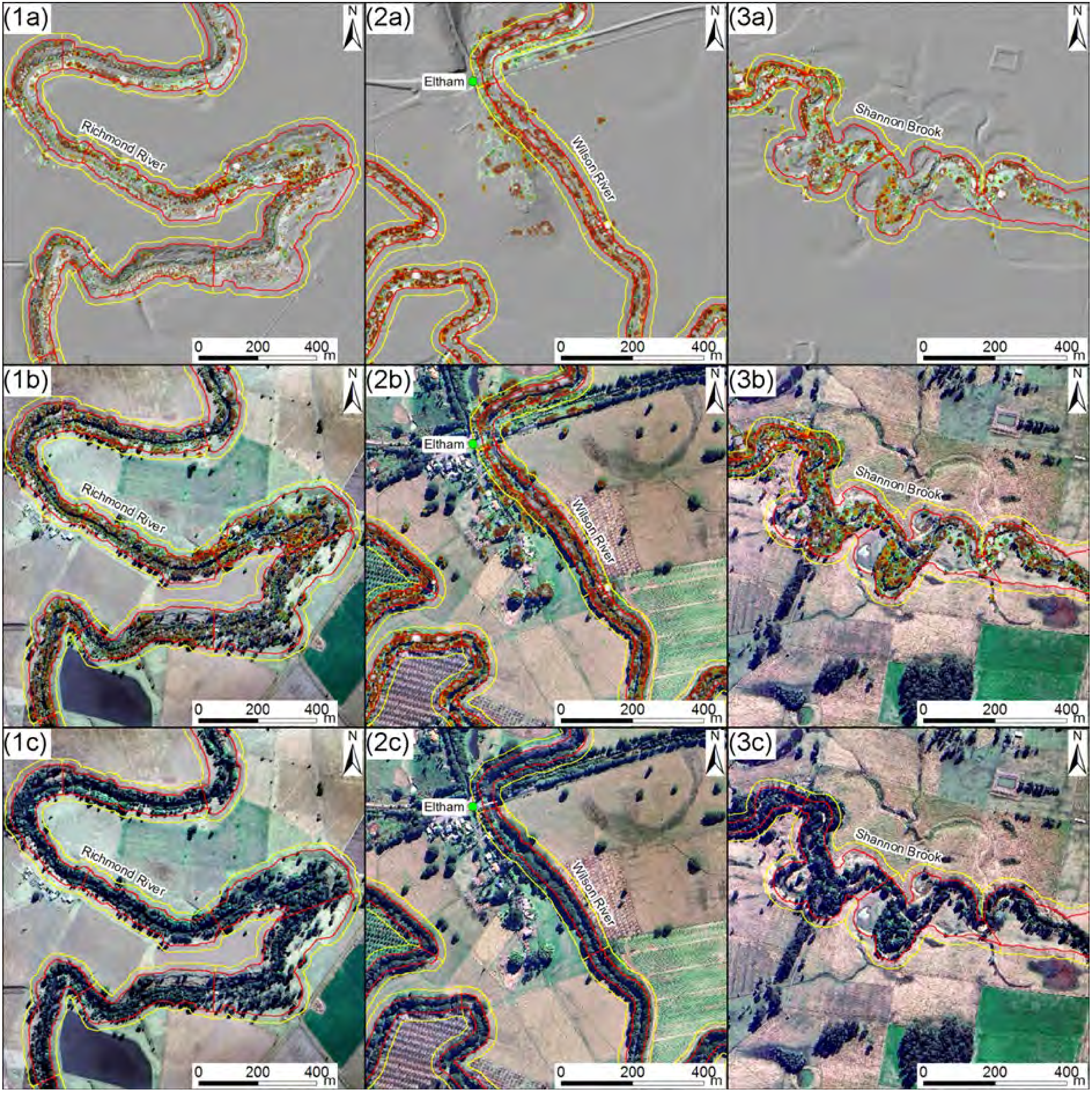

Figure 70. Examples of the reach scale riparian vegetation mapping derived from the lidar canopy height dataset (2023). The examples in 1a – 3a show the classified canopy height data on the lidar hillshade DEM. In 1b – 3b, the same data is displayed on the high-resolution satellite imagery in 1c – 3c.

Water mask generation

A water mask for the greater than 3rd order stream channels under investigation was derived from Planet Scope imagery. The approximate area of water surface area within each channel reach is required to determine the percentage area of woody vegetation cover within each reach, as indicated in the schematic diagram in Figure 71 The water surface area needs to be subtracted from the total area of each reach to provide an accurate representation of the woody vegetation percentage foliage cover for each reach, as per equation 1. The representation of the water mask coverage at the catchment scale is shown in Figure 72 and an example of what it looks like at the reach scale can be seen in Figure 73.

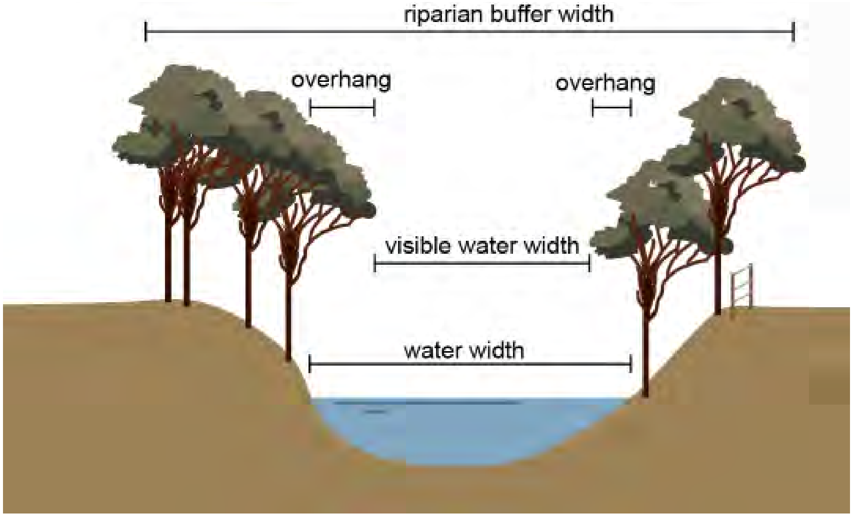

Figure 71. Schematic diagram showing the area of open water visible in remotely sensed imagery that needs to be accounted for through the use of a water mask

$$FPC = \frac{A_{veg}}{A_{reach} - A_{water}} \times 100 \qquad \text{Equation 1}$$

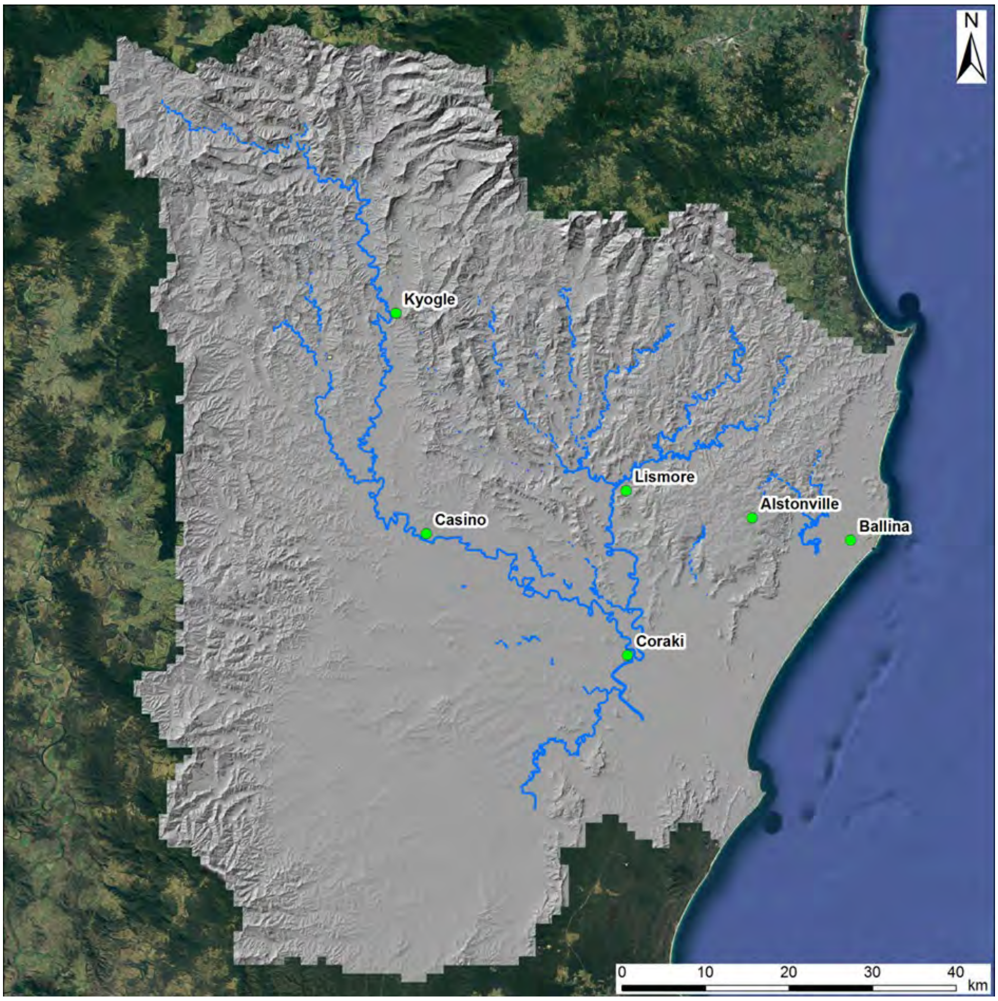

Figure 72. Map of the Richmond catchment showing the extent of the stream network analysed in this study for which the low flow water surface area was mapped using Planetscope satellite imagery.

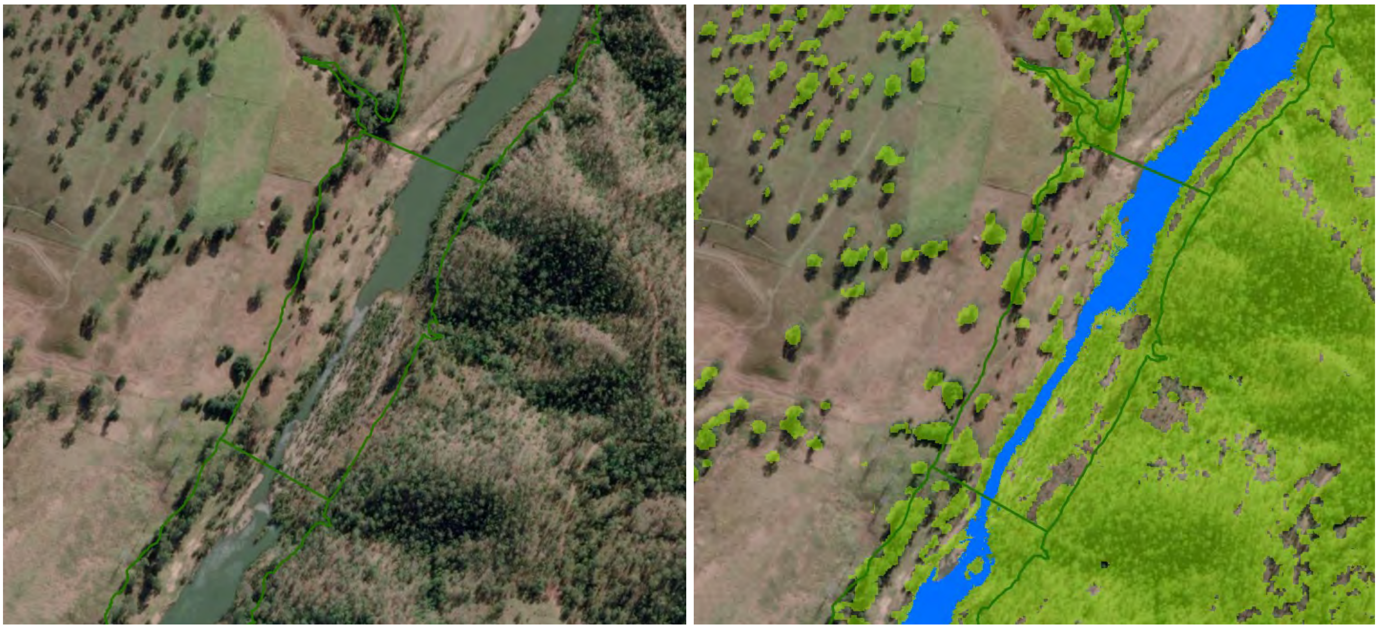

Figure 73. Example of water mask mapping at the reach scale using Planetscope imagery

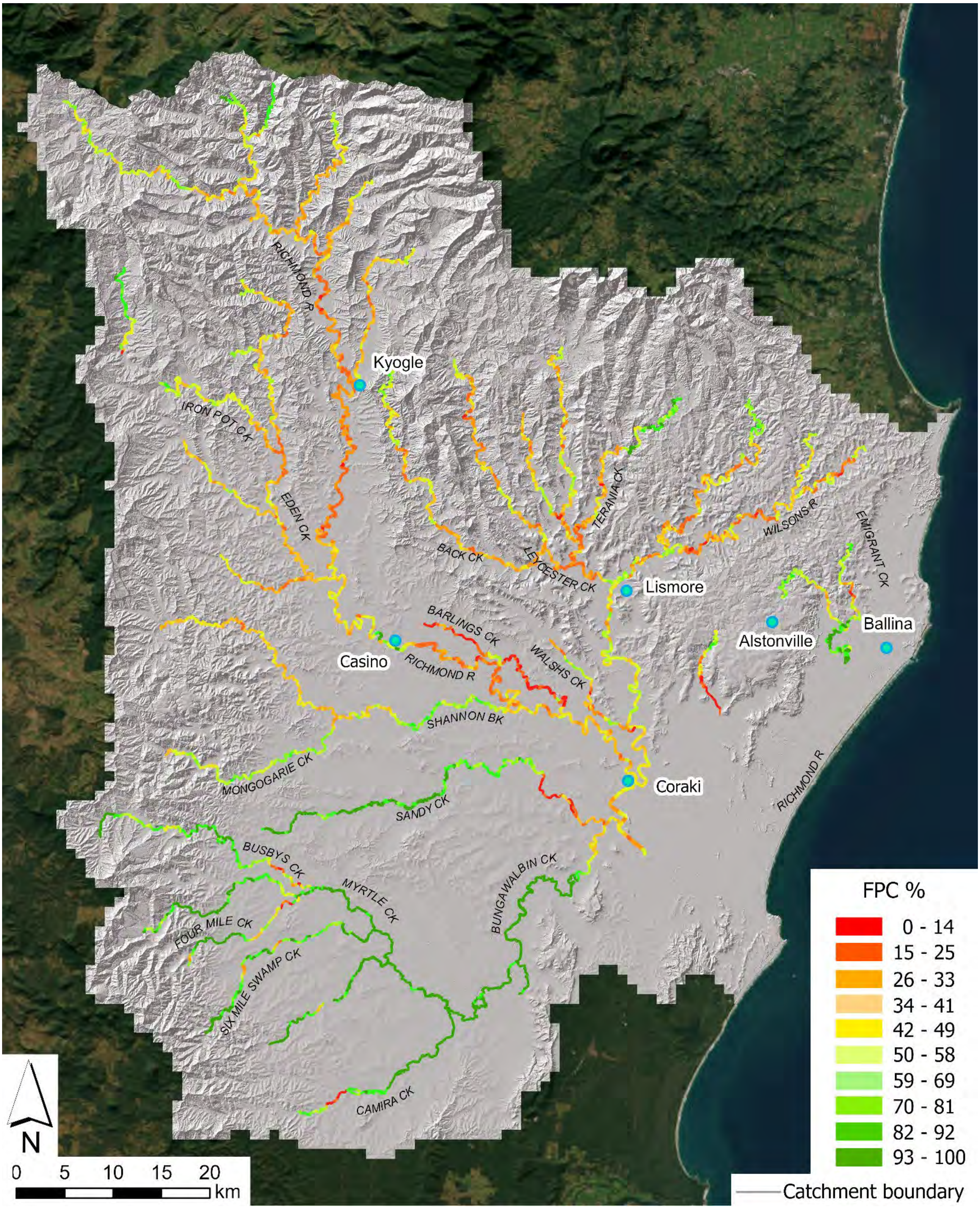

Figure 74. Map showing the distribution of reach riparian vegetation FPC across the entire channel network being analysed in this study.

Appendix 5. DoD analysis - where suitable repeat lidar exists (following QA/QC analysis)

A DEM of difference (DoD) analysis has been completed for all 2884 reaches. Differencing the elevation data within a DEM involves subtracting the elevation data for each DEM pixel ($1m^2$) of one acquisition date from the corresponding DEM cell of another acquisition date. The cell elevation values cannot be simply subtracted. As with any measurement, elevation data measured using lidar is subject to random and systematic error. These errors propagate into the DoD data and introduce considerable erroneous information. The errors/noise in the DoD data needs to be excluded from the dataset to ensure that only real ground surface data, and hence ground surface change data, is included. In this analysis, for each 500m reach, vertical offset between the DEMs of the two acquisition dates was calculated and corrected for in the differencing calculation. The range of vertical correction adjustment across the 2884 reaches is 1.13m to -1.07m, the smallest absolute value was 0.06mm. The DoD values for each reach are then analysed to determine the volumetric change pixel by pixel. Due to varying widths and channel sinuosities, the 500m reaches are a range of shapes and sizes, the number of difference values within reaches range from 605,907 to 10,792 prior to filtering. The standard deviation (σ) of the difference values was calculated for each reach, and for the complete dataset this ranged from 2.46 to 0.1. The combination of topographic variability within the reach, vegetation density, flight conditions, equipment setup, and various other factors, creates the range of standard deviation observed. Given that this dataset is extremely noisy we have filtered (i.e. excluded) 2 standard deviations around zero (+/- 2σ) to provide us with the resultant change dataset in each reach. That is, all difference values within the range of $+2\sigma$ and -2σ were calculated for each reach, and a separate filtration value excluded in every reach. Figure 75 shows DoD analysis results as a range of elevation increase (deposition) and elevation decrease (erosion) for sections of three different rivers. A value for volumetric change, both positive and negative, is summed for each 500m reach. As noted earlier, the QA/QC analysis of the lidar data revealed that within heavily forested areas, including riparian zones the lidar ground point density can be low. It was found that the summed area without elevation data (low ground point density) within many reaches has a greater than negligible effect on DoD analysis. Consequently, another dataset is required and will be generated from the lidar point cloud to identify and map areas within reaches of low point density. This new dataset will be integrated into the DoD analysis.

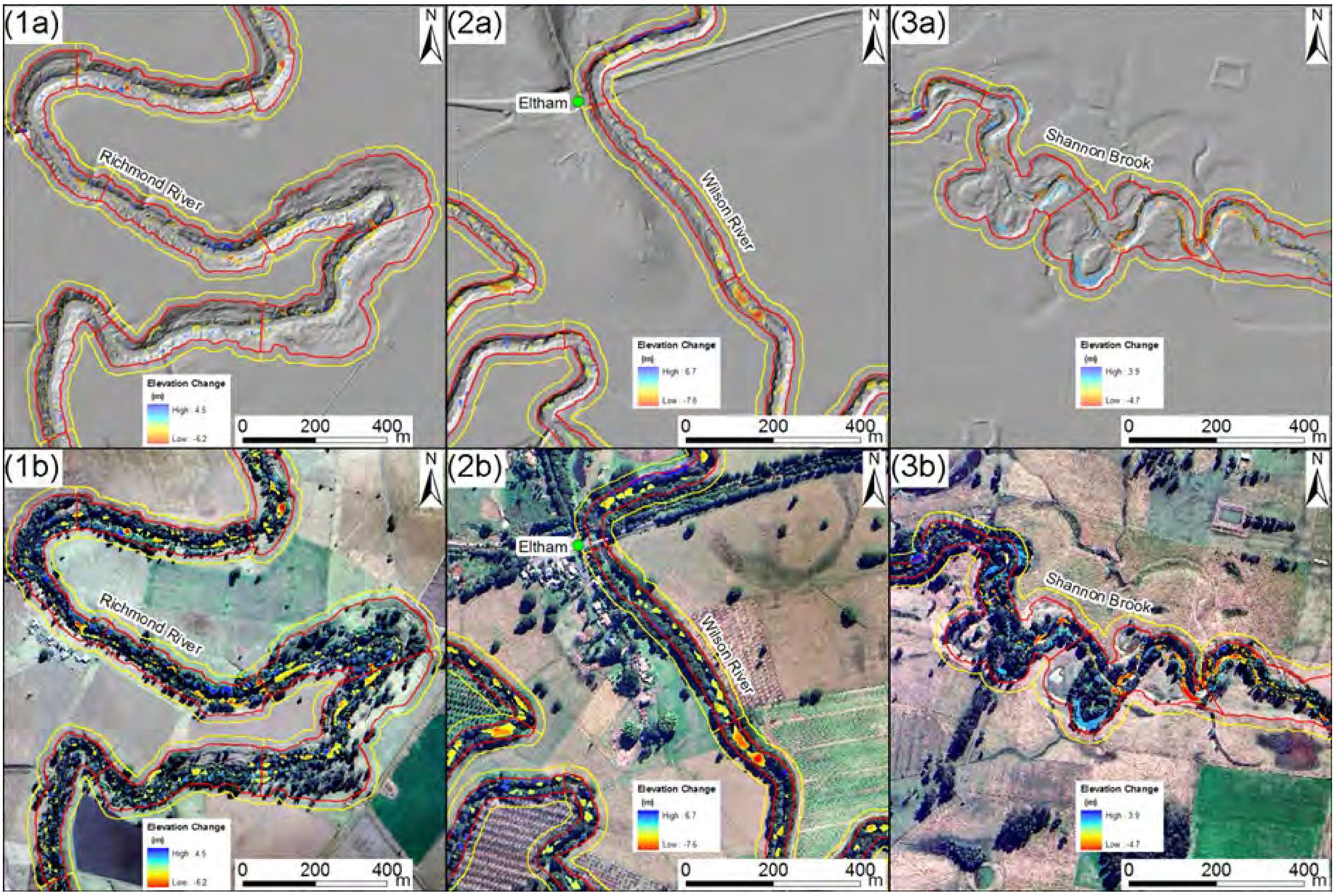

Figure 75. DoD analysis results as a range of elevation increase (deposition) and elevation decrease (erosion) for sections of three different rivers. -plotted on the bare ground hillshade DEM in 1a – 3a, and on the high-resolution satellite imagery I 1b – 3b.

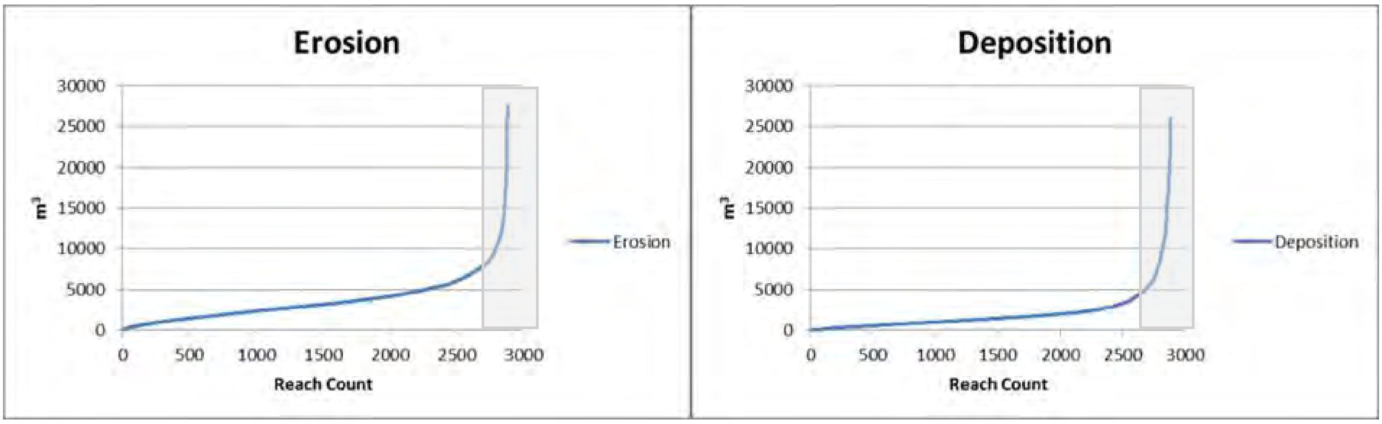

Figure 76. Plots of the erosion and deposition for each of the 2884 reaches analysed across the catchment arranged from lowest to highest. Further validation is required for these data, but the reaches highlighted by the grey box are anomalously high and are assumed to be suspect until we can validate them - either on ground or using other datasets.

Across all reaches the range of calculated erosion values are 0 to 21,202 m^3 and the deposition values are 0 to 25,961 m^3. Figure 76 shows the distribution of erosion and deposition values across the reaches. The higher values of both erosion and deposition indicated by the grey box overlay are likely to contain erroneous data and require further investigation. This is mainly a result of the areas of low ground point density within the reaches due to dense vegetation cover. This is particularly the case with the earlier lidar coverage, so areas that might have erroneously been classified as ground surface in the earlier lidar due to poor lidar penetration through the canopy, when compared to data in the recent lidar data that has penetrated the canopy, show up as erosion due to the apparent elevation difference between the two time-slices. What is really happening here is that the tree canopy elevation is mapped at time 1 and the ground surface at time 2, with the DoD recording this difference as apparent erosion. Following the creation of low ground point density area maps the erosion and deposition results will be filtered to exclude these anomalous values. The final output of the catchment-wide filtered erosion dataset prior to ground truthing cab seen in Figure 77. (Note this differs from the final erosion dataset shown in Figure 13 due to the fact that the channel boundaries for Bungawalbin Creek and Shannon Brook were modified as a result of the ground truthing).

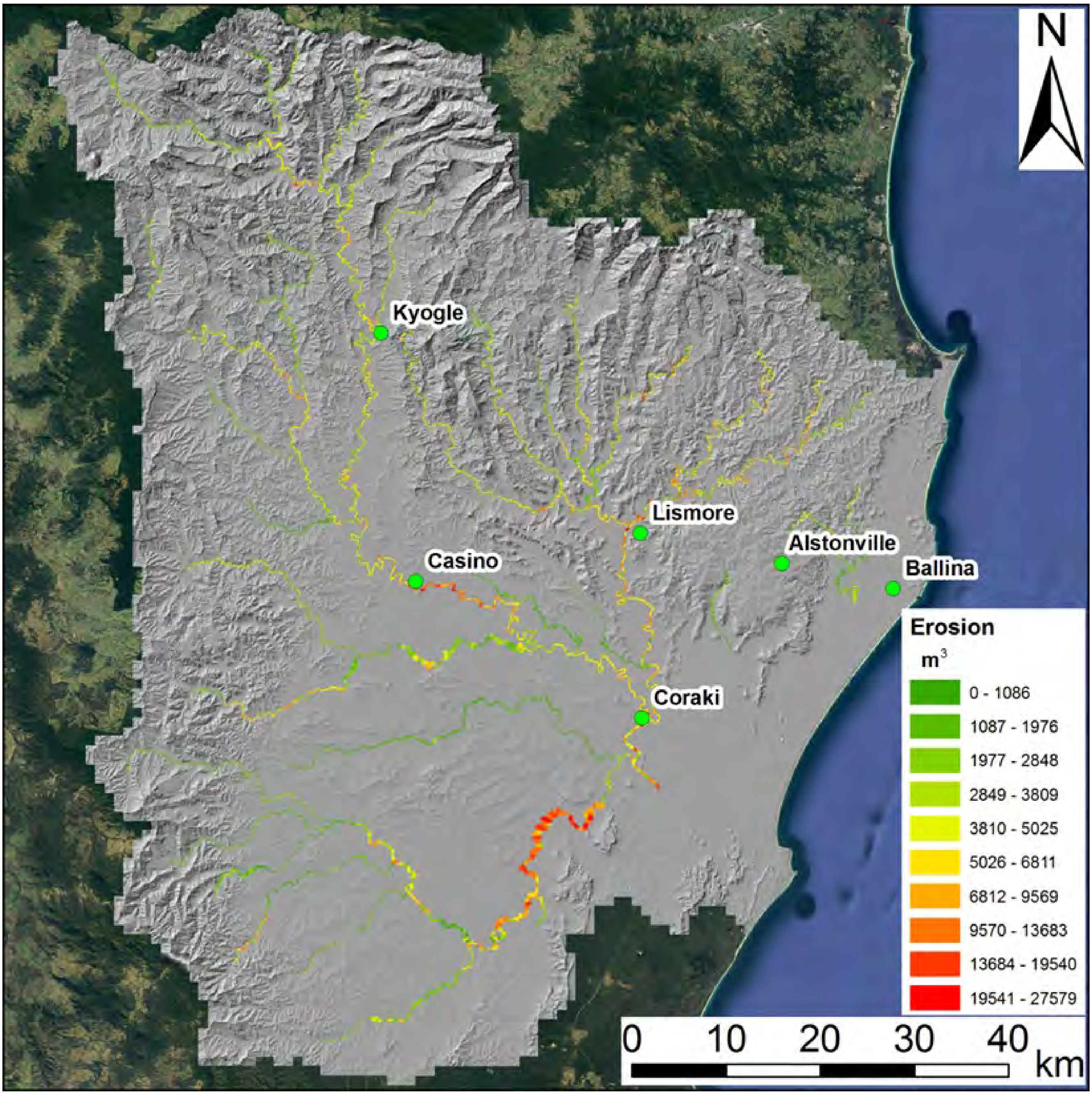

Figure 77. Map showing the spatial distribution of apparent channel erosion. The high values on the densely vegetated Bungawalbin Creek supports the theory that these high values are anomalous

Appendix 6: Delta Green analysis (reach time series analysis of 30 yrs of quarterly LandSat data)

An understanding of the trajectory of change in the vegetation cover of recent decades is gained with an analysis of seasonal Landsat imagery and the generation of the Delta Green Metric (Piestch et al., 2019, Daley et al., 2024. The Persistent Green metric is a Landsat-derived product mapped seasonally (i.e. each 3 months) across Australia from 1987 – 2022 (Figure 78). At ~30 m resolution, the product provides an estimate of areas that remain green throughout each season. It is *intended* to estimate the portion of vegetation that does not completely senesce within a year, which is assumed to primarily consist of woody vegetation (trees and shrubs). It is derived by fitting a multi-iteration minimum weighted smoothing spline through the green fraction of the seasonal fractional cover (dp1) time series.

However, there are exceptions where non-woody cover remains green all year round and therefore must be used with some prudence (Trevithick, 2017). Two examples of exceptions are persistently irrigated pasture, and reed beds growing in more or less permanently moist swampy meadow type environments. This is important within riparian zones where non-woody ground cover may remain green due to increased connectivity with the water table. The actual values of Persistent Green may not always directly relate to woody vegetation.

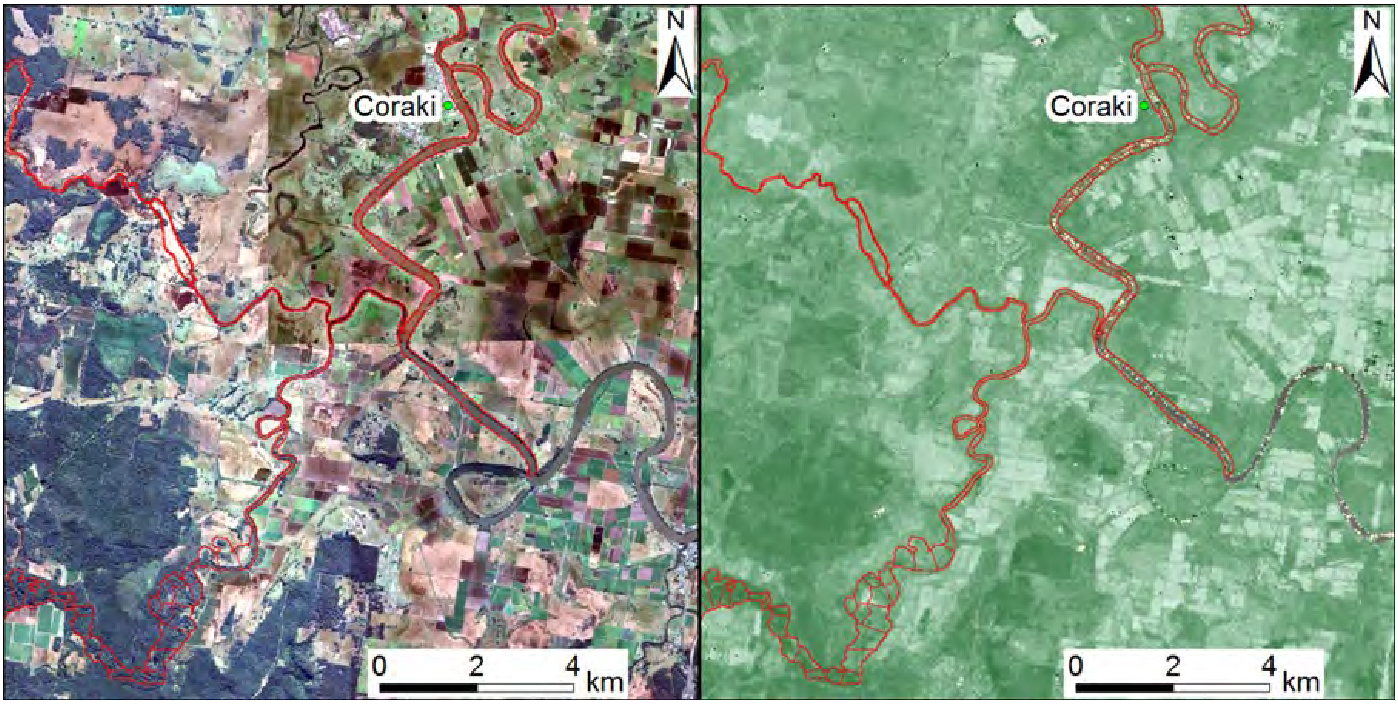

Figure 78. Example of Persistent Green data. For comparison the LHS is Google Earth imagery and the RHS is 2022 June to August Persistent Green data. As can be seen, areas of forest have higher Persistent Green values (darker green) and open fields have lower Persistent Green values (lighter green).

Individually trajectory plots are derived for every 500m river reach and the Delta Green metric is a measure of the slope of the linear regression of the 120 points (i.e. one value for each 3-month period across 30 years) making up the plot (Figure 79). Whether the line has a positive or negative slope (or is neutral) tells us whether the woody vegetation cover is increasing, decreasing or oscillating around a steady state. From the plots in Figure 79 it can be seen that the trends vary systematically over multiple years, which largely reflect the multi-year climatic cycles experienced within Australia (driven by ENSO cycles). The spatial distribution of the Delta Green metric across the catchment has been previously shown in Figure 17.

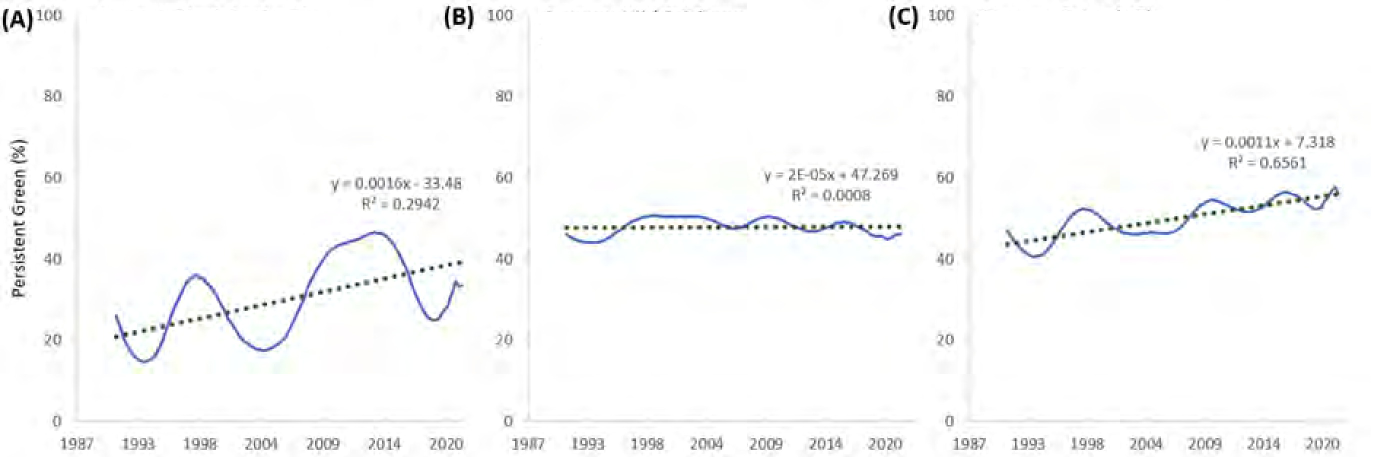

Figure 79. Examples of plots generated for 120 consecutive quarters for individual reaches. These plots enable us to determine the trajectory of change in the extent of tree cover within each reach across a 30 year timeframe.

Appendix 7: Marxan Analysis Methods –

Within a reach a variety of rehabilitation costs have been defined, depending on land use, thresholds of key reach inputs (i.e. Delta Green, FPC, % Camphor) within the Channel and the Buffer zone, as determined by the decision tree. Thus, when aggregated, the total rehabilitation cost for a reach may include one or more cost components. i.e. monitoring, fencing, revegetation, supplementary planting, and assisted natural regeneration (see Table 12).
In this study, we used Total Cost to quantify the 'cost' parameter in Marxan. This parameter defines the cost of including a planning unit in the final prioritised set of reaches. The lower the cost the more likely the planning unit will be included, provided it also meets the objectives of targeting the selected attributes. In conservation planning these attributes might be specific species, but in this case, they are the management objectives we are trying to address, namely reaches with high historical erosion that intersect reaches and with low woody riparian vegetation cover. The underlying assumption is that maximum erosion reduction can be achieved by targeting management efforts on those reaches with high erosion *and* low extant woody riparian vegetation cover. Marxan's delivery of optimal solutions can be demonstrated diagrammatically. In conservation planning, the boxes in **Error! Reference source not found.** s/b Figure 79 represent planning units, and animals represent species or features. For the Richmond project, boxes represent irregularly shaped planning units (i.e. river reaches) with variable costs based on the total cost to rehabilitate that reach according to the current state, and X symbols represent features such as management rehabilitation issues (e.g. total erosion, vegetation cover) as follows:

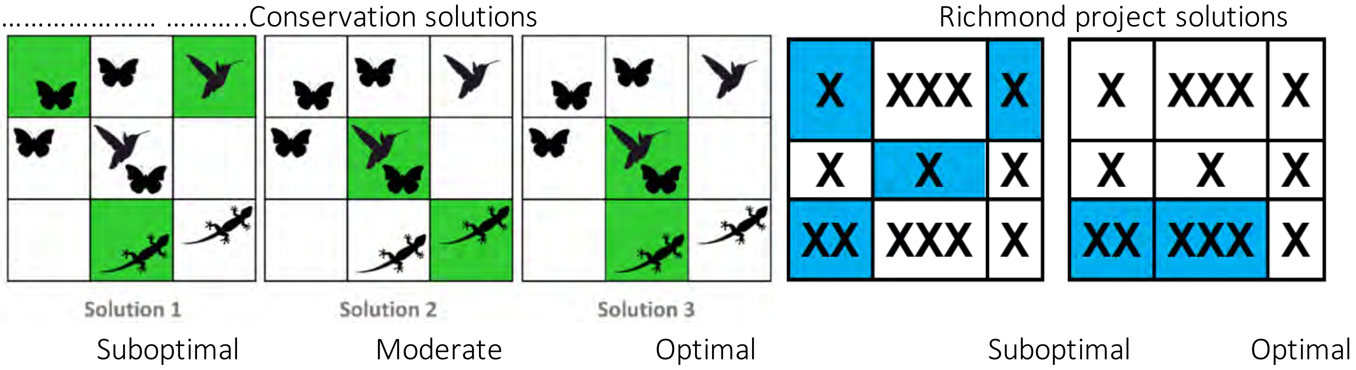

Figure 80. Diagrammatic representation of Conservation and Richmond project solutions

In this example, the conservation solution on the left is to protect one occurrence of each species. Thus, solutions 1 and 3 meet all conservation targets, while solution 2 does not (only two of three species are included in reserves). However, solution 3 with the smallest reserve area is the most efficient solution. This rationale can be also applied to scenarios with single features, where the target is to protect a specific percentage of the 'feature', shown in the Richmond project solutions on the right in **Error! Reference source not found.** s/be Figure 79. When applying Marxan to the Richmond project, the priority is to address specified percentages of a management issue or 'feature', for example, 10% of Total Erosion volume. The suboptimal solution is to prioritise the specified percent of Total Erosion over a large number of reaches, with resulting higher Total Cost, whereas the optimal solution is to prioritise a specified percent of Total Erosion for the minimum Total Cost.

The diminishing effect of reaches more distant from a subject reach has also been addressed in this study. The boundary cost parameter has been set as a function of such an effect on a subject reach. Thus, upstream reaches from a subject reach have a diminishing effect as distance increases from the subject reach. For reaches lower in the catchment, in the tidal zone, this parameter has been set both ways, to account for reaches both up- and downstream from a subject reach.

Costings

Rehabilitation costs have been sourced from recent rehabilitation projects, quotes and invoices provided by ROUS, and costs supplied by North Coast Local Land Services. Values have been compared for reasonableness with cost information sourced from Hunter LLS, Landcare Australia and the literature. Detailed costs, including a breakdown into costs for each rehabilitation scenario are contained in Table 12.

Table 12. Detailed costs including breakdown into costs included in each rehabilitation scenario.

Activity								Management option value $/ha and $/m							
Task	**Item**	**Description of work item**	**Unit**	**Qty**	**Unit cost $**	**Item $**	**Task subtotal $**	**Fencing (F)**	**Off Stream Watering (OSW)**	**Monitoring (M)**	**Assisted Natural Regeneration (Wanr)**	**Suppl. Planting with Primary Weed Mgt (SW)**	**Revegetation with Primary Weed Mgt (RW)**	**Revegetation (R)**	**Source**
Stock exclusion	Fencing - electric	Supply and install ~$10 per metre using stakes	m	500	15	7,500	7,500	7,500	-		-	-	-	-	6
	Off stream watering	Supply and install (see Note)	unit	1	18,950	18,950		-	18,950		-	-	-	-	5
		$2000-$3000 per trough - cattle	unit	1	3,000	3,000	21,950	-	3,000		-	-	-	-	4
Primary Weed Management	Spraying - total area	Spray total area	day	0.8	550	440	440	-	-		-	-	-	440	2
	Targeted spraying	Bottom up weed control of woody weeds, then strategic canopy weed mgt. Spot spraying, cut scrape & paint	day	20	550	11,000	11,000	-	-		11,000	11,000	11,000	-	1
Revegetation	Planting Y1 Buffer revegetation (random spacing)	Supply trees for 3m random spacing, describe species characteristics. Mulch, water in, water crystals	each	1111	3	3,333		-	-	-	-	-	3,333	3,333	1
		Supply bales (one per 10 trees)	each	111	8	888		-	-	-	-	-	888	888	1
		Labour. Plant, mulch, water in, water crystals. Per 8 hr day in 2025.	day	13	550	7,150	11,371	-	-	-	-	-	7,150	7,150	1
	Suppl planting Y2 Buffer revegetation (random spacing)	Suppl infill planting to increase diversity post canopy development. Prepare site, dig holes.	ha	667	3	2,001		-	-	-	-	-	2,001	2,001	1
		Labour. Plant, mulch, water in, water crystals. Per 8 hr day in 2026.	day	7	570	3,990	5,991	-	-	-	-	-	3,990	3,990	1
Supplementary planting	Suppl planting Y2 Random spacing (Y1 is weed mgt only)	Suppl infill planting to increase diversity post canopy development. Prepare site, dig holes.	ha	667	3	2,001		-	-	-	-	2,001	-	-	1
		Labour. Plant, mulch, water in, water crystals. Per 8 hr day in 2026.	day	7	570	3,990	5,991	-	-	-	-	3,990	-	-	1
Maintenance - Revegetation	Maintenance Y1 random spacing revegetation	Maintenance, Spot spraying. Excludes infill planting. 3 visits x 3 people	day	9	560	5,040		-	-	-	-	-	5,040	5,040	1,3
	Maintenance Y2 random spacing revegetation	Maintenance, Spot spraying, 3 visits x 3 people	day	12	580	6,960		-	-	-	-	-	6,960	6,960	1,3
	Maintenance Y3 random spacing revegetation	Maintenance, Spot spraying, 3 visits x 2 people	*day*	4	581	2,324	14,324	-	-	-	-	-	2,324	2,324	1,3
Maintenance - Supplementary planting	Maintenance Y1 random spacing suppl. planting	Maintenance, Spot spraying. Excludes infill planting. 3 visits x 2 people	*day*	6	560	3,360		-	-	-	-	3,360	-	-	1,3
	Maintenance Y2 random spacing suppl. planting	Maintenance, Spot spraying. Excludes infill planting. 3 visits x 3 people	*day*	9	560	5,040		-	-	-	-	5,040	-	-	1,3
	Maintenance Y3 random spacing suppl. planting	Maintenance, Spot spraying. Excludes infill planting. 3 visits x 2 people	*day*	4	560	2,240	10,640	-	-	-	-	2,240	-	-	1,3
Maintenance - Assisted natural regeneration	Maintenance Yr 1 Assisted Nat Regeneration	Maintenance, Spot spraying, 3 visits x 2 people	day	6	560	3,360		-	-	-	3,360	-	-	-	1,3
	Maintenance Yr 2 Assisted Nat Regeneration	Maintenance, Spot spraying, 3 visits x 2 people	day	6	580	3,480		-	-	-	3,480	-	-	-	1,3
	Maintenance Yr 3 Assisted Nat Regeneration	Maintenance, Spot spraying, 2 visits x 2 people	day	4	581	2,324	9,164	-	-	-	2,324	-	-	-	1,3
Monitoring & Report	Y1	Install photo point monitoring, conduct monitoring. Prepare report	day	1	550	550		-	-	550	550	550	550	550	1,2
	Y2	Conduct monitoring. Prepare report	day	1	570	570		-	-	570	570	570	570	570	1,2
	Y3	Conduct monitoring. Prepare report	day	1	590	590	1,710	-	-	590	590	590	590	590	1,2
						100% Total Cost	**$/ha**	**7,500**	**21,950**	**1,710**	**21,874**	**29,341**	**44,396**	**33,836**	
							$/m2			**0.1710**	**2.1874**	**2.9341**	**4.4396**	**3.3836**	
							$/linear m	**$15**							
						70% Cost option (100% weed, 70% planting, 70% maintenance)	**$/ha**					**$24,352**	**$34,890**	**$24,330**	
							$/m2					**2.4352**	**3.4890**		
NOTE: Off Stream Watering installation - 22,000L poly water tank, pump house (concrete slab and metal Colourbond shed, 1.5m x 1.5m), Dab Deep Well pump and 3Kva generator (draw water from lower dam), new flow and return lines (from lower dam to new Deep Well Pump, new tank supply line (from new Deep Well pump to new water tank), new 50mm poly gravity water line (from new water tank to 3 new cattle troughs). Troughs supplied by others															
Sources	1	Big Scrub 2024 34 Greengate Rd Bexhill quote	3	NCLLS costs				5	WIP Plumbing quote 34 Greengate Rd Bexhill						
	2	Goanna 2024 quotes 34 Greengate Rd Bexhill	4	HunterLLS 2022 estimates				6	S Hood personal communication						

Marxan (spatial cost-benefit analysis) Model setup

Marxan spatial cost-benefit analysis was undertaken using ArcPro using planning units derived from the compiled channel and buffer riparian datasets and based on 500 m reach lengths with variable riparian width. The riparian zone equates to the geomorphically defined channel to the top of bank with an additional riparian 'buffer' extending from the top of the bank scaled as a function of the channel width. This additional riparian buffer width ranges from ~25m to ~36 m. The channel dataset has a water mask applied to remove the low flow instream portion of the channel, and to determine its riparian portion. The water mask was derived from 3m resolution Planetscope satellite imagery.

The Marxan optimisation modelling assesses the most-cost effective reaches for rehabilitation and is derived from four key input datasets:

1) *The current (2023) extent of woody vegetation* within the channel and riparian buffer which is expressed as the % woody vegetation cover (FPC) within the reach planning units. This can also be represented as the inverse of percent woody foliage cover – the percent non woody vegetation cover.
2) The *total volume of erosion* for the reach as determined from the highly filtered DEM of difference volumetric change for the reach between lidar datasets from 2010,16 & 17 compared to the 2023 dataset. Given that the period of change between lidar captures varies around the catchment, this can also be expressed as an annualised erosion rate. It is however recognised that most of the erosion that is recorded between the majority of the lidar coverage across the catchment, occurred in the 2017 and 2022 floods (indeed the majority occurred in the 2022 flood) and hence an annualised rate is somewhat misleading.
3) The *extent of camphor laurel* in the reach, which was derived from Sentinel satellite image remote sensing-derived mapping (courtesy Dr Pat Norman Griffith University). The presence/absence of camphor laurel is taken as a proxy for other exotic vegetation, and hence as an indicator of the likely magnitude of weed control that might be required within a reach.
4) The broad trajectory of change in woody riparian vegetation cover since 1988 is derived for each reach from quarterly Landsat imagery. As outlined by Pietsch et. al. (2021) the slope of this trendline is referred to as the *delta green metric* which is the coefficient of the trendline when a linear regression is fitted to the dataset. The slope of the trend-line (as reflected by the delta green index) is assumed to represent whether reach woody vegetation is either on an increasing, declining or static trajectory across this ~35-year period. This parameter is used to infer reach rehabilitation strategies.

Decision tree

Based on the relative proportions of the four attributes outlined above, a series of rehabilitation options have been developed from the selection criteria and condition thresholds outlined in the decision tree in Figure 82 and explained in Table 13. These management options form the input into Marxan scenarios and are applied at a sub-reach scale (i.e. channel and buffer zone), which is further differentiated according to the adjacent land use, as reflected by the 2024 land-use mapping. Additional inputs to Marxan including erosion threshold parameters (to determine whether intensive intervention is required) and presence of infrastructure, position in catchment/ streamwise connectivity, and potentially land use and Local Government Area, will also be included to further refine scenario development. The decision tree (Figure 82) shows the selection criteria and associated condition thresholds that are used to differentiate management rehabilitation options for subsets of the planning units (i.e. the reach planning units differentiated by the land use subsets). Selection criteria have been applied at various scales: at the sub-reach scale for land use (to determine whether grazing is present and hence whether fencing is required), separately for channel and buffer zones at reach scale for vegetation cover and exotics cover, and at the total reach scale for vegetation trajectory. These management scenarios form the basis for determining the cost of implementing the rehabilitation strategy to achieve the long-term objective of a riparian zone within which there is 100% projected foliage cover of native woody vegetation. A second management objective with a slightly less ambitious target of achieving a 70% native woody vegetation projected foliage cover is also analysed.

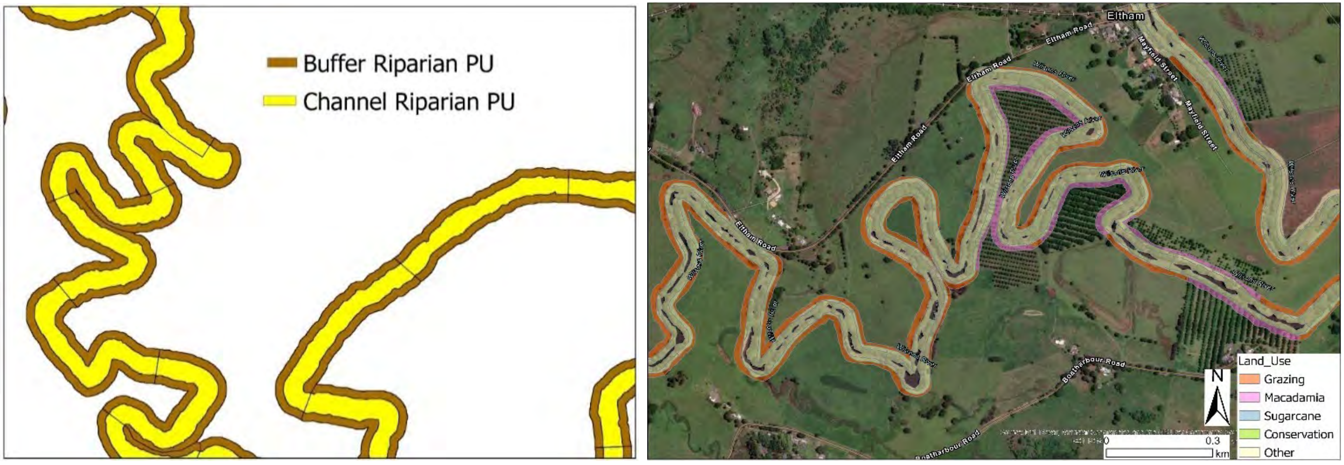

Figure 81. (LHS) Example of planning units (PU) to be used in the Marxan analysis (water mask not applied); RHS Example of the reach planning units divided into the adjacent land use sub-units.

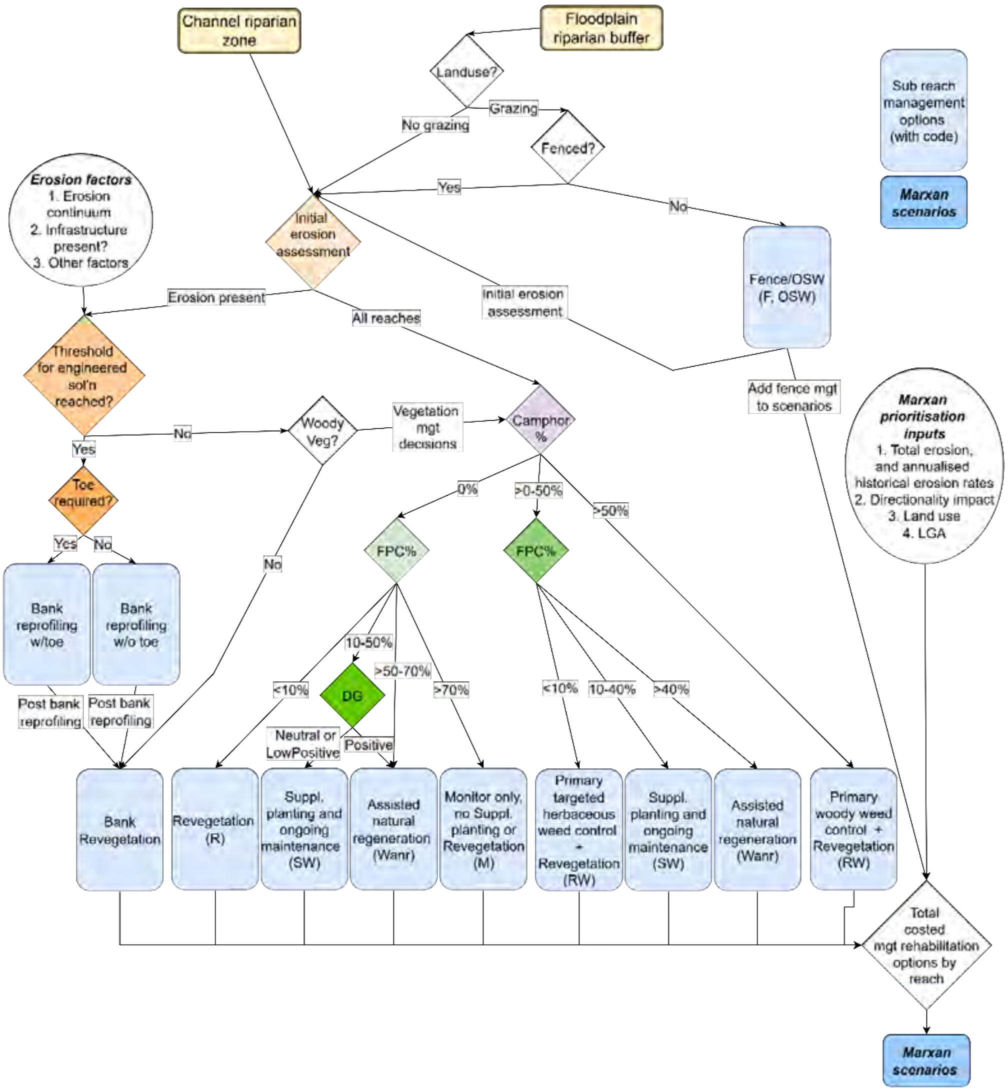

Figure 82. Marxan workflow decision tree showing how each of the management scenarios have been derived. These management scenarios are applied at the sub-reach planning unit scale and for the basis for the rehabilitation costs

Table 13. Rehabilitation options, selection criteria and condition thresholds

Issue	Selection Criteria	Range
Woody Vegetation cover	Foliage Projective cover (FPC)	0-100
Woody Vegetation trajectory	Delta Green (DG)	Neutral, LowPositive, Positive
Exotics cover	Camphor laurel (Cam)	Camphor % of total area
Management option	Condition thresholds	Management cost code
Fence	• Grazing Yes/No (Yes = fence required)	F/OSW
Monitor only - no weed mgt	• Cam=0%, FPC>70%	M
Targeted weed mgt only (for assisted natural regeneration - ANR), maintenance + monitoring	• Cam=0% AND FPC>50-70% OR • Cam>0-50% AND FPC>40%	Wanr
Supplementary planting incl primary targeted weed control, maintenance, monitoring	• Cam=0% AND FPC10-50% AND DG Neutral OR LowPositive OR • Cam>0-50% AND FPC10-40%	SW
Revegetation incl primary targeted herbaceous weed control, maintenance, monitoring	• Cam>0-50% AND FPC<10%	RW
Revegetation incl primary woody weed control, maintenance, monitoring	• Cam>50%	RW
Revegetation with minimal initial weed control, maintenance, monitoring	• Cam=0% AND FPC<10%	R
Total costs rehabilitation costs per reach (all options combined)	• F, M, Wanr, SW, RW, R	Total Cost
Active costs	• Wanr, SW, RW, R	Active Cost
Passive costs	• F, M	Passive Cost
Potential management options		
Bank revegetation, maintenance, monitoring	Erosion present + no natural regeneration	..
Bank reprofiling (no toe protection) + bank revegetation, maintenance, monitoring	Erosion present + bank reprofiling (no toe protection) + revegetation	..
Bank reprofiling (with toe protection) + bank revegetation, maintenance, monitoring	Erosion present + bank reprofiling w/toe protection) + revegetation	..

Rehabilitation Scenario Costs

A breakdown of the unit costs for each of the management scenarios are summarised in Table 14. Unless otherwise specified, the scenarios outlined refer to the total cost to achieve the long-term goal of a fully vegetated (100% FPC) riparian zone. This includes the full range of vegetative rehabilitation management options, monitoring costs and fencing costs. Where “Active costs” are referred to, this includes the rehabilitation costs that directly impact vegetation recovery, namely; Revegetation with primary broadscale weed management, Revegetation with primary targeted weed management, Supplementary planting with primary targeted weed management and Weed management only. In a number of the Marxan scenarios, the reaches that only include passive costs associated with monitoring have been excluded, as they were biasing the prioritisation to reaches

Whilst 100% vegetative cover for any given reach is the long term goal, scenarios can also be modelled that are aimed at achieving a more pragmatic target of 70% woody vegetation cover. Therefore scenarios can also be developed for revegetation and supplementary planting scenarios based on costs to achieve 70% native woody vegetation cover. Under this scenario, the following costs per reach have been included: 100% of weed control costs, revegetation and supplementary planting costs to achieve 70% woody vegetation cover, 70% of maintenance costs, and 100% monitoring costs.

Table 14. Management scenarios and their associated costs.(R = revegetation; RW = primary woody weed control + revegetation; SW = supplementary planting + ongoing weed maintenance; Wanr = assisted natural regeneration; M = monitoring only; F= Fencing).

Mgt option	Code	$/m	$/ha
Leave alone	..	..	.
Fence (Note 1)	F	$15	..
Off stream watering (Note 2)	OSW	$21,950/unit	..
Monitor only - no weed mgt	M	..	1,710
Targeted weed mgt only, maintenance, monitoring	Wanr	..	21,874
Supplementary planting incl primary targeted weed control, 3 yrs maintenance, monitoring	SW	..	29,341
Revegetation incl primary woody weed control, maintenance, monitoring	RW	..	44,396
Revegetation with minimal initial weed control, but including maintenance, monitoring	R	..	33,836
Bank reprofiling, revegetation (Note 3)	..	$500-1000	
Toe protection - rock revetment, log structures (Note 4)	..	$1,400/m	
70% SW Costs	..		24,352
70% RW Costs	..		34,890
70% R Costs	..		24,330

Notes

1. Pers. Comm. S Hood
2. 2024 WIP Plumbing quote 34 Greengate Rd Bexhill
3. Pers. Comm. S Hood
4. Includes early works, construction, post construction, excluding 20% margin. Source: ROUS Council erosion site plans and Estimates for Eltham Bridge rock revetment and large Woody Debris and pins (combined 45m)

Cost Distribution maps

The spatial distribution across the catchment of reach-scale Total Costs, Active costs and Passive Costs can be seen in Figure 83 - Figure 85.

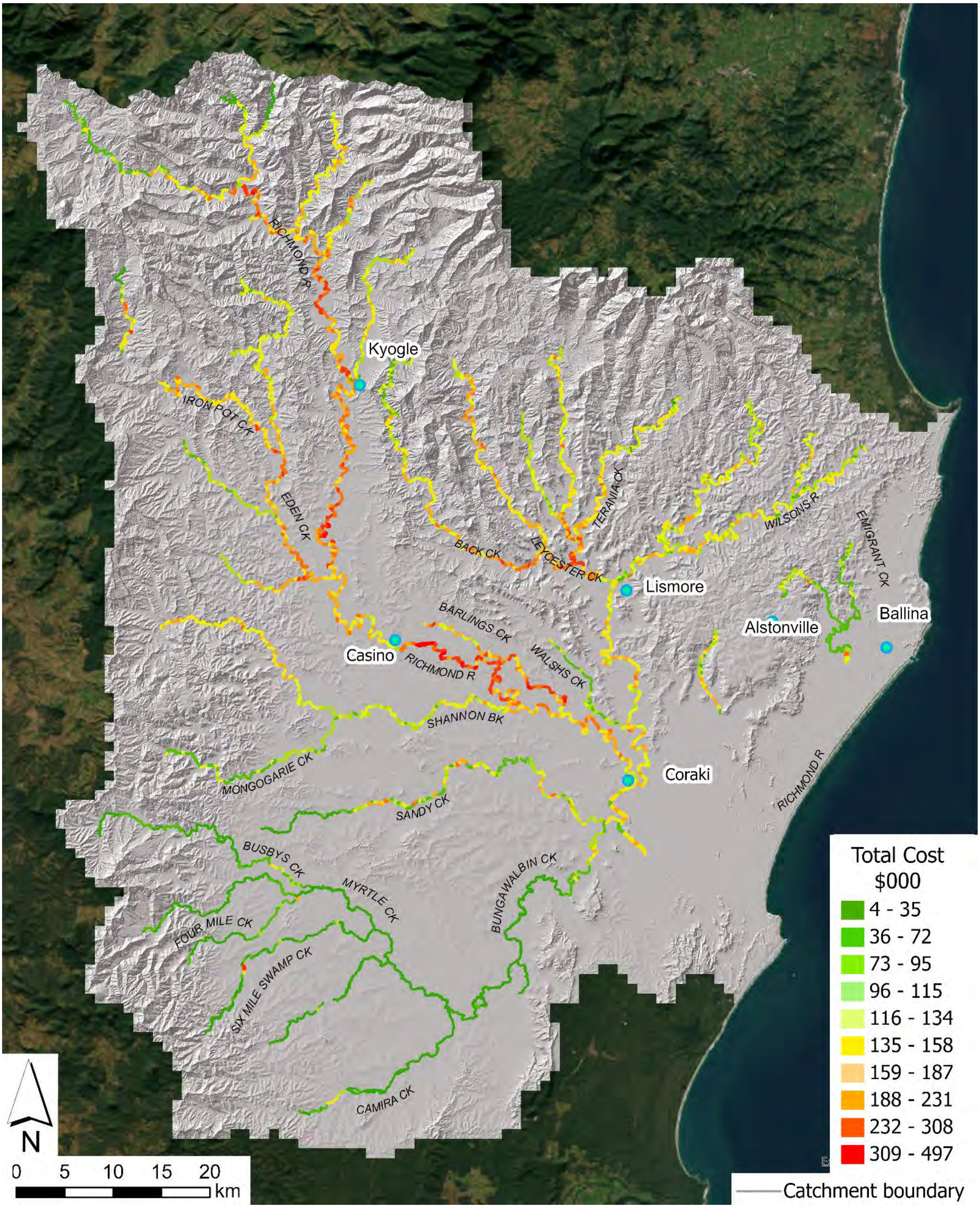

Figure 83. Catchment distribution of total reach rehabilitation costs.

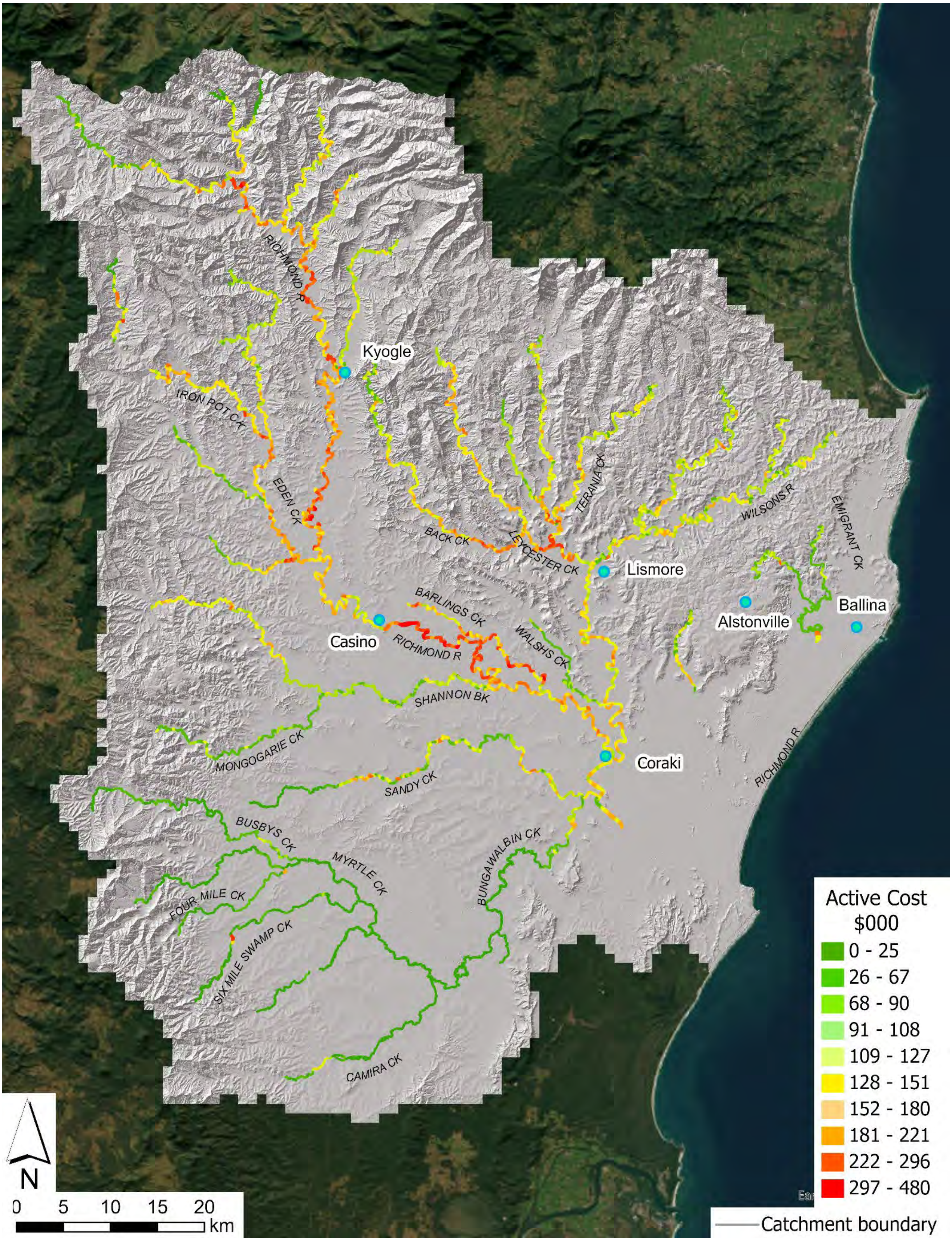

Figure 84. Catchment distribution of active reach rehabilitation costs. Active costs are those that involve active intervention within a reach to improve the native woody vegetation cover.

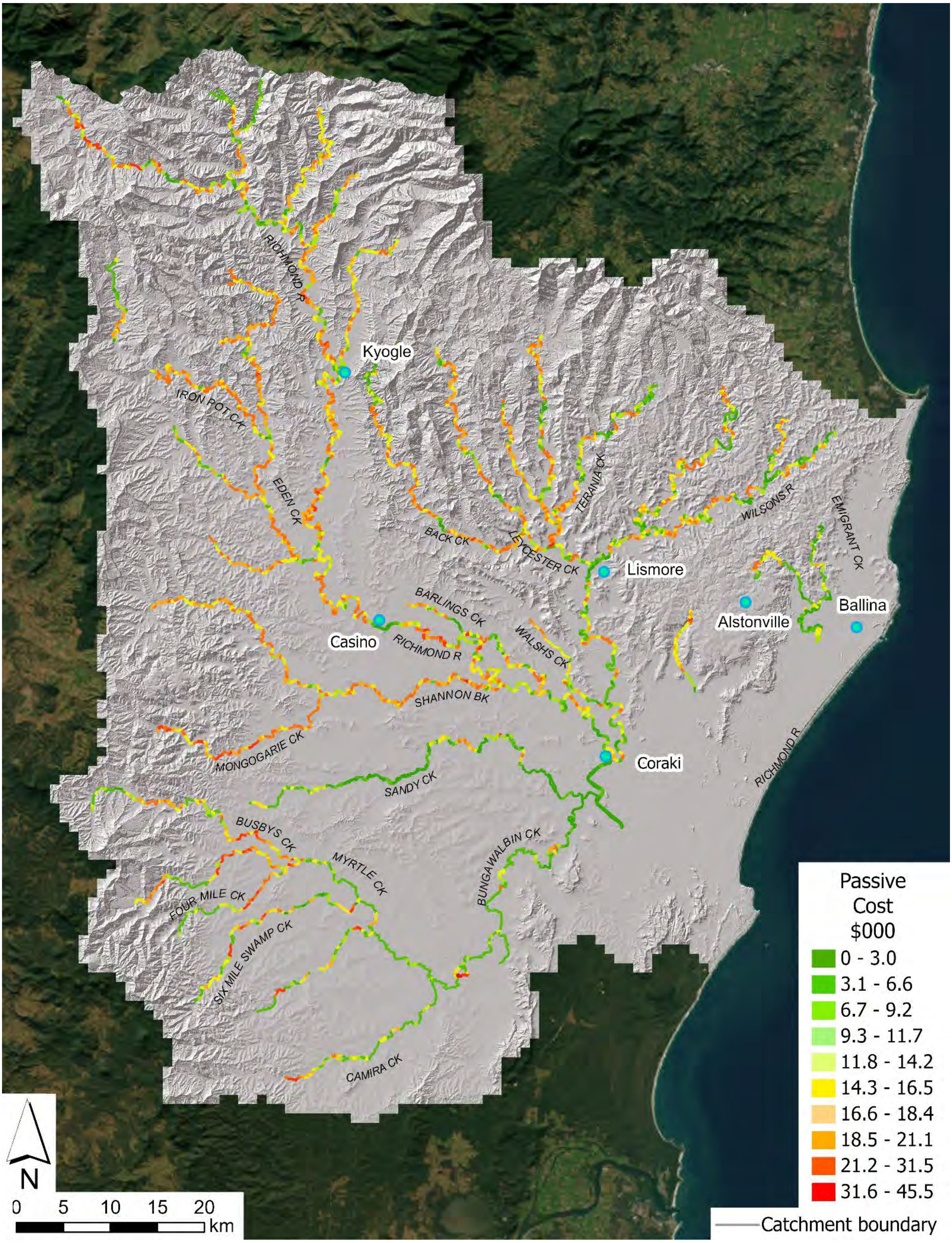

Figure 85. Catchment distribution of passive reach rehabilitation costs. Passive costs are those that involve fencing and/or monitoring only.

Appendix 8. Roads as a potential sediment source

Based on the Forestry NSW roads dataset , there are 11,038 km of roads within the Richmond River catchment. Roads are categorised by surface – sealed, wet weather gravel, major gravel, intermediate gravel, natural surface, 4WD track, and other/not constructed. Table 15 shows length and area by road types for the Richmond River catchment, and the Wilsons, Upper Richmond and Bungawalbin sub-catchments.

Table 15. Road types for the Richmond River catchment and selected sub-catchments

Road type	Wilsons	Upper Richmond	Bungawalbin	Other sub-catchments	Total catchment
Road length(km) by type and sub-catchment					
Sealed	951.2	575.8	152.5	989.7	2,669.2
Wet Weather Gravel	543.4	668.2	334.9	236.1	1,782.6
Major Gravel	30.8	46.6	71.4	50.6	199.4
Intermediate Gravel	-	-	9.3	0.0	9.3
Natural Surface	1,070.7	1,087.8	966.4	813.1	3,938.0
4WDTrack	338.4	584.5	1,224.1	84.5	2,231.5
Other/Not constructed	64.9	45.5	62.4	35.3	208.0
Total	2,999.5	3,008.3	2,820.9	2,209.3	11,038.1
Road area(ha) by type and sub-catchment					
Sealed	1,109	671	178	1,154	3,112
Wet Weather Gravel	498	613	307	217	1,635
Major Gravel	28	42	65	46	181
Intermediate Gravel	-	-	8	0	8
Natural Surface	684	695	618	520	2,516
4WDTrack	195	337	707	49	1,288
Other/Not constructed	37	26	36	20	120
Total	2,552	2,385	1,917	2,005	8,860
Road area by type and sub-catchment as % of total area					
Sealed	43.5	28.1	9.3	57.5	35.1
Wet Weather Gravel	19.5	25.7	16.0	10.8	18.5
Major Gravel	1.1	1.8	3.4	2.3	2.0
Intermediate Gravel	-	-	0.4	0.0	0.1
Natural Surface	26.8	29.1	32.2	25.9	28.4
4WDTrack	7.7	14.1	36.9	2.4	14.5
Other/Not constructed	1.5	1.1	1.9	1.0	1.4
Total	100.0	100.0	100.0	100.0	100.0

Table 16 shows length and area by road types for the study area channel and riparian buffer zones of the Richmond River catchment, and the Wilsons, Upper Richmond and Bungawalbin sub-catchments.

Table 16. Road types for the study area channel and riparian buffer zones of the Richmond River catchment and selected sub-catchments

Road type	Wilsons	Upper Richmond	Bungawalbin	Other sub-catchments	Total catchment
Road length (m) by type and sub-catchment					
Sealed	15,287.8	22,539.3	7,313.5	21,026.0	66,166.6
Wet Weather Gravel	5,063.9	15,716.7	5,015.8	2,146.4	27,942.8
Major Gravel	83.4	800.7	628.5	-	1,512.5
Intermediate Gravel		-	637.8	-	637.8
Natural Surface	17,795.7	25,535.7	13,250.4	8,973.2	65,555.0
4WD Track	13,344.3	4,158.9	19,268.4	-	36,771.5
Other/Not constructed	151.6	622.1	-	-	773.7
Total	51,726.6	69,373.5	46,114.3	32,145.6	199,359.9
Road area (ha) by type and sub-catchment					
Sealed	17.82	26.28	8.53	24.51	77.14
Wet Weather Gravel	4.64	14.41	4.60	1.97	25.63
Major Gravel	0.08	0.73	0.57		1.37
Intermediate Gravel			0.52		0.52
Natural Surface	11.37	16.32	8.47	5.73	41.89
4WD Track	7.70	2.40	11.12	0.00	21.22
Other/Not constructed	0.09	0.36		0.00	0.45
Total	41.70	60.49	33.81	32.22	168.22
Road area (m2) by type and sub-catchment as % of total					
Sealed	42.7	43.4	25.2	76.1	45.9
Wet Weather Gravel	11.1	23.8	13.6	6.1	15.2
Major Gravel	0.2	1.2	1.7	-	0.8
Intermediate Gravel	-	-	1.5	-	0.3
Natural Surface	27.3	27.0	25.0	17.8	24.9
4WD Track	18.5	4.0	32.9	0.0	12.6
Other/Not constructed	0.2	0.6	-	0.0	0.3
Total	100.0	100.0	100.0	100.0	100.0

Mean values of road width by road type have been determined by random sampling across the whole catchment. Figure 86 shows the mean values of road corridor width across the catchment's study area reaches (by road type). Based on these results, road corridors contained within the study area reaches have been excluded from the Marxan prioritisation analysis, as they are unsuitable for rehabilitation activities.

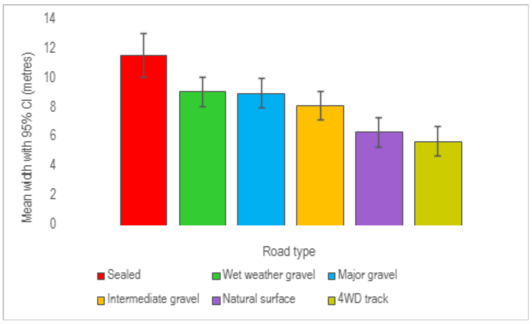

Figure 86. Road width mean values with 95% CI of road corridor network by road type for the Richmond River catchment.

Figure 87show the distribution of the road network, by road type across the Richmond River catchment. This analysis is also detailed for the following sub catchments Upper Richmond River above Coraki (Figure 89), Wilsons River above Coraki (Figure 90), Bungawalbin Creek (Figure 91), and rest of the Richmond catchment.

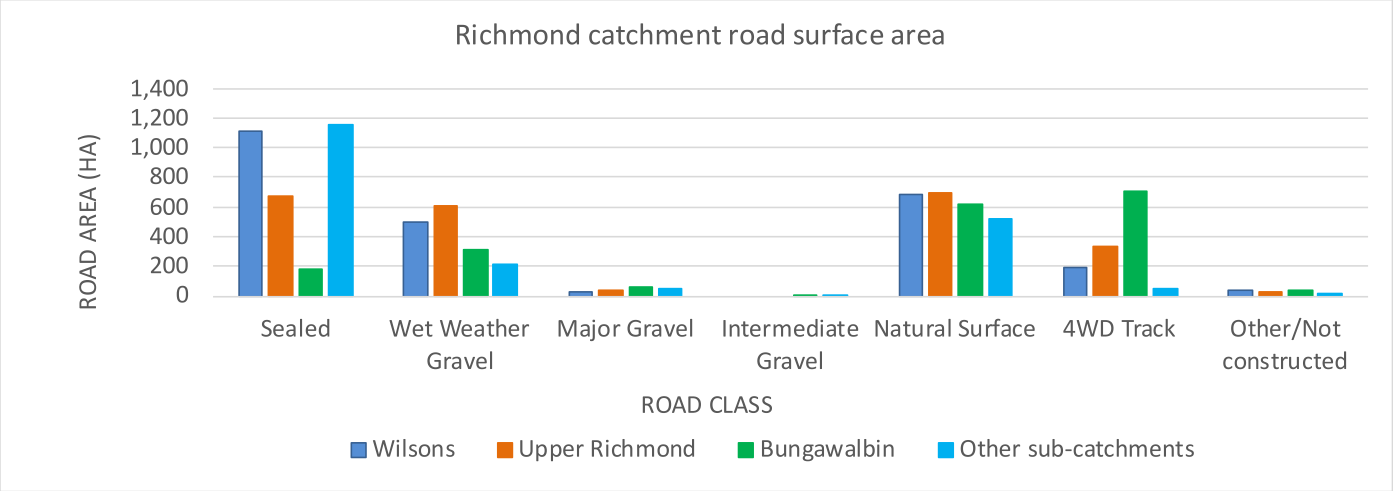

Figure 87. Road area (ha) by type for selected sub-catchments

Within the study area, 33% of reaches (954 out of 2884 – channel plus riparian buffer) contain roads. The road area (168 ha) comprises 1.2% of the total project reach area (145,874 ha). These roads have been excised from the reach areas and thus do not form part of the Marxan analysis. Table 17 shows estimates of sediment sourced from road runoff derived from the literature.

Table 17. Sediment source estimates derived from the literature

Type	Location	Findings	References
Australian studies			
Surveys suspended sediment yields	Kangaroo River State forest, NSW	Range 0-116 kg/ha (overall susp. sediment yields remained low with monthly yields ranging from 0 kg/ha during cease-to-flow conditions in all catchments to a high of 116.1 kg/ha during Feb 2009 in one catchment (increase in susp. sediment yield due to selective harvesting in this catchment limited to a few post-harvest flow events and had subsided within 12 mths of cessation of harvesting	Webb et al. (2012)
Field surveys and modelling	Forest road network, SE NSW	Mean sediment concentration in runoff plumes downslope from major access and feeder access roads significantly different, 7.18±0.66 g/L and 1.85±0.80 g/L, respectively.	Croke and Mockler (2001), Croke et al. (2005), Croke et al. (2006)
Monte Carlo simulation	Corangamite Catchment Mgt Authority, Victoria	Mean total sediment load range 2-34 MT/yr	Jha et al. (2006)
Measured plots over 2 yr period	SE Qld Pine plantation	5.7 t/km vs 3.9 t/km (gravelled vs ungravelled road plots). Susp. solids contributed 86% of total sed loss from gravelled road, and 72% from ungravelled road over the 2 yrs	Forsyth et al. (2006)
Field Surveys Survey (over 1 yr) of sediment delivery for 10 x 100-200 m sections of forest mgt activity roads	Victoria	Survey (over 1 yr) of sediment delivery for 10 x 100-200 m sections of forest mgt activity roads Total annual sediment load (normalized for slope) varied about 25-fold, from 216 mg/m2/mm of rain for a high-quality gravel surfaced road with minimal traffic to 5373 mg/m2/mm of rain for an unsurfaced road on an erodible subsoil with moderate light-vehicle traffic	Sheridan and Noske (2007)
Field surveys Surveyed	Victoria	Median susp. sediment concentration under low truck-traffic conditions (<9 return truck passes pre-storm) 269 mg/l, increasing 2-7-fold to a median of 725 mg/l under high truck-traffic conditions (>= 9 return truck passes pre-storm). These concentrations, and increases due to traffic, are substantially less than most previously reported values	Sheridan et al. (2006)
Modelled (CREAMS) data	**SE Qld** plantation forest roads	8 g/L (particle size <0.02 mm in diameter)	Costantini et al. (1999)
International studies			

Measured Measured comparison pre- and post-road construction, and post-harvest/hauling	Oregon, USA	Comparison pre- and post-road construction, and post-harvest/hauling. Pre-construction 634-2,317 mg/L, post construction 2,631-12,834 mg/L, post construction with harvesting/hauling 159-18,874 mg/L	Arismendi et al. (2017) Plus Supp data
Rainfall simulation experiments	British Columbia, Canada	Peak sediment concentration range 0.6-15.0 g/L, steady state concentration range 0.1-4.1 g/L	van Meerveld et al. (2014)
Monitored plots	Pacific Northwest, USA	Sed production 9x higher from aggregate covered silty clay loam vs gravelly loam roads	Luce and Black (1999)
Logged basins monitored	Pacific Northwest, USA	Avg sed yield range 0.51 - 500 t/km/yr, abandoned to heavy-use roads	Reid and Dunne (1984)

Figures 87 -90 show the road network and percentage of total road length by type across the Richmond catchment and by the Wilsons, Upper Richmond and Bungawalbin sub-catchments.

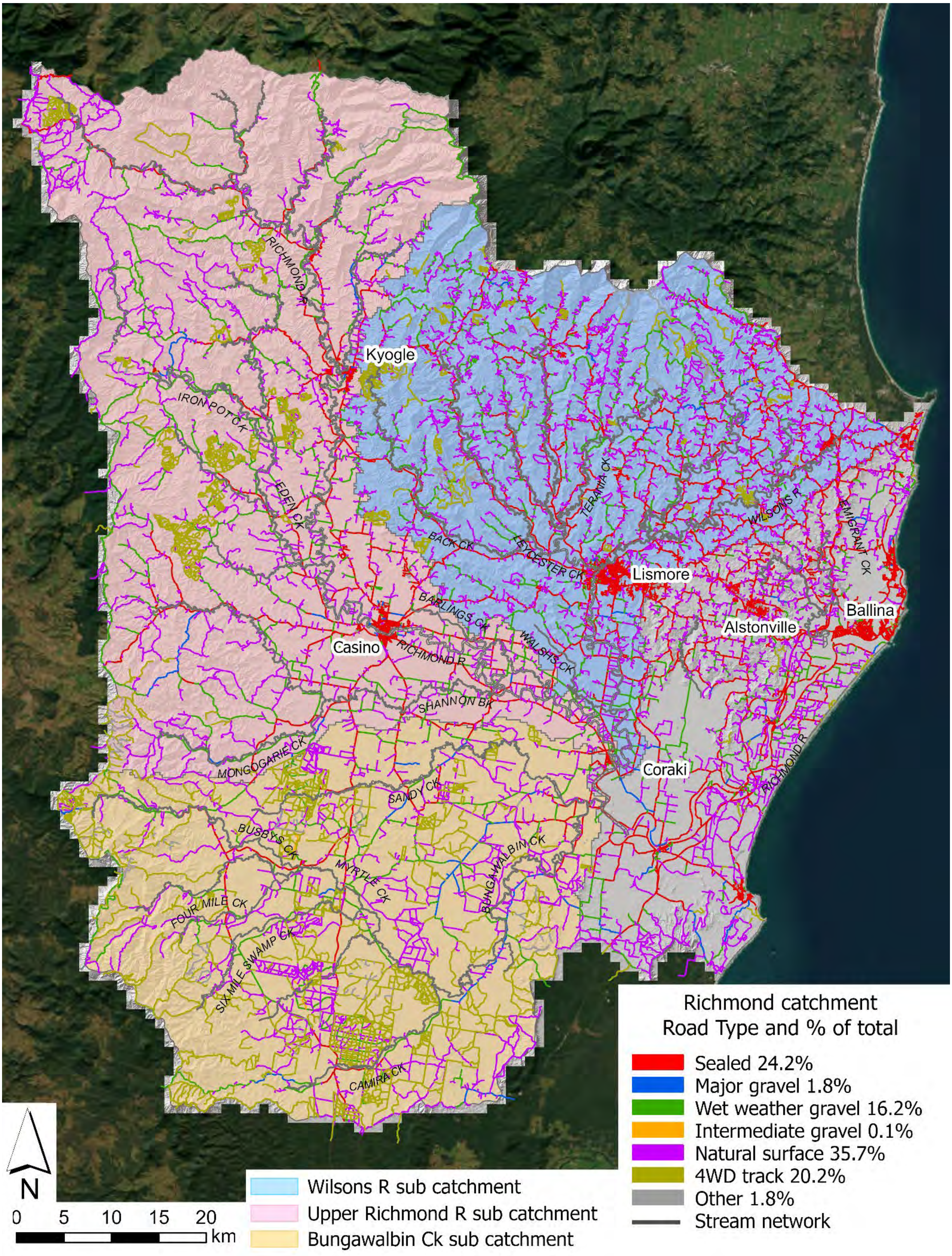

Figure 88. Distribution of road corridor network by road type (length) for Richmond River catchment

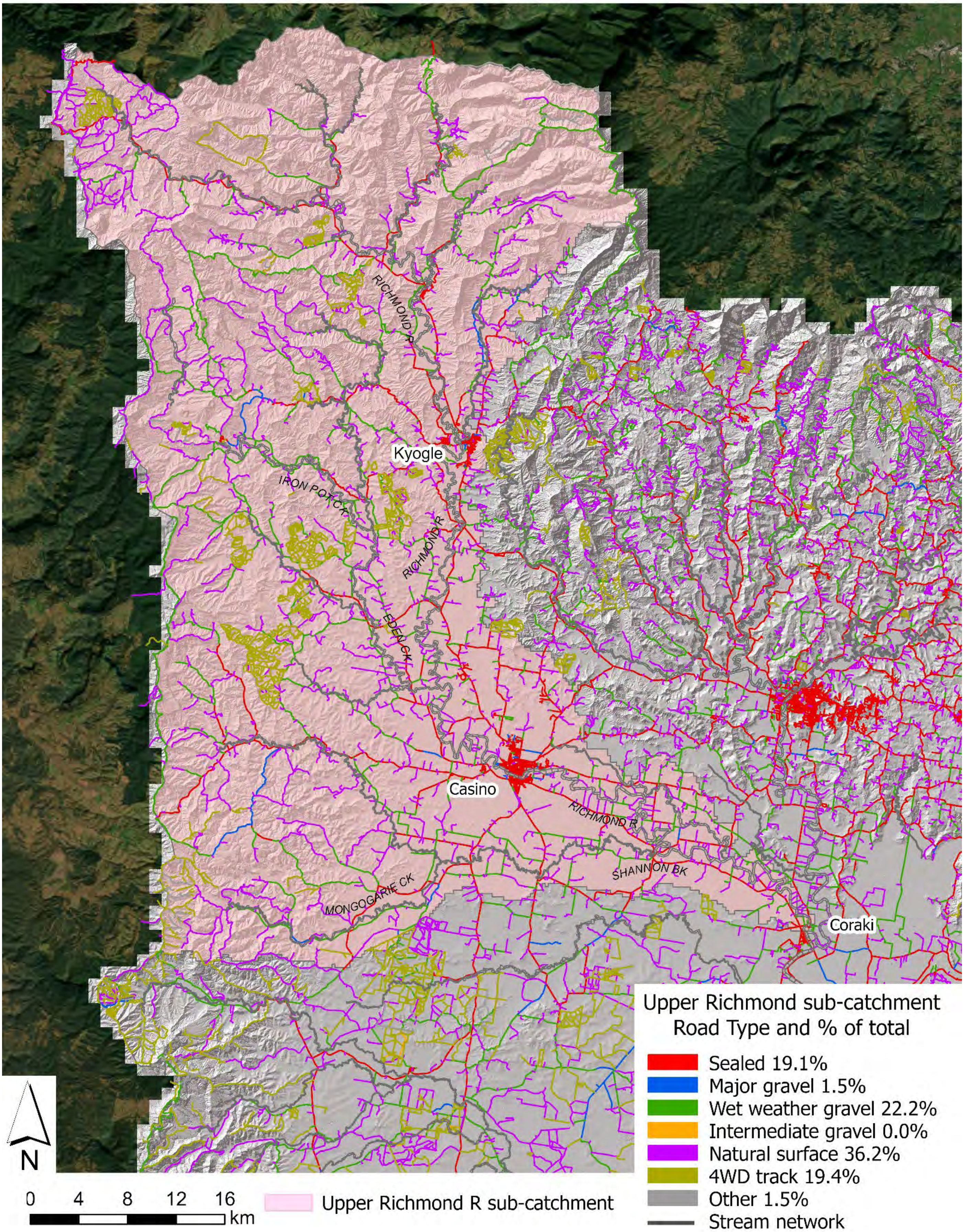

Figure 89. Distribution of road corridor network by road type (length) for Upper Richmond River sub catchment (above Coraki).

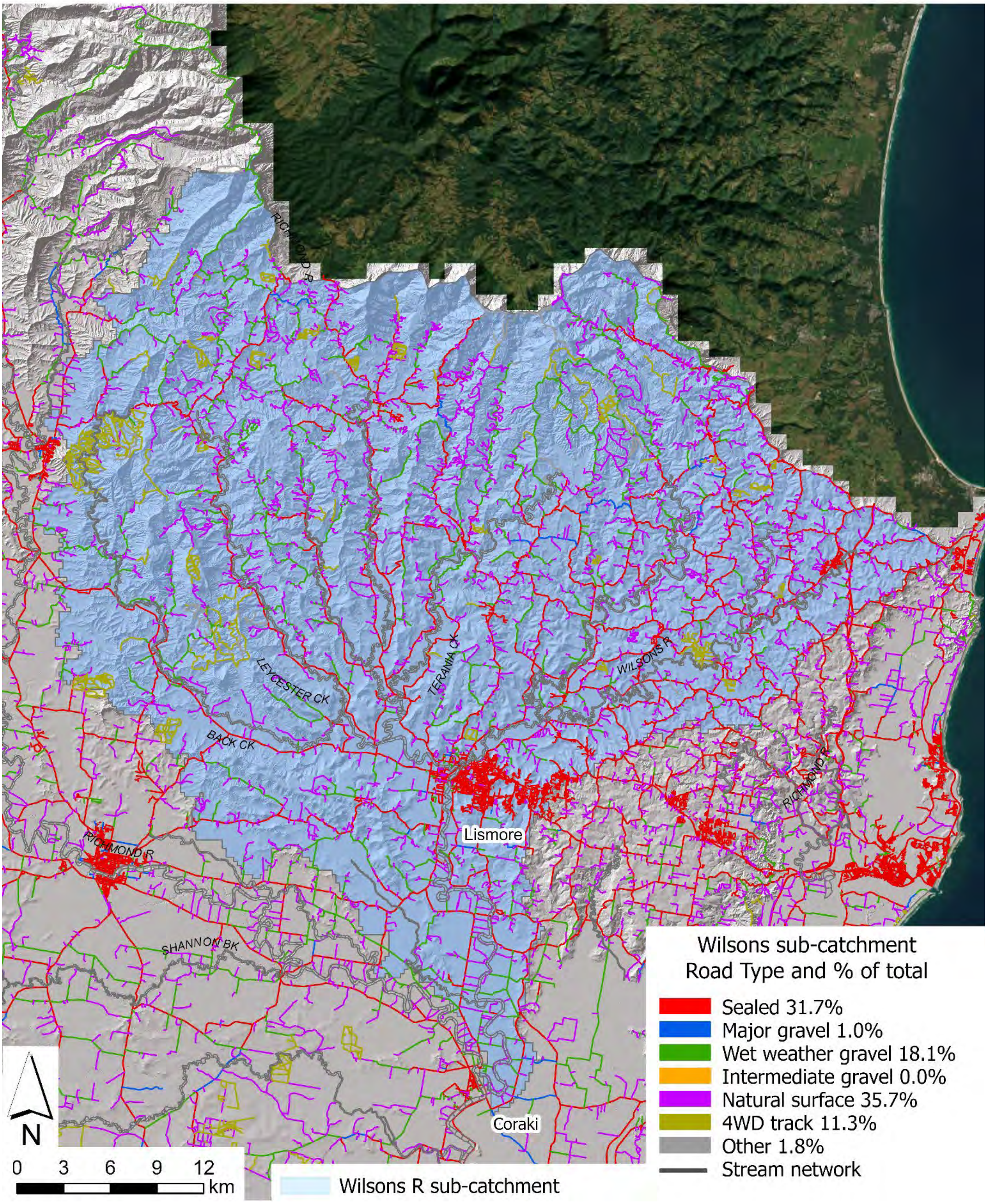

Figure 90. Distribution of road corridor network by road type (length) for Wilsons River sub catchment (above Coraki).

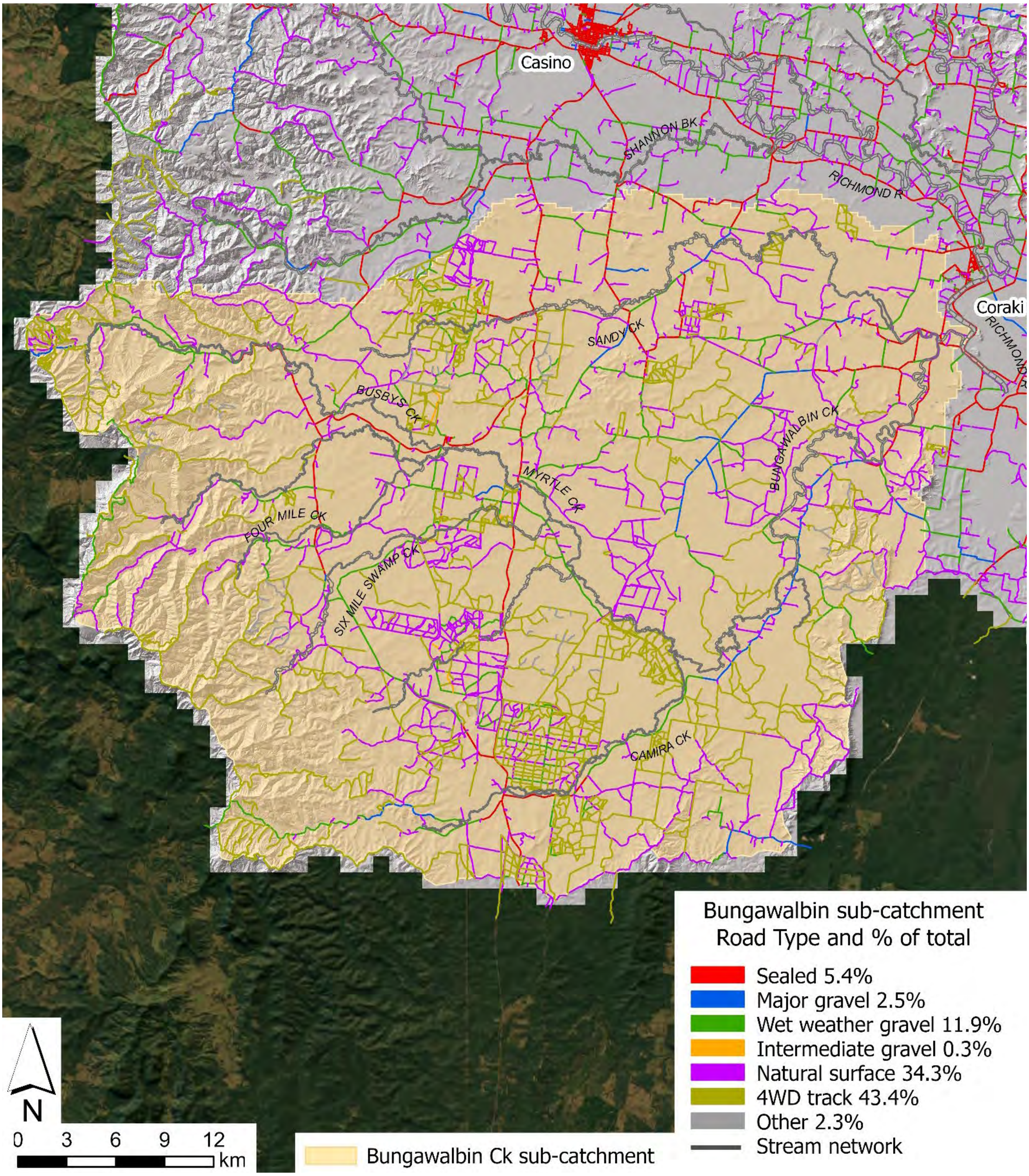

Figure 91. Distribution of road corridor network by road type (length) for Bungawalbin Creek sub catchment.

Sub catchments calculated using Australian Hydrological Geospatial Fabric (Geofabric) https://data.gov.au/data/dataset/a69bfc76-60b0-4256-8156-4ed7bba39bad

Appendix 9. Landslides as Sediment Sources.

Landslide mapping and volume calculations

Landslides were investigated across the northern part of the catchment, and it was clear that the vast majority of the landslides triggered in the 2022 flood occurred on the upper slopes of the volcanic geologies in the upper reaches of the Wilson River, Cooper Creek, Tuntable and Terania Creeks. This was also the area that received the highest rainfall intensities in the March 2022 flood. For this reason we have focused on this area to undertake detailed mapping of landslide distribution and volumetric analysis to determine the net sediment yield to the channel network from (Figure 92, Figure 93).

Many of the larger landslides coalesced into debris flows that stripped low order drainage lines to bedrock. Hence our mapping includes the combined landslip features along with the debris flow tracks that occurred downslope of the initial slips.

Further work on this dataset will include classifying with respect to channel-slope connectivity and separate landslides from other features.

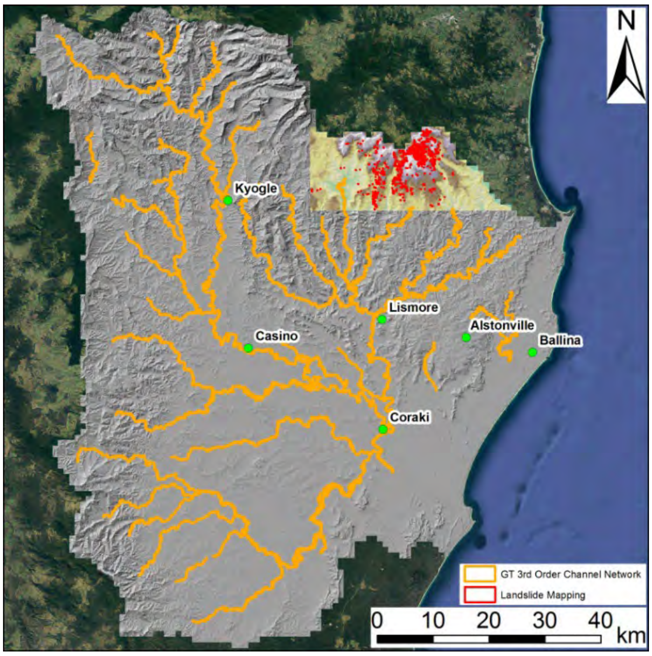

Figure 92. Map of the Richmond catchment showing the area where detailed landslide mapping and sediment yield estimates were undertaken.

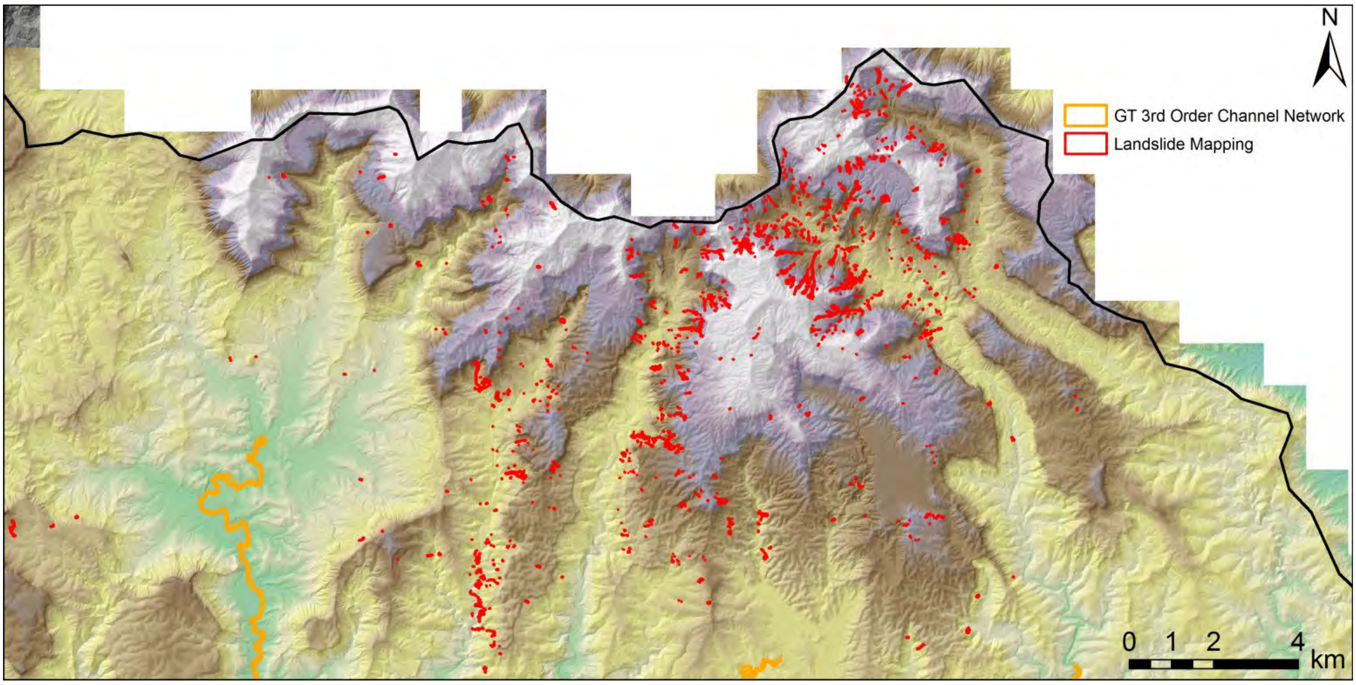

Figure 93. Blow up of the north-eastern part of the Richmond catchment showing the distribution of mapped landslides

Ground Truthing and landslide Recovery.

A number of landslides were visited on-ground to assess the extent of vegetation recovery since they were initiated in March 2022 and likely ongoing sediment delivery. Several landslides were visited in the Rocky

Creek catchment in November 2024, and these were recovering well (see Figure 94). Field reconnaissance of a significant proportion of the landslides in Upper Coopers Creek was undertaken in late July, and all landslides visited were showing signs of significant recovery, to the point where discharge from the landslide following 30mm of overnight rain was delivering relatively clear discharge (Figure 95 - Figure 97).

Figure 94. Landslide ID 235 taken in November 2024 showing the extent of natural recovery since March 2022

Figure 95. Landslide ID 846 where it enters Upper Coopers Creek (left) and 100m up from the creek (right) in July 2025 showing the significant extent of natural recovery since the landslide initiated in the March 2022 flood.

Figure 96. Landslide ID 819 after overnight rainfall of around 30mm (photo taken 27/07/2025), showing the water has very low suspended sediment load now.

Figure 97. Scarp face of a side arm of landslide ID 803 in July 2025 showing recovery of this large landslide in the 3 years since initiation.

Landslides

A total of 1630 landslides were mapped, some of which are part of larger complexes of landslides The total area of mapped landslides is in excess of 86 ha, and a highly conservative estimate of total landslide erosion volume is 966,082 m^3. Of this eroded material around 493,000 m^3 was measured to have been deposited immediately downslope of the area eroded. Thus we can infer that around 473,000 m^3, or around 710,000 t (assuming a soil bulk density of 1.5 g cm^3) was delivered to the stream network. It is likely that the deposited material represents the coarser fraction of the eroded sediment, comprising boulders and cobbles. Whilst some of this coarse sediment fraction was delivered directly to the channels downslope of the landslides, it is likely that the majority of the sediment volume that was actually delivered to the stream network represents the finer sediment fractions of sand, silt and clay. In upper Coopers Creek, large volumes of sand were reported to have been deposited on local floodplains (Jim Tait pers. comm.).

The landslide population is highly skewed, with a relatively small number of larger landslides contributing a disproportionate amount of the total sediment yield (Figure 98). Most of the eroded material is within a small number of the mapped landslide polygons, with 50% of the eroded material sourced from within 2% of mapped landslide polygons which represent 34% of the total mapped area.

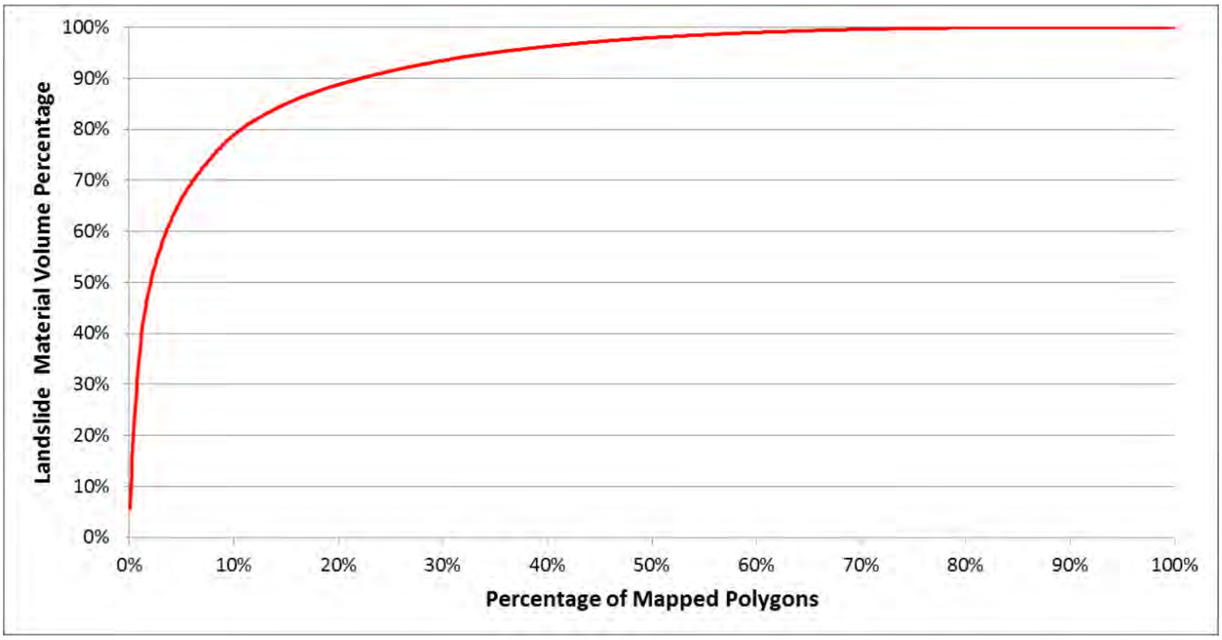

Figure 98. Plot showing the relative sediment contribution of mapped landslides ranked from the largest to smallest (left – right).

Figure 99, Figure 100, and Figure 101 show examples of these large landslide agglomerations that delivered a disproportionately large proportion of the sediment to the stream network.

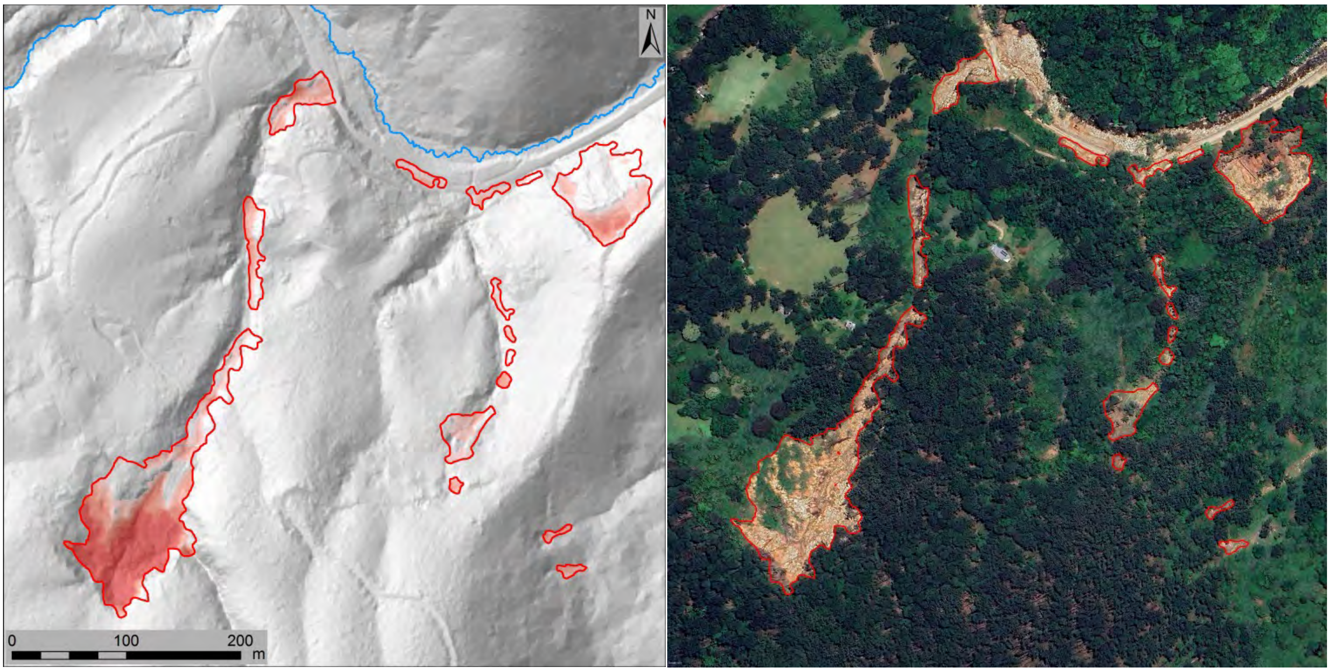

Figure 99. Landslide ID 903 had the largest land surface material loss with 55963 m^3 eroded.

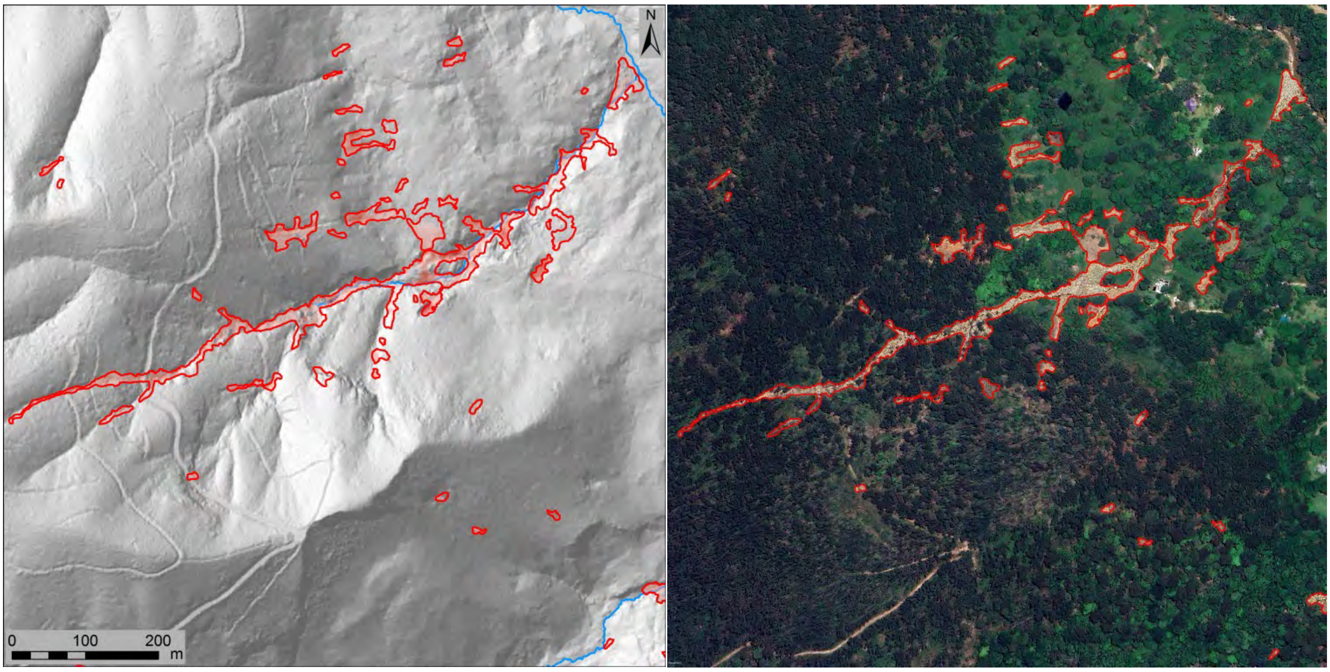

Figure 100. Landslide ID 803 had the twelfth largest land surface material loss with 16239 m^3 eroded.

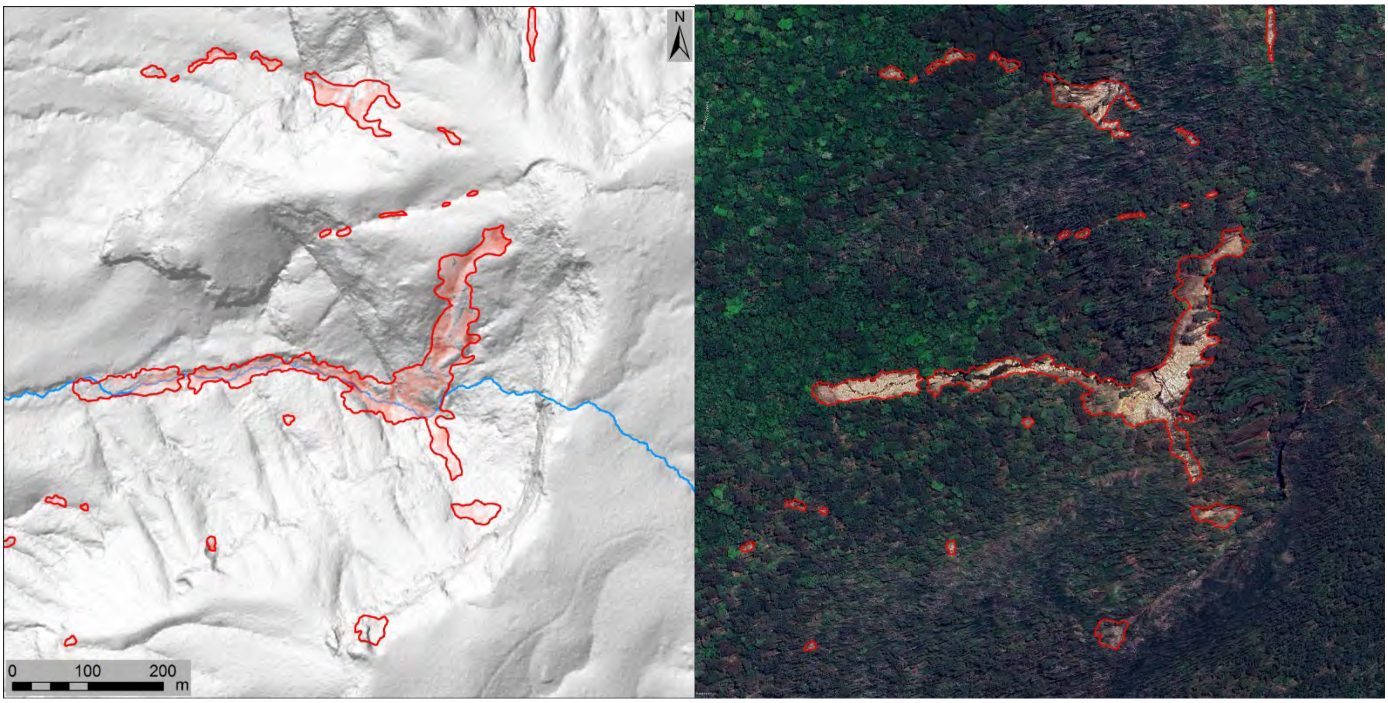

Figure 101. Landslide ID 636 had the sixth largest land surface material loss with 25054 m^3 eroded.

Appendix 10. Sub-catchment Sediment Sources

Sub-Catchments DEM differencing

NB – This is an exploratory first pass analysis to determine whether further work is needed to quantify erosion from small channels. These data should not be used for comparative purposes until more ground truthing is undertaken, couple with verification of erosion rates using independent lines of evidence (e.g. sediment tracing, SSC monitoring etc).

The contribution of sediment erosion from stream channels that are not included in or lower than 3rd order of the AHGF stream network were investigated in a subset of the low order tributaries in the upper Richmond River. The lidar DEM differencing analysis along the same lines as that undertaken from the ≥ 3rd order channel was undertaken on a sample of sub-catchments to provide an erosion/catchment area relationship.

Within the sampled sub-catchments a stream network was generated using a stream initiation area of 10,000 m^2 (1ha) and a buffer of 10 m generated either side of these streamlines (Figure 102, Figure 103). The lidar DEM differencing data within this analysis area was extracted for each sub-catchment (Figure 104). The channel and riparian buffer area of the greater than 3rd order streams used in the catchment analysis for this project were excluded from the area of the sub-catchment analysis.
The lidar DEM differencing used the same error filtering as used for the greater than 3rd order stream analysis. That is, areas greater than 3 m^2 with no ground surface data in either lidar time slice were excluded from the analysis. In addition, for all of the difference data ±2 standard deviations around the zero change excluded to remove noise and spurious data.

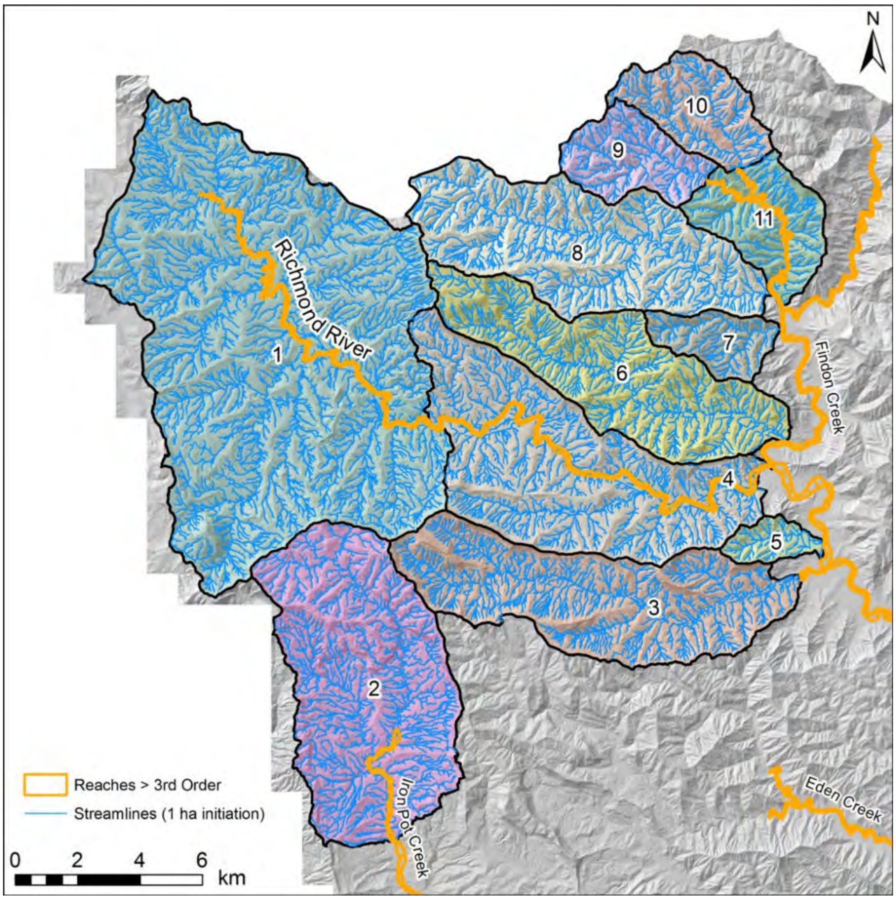

Figure 102. The 11 sub-catchments that were investigated in the Upper Richmond. The map shows the streamline network generated from the DEM data with a 1 hectare initiation (note these should not be assumed to represent actual channels).

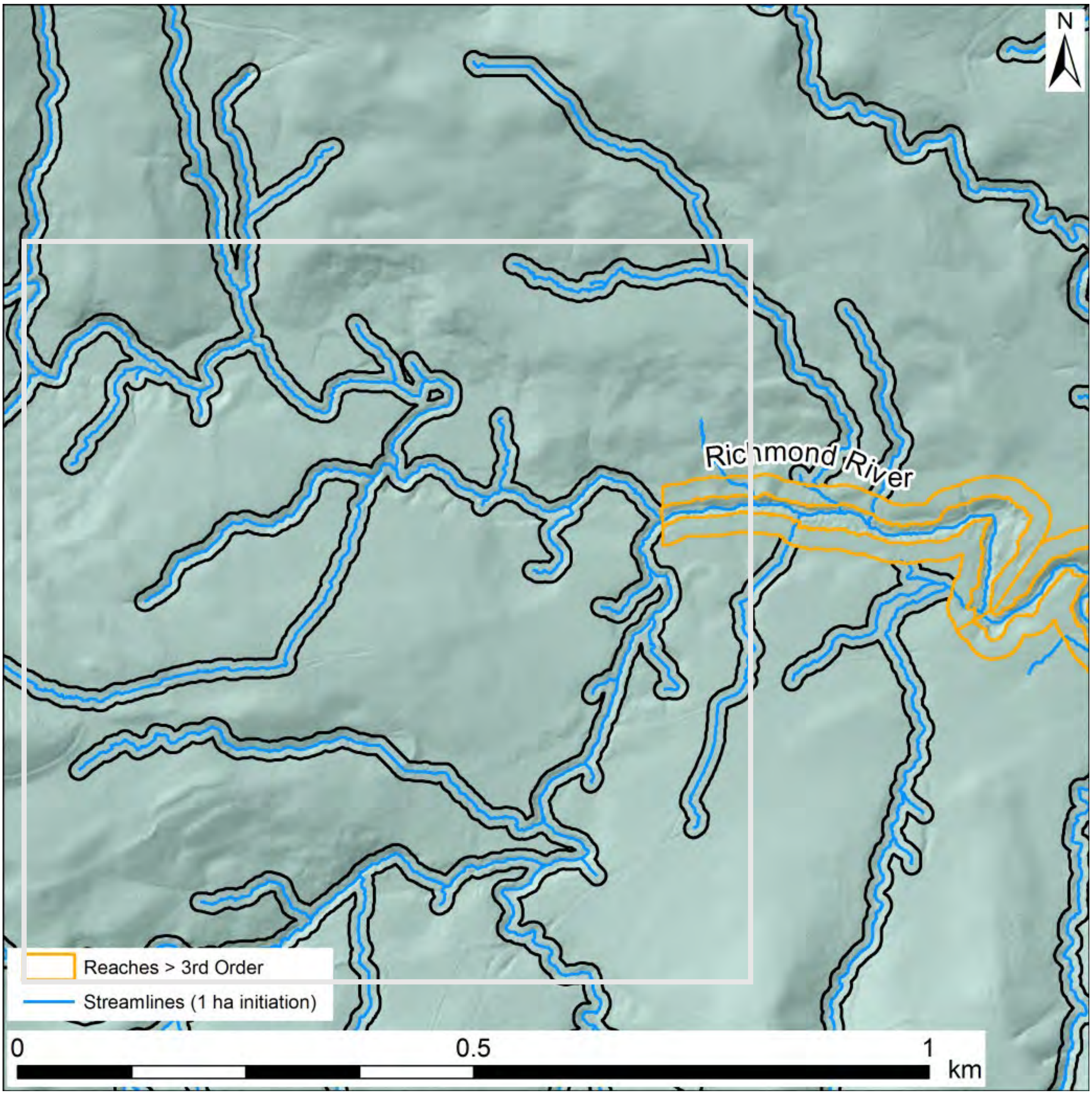

Figure 103. Examples of the 10m buffer either side of the streamlines shown here was chosen as the sub-catchment analysis area. As can be seen, the 10m buffer analysis area does not extend into the riparian buffer and channel area (outlined in orange) of the greater than 3^rd order of the AHGF network used for the catchment analysis. Box indicates coverage shown in Figure 104.

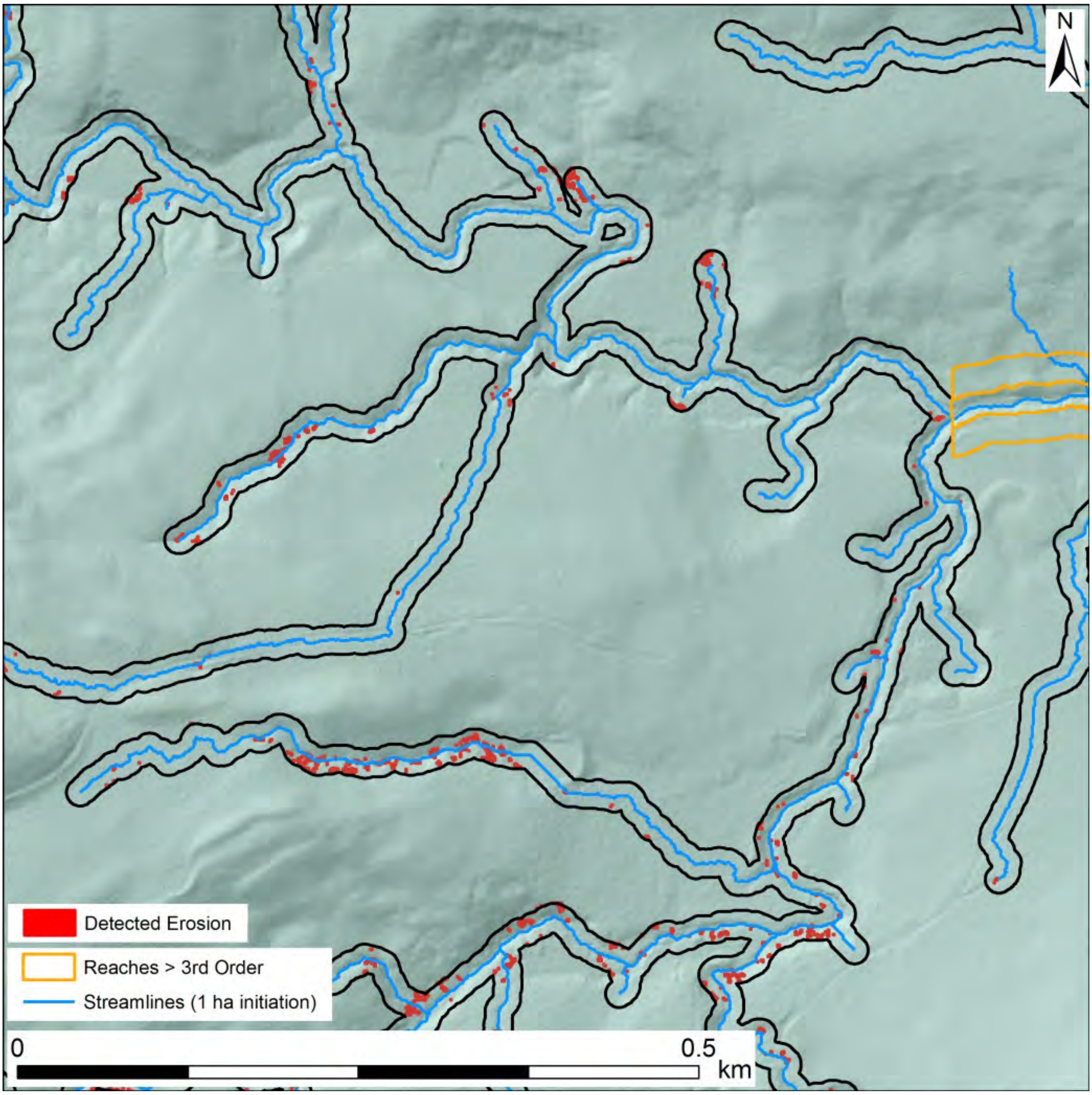

Figure 104. Examples of the detected erosion within the buffered area in low order streams using the 1 ha streamline initiation threshold – noting that an area initiation threshold may over-estimate the extent of some streamlines – and under-estimate others - depending on terrain attributes etc.

Results of Low Order Catchment Analysis

Initial results of the analysis are shown in Table 18 and Figure 105 and the data indicates that these low order channels potentially represent a significant erosion source at the catchment scale. However, it must be stressed that these data are yet to be ground verified, and they represent extremely high rates which gives us considerable cause for concern that they are significantly over-estimated.

Limitations of Analysis

The DEM differencing analysis has several deficiencies that give us cause for concern about the results of the analysis. The older (2017) lidar acquisitions in the western sector of the Richmond catchment (Figure 60. **Pre-2018 lidar acquisition campaigns**) have relatively low ground point density compared to the 2023 acquisition. This potentially introduces significant error into the analysis, which can lead to over-estimates of apparent erosion due to the poor penetration of the lidar to the ground in the earlier dataset.

There is also an issue with the generation of the low order stream network based solely on an area initiation threshold. A channel initiation of 1ha, as used here, is designed to capture the majority of low order streams, but it also captures a range of unconfined flow paths and other anomalous flow paths, such as, roadside drains. This can therefore over-estimate the true extent of the stream network (regardless of whether some of these artificial features may well be erosion sources in their own right). To implement effective and efficient analysis across catchments using the scale of lidar data that is currently available, new processing methods need to be developed to distinguish between confined and less confined streamlines and channelised/unchannelised valley bottoms. Both of these issues can create spurious results that skew the data toward an over-estimate. Hence these data should only be considered as a first attempt to quantify this source of sediment from low order channels, but the results suggest that a more detailed assessment is required. If these data are of an appropriate order of magnitude, channels of this scale would represent the dominant source of sediment in the whole catchment. Hence further investigation is clearly required to verify these initial results.

Table 18. Erosion volume from low order channels for each sub-catchment between 2017 and 2023 – using the 1ha channel initiation threshold (NB – not to be used for comparative purposes. Exploratory analysis only!)

Sub-catchment Number	Erosion (m^3)	Erosion (t)	Area (Hectares)	Sed yield (t/ha)	Sed yield (t/ha/yr)
1	245,592	368,388	114.0	3231	646
2	22,314	33,472	46.7	717	143
3	101,843	152,765	37.0	4,134	827
4	139,406	209,109	43.9	4,764	953
5	15,719	23,578	3.4	7,017	1,403
6	54,447	81,671	31.5	2,589	518
7	8,544	12,815	6.5	1,971	394
8	45,770	68,655	36.9	1,861	372
9	3,524	5,286	10.2	520	104
10	4,291	6,436	11.3	570	114
11	19,493	29,239	11.9	2461	492
Total	660,942	991,413	353.2	Av = 2807	Av = 561

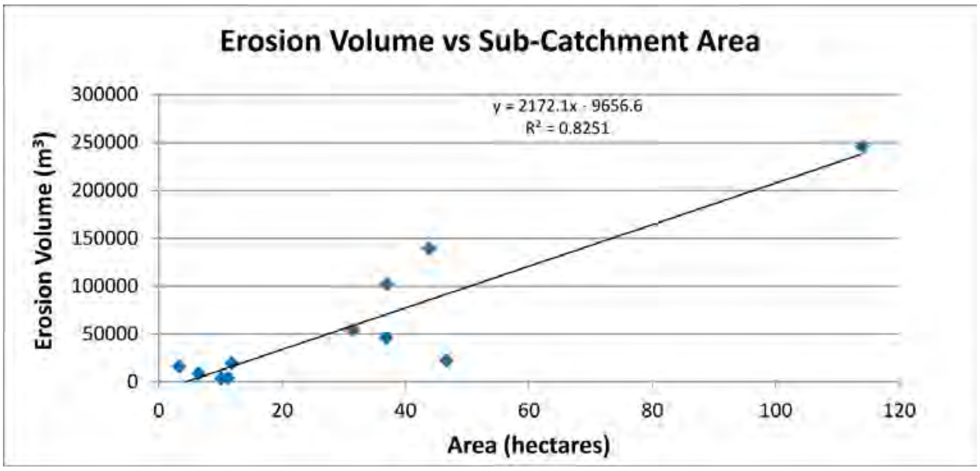

Figure 105. Relationship between sub-catchment area and detected erosion volume for low order channels using the 1ha channel initiation threshold.

Alternative Low order Stream Configuration (50ha threshold)

As a way of reducing the likely overestimation of erosion from low order channels due to the overestimation of the functional channel network, an additional analysis was run that used a higher threshold (50ha) for channel initiation using the same approach as outlined above – noting the channel and riparian buffer area of the greater than 3rd order streams used in the catchment analysis for this project were excluded from the area of the sub-catchment analysis. The generated stream network can be seen in Figure 106, highlighting the much lower density of network when compared with Figure 102. The derived erosion rates as shown in Table 19 and Figure 108 as expected are substantially lower than those derived from the more extensive low order network derived from the 1ha threshold. However, even these rates are high and warrant further investigation.

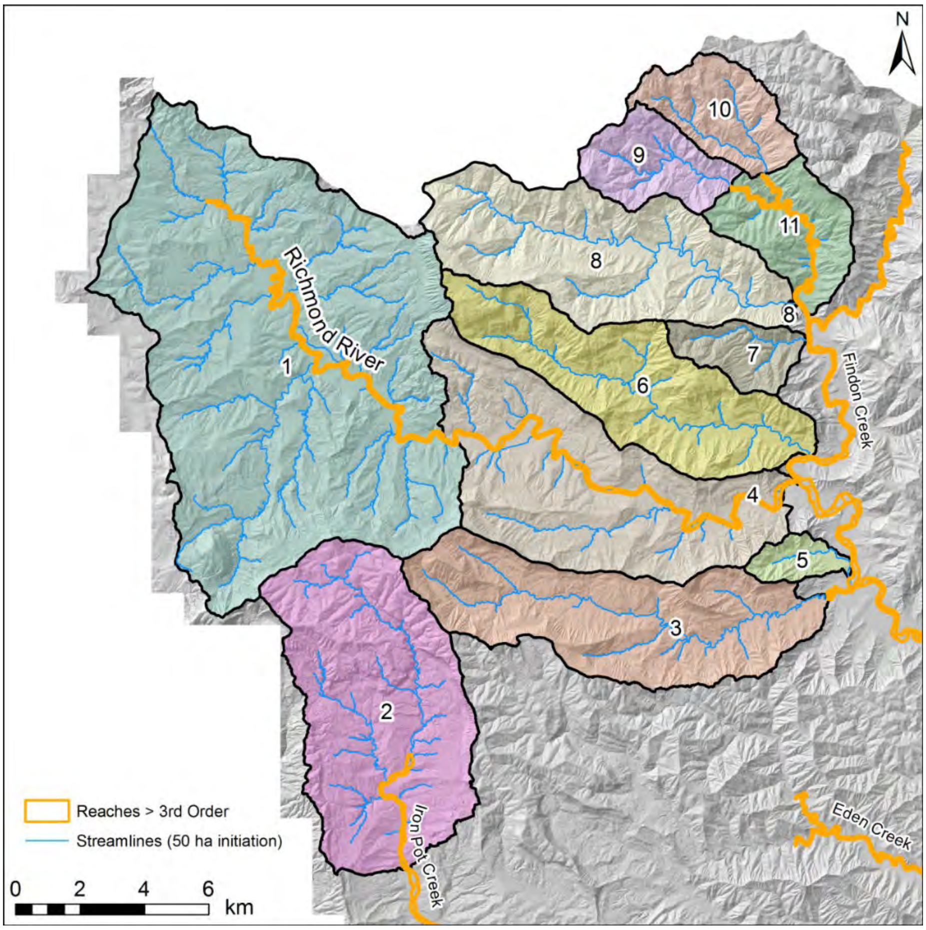

Figure 106. Low order stream network generated from a 50ha area threshold of channel initiation.

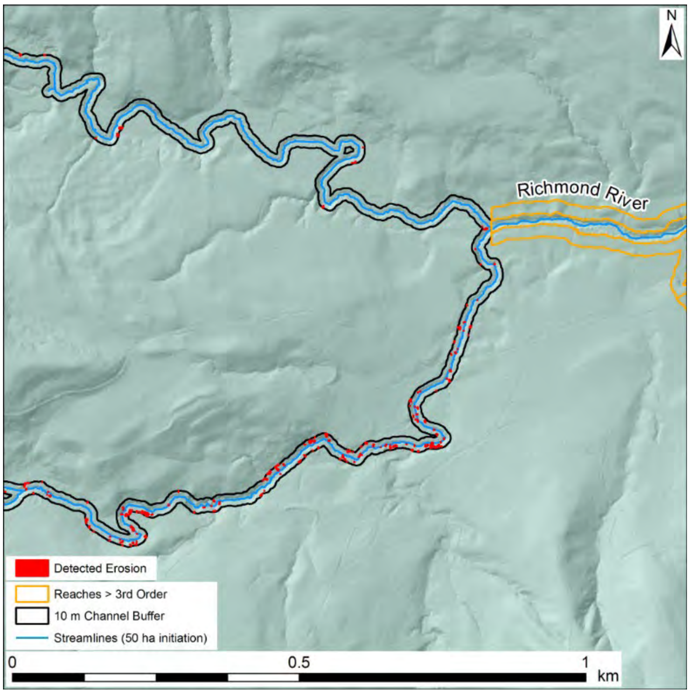

Figure 107. Examples of the 10m buffer either side of the streamlines shown here was chosen as the sub-catchment analysis area. As can be seen, the 10m buffer analysis area does not extend into the riparian buffer and channel area (outlined in orange) of the greater than 3rd order of the AHGF network used for the catchment analysis.

Table 19. Erosion volume from low order channels for each sub-catchment between 2017 and 2023 – using the 50ha channel initiation threshold. (NB – not to be used for comparative purposes. Exploratory analysis only!)

Sub-catchment Number	Erosion (m^3)	Erosion (t)	Area (Hectares)	Sed yield (t/ha)	Sed yield (t/ha/yr)
1	36,526	54,790	114	481	80
2	4,134	6,201	47	133	22
3	10,637	15,955	37	432	72
4	13,761	20,642	44	470	78
5	884	1,326	3	395	66
6	5,263	7,894	32	250	42
7	1,123	1,684	7	259	43
8	2,925	4,387	37	119	20
9	719	1,079	10	106	18
10	418	627	11	56	9
11	449	673	12	57	9
Total	76839	115259	353	Av = 326	Av = 65

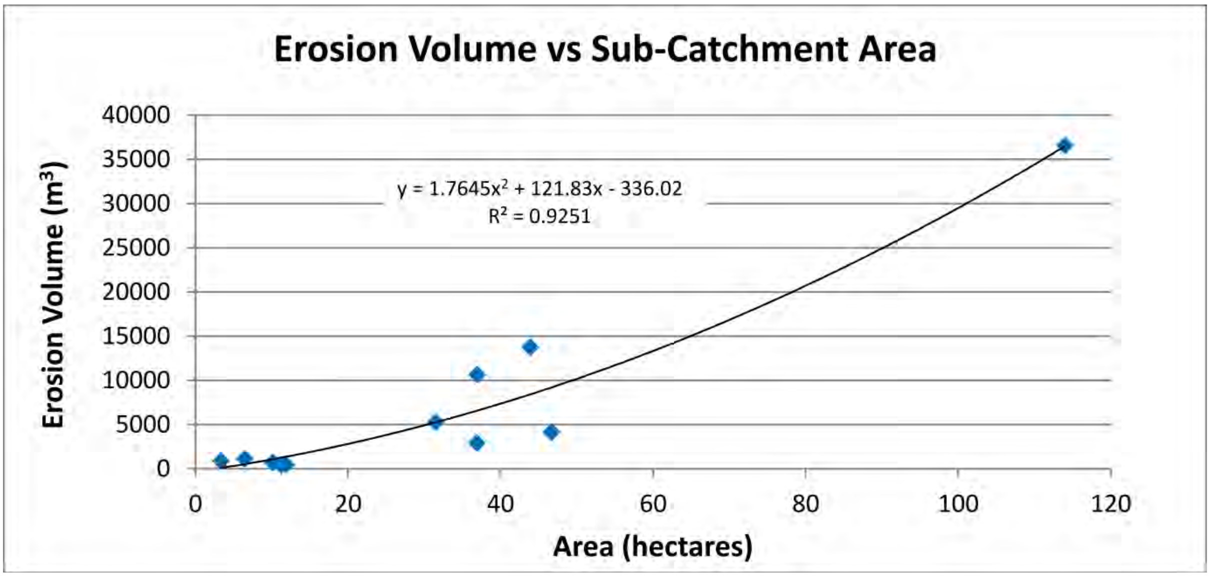

Figure 108. Relationship between sub-catchment area and detected erosion volume for low order channels using the 50ha channel initiation threshold.

Appendix 11. Relationship between River Styles and data derived in This study

Whilst this study was conducted completely independently of any pre-determined River Styles, the following plots (Figure 109 - Figure 116) show the relationship between the four key input datasets used in this study and the various River Styles classes. The channel erosion data in particular seems to conform with what might be expected, while the vegetation classes also show distinct patterns that reflect the inter-relationship between River Style and riparian vegetation extent and composition. Perhaps the most striking contrast with the River Styles classes and the data derived in this study is the relationship between the RS priority reaches and the priorities assessed for this study. In effect the priorities are inverted – which reflects the fact that this study is targeting the highest eroding reaches whereas River Styles typically prioritises the reaches in better condition first. This highlights the point that any management prioritisation is a function of the primary objective(s). The prioritisation in this study also factors in costs, which adds another layer of complexity.

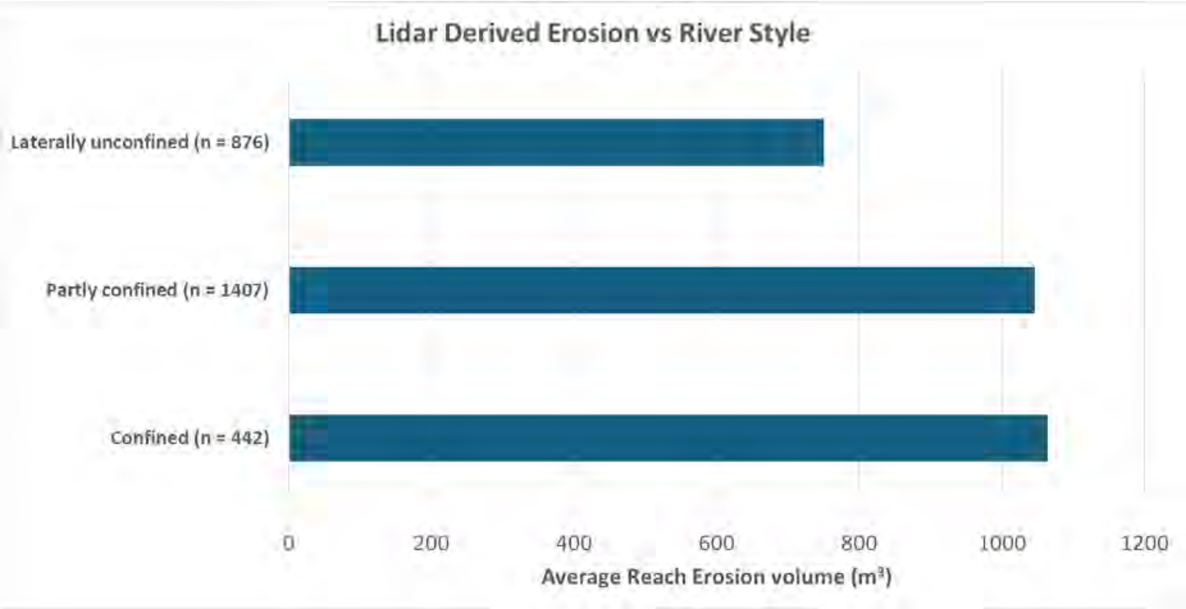

Figure 109. Comparison between high order River Style e class and channel erosion from this study

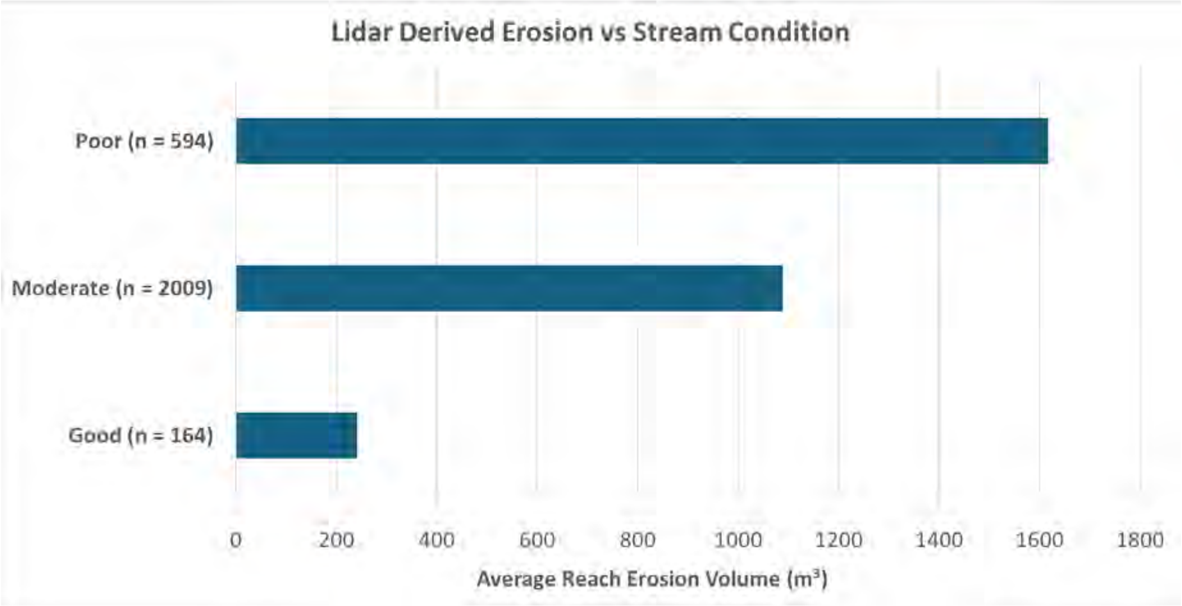

Figure 110. Comparison between River Style stream condition class and channel erosion from this study

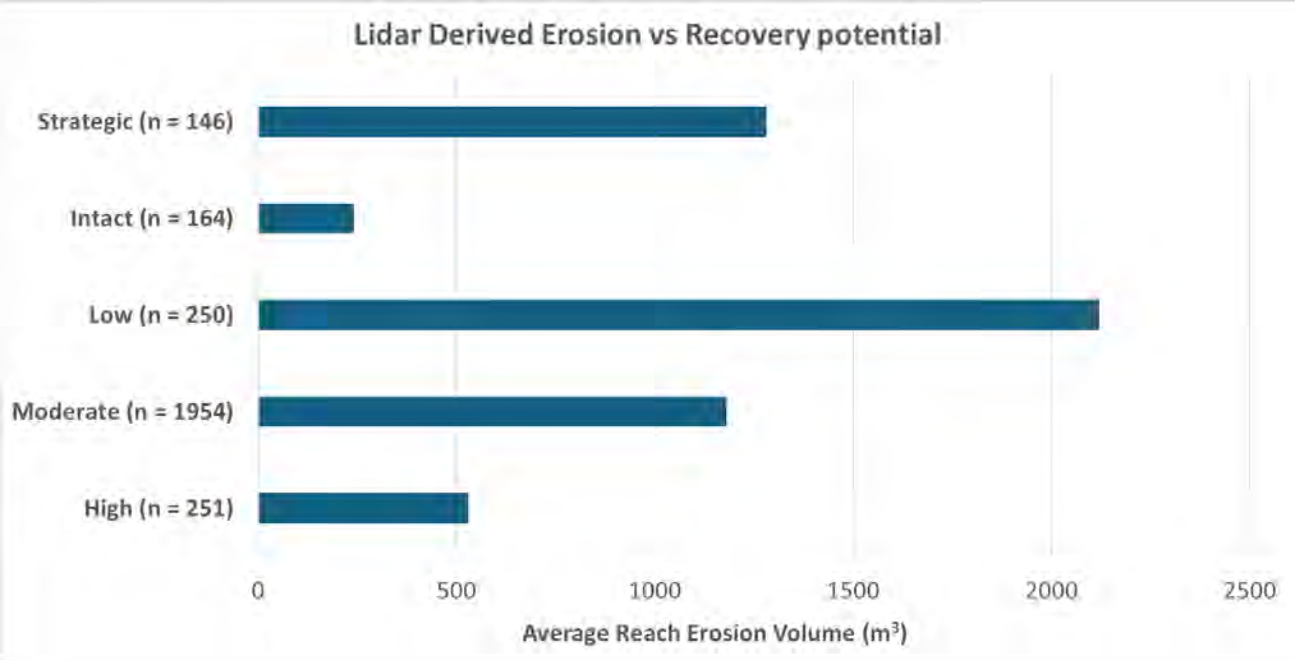

Figure 111. Comparison between River Style recovery potential class and channel erosion from this study

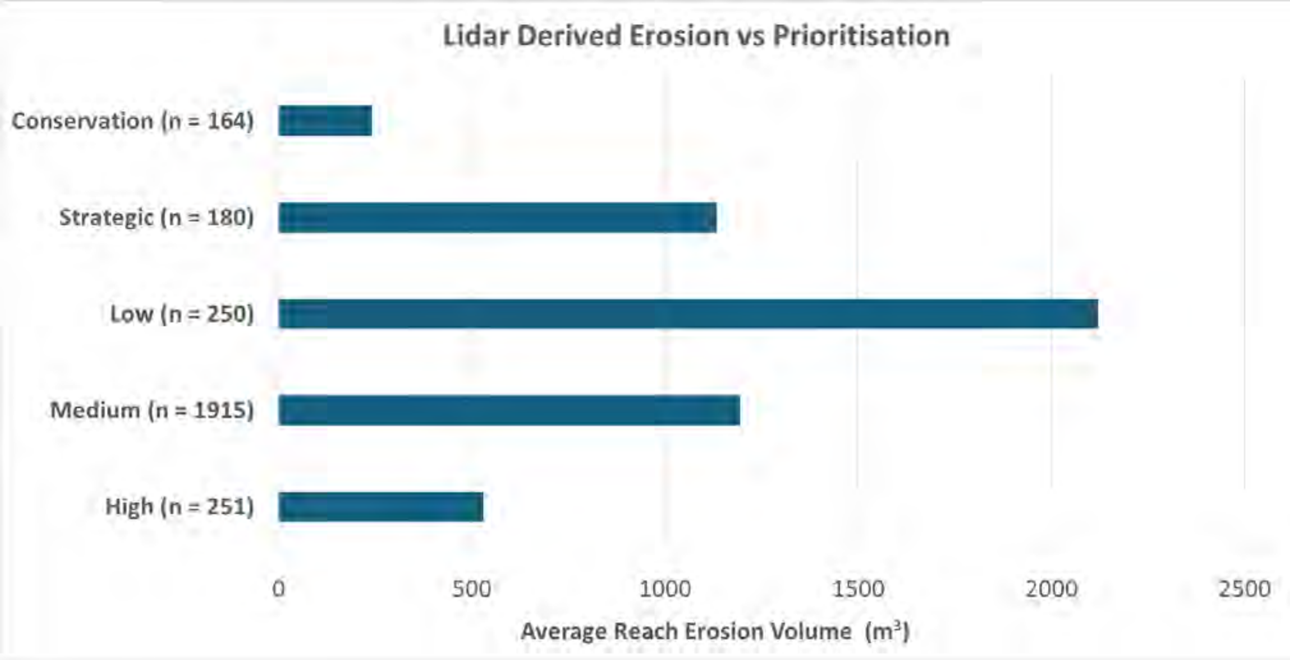

Figure 112. Comparison between River Style management prioritisation and channel erosion from this study

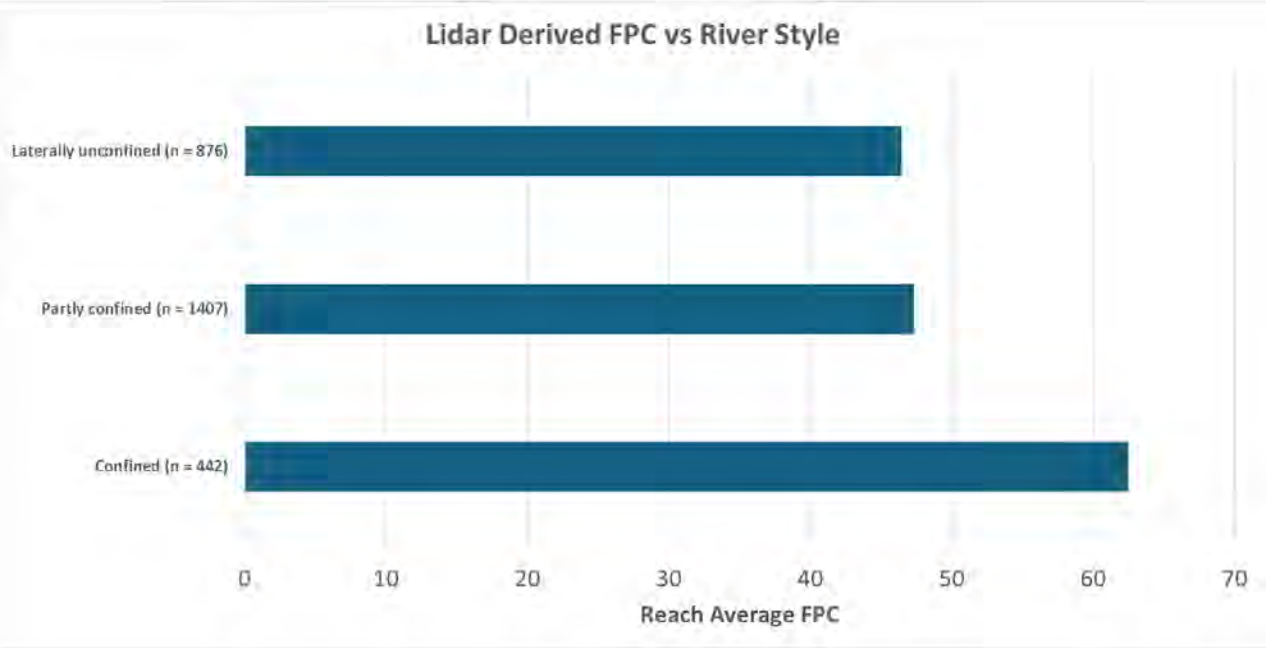

Figure 113. Comparison between River Style class and FPC from this study

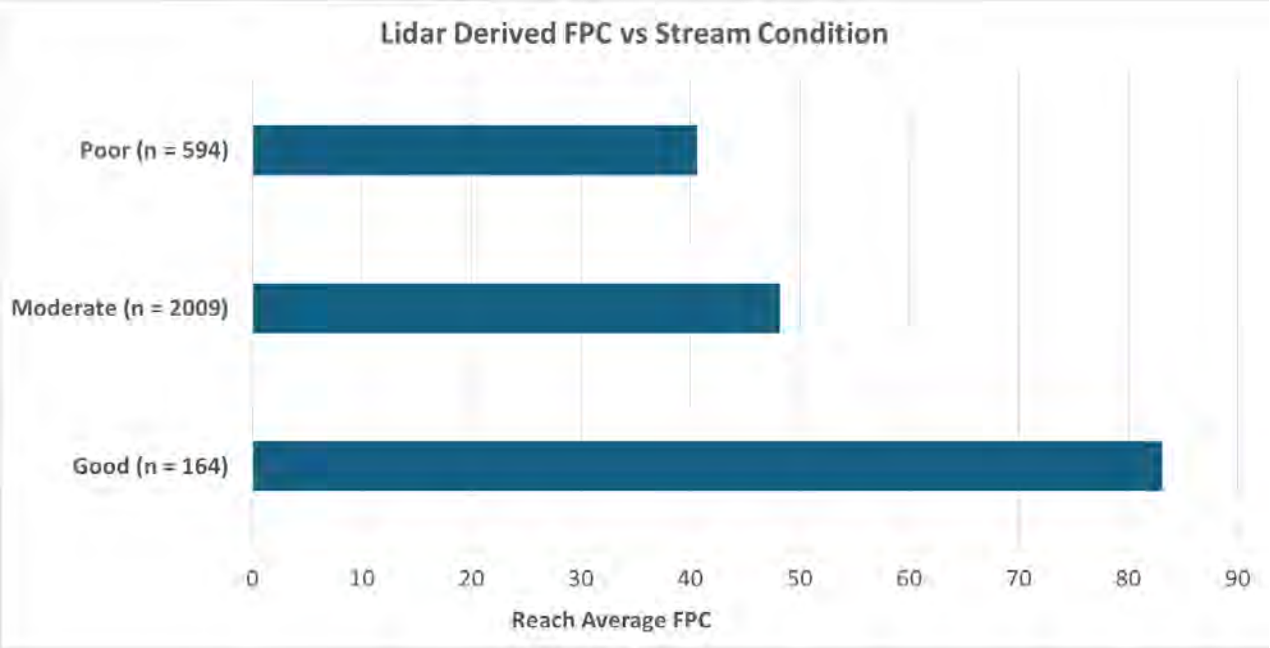

Figure 114. Comparison between River Style stream condition class and reach average FPC from this study

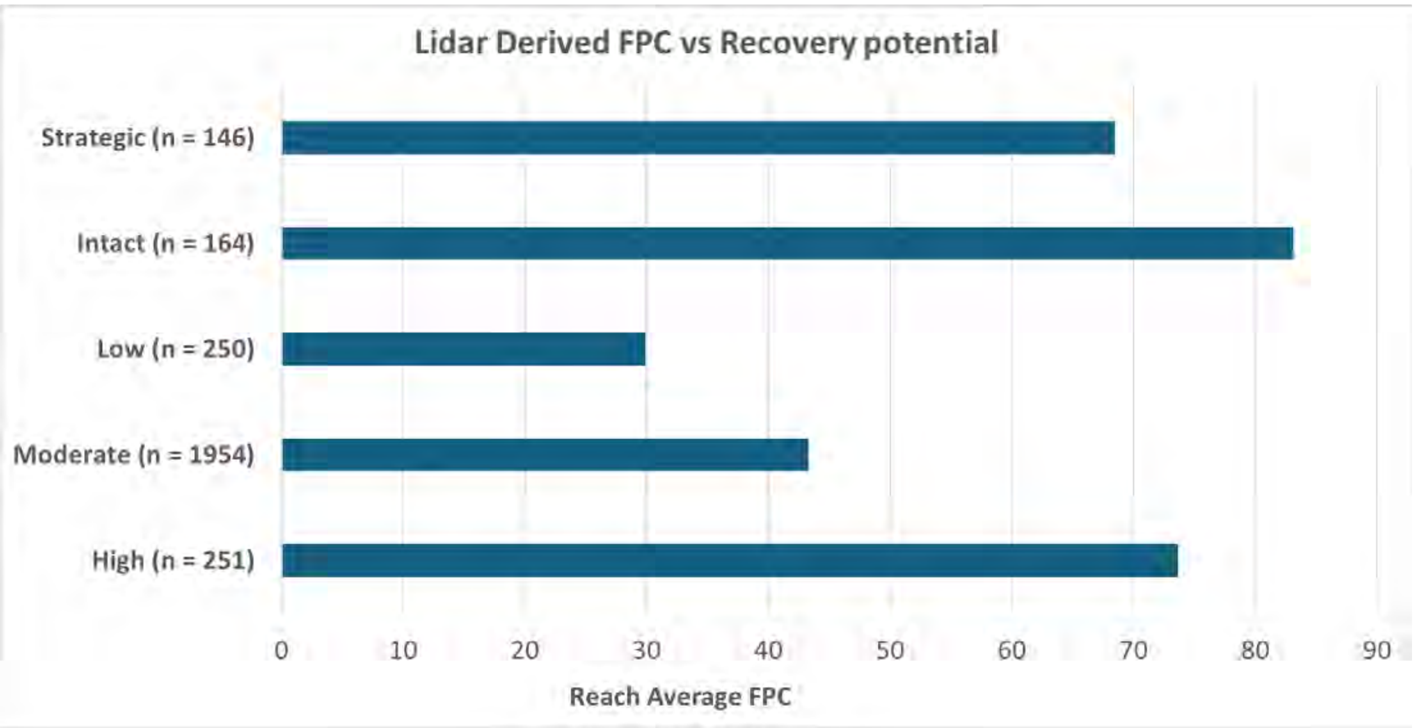

Figure 115. Comparison between River Style recovery potential class and reach average FPC from this study

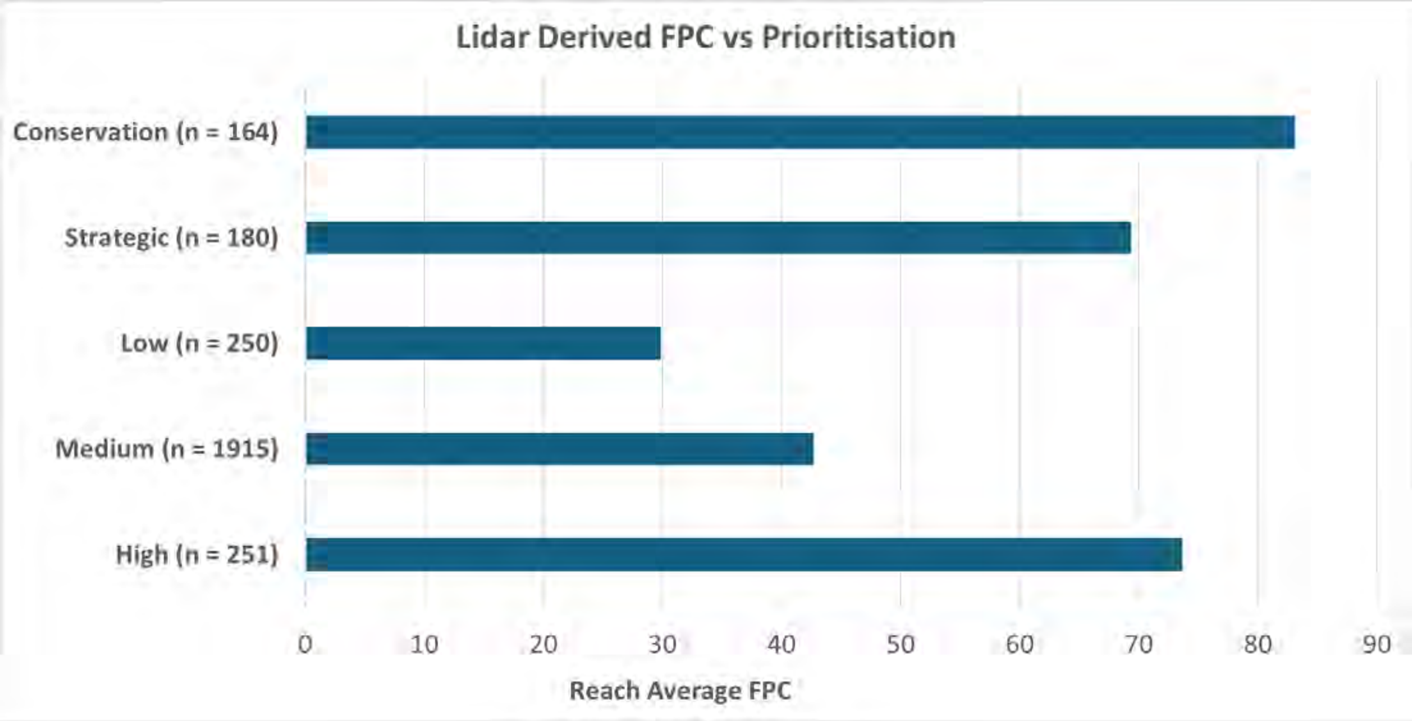

Figure 116. Comparison between River Style management prioritisation class and reach average FPC from this study

Appendix 12. Relationship between prioritisation derived from this study and the prior Estuary Health Risk Assessment Prioritisation

The following set of images show that there is considerable disagreement between the existing Estuary Health Risk Assessment (EHRA) prioritisation and the prioritisation derived from this study. This may partly be explained by the different scales/resolutions of the different approaches, but it is likely that this has more to do with the data underpinning the two strategies. In particular, the EHRA is dominated by RUSLE -based hillslope erosion modelling – which is largely driven by slope and vegetation cover (Figure 117). It is clear that the EHRA mapping suggests an entirely different management strategy from that outlined in this study (Figure 118 - Figure 120).

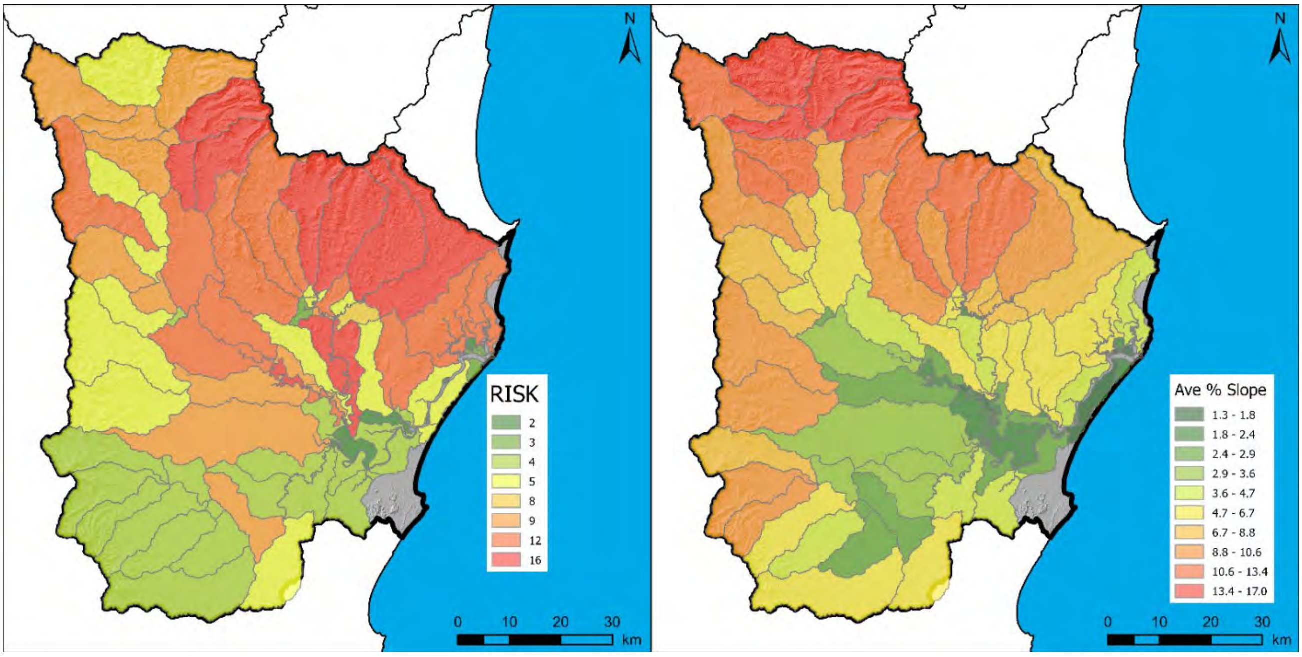

Figure 117. Comparison between the sub-catchment EHRA risk and slope – highlighting the important influence of slope on erosion risk – which does not account for the role of channel erosion.

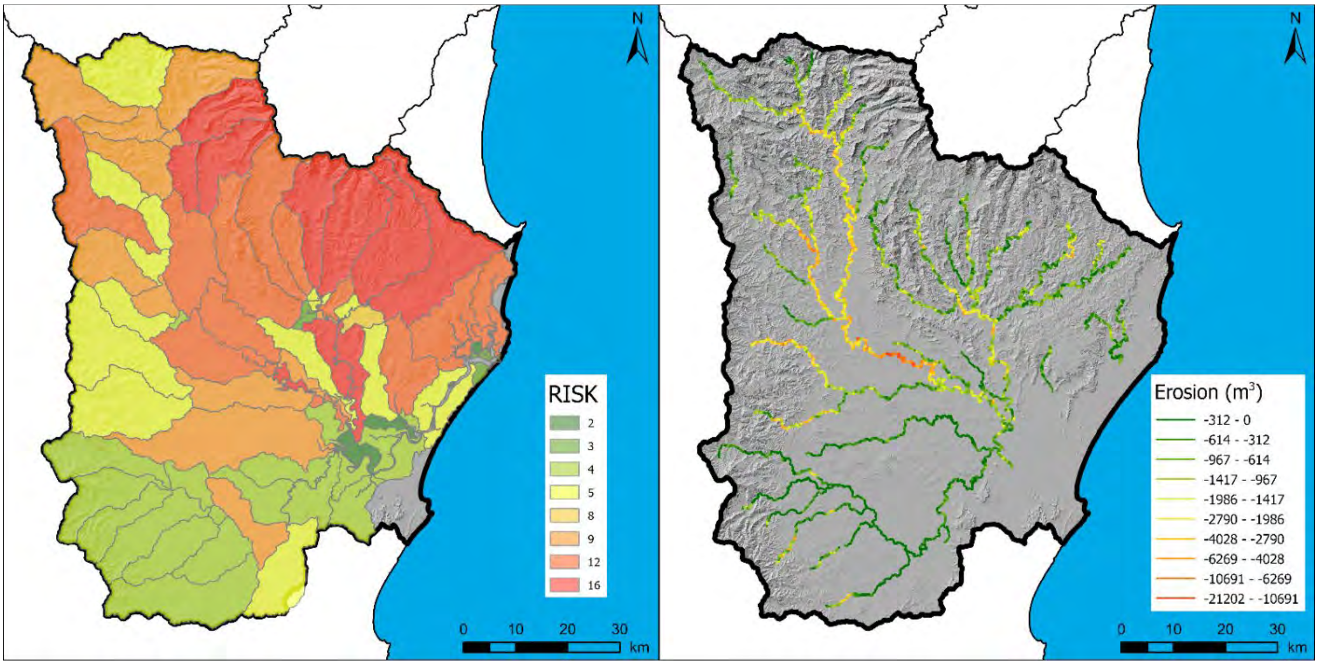

Figure 118. Comparison between EHRA sub-catchment risk and observed channel erosion (this study) highlighting the poor correlation between the two datasets.

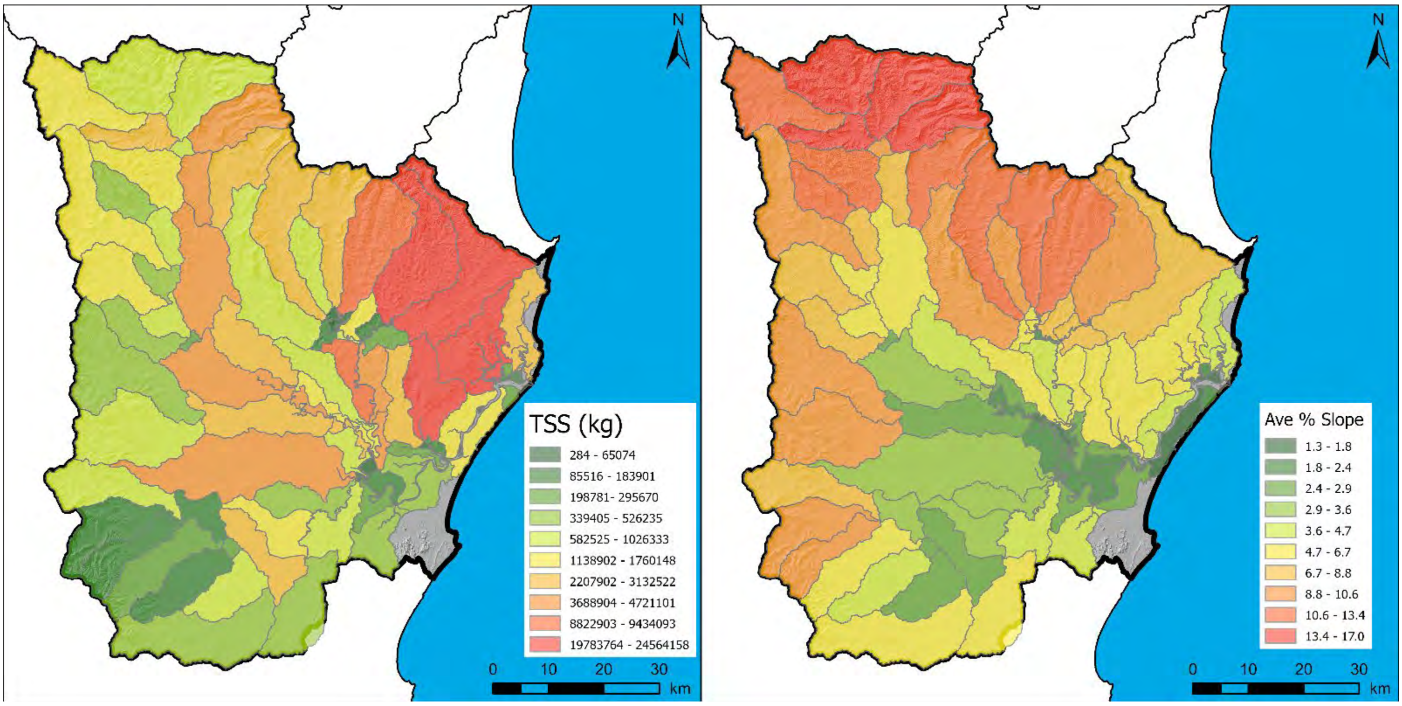

Figure 119. EHRA TSS supply prediction maps showing the close relationship between sediment yield and slope (+ cover)

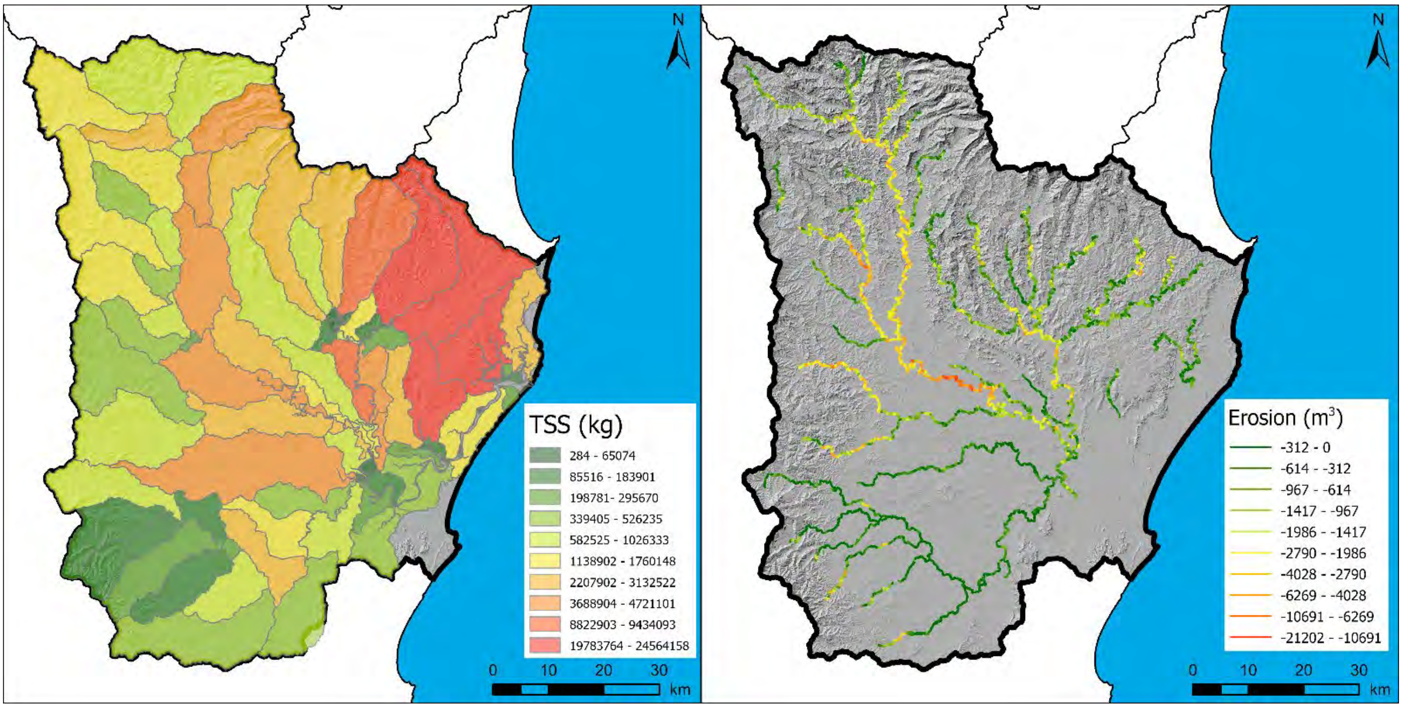

Figure 120. Comparison between EHRA TSS sources and channel erosion from this study – showing the poor correlation between the two.

Appendix 13. Examples of Richmond Catchment Bank Erosion Processes

The following set of images show a selection of examples of the key forms of bank erosion throughout the Richmond catchment (Figure 121 - Figure 128). The majority of the high erosion reaches are dominated by mass failures of various kinds, but often associated with toe scour, which likely contributes to the mass failure.

Figure 121. Example of the difference in bank erosion between a vegetated an unvegetated bank. Bank on right of image is showing evidence of toe scour coupled with mass-failure – rotational slumps. Bank on image left is primarily experiencing toe scour without mass failure

Figure 122. Example of a small rotational bank failure that has contributed LWD to the channel

Figure 123. Example of a section of the upper Richmond R showing evidence for multiple rotational mass failures. Note the bank at right of image is showing evidence for toe scour – which has led to shallow mass failure – whereas the bank at left of image has good toe protection from a line of Melaleuca citrina. Note also it is clear that there are many old mass failure scars that have self healed.

Figure 124. Example of large rotational mass failure that has self-stabilised with time post initiation.

Figure 125. Toe scour along a devegetated section of river, in which the only section of bank toe not scoured is the section associated with the root mat of the Casuarina cunninghamiana. A river reach like this would benefit significantly from stock exclusion.

Figure 126. Further example of a section of channel that has experienced previous mass failure that is now partially restabilised by grasses and herbaceopus vegetation. A site like this would respond extremely well to stock exclusion and assisted natural regeneration.

Figure 127. Example of a section of bank experiencing both fluvial scour and some mass failure – mainly via slab failure. Again this site would benefit from stock exclusion - but may also benefit from some toe stabilisation e.g. with Engineered log jams.

Figure 128. This is a reach of the Bungawalbin Ck within a fully forested reach experiencing toe and bank face scour and mass failure. The bank erosion processes in this section of river are controlled by an old Quaternary terrace and while they may respond to some stabilisation works, their location would prohibit such a management response.

Appendix 14. Examples of Reach Management Scenarios – Underpinning Marxan Costings (basis for reach rehabilitation plans)

Examples of datasets underpinning the analysis that can be used to develop initial reach rehabilitation plans.

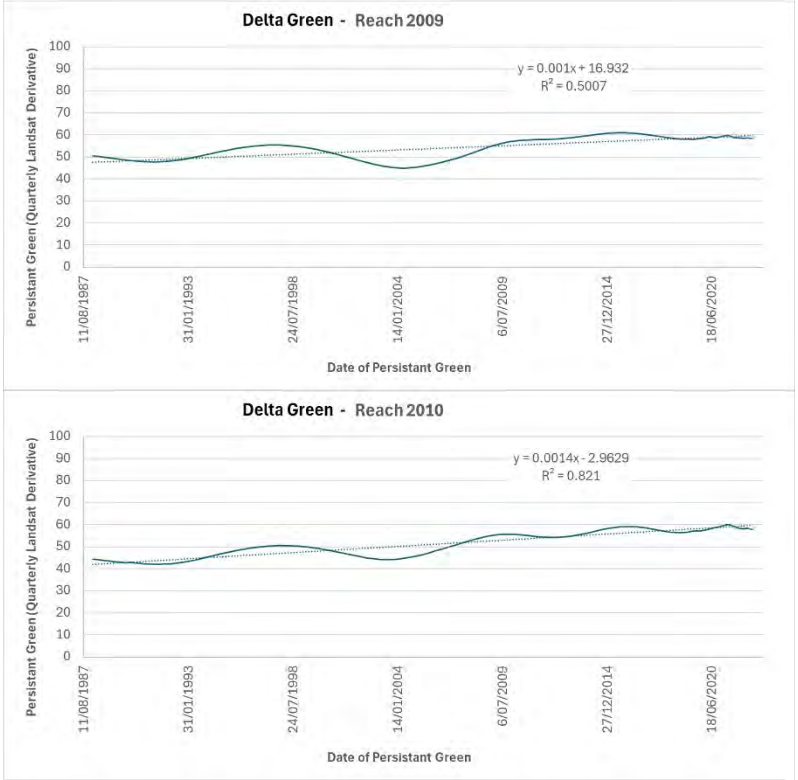

Figure 129. Delta green plots for Reach 2009 and 2010

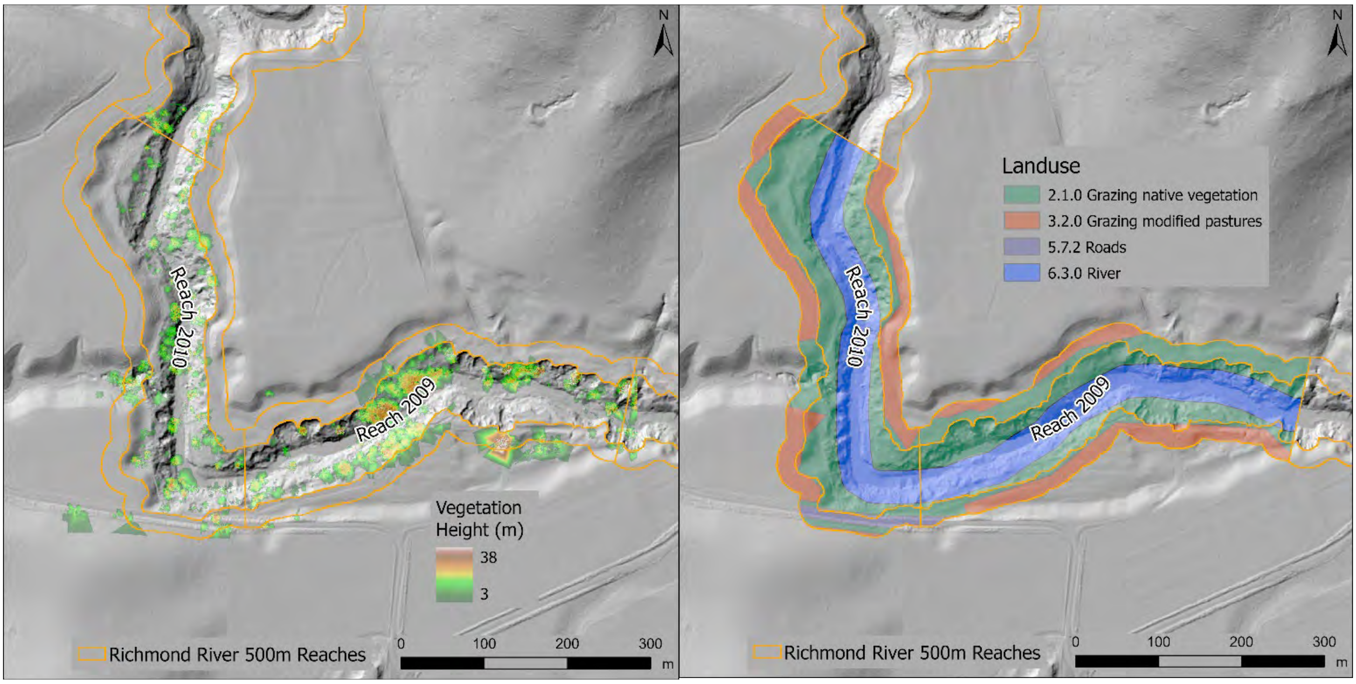

Figure 130. Woody Vegetation Canopy Height data for Reaches 2009 & 2010 as well as the landuse layers coupled with the channel and riparian buffer boundary

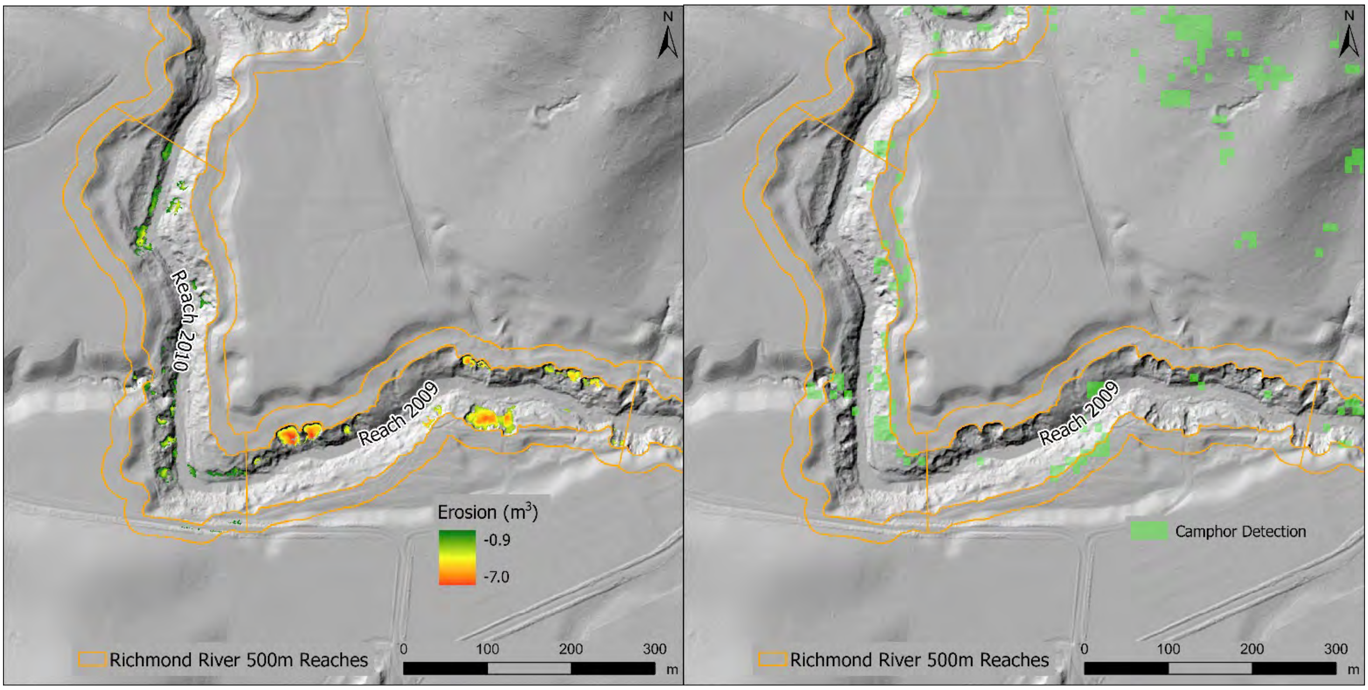

Figure 131. Channel Erosion data and Camphor distribution data overlaid on the channel and riparian buffer boundaries.

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