Hypoxic Blackwater Events - Identifying High Risk Catchments in Estuaries Now and Under Future Climate Scenarios

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Key Points:

- A methodology is presented to differentiate estuarine catchments by their potential to generate hypoxic blackwater.
- Local topographic and hydrodynamic conditions strongly influence the potential volume of blackwater generated over a catchment.
- Climate change may increase the frequency and severity and change the distribution of blackwater risk throughout an estuary.

Abstract

Hypoxic blackwater events occur worldwide, affecting inland and coastal waters. These events have been exacerbated by man-made floodplain drainage, leading to large-scale fish kills and ecological degradation. This paper presents a new method to identify estuarine catchment areas that are most likely to generate hypoxic conditions. The method uses established blackwater risk factors, including vegetation type, inundation extent and duration, ground-truthed in eastern Australia. A catchment is at higher risk of blackwater generation if (i) it is located where floodwaters are high and/or drainage is impeded, (ii) the site topography includes an extensive, low-lying floodplain; and/or (iii) the land-use and environmental characteristics have a high deoxygenation potential. Blackwater impacts in an estuary are determined by the floodplain connectivity with the estuary, and the discharge characteristics of the catchment drainage system. Where multiple, proximate catchments have similar drainage conditions, compounding blackwater plumes can overwhelm the assimilation capacity of the estuary. Climate change may significantly increase the volume and frequency of blackwater events in estuarine environments as a result of reduced drainage due to sea level rise, higher temperatures, and more intense and sporadic rainfall events. It is recommended that management measures be introduced to mitigate the effects of climate change and avoid further widespread hypoxic blackwater events.

1 Introduction

Blackwater is the common name for dark coloured water characterised by low levels of dissolved oxygen (DO) (Howitt, Baldwin, Rees, & Williams, 2007; Moore, 2006). Blackwaters are typically associated with the presence of humic substances leached from decaying vegetation (Coble, Koenig, Potter, Parham, & McDowell, 2019) or floodplain sediments (Meyer, 1990; Rixen et al., 2008). This transfer of dissolved organic matter and nutrients from riparian zones and floodplains to adjacent waterways is a natural part of the nutrient cycle. However, excessive stimulation of microbial respiration, particularly via elevated levels of organic matter and higher temperatures, can lead to hypoxic conditions, whereby DO concentrations are reduced below 2mg/L (Rabalais, Turner, & Wiseman Jr., 2002; Vithana, Sullivan, & Shepherd, 2019). Indeed, hypoxic blackwater plumes have been linked to decreased aquatic ecosystem health, including mass fish kills, and detrimental impacts on sessile flora and fauna (Hladyz, Watkins, Whitworth, & Baldwin, 2011; Pahor & Newton, 2013; Vaquer-Sunyer & Duarte, 2008). Blackwater may also affect the broader estuarine environment through disrupted trophic levels, interrupted life cycles, reductions in suitable habitat, overcrowding, and forced migration (Rabalais et al., 2002; Vaquer-Sunyer & Duarte, 2008).

Globally, hypoxia is frequently associated with the decomposition of autochthonous algal blooms fuelled by the eutrophication of inland and coastal waterways, as exemplified by the infamous dead zones of the Gulf of Mexico (Diaz, 2001; Górniak, 2017), the Baltic (Conley et al., 2011) and Black Seas (Rabalais et al., 2002). However, hypoxic conditions can also develop following direct, precipitous carbon loading of lakes, rivers or estuaries as a result of extended catchment inundation, in what are commonly known as blackwater events (Moore, 2006). Globally, flood-induced blackwater events are widespread, having been reported on the Paraguay River, Brazil (Hamilton, Sippel, Calheiros, & Melack, 1997), the Atchafalaya River, USA (Bonvillain et al., 2011; Pasco et al., 2016) and in Lake Filsø, Denmark (Kragh, Martinsen, Kristensen, & Sand-Jensen, 2020). In Australia, blackwater events have affected inland rivers in arid and temperate regions of the Murray-Darling Basin (King, Tonkin, & Lieshcke, 2012; Whitworth, Baldwin, & Kerr, 2012) and the Edward-Wakool River system (Hladyz et al., 2011); tropical waters in the Katherine (Townsend, Boland, & Wrigley, 1992) and Mary (Townsend & Edwards, 2003) Rivers of the Northern Territory; and coastal estuaries, including the Hunter (Carney et al., 2015; Hitchcock, Westhorpe, Glamore, & Mitrovic, 2021), Clarence (Johnston, Kroon, Slavich, Cibilic, & Bruce, 2003) and Richmond (Walsh, Copeland, & Westlake, 2004) Rivers in northern New South Wales (NSW).

While eutrophic and blackwater hypoxic events may occur naturally, anthropogenic activities appear to have escalated their frequency and magnitude (Carstensen, Andersen, Gustafsson, & Conley, 2014; Kerr, Baldwin, & Whitworth, 2013; Paerl, 2006; Rabalais et al., 2002; Wong et al., 2010). Dead zones have spread exponentially since the 1960s (Diaz & Rosenberg, 2008), with scientifically confirmed accounts of hypoxia affecting over 500 catchments globally (Breitburg et al., 2018; Díaz & Rosenberg, 2011). This increase has been attributed to anthropogenic impacts, including wastewater discharges (Breitburg et al., 2018), modifications to floodplain hydrology following river regulation and water extraction (Whitworth et al., 2013), and the construction of drainage and flood mitigation works

(Moore, 2006), with changes to vegetation and land-use contributing to increased nutrient loads (Arellano et al., 2019; Conley et al., 2007; Godinho et al., 2019).

Efforts to mitigate the impacts of hypoxia have included nutrient reduction schemes, primarily aimed at improving the quality of industrial and municipal wastewater discharges (Conley, 2012), reducing the impacts of agricultural land-use practices (Tallis et al., 2019), changes to river regulation procedures (Kerr et al., 2013; King et al., 2012; Watts et al., 2018), and dilution/aeration techniques (Whitworth et al., 2013). However, effective mitigation requires a thorough understanding of the mechanisms that contribute to the formation and persistence of blackwater. To this aim, conceptual models have been developed to improve blackwater management for the Atchafalaya River (Pasco et al., 2016), Gulf of Mexico (Scavia et al., 2017) and San Francisco Bay (Cloern, Schraga, Nejad, & Martin, 2020) in the United States, and the Murray-Darling River system in Australia (Whitworth and Baldwin (2016)). For example, the Blackwater Risk Assessment Tool (BRAT) developed by Howitt (2007) and Hladyz (2011) describes the carbon load generated over the Murray-Darling floodplain via litter accumulation and decomposition rates, carbon leaching, microbial degradation and respiration. The carbon load is then converted to a volumetric biochemical oxygen demand (BOD) by considering the area, depth and duration of inundation (Howitt et al., 2007; Whitworth & Baldwin, 2016). Other key variables are temperature, re-aeration and dilution potential (Howitt et al., 2007). The Dissolved Oxygen-Dissolved Organic Carbon (DODOC) model developed by Mosley, Wallace, Rahman, Roberts, and Gibbs (2021) has subsequently integrated hydrologic capability with the BRAT ecological assessment to better represent the complex interactions between catchment hydrology and floodplain inundation (Gibbs, Wallace, & Mosley, 2022; Mosley et al., 2021). Consequently, environmental flow releases in the regulated, lowland inland rivers of Australia are now managed to avoid periods of high carbon production on floodplains (Saintilan, Kelleway, Mazumder, Kobayashi, & Wen, 2021).

Many of the same risk factors that apply to the generation of blackwater over the floodplains of inland rivers also apply to coastal floodplains. However, tidal flows present a different hydrodynamic regime to that experienced in riverine environments, and within many estuarine environments the retention and release of floodplain waters has been heavily modified by extensive flood mitigation and drainage schemes. Over the course of the 20th century, meandering channels with low hydraulic gradients and limited outlets have been replaced by extensive networks of drainage channels that have breached the natural hydraulic separation between an estuary and the adjacent coastal floodplains (Tulau, 2011). Blackwaters that were once predominately retained within extensive tracts of freshwater and tidal wetlands, allowing the carbon cycle to complete and the water column to become re-aerated, are now discharged swiftly to the estuary (Johnston, Slavich, Sullivan, & Hirst, 2003).

These floodplain drainage schemes have been directly linked to blackwater events that resulted in major fish kills throughout the northern estuaries of NSW (Walsh et al., 2004). Such events closed the Macleay River to fishing for 3 months in 2001 (Walsh et al., 2004), and the Richmond River for 4.5 months in 2001 (Steffe, Macbeth, & Murphy, 2007) and 2 months in 2008 (Wong et al., 2010). Consequently, analyses of blackwater events in the Clarence (Johnston et al., 2003) and Richmond (Wong et al., 2010) Rivers of Australia have identified three characteristic stages of an estuarine blackwater event (Figure 1):

1. Initially low-lying floodplain areas are inundated as floodwaters rise. The concentration of dissolved organic carbon (DOC) in the water column starts to increase and microbial metabolization of DOC rapidly reduces the DO concentration (Stage 1).
2. Floodplain waters become anoxic and the deoxygenation potential (DOP) increases as the BOD continues to rise (Stage 2).
3. The assimilation capacity of the river decreases as the floodwaters recede and the high oxygen demand of the blackwaters discharged from the floodplain drainage systems has a substantial impact on the adjacent waterway (Stage 3). This stage may be exacerbated by the drainage of acidic groundwaters from behind the flood mitigation structures.

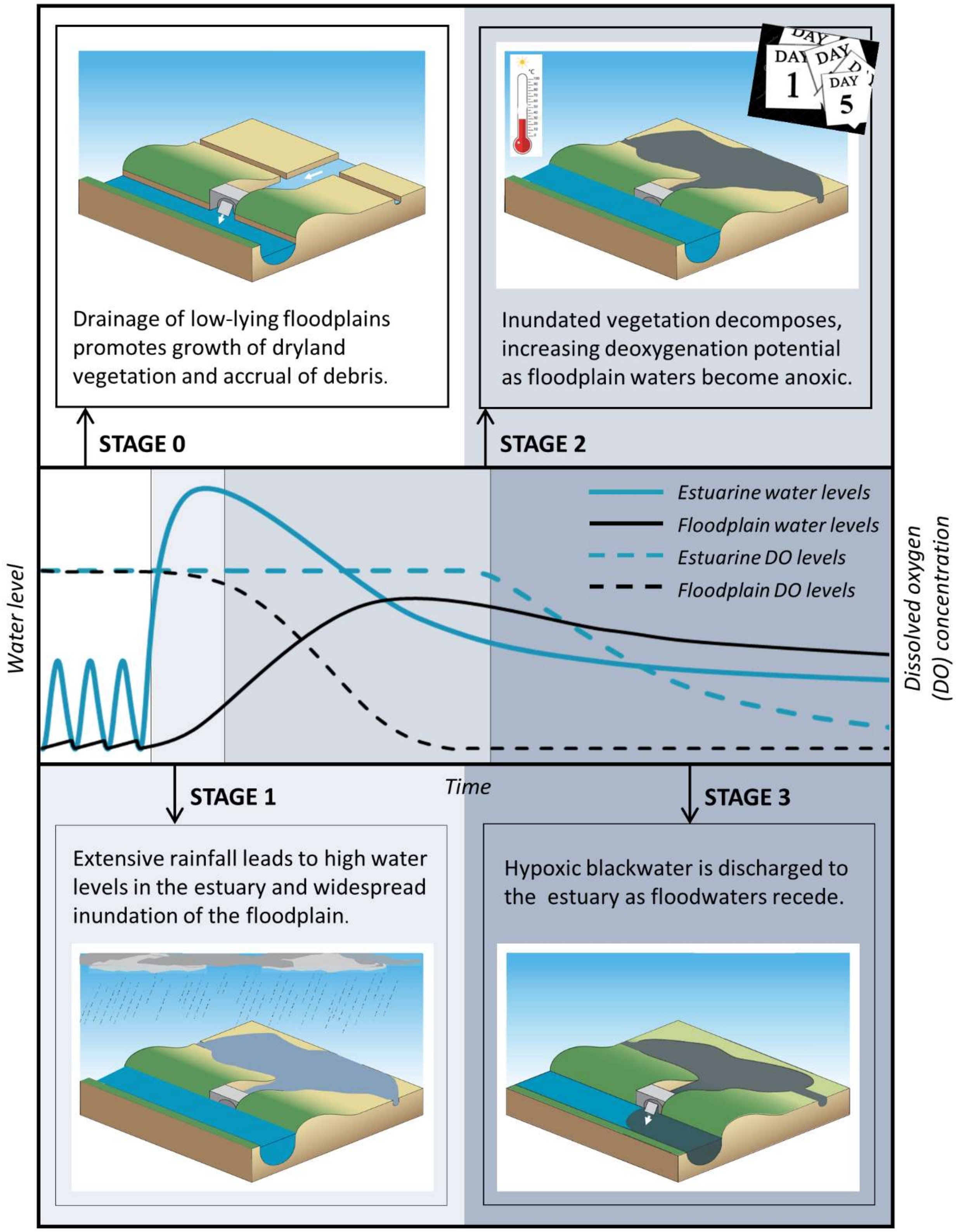

Figure 1. Conceptual stages of a blackwater event in an estuary (graph adapted from (Johnston et al., 2003))

The influence of constructed drainage systems and tidal floodgates on the magnitude and frequency of hypoxic blackwater events is evident in each of the three stages identified in Figure 1. Indeed, the construction of drainage schemes on estuarine floodplains has increased the potential for blackwater generation for a number of reasons. First, enhanced drainage promotes dry-land pastural grasses and agricultural crops in favour of water-tolerant vegetation species. These dry-land species are more susceptible to inundation and can provide a highly labile source of carbon for microbial metabolisation (Eyre, Kerr, & Sullivan, 2006; Johnston et al., 2003). Second, the reduced frequency of floodplain inundation increases the availability of carbon as organic debris accumulates between flood events (Ning, Petrie, Gawne, Nielsen, & Rees, 2015; Pahor & Newton, 2013). Finally, enhanced drainage intensifies the impact of blackwater by promoting the rapid discharge of anoxic floodwaters with high DOP directly to the estuary and by increasing the volume of blackwater that is transferred to the estuary (Wong et al., 2010).

Studies to date have focussed on the first two impacts of constructed drainage schemes; developing a detailed understanding of the local mechanisms by which blackwater is generated over estuarine floodplains. However, there have been limited investigations into the hydrodynamic interactions between the estuary and floodplain. Indeed, variability of rainfall and inundation across various drainage catchments within the floodplain has been identified as a primary difficulty in prioritising areas for blackwater management (Moore, 2006). Estuarine water levels are fundamental to the retention of water on the floodplains and the release of impounded water to the estuary. The former presents a limitation to the volume of blackwater that may be generated on the floodplain, while the latter is a determining factor regarding blackwater impacts upon the estuarine environment.

This paper presents a methodology to address this knowledge gap by incorporating the hydrodynamic regime and the topographic constraints underlying the generation of hypoxic blackwater in estuarine floodplains. The methodology quantifies the relative potential for blackwater contribution from each drainage catchment within an estuary. Water quality surveys from historic blackwater events in south-eastern Australia are used to explore the validity of the blackwater risk assessment. The results provide insights into the susceptibility of various catchments within an estuary to blackwater under current and future climate conditions. It is anticipated that this approach may be used to optimise strategic monitoring programmes and future management options.

2 Methodology

2.1 Blackwater risk factors

Differentiating the potential for blackwater generation between various catchments within an estuary requires the identification and quantification of risk factors that may contribute to a blackwater event. These include biological (carbon availability and microbial metabolization), chemical (for example, inorganic reactions, acidity and salinity) and physical (primarily temperature and pressure) mechanisms affecting the DOP of the floodwaters. Further, the extent and duration of inundation over the catchment is critical to the volume of blackwater that may be generated. An overview and the assessment of these risk factors is presented in the following sections.

2.1.2 BOD and carbon availability

BOD is a critical factor contributing to changes in DO levels within a water column, with the rate of oxidation assumed to be directly proportional to the BOD (Cox, 2003). BOD accounts for both the chemical oxidation of inorganic cations such as Fe^{2+}, Mn^{2+} and S^{2-} (Johnston, Slavich, & Hirst, 2005; Vithana et al., 2019; Wong et al., 2010), and the microbial decomposition of biodegradable organic matter (Hladyz et al., 2011).

In coastal estuaries of southeast Australia, the impacts of chemical oxidation are associated with acid sulfate soils (ASS) (Johnston et al., 2003). ASS are chemically stable when undisturbed, however constructed drainage systems have exposed large floodplain areas to oxygen, producing sulphuric acid and, via dissolution, metallic cations. Secondary oxidation of these ions can create a significant oxygen demand within the water column (Johnston et al., 2003; Lin, Wood, Haskins, Ryffel, & Lin, 2004) and the associated acidity has been independently attributed to fish kills (Walsh et al., 2004). Analysis of the geochemical signature of floodwaters in the main channel of the Clarence (Johnston et al., 2003) and Richmond Rivers (Wong et al., 2010) identified the anaerobic decomposition of floodplain vegetation as the primary process leading to generation of hypoxic blackwater conditions. Further, mesocosm experiments in the Richmond (Eyre et al., 2006) and Edward-

Wakool (Hladyz et al., 2011) Rivers determined the BOD of a variety of vegetation types and confirmed the potential for microbial decomposition of inundated floodplain vegetation to be sufficient to trigger a blackwater event.

The rate at which vegetation decays and deoxygenates water during periods of prolonged inundation differs depending on the vegetation type (Eyre et al., 2006; Johnston et al., 2005; Whitworth & Baldwin, 2016), with DOP being a factor of, *inter alia*, the labile carbon concentration (often measured as dissolved organic carbon) and temperature (Wong et al., 2011). Labile carbon is the organic component that is readily bio-available, with a higher lability associated with faster decomposition rates (Zhang et al., 2019). For example, when examining the impacts of flooding observed in the Clarence River, Johnston et al. (2003) attributed the relatively high oxygen demand from one catchment to the dominance of labile dryland pasture species compared to another that was vegetated predominately by recalcitrant *Melaleuca quinquenervia* forest. Thus, floodplains dominated by endemic wetland plant species would be less likely to generate blackwater than those that have been drained and revegetated with pasture grasses or crops that are less tolerant of inundation (Vithana et al., 2019; Wong et al., 2011). Research determining the oxygen demand of various vegetation, litter and soil types has subsequently been used to hypothesise the relative risk and potential contribution of different land-uses to blackwater events (Liu, Watts, Howitt, & McCasker, 2019).

2.1.2.1 Quantifying the DOP risk factor

It is difficult to establish strong links between land-use (for which spatial data is readily available) and BOD (Amiri & Nakane, 2008). However, a review of Australian literature identified five vegetation types typical of coastal floodplains for which experimental data regarding DOP has been established. Experimental methods differ between the various studies, making direct comparison difficult and there is limited data available regarding the spatial distribution of vegetation on coastal floodplains. Consequently, a risk-based approach linking vegetation types with comparative DOP was devised for this study, as detailed in Table 1. The vegetation types and corresponding risk factors were then assigned to each land-use identified in the 2017 (released in June 2020) Australian Land Use and Management (ALUM) classification (DPIE, 2020). Full details are presented in the Supplementary Material.

Table 1. Blackwater generation risk factors for typical vegetation types in coastal NSW

Vegetation Type	Water Tolerance		Comparative Deoxygenation Potential		Risk Factor**
	Rating	Score	Rating	Score	
Dryland grasses (e.g. pasture)	Low	3	High [a, c, e] Medium [b]	3	**3**
Forestry (other than tea tree) *	Low	3	High [b, c]	3	**3**
Tea tree leaves*	Low	3	Low [d] Low – Medium [a] Medium [e]	2	**2**
Sugar cane[+]	Medium	2	Low – Medium [a]	2	**2**
Freshwater wetland grasses (e.g. Grey rush)	High	1	Low [a] Medium [d]	1	**1**

[a] Eyre et al. (2006)

[b] Whitworth and Baldwin (2016)

[c] Liu et al. (2019)

[d] Johnston et al. (2005)

[e] Southern Cross GeoScience (2019)

* Low water tolerance is attributed to the presence of readily available leaf litter, rather than the likelihood of plants dying.

[+] Sugar cane is relatively tolerant to water, but the presence of waste after harvest increases the DOP.

** The risk factor is the average of the scores for water tolerance and comparative DOP.

2.1.3 Floodplain inundation characteristics

Flood mitigation and drainage systems have been implemented to increase floodplain productivity by limiting floodplain inundation and increasing drainage efficiency. This reduces the risk of blackwater generation during smaller, localised rainfall events, as inundated catchments can drain freely when downstream waterways are not in flood. However, regardless of the efficiency and scale of drainage infrastructure, floodplain drainage is limited by the receiving (downstream) water level. Consequently, widespread blackwater generation is more commonly associated with extensive flooding when floodplain drainage is restricted by the rate of floodwater recession in the estuary.

2.1.3.1 Inundation duration

To determine the potential for blackwater generation in a floodplain, it is important to quantify the inundation duration required to generate and sustain a blackwater event. This will vary depending on catchment characteristics, seasonal and antecedent conditions, and the unique hydrologic and hydraulic profile of each flood event.

The microbial metabolisation of highly labile carbon sources can rapidly deoxygenate a water column. Organic compounds on the floodplains will start to decompose within hours of inundation (Vithana et al., 2019; Wallace, Ganf, & Brookes, 2008), with the most labile fractions leached of carbon within the first 24 hours. In-situ mesocosm experiments on the floodplain of the Richmond River by Eyre et al. (2006) indicated that microbial metabolisation of harvested sugar cane and dropped tea tree leaves can reduce the dissolved oxygen levels in a 300 mm deep water column to 3 – 4 mg/L within 10 hours, while slashed pasture grass can deoxygenate the same volume of river water almost completely (DO < 1 mg/L) under the same conditions. Similar experiments have shown that DO was reduced to near 0 mg/L over a period of two to three days for a variety of vegetation types (Johnston et al., 2005; Liu et al., 2019; Vithana et al., 2019).

After prolonged immersion, living plants may start to die and more recalcitrant plants decompose, contributing new carbon sources to the water column (Hladyz et al., 2011). Additionally, experiments by Vithana et al. (2019) and Liu et al. (2019) suggest that both DOC and BOD can continue to rise for more than two weeks after initial inundation. Similarly, Wong et al. (2011) showed that chemical oxygen demand (COD) peaked approximately 15 to 20 days after the flood peak in a backswamp on the Clarence River, NSW. This suggests that the DOP is likely to persist for floodplain inundation durations of at least two weeks.

During the 2001 floods in the Richmond, Clarence and Macleay Rivers, it was reported that river water started to deoxygenate as floodplains began to drain, becoming completely deoxygenated within 1 to 3 days, depending on site conditions (Walsh et al., 2004). Mass deoxygenation of coastal estuaries in NSW is typically observed 4 to 6 days after the peak of a flood event (Johnston et al., 2003; Southern Cross GeoScience, 2019; Wong et al., 2010). In part, this reflects the recession of the flood hydrograph and the limited drainage from the floodplain to the estuary during prolonged floods. However, similar observations were made by Bonvillain et al. (2011) following flooding of the Atchafalaya River Basin (USA) in September 2008, where hypoxic conditions were recorded within 3 days and extensive fish kills occurred within 5 days.

Both experimental evidence and recorded observations indicate that floodplain inundation of less than 24 hours can generate blackwater during flood events. However, the limited volume of blackwater generated during this short period is unlikely to have a significant impact on receiving waters. Conversely, the longer that floodwaters are retained on a floodplain, the greater the volume of water that can be deoxygenated (Hladyz et al., 2011), the higher the DOP of the floodwaters (Eyre et al., 2006), and the greater the risk of a blackwater event when those waters are discharged to the receiving estuary (Howitt et al., 2007).

2.1.3.2 Inundation depth and extent

While there are no known long-term records of floodplain inundation within estuaries of NSW, the Department of Planning and Environment maintains a network of water level gauges throughout the estuarine channels (MHL, 2023). These gauges provide continuous long-term, historic water level records which were adopted to represent the depth and duration of floodplain inundation as onsite drainage is controlled by the downstream water levels. The spatial extent of inundation across the floodplain was determined by extrapolating these historic estuarine water levels using ground-truthed digital elevation models (DEMs) with a 5 metre grid resolution (Geoscience Australia, 2018).

2.1.3.3 Inundation depth and duration matrices

Flood hydrographs are highly variable. The influence of the hydrograph shape on the potential for blackwater generation is illustrated in Figure 2. For example, flood events 1 and 2 generate approximately the same volume of flow within the estuary, whereas the higher peak water levels generated during event 2 have a shorter duration. Despite the higher peak flood levels, for floodplain areas below 1m AHD (Australian Height Datum, which equates approximately to mean sea level), the inundation conditions presented by flood event 1 (Figure 2) are likely to generate more hypoxic blackwater than those of event 2, as inundation would be maintained over a longer period of time. Floodplain areas above 2m AHD would only generate blackwater during flood event 3 as they would not be inundated during event 1 and there would be insufficient inundation duration during event 2.

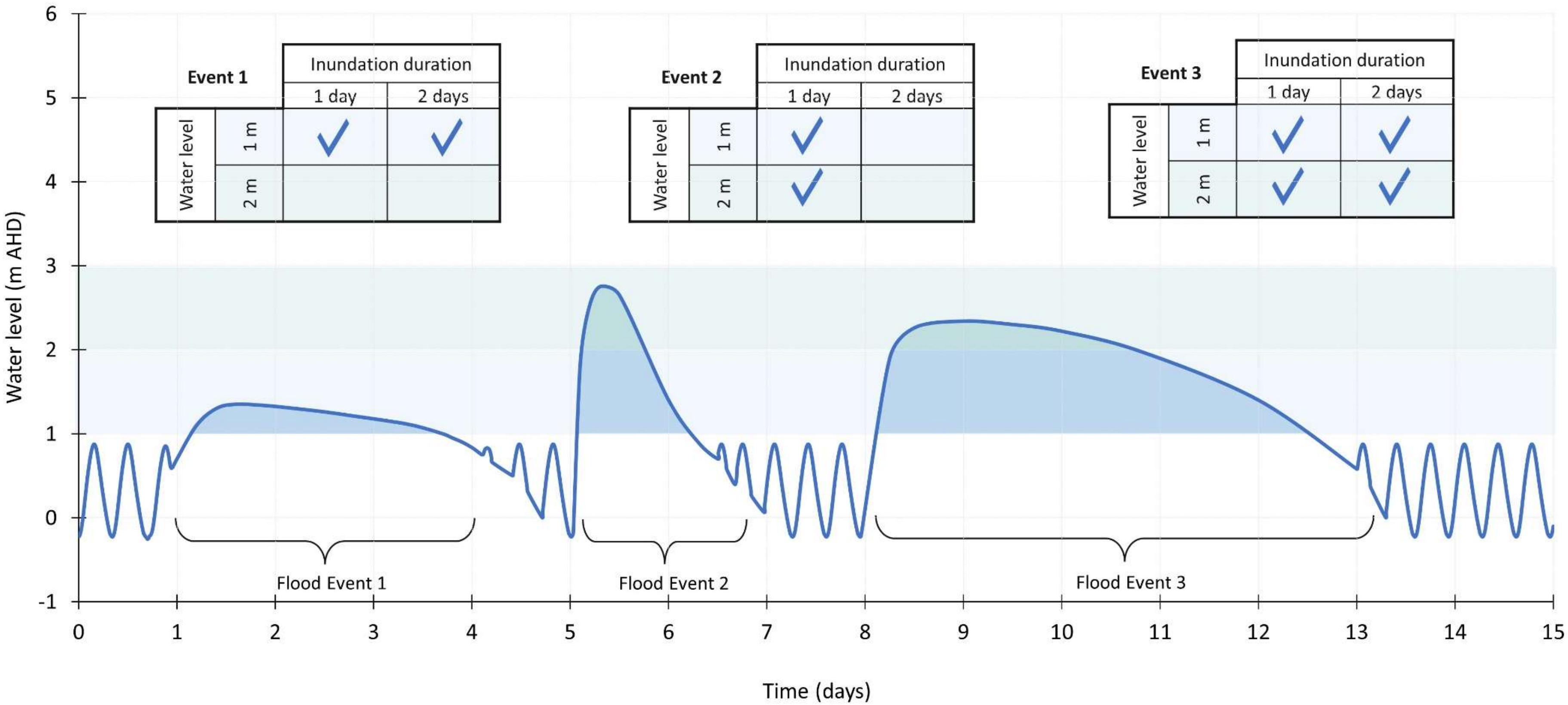

Figure 2. A conceptual hydrograph depicts three different flood events to highlight the blackwater potential risks for each event. At a floodplain elevation of 1m AHD, all floods contribute to the blackwater risk but for different inundation periods. At an elevation of 2m AHD, only flood events 2 and 3 would contribute blackwater. Flooding that persists over a broader area and a longer period (Flood Event 3) has a higher likelihood of producing larger volumes of blackwater.

Based on the conceptual model depicted in Figure 2, inundation risk matrices can be established at each water level gauge by identifying the historic frequency at which various combinations of inundation depth and duration have been exceeded. As such, the inundation duration was calculated at 0.1m increments in water level between 0.1m and 5.0m AHD. This covers the range of water levels and topographic elevations typical of estuarine floodplains. Additionally, as the tidal cycle will restrict discharges from the floodplain drainage systems during flood events, the long-term average mean high water (MHW) level (as documented by Fitzhenry, Alley, Hesse, and Couriel (2012)) was adopted as the minimum floodplain inundation level at each gauge location.

Within the estuaries of NSW, recorded flooding events rarely exceed five days. As the critical duration of inundation for the generation of blackwater may be achieved during floods with a duration of less than one day, event durations between one and five days were adopted for the inundation matrices. For each day a flood event exceeded any particular water level, it was assumed to contribute to the blackwater risk for that duration. This ensured that longer duration events contributed more blackwater risk than events of short duration, although the matrix could be extended to incorporate additional flood durations for estuaries regularly subject to longer floods.

To maximise the available data and account for any differences in the data record at each gauge, the full data record was analysed for each water level monitoring station. These results were then normalised by the length of the data record to calculate the average recurrence interval of each incremental inundation level at each gauge location.

2.2 Aggregated blackwater risk assessment

For each catchment, a blackwater contribution factor was calculated using spatial analysis tools within Geographic Information System (GIS) over a 5m square grid. This information was used to determine the area inundated and the land-use risk factor associated with that area for every 0.1m increment in water level (as illustrated in Figure 3). The blackwater contribution factor corresponding to the water level was then calculated for all combinations of inundation duration and frequency. A statistical mean of the factors calculated from the matrix of inundation levels affecting each catchment was adopted as the aggregated blackwater risk factor for that catchment. This factor was then used to rank the catchments according to their relative potential to generate blackwater.

2.3 Study area

The methodology described in Section 2 was applied to seven major estuaries within NSW, including (from north to south, as indicated in Figure 4):

- Tweed River;
- Richmond River;
- Clarence River;
- Macleay River;
- Hastings River;
- Manning River; and
- Shoalhaven River.

Each selected estuary has been previously identified as blackwater pollution sites resulting from the clearing and drainage of coastal wetlands (Fletcher and Fisk, 2017). In particular, the Richmond River has been the focus of detailed investigations into the causes of blackwater events that resulted in mass fish kills.

Details of government water level gauges used in this assessment are identified in the Supplementary Material, including gauge locations and historic flow distribution curves.

3 Results

The calculated aggregated blackwater risk factors provide an objective, data-driven evidence base to identify which catchments present the highest potential risk of generating blackwater. The ranking of catchments based on blackwater risk can be used to inform and prioritise floodplain management options. Ongoing and future monitoring programs may be optimised and used to further validate and refine the assessment methodology.

The risk factors and catchment ranking within each estuary are tabulated with a statistical analysis of the corresponding historic water levels in the Supplementary Material. Maps indicating the distribution of blackwater risk are also provided, with sample results for the Richmond River presented in Figure 5. These maps incorporate the median extent of

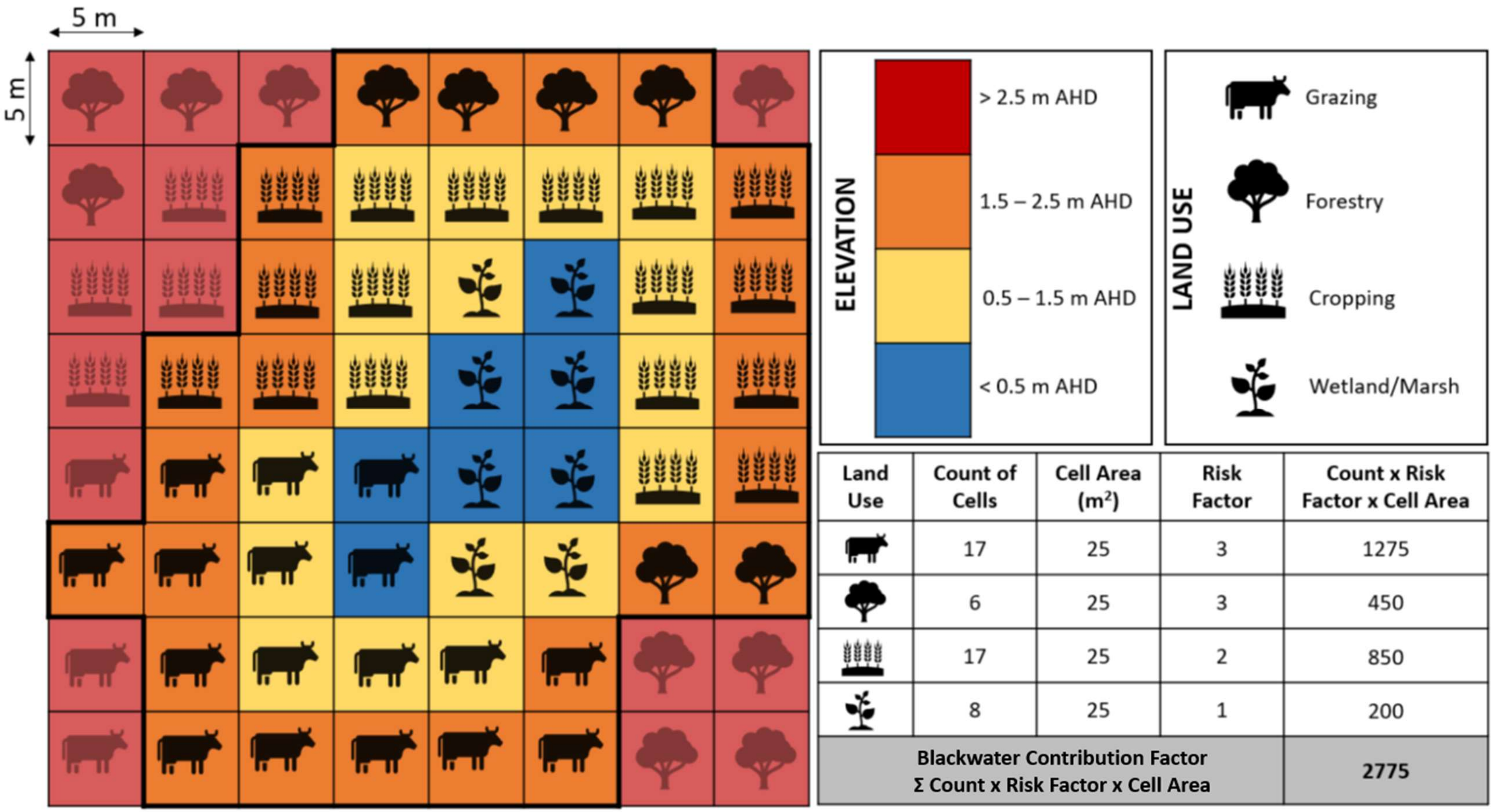

Figure 3. An example calculation of a catchment blackwater contribution factor for an inundation level of 2.5 m AHD. The coloured matrix depicts the land-use type and elevation. The number of each land-use cells multiplied by the area and risk factor summed for the catchment is the blackwater contribution factor for that catchment. Within an estuary, multiple catchments were calculated to rank priority risk areas.

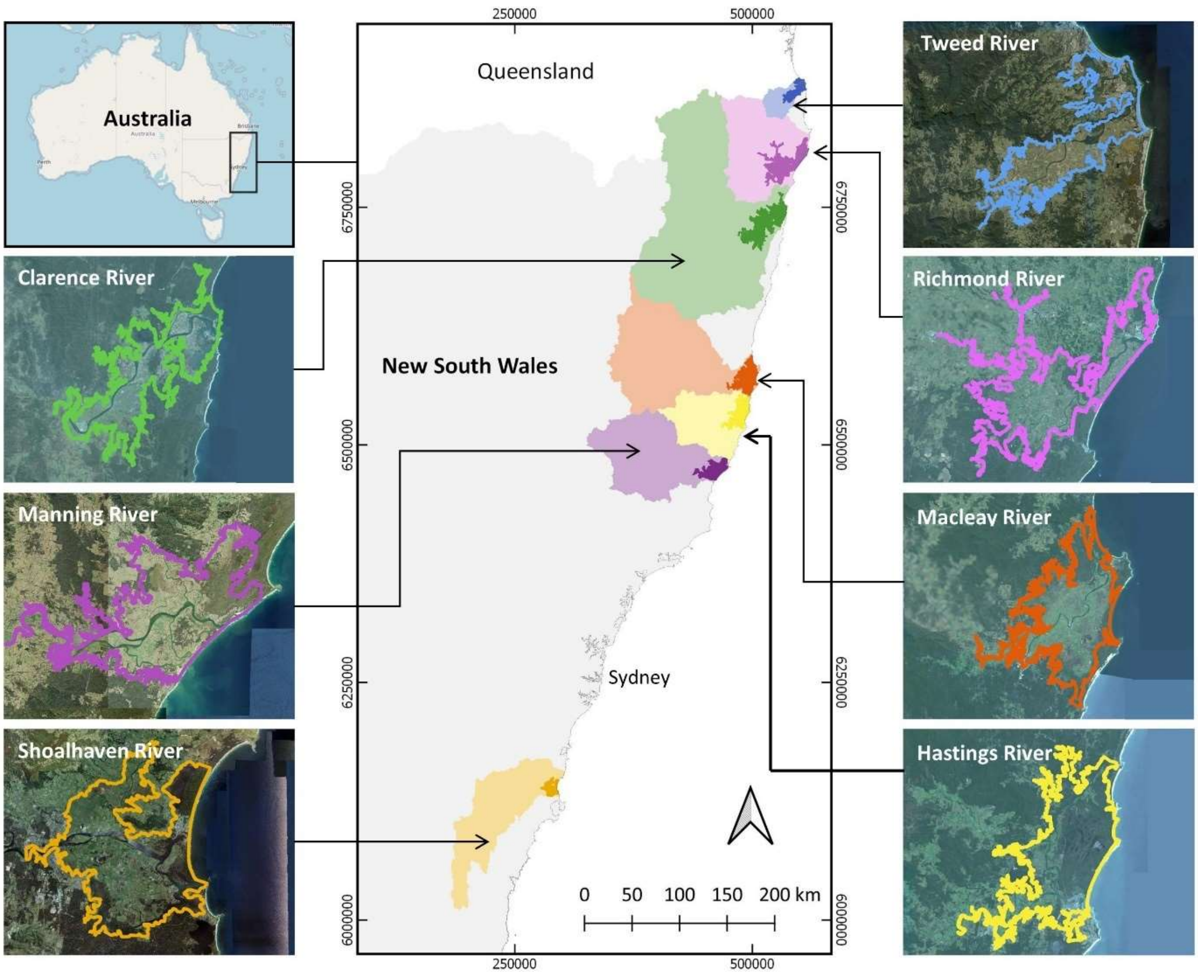

Figure 4. Selected estuaries (shaded) and estuarine floodplain areas below 5m AHD (outlined) defining the study area.

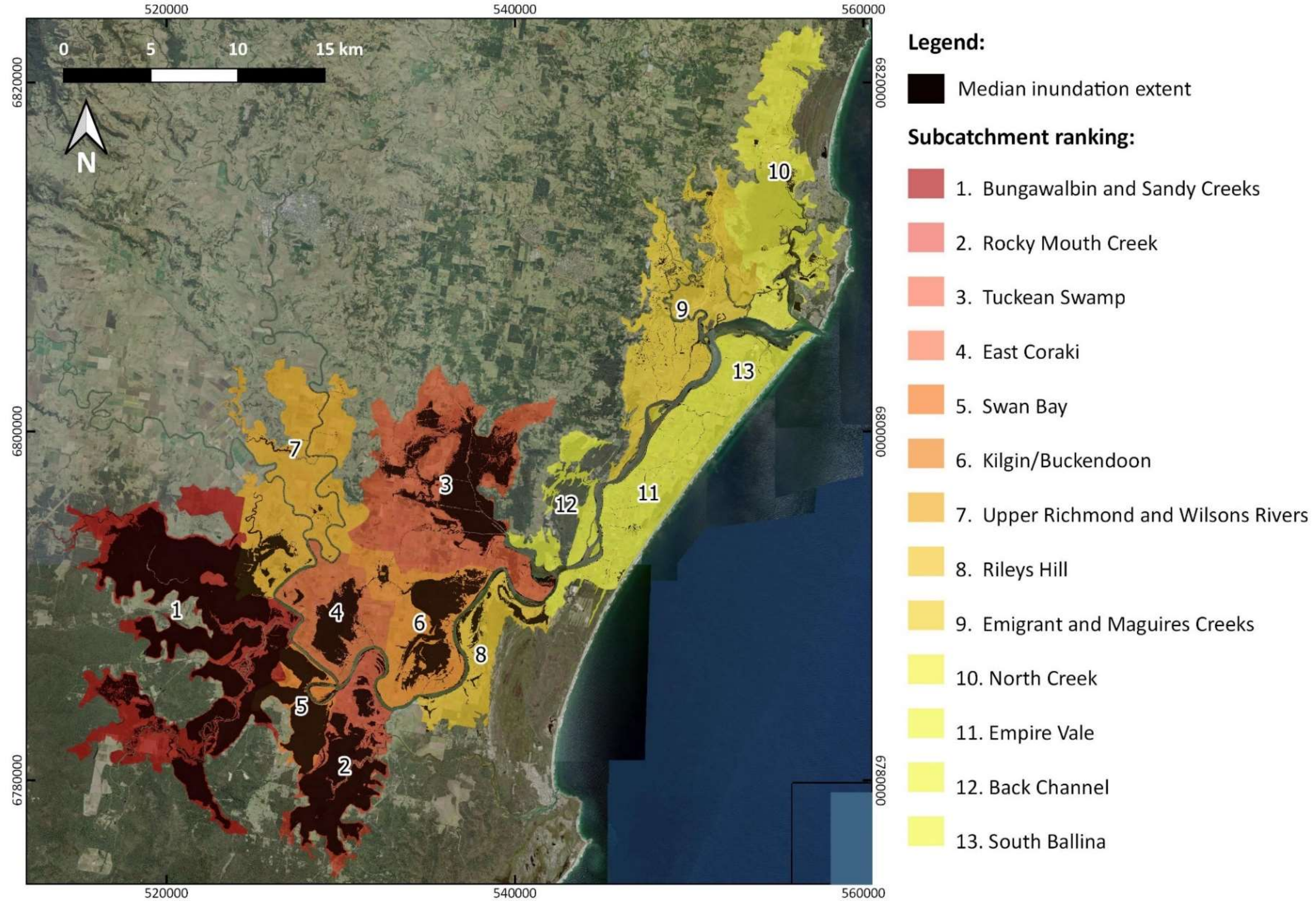

Figure 5. Ranking of catchments by aggregated blackwater risk factor and extent of inundation under median water levels for the Richmond River estuary (maps of results for all estuaries within the study area are included in the Supplementary Material).

inundation corresponding to the historic water levels in the estuary to provide an indication of the areal extent of potential blackwater generation within each catchment.

3.1 Validation of results

In the Richmond River the highest risk catchments were identified as Bungawalbyn and Sandy Creeks (ranked 1), Rocky Mouth Creek (ranked 2), and the Tuckean Swamp (ranked 3). These results correlate well with several previous scientific investigations and help to validate the assessment outcomes. Exceptionally low oxygen levels were previously recorded at Bungawalbyn and Rocky Mouth Creeks following the February 2001 flood (Eyre et al., 2006). Similarly, Wong et al. (2010) identified the Tuckean, Bungawalbyn, Sandy and Rocky Mouth Creek catchments as primary sources of DOP following the January 2008 flood. The same three catchments were attributed the highest risk of blackwater generation and impact by an expert panel under the Richmond Estuary Ecosystem Health Monitoring Strategy (Moore, 2006) and identified as the three top priority areas for blackwater management within the Richmond River floodplain by a collaborative Australian Research Council project (Southern Cross GeoScience, 2019). The latter study prioritised lower Bungawalbyn Creek as the largest blackwater generator on the floodplain.

The validity of the blackwater risk methodology is strengthened by a review of water quality, fish and crustacean mortality data undertaken by Walsh et al. (2004) following major flooding in February and March 2001. This investigation also identified blackwater risk areas within the Richmond River as Rocky Mouth Creek, Bungawalbyn Creek and Tuckean Swamp. Additionally, Walsh et al. (2004) prioritised the Coldstream River (ranked 1 under this study's methodology) and Everlasting Swamp (in the Sportsmans Creek catchment, ranked 2) in the Clarence River, and Belmore Swamp (ranked 2), the Swan Pool (Kinchela Creek, ranked 1) and Seven Oaks wetland (Collombatti-Clybucca, ranked 3) in the Macleay River, further supporting this study's methodology.

3.2 Limitations of methodology

3.2.1 Land use, ambient and antecedent conditions

Due to the relative homogeneity of land-use across the study area, the catchment rankings presented herein are highly influenced by the catchment size and inundation extent. The

Spearman's rank correlation between the aggregated blackwater risk factor and the area flooded at the median inundation level varied from 0.82 to 0.97 throughout each estuary, with the exception of the Shoalhaven River, where it was 0.55. Within the Shoalhaven River, the largest discrepancy was within the Comerong Island catchment, where over 12% of the land area is below the median inundation level but does not contribute to the blackwater risk factor as it is a tidal wetland. Further refinement of the weighting of blackwater risk factors may therefore be required in landscapes with more diverse land uses.

Where land-use is more critical in the assessment of blackwater risk, a weighting factor scaled to BOD may provide greater differentiation than the direct rank-order weighting adopted in this study. Scaled weightings may vary with time of inundation, as indicated by the results of the mesocosm and inundation experiments on which the rank-order weightings were based, (e.g. Liu et al. (2019) and Vithana et al. (2019)). The depth of inundation may also influence the rate of deoxygenation as shallow waters are likely to be warmer (increasing microbial metabolisation rates and reducing oxygen saturation levels) and subject to photochemical deoxygenation processes (Southern Cross GeoScience, 2019).

Indeed, decomposition rates are strongly affected by environmental factors such as temperature, solar radiation, salinity and acidity (Voß, Fernández, & Schäfer, 2015) and BOD has been shown to respond to plant density, shadowing, soil mineralogy and light transmission (Cox, 2003; Voß et al., 2015). Conversely, the bioavailability of organic matter has generally been found to respond more directly to land management practices, such as chemical and nutrient application, harvesting practices and stocking rates (Voß et al., 2015). Thus the potential for blackwater generation over various catchment areas may alternatively be differentiated by assessing variations in land management (both historic and current) and intensity of use (Barlow, Christy, & Weeks, 2009; Buck, Niyogi, & Townsend, 2004) rather than vegetation types or land-use categories, as the accumulation of surface litter is likely to drive the majority of oxygen demand in many environments (Mehring et al., 2014).

Similarly, seasonal changes and antecedent conditions will also impact the potential BOD. By reviewing antecedent weather conditions in the Richmond River, Wong, Walsh, and Morris (2018) found that fish kills were more common when the previous six months had been drier than usual prior to the blackwater flooding event. Conversely, wetter than average conditions are likely to reduce the amount of DOC that is available, thereby lowering the risk of blackwater generation (Hladyz et al., 2011). Antecedent conditions will influence the accumulation of organic matter and the bioavailability of carbon on the floodplain. Vegetation stress due to drought, for example, may increase litterfall (Whitworth et al., 2012), with the accumulation of organic debris increasing as the time between flood events is extended (Wong et al., 2018; Xiong, 1997). The amount of carbon leached from organic matter also reduces when the litter has been previously inundated.

Nevertheless, the spatial and temporal variability of environmental influences on BOD is unlikely to affect the intrinsic risk across a catchment or estuary within the study area presented in this assessment (refer to Supplementary Material). Indeed, current literature suggests that various vegetation and land cover types all have the ability to deoxygenate a waterbody (Kobayashi et al., 2009; Liu et al., 2019; O'Connell, Baldwin, Robertson, & Rees, 2000). Under equivalent environmental conditions, it would therefore be the extent and duration of inundation throughout a catchment which provides the greatest risk differential for blackwater generation.

3.2.2 Water level data

The accuracy of the assessment with respect to inundation characteristics relies on the suitability of the water level data available. In this regard, the results for the Shoalhaven River may also have been adversely affected by the limited distribution of water level data within major tributaries of the estuary. No gauges are located within the estuarine reaches of Broughton Creek, while water levels on the Crookhaven River are only recorded at the downstream limits of the estuary (refer to Supplementary Material). As the inundation extents were estimated by a direct extrapolation of the estuarine water levels, it is important to obtain a representative distribution of flood conditions throughout the estuary. If the adopted water levels are lower than those typically experienced at any catchment (as may occur when upstream water levels are poorly represented), the inundated area, and corresponding aggregated blackwater risk factor, will be underestimated.

4 Discussion

4.1 Floodplain inundation characteristics

Results from the catchment rankings provide insights into the influence of estuarine hydrodynamics on the blackwater risk profiles. For example, in the Tweed River the median extent of inundation over the Stotts Creek catchment (3.9km^2) exceeds that experienced in the Condong catchment (2.2km^2), yet Condong presents a higher overall blackwater risk than Stotts Creek (Figure 5). This reflects the differences in catchment size and topography as well as the water surface elevations.

As illustrated in Figure 6, Stotts Creek presents a relatively flat, low-lying floodplain below the local median inundation level of 0.7m AHD. However, the topography rises steeply, with limited additional catchment area contributing to potential blackwater generation at higher water levels. Conversely, the Condong catchment would produce limited volumes of blackwater until the surface water levels exceed 0.5m AHD. Once inundation levels reach 1.2m AHD, the area contributing to blackwater generation in the Condong catchment would exceed the Stotts Creek catchment and the risk factor would increase accordingly. At higher inundation levels (experienced during more significant, but less frequent rainfall events), the large potential volumetric contribution of blackwater from the Condong catchment outweighs that of the Stotts Creek catchment. In general, both greater topographic exposure and higher inundation levels increase the overall blackwater risk presented by any particular catchment to the receiving estuary.

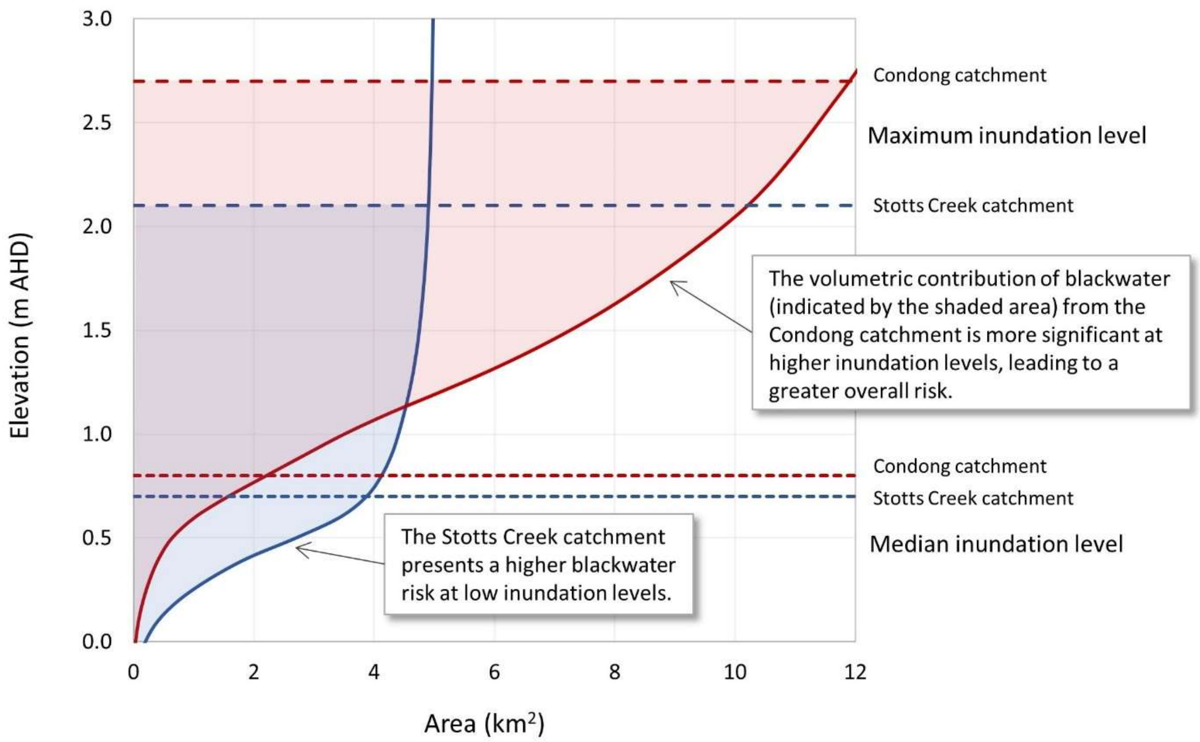

Figure 6. Hypsographic graph of the Stotts Creek (blue) and Condong (red) catchments in the Tweed River estuary, illustrating the changing risk profiles based on inundation levels.

Comparing the Stotts Creek and Condong catchments (Figure 6) also highlights the sensitivity of the method to the duration and frequency of flood events. This was further investigated by modifying the inundation matrix to assess the aggregated blackwater risk factor. Removing the 1 and 2 day inundation durations from the aggregated blackwater risk assessment matrix reduced the overall inundation levels, as lower water levels are experienced during the rising and falling limbs of a flood hydrograph. Conversely, limiting the analysis to flood events with a recurrence interval of 2 to 5 years or 3 to 5 years typically increased the median inundation levels as fewer minor events were included in the statistics. Importantly, the relative risk remained consistent throughout this sensitivity analysis, with Spearman's rank correlation remaining above 0.9 in all estuaries except the Shoalhaven River (detailed in the Supplementary Material). Notably, the ranking of catchments within the Shoalhaven River was more sensitive to the influence of shorter duration events, although the correlation between the top five ranked catchments remained above 0.9 in all analyses.

The robustness of the assessment to variations in the flood duration and recurrence interval reflects the consistency of the hydrodynamic response to flood events throughout each estuary. As illustrated in Figure 7, peak flood levels are typically highest in the upper estuary, where water levels rise rapidly and remain high due to restricted drainage from elevated tailwaters in the mid- and lower portions of the estuary. Flood profiles in the lower estuary are further moderated as the hydraulic energy and flow volumes are dispersed over the low-lying floodplains. Additionally, in the lower estuary water levels are less affected by flood flows as offshore waters can assimilate large flood volumes. These effects are exemplified in the comparison between the Condong (located in the upper estuary and subject to higher inundation levels) and Stotts Creek (mid-estuary) catchments (Figure 6).

Based on these spatial differences in drainage across an estuary, the free-draining lower reaches of an estuary typically have a lower risk of blackwater generation. The environmental impacts of blackwater discharged from these downstream catchments may also be mitigated by high tidal flushing and reduced residence times due to their proximity to the ocean (Johnston et al., 2003; Rabalais et al., 2002). To this aim, Eyre and Twigg (1997) indicated that dissolved oxygen levels were higher in parts of the estuary with higher salinity (or increased tidal flushing) for the first seven weeks after the flood event. In contrast, the upper estuary is likely to have a higher blackwater risk as residence times may be prolonged (i.e. any blackwater released would remain in the estuary for extended periods) and flood levels tend to remain elevated for longer periods (i.e. any blackwater generated may discharge into an estuary with less assimilation capacity).

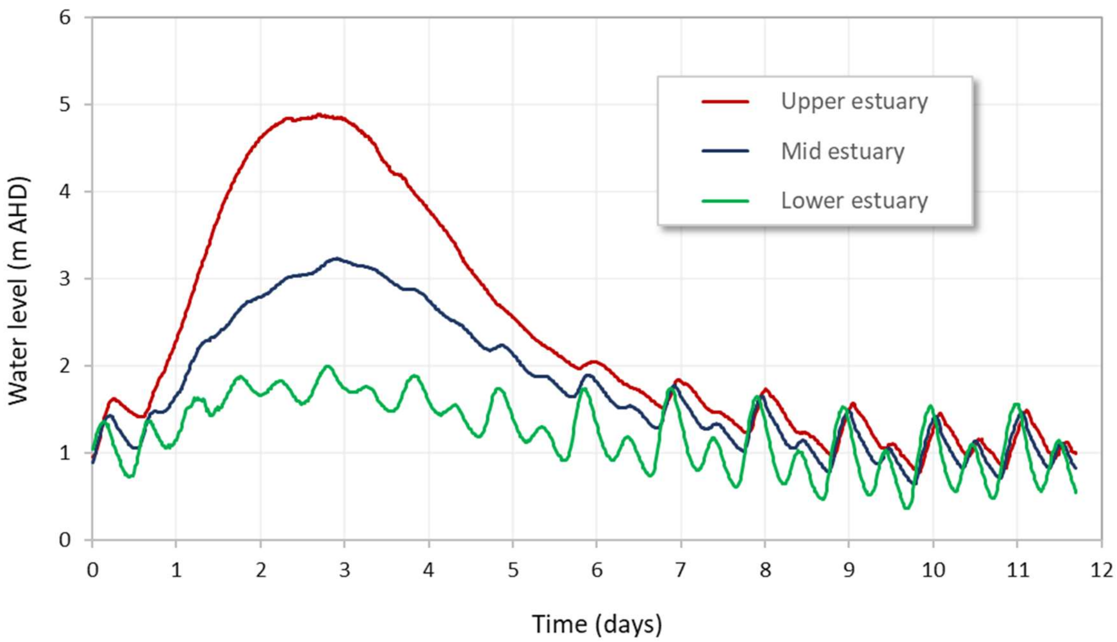

Figure 7. Spatial illustration of typical water level response to a flood in the lower, mid and upper reaches of an estuary from an event recorded in the Richmond River in June 2005. The upper estuary was measured at Coraki (refer to Supplementary Material for gauge locations) and represents conditions for the Upper Richmond and Wilsons River catchments (Figure 5). The mid estuary was measured at Woodburn (Rocky Mouth Creek catchment) and the lower estuary at Wardell (Empire Vale and Back Channel catchments.

As inundation levels and inundation durations are often spatially correlated within an estuary, the risk factors for blackwater generation and impact may be simplified to the estuarine water levels, floodplain geomorphology, and the potential for BOD generation. These primary factors are conceptualised in Figure 8 for an idealised system. Based on these factors, a catchment may present a higher risk of blackwater generation and impact if:

- it is located in a portion of the estuary where floodwaters are maintained at higher levels and/or for longer durations (Figure 8(a));
- the topography contains an extensive, low-lying floodplain that can accommodate large volumes of floodwater (Figure 8(b)); and/or
- the land use and environmental characteristics have a higher potential to generate BOD (Figure 8(c)).

The environmental impact of blackwater in an estuary is then determined by the floodplain connectivity with the estuary and the discharge characteristics of the catchment drainage system (Figure 8(d)). Modern drainage systems facilitate the rapid transfer of DOP to the estuary, with substantial volumes of blackwater discharged as the flood recedes (Figure 8(a)). These discharges can be particularly harmful when there is limited assimilative capacity in the estuary. The impact from any individual catchment discharge is also affected by discharges from nearby catchments as individual blackwater plumes can intermix. The dilution capacity and potential environmental impacts from these blackwater plumes are highlighted in Figure 9.

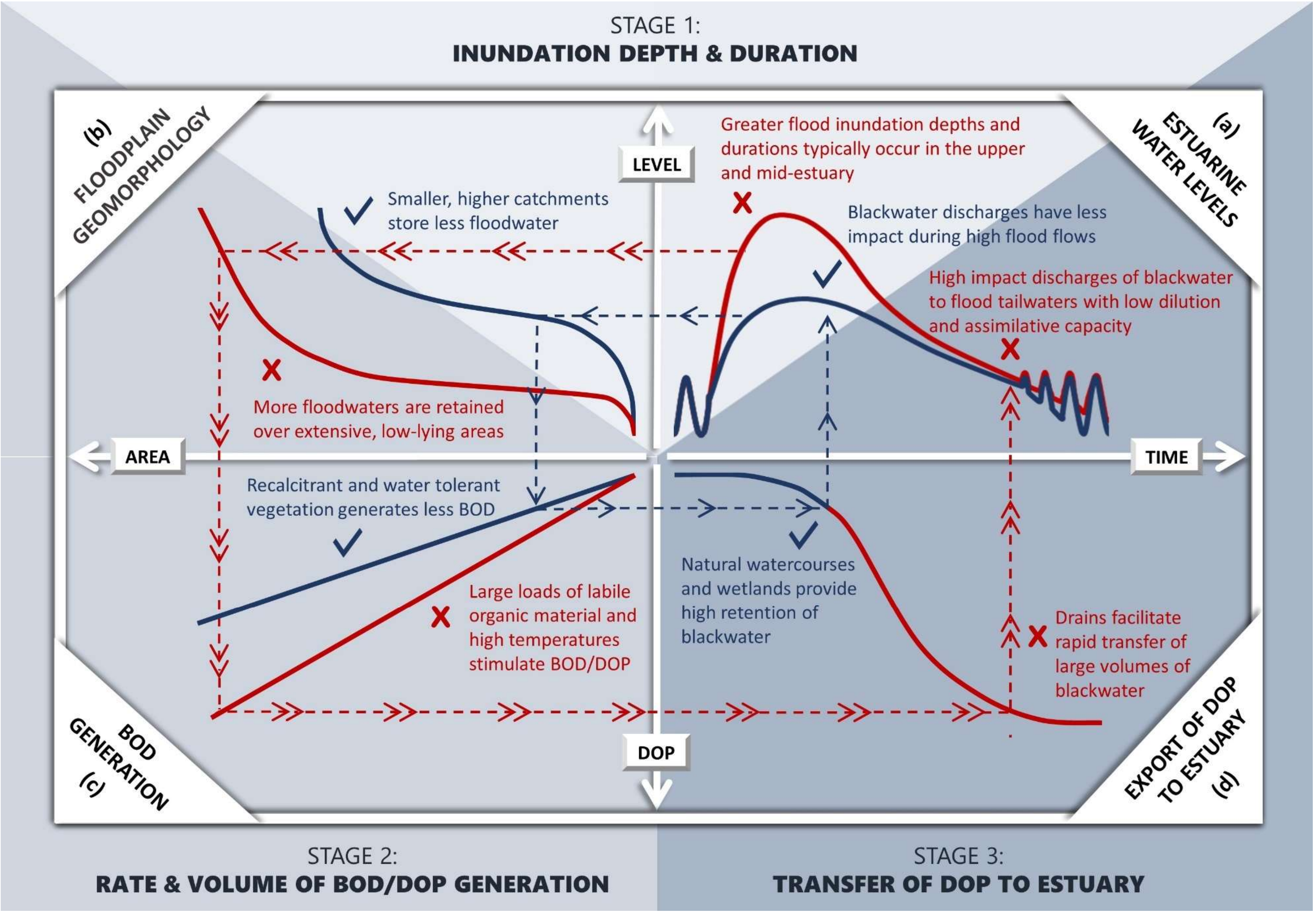
STAGE 1:
INUNDATION DEPTH & DURATION
(b) FLOODPLAIN GEOMORPHOLOGY
(a) ESTUARINE WATER LEVELS
LEVEL
Greater flood inundation depths and durations typically occur in the upper and mid-estuary
Smaller, higher catchments store less floodwater
Blackwater discharges have less impact during high flood flows
High impact discharges of blackwater to flood tailwaters with low dilution and assimilative capacity
More floodwaters are retained over extensive, low-lying areas
AREA
TIME
Recalcitrant and water tolerant vegetation generates less BOD
Natural watercourses and wetlands provide high retention of blackwater
Large loads of labile organic material and high temperatures stimulate BOD/DOP
Drains facilitate rapid transfer of large volumes of blackwater
DOP
BOD GENERATION (c)
EXPORT OF DOP TO ESTUARY (d)
STAGE 2:
RATE & VOLUME OF BOD/DOP GENERATION
STAGE 3:
TRANSFER OF DOP TO ESTUARY

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Figure 8. Conceptual diagram of the key risk factors for blackwater generation on an estuarine floodplain. The diagram should be read counter clockwise from the top right corner. A high-risk scenario is realised by following the progression of a blackwater event via the red arrows from Stages 1 to 3. Commencing in quadrant (**a**), high flood levels in the estuary lead to extensive inundation (**b**) during Stage 1. Increased biochemical oxygen demand (BOD) generated at Stage 2 (**c**) will result in a high deoxygenation potential (DOP). The greatest impacts occur when the blackwater discharges at Stage 3 (**d**) overwhelm the assimilative capacity of the receiving waters (a). An alternative low risk scenario is proposed via the blue arrows.

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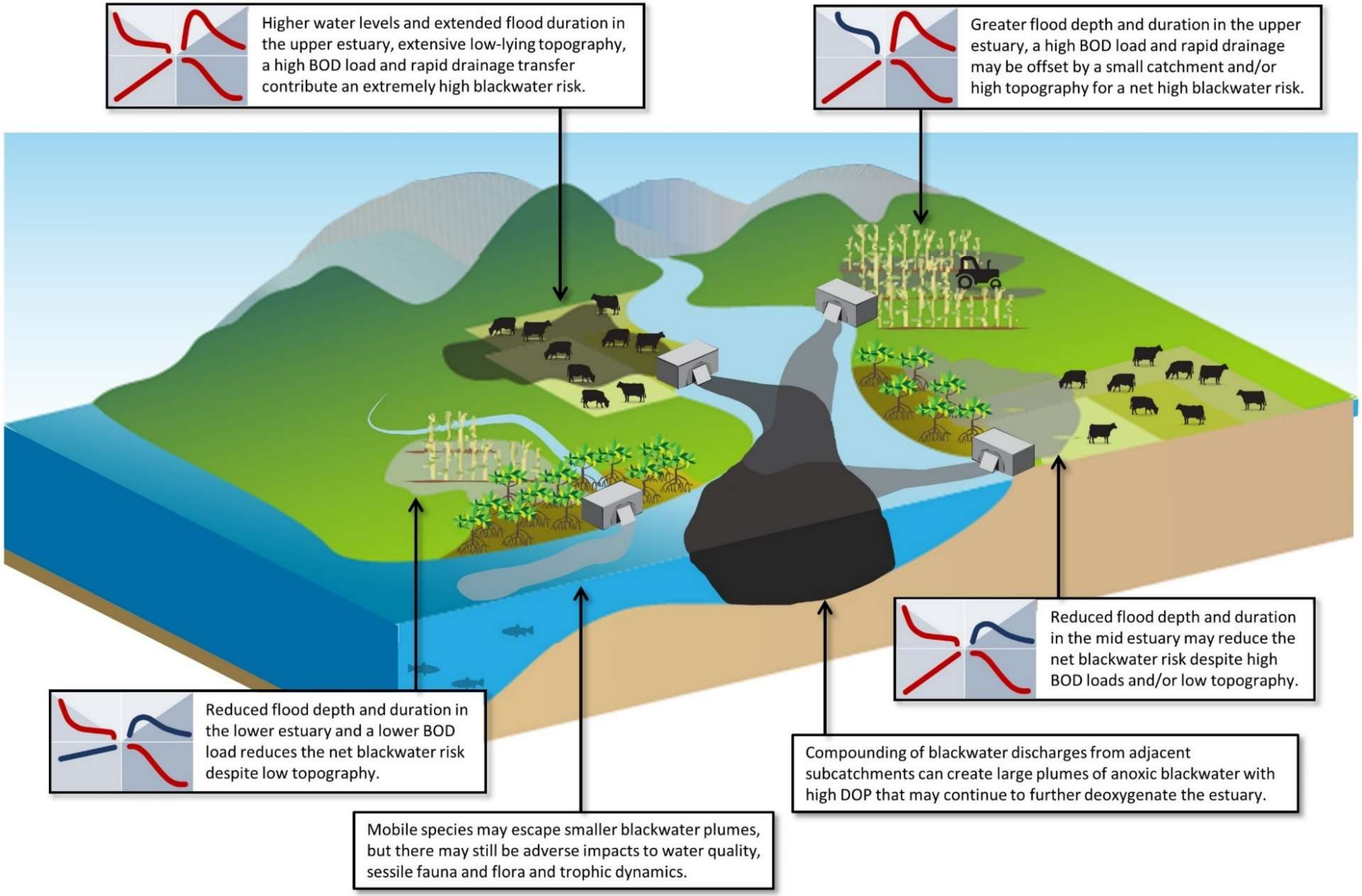

Higher water levels and extended flood duration in the upper estuary, extensive low-lying topography, a high BOD load and rapid drainage transfer contribute an extremely high blackwater risk.
Greater flood depth and duration in the upper estuary, a high BOD load and rapid drainage may be offset by a small catchment and/or high topography for a net high blackwater risk.
Reduced flood depth and duration in the mid estuary may reduce the net blackwater risk despite high BOD loads and/or low topography.
Reduced flood depth and duration in the lower estuary and a lower BOD load reduces the net blackwater risk despite low topography.
Compounding of blackwater discharges from adjacent subcatchments can create large plumes of anoxic blackwater with high DOP that may continue to further deoxygenate the estuary.
Mobile species may escape smaller blackwater plumes, but there may still be adverse impacts to water quality, sessile fauna and flora and trophic dynamics.

Figure 9. Conceptual diagram of common blackwater risk factors and compounding discharges within an estuary. The risk from each drainage catchment is described with reference to the four risk factors illustrated in Figure 8.

4.2 Spatial distribution of floodplain drainage

Impacts of compounding blackwater plumes are typified by the blackwater risk profiles of the Clarence and Richmond Rivers. The inundation extent at the median inundation level for the Clarence River (285 km^2) is more than twice the Richmond River (137 km^2). However, the impact of blackwater events in the Richmond River has been more severe, with extensive fish kills regularly reported after comparable flood events (Walsh et al., 2004). This has previously been attributed to the substantially larger river discharges and assimilation capacity of the Clarence River, which also provides opportunities for fish to seek refuge in the less affected parts of the estuary (Walsh et al., 2004).

Results from the aggregated blackwater risk analysis indicate that the highest ranked sub-catchments in the Clarence River discharge to different parts of the estuary. As such, blackwater discharges are likely to impact the estuary at different stages of a flood event. In comparison, the Richmond River has four of the five highest ranking sub-catchments discharging into the estuary within a 20km reach. With such close proximity, these individual plumes are likely to intermix, resulting in compounding impacts that are more likely to overwhelm the assimilation capacity of the estuary. These potential compounding impacts are illustrated in Figure 9.

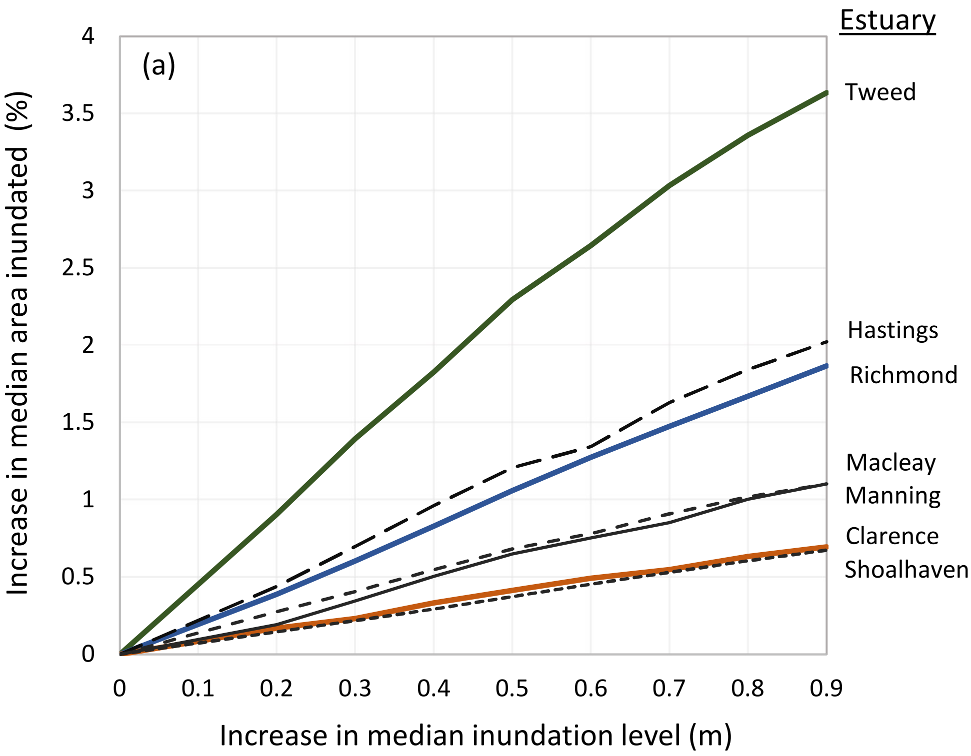
4.3 Climate change impacts

Investigating the sensitivity of spatial and temporal factors on blackwater generation also provides insights into how climate change may influence future blackwater conditions. Climate change has been predicted to increase temperatures (Masson-Delmotte et al., 2021), and create more intense and sporadic rainfall conditions (Dey, Lewis, Arblaster, & Abram, 2019). These impacts are expected to exacerbate hypoxic blackwater events (Carstensen et al., 2014; Godinho et al., 2019; Koehn, 2022; Vaquer-Sunyer & Duarte, 2008), with larger floods increasing the spatial and temporal inundation patterns, while warmer conditions may increase the microbial reaction rates (Wong et al., 2010). Changes in flood frequency and meteorological conditions may also encourage the accumulation of organic matter between floods providing high BOD potential.

In estuarine environments these effects will be further compounded by sea level rise, which is expected to increase standing water levels and reduce drainage (Waddington et al., 2022).

Higher downstream water levels may lead to increased spatial inundation, while reduced drainage will extend the temporal inundation. Overall, both factors will likely increase blackwater generation risk.

The potential for blackwater generation from sea level rise was investigated by examining the projected increase in area inundated for incremental increases in water levels across the floodplain sub-catchments. Unsurprisingly, the larger Clarence, Richmond and Macleay River systems, which already suffer the highest rate of fish mortality from blackwater events, would experience the greatest increases under rising sea levels. Normalising the increase in area inundated by the total catchment area (Figure 10(a)) indicates that the future risk of blackwater creation in the Tweed River is likely to be substantially higher than in other estuaries. This is primarily attributable to the topography of the Tweed River floodplain, where there is a greater increase in the area inundated by higher water levels.



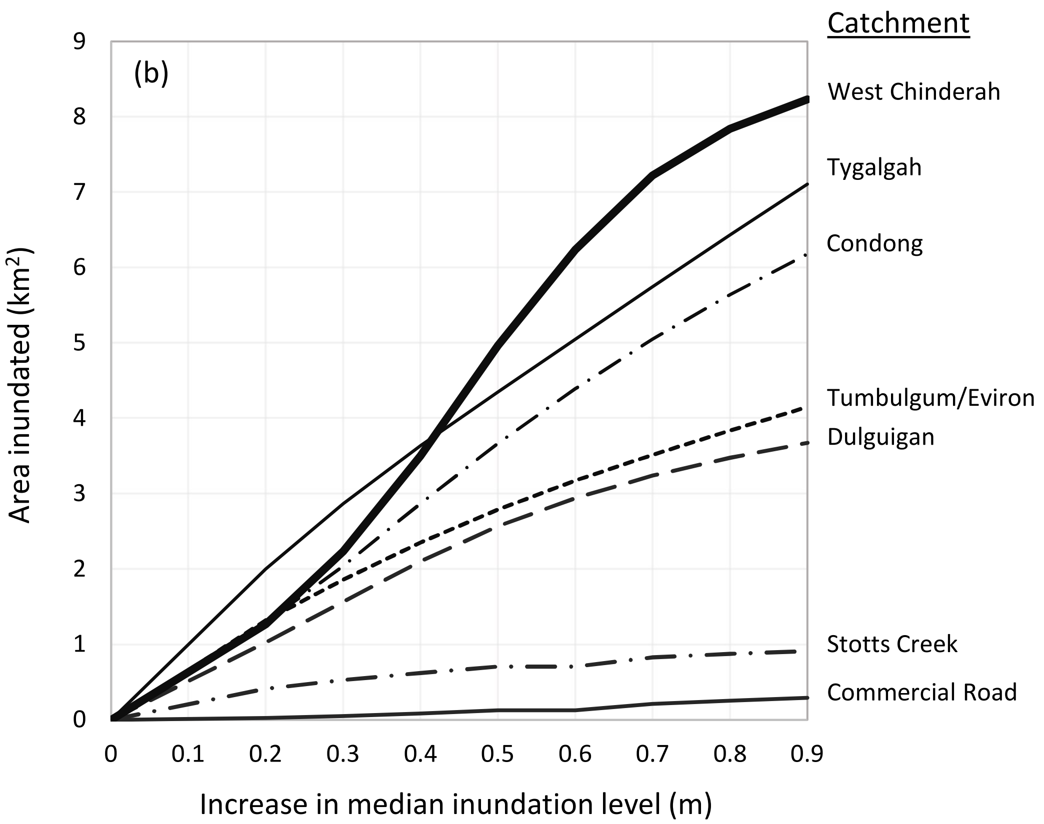


Figure 10. The (**a**) increase in median area inundated after an incremental rise in water level expressed as a percentage of the total catchment area. Within any given estuary (the Tweed River is used as an example here) the sub-catchments most extensively inundated and the locations discharging the most blackwater may change (**b**).

This analysis can be further extended to identify which catchments within a particular estuary present an increased risk of blackwater generation under existing or future conditions. For example, while the West Chinderah catchment of the Tweed River estuary currently presents a relatively moderate risk, the potential for blackwater generation may increase exponentially once the median inundation level rises by approximately 0.3m (Figure 10(c)).

4.4 Management and mitigation of blackwater risk

The improved understanding of estuarine blackwater events, as provided by this assessment, enables a nuanced assessment of potential mitigation measures. In areas identified as low risk for blackwater generation, minor changes to land management may mitigate blackwater generation by reducing the bioavailability of carbon. For example, the removal of cuttings from slashed pastures has been suggested as an effective means of reducing the DOP of grazing lands (Eyre et al., 2006). Alternatively, mechanical oxygenation has been employed to mitigate blackwater impacts in the Swan and Canning Rivers of Western Australia (Greenop, Lovatt, & Robb, 2001), although this is generally regarded as an emergency response measure as it is substantially limited by the area that can be serviced and operational costs (Baldwin, Boys, Rohlfs, Ellis, & Pera, 2022).

As the potential for blackwater generation increases, the impact of effective mitigation measures on current land uses is also likely to increase. Where the median inundation level is relatively shallow, the depth and density of floodplain drains may be reduced to encourage the growth of water-tolerant vegetation and facilitate reaeration of the water column (Hamilton et al., 1997; Rixen et al., 2008). However, in areas subject to prolonged, deep inundation, reaeration will be hampered by the lower ratio of the air-water interface to flood volume and there is likely to be greater plant morbidity and contribution to BOD. Such conditions are typified in the low energy backswamp environments, which may be best suited to reinstatement into natural wetland systems. Indeed, tidal restoration and the reinstatement of coastal and floodplain wetlands has been identified as the preferred management measure for the mitigation of blackwater events in the coastal estuaries of NSW (Moore, 2006).

Social and economic ramifications accompanying land-use change may be significant due to the level of development throughout the floodplains (Moore, 2006; Southern Cross GeoScience, 2019). Identification of areas at highest risk of backwater generation (as discussed in this paper) is recommended to support trials and further investigations into these options. This will ensure that decisions to reinstate wetland systems are evidence-based and transparent, optimising water quality benefits and ongoing floodplain productivity.

5 Conclusion

Hypoxic blackwater events occur worldwide and affect both inland and coastal waters. The mechanisms underpinning these events are associated with the microbial metabolisation of carbon and the accumulation/discharge of deoxygenated water during and post flood events. This paper presents a methodology developed to prioritise catchments within an estuarine floodplain based on their potential to generate hypoxic blackwater and to identify those catchments from which blackwater discharges are likely to have the most significant impact on the estuary. Local topography and changes to the flood hydrograph as it progresses along an estuary are shown to influence the extent and duration of inundation over the floodplain. In turn, inundation characteristics are identified as critical factors in determining the volume of blackwater generated and the DOP discharged to the receiving waters. Concerns related to increased blackwater generation from climate change, and sea level rise in particular, are highlighted.

It is anticipated that this research will be used to inform evidence-based decision making to manage catchment risks to water quality. This may enable a strategic approach to future investments in floodplain and estuarine research and management measures to optimise economic, social and environmental outcomes.

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Declaration

The authors declare that they have no known competeing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability statement

Water level data was sourced from the NSW Water Level Data Collection Program (MHL, 2023) available at https://mhl.nsw.gov.au/Data-Level. Land-use mapping was based on the Australian Land Use and Management (ALUM) classification (DPIE, 2020). Climate (monthly temperature) data presented in the Supplementary Material was downloaded from the Climate Data Online service of the Australia Bureau of Meteorology website Climate Data Online - Map search (bom.gov.au). Mapping was undertaken using the QGIS software, which can be freely downloaded from Discover QGIS. Digital elevation data (Geoscience Australia,

2018) was obtained from the National Elevation Data Framework spatial dataset [Elvis (fsdf.org.au)] managed by Geoscience Australia [Digital Elevation Data | Geoscience Australia (ga.gov.au)].

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