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Scenario-based thinking to negotiate coastal squeeze of ecosystems: Green, blue, grey and hybrid infrastructures for climate adaptation and resilience

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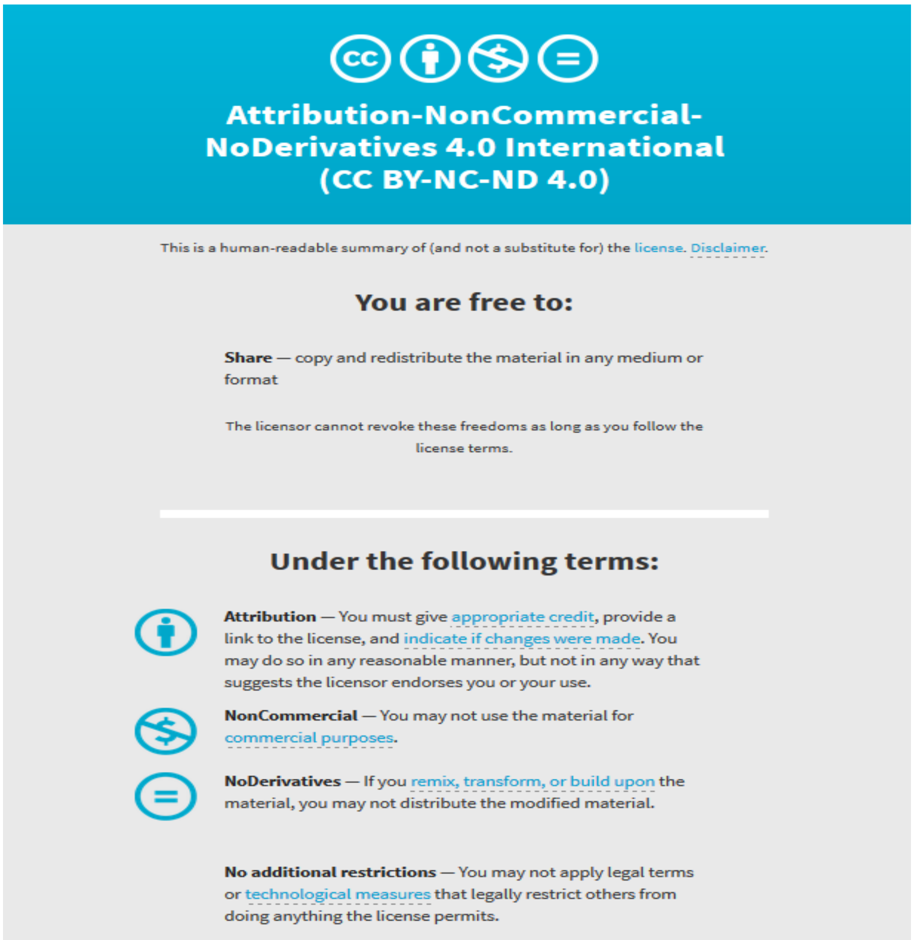

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SCENARIO-BASED THINKING TO NEGOTIATE COASTAL SQUEEZE OF ECOSYSTEMS

Green, blue, grey and hybrid infrastructures for climate adaptation and resilience

Scott Hawken, Kaihang Zhou, Luke Mosley and Emily Leyden

Introduction: scenario-based thinking for resilient coastal landscapes

Coastal landscapes are under threat globally due to climate change, in particular due to rapidly rising sea levels (IPCC, 2021). These dynamic coastal environments are valuable for a range of land uses including tidal and supratidal ecosystems, human settlement, agriculture and various built infrastructures (Small & Nicholls, 2003). Together these land uses form what we call herein "anthropogenic coastal landscapes". In describing them in this way, we acknowledge that there is a continuum of more natural and more built or artificial conditions (Hobbs, Higgs, & Hall, 2013; Hobbs et al., 2014; Lundholm, 2015; Sutton-Grier, Wowk, & Bamford, 2015; Mangone, 2016). The anthropogenic coastline has been formed through a complex combination of processes. For instance, artificial or grey infrastructure has often been designed to arrest or defend against geomorphological change to prioritize land uses such as housing and agriculture yet coastlines keep evolving regardless with landscape types such as beaches and wetlands in a continual state of flux. In many coastal suburbs, infrastructure, such as stormwater systems, housing and coastal wall defenses, have become defunct through climate-related forces including sea level rise, tidal flooding, saltwater intrusion through and across built infrastructures and storm surges. As a consequence, we need to consider how to address climate change threats. The most immediate and obvious approach to defending built and settlement assets is a linear, defensive approach epitomized by dikes and seawalls. However, this can have disastrous outcomes for all land uses, even those which are intended to be protected (Zevenbergen, Rijke, Van Herk, & Bloemen, 2015). An ultimately more powerful approach is through adaptation and making space for the integration of various natural and

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built systems to manage climate change in a resilient way (De Bruijn, De Bruijne, & Ten Heuvelhof, 2015). In particular, integrating land use such as green and blue infrastructure is critical (Hawken et al., 2021). Green infrastructure is any land uses which delivers ecosystem services (Hawken, Rahmat, Sepasgozar, & Zhang, 2021). Typically, green infrastructure involves terrestrial ecosystems such as forests or other vegetation whilst blue infrastructure includes aquatic land use such as estuaries and lakes and rivers.

Such an integrated resilient approach requires the reconceptualization of simple monofunctional land uses as multifunctional or hybrid land uses to achieve win-win outcomes for both human- and non-human-dominated environments. A key to such an approach is the by now well-known concept of "green infrastructure". Although it is in popular usage the concept of green infrastructure is complex to define and not always transparent. Silva et al. (2017, 2020) argue that green infrastructure encompasses a range of natural, semi-natural and artificial multifunctional strategies to solve ecological and socioeconomic challenges simultaneously.

To study alternative coastal landscape "futures", we use a scenario-building approach applied in the Millennium Ecosystem Assessment (2005) to systematically and creatively think about alternative courses of action. Scenarios are not about identifying correct or incorrect courses of action although they may suggest benefits and drawbacks of alternative approaches. They are most useful in generating creative choices that might not immediately be apparent using conventional, business-as-usual conditions. In scenario-based approaches, stakeholders are not tied to one outcome but can experiment and develop alternatives freeing up negotiations and avoiding adversarial politics which can stifle action (Carpenter, Bennett, & Peterson, 2006; Pettit et al., 2019; Small & Nicholls, 2003). The approach is particularly helpful in generating win-win outcomes or making choices in complex situations.

Scenario building generally involves a number of key steps. In this chapter, a multidisciplinary group of authors discuss key areas of importance in ecosystem and resource management, and environmental and urban planning for a local district that is already being affected by sea level rise. The authors then went through a series of steps to generate and design scenarios, with multidisciplinary input from local specialists, that can inform future approaches to resilience building within coastal areas. Our approach is consistent with that used by others including specialists in conservation (Peterson, Cumming, & Carpenter, 2003) and planning (Fisher, Orland, & Steinitz, 2020). We follow a series of methodical steps to define the analytic framework and the scenarios themselves. This process involves recording the stresses, pressure points, uncertainty, impacts and comparative outcomes that result for each scenario. The steps are outlined in Figure 15.1. We suggest such an approach is important in building a consensus around what resilience is in relation to urban landscapes. As many scholars have contested, *resilience* is a difficult term to define. We point to Meerow and co-authors 2016 definition that:

> urban resilience refers to the ability of an urban system—and all its constituent socioecological and socio-technical networks across temporal and

spatial scales—to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change, and to quickly transform systems that limit current or future adaptive capacity.

(Meerow, Newell, & Stults, 2016, p. 39)

Notable in this definition is the need to best understand what functions are desired and the need to assess what land uses or infrastructure limit adaptability in

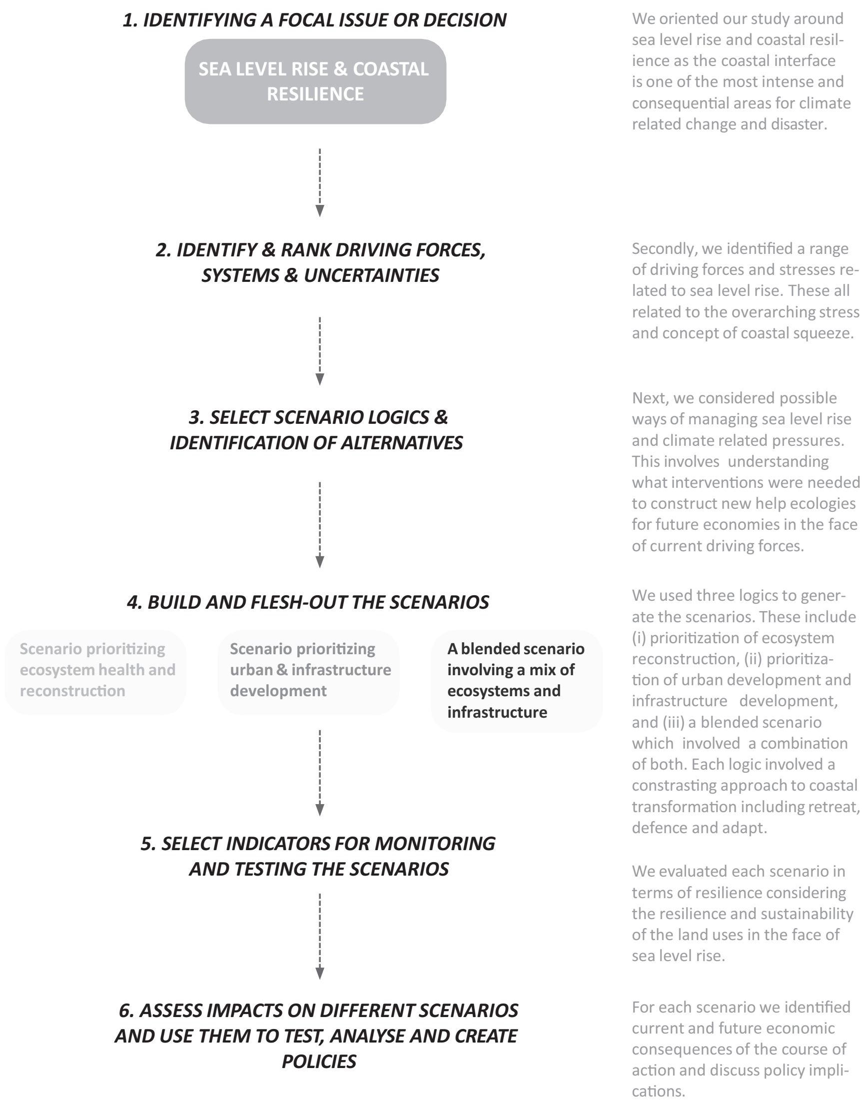

FIGURE 15.1 The six steps used in the scenario building and testing process. Generated by Scott Hawken and Kaihang Zhou. For the color figure, see the e-book.

the face of future pressures. This strong element of uncertainty and openness in relation to resilience makes the scenario building approaches useful.

History and current context: The challenge of coastal squeeze in anthropogenic coastal landscapes

The Northern Adelaide study region (South Australia) was selected as an ideal area to assess resilience to climate-related impacts due to its social, ecological and economic importance. It includes a range of important coastal and estuarine habitats, including large areas of seagrass, saltmarsh and mangroves (Figures 15.3 and 15.4). In the 1930s, the coastal landscapes of Adelaide were largely cleared of natural ecosystems and comprehensively remodeled for industrial and agricultural purposes. Chief among the industries prioritized through redevelopment was salt production. To this end, salt fields were established, and these now occupy approximately 5,500 ha of land (private and government-owned), and stretch along 28 km of coastline, north of Adelaide between Dry Creek (Figure 15.3), north to Middle Beach beyond the limits of the study area. To create the salt field, a series of ponds with associated bunds were built that disconnected coastal ecosystems. Seawater was pumped in and flowed through these ponds, where natural evaporation concentrates the salinity until finally the desired end product (common salt/halite/NaCl) is precipitated. The salt production operation has ceased at the present time, with the site under a "holding pattern" and there are plans to transition parts of the site to alternative land uses including housing and blue infrastructure such as mangroves (Dittmann, Mosley, Clanahan, et al., 2019). The site includes a large amount of locally, nationally and internationally important flora and fauna such as migratory birds and nationally listed samphire vegetation (Coleman, 2013).

The landscapes of the Northern Adelaide study area (Figure 15.3) are governed and fall across two local municipalities: the City of Salisbury and City of Playford, with the southern boundary of the study area located approximately 10 km north of the Adelaide Central Business District. In 2012, the region supported a population of 217,306 people (~13% of state population) and this is predicted to increase by 169,000 by 2040 (Adapting Northern Adelaide, 2016). The study area also includes parts of South Australia's major industrial and primary production areas (e.g., Northern Adelaide Plains). Therefore, adaptation to climate change-related impacts such as sea level rise and coastal squeeze in the Northern Adelaide study area is important not only for local residents and business owners but also for the produce supply and economic wellbeing of the state in national and international contexts. Combined, the two council areas have a gross development product of $8.12 billion, representing about 8.9% of the State's economy (Adapting Northern Adelaide, 2016).

Current and future stressors: Types of climate related stressors in coastal landscapes

As mentioned in the current study, we focus mostly on the "coastal squeeze" aspects associated with climate change in the Northern Adelaide study area. Coastal squeeze occurs when built or natural topographic conditions constrains the landward migration of ecosystems as sea levels rise, with likelihood of ecosystem loss (Borchert et al., 2018; Figure 15.2). Pressure can be placed upon ecosystems by infrastructures such as roads, embankments, natural rises or seawalls amongst other topographic features (Doody, 2004; Pontee, 2013).

The presence of the salt field stretching along a large area of coast in northern Adelaide area is currently constraining the ability of coastal vegetation to migrate, and mangroves are currently being squeezed up against artificial bund walls and roads (Figures 15.2–15.5), whereas natural sites have a much larger salt marsh transition area. There are also large hazards present at the site (i.e., hypersaline water and salt crystals) arising from salt production and maintaining the bunds and their integrity is proving challenging in the context of salt mine closure. There is potential for catastrophic failure and leakage of hypersaline brine to the coastal ecosystems, recently there has been a leakage event at St Kilda associated with localized (approx. 24 ha) mangrove and salt-marsh death.

There is also intense pressure to transform the salt fields and coastal areas into new urban developments. The Dry Creek Salt Pans have been identified in the state government's 30-Year Plan for Greater Adelaide as a Future Urban Growth Area. Whilst the precise development has not been determined, it is projected that some 10,000 homes will be accommodated in this area along with other possible uses such as shopping centers, education facilities and marinas (James, 2019). Such urban developments will consume large quantities of resources for filling low lying land and also place additional pressure on coastal ecosystems, water security and drainage systems. There are also questions of long-term social equity associated with such developments should climate change impacts cause future developments to fail (Hawken et al., 2021a).

In regard to future stressors, in the northern Adelaide area climate change will mean warmer and drier conditions, increased risk of climate hazards, such as extreme heat, fire and flooding, and changing conditions in Gulf St Vincent, includes under a high emissions scenario (Adapting Northern Adelaide, 2016):

- Annual rainfall is projected to decline by about 11% while rainfall intensity could increase by 16%
- Annual maximum temperatures are projected to increase by 2.3°C while annual minimum temperatures could increase by 2°C and extreme heat days per year (35°C or higher) could increase by 76% to 82% (up to 44 days).

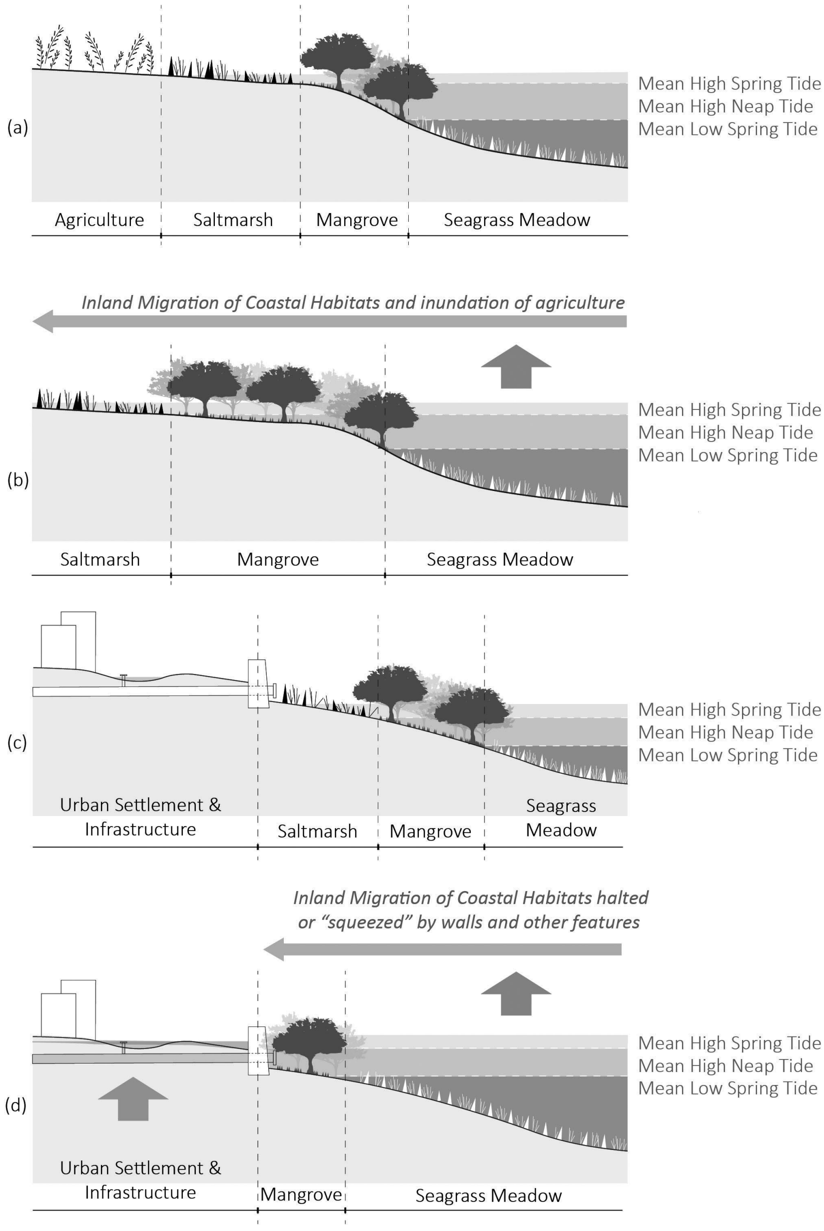

FIGURE 15.2 The coastal squeeze concept illustrated for both agricultural-coastal interfaces and urban-coastal interfaces. The first (a, b) sees tidal ecosystems migrate inland and the destruction of agricultural landscapes as they become saline. The second (c, d) sees the elimination of tidal ecosystems as sea levels rise and "squeeze" tidal ecosystems against built elements such as roads and seawalls. Tidal ecosystems largely are eliminated in this second condition. Generated by Scott Hawken and Kaihang Zhou. For the color figure, see the e-book.

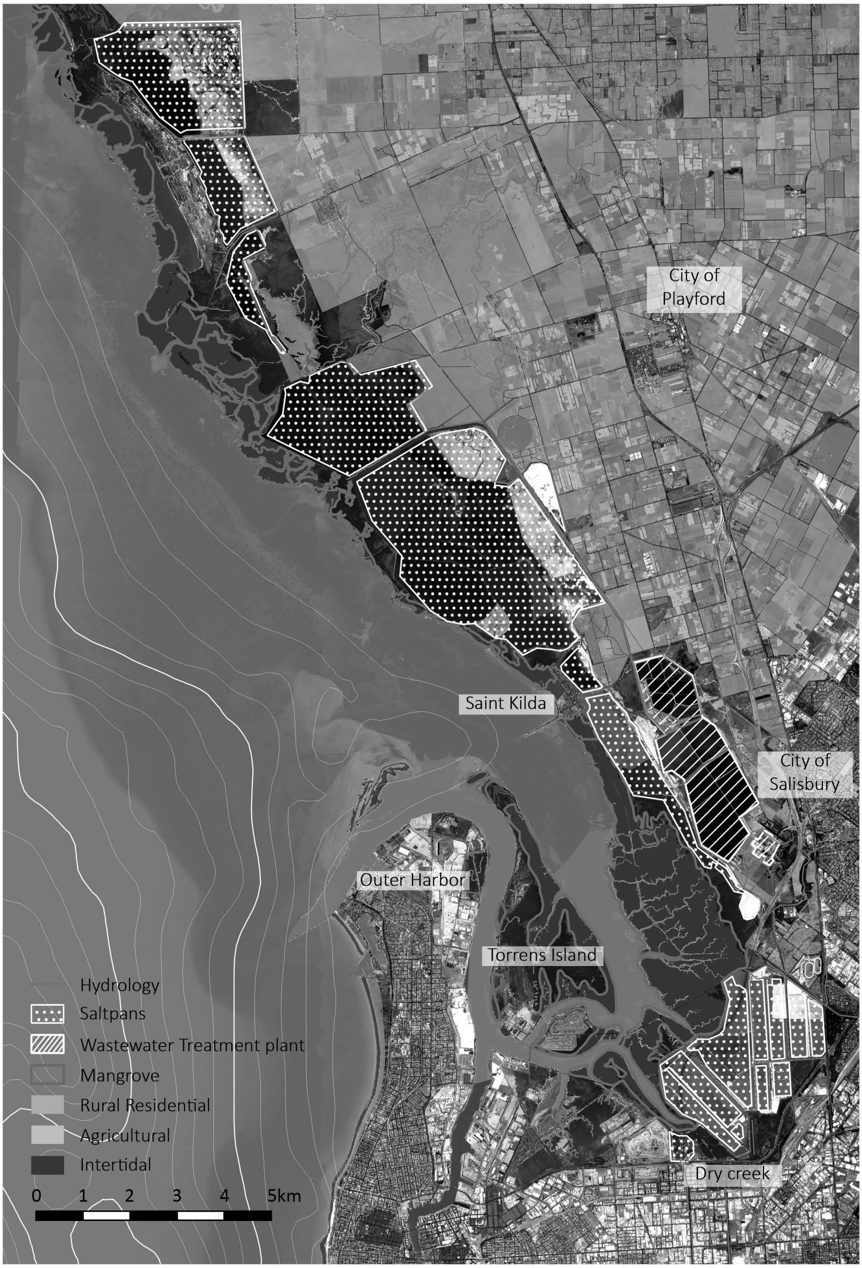

FIGURE 15.3 Study area map. Major infrastructure barriers such as the salt pan bunds, roads, levees associated with wastewater plants and sea-walls will cause coastal squeeze and limit the dynamic migration of ecosystems as sea levels rise. Generated by Scott Hawken and Kaihang Zhou. For the color figure, see the e-book.

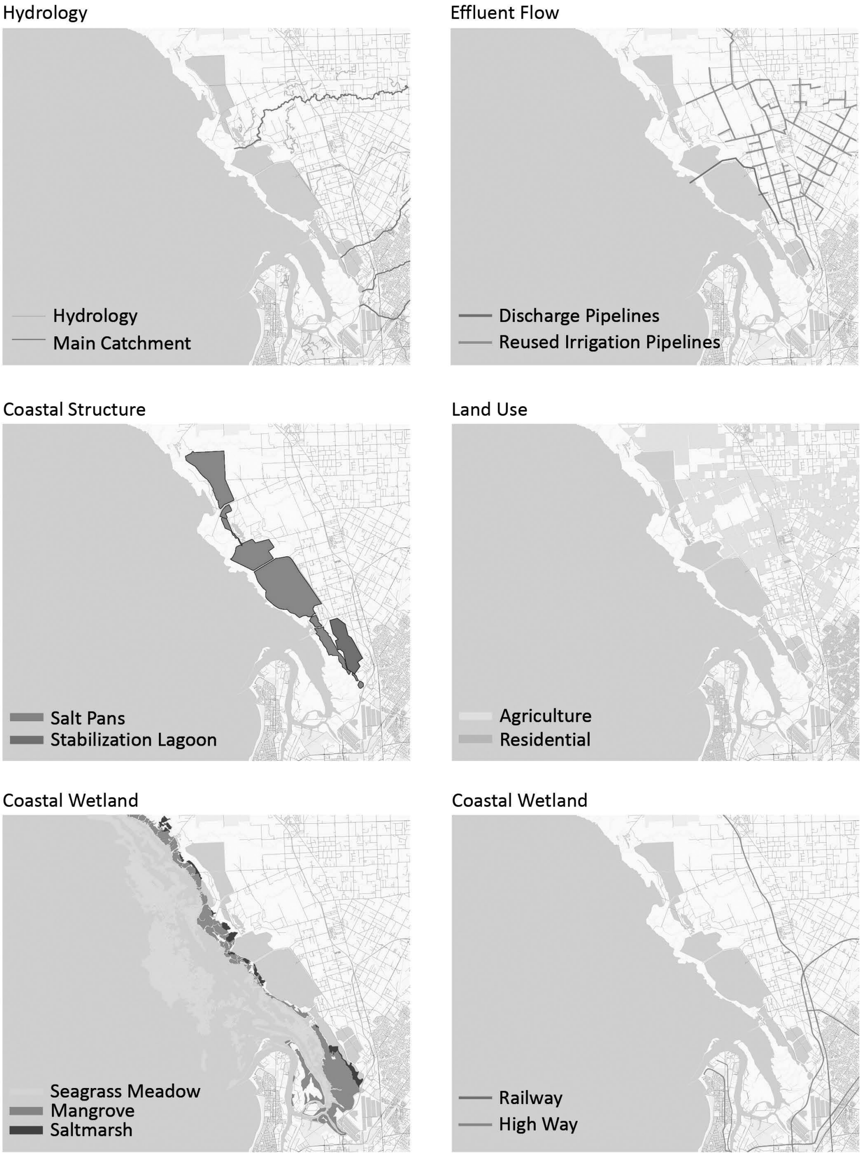

FIGURE 15.4 The tidal ecosystems, including green and blue infrastructure such as sea grass meadows and mangroves, are a fraction of the original systems prior to European settlement. Other land uses such as salt production and wastewater treatment, agriculture and suburban settlement have replaced such tidal systems. The threat and pressure placed by sea level rise may force a renegotiation of the land uses and an opportunity to reallocate land for new uses. Generated by Scott Hawken and Kaihang Zhou. For the color figure, see the e-book.

FIGURE 15.5 Photographs showing (top) coastal squeeze created by the salt field seawalls/bunds, and (bottom) a subsequent tidal restoration trial to open up one salt field pond, thus allowing drainage and flushing of hypersaline waters, and restoration and migration of coastal ecosystems. Photos by Luke Mosley and Emily Leyden. For the color figure, see the e-book.

Sea level rise is the key stressor we consider and driver of coastal squeeze in this area. Latest global sea level rise predictions (IPCC, 2021) are shown in Figure 15.6. The mid-range scenarios show approximately 0.6 m of sea level rise with higher emission scenarios approaching 1 m of sea level rise, or much higher if there is ice sheet instability. Sea level rise will likely lead to progressive inundation of the coastal ecosystems outside of the salt field bunds and begin to impact residential and agricultural land uses at parts of the site but different scenarios are explored below on how this may occur (Figure 15.7).

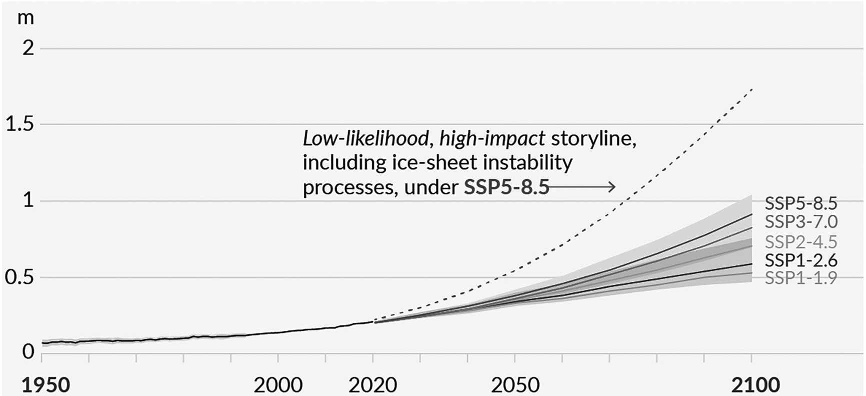

FIGURE 15.6 Global mean sea level change relative to 1900. The different colored lines represent different greenhouse gas emissions scenarios. For the color figure, see the e-book.

Source: Figure SPM.8, Panel (d) from IPCC (2021): Summary for Policymakers. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 3–32, doi:10.1017/9781009157896.001.

Vision: blue-green infrastructures for coastal adaptation

Although many strategies are available for climate adaptation in coastal environments, we consider three major approaches to explore impacts on ecosystems and infrastructure. The first is a "retreat" approach that allows and even facilitates the dynamic migration and expansion of natural ecosystems such as seagrass, mangroves, saltmarsh and supratidal environments. The second is a "defensive" approach that allows and facilitates the protection of current and future land uses through a range of approaches but most typically through seawalls and grey infrastructure engineered works. In contrast to the "retreat" approach, the "defensive" approach fixes land uses in place based on an ideal location. Finally, the "adaptive" approach integrates various strategies to create and integrate both green and grey and blue infrastructure. This approach is characterized by a greater degree of spatial and design complexity. We discuss each of the three scenario "visions" below. For each of these scenarios, the changing land uses set up a different set of questions and expectations regarding resilience. Scenarios A and B prioritize the resilience of particular land uses whilst scenario C adopts a more complex "win-win" approach. In this regard, we suggest that in any scenario, it is necessary to prioritize resilience for "whom, what, when, where, and why?" in the words of Meerow et al. (2016).

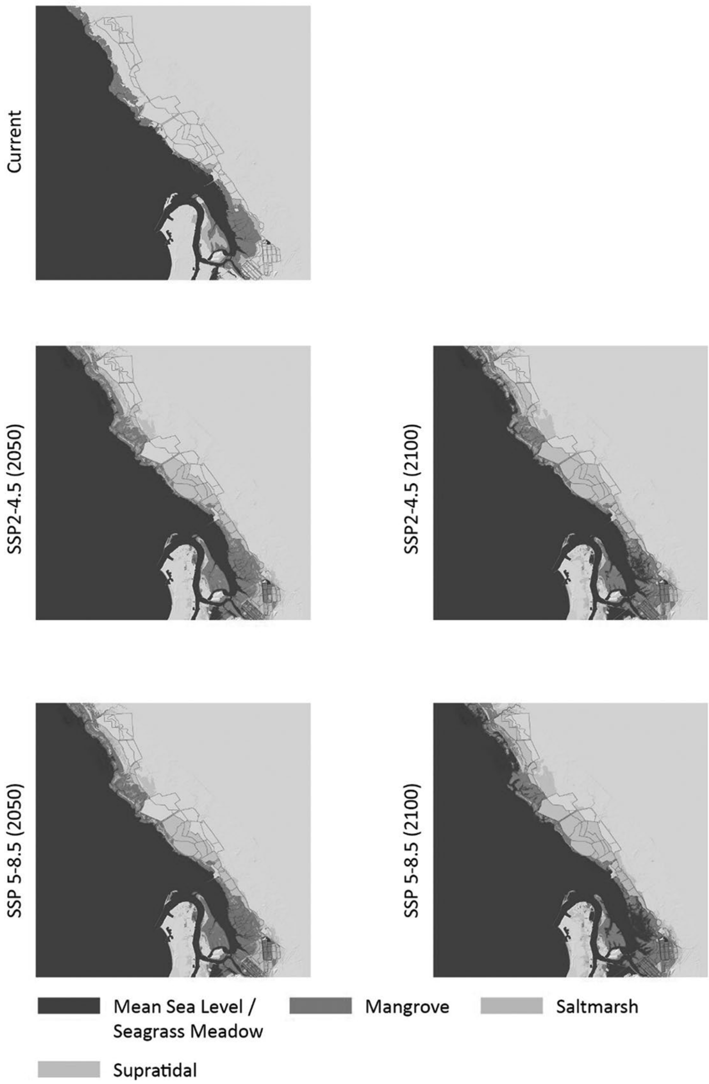

FIGURE 15.7 Sea level change under different IPCC scenarios. If ecosystem migration is allowed to take place new tidal ecosystems will form. However, in many instances, seawalls, roads and other topographic features, often associated with land tenure patters, will constrain this migration and tidal and supratidal ecosystems will instead disappear. Generated by Scott Hawken and Kaihang Zhou. For the color figure, see the e-book.

Retreat approach for maximization of coastal ecosystems

The "retreat" approach (Figures 15.8 and 15.9) enables ecosystems the space to move upwards in land elevation as sea level rises. In our study area, this requires the large-scale conversion of post-industrial salt pans to various ecosystems such as mangroves and saltmarshes and supratidal plant communities local to South Australia such as salt bush. This approach assumes ecosystems can adapt and migrate without impediment by structures or landforms. Under this scenario, the area of mangrove and saltmarshes shifts inland occupying a similar niche or hydrological profile and elevation favorable for the sustainability of the relevant coastal species. This approach also enables "marsh building", where salt marsh and mangrove ecosystems keep pace with current rates of sea level rise where sediment and organic supply is sufficient (Kirwan and Megonigal. 2014; Lovelock et al., 2015; Schuerchet al. 2018). This vertical accretion process also enables "blue carbon" sequestration to continue (Dittmann et al., 2019). This appears to the case for the northern Adelaide study area where wind and wave action on the shallow Gulf waters provides sediment, and there are large quantities of seagrass organic matter "wrack". Connecting urban stormwater to a reconfigured salt field area would also provide sediment supply benefits. Without marsh building processes, ecosystems at lower elevation will be lost, but could be replaced at higher elevations in the retreat scenario (unlike the defensive scenario). The rate of this process is highly uncertain for the project area and South Australia generally (Dittmann et al., 2019). Landward retreat options allow ecosystem connectivity to be maintained (i.e., seagrass-mangrove-salt march gradient). There are many other co-benefits associated with maintaining the ability of ecosystems to adapt to sea level rise including shoreline protection, sequestering, and ensuring permanence of blue carbon, reducing flooding, providing fisheries habitat, creating recreational opportunities and supporting valuable fish and wildlife habitat (Borchert et al., 2018; Temmerman et al., 2013), including in our study area (Dittmann et al., 2019a, b).

However, a retreat approach is difficult to implement due to current patterns of land tenure and vested interests in urban development and economic land use. Further retreat may not always be possible due to legacy infrastructure which is currently constricting migration of ecosystems. Retreat therefore requires a comprehensive spatial and financial plan to manage and make way for changing coastal geodynamics. It is difficult to envisage what resilience looks like in such contexts without consideration and the careful design and continuous management of such dynamic systems to support the evolution of novel and constructed coastal ecologies. This scenario is already visible in parts with selective breaches constructed in existing salt works bunds to allow the reconstruction of mangrove and saltmarsh ecosystems (Figure 15.5 bottom). It is calculated such constructed blue infrastructure systems can store as much as 110 tons of "blue" carbon per hectare (Dittmann, Mosley, Beaumont, et al., 2019; Dittmann, Mosley, Clanahan, et al., 2019; Dittmann, Mosley, Jones, et al., 2019; Jones et al., 2019; Sandhu et al., 2018).

Defensive approach for maximization of coastal urban and agricultural development

The "defensive" approach (Figures 15.8 and 15.9) envisages the salt marshes to be converted into settlement landscapes and high-value agricultural landscapes. It assumes the high level of investment required to convert low-lying land can be recompensated by even higher levels of real estate income through subsequent property sales. As mentioned, such assumptions are implicit in state planning policy for South Australia and other jurisdictions around Australia. Coastal settlements around Australia and globally are currently experiencing recurring and increasing frequency of flooding. To protect property and communities, there is therefore a great push to develop defensive structures such as seawalls and embankments. Retrofitting existing low-lying settlements is, however, difficult as areal flooding and surcharge can occur behind the walls and render houses and drainage infrastructure unfit for those purposes. In some instances, novel ecosystems are developing in such settlements in low-lying swales, depressions and even kerbs and medians of streets. However generally such defensive approaches result in a major loss of coastal habitats (Cooper et al., 2020).

Building walls or other engineering structure to defend from sea level rise essentially over time compresses the tidal ecosystems into a smaller area. Defensive walls that protect against storm surge or sea water incursion prevent salt marsh ecosystems and mangrove ecosystems from migrating inland (Figures 15.8 and 15.9). They are therefore progressively lost (i.e., "drowned out") and replaced by submergent vegetation such as seagrasses. A defensive approach also requires the building and maintenance of costly coastal infrastructure. Such costs will likely increase over time in the face of increased wave energy as sea levels rise. Furthermore, although surface waters may be able to be defended against, groundwater intrusion and rise on the landward side of structures could cause many issues including salinization of surface soil, salt damage to houses and other infrastructure. Conventional urban developments are not recommended for such landscapes and should take into consideration worst case scenarios involving storm surges, environmental degradation of materials and changing geomorphological conditions. Although such defensive approaches are envisaged as "fixed", building systems in such developments can incorporate adaptive features that can allow the development to evolve over time. This might include built features such as pontoons that allow developments to rise and fall with the tide or green buffer zones to dissipate storm surges (Barsley, 2020). It might also include policy mechanisms such as incentives (Fang, Howland, Kim, Peng, & Wu, 2019; Wang, Lu, Lu, & Nie, 2021) to permanently move should environmental conditions becomes extreme. Long-term uncertainty is associated with this scenario's ability to defend itself against changing environmental conditions. Long-term insurance from 50 to 100 years against sea level rise and climate-related impacts maybe prohibitively high and render the development unfeasible unless realistic assumptions about flooding are built into the development.

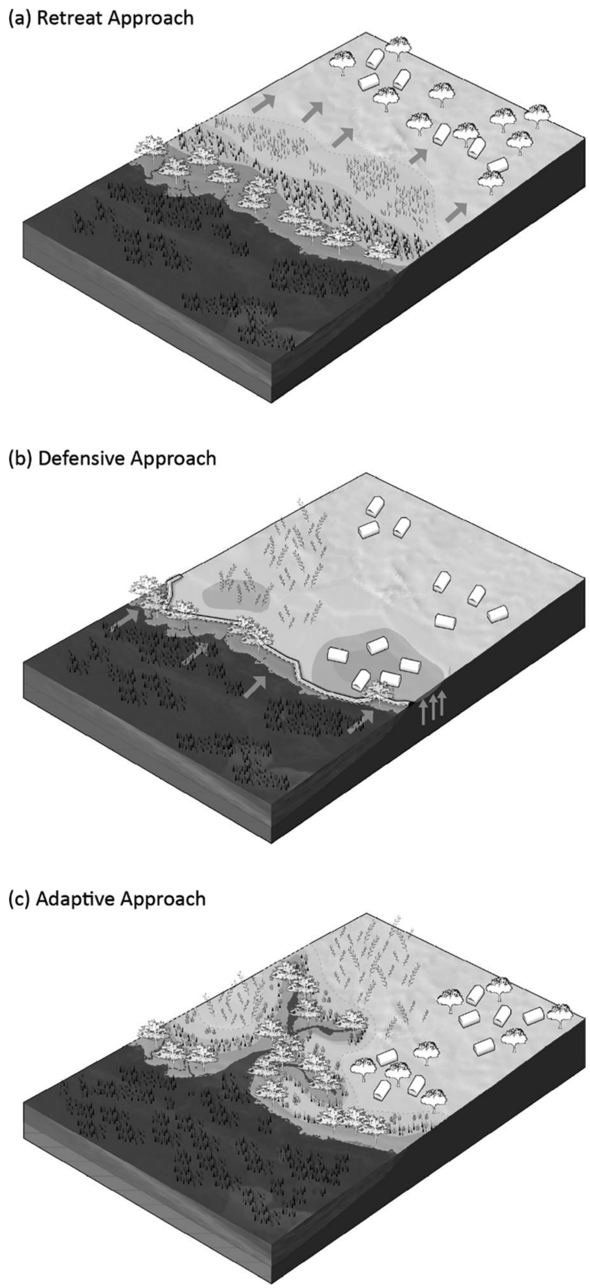

FIGURE 15.8 Strategic approaches used in the three scenarios: (a) retreat, (b) defensive, (c) adaptive. Generated by Kaihang Zhou. For the color figure, see the e-book.

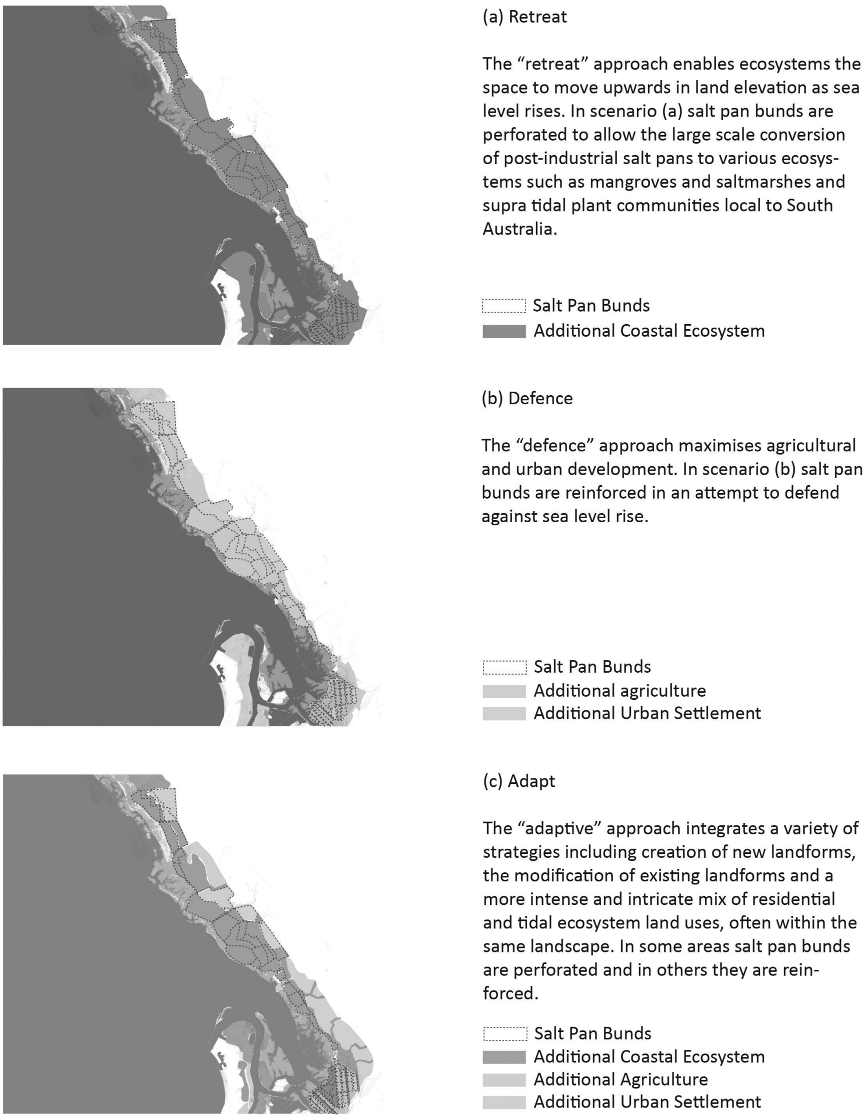

FIGURE 15.9 Three scenarios (a) retreat, (b) defense, (c) adapt, each follow a different decisive development process that either inhibits or facilitates ecosystem migration and evolution. The first shows a massive expansion of coastal ecosystems, the second shows diminishing ecosystems as sea levels rise against seawalls and infrastructure squeezing the ecosystems out, and the last shows an evolution of diverse ecosystem and settlement systems in a hybrid, incorporating a mix of urban settlements and green infrastructure in close proximity that can adapt and strengthen resilience as the climate pressures increase. Generated by Scott Hawken and Kaihang Zhou. For the color figure, see the e-book.

Adaptive approach for maximizing resilience through hybrid green-grey infrastructure

The "adaptive" (Figures 15.8 and 15.9) approach integrates a variety of strategies including creation of new landforms, the modification of existing landforms and a more intense and intricate mix of residential and tidal ecosystem land uses, often within the same landscape. The intent of hybridization is to use green infrastructure or "nature-based solutions" to generate greater resilience. This scenario utilizes "floodability" as a new paradigm for urban development (Ernstson et al., 2010; La Loggia et al., 2020; Palazzo, 2019). Cities around the world are implementing designs and settlements that are resilient and adaptable to flooding. In particular, major infrastructure such as wastewater plants and systems need to be reassessed for their suitability to new pressures and stresses that are arising through climate change. In particular, our case demonstrates the importance of providing more space for green and blue infrastructure to manage sea level rise and for replacing or adapting outdated grey infrastructure with more efficient technologies with smaller footprints and environmental costs (Kirwan & Megonigal, 2013). By working with such geomorphological and nature-based processes rather than against them in a defensive way, the urban landscape is inherently more resilient (Hawken et al., 2021b). Long-term spatial corridors dedicated to tidal ecologies allow ecosystem migration to occur. Built infrastructure such as access roads and causeways are configured to facilitate water flow and ecosystem migration whiles being orientated to deflect and disperse storm surge impacts and other coastal environmental pressures. Residential landscapes are either adapted as floating pontoon landscapes or built up as marsh islands which use the landform generating abilities of mangroves and marshlands to "grow" terrestrial landscapes over time. Such approaches involve a dynamic changing approach more in tune with the realities of climate change than any fixed masterplan. Lease arrangements are used to ensure that long-term problems do not become the problem of residents but are managed at the larger scale and remain the responsibility of developers and government.

Such an approach can also accommodate stormwater functions necessary for the treatment of runoff from adjacent urban areas (Hawken et al., 2021b). A further example of such an approach is illustrated in Figure 15.10 which communicates a proposal for the Bolivar Wastewater Plant in Adelaide, which replaces the aging technology for new advanced dual membrane and ultraviolet technologies to allow for more extensive water reclamation and circular resource use. The smaller footprint of the approach allows for the industrial polishing ponds to be turned over to tidal ecosystems such as mangroves, salt marshes and freshwater constructed wetlands. Whereas the defensive approach largely follows a business-as-usual development paradigm, the adaptive approach uses inherent dynamic aspects of green infrastructure to generate and shape coastal environments.

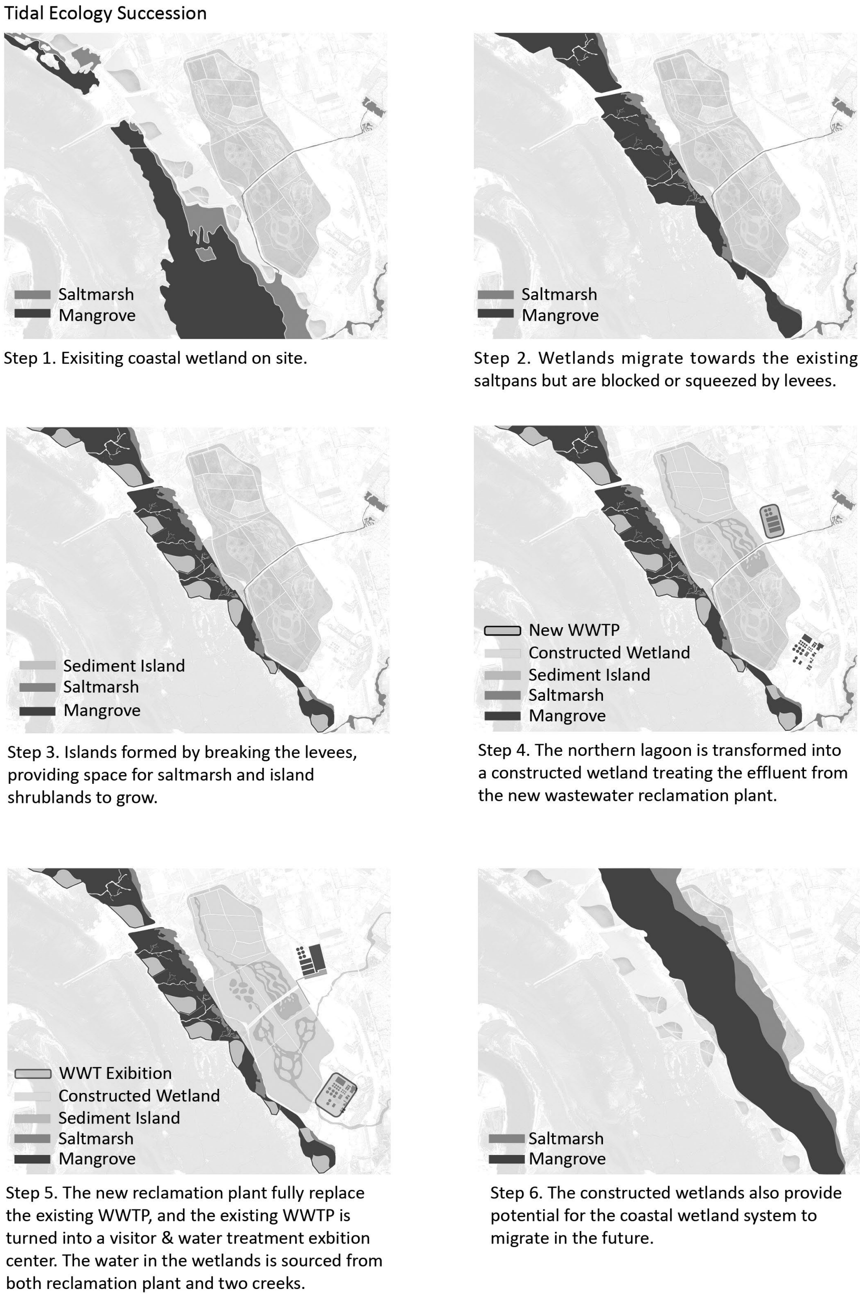

FIGURE 15.10 A hypothetical scheme for the Bolivar Waste Water Plant demonstrates how grey and green infrastructure can be designed together to facilitate win-win outcomes. Generated by Kaihang Zhou. For the color figure, see the e-book.

Path to the future

Climate change and associated sea level rise is placing unprecedented pressures on natural and built environments in coastal zones globally. Coastal squeeze arises from the inability of coastal ecosystems to adapt or migrate to higher elevations due to the presence of walls and other infrastructure, and is a major issue that cannot be ignored if we are to sustain the values of these ecosystems (e.g. recreation and tourism, erosion protection, fisheries, carbon sequestration and flood mitigation). The three scenarios presented in this chapter for the same coastal urban landscape in Adelaide offer different ways of thinking about resilience in uncertain economic, environmental and social context. There are complexities in all three approaches and their potential combinations, that require careful consideration in the local context. Allowing ecosystems to adapt also provides benefits essential for increasing resilience of built environments to sea level rise (e.g., marsh building and buffering of storm surges). Localized examples of scenarios 1, 2 and 3 are all evident within the study area. By considering such approaches on a large scale, we can begin to envisage the potential and impacts of each approach. Whilst each approach has its strengths and weaknesses, we suggest that a hybrid, utilizing adaptive strategies integrating both grey and green infrastructure, is superior when it comes to maximizing resilience and a balance of social and ecological outcomes. However, to advance such an approach in the Northern Adelaide area, a greater consultation across sectors and disciplines is required to identify opportunities to challenge and critically reconsider business-as-usual approaches in making key decisions. Such scenario-based approaches to resilience are also important to raise political and public knowledge of alternative approaches to providing resilience in the face of major sea level rise.

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