GROUNDING: Armatures for coastal resilience
Kristina Hill

The edge of the sea is a strange and beautiful place. – Rachel Carson
Geography is destiny. – Napoleon Bonaparte

Introduction

Cities built on the edges of tidal estuaries are the most vulnerable to the processes of coastal change. Understanding these estuary cities involves a study of opposites – brittle structures made of concrete and steel are trying to claim stable territory, while oceans increasingly claim the same locations with saltwater and dynamic wave energy. Cities that try to simply block out the ocean with concrete and steel will eventually lose; as Herman Melville wrote of the sea, no power but its own controls it. Resilience and adaptation will be a long game, requiring many strategies better than brittle walls.

In North America, estuary cities originated as outposts of trade and resource control during colonization by European nations. The first components of their ocean edges were often built more quickly than well. For example, San Francisco's waterfront was built using a fast-and-cheap berm of piled-up rocks as the basis for its seawall (Figure 1) (GHD-GTC Joint Venture 2016). Near downtown, this rock berm is interspersed with the wooden hulls of ships abandoned by gold miners who were far more interested in claiming resources elsewhere. The ship hulls and rock berm were both covered with sandy fill scraped off the city's pre-urban dune fields, and wooden wharves were constructed towards the ocean from the fill. It wasn't the kind of foundation designed to last in a seismic region, and its first full-scale replacement is underway – estimated at a cost of $4-5 billion (Watts 2016). In 150 years, geologic resilience has replaced geologic exploitation as the goal for infrastructure, and the "time problem" has been re-framed as one of longevity rather than speed.

Re-framing a coastal city's needs as longevity raises several new questions in a rapidly changing global environment. How many generations will a new seawall serve? How many do we want to be indebted to pay for it? What if our children have to pay for it longer than it is effective? What, if anything, do present generations owe the future? A century and a half after San Francisco was founded, the tangle of questions around resilience is genuinely cultural, not simply technical.

American coastal cities expanded from bare colonial outposts using housing and street design standards that have nothing to do with the dynamics of the sea. In the 1850s, roads and wharves were built on fill made of sand (Booker 2013). For the next hundred years, the strategy was to fill the shallow waters of San Francisco Bay and other estuaries with municipal waste and building rubble, placing profitable industries, public works and private housing on top. The typology of buildings and infrastructure was not specific to an estuary environment, except for the presence of working docks and wharves. American estuary cities don't reveal the dynamics of the landscape they are built in, except through occasional failures – such as the collapse of buildings constructed on filled land in an earthquake event, or highway lanes flooded by high tides. Our streets and structures are mute, inexpressive of the real world around them except through failure. These structures blunt or even remove our awareness of the processes associated with our estuary environment, rather than heighten our sense of the strange beauty Rachel Carson wrote about at the edge of the sea (Carson 1955).

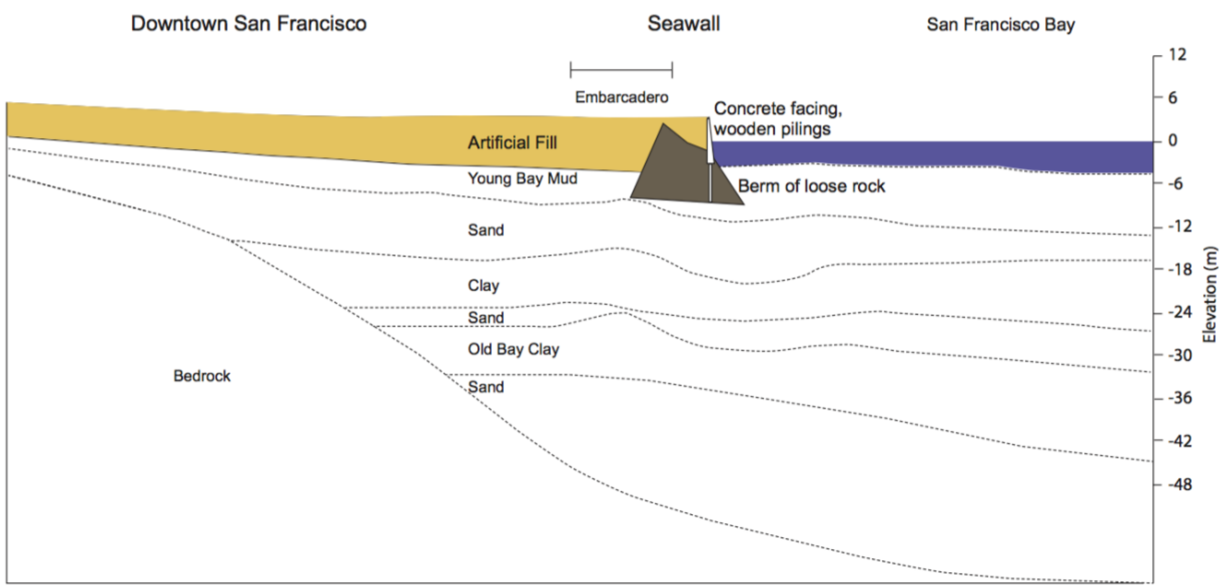


Illustration by the author, simplified from detailed sections in: Port of San Francisco (2016).

Figure 1. The existing San Francisco seawall was hastily constructed in the 19th century, during the gold rush era. It is literally a berm of loose rocks, with wooden and concrete piles driven into it. Concrete panels are used as a seaward facing material. The wall holds back the sandy fill on the landward side, and provides a quay for boats to dock. It needs to be replaced, at an estimated cost of $4-5 billion USD. The question is, how high should it be built?

Building cities that reduce our awareness of the environment was never a good idea, and is now a practice that reduces our cultural capacity for resilience. In an era of rapid environmental change, humans will need to use all of our animal senses, all of our emotional, cultural and intellectual resourcefulness, to focus and prepare. In 2017, we've watched Houston, Miami and San Juan, Puerto Rico, flooded by extreme storms and seen Mexico City heavily damaged by earthquakes, along with the rhythm of monthly high tides blocking roadways in Virginia and California. The aesthetic experience of this may best be captured by the original description of the sublime – an experience of magnitudes beyond comprehension, and of processes beyond our control (Doran 2015). The desire for greater resilience is a clear response to the failure of the modern project to control "nature." If floods can't be controlled by technology, cities need to emphasize a new set of strategies.

As a result of the changing global climate, all cities – not only estuary cities – can be said to be moving to a new planet. Storm forecasters struggle for words to describe weather events that are more intense than they have ever seen. Permanent changes in sea levels and precipitation patterns alone (and there are many more) will affect high tide levels, groundwater, food supply chains, transportation networks, water supply and waste treatment systems. The breadth and complexity of these extreme events and permanent changes literally prevent us from knowing what specific changes will happen in a particular location. Without that ability to know how these dynamics will become location-specific, our urban design and planning epistemology shifts away from a deterministic frame and towards a heuristic frame.

My own writing and projects have tried to explore these five questions, as the beginning of a heuristic frame for reasoning about resilience:

- What is stable, and what is likely to change quickly?
- What kinds of spatial armatures can we use to establish relatively fixed territories?
- How can we organize ourselves to implement adaptation strategies?
- What kinds of physical designs and ways of occupying space can help us learn faster?
- Do we have a broadly shared understanding of what resilience means?

In this chapter, I begin with the last question, then use the example of Christchurch, New Zealand, as a kind of rhyzomatic node linked to other places and ideas to help reason through some possibilities for design. My chapter closes with a discussion of the implications of sharing an understanding of resilience more broadly, with a wider public that focuses on justice arguments rather than design or technology.

What is resilience?

The concept of *resilience* as a property of a human bodily organ dates back to the 17th century, when it was used by Francis Bacon and others to describe the action of rebounding, recoiling or returning to an original position (Oxford English Dictionary, 2014). At that time, it was used in physiology to refer to a quality of human lung tissue. By the 19th century, scientists used the term in a formalized definition of material elasticity. The term was later used in ecology, where *resilience* refers specifically to the capacity of an ecosystem to return to a previous state after a disturbance (Allaby 2010). “Resilience” has also referred to the ability of people to recover from or resist a shock, since the 19th century, when it was synonymous with robustness and adaptability (Oxford English Dictionary, 2014).

Among North American planners and designers, “resilience” came into common usage after 2005, when major storms first caused extensive damage in New Orleans. Usage expanded dramatically after Hurricane Sandy hit the New York region in 2012. In Europe, scientific awareness of climate change and biodiversity losses created an impetus for the Stockholm Resilience Centre, which was founded in 2007 with the mission to study the complex interdependencies of humans and their environment. The Stockholm Centre uses “resilience” in a broader sense that includes biodiversity, while most North American urban planners do not.

It is important to note that the concept of “strategic resilience” dates to the era immediately before Hurricanes Katrina and Sandy. According to the authors of an influential article in the Harvard Business Review in 2003, large industrial corporations need resilience. They claimed that the success of a private company, even a very large one, relies on its ability to dynamically reinvent business models and strategies as circumstances change (Hamel and Valikangas 2003).

They wrote, "strategic resilience is not about responding to a one-time crisis. It's not about rebounding from a setback. It's about continuously anticipating and adjusting to deep, secular trends that can permanently impair the earning power of a core business. It's about having the capacity to change before the case for change becomes desperately obvious," (p.). The authors proposed that a corporation could adopt the philosophy and tactics of strategic resilience to pursue the goal of "zero trauma" to the corporation.

What would it look like if cities pursued this same goal, of achieving resilience to achieve "zero trauma"? Cities would have to be actively managed, but perhaps take on some of the recommendations for big corporations – eg, allowing smaller, nimble units to self-organize and pursue shared goals in unique ways, experimenting to find success. Making room for lots of small pilot projects, some of which might fail - instead of trying to implement new standardized changes on the whole city, all at once. Clearly, cities would face different challenges in a climate of experimentation than corporations would, such as attending to equity in the use of public funds.

Maybe the right scale and aesthetic of experimentation for resilience is different for cities. In this next section, I'll argue that it requires an understanding of the landscape armatures of a coastal city, and that it should tinker with the barriers to shared prosperity – including the impacts of repeated flooding, or earthquake risks, on housing markets.

Physical geography: the ultimate armature

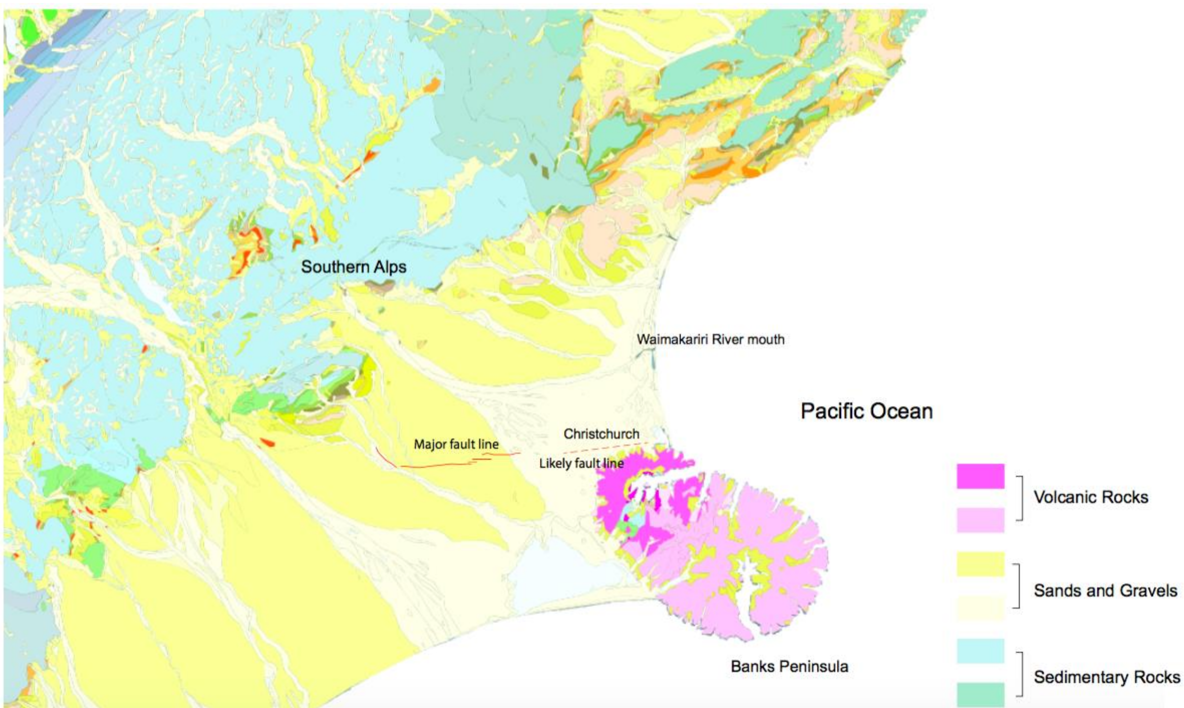
Geography provides a context for the evolution of resilience strategies. Napoleon may have been the first to say that geography is destiny, precisely because he and many other territorial strategists have learned that technology and strategy operate within geologic conditions. For example, the contemporary Irish word for topography is "dinseanchas," but this is a word with an older set of more complex meanings that could be described as something more like "strategic landscape knowledge." It was the kind of knowledge prized by military chiefs and bards alike, because it allowed them to both plan actions and tell the story of those actions according to the terrain. Knowing where a river was narrow enough to cross, and in which months, or where wetlands could bog down troops, or where a tide might cut off or create access to a coastal headland was critical strategic knowledge. Contemporary people need to recover the capacity to synthesize and tell stories like these, but about the dynamics and structures in our own urban landscapes that will allow us to adapt successfully to a new climate. Estuary cities need to know their own stories, and tell them.

Estuaries lie inside what are sometimes referred to as geologic basins. These basins are lower than the surrounding rock, and often are in the process of subsiding. Like shallow bowls that tilt towards the ocean, basins provide pathways both for the water draining out of the higher ground around them, and for saltwater tides to enter. These basins may be shaped by fault zones, as in the San Francisco Bay, or by a long, shallow tilting of the earth's crust, as in the Boston area. Cities have been built in basins because they're relatively flat, with access to both freshwater and saltwater harbors.

To visualize the structures and dynamics that matter to coastal adaptation, it's helpful to think about geological patterns as armatures cutting through a three-dimensional volume of material. Geology produces a connected regional anatomy analogous to bones and muscles, circulatory systems and skins. These can be deep or shallow, and are often expressed at the surface if you know what to look for. A drastic contrast in materials, such as a contact between old volcanic rocks and recent sandy gravels deposited by rivers, can form an important structural boundary. Faults cut through all materials, re-directing the flow of surface water to create small lakes, and altering underground flows of groundwater and seismic energy. When seismic energy is generated, materials change their behavior- sand, clay and fill materials can behave like a liquid as an energy wave passes through them.

Reading landscape armatures

In 2011, the coastal New Zealand city of Christchurch experienced a major earthquake that killed 185 people and left thousands of structures in ruins, destroying 80% of the city's underground infrastructure (New Zealand History 2011). As the city plans for its future, its elected officials and designers also have to consider sea level rise. Christchurch offers an example that cities of the American west coast can and should learn from, because their major earthquakes are coming. By reviewing the conditions that shape future options for Christchurch, we can see how synthesizing the geology of an urban estuary's basin creates a context for adaptation to sea level rise.



Geological base map by GNS Science, http://data.gns.cri.nz/geology/, fault line annotations by the author.

Figure 2. The Christchurch geologic region contains a set of armatures at a larger geographic scale, that mark structures produced by a longer geologic time frame of processes. The steep slopes of the sedimentary Southern Alps produced huge outwash plains, that provide useful sands and gravel to Christchurch as rivers carry them to the coast.

Christchurch was built in a basin that drains to the Pacific Ocean on the east coast of New Zealand (Figure 2) (Brown et al. 1995). The basin is bounded by sandstone mountains to the west, accreted "terranes" that arrived when the Pacific plate collided with the Australian plate, and a peninsula formed from an old volcanic cone to the south. A braided river, the Waimakariri, forms the northern boundary of the urbanized plain, which is itself made of successive river deposits of outwash gravels and sands originating in mountain glaciers that have mostly melted away. Stable ancient dunes fan out at the point where the riverbed begins to slant more steeply towards the western mountains, and run southward from the Waimakariri's mouth. Two smaller rivers, the Avon and the Heathcote, drain the city and empty into its estuary. A sand spit supplied by the sediment load carried by the Waimakariri closes off most of the estuary mouth, blocking out the ocean's waves (Figure 3).

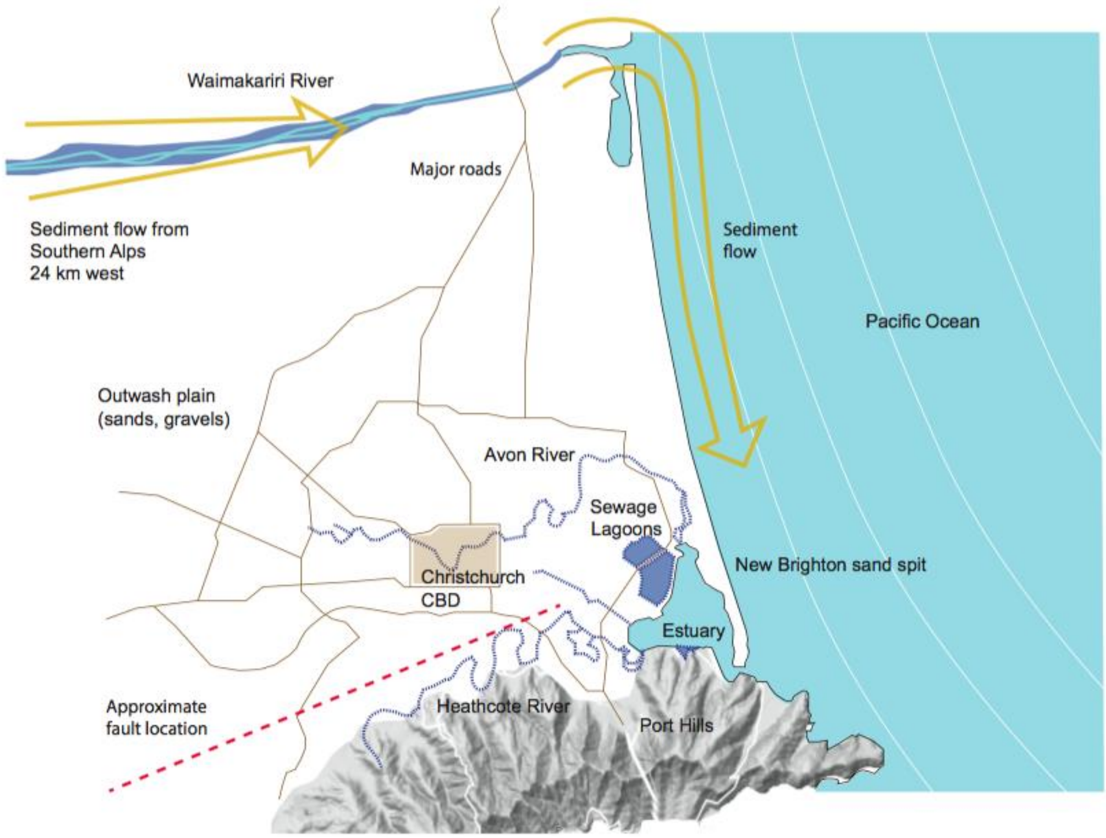


Figure 3. Mapping the armatures of the Christchurch landscape reveals a fishnet of roadways, one big fault line, the accreting sand spit, a radiating set of smaller rivers, and the basin boundaries created by the Waimakariri River to the north and the Port Hills to the south.

While the western mountains are known to contain many faults, the earthquake of 2011 occurred on a "blind" fault, one that was previously unknown (Bradley and Cubrinovski 2011). It stretched down towards the ocean from the sandstone mountains to the west, along the volcanic Port Hills on the southern boundary of the city's basin. When the fault slipped, it created a rippling energy wave with a magnitude of 6.7, which doesn't sound catastrophic – but it was. Geologists think that part of the energy wave reflected off of the volcanic rocks to the south, cracking large boulders off the bluffs, and returned towards the city – leading to the fastest vertical acceleration ever recorded in an earthquake event, and a very high lateral acceleration.

And because the city was built on the sands and gravels of an old glacial outwash plain with underground water (groundwater) very close to the surface, the ground movement produced extensive liquefaction (Arnold 2016). Cars were literally sucked down into the streets, which re-solidified around them when the shaking was done. Most of the people who were killed were in buildings that collapsed, and a few died when boulders crashed through homes. More than 5000 damaged homes were purchased and removed to prevent future loss of life, particularly in the so-called “Red Zone” along the Avon River where liquefaction was dramatic.

The question of coastal resilience is significant in relation to seismic events like the Christchurch earthquakes because many active tectonic margins occur along coastal areas with large cities. From Anchorage to Santiago and Seoul to Christchurch, the active tectonic margins of the Pacific plate create vulnerability to tsunamis and earthquakes that can not only cause solid earth to behave like a liquid, but can permanently change the tilt direction of flat plains. In Christchurch, the land near to the south near the quake’s epicenter tilted up by half a meter; in the area around the Avon River, closer to the city center, the land subsided by half a meter. What was flat became tilted, dropping the basin a little further, and creating a larger area that could be flooded by high tides as sea levels rise.

Christchurch has some geologic advantages as well. For one, it is well south of the main belt of cyclone activity in the South Pacific, which are more likely to hit northern Australia than New Zealand’s South Island. Not having to design coastal adaptation to accommodate or block cyclone waves is a major advantage, since everything they build can be smaller to start, and be raised incrementally. Second, the steep sandstone Southern Alps to the west are soft and eroding. They provide a constant supply of sand and gravel to the coast -- carried by the ‘conveyor belt’ of the Waimakariri River. In its current position to the north, this big, braided river supplies sand to the spit that protects the Christchurch estuary from waves. The beach along this spit is growing wider naturally, as are its dunes (Figure 4). This sand and gravel supply could be used to build protective landforms along the inside edge of the estuary to prevent flooding from rising seas. The Japanese have used river gravels to build superdikes that are extra wide, and seismically stable for safe building construction (Figure 5). The Dutch use sand to build protective dunes and widen their beaches artificially, as their main defense against sea level rise. Those are the kinds of advantages that make Christchurch a place where landforms can be used for long-term adaptation.

Superdikes and sand gates

Suppose, for instance, that the city’s estuary was ringed with wetlands instead of the small walls typical of waterfront residential landscapes. Wetlands that are only 40 meters wide are likely to reduce incoming wave heights by as much as 70% during the year’s highest tides (BCDC 2013, Bay Institute 2014). The shallow substrate “trips” the waves and the vegetation slows them by friction. Proposals have been made arguing that levees would only have to be half as high, if they were fronted by gently-sloping marshes (Bay Institute 2014). If those “habitat wedges” of marsh can be designed to grow as sea levels increase, it’s not hard to add to the levee on the landward side as well – adding up to a biologically-active version of the Japanese superdike that does multiple kinds of work at once. These wedges of habitat could protect inland areas from storms, provide habitat, help to filter water quality, sequester carbon from the atmosphere, and provide recreational landscapes for people. Building a wider "wetland superdike" (or "eco-dike") may cost about half of what a conventional levee would cost, per kilometer (Bay Institute 2014).

Figure 4. Sand is already accreting onto the tip of the New Brighton sand spit. This diagram illustrates the process by which sand could close the estuary mouth, as more sand is delivered by waves over time. Eventually rising seas could overtake this process, however, and erode the sand gate.

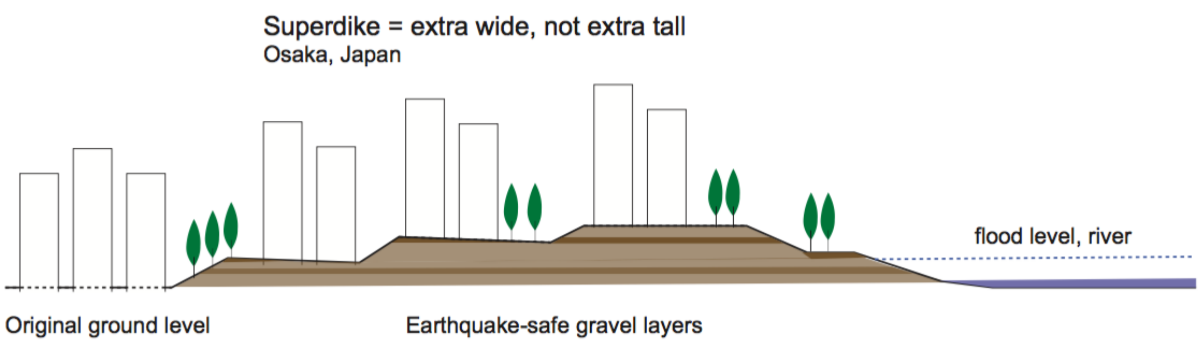


Figure 5. The Japanese superdike strategy uses layered gravels to achieve seismic resilience, using locally-available gravels that are carried down from the mountains by steep rivers.

On the ocean coast of cities like Christchurch, sand can be used to build a similar kind of habitat wedge. The Dutch refer to the width and height of sandy beaches and dunes as a 'prism,' representing and tracking changes in its sectional dimensions using the three sides of a long triangle. The coast is treated as a volume that changes over time through the addition of sand, not a two-dimensional line that must be preserved because it existed at a specific moment in time. Geomorphological theories of beach dynamics put this prism into the context of a dynamic equilibrium, in which accretion and erosion are like two directions the same system can travel in – depending on the direction and magnitude of waves as well as the mean sea level. In places where sand is accreting, a rising sea level could push back against today's balance of forces and tip the dynamics towards erosion (Figure 6). But because those theories were developed in a sectional representation of the beach, using only two-dimensions as a way of simplifying complex processes, we don't really know that accreting beaches will become erosional. Public agencies need to engage in reversible pilot projects on sandy coasts in order to learn, and be ready for surprises as the global climate shifts.

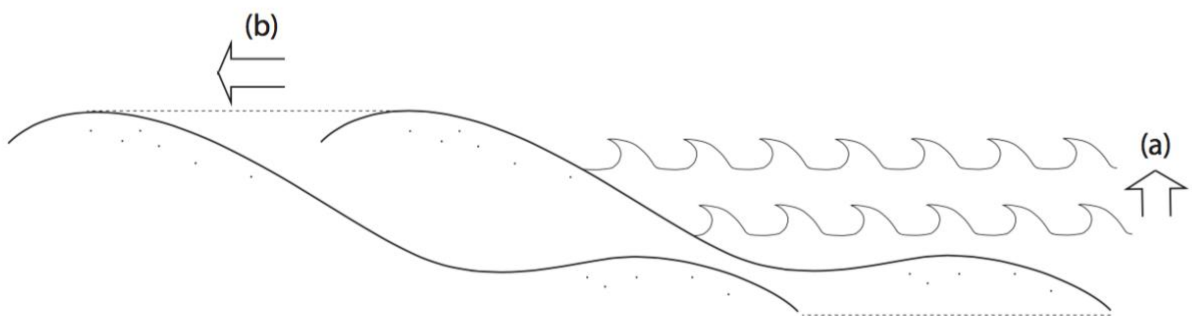


Figure 6. Bruun's Rule predicts that as sea level rises 1 unit of height (a meter, for example), the sandy profile of the beach will migrate inland 80-100 times that distance – unless it is blocked by a wall, in which case it would likely erode.

In some landscapes, like Christchurch, sand carried by rivers and waves is available as an asset that grows the beach and extends sand spits. But that's an unusual asset. On most sandy urban coasts, the beach is eroding because coastal structures like jetties at boat marinas redirect the flow of sand outwards, away from the shore, or because dams higher up in river systems trap sand before it reaches the coast. Even without these structures, many sandy shores are eroding simply because there are no more ice-age glaciers pushing sand into the system. To use sand on an eroding coast is to take on a role like that of Sisyphus in the Greek myth of a human being forced to roll a rock up a hill only to watch it roll back down, for all of eternity. This may sound like a bad thing at first. But one of the reasons for the longevity of this myth is that it represents something fundamental about being human – that mortality means all the projects we "roll uphill" will eventually roll down again, to be taken up (or not) by our children. Adaptation is a multi-generational process, a process of re-learning the world in each successive generation.

Re-learning a contemporary version of a landform-based approach to coastal resilience relies on our ability to recognize that landscapes have armatures – spatial elements that strengthen and support the processes we rely on. A ring of wetlands around an estuary can be seen as an armature. Expanding the width of these wetlands and buttressing them with earthen levees is a way of hybridizing a natural system with an urban system, particularly when buildings and roads are built on top. These hybrids make sense. People get to see the dynamics of their environment, instead of hiding behind walls that keep them unaware of the changes happening around them. We become something more unabashedly like gardeners of our larger environment, learning from the past forms of a landscape rather than trying to "freeze" the processes of change. When the world begins to change more rapidly, we can engage with it to a greater degree -- adding to and incrementally re-shaping our own habitat. Understanding the strength and value of landscape armatures, of landforms in a geological and ecological context, is the key to our success.

One of the most difficult coastal adaptation questions is what to do where a large body of water enters the open ocean (as at an estuary or river mouth), or where a tributary river or stream enters an estuary. Some major port cities have built iconic storm surge barriers that open and close mechanically at the mouths of estuaries and tributaries (Hill 2015). These are big, expensive pieces of concrete and steel infrastructure with complex moving parts, like the Rotterdam Barrier. They were designed for a world that didn't have rapid sea level rise. The footings of the structures that support the moving parts, like the footings of any wall, are sized to the height of the structure. The mechanical movement itself is effective within a range of sea levels, but can't be extended above that range. Unless these storm surge barriers are built for 100 years of sea level rise (which may be as much as 3 meters above today's storm surges), future generations will have to replace them. The Thames Barrier already has to close much more often than it once did, and will eventually have to be closed all the time unless the shores of London's metropolitan areas are themselves raised (Reeder and Ranger 2011). As the sea rises, mechanical barriers will have to remain closed because the land behind them is not able to handle the higher water levels when they open (Walsh and Miskewitz 2013).

In addition, tide gates and surge barriers alter the ecology and geomorphology of the water bodies and ecosystems on the landward side (Giannico and Souder 2005). Even if a tide gate is only closed at high tide, the closure starves inland marshes of the sediment deposits that would come primarily on the incoming tide, and which they need to both sustain their biological diversity and grow upwards to keep pace with sea level rise. These inland waters also often decrease in water quality, because they are no longer "flushed" as effectively by high tides. Invasive species that can tolerate lower water quality often expand in the area they occupy. In other words, a gate that opens and closes is not an effective long-term solution to adaptation at a tributary or estuary mouth. What alternatives exist?

The tip of the sand spit that protects Christchurch's estuary is also growing (Figures 7 and 8). It's a normal thing for many coastal lagoon openings to be closed by sand spits seasonally, during months when the volume of sediment transported along the shore increases. Some of those sand closures on lagoons open naturally when high river flows force the sand out of their way. Others are literally bulldozed open by people, when freshwater entering the lagoon from the landward side threatens to cause flooding. What if we thought of that as an alternative to today's tide gates, a feature we might call a "sand gate"?

Figure 7. The New Brighton sand spit in Christchurch, New Zealand.

Figure 8. View of the New Brighton sand spit from the south, at Shag Rock.

Sand mounds could be placed artificially at the mouth of a small tributary, allowing small amounts of water to flow through the sand at a regular rate, while keeping out the erosional energy and height of waves. It's a common natural landform in dry climates, where tributaries may only flow seasonally and rarely have the force to push the sand out of their way. During low flow months, the freshwater disappears into the sandy delta at the mouth, slowly percolating through to the estuary or open ocean. In a rare heavy rain event, the water can push the sand open – or bulldozers can. A sand gate would mimic natural processes, and have multiple benefits in addition to blocking waves, such as providing some filtration of the freshwater as it passed through, providing habitat for sand-nesting birds, and giving both humans and animals humans a way to cross the tributary mouth without a bridge.

The use of "sand gates" as flexible barriers at the tidal mouths of tributary rivers is a new proposal, a landform for which I have become the first tentative advocate. Like tide gates, they would change the flow of sediments and fish. They might not work, and should be tested using reversible pilot projects. But sand gates are an example of a flexible landform approach that, like wetlands, dunes and beaches, can be raised incrementally.

The work we do to build resilience by artificially enlarging coastal landforms would be a legacy for future generations, a foundation they can build on or expand – rather than a liability that they will still be paying for after it has ceased to function. In the worst maladaptive case, fixed structures that are built too small for future conditions might represent an additional liability because not only are they insufficient, but they also have to be removed and replaced with a newer and more expensive structure. The concrete-and-steel foundations of walls and tide gates could easily be undersized, and limit the capacity to raise their height.

In contrast, experimental landforms are part of our human legacy; we've learned to make them from thousands of years of living on the coast (Hill 2011). Dunes and wetlands can be created with many laborers and lots of shovels, or few laborers and large mechanical equipment. What we need to re-discover is that these landform experiments belong in urban districts adjacent to coastal structures as well. When we pair an urban district strategy with an expandable coastal edge strategy, we will form a hybrid that (like many hybrids in plant ecology) is more robust than either of the original types (Hill 2015).

Ponds and canals

There are two driving processes that require us to rethink the goal of achieving dry ground behind new coastal structures.

One is the storm-surge (salty) or rain-driven (fresh) flooding that occurs at the mouths of rivers and small tributaries (Figures 9 and 10). Some of that flooding is permanent, as the mean sea level rises and low tides are higher. Some of it is temporary, as surge- or rain-driven floodwaters recede when the storm is over. If we can't manage this type of coastal flooding completely with a sand gate or mechanical gate, we are left with two choices: build long dikes along the edges of the river mouth, which can fail catastrophically if an event exceeds the designed height and strength of those dikes, or re-design the adjacent urban districts to be resilient to temporary flooding.

Figure 9. Flooding during an extra-high tide on Plover Street, Christchurch. Seawater from the estuary is flooding into the street, and being conveyed from there into the neighborhood.

Figure 10. A woman tries to clear a storm drain on Tern Street during the high tide event. As groundwater rises, drain inlets like this one will be filled and will not drain unless special flaps are installed on the ocean outlet of drain pipes, and unless pipes are replaced when they crack.

Under normal circumstances (ie, without sea level rise), designing for temporary flooding would be enough – surge- or rain-driven floods would indeed be temporary. But as sea level rises, some saltwater flooding will become permanent. Temporary fresh and saltwater flooding will occur farther inland. These kinds of flooding are familiar, but will show up in surprising places. What is unfamiliar is that the freshwater “lens” we call the water table will rise on top of rising seawater. Seawater is denser than fresh water. The lighter-weight freshwater that is stored in the ground after many rainfalls will be forced upwards. This rising water table will be the second major driver of flooding in coastal areas (Rotzoll and Fletcher 2012).

A rising water table reveals the extent to which the design of conventional urban districts relies on having a predictable “dry zone” immediately below the ground surface. Pipes that convey sewage and rainwater away from buildings and roadways can be infiltrated by groundwater if it rises to surround them. If the pipes are not regularly replaced or repaired, they will have cracks that make infiltration by groundwater very common. Seismically-active regions often have cracked pipes. Countries like the United States where local communities do not regularly maintain or replace their underground infrastructure have cracked pipes. Cities where major flooding occurs, like New Orleans, can also have cracked pipes from the weight of water sitting on top. In short, many and possibly most cities have cracked underground pipes that are meant to carry waste and excess water away. These pipes won't function for either purpose if they are filled with groundwater most of the time. Basements and toilets can back up with raw sewage; rainfall can cause more serious flooding because it has nowhere to go. If we lose the shallow dry zone where most cities place critical urban infrastructure, we can also lose the function of the infrastructure.

Urban areas where land has sunk or 'subsided' offer us a preview of that future. Using pumps to turn wet lands dry in the Netherlands and the US Gulf Coast led to very significant land subsidence, because the dry soils have less volume. Pumping up large amounts of groundwater for drinking water, irrigation and industry - as well as drilling for oil and natural gas - have also caused major land subsidence in coastal areas. In the California Delta, areas of land called "islands" that once sat above the level of the river waters were diked and dried for agriculture; now they sit several meters below the water level of adjacent rivers. In all of these areas, gravity can no longer do the work of removing wastewater or floodwater. The Dutch maintain a sophisticated system of pumps that allow them to legislate the depth of the water table, using a lot of energy and relying on a culture of skilled operators and frequent maintenance. Most other countries lack this deep-rooted culture, which includes political support for the costs of expensive mechanical infrastructure.

Before the development of highly efficient mechanical groundwater pumps, low-lying cities were designed with ponds and canals to collect and convey both stormwater and shallow groundwater. In cities with high water tables, like Amsterdam and Venice, canals were used to drain groundwater away from the interior of a buildable urban block. The same canals served as transportation infrastructure, bird habitat, and as locations for low-cost floating homes. In Chinese cities like Suzhou, a complex system of ponds was integrated with urban blocks and used to manage stormwater.

Ponds and canals are spatial strategies for coping with a shallow water table. Ponds are also often used in sequence, to manage the quality of water coming off the land and into the nearshore environment by providing filtration and sequestration of nutrients like nitrogen and phosphorus. Together, ponds and canals can perform as transportation and recreational resources, and create stable sites for buildings. They're interesting as strategies in and of themselves, but what's really useful about ponds and canals is evident from a simplistic characterization of the way they are constructed.

The oldest idea in landscape architecture, and perhaps in human manipulation of the land, is to dig a hole and use the material from the hole to build a mound. Medieval castles were built on mounds, which were themselves built with the material that came from a trench surrounding the site – the defensive moat. With rising sea levels and water tables accompanied by more frequent river flooding, coastal cities should embrace the beneficial re-use of sediment from dredging to build superdikes with wetland habitat wedges on the estuary side. But we can do more than that. We can avoid the creation of a complex system of pumps whose failure would be a disaster by digging ponds and canals behind the superdikes, and using that sediment as well to build the coastal landforms higher over time. With all that we've learned in recent years about the use of pontoons in heavy construction of bridges and wind turbines, it has become clear that ponds can support entire urban districts – districts that are genuinely adapted to flooding, because they simply rise and fall on the smooth water surface of a pond that has no waves.

Ponds surrounded by superdikes on the estuary side can provide safe waters for floating pontoons that support whole urban blocks, with 3 to 5 story buildings (Figure 11). By placing the ponds behind the superdikes, a water-based urban district can accommodate both a high water table and flooding from rainwater. In fact, the ponds can be used to remove flooding problems in adjacent neighborhoods by receiving the stormwater from existing streets. The ponds would serve as a district-scale infrastructure for managing stormwater, while expressing the level of the groundwater and providing a recreational amenity. Perhaps best of all, for places like Christchurch and San Francisco, floating urban blocks would provide protection from seismic energy waves using the "cushion" of the water. Instead of putting buildings on deep, expensive foundations in urban fill areas, those buildings can be floated on water displacement foundations – pontoons, with flexible infrastructure lines linking them to fixed infrastructure on land. This means that instead of engineering soils to prevent liquefaction, housing can be built that anticipates liquefaction – by floating on a liquid surface. When lateral spreading occurs, it would only be the edges of the pond and the land under the adjacent roadways that slump – not the ground under the buildings (Figure 12).

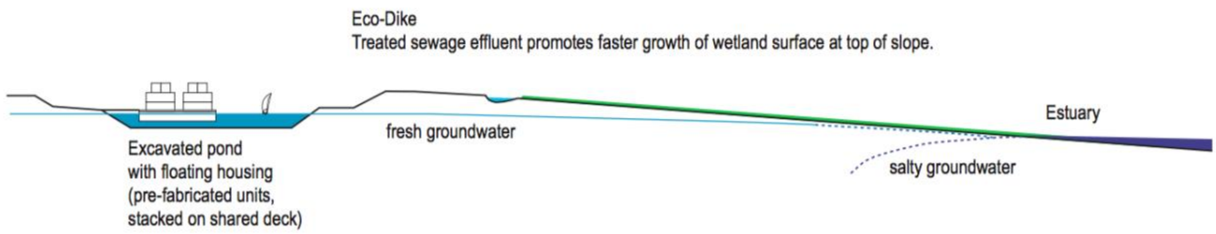


Figure 11. An "eco-dike" is a superdike (an extra wide dike) with a wetland on its seaward face.

From an ecological perspective, the opportunity to collect stormwater from a larger area translates into an opportunity to filter it before it enters an estuary. The canal and pond systems can allow sediment that has pollution attached to it, like phosphorus or metals, to drop to the bottom in designated locations, and periodically remove that polluted sediment with a hydraulic dredge truck. Green infrastructure systems can be extended out from the ponds on surface streets and parking areas to increase the filtration performance of the whole landscape, letting the ponds collect only the overflow sediment from extreme rainfall events.

Now imagine that these ponds, which are providing safe space for new housing and recreation while helping to clean urban runoff water, are "built upon" in a modular way – with pontoons and prefabricated housing units that can be craned in and stacked, and then craned out if the location is overwhelmed by a faster sea level rise. The prefabricated housing units can be re-stacked elsewhere with no loss in value, no abandoned pile foundations, no underground pipes

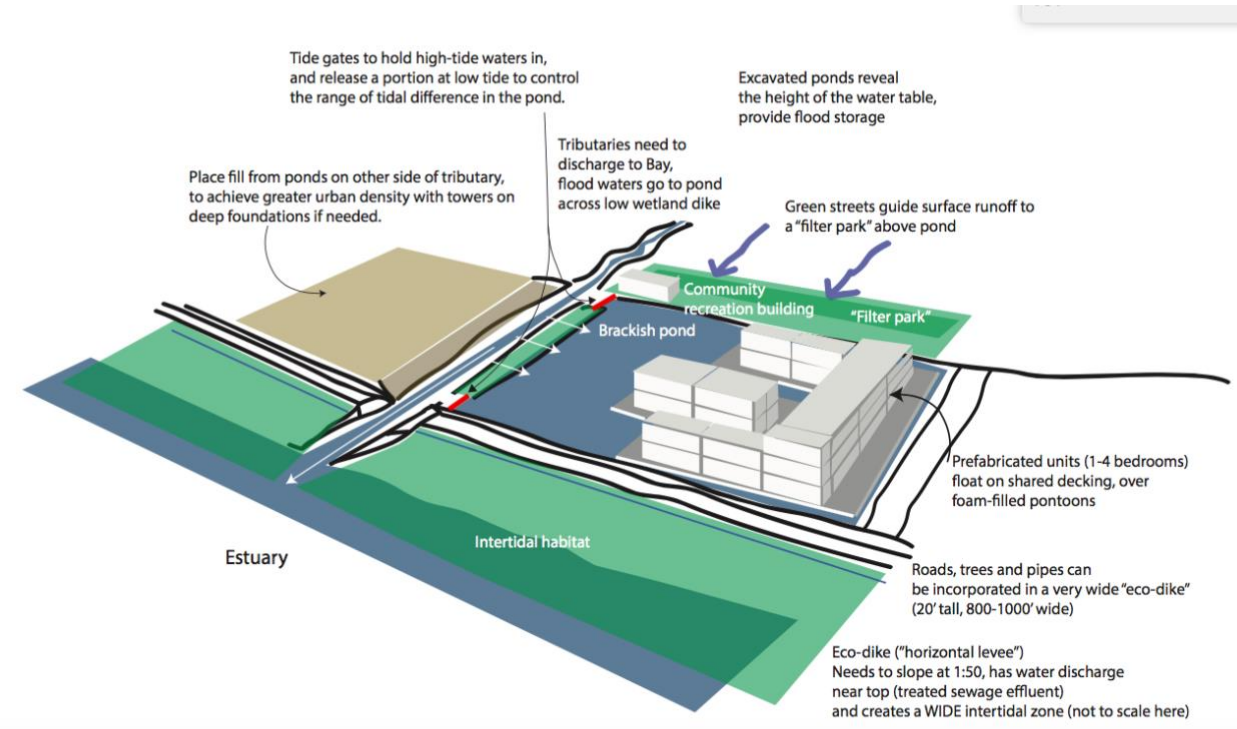


Figure 12. Artificial armatures of topography can be used to create protected ponds for floating housing. Creek water would be directed away from the pond, while stormwater would be directed into it for temporary storage and to flush the water of the ponds. Tide water could be captured and held to mute the vertical difference of the water level as tides rise and fall. Groundwater would be expressed by the excavation of the pond, and become an asset rather than a flooding and liquefaction hazard.

left behind. New sets of ponds can be dug farther up slope, where conventional housing can't be sustained because of rising water tables and tributary flooding. And the cut material can be used for expanded superdikes, continuing to protect the built environment while building a higher foundation for wetland habitat. All of this adaptation using landforms can be accomplished incrementally, so that each generation can add layers of material without having to pull out and replace the last generation's investments. We would be genuinely building a foundation for the future, something that is a legacy instead of a liability.

Extending the strategies

Almost all coastal urban areas need to re-think both their shorelines and their adjacent urban districts. Taking a landform-based approach offers the advantages of being incremental, creating multi-benefit edges that support habitat and recreation, and being translatable to economies where extensive grading work is done with shovels instead of bulldozers.

The alternatives have serious drawbacks. Building walls in an environment with wave energy often leads to loss of habitat on both the ocean and land sides of the walls. In general, walls of all kinds are brittle – they can fail catastrophically, and will require replacement instead of placing new layers of material to increase their height over time. Landforms can fail too, but the superdike model offers an example of how going "big" (really, going wide) can reduce or eliminate the risk of sudden failures. Landform materials offer multiple benefits, as in the way that sand allows slow percolation of water, with filtration benefits, while blocking out waves. Removal of existing urban districts may work in some areas, and may be the best solution. But in many cases, it will be expensive to remove foundations, underground pipes, and contaminated soils, and relocation may be too difficult a process from a political standpoint to complete in a timely way. Allowing people the option to buy new houses in an infrastructure of ponds has proven popular in the Netherlands, and can be in many other areas as well.

In constrained coastal urban areas where land is at a premium, such as Singapore, concrete caissons are being filled with sediment and used to build what is effectively a hybrid wall/landform combination. A caisson is essentially a concrete container, open at the top and bottom, that sits with its base buried in the sand and serves to hold fill material. Like a honeycomb made of concrete and fill, an interlocking series of these containers is used to create a stable base for buildings. The purpose of these structures is to act as a stable base for building and road construction. In deeper water, this may be the only real option. But a series of caissons can also serve as an outer ring of defense against waves and storm surge, with ponds on the inland side. Ponds can be constructed behind the outer ring of caissons that provide shallow water habitat and a wide range of recreational benefits, along with the potential for adding floating blocks of buildings and floating roadways.

Being resilient and adaptive

Our climate is changing, and as a result, everyone and everything exists in a changing environment. Strategic resilience is a concept that was proposed specifically to address this need to be nimble and adapt. Ecological resilience is a different concept, which refers to the ability of an ecosystem to recover from an event. But recovering from an event is no longer enough. It’s necessary, but not sufficient.

Because climate change is driving global sea levels higher, coastal resilience is a condition that can no longer exist without adaptation. We must be adaptive to long term, permanent changes like higher seas as the foundation for our capacity to be resilient to events. I would argue that it’s useful to distinguish between these terms, because the strategies we use to adapt may both be distinct from and influence the strategies we use to recover from temporary disaster events such as hurricanes and earthquakes.

One example of why it is important to distinguish between these two goals is the question of how high coastal cities should build their defenses, whether those are landforms or concrete-and-steel walls. The answer depends on whether those cities’ urban districts are vulnerable to major damage and loss of life when flooding occurs, or whether they are designed adaptively so that they can function even when flooding occurs. Without deciding on a strategy for urban districts inside the coastal barriers, there is no logical way to decide how high the coastal defenses should be.

We studied the cost of raising coastal barriers all around San Francisco Bay, so that everyone could see the enormous cost of using levees and walls vs. other strategies. The numbers are big: approximately $57 billion USD for adapting to 1 meter of sea level rise, along 1300 kilometers of shoreline where flooding would otherwise occur. We found that one of the largest single influences on cost for conventional flood control structures will be the requirement to build seawalls and levees high enough to prevent water from flowing over the top in extreme events, a phenomenon known as “overtopping.” The cost of building walls and levees to prevent flooding in events with a 1% probability of occurrence would be almost twice the cost of building the same structures to protect against typical tide heights with a 1-meter higher sea level. The strategic implication of these findings is that it makes sense to consider allowing temporary, extreme events to overtop coastal structures and cause some temporary flooding in adjacent urban areas. If those urban areas themselves are required to adapt to this condition, so that people will be safe and urban functions can continue during a flood event, coastal structures can be smaller and more multi-functional – providing habitat and recreational value as well as flood reduction.

Building “floodable” urban districts will allow people to maintain an awareness of the coastal dynamics where they live, and may result in helping urban populations become more truly resilient over time. If typologies such as floating urban blocks and floating roadways or secondary mobility systems allow people and property to remain safe during temporary flood events, and also protect functional urban infrastructure during the event, our ability to live near the coast during this time of rising global sea levels and rising groundwater will be enhanced.

Floodable urban districts can use pond excavation to expose shallow groundwater, revealing its seasonal and year-to-year fluctuations, as well as provide room to store temporary flood waters due to overtopping from coastal surges. Floating urban blocks in these permanent ponds would provide safety from seismic events as well. Canals can extend from the ponds into existing dense urban areas, helping to drain away their high water table as well as excess rainfall. A filtration zone of wetland ponds can be used uphill of the “housing ponds” to capture contaminants in stormwater as it flows downhill, keeping the ponds relatively clean. Ponds at the shoreline can also store enough rainwater to remove upland neighborhoods from flood zones that are defined by rainfall accumulation, protecting people in those neighborhoods and allowing them to avoid expensive insurance costs.

The key is to achieve coastal resilience in a way that kick-starts a long-term process of adaptation. Any proposal for resilience that doesn’t consider this long-term need for change over the next two centuries is at best a delaying tactic, and may be actually maladaptive – like the construction of brittle concrete-and-steel walls that can fail catastrophically, or will need to be replaced by future generations at great cost. Otherwise, future generations could conceivably have to replace these massive structures while they are still paying off the bonds used to finance them, if sea level rises faster than the estimates being used to design those structures.

The justice rule for resilience

In order to hold a broader public conversation about resilience it may be critical for designers and planners to consider justice arguments. These include arguments about who pays and who benefits, as well as arguments about whether change needs to happen now, affecting today’s occupants of seashore homes, or whether it can happen later instead.

The decisions urban regions make in the next ten or twenty years about coastal resilience and adaptation should be grounded not only in geography, but in concepts of inter-generational and international justice. From a practical perspective, decisions that don't consider a justice context may well be unstable, and result in a waste of resources when they are eventually abandoned. And from a justice perspective, the generations and nations that have used the most fossil fuel and contributed the most CO_2 to the atmosphere owe a debt to other nations, and to future generations.

Today's children in coastal areas all over the world will inherit radically more difficult environments because of a legacy of consumption patterns in the developed world, even if people in developed countries changed to entirely renewable energy sources immediately. Seen from that perspective, coastal resilience can only be achieved if there is a transfer of wealth from today's generations to tomorrow's – by building a new coastal edge that is genuinely a legacy, a foundation for their future efforts, not a liability. Similarly, developed nations like the United States that have generated by far the most greenhouse gases must adapt in ways that are inexpensive enough to allow them to continue to pay for adaptation in other countries. Without this transfer of wealth between nations, crises caused by waves of refugees, resource shortages, and militarized territorial disputes will make adaptation much harder, if not impossible.

As we consider what coastal resilience means, both the armatures contained in landscapes and the underlying need for justice should be central elements of that definition.

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