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Opportunistic management of estuaries under climate change: a new adaptive decision-making framework and its practical application

William Peirson[(a)], Erica Davey[(a)], Alan Jones[(b)], Wade Hadwen[(c)], Keith Bishop, Maria Beger[(d)], Samantha Capon[(c)], Peter Fairweather[(e)], Bob Creese[(f)], Timothy F Smith[(g)], Leigh Gray[(h)] and Rodger Tomlinson[(i)]

[(a)] *Water Research Laboratory, School of Civil and Environmental Engineering, the University of NSW, Sydney, NSW, Australia*

[(b)] *Division of Invertebrates, Australian Museum Sydney, Sydney, NSW, Australia*

[(c)]*Australian Rivers Institute, Griffith School of Environment, Griffith University, Nathan, QLD, Australia*

[(d)]*ARC Centre of Excellence for Environmental Decisions, School of Biological Sciences, The University of Queensland, Brisbane, QLD, Australia*

[(e)]*School of Biological Sciences, Flinders University, Adelaide, SA, Australia*

[(f)]*Department of Primary Industries, Port Stephens Fisheries Institute, NSW, Australia*

[(g)]*Sustainability Research Centre, University of the Sunshine Coast, Maroochydore, QLD, Australia*

[(h)]*Coastal Ecosystems & Water Quality Group, Environment & Sustainability Branch, Great Barrier Reef Marine Park Authority, Townsville, QLD, Australia*

[(i)]*Griffith Centre for Coastal Management, Griffith University, Gold Coast, QLD, Australia*

CORRESPONDING AUTHOR: W.L. PEIRSON, E-MAIL: BILL.PEIRSON@WRL.UNSW.EDU.AU, FAX: +61 2 9949 4188

Abstract

Ongoing coastal development and the prospect of severe climate change impacts present pressing estuary management and governance challenges. Robust approaches must recognise the intertwined social and ecological vulnerabilities of estuaries. Here, a new governance and management framework is proposed that recognises the integrated social-ecological systems of estuaries so as to permit transformative adaptation to climate change within these systems. The framework lists stakeholders and identifies estuarine uses and values. Goals are categorised that are specific to ecosystems, private property, public infrastructure, and human communities. Systematic adaptation management strategies are proposed with conceptual examples and associated governance approaches. Contrasting case studies are used to illustrate the practical application of these ideas. The

framework will assist estuary managers worldwide to achieve their goals, minimise maladaptative responses, better identify competing interests, reduce stakeholder conflict and exploit opportunities for appropriate ecosystem restoration and sustainable development.

1. Introduction

Estuaries are highly valuable ecosystems for intrinsic ecocentric and instrumental anthropocentric reasons (UNEP 2006). They are facing acute contemporary anthropogenic pressures due to bourgeoning coastal human populations (Martinez et al. 2007). These pressures include nutrient enrichment, organic carbon loading, chemical contamination, fisheries exploitation, introduced species, freshwater diversions, shoreline development and dredging, and habitat loss and alteration (Kennish 2002). Human coastal communities and estuarine ecosystems are also threatened by climate change (Bellard et al. 2012; Byrne 2011; Gillanders et al. 2011; Harley et al. 2006; IPCC 2007; USEPA 2011). Estuaries are particularly vulnerable to climate change since they are highly exposed and acutely sensitive to many of the projected changes in important ecological factors such as temperature, pH, saline intrusion, wetland inundation, freshwater flows and storminess (Hadwen et al. 2011).

Estuarine planning and management have conventionally focused on four major aspects: 1) ports and harbours; 2) flooding; 3) water quality; and 4) environmental flows (e.g. ARMCANZ 2000; Coltheart 1997; DIPNR 2005; Peirson et al. 2002). As each aspect has different implications for management and planning, interaction between them often occurs in a disjointed fashion, exacerbated by the tendency of marine, terrestrial and freshwater agencies to act independently (Beger et al. 2010).

Due to the coupling of multiple stressors (e.g. Short et al. 2012, Table 2 and associated discussion) impacting diverse values, effective estuarine management requires holistic recognition of the interdependencies of both the socio-economic and ecological components (e.g. PIANC 1999). Such holistic recognition is necessary to minimise the occurrence of maladaptation— unintended negative

consequences issuing from fragmented and sectional approaches to management. To minimize the risk of climate-related maladaptation (Segan et al. 2010; Wintle et al. 2011), explicit, integrated management objectives are needed. Moreover, management should be underpinned by a defined vision (e.g. UNEP 2012), accompanied by: 1) goals; 2) strategies for reaching these goals; 3) monitoring to assess progress; and, 4) adaptive capacity to correct failure.

For estuarine ecosystems and their adjacent communities, climate change is not just a threat which triggers the conventional *protect*, *accommodate* and *retreat* reactions (e.g. IPCC 2014b). Rather, climate-related responses will provide opportunities for managers to improve the condition of degraded estuaries (e.g. increases in sea level will increase tidal prism and therefore flushing). . Estuaries are therefore less constrained by some of those inertial and institutional barriers to climate adaptation that are characteristic of other systems (IPCC, 2014c).

The need for transformative climate adaptation (IPCC, 2014a, c, d) has motivated us to develop this novel framework for estuary planning and management. This framework will enable managers to identify and exploit opportunities that emerge from climate changes. It comprises: 1) a vision for estuaries under a changing climate to provide focus ; 2) a comprehensive categorisation of estuarine values and stakeholders to identify potential trade-offs; 3), a list of potential adaptation goals with associated strategies and, 4) an outline of the overall estuary climate adaptation management process. We conclude with two contrasting Australian case studies to illustrate the practical application of this approach.

2. Vision

Clear goals enable the development of appropriate management strategies. We have captured the overall goals of estuary management in the following vision statement: “Estuaries will sustainably meet the needs and aspirations of society and maintain ecological integrity in the face of change with appropriate recognition of the intertwined human and ecological values. This will be achieved through

the adoption of integrated and holistic adaptive strategies." This is consistent with government policies internationally (e.g. UNEP 2006). Without such a vision, either ecosystem integrity will be sacrificed in the face of unsustainable coastal development, or coastal communities will become impoverished by inadequate environmental protection.

3. Stakeholders: their uses and values of estuaries and potential goals for the future

Effective engagement with stakeholders is essential for effective environmental management. Based on our professional experience, we identified seventeen major stakeholder groups (Table 1) with twenty-three corresponding intrinsic or instrumental uses and values (Table 2). Specific individuals may belong to several groups. Groups may have multiple estuarine uses and values. Instrumental values, i.e. socio-economic benefits dominate in Table 2.

Stakeholders are categorised according to their level of estuarine contact using classes of likely duration and scope (Table 1). Stakeholders with a "high-high" contact would probably have a greater understanding of and concern for estuarine integrity than stakeholders with a "low-low" level of contact. Stakeholder sets will differ between estuaries and differences will be apparent amongst individuals within major stakeholder groups. This multi-scale heterogeneity is also dynamic as the mix of stakeholders can change over time.

The potential goals (Table 2) associated with the twenty-three uses/values have been partitioned among ecosystems; private property; public infrastructure; and human communities. Dynamic heterogeneity exists between these goals. For example, individual farmers may have vastly different goals according to their varying commitment to traditional practices in the context of changing commercial return due to climate. Successful adaptive planning for estuaries must take into account the inter- and intra-stakeholder heterogeneity and dynamism to achieve the goals in Table 2. However, some goals may be in direct conflict. For example, it may be impossible to simultaneously

maximise biotic habitat and adequately protect physical infrastructure. Such conflicts require political resolution after careful examination of potential trade-offs.

4. Adaptation Strategies

Having identified the potential adaptation goals (Table 2), we now articulate accompanying strategies to provide overall structure to the estuary management decision-making process. Here, we present values in non-economic terms, but recognise that relevant economic work is progressing with the evaluation of ecosystem services an important component (Millennium Ecosystem Assessment 2005; Costanza et al. 2014).

Climate change is complex with high decision stakes (Smith 2009; Gidley et al. 2010; Clarke et al. 2014). Consequently, we advocate a cautious and holistic systems approach to adaptation decision-making for several reasons. First, well-meant management interventions may turn out to be maladaptive since ecological and social entities have interacting components with feedback loops so that changes to one component can also negatively affect other components (Harris 2007; Walker and Salt 2006). Consequently it would be a fundamental mistake to consider human systems in isolation from ecosystems or vice versa.

Secondly, a given ecosystem can flip to an alternative state if thresholds of controlling variables are exceeded. For example, if too much nitrogen pollutes a clear-water, seagrass-dominated estuary, it may become a turbid, phytoplankton-dominated estuary (Harris 1999). While environmental variables such as nutrients can often be controlled, climate-caused changes to sea level, temperature, salinity and pH are inevitable. Ecosystem flips are often maladaptive since large changes to ecosystems that we depend upon can be devastating for humans (Scheffer et al. 2001) and, moreover, they may not be reversible (Harris 1999). It is therefore important to enhance ecosystem resilience by anticipating and minimising maladaptation (i.e. decisions must not be based solely on economic, social or environmental grounds, but also on the flow-on consequences of the adaptation action across

all three sectors). Monitoring to detect the early signs of maladaptation and guide corrective action will be important.

Furthermore, decisions must accommodate the likelihood of arriving at different outcomes via options. These , in turn, will require modelling different scenarios to scope out possible futures (e.g. Lester et al. 2013),the outcomes of which will strongly influenced by:

- the use of local context and knowledge in identifying stakeholders and distilling their specific values and goals;
- the spatial and temporal scales of consideration;
- an ability to maintain values and attain goals;
- identifying flow-on consequences in a highly connected landscape; and,
- possibly trading off values among the interested parties (e.g. Hadwen et al. 2011) to obtain the most efficacious adaptation strategies (for examples, see the case studies below).

Conventional ecological adaptive management often involves repetitive planning, implementation and monitoring. However, in systems with interacting intrinsic and instrumental values, industry and human modification are continuous processes and implementation activities must be interwoven within ongoing assessment activities (Short et al. 2012). Decision-making links an alert state (during which monitoring or assessment activities would take place) with an active state of implementation (which may or may not include monitoring and evaluation activities).

The approach adopted here (see flowchart in Figure 1) retains the three distinct climate adaptation actions (retreat, accommodate and protect, Nicholls et al. (2007). However, to better incorporate the necessary integrative systems thinking, we emphasize the importance of being alert to the potential impacts of climate change without necessarily taking any action. We propose three alert adaptation strategies: “wait and see”, “hedge” and “investigate”. All strategies and their tactics are summarised in Table 3, with accompanying specific examples.

"Wait and see" recognises that the uncertainties may be significant with regard to both the impacts of climate changes and the efficacy of any intervention or change in present activities. Since intervention will have economic costs, it will often be appropriate to monitor the situation in the context of identified action thresholds.

"Hedge" acknowledges that intervention is required once a certain threshold is exceeded. Such intervention will require funding that needs to be allocated. The responsible organisational unit has not been specified since the hedging process may be appropriate at any or all individual, corporate or government jurisdictional levels. The hedging could, potentially, take the form of insurance (IPCC 2014c).

"Investigate" recognises that appropriate research may yield new solutions that can transform stakeholder perspectives, mitigate the economic impact of intervention or expose new or improved options.

In the active mode the conventional three climate change actions are retained, namely: "protect" (intervention to better resist or buffer against climate impacts)**,** "accommodate" (modifying existing systems or structures to minimise disruption by climate impacts), and "retreat" (realignment of existing activities to increase the buffer against climate impacts).

To these we add another two actions (so-called "improve" and "abandon") and a decision pathway "liberate".

The "liberate" pathway recognises that for large-scale pristine or near-pristine ecological systems, the costs might be so great and/or the outcomes so uncertain that intervention would be inappropriate or politically infeasible. Consequently, no more resources would be invested in adaptive management and the system is liberated to respond naturally to external climatic changes. This pathway

acknowledges the magnitude of potential climate change impacts and involves making a conscious decision to not interfere. The liberate pathway implies adaptation over much longer time scales, possibly geological, although significant immediate changes may be observed in the wake of major climatic events: floods or coastal storms. The liberate pathway contrasts with active adaptation which focuses on the manipulation of external environments (with no internal self-regulation), which is reflected in most contemporary notions of adaptation (Thomsen et al. 2013).

"Retreat" implies that ongoing administration or monitoring will be undertaken and can be applied to the target community, infrastructure and/or ecological system. However, for some ecological systems or built infrastructure, the vulnerability to climate impacts will be so significant that future investment in adaptation is unjustifiable. The action used to describe this situation is "abandon", its outcome being similar to "liberate" in that the system is left to respond to climate pressures without intervention. These differ in that "liberate" refers to relatively pristine systems while "abandon" applies to estuaries with human barriers, modified habitats and infrastructure that will remain in place (but simply be abandoned). Action may be required to remove or modify any constructed facilities so that they do not become a future hazard themselves.

The "improve" action signifies that in modified estuaries, degradation of ecosystems or construction of substantial infrastructure may have occurred but these systems do have future value that can be maximised by climate adaptation **-** transformational adaptation (IPCC, 2014d). Utility or diversity can be improved via upgrading, rehabilitation or greater management intervention. For example, the elevation of residences to accommodate sea level rise may also be a cost-effective opportunity to improve their value by reducing the impacts of catchment flooding.

5. Adaptation methodology

The following stepwise process is proposed to manage climate adaptation of estuaries (Figure 1):

1. Identify stakeholders (Table 1). This becomes more complicated with the level of anthropogenic development. For example, surrounding and within an estuary there may be farms, a minor port

development, recreational water users, and breeding grounds for commercial fish caught which all may be influenced or regulated by some sort of government intervention. Small increments in the level of development can entrain a much wider base of stakeholder involvement.

2. Determine the uses and values in consultation with the stakeholders (Table 2). For example, farmers, recreational water users and fisher-people would be concerned about water quality, while a port operator may be concerned about impacts on navigation (e.g. PIANC 1999).
3. Informed by system knowledge obtained from the stakeholders as well as climate science, assess climate change-related consequences and costs. For example, changes in the rainfall regime may lead to decreased freshwater flow, changing the habitat of an existing fish breeding ground, subsequently resulting in colonisation of different species.
4. A choice of adaptation strategies can be made once there is an understanding of potential outcomes from climate change as well as the degree to which the strategies will influence the system. This cyclical process (Figure 1) may involve development of both short-term and longer-term plans, including a combination of the alert, pathway and active adaptation strategies.

The onset of many climate change adaptation triggers (particularly those related to climate events) will occur suddenly. In such instances, mandatory adoption of active adaptation strategies is likely due to stakeholder demands, with possible unintended consequences. Pre-emptive assessment of the climate change impacts and adaptation strategies will be important to ensure that the outcomes protect and, possibly, enhance both ecological and stakeholder values as much as possible. Such an approach aligns well with conventional, corrective adaptive management.

6. Case Studies

Existing management actions conform to the eight adaptation strategies presented in Table 3. To demonstrate the broad applicability of these strategies despite inter-estuary differences, we present two contrasting case studies that review historical management and application of the adaptation strategies. A case-by-case approach and careful consideration of adaptation options using local

knowledge is necessary to ensure positive outcomes and maximisation of intrinsic and instrumental values.

6.1 The Mary River, Northern Territory, Australia

The Mary River estuary is located 90 km east of Darwin in tropical Northern Australia (Figure 2). Its catchment area of approximately 7,700 sq km has high rainfall over the wet season (generally November to March) and low rainfall over the remainder of the year. A concise description of characteristics of the Mary, its catchments and the significant changes that have occurred in this estuary over the past 60 years is presented in Williams (2014).

Of greatest contemporary concern is the penetration of saltwater into the estuary, resulting in extensive coastal vegetation dieback, the destruction of freshwater ecosystems in swamps and billabongs, filling of billabongs with tidal sediments, tidal flooding and accretion of sediment on the floodplains adjacent to the tidal channels (Finlayson et al. 1988). These issues are likely to be exacerbated by climate change-related sea level rise. A recent review of the conservation status of the Mary (NRETAS 2011) identifies the principal catchment stakeholders (as summarised in Table 1).

The economic feasibility of the prevention of saline intrusion has been assessed by McInnes (2004). Commercial interests in the future management of the Mary, as identified by McInnes, have also been noted in the 6th column of Table 1. The absence of major industrial or urban developments coupled with the limited navigability of the entrance has precluded port development (Williams 2014).

Although there are several ecological management challenges for the Mary estuary (NRETAS 2011), present discussion is restricted to the impacts of increased saline intrusion. In this regard, the aims for the estuary, management actions and independent professional assessment are inconsistent:

1. The first stated management aim (NRETAS 2011, p. 23) is to “Protect and maintain the natural values of national and international significance including wetlands/floodplains, high species

richness, wildlife aggregations, habitat diversity, and species of conservation significance". Stakeholder expectations are that protection (Figure 1) is the preferred strategy for change management.

2. Approximately AU$500,000 p.a. was spent on protective works in the decade preceding 2004 (D. Williams, pers. comm.). These protective works were largely *ad hoc* structures. They have produced no recognised outcome (the claims of McInnes, 2004, p. 5 are unsubstantiated) and illustrate the real costs of decision making in the absence of proper assessment and stakeholder engagement.
3. McInnes (2004, §1.3) presents proposed works to protect the estuary (including from the effects of climate change, p. 80). On page 76, a net present benefit is predicted for the protect option. This programme has not been implemented to date nor is there explicit present accumulation of funds to do so.
4. Williams (2014, pp. 286, 287) anticipates that protect strategies will fail and (in the terms of Figure 1) recommends the equivalent of a liberate strategy for the lower estuary, a possible hedge strategy in relation to the more modest Shady Camp barrage with wait-and-see/retreat strategies for affected stakeholders.

In terms of the decision framework (Figure 1), stakeholder communities of the Mary understand that the stated present strategy is protection. However, given the failure of previous attempts to protect the estuary and the inconsistencies between published assessments of future options, stakeholder conflict can be predicted to intensify as the impacts of climate change on the Mary River become apparent.

Two ways forward would potentially mitigate stakeholder conflict. Appropriate hedging could be established so that the funds are available and to ensure effective engagement with the actual costs of protection. Alternatively, present assessment inconsistencies could be resolved with a view to establishing an agreed stakeholder vision for the estuary. Figure 1 would facilitate achievement of an agreed vision by making stakeholders aware of the full suite of strategic options available.

6.2 Tomago – New South Wales

The Tomago wetlands are a large estuarine Ramsar site (www.ramsar.org) located near Newcastle, one of Australia's largest ports at the mouth of the Hunter estuary (Figure 3). Extensive flood mitigation works consisting of hundreds of kilometres of levees, canals and bank protection works prevent inundation of the estuary flood plain by floods or high tides (Saintilan and Williams 2000). The construction of the flood mitigation works has coincided with a 41% decrease in the area of saltmarsh, a critical migratory wading bird habitat, due to loss of tidal inundation (PWD 1980). Reclamation associated with adjacent farms and industrial developments have also created terrestrial stresses on the saltmarsh (Hydro Tasmania Consulting 2010). Mangrove invasion is causing further saltmarsh habitat loss (Winning 1996) and climate-related sea level rise will exacerbate these pressures on the saltmarsh communities (Saintilan and Williams 2000).

On the lower Hunter, economic, social and ecological values are in significant conflict due to the competing interests (as indicated by the rightmost column in Table 1).

In terms of our proposed strategies and tactics summarised in Table 3 and Figure 1:

1. The extensive and ongoing anthropogenic modification of the lower Hunter precludes the liberate option.
2. International treaties regarding the Ramsar-listed wetlands and the significant port infrastructure preclude the abandon strategy as an option.
3. Intense stakeholder conflict has continued. The principal impact has been ecological due to the importance of the economic and social drivers.
4. The ongoing, rapid loss of saltmarsh made wait-and-see and hedge strategies irrelevant. If the observed loss is to be arrested or (possibly) reversed, immediate action is required.

The saltmarsh habitat can be protected if the tidal inundation depth is limited to 0.3 m (Howe et al. 2010). Moreover, floodgate modifications could achieve this objective with no impact on adjacent landholders (Rogers et al. 2012). This outcome highlights the beneficial impact of focussed research as an appropriate investigation strategy.

The outcome has been the development of an effective strategy for estuarine improvement. Modified floodgates were installed in August 2007 with accompanying modest levee construction and clearing of exotic and undesirable species (Glamore and Rayner 2012). By June 2012, 2.5 sq. km of new restored saltmarsh habitat had been created. The ability to design and cost saltmarsh rehabilitation has created a stakeholder environment of acceptance and support for broader application locally and within other estuarine systems. Glamore and Rayner (2012) describe these improvements and their ability to remain robust under anticipated sea level rise without stimulating new stakeholder conflict.

In terms of Figure 1, proper establishment of a vision for the estuary, coupled with effective investigation has created an ongoing and widely-accepted strategy for improvement with ecological, social and economic benefits that will not be degraded by future climate change.

7. Concluding Remarks

Appropriate estuarine climate adaptation management must recognise the intertwined socio-economic and ecological aspects. In this paper, a comprehensive list of the different stakeholders within estuaries have been assembled (Table 1), as well as the likely uses/values and associated goals (Table 2) of these stakeholders. This information enables estuarine managers to identify and address the diversity of groups and their objectives within any given estuarine system.

A set of climate adaption management strategies applicable to multi-facetted and highly dynamic estuarine environments is presented (Figure 1 and Table 3). The opportunity to improve estuaries that are degraded is highlighted. Our case studies demonstrate that transformative climate adaptation to

estuarine systems is possible if: communications with stakeholders and estuary trajectory are aligned; and research is focussed on estuary restoration that is compatible with stakeholder uses and values. This adaptation methodology can be applied to estuaries worldwide, and will provide a basis for successful climate adaptation of crucial, but often overlooked, estuarine environments.

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Table 1: Values, uses, duration and scope of interactions between estuary stakeholders. References applicable to the case studies are included at right.

Stakeholders	Identification codes for primary uses/values[A] (see Table 2)	Primary domain of use/value • intrinsic value (ecological character) • instrumental value (socio-economic benefits)	Duration (Level of contact with the estuary)	Scope (Spatial extent and ecological functional understanding)	Case Study 1: Mary River, Uses Reference	Case Study 2: Tomago Saltwater Wetlands, Uses Reference
1. Local conservation agencies and managers	existence; **conservation**; bird, animal or fish watching; heritage; research	intrinsic value	moderate	high	(NRETAS 2011)	(Russel et al. 2012)
2. Voluntary conservation workers	existence, **conservation**, bird, animal or fish watching; heritage; research	intrinsic value	high	high	(NRETAS 2011)	(PBWBM 2006)
3. Observers of natural ecosystems and species	existence; conservation; **bird, animal or fish watching**	intrinsic value	high	high	(NRETAS 2011)	(PBWBM 2006)
4. Indigenous people	**indigenous activities**	both	moderate	high	(NRETAS 2011)	(PBWBM 2006)
5. Recreational water and shoreline users	**recreational water uses; recreational shore uses**	instrumental value	moderate	low	(NRETAS 2011)	(PBWBM 2006)
6. Tourists and tourism industry	**tourism**; heritage	instrumental value	low	low	(NRETAS 2011)	(PBWBM 2006)
7. Farmers within the catchment	**agriculture**	instrumental value	low	low	(NRETAS 2011)	(Russel et al. 2012)
8. Recreational fishers and hunters	**Recreational fishing and hunting**	instrumental value	high	high	(NRETAS 2011)	(Russel et al. 2012)

9. Commercial fishermen (incl. aquaculturalists) and hunters	**commercial fishing and hunting; aquaculture**	instrumental value	high	high	(McInnes 2004)	(Russel et al. 2012)
10. Boat users and marina operators	**ports, shipping and marina operations**	instrumental value	moderate	moderate	(NRETAS 2011)	(PBWBM 2006)
11. Port managers and operators	**ports, shipping and marina operations**	instrumental value	high	low	Not applicable	(PBWBM 2006)
12. Miners and dredge operators	**mining, sand extraction and dredging**	instrumental value	high	low	(NRETAS 2011)	(PBWBM 2006)
13. Residents	**residential use**; heritage	instrumental value	moderate	low	(McInnes 2004)	(PBWBM 2006)
14. Asset owners/ investors	**commercial enterprise** and **residential use**	instrumental value	low	low	(NRETAS 2011)	(PBWBM 2006)
15. Local governments	water supply; land transport; stormwater/ wastewater; floodwater conduit; waste disposal; heritage	instrumental value	low	low	(McInnes 2004)	(PBWBM 2006)
16. Utilities providers	commercial enterprise; water supply; communications; land transport; stormwater/ wastewater; floodwater conduit; waste disposal	instrumental value	high	low	(McInnes 2004)	(Russel et al. 2012)
17. Researchers	**research**	both	high	high	(Williams 2014)	(Russel et al. 2012)

Bold = obvious primary use/value; multiple uses/values are given where applicable or the classification represents multiple stakeholders

Table 2: Potential goals for estuarine uses and values partitioned in relation to key components requiring consideration. SE = socio-economic component

Uses/values	Key components requiring consideration			
	Ecosystems	Private property (SE)	Public infrastructure (SE)	Human community (SE)
1) Existence[1]	Healthy ecosystems, biodiversity, functional processes, resilience	Visual access	Not relevant	Happiness and wellbeing, ethical and religious beliefs
2) Conservation	Healthy ecosystems, biodiversity, functions, maintenance of habitat diversity, persistence of all species	conservation incentives for private initiatives, property value associated with an adjacent to intact environment	Protection of historical landmarks	Conservation, preservation, tourism, enjoyment of iconic species
3) Bird, animal or fish watching	Persistence of all species, maintenance of habitat diversity, low turbidity	Possible visual access, public trespass or access arrangements	Access to habitats, facilities to observe/ target species, car parking and public facilities	Lifestyle, tourism, leisure opportunity, access
4) Indigenous activities	Abundance of traditional food species	Recognition of Indigenous access rights	Recognition of Indigenous access rights	Right of Indigenous access, preservation of traditional hunting or cultural areas
5) Recreational water uses	Swimmable and fishable water quality, absence of nuisance species.	Protection of moorings and boatsheds from storm damage or inundation.	Safe navigation, adequate access, boat ramps, car parking, public wharfs and facilities	Lifestyle, tourism, leisure opportunity, access
6) Recreational shore uses	Absence of nuisance species, shoreline stability	Development rights	Access, car parking, public parks with recreational and public facilities	Lifestyle, tourism, leisure opportunity, access
7) Tourism	Abundance of iconic species, absence of nuisance species, healthy ecosystems, good water quality	Aesthetics, commercial tourist facilities, adequate temporary accommodation, aligned industries, protection from storm damage or inundation	Aesthetics, adequate access, car parking and public facilities.	Commercial opportunity and employment, lifestyle, tourism, leisure opportunity, access
8) Recreational fishing and hunting	Continued abundance of disease-free target species, absence of nuisance species	Protection of moorings and boatsheds from storm damage or inundation	Safe navigation, adequate access, boat ramps, car parking, public wharfs and facilities	Right to fish/hunt, lifestyle, tourism, leisure opportunity

[1] We recognise that 'Existence' is not an active use having an instrumental value as a resource for humans, but rather a non-use having intrinsic value.

Uses/values	Key components requiring consideration			
	Ecosystems	Private property (SE)	Public infrastructure (SE)	Human community (SE)
9) Commercial fishing and hunting	Continued abundance of disease-free target species, absence of nuisance species	Protection of boats, nets, moorings, wharves and shore facilities from storm damage/ inundation	Safe navigation, adequate access, maintenance of waterways and roads	Permission to fish/hunt (via social license), commercial opportunity and employment, food production
10) Aquaculture	Absence of nuisance species and diseases, good water quality, primary productivity	Protection of private aquaculture infrastructure from storm damage or inundation.	Adequate access. Appropriate provision, management and regulation of stormwater/ wastewater discharges and land waste disposal	Permission to operate (via social license and environmental regulation), commercial opportunity and employment, food production.
11) Ports, shipping and marina operations	Absence of nuisance species, possible import of exotic species	Protection of facilities from storm damage or inundation	Safe navigation, adequate and maintained waterway and land transportation access, adequate facilities for disposal of wastes	Commercial opportunity and employment
12) Mining, sand extraction and dredging	Presence of substrate and dependent habitats	Protection of equipment from storm damage or inundation	Adequate access	Permission to operate (via social license and environmental regulation), commercial opportunity and employment, settlement development, safe navigation
13) Agriculture	Suitable low salinity water quality, shoreline stability, absence of nuisance species and diseases; supply of nutrients from deposited sediment	Protection of lands and facilities from storm damage or inundation, shoreline stability	Adequate transport access, drainage and protection from flooding (levees)	Food production, commercial opportunity and employment
14) Residential use	Shoreline stability	Protection from storm damage or inundation, improved microclimate, shoreline stability	Adequate transport access, water supply, power, communications and disposal of waste	Housing and accommodation
15) Commercial enterprise (place based)	Shoreline stability	Protection from storm damage or inundation, shoreline stability	Adequate transport access, water supply, power, communications and appropriate disposal of waste	Commercial opportunity and employment

Uses/values	Key components requiring consideration			
	Ecosystems	Private property (SE)	Public infrastructure (SE)	Human community (SE)
16) Water supply (directly from the estuary or from adjacent groundwater systems)	Good water quality of low salinity	Access, license to extract	Protection and maintenance of water supply infrastructure from storm damage or inundation, access, appropriate provision, management and regulation of wastewater discharges & land waste disposal	Settlement resilience, employment
17) Communications	Generally negligible impact on habitat	Protection and maintenance of private communications systems	Protection and maintenance of communications infrastructure during storms inundation and from vessel damage (submarine cables), adequate access	Settlement resilience
18) Land transport (roads, railways and bridges)	Direct impacts on habitat and species or indirect impacts due to changed physical estuary function.	Protection and maintenance of private roads and bridges	Protection and maintenance of transport infrastructure during storms and inundation	Transport system resilience
19) Estuary stormwater and wastewater discharges	Adequate ecosystem assimilative capacity or flushing	No impact on private premises	Protection and appropriate sizing of pump or treatment infrastructure during storms and inundation	Permission to operate (via environmental regulation), settlement resilience, community health.
20) Floodwater conduit	Negligible impact on habitat, no disruption of migration pathways	No impact on private premises	Protection and appropriate sizing of levees and other flood mitigation infrastructure	Settlement resilience, community health.
21) Waste disposal	Adequate ecosystem assimilative capacity	No impact on private premises	Protection of waste infrastructure from inundation	Permission to operate (via environmental regulation), settlement resilience, community health.
22) Heritage	See 2) Conservation	Only if of historical value	Only if of historical value	Community well-being, commercial opportunity and employment
23) Research	Characteristics depends on research objective	Adequate access	Adequate access	Future, informed decision making

Table 3: Summary of climate change adaptation management strategies, tactics and examples.

	STRATEGY	TACTICS	EXAMPLE
ALERT	Wait and see	Regular stakeholder consultation and education Ongoing impact assessment	Monitoring changes in water levels and flow with corresponding water quality and ecosystem response. Revise costs of possible intervention.
	Hedge	Programmed preparatory institutional reform and stakeholder education Funds acquisition, management and audit	Define trigger levels for intervention. Set aside funds for future capitalisation of existing infrastructure or intervention.
	Investigate	Research	Identify possible methods of reducing the costs of climate adaptation or developing new adaptation approaches.
PATHWAY	Liberate	Ongoing stakeholder education Allow nature to take its course – autonomous adaptation Development restriction	Adaptation in large, near-pristine estuarine systems in which intervention is economically infeasible.
ACTIVE	Accommodate	Management of stakeholder expectations Regulate development	Accept reduced level of utility of existing facilities. Accept changes in estuarine ecosystems Targeted species harvesting
	Protect	Construction Ecosystem protection Species conservation Species barriers	Barrages and other constructed protection Dredging and nourishment Aquaria Trapping of nuisance species
	Retreat	Provide stakeholder incentives Regulate development	Relocate or reconfigure existing protection and facilities Species translocation
	Improve	Alleviate non-climate change related impacts Rehabilitate degraded ecosystems Increase the utility of existing infrastructure Foster innovation and entrepreneurship	House relocation that reduces existing flood impact. Creation of new ecosystems and habitat areas Upgrade of existing port facilities to enable berthing of larger vessels without increasing footprint in estuary Improved native species husbanding Improved catchment and waterway management
	Abandon	Prohibit further development/ Legislation Provide stakeholder incentives Property acquisition and demolition	Remove or nullify risks arising from deterioration of existing structures Change navigation arrangements to reflect changed administrative arrangements

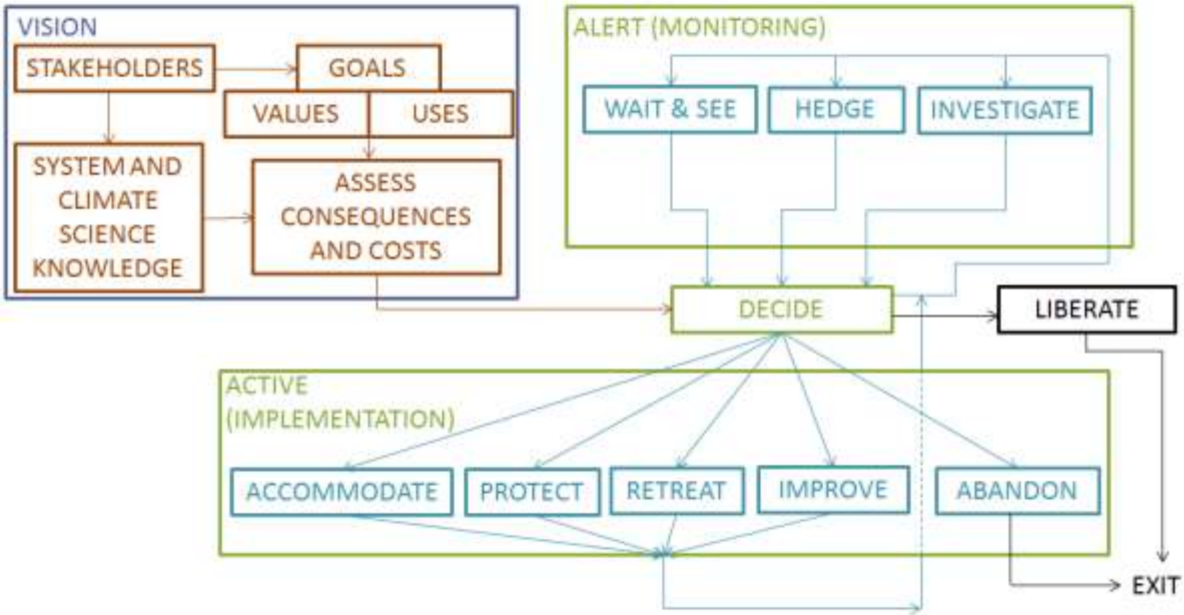

Figure 1: Decision framework for climate change adaptation of estuarine ecosystems, private property, public infrastructure and human communities

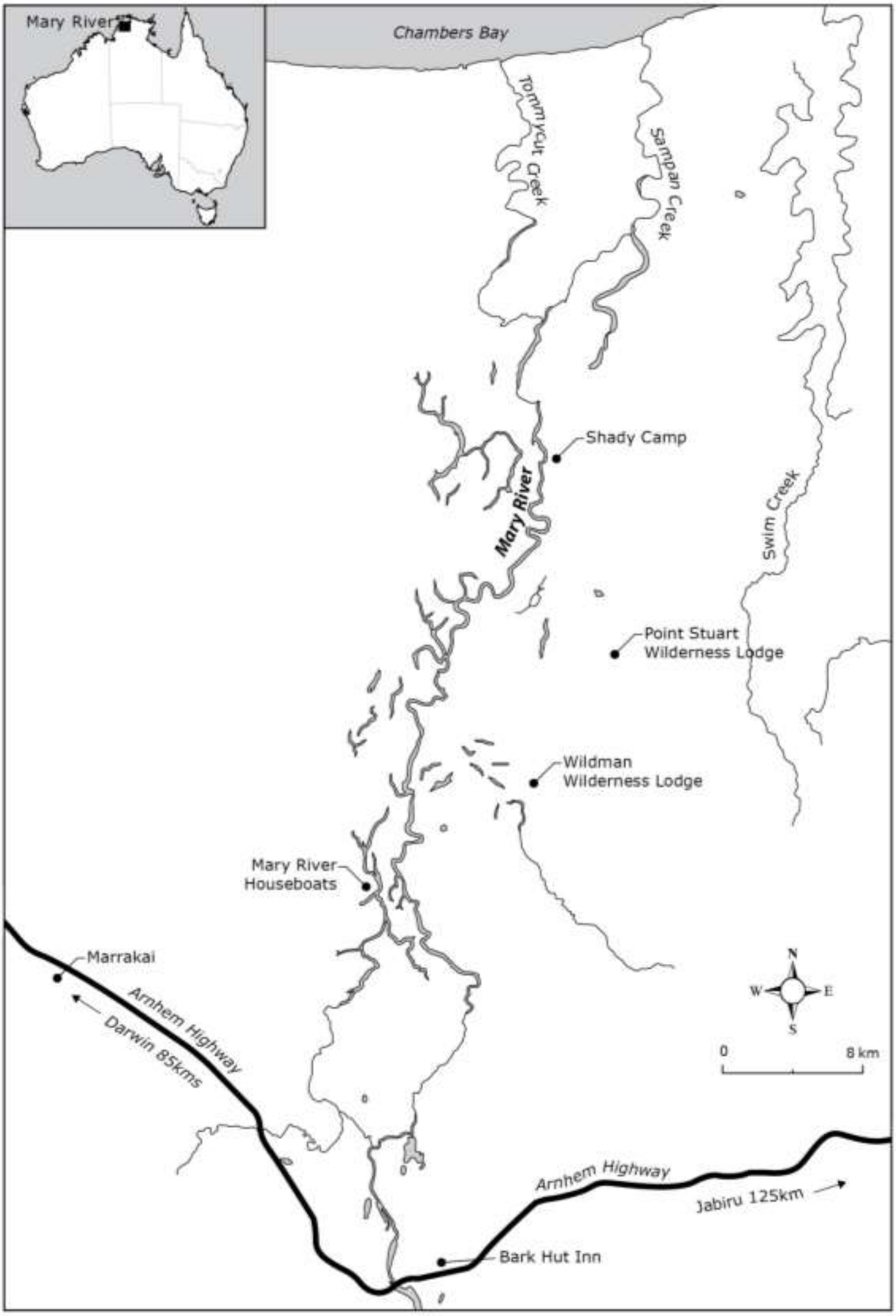

Figure 2. The lower Mary River, Northern Territory. The estuary and its adjacent foreshores are relatively undeveloped except at the locations shown.

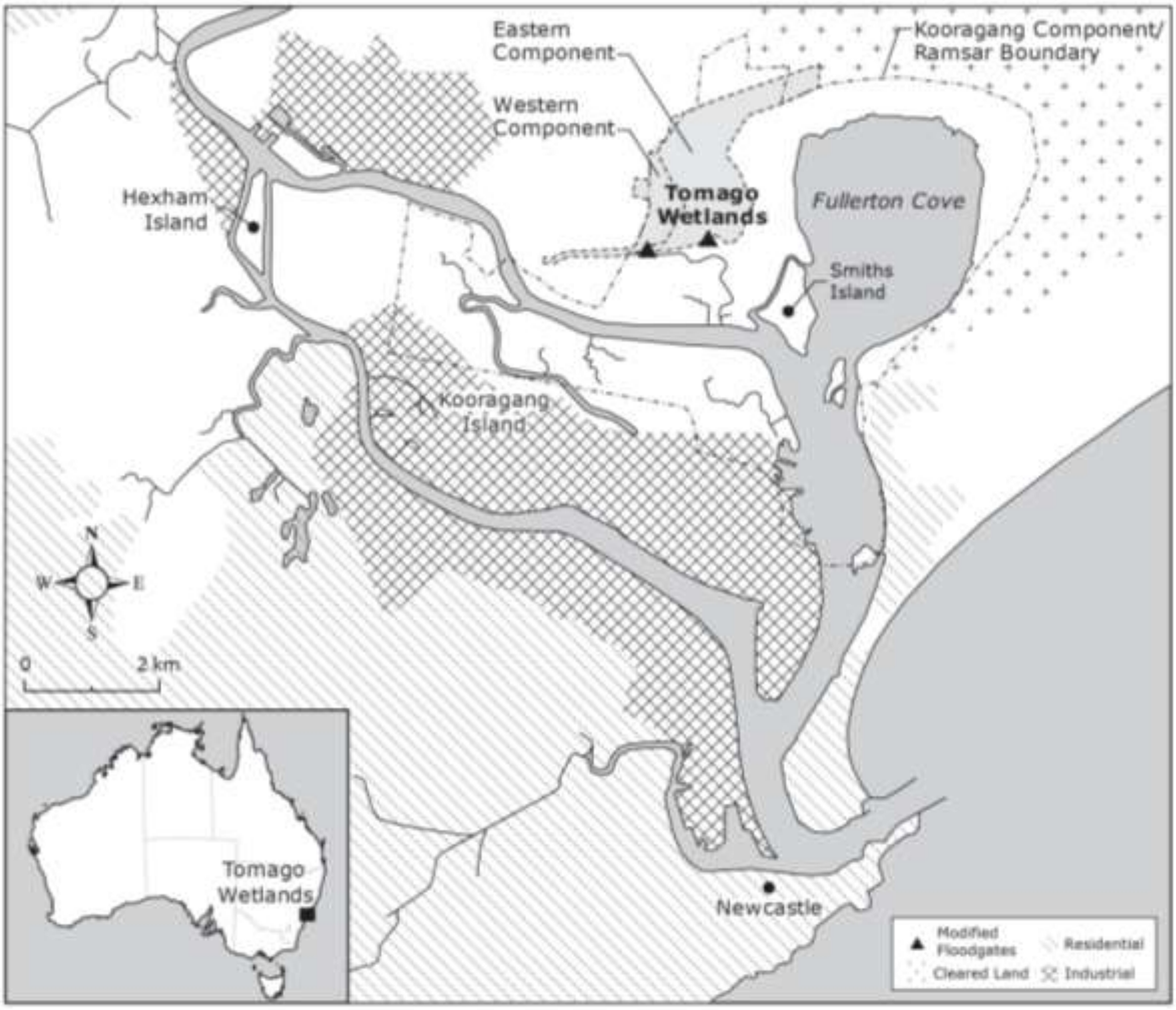

Figure 3. Tomago Wetlands and the lower Hunter River estuary in New South Wales.