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)] *Marine Ecology, 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*

Abstract

Ongoing coastal development and increasing 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 estuary governance and management framework is proposed that recognises the integrated social-ecological systems of estuaries so as to permit transformative climate adaptation within these systems. The framework lists stakeholders and identifies a comprehensive set of 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). Intrinsic values primarily concern resident ecosystems containing hundreds of species, some of which are undescribed or endemic to estuaries (Pendleton 2008; Perkins 1974). Instrumental values (ecosystem services) can often be expressed in economic terms (Costanza et al. 1997).

Estuaries are dynamic environments that change across tidal, climatic, modification and geomorphological time scales (e.g. Roy et al. 2001; Peirson et al. 2002). Moreover, estuaries are facing contemporary anthropogenic pressures that are likely to become both more widespread and acute 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). Another major threat to human coastal communities and estuarine ecosystems is 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 multiple stressors and diverse values, effective estuarine management requires holistic recognition of the intertwined dependencies and interrelatedness of both the socio-economic and ecological components (e.g. PIANC 1999). Indeed, sustainable management measures, such as those proposed by Elliott (2013), incorporate tenets that are ecological, economic, technical, social and political. Such holistic recognition is necessary to minimise the occurrence of maladaptation—the unintended negative consequences that can flow from such issues as fragmented and sectional approaches to management. To minimize the risk of climate-related maladaptation (Segan et al. 2010; Wintle et al. 2011), it is imperative that explicit, integrated management objectives be developed. It is good practice for management to 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 be engaged if the strategies are failing.

For estuarine ecosystems and their adjacent communities, climate change is not just a threat which triggers the conventional *protect*, *accommodate* and *retreat* reactions or their slight variants (e.g. IPCC 2014b, §5.5.2). Rather, climate change will elicit a variety of responses in estuaries, some of which will provide opportunities to improve the condition of degraded estuaries (e.g. increases in sea level will increase tidal prism and therefore flushing). In addition, the dynamic character of estuaries requires estuary managers to make timely, ongoing decisions regarding physical, biological and water quality modifications. Estuaries are therefore less constrained by some of the inertial and institutional barriers to climate adaptation are characteristic of other systems (IPCC, 2014c, §15.5). It is crucial (and the motivation of this present contribution) that managers should be alert to potential opportunities; as well as, the other social and economic impacts of climate change. As stated in IPCC (2014d, §16.8), less attention has been paid to the opportunities associated with climate change adaptation.

Here we propose a new framework for estuary planning and management that will enable managers to identify and exploit opportunities that emerge from climate changes: transformative climate adaptation (IPCC, 2014a, §2.5.3; IPCC, 2014c, final paragraph of §15.6; IPCC, 2014d, §16.4.3). This framework comprises: 1) a vision for estuaries in human landscapes under a changing climate to enable objective-driven assessment and analysis; 2) a comprehensive categorisation of estuarine key values and associated stakeholders to identify potential trade-offs; and 3), a list of potential adaptation goals with associated strategies and tactics to provide overall structure to the estuary management decision-making process. We conclude with two contrasting Australian case studies to illustrate the practical application of this approach.

2. Vision

Clear goals and objectives will enable the development and implementation of appropriate management strategies and facilitate stakeholder support as climate change triggers modification of estuarine systems. 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." Healthy estuarine ecosystems and flourishing human communities are envisaged for the future, 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 disenfranchised by inadequately considered and communicated environmental protection actions.

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

Effective engagement with stakeholders is essential for effective environmental management. Consequently, we begin with comprehensive identification of stakeholders and their potential intrinsic or instrumental interests in estuaries. We recognise seventeen major stakeholder groups who use and value estuarine systems (Table 1) and twenty-three uses and values associated with these groups (Table 2). Specific individuals may belong to several groups and the groups can have multiple estuarine uses and values. The largest proportion of all stakeholders is associated with instrumental values, i.e. socio-economic benefits that arise for the estuary system.

To categorise stakeholders according to their level of contact with a given estuary, classes of likely duration and scope are presented in Table 1. Stakeholders with a "high-high" contact would be expected to have a greater understanding and therefore greater concern for the integrity of the estuary in comparison to stakeholders with a "low-low" level of contact. Stakeholder sets will differ between estuaries and differences will be apparent in the mixture of individuals within major stakeholder groups. This multi-scale heterogeneity is also dynamic as the mix of stakeholders can change over time.

A summary of the potential goals associated with the twenty-three uses/values are given in Table 2. These have been partitioned between the following four key components: 1) ecosystems; 2) private property; 3) public infrastructure; and 4) human communities. Importantly, dynamic heterogeneity exists between these goals. For example, individual farmers may have vastly different goals for the future of their property according to their varying commitment to traditional practices in the context of changing commercial return on primary produce due to climate. Successful adaptive planning for estuaries must take into account the inter- and intra-stakeholder heterogeneity and dynamism in understanding and working together to create a better future for their estuary as outlined by 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.

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

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; Coastanza et al. 2014). This economic approach represents a way to compare and trade-off the environmental and human values of estuaries. However, climate change is characterised as being 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. There are several reasons for this caution. First, well-meant management interventions may turn out to be maladaptive (i.e., unforeseen negative or perverse outcomes occur). Such maladaptive consequences arise because of the intertwined, systems nature of ecological and social entities (Harris 2007; Walker and Salt 2006). These entities have interacting components with feedback loops so that changes to one component can also affect other components. Importantly, there are also feedbacks between social and ecological systems so that 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). Further examples of ecosystem flips feature within the case studies presented below. While environmental variables such as nutrients can often be controlled, climate-caused changes to important variables such as 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 our options and that, in turn, will require modelling different scenarios to scope out possible futures (e.g. Lester et al. 2013). Of course, the outcome of these deliberations will largely be determined 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 and clarifying on flow-on consequences in a highly connected landscape; and,
- possibly trading off of 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).

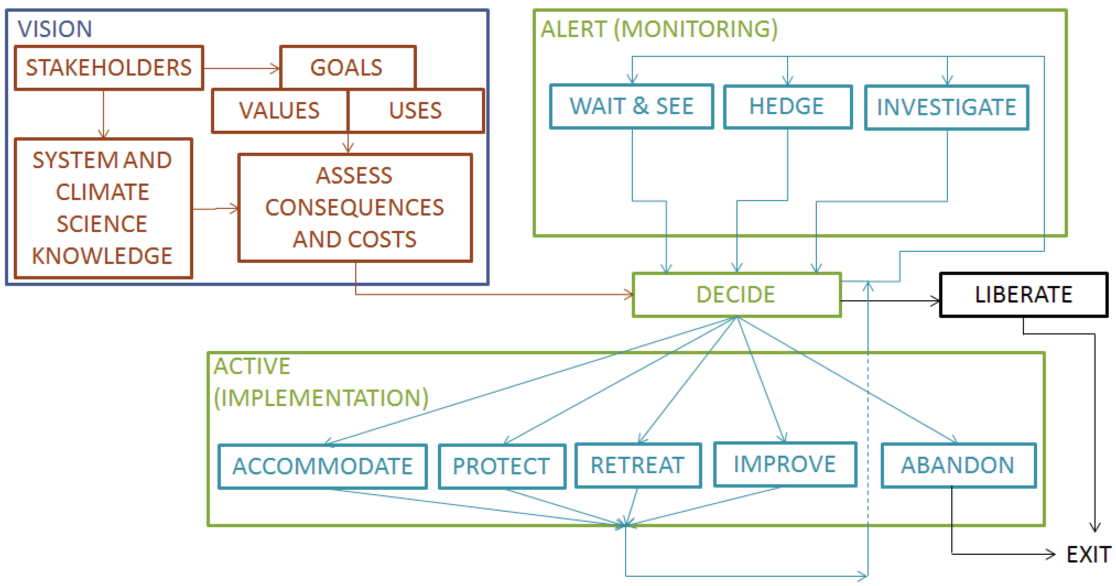

Figure 1: Decision framework for climate change adaptation of estuarine ecosystems, private property, public infrastructure and human communities

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, p. 1959ff). 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 is summarised graphically in Figure 1.

In terms of adaptive management, three distinct actions (retreat, accommodate and protect) are as previously been proposed (e.g. Nicholls et al. 2007, Figure 6.11). However, to better incorporate the integrative systems thinking required for effective estuarine management, we emphasize the importance of being alert to the potential impacts of climate change without necessarily taking any action. Within this revised methodology, three alert adaptation strategies are recognised: "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 major intervention is required once a certain threshold is exceeded. It is therefore appropriate to set aside appropriate funds from consolidated revenues and/or levied from estuary users, so that the necessary financial resources are available to take action when the climate change impact is realised. Note that the responsible organisational unit has not been specified within this framework. This is because 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, §15.4.4).

"Investigate" recognises that appropriate research may yield new solutions that can transform stakeholder perspectives, mitigate the economic impact of intervention or expose new improve options. We refer to this alert state as investigate to signify that appropriate technological development may make new adaptation approaches possible.

In the active mode the conventional three climate change actions are retained, namely: "protect" (defence by 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. From an administrative point of view, no more resources would be invested in adaptive management and the system is liberated to respond naturally to external climatic changes. Some may consider this to be opting out, or doing nothing, however this pathway acknowledges the magnitude of potential climate change impacts and involves making a conscious decision to not interfere with the process. The liberate pathway implies adaptation over much longer time scales, possibly geological although significant changes may be observed in the wake of major climatic events: floods or coastal storms. The liberate pathway can be contrasted with active adaptation which has a principal focus on the manipulation of external environments (with no internal self-regulation), which is reflected in most contemporary notions of adaptation (Thomsen et al. 2013).

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

"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). Artificial structures may influence subsequent ecosystem response. In practice, action may be required to remove or modify any constructed facilities so that they do not become a future hazard themselves.

As stated in the present IPCC (2014) report series (especially IPCC, 2014d §16.4.3 and §16.8), a present major challenge is the development of transformational approaches to adaptation which seize the beneficial opportunities afforded by climate change. Within estuaries, conventional adaptation nomenclature ("protect", "accommodate" and "retreat") immediately triggers negative perceptions of climate change. In contrast, a specific objective of effective estuary management and climate adaptation of degraded estuaries must be to improve existing conditions.

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. 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. The process of change is always facilitated when stakeholders perceive that real benefits can be gained from the proposed modification.

Adaptation decision approach

In order to identify climate change adaptation opportunities and assess response options, we propose the following stepwise process (summarised in Figure 1):

1. Identify stakeholders (using 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 (using 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 other aspects (and values) of 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.

5. Case Studies

Existing and historical 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. These examples demonstrate that management actions must be informed by local knowledge. A case-by-case approach and careful consideration of adaptation options is necessary to ensure positive outcomes and maximisation of intrinsic and instrumental values.

5.1 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 lower 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 with respect to climate change is the penetration of saltwater further 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). A recent review of the conservation status of the Mary (NRETAS 2011) identifies the principal catchment stakeholders (as summarised in Table 1).

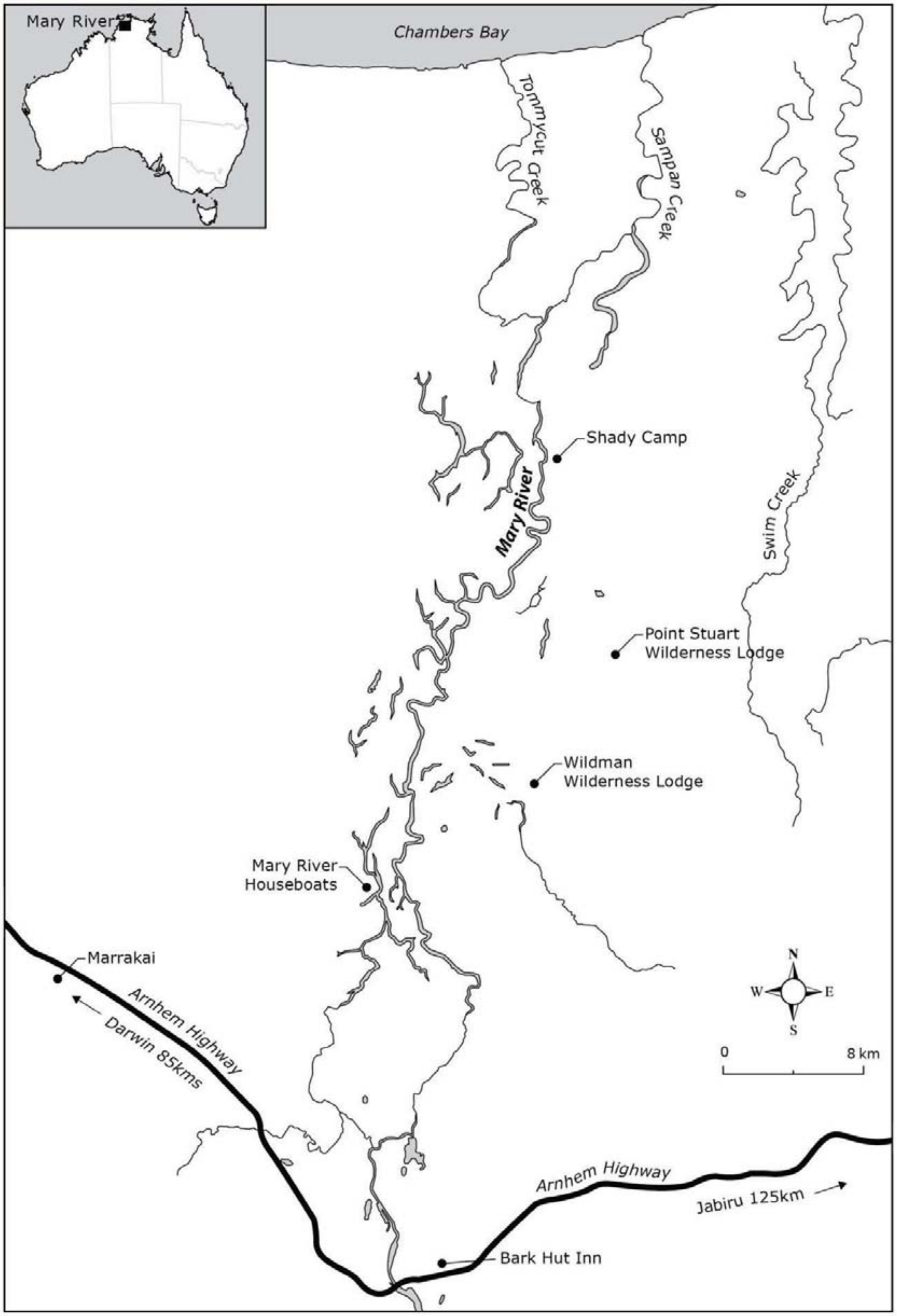

Figure 2. The lower Mary River, Northern Territory. The estuary and its adjacent foreshores are relatively undeveloped except at the locations shown.

The economic feasibility of constructed intervention 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 and historical limited navigability of the entrance has precluded port development (Williams 2014). Although numerous contemporary ecological management challenges exist for the Mary (NRETAS 2011), we restrict our present discussion to the issue of increased saline intrusion and consequent changes in ecological character.

A vision for the estuary states that ongoing research is a priority under Northern Territory government climate change policy (NRETAS 2011, esp. pp. 23ff). However, there are discordant aspects within the stated aims and management directions as follows.

1. The first stated aim 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”. At a naïve level, this statement creates stakeholder expectation that to protect is the dominant tactic for engagement with change.
2. A concise description of works undertaken to protect the estuary is provided in McInnes (2004, §1.3). Approximately AU$500,000 p.a. was spent on protective works in the decade preceding McInnes’s report (D. Williams, pers. comm.).
3. Although McInnes (2004, p. 76) predicts a net present benefit of the protect option, to our knowledge the Territory Government has not proceeded with this programme nor is it explicitly accumulating hedge funds so that a protect option can be exercised in the future. McInnes (2004, p. 80) does state that these benefits will be achieved in spite of any subsequent climate change. He does state that without intervention, longer-term sea level changes may transform the estuary into a large-scale salinity-dominated system.
4. Williams (2014, pp. 286, 287) anticipates that protect options will fail and recommends that a retreat option be adopted. In terms of the our proposed strategies, this corresponds to a liberate

option for the lower estuary, a possible hedge option in relation to the more modest Shady Camp barrage and wait-and-see/retreat options for affected stakeholders.

This present study team is not involved with the Mary estuary management process and it is not our purpose to criticise those responsible. However, this brief summary does highlight significant mismatches between published stakeholder communication and present estuary trajectory.

5.2 Tomago – New South Wales

Newcastle, one of Australia's largest ports, is located at the mouth of the Hunter estuary (Figure 3). Devastation by major floods during the 1950s led to construction of extensive flood mitigation works that now consist of hundreds of kilometres of levees, canals and bank protection works. Approximately 175 floodgates were constructed to prevent inundation of the flood plain by floods or high tides (Saintilan and Williams 2000).

The lower Hunter also features one of Australia's largest Ramsar wetlands (Figure 3). 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). Adjacent farm 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).

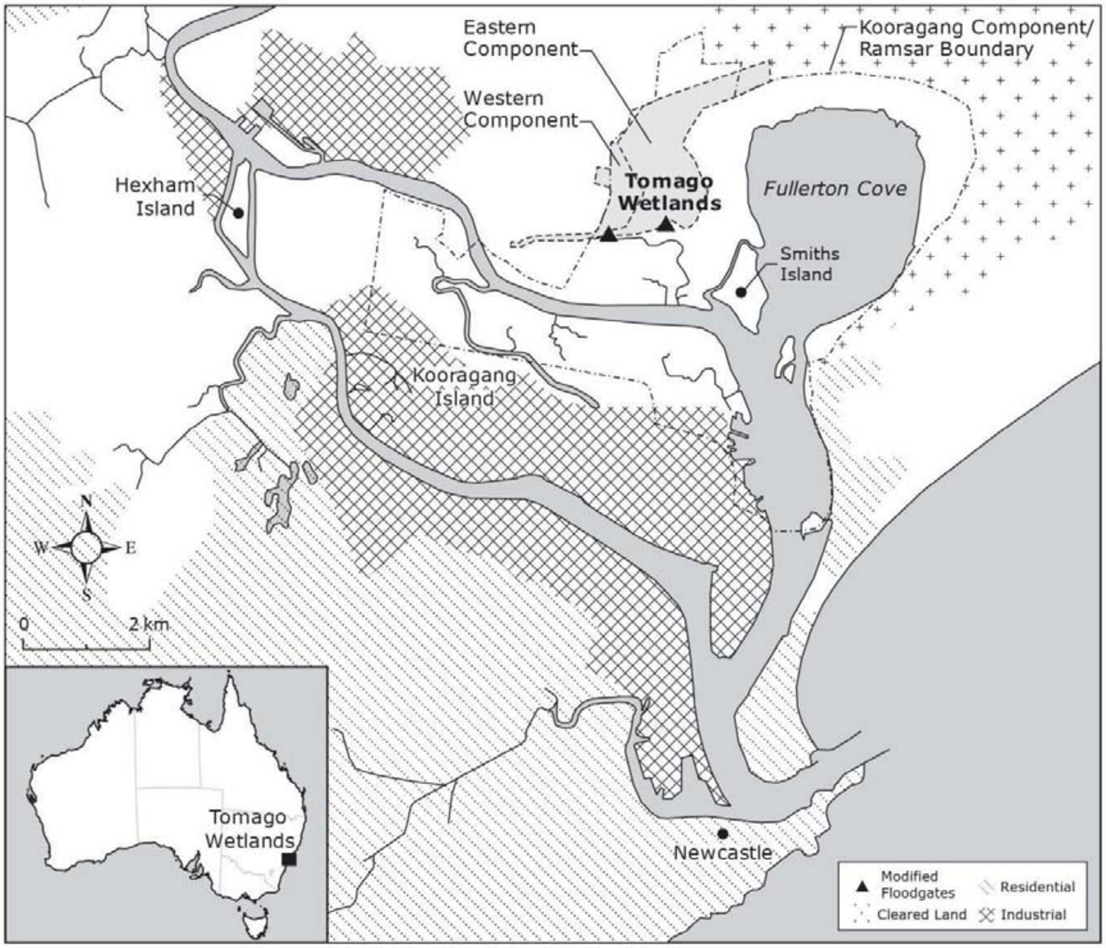

Figure 3. Tomago Wetlands and the lower Hunter River estuary in New South Wales.

The economic importance of the lower Hunter, its extensive modification and internationally significant wetland features has created a singularly complex system of interacting stakeholder ambitions (Table 1, rightmost column) that includes ecological and climate-related pressures. The significant loss of saltmarsh habitat makes the Hunter an excellent case study with respect to our adaptation framework. Not only are conventional climate change tactics of accommodate, retreat and protect (Figure 1) likely to be expensive, methods of implementation are not clear. Such uncertainty leads to an anticipated increase in stakeholder conflict over the consequent economic uncertainty.

In terms of our proposed tactics summarised in Table 3 and Figure 1, we make the following remarks:

1. Although there has been a clear vision for the restoration of Hunter saltmarsh, assessment had shown significant climate impacts and likely intense stakeholder conflict and economic impact.
2. The ongoing, rapid loss of saltmarsh has made the alert states of wait-and-see and hedge irrelevant. If the observed loss is to be arrested or (possibly) reversed, action will be required based on a possible investigate option.
3. The extensive and ongoing anthropogenic modification of the lower Hunter has precluded the liberate option.
4. International treaties regarding the Ramsar-listed wetlands preclude the abandon tactic as an option.

Despite the current situation, research has shown that the saltmarsh habitat can be protected if the tidal inundation depth is limited to 0.3 m (Howe et al. 2010). Judicious environmental engineering design has demonstrated that 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 investigate alert tactic.

The outcome of this research has been the development of an ecologically and economically effective improve tactic. Modified floodgates were installed in August 2007 with accompanying modest levee construction and clearing of exotic and undesired 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 strong support in which broader application of the approach locally and within other estuarine systems is now taking place. As discussed by Glamore and Rayner (2012), it is important that improvements must remain robust for anticipated sea level rise without stimulating new stakeholder conflict.

6. Concluding Remarks

Appropriate future estuarine management under a changing climate 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 is presented (Figure 1 and Table 3) which builds on the traditional adaptive management strategies of protect, accommodate and retreat. This enhances the integrated thinking that will be required for future effective management, particularly within the multi-facetted and highly dynamic estuarine environment. Further, this contribution highlights the opportunity to improve estuaries that are either degraded or impacted by major construction. Our case studies demonstrate that transformative climate adaptation to estuarine systems is possible if: communications with stakeholders and estuary trajectory are aligned; and, appropriate research is focussed on developing opportunities for estuary restoration that is compatible with stakeholder uses and values. It is envisaged the concepts and adaptation strategies described can be applied to estuaries worldwide, and will provide a basis for successful adaptive management of crucial, but often overlooked, estuarine environments.

7. Acknowledgements

Financial support from the Australian Federal Government via the National Climate Change Adaptation Facility, the Adaptation Research Network for Marine Biodiversity and Resources, the Water Resources and Freshwater Biodiversity Adaptation Research Network and the Australian Climate Change Adaptation Research Network for Settlements and Infrastructure is gratefully acknowledged.

8. References

ARMCANZ. 2000. *Australian and New Zealand guidelines for fresh and marine water quality: Volume 1 - The guidelines*: Agriculture and Resource Management Council of Australia and New Zealand and the Australian and New Zealand Environment and Conservation Council.

Beger, M., H.S. Grantham, R.L. Pressey, K.A. Wilson, E.L. Peterson, D. Dorfman, P.J. Mumby, R. Lourival, D.R. Brumbaugh, and H.P. Possingham. 2010. Conservation planning for connectivity across marine, freshwater, and terrestrial realms. *Biological Conservation* 143: 565-575.

Bellard, C., C. Bertelsmeier, P. Leadley, W. Thuiller, and F. Courchamp. 2012. Impacts of climate change on the future of biodiversity. *Ecology Letters* 15: 365-377.

Byrne, M. 2011. Impact of ocean warming and ocean acidification on marine invertebrate life history stages: vulnerabilities and potential for persistence in a changing ocean. In *Oceanography and Marine Biology: An Annual Review. Vol 49*, ed. R.N. Gibson, R.J.A. Atkinson and J.D.M. Gordon, 1-42.

Clarke B, Stocker L, Coffey B, Leith P, Harvey N, Baldwin C, Baxter T, Bruekers G, Danese Galano C, Good M, Haward M, Hofmeester C, De Freitas D, Mumford T, Nursey-Bray M, Kriwoken L, Shaw J, Shaw J, Smith T, Thomsen D, Wood D and Cannard T (2014) Enhancing the knowledge-governance interface: Coasts, climate and collaboration. *Ocean & Coastal Management* 86: 88-99.

Coltheart, L. 1997. *Between wind and water*. Sydney: Hale & Iremonger.

Costanza, R., R. d'Arge, R. de Groot, S. Farber, M. Grasso, B. Hannon, K. Limburg, S. Naeem, R.V. O'Neill, J. Paruelo, R.G. Raskin, P. Sutton, and M. van den Belt. 1997. The value of the world's ecosystem and natural capital. *Nature* 387: 253-259.

DIPNR. 2005. *Floodplain Development Manual*: New South Wales Government. Department of Infrastructure, Planning and Natural Resources.

Elliott, M. 2013. The 10-tenets for integrated, successful and sustainable marine management. *Marine Pollution Bulletin* 74: 1-5.

Finlayson, C.M., B.J. Bailey, W.J. Freeland, and M.R. Fleming. 1988. Wetlands of the Northern Territory. In *The Conservation of Australian Wetlands*, ed. A.J. McComb and P.S. Lake, 103-126. Sydney: Surrey Beatty & Sons.

Gidley JM, Fien JF, Smith JA, Thomsen DC and Smith TF (2010) Participatory Futures Methods as Social Learning: Towards Adaptability and Resilience in Climate-vulnerable Communities. *Environmental Policy and Governance* 19(6): 427-440.

Gillanders, B.M., T.S. Elsdon, I.A. Halliday, G.P. Jenkins, J.B. Robins, and F.J. Valesini. 2011. Potential effects of climate change on Australian estuaries and fish utilising estuaries: a review. *Marine and Freshwater Research* 62: 1115-1131.

Glamore, W., and D. Rayner. 2012. Coastal wetland remediation in a changing climate. In Proc. 21st NSW Coastal Conference.

Hadwen, W.L., S.J. Capon, E. Poloczanska, W. Rochester, T. Martin, L. Bay, M. Pratchett, J. Green, B. Cook, A. Berry, A. Lalonde, and S. Fahey. 2011. Climate change responses and adaptation pathways in Australian coastal ecosystems: Synthesis Report.: Report to the National Climate Change Adaptation Research Facility, Australia.

Harley, C.D.G., A.R. Hughes, K.M. Hultgren, B.G. Miner, C.J.B. Sorte, C.S. Thornber, L.F. Rodriguez, L. Tomanek, and S.L. Williams. 2006. The impacts of climate change in coastal marine systems. *Ecology Letters* 9: 228–241.

Harris, G.P. 1999. Comparison of the biogeochemistry of lakes and estuaries: ecosystem processes, functional groups, hysteresis effects and interactions between macro- and microbiology. *Marine and Freshwater Research* 50: 791 - 811.

Harris, G.P. 2007. *Seeking Sustainability in an Age of Complexity*. Cambridge: Cambridge University Press.

Hydro Tasmania Consulting. 2010. Ecological character description of Kooragang component of the Hunter Estuary wetlands Ramsar site.

IPCC. 2007. Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change: [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland, 104 pp.

IPCC. 2014a. Climate Change 2014: Working Group II, Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Chapter 2. Foundations for Decision Making., ed. Core Writing Team, R.N. Jones, A. Patwardhan, 104. Geneva, Switzerland: IPCC.

IPCC. 2014b. Climate Change 2014: Working Group II, Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Chapter 5. Coastal Systems and Low-Lying Areas., ed. Core Writing Team, P.P. Wong and I.J. Losada, 104. Geneva, Switzerland: IPCC.

IPCC. 2014c. Climate Change 2014: Working Group II, Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Chapter 15. Adaptation Planning and Implementation., ed. Core Writing Team, N. Mimura, R. Pulwarty, 104. Geneva, Switzerland: IPCC.

IPCC. 2014d. Climate Change 2014: Working Group II, Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Chapter 16. Adaptation Opportunities, Constraints, and Limits., ed. Core Writing Team, R.J.T. Klein, G.F. Midgley, B.L. Preston, 104. Geneva, Switzerland: IPCC.

Kennish, M.J. 2002. Environmental threats and environmental future of estuaries. *Environmental Conservation* 29: pp. 78 - 107.

Lester, S.E., C. Costello, B.S. Halpern, S.D. Gaines, C. White, and J.A. Barth. 2013. Evaluating tradeoffs among ecosystem services to inform marine spatial planning. *Marine Policy* 38: 80-89.

Martinez, M.L., A. Intralawan, G. Vazquez, O. Perez-Maqueo, P. Sutton, and R. Landgrave. 2007. The coasts of our world: ecological, economic and social importance. *Ecological Economics* 63: 254–272.

McInnes, R. 2004. *Cost-benefit analysis of Mary River salinity mitigation*: Australian Greenhouse Office.

Millennium Ecosystem Assessment. 2005. *Ecosystems and Human Well-being: Synthesis*. Washington DC: Island Press.

Nicholls, R.J., P.P. Wong, V.R. Burkett, J.O. Codingnotto, J.E. Hay, R.F. McLean, S. Ragoonaden, and C.D. Woodroffe. 2007. Coastal Systems and low-lying areas. In *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, 315-356. Cambridge, UK: Cambridge University Press. pp. 315-356.

NRETAS. 2011. *Mary River National Park Draft Joint Management Plan*. Palmerston: Parks and Wildlife Service of the Northern Territory, Dept. of Natural Resources, Environment, The Arts and Sport.

PBWBM. 2006. Hunter Estuary Issues Paper, ed. Parsons Brinkerhoff and WBM Oceanics Australia: Hunter Coast and Estuary Management Committee.

Peirson, W.L., Bishop, K., Van Senden, D., Horton, P. R. and Adamantidis, C. A. . . , . 2002. Environmental Water Requirements to Maintain Estuarine Processes. In Environmental Flows Initiative Technical Report Number 3. Canberra: Commonwealth of Australia.

Pendleton, L.H. 2008. Executive Summary In *The Economic and Market Value of Coasts and Estuaries: What's At Stake?*, ed. L.H. Pendleton: Restore America's Estuaries.

Perkins, E.J. 1974. *The Biology of Estuarine and Coastal Waters*. London: Academic Press.

PIANC. 1999. Environmental Management Framework for Ports and Related Industries: Report of Working Group 4 of the Permanent Environment Comission. International Navigation Association.

PWD. 1980. The Lower Hunter Valley Flood Mitigation Scheme: Public Works Department New South Wales.

Rogers, K., N. Saintilan, and C. Copeland. 2012. Modelling wetland surface elevation dynamics and its application to forecasting the effects of sea-level rise on estuarine wetlands. *Ecological Modelling* 244: 148-157.

Roy, P.S., R.J. Williams, A.R. Jones, I. Yassini, P.J. Gibbs, B. Coates, R.J. West, P.R. Scanes, J.P. Hudson, and S. Nichol. 2001. Structure and function of South-east Australian estuaries". *Estuarine, Coastal and Shelf Science* 53: 351-384.

Russel, K., J. Erskine, and W. Glamore. 2012. Tomago wetland rehabilitation project: integrated, innovative approaches. In Proc. 21st N.S.W. Coastal Conference. Kiama, Aust. Nov. 2012.

Saintilan, N., and R.J. Williams. 2000. The decline of saltmarshes in Southeast Australia: results of recent surveys. *Wetlands (Australia)* 18: 49-54.

Scheffer, M., S. Carpenter, J.A. Foley, C. Folke, and B. Walker. 2001. Catastrophic shifts in ecosystems. *Nature* 413: 591-596.

Segan, D.B., J. Carwardine, C. Klein, H. Grantham, and R.L. Pressey. 2010. Can we determine conservation priorities without clear objectives? *Biological Conservation* 143: 2-4.

Short, M.D., W.L. Peirson, G.M. Peters, and R.J. Cox. 2012. Managing Adaptation of Urban Water Systems in a Changing Climate. *Water Resources Management* 26: 1953-1981.

Smith TF (2009) Beyond Knowledge: A Neo-Research Approach to Climate Change Adaptation. In: Martin J, Rogers M and Winter C (eds.) Climate Change Responses across Regional Australia: Social Learning and Adaptation. VURRN Press, Victoria, pp 30-44.

Thomsen, D. C., Smith, T.F. & Keys, N. 2012, 'Adaptation or Manipulation? Unpacking Climate Change Response Strategies', Ecology & Society, 17 (3): 20.

UNEP. 2006. Marine and coastal ecosystems and human wellbeing: A synthesis report based on the findings of the Millennium Ecosystem Assessment.: UNEP. 76pp.

UNEP. 2012. Global Environmental Outlook 5 (GEO 5) In Summary for Policy Makers.

USEPA. 2011. Climate Ready Estuaries, 2011 Progress Report.

Walker, B., and D. Salt. 2006. *Resilience Thinking: Sustaining Ecosystems and People in a Changing World*. Washington DC: Island Press.

Williams, D. 2014. Recent, rapid evolution of the Lower Mary River Estuary and Flood Plains. In *Estuaries of Australia in 2050 and Beyond*, ed. E. Wolanski: Springer.

Winning, G. 1996. Vegetation of Kooragang Nature Reserve and Hexham Swamp Nature Reserves: Prepared by Hunter Wetlands Research and Management for NSW National Parks and Wildlife Service

Wintle, B.A., S.A. Bekessy, D.A. Keith, B.W. van Wilgen, M. Cabeza, B. Schroder, S.B. Carvalho, A. Falcucci, L. Maiorano, T.J. Regan, C. Rondinini, L. Boitani, and H.P. Possingham. 2011. Ecological-economic optimization of biodiversity conservation under climate change. *Nature Climate Change* 1: 355-359.