Coastal Hazards Adaptation Planning

Catalogue of Coastal Hazard Adaptation Options

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Christchurch City Council

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1 Introduction

The Christchurch City Council (the Council) has initiated a Coastal Hazards Adaptation Planning (CHAP) programme in low-lying inland and coastal communities across the Christchurch district that are at risk of three main coastal hazards that will be exacerbated by climate change - coastal erosion, coastal inundation and rising groundwater. Coastal erosion refers to the loss of land or sediment due to wave, current, wind or tidal action, while coastal inundation is defined as flooding from the sea which may occur as a result of events such as storm surges or long term sea level rise. Near the coast, groundwater levels are also often strongly influenced by the level of the sea. As sea levels rise, the interface between saltwater and the overlying freshwater also rises leading to saltwater intrusion in coastal aquifers, and a height increase in the water table. As the water table rises along with the sea level, it may cause water to rise above the ground surface more frequently. The effects seen from each of these three hazards may be worsened by impacts of climate change such as sea level rise and increased storminess.

The CHAP programme generally follows the approach recommended by the Ministry for the Environment in the 2017 ‘Coastal Hazards and Climate Change Guidance for Local Government’, with modifications undertaken where appropriate. The guidance document sets out a 10-step decision cycle of structured engagement which aims to increase awareness of the impacts of sea level rise, and lead to the development of community-led adaptation plans that consider the social, cultural, natural and built environments.

Climate change mitigation and adaptation to climate change are heavily related and should both be considered when creating a holistic climate plan or policy. Climate change mitigation aims to reduce greenhouse gas emissions that trap heat in the earth’s atmosphere and lead to global warming. Without mitigating, preventing or addressing the causes of accelerated climate change, adapting to the consequences of them will quickly become un-feasible and ineffective. Mitigation measures are covered in the Council’s wider *Ōtautahi Christchurch Climate Change Strategy*.

This report provides an insight into different adaptation options and how they have been utilised both nationally and internationally, with the knowledge that these must be combined with mitigation measures for the best outcome. Adaptation options may need to be used in parallel to provide risk reduction to multiple hazards as different options adapt to different hazards at different temporal and geographic scales, and are suitable and effective in different areas depending on varying processes, hazards and the type and intensity of development.

2 Purpose

Step five of the Ministry for the Environment recommended decision cycle in the 2017 'Coastal Hazards and Climate Change Guidance for Local Government' involves identifying current measures that manage coastal hazards and investigating whether any changes are required, or whether new approaches are needed to address future risks.

The purpose of this report is to provide contextual information on a wide range of possible adaptation options for low-lying inland and coastal communities for use during the Council's CHAP programme. This has been achieved through the desktop review of relevant national and international literature, policy and planning documents and case studies focused on adapting to coastal erosion, coastal inundation and rising groundwater hazards. It should be noted that this review method may have led to the global north being over-represented in case studies.

This report sits alongside the Coastal Adaptation Framework which outlines the initial proposed process by which adaptation pathways are made from the options discussed here, or identified later in the process. It is not intended for this report to be the sole tool for identifying potential adaptation options or to be an exhaustive list of all available adaptation options and their advantages and disadvantages. It is intended to inform and support the identification of suitable adaptation options for consideration in the development of adaptation pathways for low-lying inland and coastal communities in the Christchurch district. Once possible options are identified for an adaptation pathway, it is anticipated that they will be further assessed and developed through the process set out in the Coastal Adaptation Framework. Ultimately, it is the Council that makes the final decision on adaptation pathway implementation.

The Council's Coastal Hazards Plan Change sets the regulatory framework to manage general increased risk across the district.

3 Approach

There are five main types of options:

Maintain	Enhance what is already being done. Continue to live in an area and use assets by maintaining existing infrastructure, continuing emergency management, and carrying out environmental monitoring. The aim will also be to increase community risk awareness.
Accommodate	Live with the hazard. Continue to use land in an area by raising the tolerance to hazards. These options can avoid or delay the need to remove or relocate at-risk assets in the short to medium term.
Protect	Keep the hazard away. Interrupt coastal hazards using soft engineering approaches, hard engineering structures, or a combination of the two to form a barrier between assets and the hazard.
Retreat	Move away from the hazard. Retreat or relocate existing and planned development to reduce hazard exposure. The hazard risk to assets is reduced or removed entirely, leaving the coast to respond to natural processes.
Avoid	Don’t move in the way of the hazard. Planning tools are used with the aim of avoiding increased risk of harm due to hazards in social, environmental and economic terms.

Within each of the above type of option, there are a range of potential options which vary over temporal and geographic scales. Physical or regulatory constraints differ between options and can add cost, time and uncertainty. To achieve the best outcomes, it is likely that a combination of types and options will need to be implemented over time as circumstances change and specific trigger points are reached.

Some options may ‘cross-cut’ and could be placed under multiple types of options. For example, emergency management could be placed under the maintain, accommodate or protect type due to its current use and the nature of works that are carried out under its description. In terms of adaptation planning this doesn’t make much difference as an option should be chosen based on its suitability and effectiveness in an area, not what type of option it is listed under in this report.

All options discussed in this report rely on the sound understanding of climate change data and predictions, and understanding of the local environment which includes the physical environment, hazard risk, historical data, and future regional and local climate scenarios. It is also important to understand the recent mechanisms of hazards in the area to alter any options to site specific requirements.

It should also be noted that during the desktop review of national and international examples, it was found that in the past, more emphasis has been placed on engineered adaptation options when compared to social, institutional or eco-system based options. This difference in knowledge and information may be seen to be mirrored in this report, however, it does not suggest that the Council prefers one approach over another. Full references are listed at the end of each section.

Some literature also mentions an ‘attack’ type of option that works to advance towards the sea by ‘claiming’ land. However, there have only been examples found where this option is used as an economic tool, rather than a coastal adaptation tool. For this reason, the attack option has not been included in this report.

4 Maintain

Maintain options seeks to continue managing coastal hazards as we currently do. This means to:

- Maintain current infrastructure systems
- Continue to increase community education and risk awareness
- Continue emergency management
- Continue environmental monitoring

Current infrastructure systems such as wastewater, stormwater and drinking water infrastructure, telecommunication infrastructure, and roads will be maintained to restore the present day level of service. More information on how these infrastructure systems could be improved can be found in sections 5.2, 5.5, 5.6 and 5.7.

Education is an essential element of the global response to climate change. As people build an understanding of the impacts of climate change it is seen to encourage changes in their attitude and behaviour, and helps them adapt to climate change (UNESCO, 2018). Education and awareness also allow people to make informed decisions and play a role in both climate change mitigation and adaptation (UNESCO, 2018).

Emergency management, including the creation of hazard maps, evacuation plans, civil defence emergency management, and temporary accommodation and protection measures, is an ongoing activity in Christchurch. Emergency management increases community awareness and understanding of hazards, and increases community preparedness to deal with hazard impacts. These results lead to emergency management increasing overall community resilience (Linham & Nicholls, 2012; Geological and Nuclear Sciences, n.d.). Emergency management is discussed in more detail in section 5.8.

Environmental monitoring is important in helping us to understand future conditions more accurately at local, regional, national and global scales which is becoming more and more cricial as climate variability increases and historical patterns shift (CTCN, 2016). Monitoring involves systematic observations and measurements at standard pre-set times and locations which over time, help us to understand how the environment is changing (CTCN, 2016). Environmental monitoring in terms of climate change adaptation is important as it helps us to understand how our local environments are changing, at which point we need to start adapting to these changes and whether adaptation options have achieved their goal. Environmental monitoring may include topographic and bathymetric surveys, shoreline mapping, storm events, ecological surveys, structural assessments, and morphological change assessments (Linham & Nicholls, 2010).

Maintain options have the advantage of being easily implemented with no major change witnessed by the wider community, however it may not be the most effective in all areas and it may not be viable as a standalone option as hazard risks become more severe.

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5 Accommodate

Accommodate options seek to continue land use in an area by raising the hazard tolerance of assets. These options can avoid or delay the need to remove or relocate at-risk coastal assets and can offer a more cost-effective approach to reducing risk in the short to medium term. These options can include measures such as adapting buildings and infrastructure, and increasing water storage and treatment capacity (Sinay & Carter, 2020). Accommodate options can be implemented at various different levels from regional and community level to individual households. They can also be retrofitted to existing infrastructure or incorporated into the initial design and construction. When implemented during the initial development stages, accommodate options can be relatively low cost options (CTCN, 2017).

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5.1 Flood proofing buildings

A house in Christchurch, New Zealand that is built to accommodate inundation (Image source: Property Value, 2021).

Temporary door block to prevent inundation inside the building (Image source: Hydro Response Ltd., 2006).

Flood proofing measures are best applicable to coastal areas with a small inter-tidal range and where flood depths are low (Linham & Nicholls, 2010). Flood proofing buildings is achieved using two main methods: wet or dry flood proofing (Linham & Nicholls, 2010). Wet flood proofing involves three main techniques; allowing water to enter and leave structures easily to minimise structural damage, using flood resistant materials, or elevating structures and utilities (Linham & Nicholls, 2010; FEMA, 2012). Dry flood proofing on the other hand makes buildings watertight up to a certain level (Lloyds, 2008; Linham & Nicholls, 2010; FEMA, 2012). The type of flood proofing that is most effective in an area depends on flood water velocities, flood duration, water pollution and flooding frequency (FEMA, 2012; FEMA, 2013). Flood proofing measures may be temporary (such as blocking water from entering doors when the water level is high, or having a flood gate across a driveway), or permanent (such as waterproofing the walls, raising houses or elevating electrical sockets) (Christchurch City Council, 2014; CTCN, 2017; AECOM, 2015).

Wet flood proofing has the ability to ensure that the internal and external pressures acting on a structure are equal and prevents large loads on the building, while the reduction of impermeable obstacles also provides a more natural movement of sediment and water (Linham & Nicholls, 2010). More benefits of flood proofing buildings is that it requires no extra land, can be carried out by individual property owners, can increase property resale values and reduce future damage costs (Linham & Nicholls, 2010; FEMA, 2012).

Flood proofing measures also have some disadvantages; they may adversely affect the appearance of buildings or impact the visual amenity of the wider area, there may be a significant amount of clean up required after a flood event as properties and parts of buildings are still exposed to flood waters, and if a flood event exceeds design parameters, flood proofing measures may provide little to no protection at all (Linham & Nicholls, 2010; FEMA, 2012). Therefore, the residual risks of flooding must be very well understood. Flood proofing buildings also does not address damage to infrastructure and the potential lack of property access during a flood event. Temporary flood proofing measures also require that someone is available to implement them before flood waters reach a structure.

Case studies

Christchurch, New Zealand

In New Zealand, minimum floor levels for habitable buildings can be given effect to through rules in a District Plan or as part of conditions imposed on resource consents for new development in identified coastal hazard areas. Minimum floor levels can be useful in areas experiencing high groundwater and surface ponding while providing for transitional use of residential land that could succumb to hazards in the future (Bell et al., 2014).

The Christchurch City Council sets minimum floor level requirements to protect buildings from inundation risk (Christchurch City Council, n.d.). These requirements ensure that buildings in certain flood management areas will be protected from floods to a certain level.

Note: To date, this has largely been applied in the context of more static flood risk rather than coastal hazards.

Lake Macquarie, Australia

Development conditions have been revised to manage increased risk from flood events and permanent inundation around a tidal estuary (Giles, 2012). Lake Macquarie City Council has applied new floor height requirements that include an allowance for sea level rise during the life of a building (Giles, 2012).

Florida, United States

Inspection services are provided to homeowners to help them identify ways they could retrofit their homes to make them more resilient to storm damage (Young, 2009). Homeowners received up to $5,000 in state matching funds to implement these measures (Young, 2009).

Ireland

The Homeowner Flood Grant is a Government funded scheme in Northern Ireland that incentivises homeowners to modify their residential properties to make them more resilient to inundation. The Government will fund 90% of survey and installation costs up to the value of £10,000. To qualify for this grant, properties must have been flooded internally in the past or be in a known flood risk area (Department for Infrastructure, 2019).

International

Globally, there have been adjustments made to housing for centuries. For example, houses raised above floodwaters on stilts have been seen in areas such as Malaysia, Thailand and Hong Kong (Parker, 2000). Houses can also be built in swamp-like areas by being raised up on piles as the Cajun people have done in North America since the eighteenth century (Parker, 2000).

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5.2 Flood proofing infrastructure

Raised road through a floodplain in Vietnam (Image source: Mallick et al., 2011).

Flood gates allow water to flow out but not in prevent saltwater intrusion (Image source: Weida, 2018).

Similar to flood proofing buildings, flood proofing infrastructure such as wastewater, stormwater and drinking water infrastructure, telecommunication infrastructure, and roads may involve modifying existing infrastructure or designing new or replacement infrastructure to withstand coastal hazards (Linham & Nicholls, 2010). This can be done by reviewing design standards, upgrading and replacing assets using more resilient designs and materials, and embedding hazard resilience into the planning process. As mentioned above in section 5.1, flood proofing measures are best applicable to coastal areas with a small inter-tidal range and where flood depths are low (Linham & Nicholls, 2010). It should be noted that this option may involve land acquisition (discussed in section 7.1) where modifications are reliant on the ability to expand the footprint of infrastructure, for example where roads are being elevated or moved, or the capacity of storm-water retention infrastructure is being increased.

Case studies

Christchurch, New Zealand

Following the Canterbury Earthquake Sequence, significant repairs to the causeway in front of McCormacks Bay and along Main Road were required, and hazard resilience was integrated into the planning process (Radio New Zealand, 2013; Christchurch City Council, 2014a). There is critical infrastructure within the road corridor which is a strategic route for community access, evacuation and is an alternative freight route from Lyttelton Port. The corridor was widened to allow for additional lanes, a services corridor and the coastal pathway that could be raised in the future as sea levels rise (Radio New Zealand, 2013). Rock revetment was also placed along the seaward edge of the pathway to manage erosion risk.

Florida, United States

‘Sacrificial’ roads are constructed in high risk coastal areas where roads are at risk of washout. These roads are designed with the intention that they wash out with minimal environmental consequences during storm surges (Adaptation Clearinghouse, 2007). They are designed as temporary cost-effective solutions to the problem of repeated washout (Adaptation Clearinghouse, 2007).

Virginia, United States

Two waterfront roads in Norfolk, Virginia have been widened and elevated by the Virginia Department of Public Works to address recurrent inundation which caused frequent road closures (Adaptation Clearinghouse, 2014). The project is part of Norfolk’s Coastal Resilience Strategy (Adaptation Clearinghouse, 2014).

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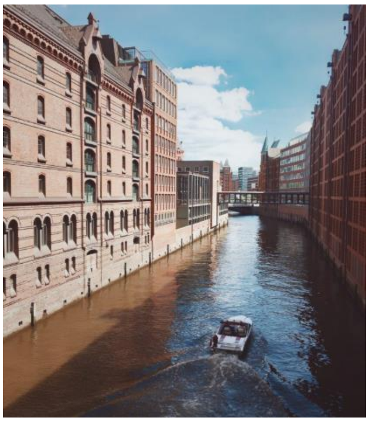
5.3 Adaptable buildings

Floating houses sit on top of the water all year long (Image source: Lubell, 2018).

Relocatable homes can be moved (Image source: The Relocatable House Company, 2020)



Dyke houses forming a flood barrier in Hamburg, Germany (Image source: Kreig, 2018).

This amphibious pavilion is built on pontoons to increase its resilience to inundation (Image source: Buoyant Foundation Project, 2020).

Adaptable buildings are designed to respond to an environmental change while avoiding structural damage. Adaptable buildings allow for the recognition of the high demand and property value in coastal areas while avoiding the construction or expansion of protection structures and also providing measurable cost savings compared to other options (English et al., 2016; CTCN, 2017). An adaptable approach to planning and building also helps people to recognise that seasonal and occasional inundation will occur and that we must live with water (English et al., 2016). As with flood proofing, these types of options do not address all components of coastal hazards.

One example of adaptable buildings are amphibious buildings which are designed to rest on solid ground under ‘dry’ conditions, and rise to float on water through the use of pontoons during times of flood. Amphibious houses work with natural processes and allow flood waters to flow under structures rather than obstructing the water (English et al., 2016). As the height of the structure adapts to the changing water level, these structures can accommodate rising sea levels, flood waters and subsiding land (English et al., 2016). Another example of adaptable buildings are floating buildings which float on the water at all times (Strangfeld & Stopp, 2014). Floating buildings are very resilient to sea level rise and coastal inundation. Dyke houses are also a form of adaptable buildings and have a double function as they build a dyke line to protect against inundation while also have housing capabilities. Relocatable buildings are also adaptable in the sense that they can be moved as needed and thus provide flexibility to deal with changing risks and uncertainties of the impacts of coastal hazards.

Case studies

Kaiapoi, New Zealand

An amphibious house sits on a catamaran pontoon made of polystyrene, wrapped in a waterproof material and sheathed in plywood for protection from ultra-violet light and the weather (Williscroft, 2018). The pontoons are attached to piles to stop the house from floating away, but it can rise in a flood, resist water flows of up to 3 meters per second, and settle back in the same place after the floodwater recedes (Williscroft, 2018). This option is more expensive than building a regular home.

Marlow, England

A home constructed on an island in the River Thames rests on the ground like a conventional building under normal, dry conditions and then during floods, it floats on water that flows into a bathtub-shaped outer foundation (Wainwright, 2016).

Maasbommel, the Netherlands

A community of floating and amphibious houses that float on hollow pontoons made of concrete and timber. These buildings rise as the water levels increase and when floods subside they sink to their original position (Urban Green-Blue Grids, n.d.).

Oregon, United States

There are around 1,400 floating homes in the Portland metro area, making it the largest collection of floating homes in the United States with the creation of many communities along the Willamette, Columbia and surrounding rivers (Hayden Island, 2020).

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5.4 Raising land levels

The Netherlands use artificial earth mounds called 'terps' to build homes, farms or even whole villages on (Image source: Frisia Coast Trail, 2021).

Land levels can be raised to above an expected inundation level for the purpose of reducing current and future coastal hazard risks. In most cases, this method can be more cost effective than other structural coastal adaptation options when proactively implemented before structure construction (Lloyds, 2008; Climate Adapt, 2015). The edge of the raised land may need protection from erosion in the form of beach nourishment, vegetation planting or engineered structures such as seawalls.

While raising new land may be cost effective, raising developed land or historical sites provides challenges such as timelines with respect to infrastructure design lives or cost (Lloyds, 2008; Climate

Adapt, 2015; Brown et al., 2020). Options such as this that create a barrier for flood water may also increase the hazard in adjoining areas as water is redirected here, while another potential limiting factor is the type of material that is used, how much it needs to be compacted and how much it will subside (local soils and water content also affect this) (Climate Adapt, 2015). Raising land in sections also poses access issues if for example, roads are flooded for periods of time.

Case studies

Bilbao, Spain

The city is undertaking a major urban regeneration project to redevelop a flood prone district into a new flood-proof residential area (Climate Adapt, 2016). Protection measures include elevating the ground level by 1.5 meters for new buildings, opening a canal, constructing a flood protection wall, installing stormwater tanks and providing green, public spaces (Climate Adapt, 2016).

Wadden Sea, Europe

Before the construction of dikes in the area that is now Denmark, Germany and the Netherlands, the area was a wide, regularly inundated saltmarsh area (Climate Adapt, 2015; Nieuwhof et al., 2019). Historically, the area had small settlements built on man-made mounds to protect them against floods (Climate Adapt, 2015; Nieuwhof et al., 2019). This was a successful way of life for over 1500 years until the construction of dikes largely replaced this form of coastal protection. Today, many of these mounds remain and some are heritage sites (Climate Adapt, 2015; Nieuwhof et al., 2019).

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5.5 Groundwater management

'French drain' utilises pipes below permeable materials (Image source: Tigard Sand and Gravel, 2020).

Groundwater well (Image source: United States Geological Survey, 2018).

A number of accommodate and protect options (discussed in section 6), that impact the interface between the land and the sea will require groundwater management to be a part of the adaptation pathway to allow ongoing land use. There are several measures that can be implemented to reduce the effects of rising groundwater levels. The first method is improving or raising the land. As discussed in section 5.4 above, this can help raise low-lying areas, or fill can be used to create a permeable layer that enhances drainage (Otago Regional Council, 2017).

The second method involves the use of open land drains, canals or channels that guide water away from developed areas (Brouwer, 1985; Colorado Department of Transportation, 2019a). The water flow in these systems may either be driven by gravitational force or through pumping (Otago Regional Council, 2017; Colorado Department of Transportation, 2019a). The surface water in drains, canals or channels can add recreational and ecological benefits to an area.

Similar to the second method, seepage drains or canals collect subsurface water to prevent the weakening of structure-supporting soil, surface inundation and ponding (Brouwer, 1985; Otago Regional Council, 2017; Colorado Department of Transportation, 2019b). Horizontal subsurface drainage (or 'French drains'), use pipes in permeable soils below ground level to divert water and thereby reduce the local groundwater levels (Brouwer, 1985; Otago Regional Council, 2017; Colorado Department of Transportation, 2019b).

Vertical drainage networks (or wells) can lower the local groundwater table through pumping (Otago Regional Council, 2017). This method is more effective than horizontal drainage systems in areas where trenching is unfavourable or where there are low permeability top soils (Otago Regional Council, 2017). Pumping groundwater can have adverse effects such as causing land subsidence if too much water is removed, or leading to saltwater intrusion if too much fresh groundwater is removed too close to the coast and saltwater comes in to replace it.

Groundwater management systems can provide layered benefits, including reduced liquefaction potential and if combined with stormwater drainage systems, they can both drain water when the water level is too high, and infiltrate stormwater into the ground when the water table is too low (Otago Regional Council, 2017). The effectiveness and suitability of these options is reliant on the type of soils and groundwater sources in the area. Relocatable infrastructure such as moveable pump stations can also increase the resilience of the system in the face of climate change.

Different groundwater methods may be used in conjunction with one another to combat more than one issue. It should also be noted that liquefaction and seismic activity may severely affect some subsurface infrastructure.

Case studies

Den Helder, the Netherlands

Even in the presence of protection structures such as seawalls or stopbanks, groundwater levels in areas close to the sea can rise at high tide as a result of seepage beneath the protection measure.

Den Helder is a port city in the Netherlands, which is bounded by the sea on three sides. The city is protected from sea water inundation by dunes in the west and seawalls along the northern and eastern boundaries (Otago Regional Council, 2017). A network of canals was constructed in historical times and serves as a discharge point for stormwater. The canals receive seepage of fresh groundwater from the western dune area and saline groundwater from the sea. Since 2008 all city and district councils in The Netherlands are responsible for investigating groundwater issues and taking appropriate measures where there are issues (Otago Regional Council, 2017). Den Helder City Council has acknowledged groundwater issues and has implemented some measures. As part of an on-going sewage and stormwater network upgrade programme, the stormwater pipes are being partially replaced with ‘drainage and transportation’ stormwater pipes to provide sufficient storage and diversion capacity, but also have a drainage and infiltration function to manage groundwater levels (Otago Regional Council, 2017).

Haarlem, the Netherlands

Over decades, the installation of horizontal drainage alongside sewage pipes has become widespread as part of building site preparation, sewer replacement and road (re)construction projects throughout The Netherlands (Otago Regional Council, 2017).

In the 1980's, the Leidsebuurt district in Haarlem was one of the first locations in the Netherlands experiencing groundwater rise after sewer replacement. In response, the city of Haarlem financed and installed a horizontal subsurface drainage system in public land in 1989 (Otago Regional Council, 2017). The drainage level can be changed with adjustable weirs in (dry) catch pits to keep the groundwater at an acceptable level (Otago Regional Council, 2017). The drainage pipes are cleaned by medium pressure flushing every one or two years, and after 26 years, the state of the subsurface drains was investigated (Otago Regional Council, 2017). There was no clogging or root growth, and the coating material was hardly worn, so as a result, the lifetime expectation of the drainage system was increased by another 60 years (Otago Regional Council, 2017).

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5.6 Stormwater management

Water squares such as this in the Netherlands have a recreational purpose under dry conditions but can flood under wet conditions (Image source: Public Space, 2020).

Rain gardens collect and filter storm water before it infiltrates into the groundwater.

Swales collect and divert surface water to flow in desired location.

Retention basins are areas of relatively lower ground elevation where surface water can collect without affecting the use of an area.

The hard landscapes of urban environments brought about by pavements, roads and other impermeable surfaces change the flows in urban waterways. For example, waterways may experience sudden surges in volume and velocity during heavy rainfall as a result of stormwater running off impermeable surfaces rather than infiltrating into soils (Foster, 2016).

There are several ways to manage stormwater as the groundwater table and sea levels rise. Primary stormwater networks consist of surface inlet structures connected to underground pipes and tunnels that are often designed to drain the water from low intensity rainfall events such as a 1 in 10 year event (10% Annual Exceedance Probability) (White & Storey, 2017; Colorado Department of Transportation, 2019b). The secondary stormwater network is made up of overland flow paths that will drain larger rainfall events (White & Storey, 2017). Overland flow paths are designed to minimise the inundation impacts on urban areas and provide space for the water to go (White & Storey, 2017).

Stormwater networks in low-lying coastal areas must be designed to address challenges such as flat topography that does not highly support gravity-induced systems, backflow into the system from the sea, damage caused by erosion, clogging due to debris and the more frequent, higher and longer-lasting storm events (NOAA, 2020). Where the topography is too flat or too low lying and gravity does not move the water, pumping stations may be needed. However, due to the high costs and potential problems associated with pumping stations, they are only recommended where other options are not suitable or feasible (Colorado Department of Transportation, 2019a). Other options such as tide gates that can stop backflow in pipes, raingardens and swales that collect and filter water, detention basins that store water to relieve pressure on the system, and pervious concrete or asphalt alternatives can also be implemented as part of a stormwater management plan to deal with issues arising from coastal hazards (White & Storey, 2017; Colorado Department of Transportation, 2019a).

Case studies

Christchurch, New Zealand

The Comprehensive Stormwater Network Discharge Consent issued in 2019, sets out the framework for development of stormwater management plans within the Christchurch district (Environment Canterbury, 2018; Environment Canterbury, 2019). These plans look forward in time to plan for both changes in climate and changes in development patterns. The plans set out future stormwater management infrastructure approaches within each catchment utilising a range of different methods to manage stormwater quality and inundation.

Amsterdam, the Netherlands

The Amsterdam Rainproof project is a platform that activates different stakeholders from organisations to businesses to individuals to create a more resilient city that is more adapted to heavy rainfall (Amsterdam Smart City, 2016). The city is not well-equipped to deal with heavy downpours due to the large expanses of impermeable surfaces that result in flooding. The public sewer system is having to deal with larger and larger quantities of water, but rather than continually expanding the network, Amsterdam is designing smarter outdoor urban spaces that can retain and store water (Amsterdam Smart City, 2016). The project supports initiatives such as green roofs, water roofs, rain gardens, trenches, open gutters, permeable surfaces, and green tramways (Amsterdam Rainproof, 2021).

Rotterdam, the Netherlands

The Netherlands have implemented a series of water squares (with a similar purpose as detention basins) in Rotterdam that have recreational uses such as a basketball court and skate park under normal, dry conditions but can flood under wet conditions (De Urbanisten, n.d.). Water can be stored in the squares to relieve pressure on the stormwater system and can then be filtered and released after the rainfall has stopped (De Urbanisten, n.d.). The community was involved in the design of the squares to ensure maximum use and support. The squares also increase engagement and awareness of hazards such as inundation in the community and promote a paradigm shift to living with water.

Copenhagen, Denmark

Copenhagen is situated on the coast of the Øresunds region that connects the North Sea with the Baltic Sea, and is vulnerable to sea level rise, warmer weather and more extreme weather events in the future, including heavy rain events (C40 Cities, 2016). Spurred by a series of highly damaging events, including the July 2011 cloudburst that caused close to €1 billion in damages, Copenhagen needed a better way to manage inundation in the city during these downpours (C40 Cities, 2016). In 2011, the City of Copenhagen adopted the Copenhagen Climate Adaptation Plan, complemented by the Cloudburst Management Plan (2012) which addresses 300 separate projects that are expected to run over the next 20 years across 8 central city catchments (C40 Cities, 2016; Vilhelmsen, 2016; Oppla, 2021).

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5.7 Diversifying energy and water supply

The diversification of energy and water supply refers to using different sources, suppliers and transportation routes for these resources to reduce the dependency on a single source or provider. Diversification means that even if a hazard or accident causes a disruption to one source, there will be others that can supply for the demand, and therefore increase a community's resilience.

Developing renewable energy resources such as wind power or sustainable water supplies such as treated wastewater can also lead to environmental protection in the sense that these sources emit little to no pollutants, limit the extraction of resources, have minimal impact on the environment and allow for innovation, research and development (Ream, 2015).

Diversification constraints vary between countries depending on the quantity of natural resources available, the demand experienced, and geopolitical constraints (Ream, 2015). However, diversification can be encouraged by creating a policy framework that rewards entrepreneurship and innovation while constraining inefficiency and waste, partnering with experts to identify the best mix of sources and working with the international community (Ream, 2015).

Case Studies

Singapore

Hazard resilience has been embedded into the planning process of water networks in Singapore. The Public Utilities Board has three main strategies in regard to water supply; collect every drop, reuse water endlessly, and desalinate more seawater (International Water Association, 2016). These strategies have led the Singapore water supply network to be able to draw on four different sources of water; imported water, wastewater reuse, stormwater, and desalinisation (International Water Association, 2016; Public Utilities Board, 2017). This diversification ensures that water demand can be met even if some sources are running low.

The NEWater initiative which is high-grade reclaimed water is in particular a pillar of Singapore's water sustainability strategy. Used water is treated and purified until it is clean and safe to drink. NEWater is well within World Health Organisation requirements and regularly undergoes rigorous testing and auditing (International Water Association, 2016; Public Utilities Board, 2017).

Canada

As of 2020, Canada leads the world in terms of energy security (World Energy Council, 2020). Energy security reflects a nation's capacity to meet current and future energy demands reliably while also having the ability to recover from shocks with minimal disruption (World Energy Council, 2020). As well as being secure, Canada has a large share of renewables, especially hydroelectricity and nuclear power, and plans to phase out the use of coal by 2030 and has already introduced a federal price on carbon which will continue to increase annually up to CAD 170/tome in 2030 (International Energy Agency, 2021).

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5.8 Emergency management

Temporary flood barrier
(Image source: Fluvial Innovations, 2017).

Emergency sand bagging
(Image source: Coastal Care, 2010).

Emergency management tools such as hazard mapping and warning systems improve community awareness and understanding of hazards which can then minimise the impact of them (Linham & Nicholls, 2012; Geological and Nuclear Sciences, n.d.). Although these tools do not reduce the risk of hazards themselves, the responses that come as a result of this management such as evacuation plans, civil defence emergency management, temporary accommodation and protection measures do increase community resilience and reduce the risk to hazards (Linham & Nicholls, 2010).

Hazard maps identify at-risk areas and can help with the prioritisation of mitigation and adaptation responses, and they can be used by many different stakeholders (Linham & Nicholls, 2010; Linham & Nicholls, 2012). For example, the public can gain awareness and education about hazards in their area, organisations can use them to plan land use zones in flood-prone areas and insurers use them as part of determining insurance premiums (Linham & Nicholls, 2010). Mapping also allows for planning ahead and is linked to coastal management planning and actions such as developing setbacks and buffers, as discussed in section 8.3, and creating evacuation plans. Emergency management procedures that include things like early warning systems and evacuation protocols must accompany hazard maps to highlight the plan to the community and prevent unnecessary fear and panic (Linham & Nicholls, 2010; Geological and Nuclear Sciences, n.d.).

Emergency management also includes the responsive measures that are taken after or during an event. These measures may include temporary works such as bunds that stop water entering an area or trenches that drain surface ponding (Christchurch City Council, 2014). It should be noted that these measures may have negative environmental effects or be poorly engineered and have a shorter life span due to the time constraints during planning and construction. These responsive emergency measures also lead to emergency management being relevant during protection options that are discussed in this section 6 of report, along with the accommodate approach.

Climate change must be carefully considered when mapping hazards and presenting them to stakeholders due to the dynamic nature of hazards associated with it. It is also important to update maps frequently to reflect the changing risks to hazards (Linham & Nicholls, 2010). The uncertainties of climate change, the associated impacts and the available collected data must also be conveyed when maps are presented to stakeholders (Linham & Nicholls, 2010).

Case studies

Christchurch, New Zealand

The Christchurch City Council continuously monitor rainfall and water levels at various sites across the district, and rainfall that occurs between these sites is measured using gauge corrected data in hourly or 24 hour increments. This water level and rainfall data is available to the public online. The Council also subscribes to MetService's MetConnect which provides information such as rainfall forecasts. Astronomical tides have been calculated for the next 20 years and more accurate tidal levels that include storm surge effects are available up to two and a half days in advance. A system has been set up that email and text alerts can be sent out to nominated people when recorded or forecasted rainfall or tides exceed a specified threshold.

There is also a wet weather management plan in place in Christchurch that sets out responses in advance and during regular storm events. Actions include cleaning sumps, grills and grates, clearing outfalls, network inspections and road closures. This can be escalated to an emergency response procedure in more extreme events.

Civil Defence in New Zealand also have consistent emergency management messaging across regions; before a flood, if your home or property lies within an area that may be affected there are steps you can take to help protect yourself, during a flood you should listen to the radio and follow the instructions of emergency services, and after a flood you should ensure that it is safe to return home if you evacuated (Get Ready, 2021).

The Netherlands

Flood protection structures are heavily used in the Netherlands and are built to withstand very extreme conditions. However, in the case of an emergency regional flood emergency response plans set out the steps to be taken through the preparation phase, response phase and recovery phase of a flood event and the National High Water and Flooding Emergency Response Plan sets out the process to be taken at a larger scale (MIKR, 2007).

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6 Protect

Coastal protection measures can be constructed to aid in flood protection, the management of erosion, or both, by altering wave patterns and helping the land to resist energy from wave and tide influences (French, 2001; Fröhle & Kohlhase, 2004). Protection measures can come in the form of hard engineered structures, soft engineering approaches or a combination of the two (Cooper & McKenna, 2008).

Protection measures are generally proposed in developed areas where the protection of existing development is desired (Fröhle & Kohlhase, 2004). The cost of protection structures varies depending on the size and scale of the structure and large and specialised construction equipment is often required. Protection measures also require ongoing monitoring and maintenance to ensure continued effectiveness and make sure no adverse effects become unacceptable, and the increased wave heights and storms caused by climate change must also be taken into account when designing these options (Linham & Nicholls, 2010).

Depending on their intended purpose, hard engineered structures can be placed along the shoreline to form a barrier between the ocean and the land, be placed offshore to dissipate wave energy, or be perpendicular to the shoreline to catch sediment. Soft engineering approaches aim to work with nature and act as buffer zones to reduce wave energy before it reaches the land. A combination of hard and soft engineering is referred to as a hybrid approach and is often recognised to be best at managing and reducing the risk of coastal hazards on human developments while also supporting the environment (Spalding et al., 2014; Sutton-Grier et al., 2015; Morris et al., 2018).

There is a large knowledge base when it comes to hard engineered protection and the level of protection that they can provide (Sutton-Grier et al., 2015). Although protection structures are ready to provide protection as soon as construction is finished, they are fixed, do not adapt with changing conditions such as sea level rise without further construction, and they weaken over time (Linham & Nicholls, 2010; Sutton-Grier et al., 2015). In addition, they can cause coastal habitat loss and have negative impacts on ecosystem services, and they can lead to adverse impacts on the coastal processes of adjacent areas (French, 2001; Fröhle & Kohlhase, 2004; Linham & Nicholls, 2010; Sutton-Grier et al., 2015). This environmental effect may also have negative effects on the recreational value of the area. Hard protection structures are also seen to provide a false sense of security to communities, which may then lead to more development and investment occurring on the previously flooded land which then leads to more losses when the protection measure fails (Ferdous et al., 2020).

Soft engineering approaches provide many environmental co-benefits, grow stronger over time, have the potential to self-recover after an extreme event, can change with and adapt to sea level rise and can be much cheaper to construct when compared to hard engineered solutions (Linham & Nicholls, 2010; Linham & Nicholls, 2012; Sutton-Grier et al., 2015; Narayan et al, 2016). However, some disadvantages are that they provide variable levels of protection that are not extremely well understood, they may take a long time to monitor, maintain and grow to the desired level, and there is limited data on the cost to benefit ratio and when and where to use them (Linham & Nicholls, 2010; Linham & Nicholls, 2012; Sutton-Grier et al., 2015; Narayan et al, 2016; Morris et al., 2018). In the context of New Zealand, the New Zealand Coastal Policy Statement 2010 promotes the use of natural defences to protect land from coastal hazards (Department of Conservation, 2017).

Hybrid approaches result in some of the benefits and disadvantages from both hard and soft engineered protection structures by combining the two. Hybrid solutions allow for environmental co-benefits while also providing a higher level of confidence in the protection that will be supplied due to the inclusion of a harder solution (Sutton-Grier et al., 2015). However, hybrid approaches also result in some adverse environmental and social impacts due to the hard structures they involve, and only provide some of the environmental benefits that natural systems provides (Sutton-Grier et al., 2015). In the places where soft engineering structures alone may not offer sufficient protection but the economic and social costs of hard engineered solutions are unacceptable, hybrid approaches may be considered (Spalding et al., 2014).

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6.1 Shoreline nourishment

Sediment being deposited on the Gold Coast in Australia (Image source: City of Gold Coast, 2021).

Redistribution of sediment (Image source: Environment Agency, 2019).

Shoreline nourishment involves the addition or redistribution of sediment on foreshores, beaches or dunes to help maintain or advance the shoreline position (Linham & Nicholls, 2010). This can help combat erosion by providing a temporary buffer zone, allowing waves to run up and dissipate energy, and addressing the sediment deficit – the cause of erosion – by increasing the volume of sediment available in the system (French, 2001; Linham & Nicholls, 2010).

This process does not prevent or stop erosion, it merely adds sediment to the shoreline which will then normally require a re-nourishment, maintenance and monitoring programme which can become costly (Bird, 1990; UNFCCC, 1999; Linham & Nicholls, 2010). To be effective, shoreline nourishment must use material that is compatible with the native material and contain no significant pollution (Linham & Nicholls, 2010). Armouring, discussed in section 6.7, such as rock revetment or cobble beaches, is placing larger, heavier material on top of the existing coast, rather than shoreline nourishment which places material that is similar to the native sediment.

There are several different sub-categories of shoreline nourishment that determine how and where the sediment is collected from and supplied to. The first is artificial nourishment which involves the importation of sand to a beach or offshore sediment depository that supplies a beach, from a site outside of the beaches coastal compartment (Linham & Nicholls, 2010). Another is beach replenishment which uses local sand as the supply sediment, and another is beach scraping (also referred to as beach skimming, beach recycling and re-profiling), which mechanically redistributes sediment on a beach without change to the total volume (Wells & McNinch, 1991).

Shoreline nourishment is a flexible option that is unlikely to prevent or inhibit the pursuit of other options in the future (Linham & Nicholls, 2010). It is also likely to benefit adjacent areas which are not directly nourished through natural coastal processes such as longshore drift that redistributes material (Linham & Nicholls, 2010). Benefits can also be seen on hard structures such as seawalls behind a wide, nourished beach as some wave energy is absorbed before hitting the structure (Bird, 1990).

Shoreline nourishment is usually carried out on dissipative, sandy beaches (beaches of lower gradient that dissipate wave energy rather than reflect it back offshore), but can also be undertaken on mixed sand and gravel or cobble beaches (Linham & Nicholls, 2010). It is also often combined with other adaptation options including dune reconstruction or regeneration, groynes, breakwaters or artificial reefs, all of which are also discussed in section 6 of this report (Linham & Nicholls, 2010).

Case studies

Amberley, New Zealand

Amberley Beach has a small settlement located behind a low mixes sand and gravel beach at the northern end of Pegasus Bay in Canterbury. As the beach changed from accretionary to erosional due to a lack of sediment supply, shoreline nourishment has been carried out (Todd, 2003; MacDonald & Sheppard, 2020). What started as a community-led scheme along 250m of coastline in 2002, resulted in continued nourishment of a 1km stretch after more flooding and erosion occurred (Todd, 2003; MacDonald & Sheppard, 2020). This extended nourishment has been effective in preventing coastal inundation into the settlement but erosion as a result of significant storm events has led to the beach being topped up in 2009, 2015 and 2018 (MacDonald & Sheppard, 2020).

Wellington, New Zealand

In 2003, beach nourishment was carried out in Oriental Bay, Wellington to combat erosion and build a sandy beach in front of a seawall (Chapman, 2015). Sediment was replenished in 2015 after a loss of about 120 cubic meters of sand was seen each year (Chapman, 2015). Sand for the beach was originally sourced from Nelson and more recently from a quarry in Dunedin (Chapman, 2015). It is understood that future re-nourishments will need to occur to keep the beach in the area.

Ōrewa, New Zealand

Annual sand replenishment occurs at Ōrewa Beach, north of Auckland (Auckland Council, 2018). Sand replenishment is usually carried out prior to the busy summer season, unless there are severe erosion events at other times during the year (Auckland Council, 2018). Replenishment involves collecting sand that has accumulated at the groyne at the south end of the beach and transporting it north (Auckland Council, 2018).

Mandurah, Australia

After a risk assessment revealed that the beaches in this area were vulnerable to the effects of sea level rise, the local council implemented beach nourishment activities to preserve beaches and maintain their recreational amenity (Bird, 1990; Mathew et al., 2016). The effectiveness of the project is being monitored to ensure that the council's environmental, economic and social objectives are met (Mathew et al., 2016). Additional measures such as sea walls or groynes are being considered for the future (Mathew et al., 2016).

The Netherlands

A 'mega-nourishment' project with a long-term design life of 20 years, known as the Sand Motor has been implemented along the North Sea coastline of the Netherlands to act as a buffer against sea level rise and mitigate the impacts of coastal inundation and storm surges (Climate Adapt, 2019). The intervention involved the offshore collection of a large amount of sand, and the deposition of it to form a hook-shaped peninsula (Climate Adapt, 2019). The project relies on natural wind and current processes to redistribute the sand along the coast (Climate Adapt, 2019).

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6.2 Dune reconstruction and regeneration

Vegetation planting to promote dune growth.

Established dunes.

Dunes provide a dynamic store of sediment landward of the high tide line that changes in response to wind, waves or sea level (Linham & Nicholls, 2010). This store of sediment acts as both a barrier to water and it is able to supply sediment to the beach during times of erosion and store it again after (French, 2001; Linham & Nicholls, 2010; USACE, 2013). These functions result in dunes offering protection against both inundation and erosion risks (Linham & Nicholls, 2010; USACE, 2013).

Dunes may be degraded by human activities such as urban development and the removal of vegetation. When this is coupled with extreme storm events, a series of storms or sea level rise, dunes do not have the chance to recover as they naturally would (Sigren et al., 2014). It may be decided to regenerate the dunes through restoration and rehabilitation so that they may provide protection again (Linham & Nicholls, 2010). Dune regeneration can take many forms including building fences on the seaward side of an existing dune to trap sand and promote dune growth, and vegetation planting to stabilise dunes (Linham & Nicholls, 2010). The presence and type of vegetation on dunes can have a large influence on the shape of the dunes and the protection provided. It has been found that densely covered dunes are more fixed and lack the mobile habitat needed by some species (Arens et al., 2013; Delgado-Fernandez et al., 2019; Bird et al., 2020). When sand movement is too restricted through the use of the wrong types of plants, coastal dune systems may no longer be functional (Bird et al., 2020).

Artificial dunes can also be engineered to mimic natural dunes (Linham & Nicholls, 2010). Dune construction is usually carried out at the same time as shoreline nourishment (see section 6.1) as suitable sediment is placed on a beach and then is reshaped into dunes (Linham & Nicholls, 2010).

Dunes are a relatively inexpensive, flexible protection option that can support other adaptation options in the future. They have the ability to restore natural character to an area, provide habitats for animals and plants, and may even encourage sustainable coastal developments in the future (Linham & Nicholls, 2010).

Despite being a natural feature, dunes can act as a barrier to beach access and coastal views that people living at the coast are accustomed to (UNFCCC, 1999; Linham & Nicholls, 2010). Dunes also have a large footprint and therefore require a large amount of land that may currently be used for other purposes (UNFCCC, 1999; Linham & Nicholls, 2010). Depending on the size and extent of the dunes, the severity and frequency of storms, and the amount of sea level rise, dunes require frequent monitoring and maintenance along with the possibility of requiring re-nourishment.

Case studies

Dunedin, New Zealand

The Dunedin City Council manages dunes in several different ways. Dune notching has been carried out which digs gaps in the dunes to encourage sand to be moved further inland by the wind and thus growing the dune system, and dune planting has been carried out to help create, re-establish or stabilise dunes through the trapping of sand (Dunedin City Council, 2020).

Bay of Plenty, New Zealand

The Coast Care Bay of Plenty Dune Restoration programme is a community partnership programme between the regional and district councils and the Department of Conservation. The programme aims at reducing the risk of erosion through dune restoration to provide a buffer zone for when storms occur (Ministry for the Environment, n.d.).

New South Wales, Australia

To help combat the long history of beach erosion, the Bryon Shire Council has artificially increased dune volume to reduce the risk of coastal hazards to coastal assets (Dowsett, 2017). The method of scraping is being used which does not provide a long-term solution, only reduces the risk posed by coastal hazards in the short to medium term (Dowsett, 2017). Scraping has been carried out in 2010, 2013 and there are plans for future projects (Dowsett, 2017).

The Netherlands

After two sea dikes no longer met safety standards, it was reinforced in 2015 with a soft, natural sand barrier on either side of it and was renamed to be the Hondsbossche dunes (EcoShape, 2016). The dunes now provide the primary measure of coastal protection in the area (EcoShape, 2016).

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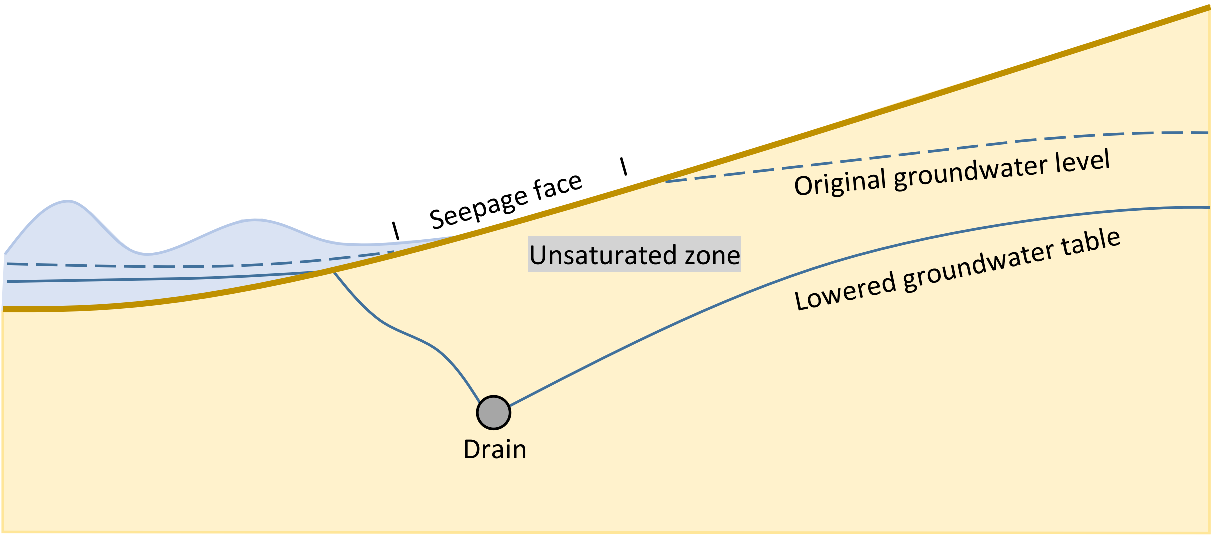
6.3 Beach drainage



Mild upper beach and dune erosion can be controlled by beach drains. Beach drainage (also referred to as coastal drainage or beach dewatering) involves the placement of drains parallel to the shoreline, under the exposed beach face, which are connected to a well so that water which enters the system can be pumped out (Turner & Leatherman, 1997; Saponieri, 2019). Beach drainage lowers the water table and therefore increases the depth of the unsaturated zone under the ground. This lowering of the ground water table also encourages sediments to be deposited on the beach and reduces the sea-ward transport of sediment and therefore accretes sediment at the shore (Turner & Leatherman, 1997; Saponieri, 2019).

Beach drainage has been seen to work best on micro-tidal beaches (with less than 2m of tidal range) where landscape values prevent the use of other options (Risc-Kit, n.d.). This option is considered to have a relatively low impact on the environment, and it can provide long-term coastal protection with little effect on the visual amenity of the area (Turner & Leatherman, 1997; Saponieri, 2019). It is also relatively low-cost to implement but has high maintenance and management costs and although the drains should increase upper beach volume under low to moderate wave conditions, they will not be significantly effective during storms and may result in the beach being drawn down to the point where the pipes become exposed (Risc-Kit, n.d.). Beach drainage can also be used to increase the design life of other options such as shoreline nourishment which is discussed in section 6.1.

Case studies

Quend-Plage, France

The Quend-Plage beach in northern France was facing increased beach and dune erosion until a beach drainage system was installed by the community in 2008. As a result of this system, the beach has stabilised and resulted in the preservation of natural habitats and the ability to continue use of recreational spaces in the area (Bain et al., 2016). In this case, it was considered to be a feasible and effective solution providing a significantly different beach morphology after five years which lead to the overall increase of stability and usage of the area (Bain et al., 2016).

Procida Island, Italy

Chiaiolella Beach on the island of Procida in Italy is a 1.5km long beach that had a beach drainage system installed in April of 2002 (Vicinanza et al., 2010). The system was installed to provide a wider beach to users and prevent the cliff behind the beach from undercutting during storms (Vicinanza et al., 2010). No evident positive effects were seen from the beach drainage system for mild wave energy conditions and the system was not able to compensate sediment losses from high wave energy condition during a storm in December 2002 (Vicinanza et al., 2010). The system has not been operative since 2004 and the study highlights the inadequacy of beach drainage systems under high energy conditions (Vicinanza et al., 2010).

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6.4 Coastal wetlands, riparian management and living shorelines

Wetlands such as the Brooklands wetland in Christchurch, New Zealand can provide flood and erosion protection, environmental benefits and recreational amenity.

Riparian planting in Christchurch, New Zealand.

Coastal wetlands and riparian corridors are vegetated areas that act as a buffer to inundation and erosion, while also providing new habitats and environmental benefits (Linham & Nicholls, 2010). Vegetation protects the shoreline by increasing the roughness of the surface which causes waves to dissipate energy (Climate Adapt, 2015). In addition to this, vegetated areas act as a sediment trap which causes accretion, while the vegetation roots stabilise sediments and minimise erosion (Linham & Nicholls, 2010).

The most common vegetated coastal areas are saltmarshes and mangroves, while seagrasses and coastal forests also offer protection (Linham & Nicholls, 2010). These natural areas are capable of adapting to sea level rise autonomously, they can relieve pressure on hard structures built on the landward side of them, and they provide ecosystem services such as accumulating contaminants and nutrients, filtering water, providing habitats and providing vital nutrients to the food web through the deterioration of organic debris (Nicholls & Klein, 2005; WSGP, 2005; Linham & Nicholls, 2010; Climate Adapt, 2015; Narayan et al., 2016; NOAA, 2020).

Coastal wetlands are some of the most productive ecosystems on earth. In the United States, coastal wetlands generate more than half of the commercially harvested seafood (NOAA, 2020). This boosts employment rates and the economy. Wetlands are also a great source of timbre, fuel and fibre (Linham & Nicholls, 2010; NOAA, 2020). It was also found that more than one third of adults in the United States hunt, fish, birdwatch or photograph wildlife in natural wetlands which makes them a great recreational and tourism resource (NOAA, 2020). New wetlands can be established in open areas or when combined with other options such as managed retreat, and they are low maintenance once they are established (Linham & Nicholls, 2010).

Many natural wetlands and riparian plantings have become degraded due to natural processes and human activities and require rehabilitation to improve their overall function (Linham & Nicholls, 2010). These systems should be carefully enhanced or designed by taking into account the relationship between the habitat and hydrodynamic variables, to maximise the efficiency of wave reduction (Narayan et al., 2016). The careful selection of plant species is also important when designing areas to modify the light, temperature, nutrient and sediment regimes, channel and bank stability, carbon inputs, or habitat for species (Collier et al., 1995).

Similarly to coastal wetlands and riparian plantings, living shorelines use natural materials such as rocks, plants and oyster beds to connect the land and water and aid with erosion control in coastal environments. The materials and species used are dependent on factors such as the climate, wave energy and tidal range of an area. Living shorelines are suited to lower energy environments such as estuaries, inner bays and tributaries, while they are not commonly used on the open coast (NOAA, n.d.b).

Case studies

Christchurch, New Zealand

Jellicoe Saltmarsh in South New Brighton, Christchurch provides a vegetated buffer between the Ihutai / Avon – Heathcote Estuary and the engineered bund protecting Estuary Road. The vegetation, along with the breakwater, dampens wave action.

Hunter Valley, Australia

A wetland restoration project has been undertaken to restore 650 hectares of wetlands that were undergoing 'coastal squeeze' due to land use conversion and sea level rise (Rogers, 2016). Restoration, wetland rehabilitation and realignment of management boundaries was undertaken (Rogers, 2016). Ecosystem services have been improved and there are plans are in place to extend the wetlands through land acquisition (Rogers, 2016).

Florida, United States

GreenShores is a multimillion dollar habitat creation and restoration project along the urban shoreline of Pensacola Bay in Florida (DEP, 2019). The project aims to restore oyster reef, saltmarsh and seagrass habitats in the bay to aid in shoreline stabilisation and provide wildlife habitats (DEP, 2019). First, seven acres of oyster reef and eight acres of saltmarsh and seagrass habitat were constructed using sediment nourishment and plantings (DEP, 2019). After this, two offshore breakwaters were placed at a second site to lower wave energy before it reaches three intertidal marsh islands that were constructed using spoil material from previous dredging materials (DEP, 2019). The intertidal islands have been planted and there are plans for further breakwaters and saltmarsh areas (DEP, 2019).

United States

The Coastal Wetlands Initiative aims to address the significant loss of coastal wetlands that is occurring across the United States (EPA, 2020). The initiative has the goals of better understanding the underlying causes of wetland loss and the contributing stressors, it aims to recommend new or revised policies and programs that protect and restore coastal wetlands, identify and disseminate tools, strategies, policies and information to protect and restore coastal wetlands and create public understanding of the functions and values of the wetlands and the threats to them (EPA, 2020). The initiative is carrying out reviews and studies while also implementing living shorelines that promote the conservation and restoration of coastal wetlands (EPA, 2020).

North Carolina, United States

The National Oceanic and Atmospheric Administration has created a living shoreline on Pivers Island in Beaufort, North Carolina (NOAA, n.d.a). This area is prone to being hit by hurricanes and has experienced significant erosion since the late 1990’s (NOAA, n.d.a). An example of this was Hurricane Florence that brought 0.5-1.5 meter waves under 120 km/hour winds for over 72 hours in 2018 (NOAA, n.d.a). The Beaufort living shoreline marsh and oyster reef remained intact with only minimal erosion in non-vegetated areas on the landward side of the living shoreline (NOAA, n.d.a). It has been seen that the created shoreline provides valuable fishery and bird habitats, increases the water quality through the trapping of sediment, and the sequestration of carbon (NOAA, n.d.a).

Washington, United States

A review of literature to understand the riparian functions in Puget Sound found that both freshwater and marine riparian plantings serve almost identical purposes with marine riparian plantings offering additional services that support marine biota and protect the nearshore ecosystem (Brennan & Culverwell, 2004).

United Kingdom

There are several examples of coastal realignment schemes undertaken to create a new intertidal inundation zones in the UK. The intention of the projects is to provide space for coastal ecosystems to develop and act as defences from inundation and erosion while also increasing the capacity for the system to respond to future sea level rise (NCCARF, 2017).

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6.5 Groynes and attached breakwaters

Concrete and rock groyne
(Image source: Town of Cambridge, 2020).

Concrete attached breakwater
(Image source: The Coastal Path, 2013).

A groyne (or artificial headland) is a structure built perpendicular to the shoreline out into the sea to catch sediments that are transported along the coast by longshore drift, to reduce coastal erosion (University of Aberdeen, 2010; Climate Adapt, 2015). They are typically built out of rock but can be constructed using a range of materials, such as timber, gabion baskets, sand-filled geotextile tubes, steel or concrete elements (Climate Adapt, 2015).

By trapping sediment, groynes can result in beach widening and therefore greater wave energy dissipation and reduced erosion (Climate Adapt, 2015). However, structures that impact the longshore drift of a coastal system can have a negative impact on the transportation and sedimentation patterns of down-drift areas, causing erosion in these areas (Climate Adapt, 2015).

Groynes can complement other protection measures such as beach nourishment, dune construction and seawalls through the reduction of wave energy (University of Aberdeen, 2010). Groynes can also be constructed in a 'groyne field' which consists of a series of groynes that act together to protect a large stretch of coastline (Climate Adapt, 2015).

Usually constructed of loose rock or piled concrete blocks, breakwaters also project into the sea and are designed to shelter areas from waves and currents (Climate Adapt, 2015). This sheltering action provides the additional benefit of creating an area where sedimentation can occur and ecosystems such as saltmarsh can establish, providing further coastal protection (Sutton-Grier et al., 2015).

Case studies

Christchurch, New Zealand

A breakwater in Sumner, Christchurch was built in 1884 and currently protects the Sumner Lifeboat Institution, the Sumner Boating and Fishing club and the public boat ramps (Christchurch City Council, 2016). Rock armouring has moved over time through wave action and the 2010/2011 Canterbury Earthquake Sequence which weakened the structure (Christchurch City Council, 2016). In 2017 the breakwater was repaired and reconstructed (Ineson, 2017).

Omaha, New Zealand

After a large storm in 1978 eroded part of the dunes protecting a subdivision, three groynes were built at the northern end of Omaha Beach (Schofield, 1985). Additionally, 450,000m^3 of shelly sand and shingle were added to the beach south of the groynes (Schofield, 1985). By 1980, this artificial nourishment had been redistributed by the sea and had extended the beach width by 50 - 70 meters in front of the subdivision and 20 meters at the southern end of the beach (Schofield, 1985). A natural storm berm approximately 30 meters wide also formed along the beach as a result of the groynes and nourishment (Schofield, 1985). In 2020, a tender to carry out physical works of rock placement and re-building the groynes was awarded (Auckland Council, 2020).

New Plymouth New Zealand

In Waiwhakaiho, a groyne was constructed of timber in 1973, with 50 meters of the structure covered in boulders in 1977, and a further 50 m covered in 1978, with rock rip rap recently extended upstream (Taranaki Regional Council, 2019). The groyne has a dual purpose in maintaining the mouth of the Waiwhakaiho River and stabilising the adjacent beach (Taranaki Regional Council, 2019). The presence of the groyne has resulted in sand accumulating on the southern side of it, on Fitzroy Beach (Taranaki Regional Council, 2019).

Sunshine Coast, Australia

As part of the council’s 10-year shoreline management erosion plan, the Maroochy groyne field that is currently being renewed, was conducted in 2003 to help protect a holiday park and other nearby assets from coastal erosion (Sunshine Coast Council, 2020).

Aberdeen Beach, Scotland

Along the 600 meter length of Aberdeen Beach, 30 timber groynes and blockwork revetments were established in 2006 to protect the beach in front of a seawall from coastal erosion (University of Aberdeen, 2010). Beach nourishment was also undertaken in 2006 (University of Aberdeen, 2010).

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6.6 Detached breakwaters and artificial reefs

Detached breakwaters
(Image source: Caribbean Geotextiles, 2014).

Textured concrete balls forming an artificial reef
(Image source: The Economist, 2014).

Detached breakwaters are usually constructed of rock and rubble and are placed parallel to the shoreline with a height slightly above the water level (Climate Adapt, 2015). The purpose of detached breakwaters are to reduce the wave energy that is reaching the shore through the dissipation, reflection and diffraction of oncoming waves (UNFCCC, 1999; Nordstrom, 2013). This creates a low-energy environment close to the shore that encourages the deposition of sediment, and therefore the build-up of a wider beach (Nordstrom, 2013). The characteristics of the beaches and currents on the landward side of the breakwaters is determined by the location, size and spacing of structures (Nordstrom, 2013).

Similarly to detached breakwaters, artificial reefs are also placed parallel to the shoreline with the goal of reducing wave energy at the shore. However, they have a crest height at or below sea level and can be continuous or segmented (Climate Adapt, 2015). The decrease in water height above these structures causes waves to break, and disperse their energy. Artificial reefs can be less expensive, less intrusive and less likely to suffer damage when compared to regular breakwaters as they are exposed to less of a direct impact (Nordstrom, 2013).

Materials used for artificial reefs can vary from loose rocks to sand-filled geotextile tubes, to textured concrete balls. Impacts seen from the construction of artificial reefs vary depending on the material used, the size of individual components, the scope and scale of the project as a whole, and the methods of implementation. There is limited data on artificial reefs in regard to what the optimum crest height and distance offshore are. These factors are important as they can minimise undesired currents that may strip sediment or provide dangerous conditions for recreational users (Nordstrom, 2013). Careful analysis of beach slope, wave patterns, storm climate and sediment transport conditions is required to determine the size and scale of structures as in some instances erosion is thought to be made worse by the construction of breakwaters or artificial reefs.

Barrier reefs and chenier plains are natural features that act in a similar way to a detached breakwaters. A barrier reef is a coral reef that runs parallel to the shore but is separated from it by a channel of deep water while chenier plains are shell barrier beaches comprising of shell fragments and coarse sand that is moved by longshore currents. Chenier plains are globally rare, but the largest in New Zealand, at Miranda, is the only one that is still aggrading across the globe (Land Care Research, n.d.). Both these types of natural features act in a similar way to detached breakwaters and artificial reefs in that they dissipate oncoming wave energy before it reaches the shore.

Case studies

Gold Coast, Australia

Narrowneck reef is an artificial reef that was constructed in 1999 with the aim of providing a storm buffer, reducing the flood risk posed by the Nerang River and providing additional recreational amenity (Corbett et al., 2005). It also involved a major beach re-nourishment program. The reef cost approximately $2.1 million AUD (Raised Water Research, n.d.). Monitoring shows that the reef has been effective in providing resilience to the Narrowneck beach against the impacts of storm surges, and it has been successful in supporting a diverse marine ecosystem (Corbett et al., 2005; City of Gold Coast, 2017).

Liseleje, Denmark

Historically, small detached breakwaters were built in shallow water to provide sheltered conditions. Due to poor design and a lack of maintenance, these structures have deteriorated (Eurosion, 2001). Six new detached breakwaters were designed with lengths between 40 to 60 meters, and two old, small detached breakwaters were strengthened to retain the beach in this area (Eurosion, 2001). The minimisation of aesthetic impacts was also considered when designing the new breakwaters (Eurosion, 2001). Beach nourishment and slope protection measures were also implemented in conjunction with the detached breakwaters (Eurosion, 2001).

Dominican Republic

In the summer of 1998, textured concrete balls were distributed along the southern Caribbean shore of the Dominican Republic to encourage the accretion of beaches that are utilised for the tourist industry (Harris, 2009). Approximately 450 reef balls were installed in three lines to form an artificial reef that acts like a submerged breakwater (Harris, 2009). The balls were placed so that they were 0.3-0.8 meters below the mean water level (Harris, 2009). The textured nature of these artificial reef balls encouraged the growth of algae, seagrasses and the general inhabitation of the area by marine organisms (Harris, 2009). Shortly after the installation of the reef balls in 1998, the system was directly hit by Hurricane Mitch. Not a single reef ball was displaced or damaged during the storm and beach profiles show that the artificial reef system was very effective in stabilising the beach, with a significant increase in beach width and elevation along the project shoreline (Harris, 2009). The individual reef balls are also relatively small which means that they have a small footprint on the seabed. The reef balls can also be easily distributed by floating them to the desired position which is relatively unobtrusive. Other reef ball submerged breakwaters have been constructed in the Caribbean Sea with success.

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6.7 Armouring

Rock revetment in Christchurch, New Zealand.

Concrete step revetment in Christchurch, New Zealand.

Seawall made of gabion baskets in Christchurch, New Zealand

Concrete seawall in Akaroa, New Zealand with rocks in front of it.

The edge between water and land can be armoured with hard protection structures. These structures prevent erosion by protecting the land from light to moderate wave action (UNFCCC, 1999; French, 2001; Linham & Nicholls, 2010). They are built parallel to the shoreline and can take many forms, such as rock revetments, concrete walls, sand-filled geotextile tubes or gabion baskets and can be on the shoreline or set back, vertical or sloped and exposed or buried (Linham & Nicholls, 2010). Impermeable structures can also provide flood protection up to a design height (French, 2001; Linham & Nicholls, 2010).

The design of the seaward face of such structures is important in the deflection of oncoming waves. For example, smooth, vertical seawalls cause the reflection of wave energy back offshore and can create turbulence which is capable of suspending sediment in the water column and therefore causing erosion, while irregular surfaces, such as those of rock revetments, will scatter the direction of wave reflection (French, 2001; Linham & Nicholls, 2010).

Armouring structures are typically engineered, inflexible structures that are expensive to design and construct (UNFCCC, 1999). However, they require less space than some other coastal protection structures, especially if they are designed to be vertical (Linham & Nicholls, 2010). The height of structures may also be increased over time to respond to sea level rise, with special design thought given to the new ‘construction joint’ that may compromise the integrity of the structure (Linham & Nicholls, 2010).

A potential issue of hard armouring at the coastline is overtopping which occurs when water exceeds the height of the structure (Linham & Nicholls, 2010). Excessive overtopping can saturate, weaken and strip away sediment behind the structure and can lead to an increase in pressure that can result in structure collapse (Linham & Nicholls, 2010). Overtopping or water seepage through the structure may also lead to water collecting behind the structure which needs to be managed using options such as one-way drainage culverts or pumps.

Hard protection structures interrupt natural processes such as habitat migration, causing ‘coastal squeeze’, where inter-tidal areas are squeezed between hard structures and rising water levels (Linham & Nicholls, 2010). The hard characteristic of armoured structures can also cause issues in estuaries as it can reduce the area that is available for the occupation of water (Linham & Nicholls, 2010). With the same volume of water flowing into the estuary, but having less area to spread to, it may lead to areas being submerged to a greater depth, for a longer period of time which in turn can affect the type of habitat in the area and increase the tidal range upstream of the estuary (French, 2001; Linham & Nicholls, 2010). Where only sections of an estuary edge are protected by hard structures, water may also be displaced to unprotected areas.

Sediment availability along the coastline can also be affected by the implementation of armouring. Hard barriers halt the natural erosion process that would usually supply sediment to the beach during times of a deficit and the area in front of the structure can continue to erode which can have flow-on effects on areas alongshore that are receiving no sediment via longshore drift (French, 2001; Linham & Nicholls, 2010). The area where the structure ends is also a known problem area as the unprotected adjacent areas are free to interact with natural processes and could move inland causing a stepped appearance to the coast and cause undermining and instability of the wall in extreme cases (French, 2001; Linham & Nicholls, 2010). The use of hard structures in conjunction with beach nourishment or managed retreat can minimise effects such as coastal squeeze, beach erosion and the erosion of adjacent areas (Bird, 1990; Linham & Nicholls, 2010). Hard protection structures may also hinder access to the beach, be aesthetically displeasing and decrease property value which needs to be considered during decision making and design processes (Linham & Nicholls, 2010).

For the purpose of this catalogue of options, cobble nourishment on beaches where cobble is not the native sediment, is also classed as a type of shoreline armouring and is included in this section.

Case studies

Christchurch, New Zealand

Inundation and erosion issues in Southshore and South New Brighton after the 2010/2011 Canterbury Earthquake Sequence have been addressed. To protect from erosion on the estuary edge, a cobble beach with existing reno mattress (a rock layer held in place with mesh) is being implemented (Christchurch City Council, 2020). This approach achieves pre-earthquake erosion management levels, allows for the establishment of saltmarsh and was supported by the community (Christchurch City Council, 2020). The estimated cost is $1.2 million (Christchurch City Council, 2020).

Christchurch, New Zealand

Following the Canterbury Earthquake Sequence, significant repairs to the causeway in front of McCormacks Bay and along Main Road were required. The rocks placed on either side of this causeway result it in acting like a revetment to protect the road and shared pathway between McCormacks Bay and the Ihutai / Avon - Heathcote Estuary. The 720 meter long, 4 meter wide shared pathway section is a part of the wider, community-driven Coastal Pathway Scheme which plans to extend from Ferrymead to Sumner and has the goals of supporting safer commuting and encouraging seaside leisure (Fulton Hogan, 2019). This part of the coastline was previously classed as sheltered and protected by a rock revetment while another part was classed as an unprotected, unconsolidated shoreline (Tonkin & Taylor, 2017).

Christchurch, New Zealand

The 1.2km Sumner seawall that is exposed to the Pacific Ocean was constructed in 1932, and a rock armour revetment was constructed in front of this in the 1940’s to 1950’s (Jacobs, 2019). The level of the beach is variable and issues with stormwater outfalls are common. The sea wall has been modified and repaired a number of times.

Thames, New Zealand

The suburb of Moanataiari in Thames was flooded due to coastal inundation and stormwater drainage problems in 1995 and 1997, with damage to over 30 properties (Ministry for the Environment, 2001). The suburb was built on reclaimed land that is slowly sinking below sea level (Ministry for the Environment, 2001). In 1999, engineers were engaged to rectify the problems from coastal inundation and rainfall ponding to a 1 in 50-year design for independent events (Ministry for the Environment, 2001). The old seawall was reconstructed, made impermeable, raised, and a timber parapet added for further run-up protection (Ministry for the Environment, 2001). A pump system was installed to pump rainfall or seawater from the subdivision, the back-beach 'dune' was built up and swale drainage was constructed to channel stormwater around the subdivision (Ministry for the Environment, 2001). Construction work alone cost $1.08 million (Ministry for the Environment, 2001).

Australia

The 'Living Seawall' project investigates how 3D printed geometry can be used to create habitat for native intertidal species that live on seawalls (SIMS, n.d.). Research is being conducted to investigate which designs encourage native species colonisation and foster biodiversity (SIMS, n.d.). The research and implementation of such ideas can also help to combat some of the adverse environmental effects caused by smooth seawalls.

California, United States

Erosion is a natural process along about 86% of California's coastline (Griggs & Fulmn-Benne, 1988). When this is combined with an increasing population that desires ocean views and beach access, developments are made in high risk areas (Griggs & Fulmn-Benne, 1988). Ocean Beach in San Fransisco is home to the O'Shaughnessy Seawall, a curved concrete wall initiated in 1915 that protects the highway and Golden Gate Park by deflecting wave energy back offshore (Cabanatuan, 2015). It is approximately 1.6km long and has concrete stairs at its base to diffuse wave energy like a revetment (Mclaughlin, 2012). The careful design of the shape, solid mass, deep foundations, material selection and regular maintenance have contributed to its longevity.

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6.8 Stopbanks and bunds

Vegetated stopbank protecting a road from flooding in Ngātea, New Zealand (Image source: Waikato Regional Council, 2019).

Jellicoe marsh bund in Christchurch, New Zealand.

A stopbank (also referred to as a dyke or levee), is a continuous elongated structure designed to protect low-lying areas from inundation (Linham & Nicholls, 2010; Christchurch City Council, n.d.). They are usually earthen, covered with vegetation and in the context of coastal hazards are parallel to the shore of low-lying coastlines. The crest height of coastal stopbanks is designed to be sufficient to prevent or minimise overtopping in a specific flood event, and they normally have different seaward and landward slopes. On the sea side they have a gentler slope to reduce wave loadings while on the land side they have a steeper slope to minimise space requirements (Linham & Nicholls, 2010; Christchurch City Council, n.d.).

When compared to vertical structures, stopbanks have reduced wave loadings and a reduced risk of toe scour due to the angle of the slope on the seaward side that directs down-rush away from the base of the structure (Linham & Nicholls, 2010). This slope does however, result in a large footprint that requires significant areas of land. This footprint may also grow if the height of the dike is increased while the same slopes are maintained (Linham & Nicholls, 2010). In addition to a large footprint, this type of barrier also impacts inland habitat migration, the size of the intertidal area and access to the coast (Linham & Nicholls, 2010).

Even when the stopbank crest height is designed by considering tidal fluctuations, storm surges and wave run up, there is potential for water to seep through the structure and for ground or stormwater to collect behind the barrier (MWLAP, 2003). Water needs to be managed on the 'dry' or landward side of the stopbank, which can be done by implementing one-way drainage culverts or pumps (MWLAP, 2003). The operation of pumps can be minimised through the use of storage facilities such as drainage canals and storage basins on the landward side of the structure (MWLAP, 2003).

Bunds are similar physical structures when compared to stopbanks and serve a similar purpose to reduce flood risk (Christchurch City Council, n.d.). Bunds can be built quickly, they generally use local materials and only involve minor foundation preparations (Christchurch City Council, n.d.). Generally, a bund is less-engineered than a stopbank and has a shorter designed life span (Christchurch City Council, n.d.). The term bund can also be used when referring to structures that have the purpose of trapping a liquid, such as floodwater, to reduce ponding in other areas (Waikato Regional Council, 2014).

Case studies

Christchurch, New Zealand

A $12.5 million package of works to address the flooding and erosion risks in Southshore and South New Brighton was approved by the Christchurch City Council in late 2020 (Christchurch City Council, 2020). This work will include the construction of a new bund to 11.4m RL near an existing bund and another to the same level set back 25-100 meters from the estuary edge within the South New Brighton Park to reduce flood risk, alongside other measures (Christchurch City Council, 2020).

Christchurch, New Zealand

Stopbanks along the Ōtākaro Avon River were first constructed in the early 20th century and have been progressively raised and extended after being overtopped during storm events multiple times (Christchurch City Council, 2014). The 2010/2011 Canterbury Earthquake Sequence caused significant slumping along the banks of the Ōtākaro Avon River due to liquefaction and lateral spreading of land leading to reconstruction work being carried out (Christchurch City Council, 2014).

Christchurch, New Zealand

Primary and secondary stopbanks are in place to protect the Christchurch area from flood waters out of the Waimakariri River. These structures allow for the river to flood, without causing severe damage to the city. Before the primary stopbanks were installed in the 1930's, large flood events caused overtopping of the river and areas such as Kaiapoi and Christchurch flooded. Since the implementation of stopbanks, the Waimakariri has not flooded the city (Environment Canterbury, 2019).

The Netherlands

The Holland Dyke Ring protects the major cities of Amsterdam, Rotterdam, and Den Haag (Jonkman et al., 2008). The dyke ring consists of a range of different protections, including sand dunes along the coast and stopbanks along the rivers (Jonkman et al., 2008). Barriers have also been constructed to prevent storm surges from the North Sea inundating low lying land via the river system (Jorissen et al., 2016).

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6.9 Storm surge barriers

The wings of this movable barrier swing across the river as necessary in the Netherlands
(Image source: Dutch Water Sector, 2018).

Permanent barrier in the Netherlands with gates that open and close
(Image source: Dutch Water Sector, 2015).

Storm surge barriers are hard engineered structures that are primarily designed to prevent inundation due to storm surges in tidal inlets, rivers and estuaries, while also decreasing reliance on other flood defences inland of the barrier (UNFCCC, 1999; Hillen et al., 2010; Linham & Nicholls, 2010). The physical barrier prevents storm surges from travelling inland and therefore keeps upstream water levels low to prevent inundation (Linham & Nicholls, 2010). Movable barriers or gates can close across a water body when an extreme water level is forecasted.

Fixed barriers permanently span across a water body to prevent storm surges travelling towards land, and also manage tidal fluctuations or gradual increases in water level over time, while regular discharge is pumped over the barrier (Linham & Nicholls, 2010). Storm surge barriers may also be fixed but have gates or bulkheads installed that allow water to pass through under normal conditions and then have the ability to close and block an incoming storm surge (Climate Adapt, 2015).

Storm surge barriers can easily be integrated into a larger flood prevention system and used in conjunction with options such as stopbanks and emergency management plans (Linham & Nicholls, 2010; Climate Adapt, 2015). Movable barriers that are open under normal conditions allow the continued use of the environment for transport, recreational use and a migration passage for organisms (Linham & Nicholls, 2010).

Significant investment is required for the construction and maintenance of these structures. In addition to these costs, when designing and using a movable barrier, investments in flood warning systems must be made to ensure the barrier is closed at appropriate times (Linham & Nicholls, 2010; Climate Adapt, 2015). Inundation that may occur on the landward side of the barrier when river levels are high or when movable barriers are closed for an extended period of time must also be accounted for, and a study on the maximum time that a movable barrier can be closed for should be conducted to mitigate the risk (Linham & Nicholls, 2010). Changes in water salinity, temperature, suspended matter and nutrients in the water also need to be assessed as they can have impacts on organisms in the area (Linham & Nicholls, 2010). Highly effective meteorological forecasting systems are needed to ensure that there is enough time to close barriers while another issue of these barriers is the risk of failure, both due to mechanical issues and in the future under climate change (Climate Adapt, 2015).

Case studies

Christchurch, New Zealand

The Woolston cut was dug in the Ōpāwaho Heathcote River in the 1980s to allow floods to bypass a long, narrow, curved length of the river and to reduce upstream water levels. However, the cut allowed saline water to reach further upstream causing a loss of mature trees and erosion of the river banks (Orchard & Measures, 2016). In response, the Woolston Tidal Barrage was built to route water along the old narrow length of the barrier and prevent saltwater intrusion (Orchard & Measures, 2016). Now, the barrage is only opened during flood conditions to allow water to flow to the coast easily (Orchard & Measures, 2016). In 2016 it was found that saltwater was still leaking through the barrage causing a more saline environment further upstream (Orchard & Measures, 2016).

Christchurch, New Zealand

Consideration has been given to a tidal barrier at or near to the mouth of Ihutai / Avon – Heathcote Estuary or at the mouths of the Ōtākaro Avon and Ōpāwaho Heathcote Rivers a number of times, but none have been implemented (Scott, 1963; Hydraulics Research Station, 1970; GHD, 2015; Jacobs, 2015).

London, United Kingdom

The Thames Barrier was built in 1982 and is designed to protect 125 square kilometres of central London, and more than one million people from inundation caused by a 1 in 1000 year storm event until 2030 (Lavery & Donovan, 2005; Lloyds, 2008; De Castella, 2014; Environment Agency, 2014). The barrier spans 520 meters across the river and has 10 steel gates that are as tall as a five storey building when raised (Environment Agency, 2014).

The Netherlands

Built between 1991 and 1997, the Maeslantkreing gate on the Nieuwe Waterweg between Rotterdam and the North Sea can close the shipping canal that is 360 meters wide (Climate Adapt, 2015; Rijkswaterstaad, n.d.). The gate itself consists of two wings (each 210 meters wide and 22 meters high), that swing across the river to meet in the middle (Climate Adapt, 2015; Rijkswaterstaad, n.d.).

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7 Retreat

There are different triggers for when retreat from affected areas could occur ranging from pre-emptive to post-event. In this report, retreat refers to a proactive or planned withdrawal of assets from high risk coastal areas, rather than an unplanned or forced retreat which may also be an option after an extreme event or continued sea level rise (Linham & Nicholls, 2010). When retreating assets to allow for the inundation or erosion of the previously protected area, managed retreat may also be referred to as managed realignment (Appelquist et al., 2016).

Managed retreat in coastal areas involves the landward relocation of existing and planned development to reduce exposure to hazards. The hazard risk to assets and infrastructure is reduced or removed entirely, leaving the coast to respond to natural processes (Owen et al., 2018).

The buffer zone that retreat options create can prevent the need for hard protection structures, and can provide enough space to establish or enhance natural protection options that dissipate wave energy, reduce erosion and allow any protection measures inland of them to be built at a lower level compared to if there were no natural protection options present (Linham & Nicholls, 2012; Appelquist et al., 2016). Retreat options also maintain the natural aesthetic, function and processes of the coastline so that sedimentary processes can occur unabated, ecological habitats can thrive, flood storage is increased, and opportunities for recreational activities are created (Linham & Nicholls, 2012; Robb et al., 2020).

Managed retreat requires landowners to surrender coastal land that may have significant value to them. This is often socially and politically controversial, as it can be challenging to promote the idea of public benefits, such as the amenity of the natural coastline, when people are experiencing private loss (Linham & Nicholls, 2012). Retreat options can also be administratively heavy as government staff are needed for roles such as community development, grant management, drafting leases, monitoring compliance and managing land and potential lessees (Georgetown Climate Center, 2020a; Georgetown Climate Center, 2020b).

Managed retreat can occur at different scales; it can involve moving structures within property boundaries, to another site, or the staged relocation of entire communities (Turbott, 2006). Some retreat options also rely on new development areas being available for displaced residents to ensure minimal social and cultural impacts. Financial limitations and uncertainty about who will bear the cost can also constrain consideration of managed retreat options (Boston, 2017). Costs are dependent on the location, size and quantity of land. The costs of land clearance and holding and maintaining land after acquisition also need to be considered.

In practice, managed retreat employs a number of staged actions, including anticipating the removal of hard protection structures, decisions to stop maintaining such structures, restrictions on land use, identifying new places for retreating communities to go, and the removal or relocation of at-risk infrastructure (Owen et al., 2018). Managed retreat is an anticipatory strategy to avoid and reduce risk and while upfront costs can be substantial, it can reduce future disaster response costs and enable the phasing out of infrastructure and services (Turbott, 2006).

In the local context, the New Zealand Coastal Policy Statement 2010 requires consideration of managed retreat as a response to managing coastal hazard risk for existing and planned development. The Government has also signalled that it is working on the 'Climate Change Adaptation Act' to address the complex legal and technical issues associated with managed retreat and funding and financing adaptation.

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7.1 Acquisition tools

Land acquisition can occur through the purchase of land in fee simple or involve the purchase of development rights to an entire land parcel or part of it (Georgetown Climate Center, 2020). When at-risk land is acquired, it can be leased back to the previous owner or a third party until a certain pre-determined trigger is reached, or assets and rights may be removed immediately to reduce the risk to hazards (Macintosh et al., 2013; Robb et al., 2020). Acquired land can be used to manage coastal hazards by allowing space for erosion and inundation, or for the installation of protection measures (EHP, 2012; Robb et al., 2020). Land acquisition is not typically combined with the use of hard protection structures as it is desired to have the land act as a buffer zone to developments behind, however, environmental options such as wetland and dune restoration have been seen to work well in combination with land acquisition (EHP, 2012). Land acquisition can save governments money in the long term as it avoids future maintenance, service, infrastructure and disaster recovery costs (Georgetown Climate Center, n.d.).

A challenge of land acquisition is the message that is sent to property investors when the decision to purchase at-risk land is made. People may view land acquisition as a tool to continue to invest in at-risk coastal land without financial risk (Turbott, 2006).

There are several key factors that encourage the success of land acquisition programmes (Robb et al., 2020);

- A large up-front public fund is needed to acquire land when local or central governments do not fund the activity.
- The programme needs to focus on areas that have experienced repetitive loss or damage.
- Strong community support is highly important.
- To limit the financial losses experienced by landowners and the potential social disruption, programmes can offer incentives to encourage people to relocate within the same region, or programmes may provide relocation support services.
- The value that land is purchased for must be carefully considered to avoid the inflation of acquisition costs and manage landholder expectations of government assistance.
- Some challenges may be overcome by acquiring early and implementing leaseback schemes.
- Rights to compensation should be established evenly to all landholders in similar situations.

The acquisition tools identified in this section are all discussed within the context of acquisition occurring by agreement. While compulsory acquisition may be able to be considered as an option for undertaking managed retreat, it is not explored in this report.

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7.1.1 Buyouts

Land buyout programs involve the government acquiring land in at-risk areas by agreement, to reduce vulnerability to hazards (Macintosh et al., 2013). Buyouts can be useful in areas where the land is seen to be unsuitable for any land use due to its hazard exposure. Buyouts involve the transfer of title to land and are typically only used in very high risk areas due to the cost associated with them (Macintosh et al., 2013). After land has been acquired, it will usually have all structures removed and a deed restriction or conservation easement will be placed on the land to prevent future development (Georgetown Climate Center, 2020).

Buyout programs with compensation schemes can be extremely expensive for governments, especially with the cost of land restoration and long term management also factored in. However, retreating from at-risk areas can create an overall cost saving due to the phasing out of infrastructure and services in the area (Georgetown Climate Center, 2020).

Case studies

Matatā, New Zealand

Awatarariki suffered a storm event in 2005 which destroyed 27 homes and caused $20 million in damage (Whakatāne District Council, 2020). In response, the District Council initiated a managed retreat programme for 34 properties at high risk from future debris flow events, to become coastal reserve area (Whakatāne District Council, 2020). The programme is jointly funded by the Whakatāne District Council, the Bay of Plenty Regional Council, and the Department of Internal Affairs (Whakatāne District Council, 2020). The purchase offer is at current market value plus contributions to legal fees, relocation costs and mortgage break fees (Whakatāne District Council, 2020).

Waitākere City, New Zealand

The city undertook an urban sustainability project known as Project Twin Streams to restore 56 kilometres of the Waitākere Stream through the purchase of 156 full and partial properties located within the 100-year flood plain of the catchment (Atlas Communications and Media Ltd., 2011). At-risk properties were acquired at market value and property owners could recover moving and legal costs (Atlas Communications and Media Ltd., 2011). A flexible approach to acquisition was adopted to enable consideration of individual circumstances (Atlas Communications and Media Ltd., 2011).

Medmerry, United Kingdom

Medmerry completed a managed realignment project in 2013 at a cost of £28 million to combat frequent coastal inundation by replacing the shingle bank structure that was costing £300,000 to maintain each year (NCCARF, 2017). Three farms were purchased to form a saltwater marsh by breaching the existing 3km bank to allow the sea to reclaim an area of land (NCCARF, 2017). A total of 348 properties, plus sewage works, caravan parks and a main road are now protected to a standard of 1 in 100 years (previously just 1 in 1 year) (NCCARF, 2017).

New York, United States

Oakwood Beach was designated a ‘buyout area’ by the State of New York to address hurricane and storm damage as well as common nuisance inundation that occurred after most rainfall events (LILP, 2016). Home owners were offered the pre-storm value of their homes, plus incentives for group participation. The buyout program was community-driven with residents petitioning the State to purchase 326 properties (LILP, 2016).

New Jersey, United States

The state is spending $300 million in federal disaster recovery funds to acquire about 1000 properties in areas affected by Superstorm Sandy and an additional 300 homes in places that have repeatedly flooded (State of New Jersey, n.d.). Owners are being offered pre-storm value if they sell their properties to the state (State of New Jersey, n.d.). Clusters of affected properties or neighbourhoods will have homes removed so that the land can be converted to open space that will act as a natural buffer to hazards and provide public recreation space (State of New Jersey, n.d.).

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7.1.2 Land swaps

During a land swap, landowners in a hazard zone are given the opportunity to swap their title to land for a comparable sized parcel in a lower risk area (Macintosh et al., 2013). The land that has been swapped then acts as a buffer against coastal hazards (EHP, 2020). This approach is an in-kind exchange of land between parties rather than a purchase of land, although monetary payments are sometimes involved to achieve an equality of exchange (Georgetown Climate Center, 2020). Land swap schemes can be highly diverse and complex, often involving more than two parties but they are an effective method of implementing retreat at large scales (Georgetown Climate Center, 2020).

Land swaps can be useful when the land that is being offered is already public land and it can help governments avoid spending money. However, this can also be controversial as some people may oppose the idea of privatising existing public land (Georgetown Climate Center, 2020). The environmental effects of land use changes also need to be considered and managed. When compared to other land acquisition tools, land swaps may have a higher participation rate as landowners know where their new land is located at the beginning of the process (Georgetown Climate Center, 2020). Land swaps also preserve social cohesion when planned so that whole communities are able to move to a new location (Georgetown Climate Center, 2020).

Identified examples of land swap programmes have occurred in situations where damage or loss has already occurred and rebuild rights can be transferred to a new site. If adopted as a pre-emptive managed retreat approach, the costs of relocating or rebuilding homes will need to be considered. The costs of preparing land to be swapped also need to be factored in.

Case studies

Grantham, Australia

The town located in the Lockyer Valley experienced extreme inundation in early 2011 (Queensland Reconstruction Authority, 2011; EHP, 2020). In response, the Regional Council purchased parcels of freehold, elevated land, covering an area of approximately 378 ha, to enable the voluntary relocation of residents displaced by the significant flood event (Queensland Reconstruction Authority, 2011; EHP, 2020). The land swap program allowed eligible landowners to swap their land for part of the newly purchased council land (Queensland Reconstruction Authority, 2011; EHP, 2020). Landowners were responsible for meeting the cost of building homes on the new blocks (Queensland Reconstruction Authority, 2011; EHP, 2020).

Louisiana, United States

The Isle de Jean Charles is rapidly disappearing into the Gulf of Mexico (State of Louisiana, 2019). A team of state officials, planners, engineers, architects, and policymakers is collaborating with current and past island residents to implement a resettlement program of the whole island (State of Louisiana, 2019). From the beginning, the states aim was to offer relocation options to all current permanent residents that reflect the values of the Isle de Jean Charles people (State of Louisiana, 2019).

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7.1.3 Leasebacks

Leasebacks involve the acquisition of at-risk land with provision for it to be leased back to the former owner or a third party with terms and conditions that facilitate the management of hazards (Macintosh et al., 2013; Georgetown Climate Center, 2020). The former owners or third party, now the lessee, pays rent and uses the land in accordance to the terms of the lease, but no longer owns the land (Georgetown Climate Center, 2020). Benefits of this option include allowing continued use of the land until a certain point in time, or a hazard trigger has been reached (Macintosh et al., 2013; Georgetown Climate Center, 2020), as well as generating revenue to reduce maintenance costs (Georgetown Climate Center, 2020). Leasebacks also provide for landowners current needs and facilitate an easier transition to a new location while preserving social cohesion (Georgetown Climate Center, 2020).

Leasebacks are most effective when they are used as a part of a wider acquisition program to avoid a checker boarding effect where some land is government owned and some remains privately owned (Georgetown Climate Center, 2020). This option is not viable where risk is imminent and immediate retreat is necessary.

Case studies

<u>Waitākere City, New Zealand</u>

Leasebacks were used for some property owners as part of an urban sustainability project known as Project Twin Streams (discussed above in section 7.1.1) (Atlas Communications and Media Ltd., 2011).

North Carolina, United States

Charlotte-Mecklenburg Storm Water Services (CMSS) has been administering a flood buyout program to relocate vulnerable residents out of flood plains (Adaptation Clearinghouse, 2020). Once bought out, properties are returned to open spaces to restore their natural flood mitigation capabilities and provide community amenities (Adaptation Clearinghouse, 2020). CMSS has also offered leasebacks of acquired properties to some specific property owners to increase the uptake of the program and reduce maintenance costs (Adaptation Clearinghouse, 2020). To date there has been a low uptake with only a dozen property owners electing to leaseback their land (Adaptation Clearinghouse, 2020).

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7.1.4 Future interests

The acquisition of a future interest involves the purchase of a right to acquire land in specified circumstances in return for an agreed upfront fee. For example, it may be agreed upon that once a certain height of sea level rise has been reached, the holder of the future interest (usually a government agency) has the right to acquire the land (Georgetown Climate Center, 2020). Future interests can offer a more flexible and attractive approach for both governments and landowners than a buyout scheme (Georgetown Climate Center, 2020). They can also increase participation and help minimise some negative consequences of buyouts by allowing owners to stay on the land for longer (Georgetown Climate Center, 2020). Future interests can also enable the phasing of acquisition costs over a longer time period (Georgetown Climate Center, 2020).

This tool can also take the form of a purchase option. A purchase option is a real estate option which does not come into effect until a hazard, such as sea level rise, imposes tangible effects on the land

(Henderson, 2018). The key difference between the purchase of a future interest and a purchase option is that under a purchase option there is no obligation to purchase (Henderson, 2018).

Purchase option agreements can include (Henderson, 2018):

- Restrictions or prohibitions on the construction of private coastal defences
- Acknowledgements that existing coastal defences will not be maintained or enhanced
- Limitations on additions or improvements to land
- Additional option triggers i.e. if land is placed on the market for sale in normal circumstances.

Land can also be designated for future acquisition by declaring it to be ‘acquisition land’. Once land is declared as acquisition land, it does not need to be acquired immediately, the status just prohibits the land to be sold to anyone other than the declared government authority (Macintosh et al., 2013). This option may change the public perception and political acceptability of land acquisition.

Case studies

No case studies of purchase of life interests or purchase option agreements being implemented in the context of managed retreat have been identified.

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7.1.5 Conservation easements

A conservation easement (also referred to as conservation agreements or conservation restrictions) is a legal agreement under which permanent limitations are placed on land use in order to sustain an area’s natural function (SCOS, 2018). These agreements can manage hazards such as sea level rise and erosion by prohibiting further development in some areas (SCOS, 2018).

Conservation easements can be used to proactively plan for sea level rise by tailoring agreements to the areas current and future risk, suitability for industry, and values. Some examples of what conservation easements can include are prohibitions against shoreline armouring, preclusions against erosion-inducing activities, or the conservation of natural buffer areas (SCOS, 2018). This option can therefore preserve shorelines as well as access to the coast, and can help native ecosystems migrate landwards as sea levels rise (Titus, 2011).

Rolling easements are a type of conservation easement placed along the shoreline to prevent landowners from holding back the sea through hard protection structures, but allow any other type of use and activity on the land (Grannis, 2011). Rolling easements allow for limited development of upland portions of a land parcel but as the shoreline line recedes, the easement automatically moves or 'rolls' landward and requires the removal of structures once they encroach on the easement area (Grannis, 2011). Private landowners receive up-front compensation for agreeing to limit development in the future. Meanwhile, they can continue to develop and use their land until the rising seas threaten their development (Grannis, 2011). The purchase of an easement can be less costly than the purchase of a whole land parcel (Titus, 2011).

Case studies

Maryland, United States

A 'coastal resilience' easement responds to sea level rise and applies to 221 acres of wetlands near the Blackwater National Wildlife Refuge (SCOS, 2018). The easement contains provisions permanently eliminating development, restricting impervious surfaces, and protecting areas that allow wetlands to migrate, to help with quick recovery from inundation events (SCOS, 2018).

South Carolina, United States

Rolling easements were established on South Carolina's coast in the Beach Front Management Act of 1988. This allows development, but prohibits structures from being built within a certain zone which rolls back as the sea encroaches towards the land (LRAP, 2017).

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7.1.6 Transferable development rights

Transferable development rights (TDR's) are a market-based mechanism that can be used to increase development potential in areas where development is desired, and decrease or eliminate the potential in areas that should be preserved, without requiring public investment (Pruetz & Standridge, 2008; Macintosh et al., 2013; SCOS, 2018). Areas that have been identified for preservation are called 'sending areas'. Development rights are separated from the land and are transferred from the sending parcel to land in an area where development is considered appropriate or is even desired, which are called 'receiving areas' (Pruetz & Standridge, 2008; Macintosh et al., 2013; SCOS, 2018). TDR's from the sending area can either be sold to a landowner or developer in the receiving area, or they can be transferred directly if both parcels of land are under common ownership (Macintosh et al., 2013).

Factors that may influence the successful implementation of TDR programs (Pruetz & Standridge, 2008; Robb et al., 2020);

- Incentives aimed at attracting development investment in receiving areas
- Receiving areas with a high demand for development
- Additional incentives such as allowing development in receiving areas without TDR obligations, but offering additional development potential when developers buy TDR's
- Having strong public support for preserving sending areas

Once development rights have been transferred, sending areas are conserved through the use of restrictive deeds, covenants or easements that prevent the current and any subsequent landowner from undertaking development on the land (Macintosh et al., 2013).

Case studies

Bay of Plenty, New Zealand

The Western Bay of Plenty district plan includes rules that allow for transferable development rights in return for the protection of significant ecological, landscape or heritage values (WBOPDC, n.d.).

Washington, United States

The King Country TDR Program seeks to transfer development out of areas with current or future high-flood risk, or valuable natural resources into urban 'receiving areas' that are appropriate for additional growth or increased density (e.g., areas with lower flood risk, affordable housing and existing supporting infrastructure and services) (Spidalieri et al., 2020). Development rights can be bought and sold as a tradable commodity separate from the land itself. By acquiring TDR credits, developers can increase the density of proposed development above base zoning standards in receiving areas, while the sending parcel is preserved through a conservation easement (Spidalieri et al., 2020). Between 2000 and July 2019 2,467 potential dwelling units have been relocated (Spidalieri et al., 2020).

Florida, United States

The Miami-Dade County has two TDR programs in use. The first benefits the East Everglades area and the second program allows density bonuses to be ported to another site (Urban Land Institute, 2017). Since, there have been recommendations for the creation of two new TDR programs for historic site preservation and agricultural area preservation (Urban Land Institute, 2017). A frequent complaint about existing programs is that there is little to no market for the credits and thus decreases their value (Urban Land Institute, 2017). To combat this, it has been suggested that the supply and demand of credits is carefully managed, more research about the value of TDR's is carried out and a bank of credits is to be set up (Urban Land Institute, 2017).

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8 Avoid

These options aim to avoid increasing the risk of harm due to hazards in terms of social, environmental and economic terms (Bell et al., 2017). Avoidance measures are highly effective in minimising building damage due to coastal inundation or erosion, and they can also provide buffer zones that allow for natural processes to occur (Linham & Nicholls, 2010). In the local context, the Ministry for the Environment's 2017 'Coastal Hazards and Climate Change: Guidance for Local Government' sets out a number of planning methods and techniques available to help avoid coastal hazard risks, which include (Bell et al., 2017):

- Zoning
- Identifying hazard lines or overlay areas
- Creating no subdivision areas
- Excluding particular activities from identified areas
- Prohibiting activities

There is existing direction in the 2010 New Zealand Coastal Policy Statement which advocates for the use of avoidance measures nationally. The Policy states that (Department of Conservation, 2010):

- Increases in the risk of harm from coastal hazards should be avoided
- Development or change in land use that increases risk of hazards should be avoided
- Redevelopment or change in land use that reduce risk of hazards is to be encouraged

The Council's Coastal Hazards Plan Change sets the regulatory framework to manage general increased risk across the district.

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8.1 Zoning

Zoning can be used in several ways to manage coastal hazard risks (Georgetown Climate Center, 2020);

- Allowing increased development density in lower risk areas
- Downzoning at-risk areas
- Creating areas where new development is not permitted
- Changing future land uses in at-risk areas from low resilience to high resilience (e.g. from residential to public space)
- Prohibiting hard shoreline protection structures and promoting natural shoreline protection measures that support inland ecosystem migration

Downzoning at-risk areas can implement rebuilding and redevelopment restrictions. These restrictions limit a landowner’s ability to rebuild destroyed structures by prohibiting redevelopment, or requiring that it be more resilient to hazards. Although this option does not proactively protect land and people from coastal hazards, it phases out high risk land uses over time while still allowing landowners to continue to use their land for a time (Grannis, 2011). These restrictions can prompt planned retreat from a coastal region by incrementally restricting replacement structures in at-risk areas, and can also accommodate sea level rise by requiring that redeveloped or rebuilt buildings incorporate resilient engineering approaches (SCOS, 2018).

Restricting intensification and subdivision is able to prevent new development in at-risk areas. Zoning changes can ensure that proposed future land uses are compatible with projected coastal hazard risks and enable the creation of buffer areas.

As well as using zoning to proactively manage coastal hazard risk in undeveloped areas or in areas where current activities are not exposed to hazards, zoning is also often combined with managed retreat tools. For example, acquired land may be zoned to open space in order to prohibit new development and only allow for appropriate land uses such as recreational uses (Georgetown Climate Center, 2020). Phasing out development in at-risk areas through limiting or prohibiting new development or redevelopment can also be used in conjunction with extinguishing existing use rights to support managed retreat. In New Zealand, the Resource Management Act 1991, through regional plan rules, provides a means to manage existing uses in hazard areas. Changes to the district planning framework would be required to rezone land, while a regional council has the power to extinguish existing uses through changes to regional planning documents.

Case studies

Matatā, New Zealand

A plan change process was undertaken for areas of high hazard risk on the Awatarariki Fanhead in Matatā, to change the zoning of the land from residential to coastal protection to reflect the natural hazard risk, and to remove its ability to be used for residential purposes from March 2021 (Hanna et al., 2018). At the hearing for these proposed plan changes, legal counsel for Whakatāne District Council advised that the proposal would be the first example of regional plan provisions being used in such a way (through extinguishing existing use rights) in New Zealand (Hanna et al., 2018). The Regional Plan changed the rules permitting residential activity on high risk properties within the fanhead, and thereby extinguished existing use rights on those properties. The plan change process was undertaken in conjunction with the District Council offering to buy the properties.

Māpua, New Zealand

The Māpua/Ruby Bay area in the Tasman district has coastal areas subject to coastal inundation and erosion. Plan Change 22 to the Tasman Resource Management Plan involved a proposal to allow for future expansion of the Māpua Township and Ruby Bay away from the low-lying land and erosion prone coastline, on to more elevated land northwest of the township (Tasman District Council, 2011). It had the effect of imposing controls on the subdivision and development of coastal land within the identified at-risk area (Tasman District Council, 2011). Controls included the avoidance of any new buildings on at-risk parts of the coastal margins, Māpua channel entrance, and Ruby Bay (Tasman District Council, 2011). Furthermore, a coastal hazard area between Māpua and Ruby Bay was to be identified where all subdivision and development will be strictly limited to avoid the long-term adverse effects of coastal erosion and inundation (Tasman District Council, 2011).

Gisborne, New Zealand

The Tairāwhiti Resource Management Plan which was made partially operative on 30 March 2020, captures all of Gisborne District Council’s resource management plans. Under the Tairāwhiti Resource Management Plan, subdivision to create new development in the Coastal Hazard Overlay 1 (Extreme Risk) and 2 (High Risk) is prohibited (Gisborne District Council, 2020).

New Jersey, United States

Woodridge Township in New Jersey combined buyouts with zoning changes to implement retreat for 200 homes. The buyout area was rezoned from residential to open space to prohibit new development and only allow for passive recreational amenities to preserve the area as a natural flood buffer (Spidalieri et al., 2020).

Maine, United States

The Maine Department of Environmental Protection limits reconstruction of buildings that have been damaged by wave action (Adaptation Clearinghouse, 2006). A permit is required if the structure is damaged by more than 50 percent of its appraised value, and rebuilding must comply with strict design and planning requirements, which in many instances severely limits reconstruction (Adaptation Clearinghouse, 2006). For example, a project may not be permitted if, within 100 years, the property may reasonably be expected to be eroded as a result of changes in the shoreline.

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8.2 Trigger based or time limited land use consents

Trigger based or time limited land use consents include conditions linked to hazards such as sea level rise or erosion rates that create a finite term for a particular land use. The land use consents allows development or redevelopment with the expectation that such uses can only continue until specified trigger points are reached or for a specified time period. Due to the reliance on contingent rather than firmly predicted outcomes, event trigger conditions are preferred over time-bound conditions (England, 2013). Uncertainties associated with different hazards over time may lead to maladaptation if time-bound conditions are imposed.

Case studies

<u>Christchurch, New Zealand</u>

In December 2018, a change was made to the Christchurch District Plan to provide policy support for the Residential Unit Overlay (RUO) and broaden the application of an existing rule which permits replacement of existing houses. Within the High Flood Hazard Management Areas (HFHMA) that are mapped in the District Plan, there are residentially zoned areas which may be susceptible to high flood hazard from coastal or tidal inundation in the future as a result of sea level rise. In the RUO which only applies to parts of New Brighton, South New Brighton, Southshore, Monks Bay and Redcliffs, an unacceptable high flood risk does not currently exist, but will at some point in the future due to sea level rise.

A restricted discretionary activity consent is required before the construction of a replacement or new dwelling in a HFHMA within the RUO where existing use rights do not apply or it is being built in accordance with a previous resource consent. An assessment of the potential risk to safety, wellbeing and land is required and if there are appropriate mitigating factors, for example, the application could be for a limited duration consent only.

An example is resource consent RMA/2019/622 that was granted by the Christchurch City Council in September 2019 for an 8 lot subdivision and associated land use in Southshore. The consent was granted subject to a number of conditions including the requirement for buildings to have a raised floor level. It also required buildings to be relocatable and stated that within 12 months of 0.41m of sea level rise occurring, all buildings, fencing and structures were to be removed at the cost of the property owners.

The consent document is available by request from the Christchurch City Council.

Shire of Wellington, Australia

The Wellington Shire Council in Australia requires the preparation of a Climate Change Response Plan (CCRP) for coastal development (Wellington Shire Council, 2020). A CCRP must specify the actions that will be undertaken by the property owner to mitigate against coastal hazard risks and include triggers for actions when specified inundation levels are reached including a requirement to remove structures (Wellington Shire Council, 2020). The plan must be prepared to the satisfaction of the Council, registered on the property title and reviewed every 10 years (Wellington Shire Council, 2020).

Byron Shire, Australia

The Byron Shire Council in Australia adopted a policy of planned retreat in 1988 considered to be the leading example of event trigger conditions in Australia (Byron Shire Council, n.d.). New development must be located outside the 20m erosion escarpment and must be readily removable (Byron Shire Council, n.d.). Prescriptive measures apply to new dwellings such as single storied and entirely modular in construction, and existing buildings such as gross floor area restrictions for any extensions (Byron Shire Council, n.d.). Provision is also made for development to be relocated, demolished or to cease operation when the erosion escarpment comes within 50m of any building (Byron Shire Council, n.d.).

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8.3 Setback controls

New development and land use in high risk areas can be restricted through the imposition of building setback controls. Setbacks are building restrictions that establish a distance from a pre-determined point that factors in future erosion rates where landowners are prohibited from building structures, or they establish a minimum elevation for development that factors in sea level rise and coastal inundation (Linham & Nicholls, 2010). Setbacks are highly effective in minimising building damage due to coastal inundation or erosion, and they also provide buffer zones that allow for natural processes to occur (Linham & Nicholls, 2010).

For example, coastal setbacks may prohibit landowners from building on or immediately adjacent to wetlands and sand dunes as these natural features buffer erosion and flood impacts, preserve views, provide recreational opportunities, and serve as important habitat. Setbacks can be determined as either a fixed setback that prohibits development up to a fixed distance landward of a reference feature, or as a floating setback which can change according to an areas topography or shoreline position (Linham & Nicholls, 2010). Regardless of how setbacks are determined, they need to be periodically reviewed to ensure they are still serving their purpose and providing sufficient protection (Linham & Nicholls, 2010).

Case studies

<u>Franklin District, New Zealand</u>

The Franklin District has an extensive coastline which is susceptible to naturally occurring erosion and inundation in low-lying areas. In recognition of the coastline's different environments, the Franklin District Plan, updated in October 2013 and administered by the Hauraki District Council, has adopted three coastal management areas: Tasman Coast Management Area, Manukau Harbour Fringe Management Area and Seabird Coast Management Area (Hauraki District Council, 2013). This Management Area approach enables the development of objectives, policies and outcomes specific to each area and allows these areas to be managed in response to different coastal hazards (Hauraki District Council, 2013). There are also two underlying zones (Coastal Zone and Village Zone) with associated rules relating to land use and subdivision (Hauraki District Council, 2013). Within the Coastal Zone, the Franklin District Plan adopts a different coastal protection setback for each Coastal Management Area to provide for the preservation of the natural character of each area and to best ensure the avoidance and mitigation of coastal hazards in those areas (Hauraki District Council, 2013). It is a non-complying activity to establish buildings and associated earthworks within a Coastal Protection Setback in the Coastal Zone and the Council may grant or refuse consent to a non-complying activity, and may attach conditions of consent (Hauraki District Council, 2013).

Coromandel, New Zealand

The Coromandel has included two coastal erosions setbacks in its District Plan – the Current Coastal Erosion Line which provides for the maximum likely erosion associated with existing coastal processes, and the Future Coastal Protection Line which identifies the further erosion that could occur over the next 100 years due to projected sea level rise (FOCUS, 2012).

Hawaii, United States

Hawaii has strict setback requirements where structures are required to be set back 50 times the annual erosion rate plus 20 feet (Andrews, 2016). This regulation allows for variance if, after the imposition of the setback, the lot does not have 30 feet of buildable space left (Andrews, 2016).

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