Title
Coastal infrastructure: a typology for the next century of adaptation to sea-level rise

Permalink
https://escholarship.org/uc/item/6tq625j0

Journal
Frontiers in Ecology and the Environment, 13(9)

ISSN
1540-9295

Author
Hill, Kristina

Publication Date
2015-11-01

DOI
10.1890/150088

Peer reviewed

Coastal infrastructure: a typology for the next century of adaptation to sea-level rise

Kristina Hill

Categorizing the choices in coastal infrastructure that are available to policy makers will allow for comparisons of their potential impacts on ecosystems and of their value in preparation for long-term sea-level rise. Although similar approaches have been described elsewhere in different policy contexts, this article focuses on evaluating physical infrastructure types – including hybrid structures that combine landforms with concrete and steel elements – based on historical differences in engineering practices. Such structures can be optimized for different phases of coastal adaptation and can provide multiple benefits (eg supporting ecosystems as well as minimizing flooding in coastal cities). Key factors in a geomorphological, ecological, and land-use context must be taken into account when selecting various infrastructure strategies, to ensure that they function as intended. The San Francisco Bay region provides an example of how this typology can be applied to help policy makers choose more successful strategies as coastal areas plan for sea-level rise.

Front Ecol Environ 2015; 13(9): 468–476, doi:10.1890/150088

Humans have altered coastal areas by introducing artificial structures dating back to at least 2580 BCE, on the shores of the Red Sea in modern Egypt (Tallet and Marouard 2014). The first coastal structures that appear in the archaeological record were rock breakwaters, built to protect harbor entrances from wave energy. Artificial harbors shaped by rock walls were also an early invention, often contained within early cities by gates built both for protection from attacking navies and to control the passage of goods and travelers (Blackman 1982). In 79 CE, Pliny the Elder reported encountering people on the northern coasts of present-day Germany and the Netherlands who built artificial mounds that enabled them to live in a tidally flooded environment (Henry 1855). The initial driver for mound construction in sandy tidal areas was access to small-scale fishing and trade, while the main driver of later dike construction was urban growth, which led to more land being dedicated to intensive food production (Charlier *et al.* 2005).

In a nutshell:

- Typologies are useful when many examples of alternative infrastructure design strategies exist, and a high-level categorization allows planners to perceive the pattern of alternatives under consideration
- Many coastal regions have begun to plan for adaptation to sea-level rise, and are in need of a clear overview of options that can be discussed with policy makers, advocacy organizations, and the public
- A mix of adaptation strategies often provides the broadest suite of benefits, including newer approaches that involve living system components such as wetlands, sandy beaches, sandbars, or living breakwaters
- Some regions have limited experience with these new approaches and may benefit from using decision-support tools that identify such ecosystem-based strategies
- Investment may need to be in phases to accommodate higher rates of sea-level rise over time (ie investing in a new seawall or floodwall structure that may require replacement or relocation in the future)

Department of Landscape Architecture and Environmental Planning, University of California, Berkeley, Berkeley, CA (kzhill@berkeley.edu)

In past centuries, the term "infrastructure" referred primarily to masonry and metal constructions, but more recently it has come to signify any structures (eg powerlines, floodwalls, wetlands) that support or alter the spatial and temporal distribution of resources and risks for human benefit. Several new terms have emerged to serve this new definition of infrastructure; for instance, "landscape infrastructure" alludes to the capacity of topography, soils, and entire ecosystems to support human needs (Beach 2003; Hill 2011), whereas "green infrastructure" typically relates to the use of plants and soils to provide ecosystem services (eg Arcadis 2014). Coastal wetlands, sand dunes, beaches, and freshwater ponds are treated as supporting structures for flood management, co-existing in hybrid systems with levees, breakwaters, seawalls, floodwalls, tide gates, storm-surge barriers, pumps, and pipes. The US Army Corps of Engineers (USACE) has developed guidelines for what they call "natural and nature-based features" (NNBFs) that are now considered by federal agencies as functional components of coastal infrastructure designs (Bridges *et al.* 2015).

Drivers of new investment

In the second half of the 20th century, new residential and recreational land uses have been the primary drivers of investment in engineering projects at local and regional scales in coastal areas in the US (Beach 2003; Hill 2011). Marina development, breakwater or jetty construction to protect marinas and harbors, and the addition of highways, bridges, and pipelines have all been major public projects, along with the development of deep-water ports with dredged shipping lanes (Pilkey and Dixon 1996). Tide gates and upriver dams used for flood protection, irrigation, and hydroelectric power generation have also had major impacts on sediment dynamics in coastal areas, often accelerating erosion by depriving coastal landscapes of sand or silt (Giannico and Souder 2005). Factors that are likely to increase investments in coastal infrastructure over the next century include increased vulnerability of developed areas to flooding (Aerts *et al.* 2011), higher rates of salinization of water supplies and a corresponding and growing need for fresh water (Sekovski *et al.* 2012), ecosystem losses from erosion and development (Gedan *et al.* 2009; Jennerjahn and Mitchell 2013), and intensified international trade connections via ever-larger ships (Bruun 2005).

■ Impacts of coastal infrastructure on natural systems

Artificial coastal structures, along with their construction and maintenance, have had a variety of effects on the geomorphology and ecology of coastal systems (Bulleri and Chapman 2010; Nordstrom 2014). For instance, these structures often interfere with the spatial dynamics of sediment transport, salinity, flooding, and animal movement or reproduction. At the same time, the physical and biological systems of the marine environment have extensive impacts on built structures (see Burcharth *et al.* 2014).

On open sandy coasts, structures such as groins, channels, and breakwaters typically alter wave energy regimes and sediment supply (Nordstrom 2014), which affect fundamental processes of longshore sediment transport that influence levels of turbidity and rates of accretion and erosion. This in turn generates changes in barrier island and beach dynamics, dune growth and migration, and inlet locations, even where these landscapes are protected from human development (Louters *et al.* 1991). The geomorphological impacts of coastal infrastructure (those that alter patterns of sediment erosion and deposition) often lead to changes in biotic communities above, within, and below the intertidal zone (Mattheus *et al.* 2010). The material, shape, anchoring method, and surface roughness of coastal infrastructure can also influence diversity and population sizes within biotic communities (Perkol-Finkel *et al.* 2012). Tide gates, seawalls, bridge ramps, and roadways may all cease to function as designed when relative sea levels rise or when storm-driven flooding becomes more frequent or more severe (Johnston *et al.* 2014). Bluffs may become highly eroded by changes in the relative height of waves, which can destabilize coastal infrastructure located outside the actual tidal zone (eg roads; Barton *et al.* 2014).

Historically, coastal cities were usually built in naturally sheltered bays or on the banks of tidal rivers that provided safe harbors for ships. In large bays and estuaries, artificial structures can alter salinity dynamics as well as sediment concentrations and transport (Kadiri *et al.* 2012). Changes in sediment or wave energy dynamics can lead to erosion of wetlands and other ecosystems along estuary shores, together with changes in water quality if the flux of ocean water into the estuary is reduced (Eelkema *et al.* 2013). Exotic species, which can have widespread negative impacts on the biodiversity of urban estuary systems, often enter estuaries via ships' ballast water (Ruiz *et al.* 2000). Activities at commercial or military ports, and the industrial sites typically associated with those ports, introduce chemical pollutants into estuaries that can be dissolved or suspended in the water column or deposited in sediments. Major energy-generation, desalinization, and sewage treatment facilities in bays and estuaries can also affect biota through pollution or by altering physical characteristics such as water temperature (Schifter *et al.* 2011). Marine borers and other organisms may also damage or cause failure in coastal infrastructure systems by blocking flows or removing material (Borges 2014). Sea-level rise is expected to have major impacts on infrastructure in the shore zone of estuaries (Flood and Cahoon 2011; Biging *et al.* 2012).

■ A typology of infrastructure strategies

Structures

One method of gaining insight into the advantages and disadvantages of different coastal infrastructure types, and how they might be applied in a given environmental and land-use context, is to organize a typology based on the history of coastal engineering practices. Typologies are defined here as "conceptually derived interrelated sets of ideal types" (Doty and Glick 1994), which can be used to develop hypotheses about the causes of deviations from graded-membership ideal types. Graded-membership types are defined by a best example, but are grouped by degrees of similarity. For instance, "walls" are typically represented as solid barriers, but they can also be built to allow water to filter through them, and would still be considered walls. Leaky walls are sufficiently similar to impermeable walls to be considered as the same type of structure. A typology can be a valuable heuristic tool in decision theory, used to reveal omissions of important options within sets of alternatives that occupy a solution space (Chernoff and Moses 1959; Mees *et al.* 2014). The historical record of coastal engineering practices provides a starting point for the development of a simple typology, consisting of four ideal types of coastal strategies that may become more useful over time as new innovations and hybrid strategies are introduced.

The top-tier categories in this typology have their origins in the history of structures associated with rocky shore environments – such as walls and breakwaters – rather than sandy/marshy environments, where

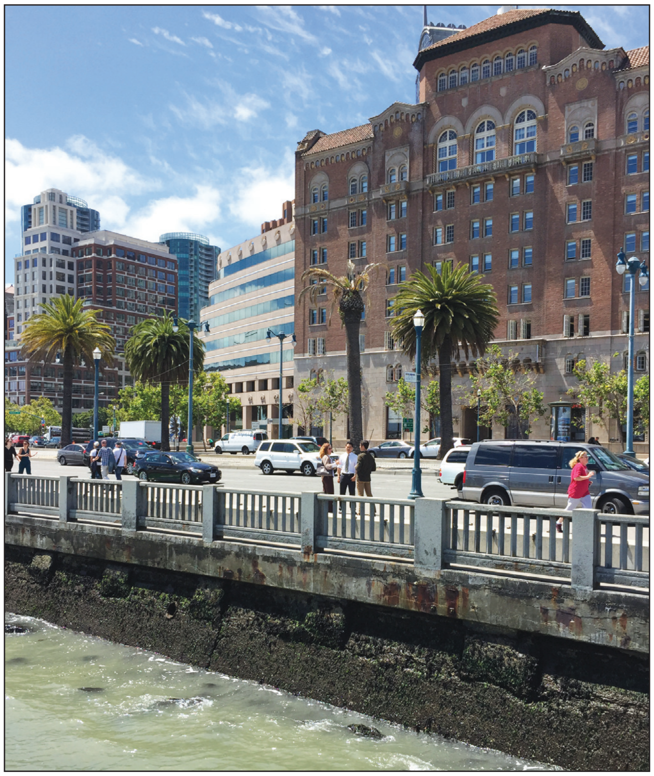

Figure 1. *Seawall in San Francisco, California. Seawalls are fixed walls made of reinforced concrete or steel, often combined with wooden pilings treated with creosote. They are designed to retain unconsolidated fill on the landward side, which contains the footings of buildings and other infrastructure. Relieving platforms constructed of wood, or concrete and steel, hold the walls in place. These walls were essential for bringing ships directly into urban quays to efficiently load and unload cargo or passengers.*

silt, sand, and gravel materials were used to shape new landforms such as mounds and dikes. The second tier of the typology is defined by whether the structure is static, meaning it is not designed to move, or dynamic, meaning it is designed to move in specific ways. These two simple tiers create four classes of coastal infrastructure strategies, which can be used to generate hybrids that combine elements of the four classes. The purpose of this typology is to gain a better understanding of approaches that may be underutilized relative to their potential.

Walls: static or dynamic

The structures that developed from design practices in rocky shore environments with fortified harbors tend to be wall-based and rigid; be made of stone, concrete, and metal; and function as either movable gates or static walls (Figure 1). In contemporary practice, these structures typically consist of inflexible walls made of concrete and steel, and are fixed structures, such as a seawall or dam. Tidal energy dams, or "barrages", may be built as a hybrid of fixed concrete-and-steel walls and earthen dikes, but like other dams they alter the fluxes between downstream brackish water and upstream fresh water as they generate power (Kadiri *et al.* 2012). At the Annapolis Royal tidal barrage in eastern Canada, for instance, researchers have documented higher rates of shore erosion in the freshwater zone upstream of the barrage, most likely the result of wind-driven waves that have become more powerful after the construction of the barrage (Morris 2013).

Walls can also be designed to function dynamically, moving into position only when needed – tide gates, which are usually closed during the highest tides to prevent inundation, are simple examples. The Thames Barrier outside London, UK, is a much more complex version of a dynamic wall, formed by long steel sections between towers that "rest" flat in the riverbed and are rotated into place to block storm surges (Figure 2). The Eastern Scheldt Barrier in the Dutch Deltaworks system uses vertical gates in a similar way, whereas the Maeslant Barrier in the Dutch city of Rotterdam consists of two triangular frames with a curved wall at the end of each. These move laterally on tracks in the riverbed using hydraulic systems, dropping into the channel once they are in position to close off storm surges

While providing immediate functional benefits, these technically complex structures may offer a narrower range of functions because they do not typically provide any additional natural habitat or recreational opportunities. They may also be less adaptable to future needs given that they often require complete replacement if it becomes necessary to enlarge their height or

Arpingstone/Wikimedia Commons CC BY-SA 3.0

Figure 2. *Thames Barrier, with one gate raised for maintenance. The Thames Barrier consists of a series of moveable walls, built in response to a major North Sea flood in 1953. The Barrier protects valuable land in central London. Its walls rotate into place between towers placed at approximately 200-ft intervals across the Thames River near Woolwich, in response to storm surge predictions. Plans are being discussed to replace or enlarge the barrier as sea levels rise (see Reeder and Ranger 2011), which will be extremely costly.*

extent. Although well-suited to small construction spaces, such structures also introduce new risks associated with mechanical or electrical failures; the weaknesses resulting from relying on walls and pumps were evident in New Orleans, Louisiana, during and after Hurricane Katrina (Reid 2013).

Figure 3. *A superdike. This fixed landform is innovative because, unlike most earthen dikes, it is designed to allow buildings and trees to be built on the top level and on its back terraces. This gives residents a water view, increasing property values as well as raising awareness of the dynamic environment that surrounds them. This superdike was built in Osaka, Japan; it gains its unique structural qualities from being much wider (approximately 1200 ft) than a normal dike, which might be 400 ft wide to support 30 ft of height.*

Landforms: static or dynamic

In the past, coastal infrastructures in sandy and marshy areas were more likely to be landforms composed of materials that could be excavated and mounded but which required frequent labor for maintenance, and could be deformed and redistributed either incrementally by human labor or suddenly by natural processes associated with an extreme weather event (Charlier *et al.* 2005). The contemporary analogs of these ancient structures are designed either as rigid landforms that require frequent monitoring and maintenance, as in the case of levees or raised mounds, or as dynamic forms that are intended to be altered by predictable forces over time (VanKoningsveld *et al.* 2008). In the Netherlands, for instance, static landforms include many different types of dikes, such as the Afsluitdijk, built in 1932; this 32-km dike closed off a saltwater inlet of the Zuiderzee that was consequently transformed into the freshwater lake known today as the Ijsselmeer (Van de Ven 1993; VanKoningsveld *et al.* 2008). Likewise, in the 1990s, Japanese engineers built an ultra-wide platform, the superdike, to allow construction of an urban district on top of the dike (Figure 3).

The Dutch have also embraced dynamic landforms, most notably the Zandmotor (referred to in English as the "Sand Engine" or "Sand Motor"; Figure 4): a massive project initiated in 2011 – in which an artificial sand delta was dredged and positioned on the ocean coast between Rotterdam and The Hague, where wind and wave energy are expected to move the sand north and south – in order to widen the protective dune and beach shore zone of that region (Aarninkof *et al.* 2010). This dynamic sand landform is intended as a replacement for the annual nourishment of beaches and dunes (ie the addition of more sand following erosion) using heavy equipment, and is already producing benefits for birds and plants associated with less-disturbed sandy habitats along the Dutch coast, as well as providing recreational surfing opportunities for humans (van Slobbe *et al.* 2013).

While dynamic landforms, such as beaches or marshes,

Figure 4. *The Sand Engine. This 128-ha dynamic landform was built using 21 million cubic meters of dredged sand on the Dutch coast near The Hague in 2010. If it performs as designed, it will add 200 ha of beach along 10–20 km of coastline over 20 years as a result of wind and wave action, while adding habitat and recreational value (Stive* et al. *2013). The dredged sand delta is intended to erode, feeding beaches and dunes up and down the ocean coast. If it is successful, more sand may be placed in this location to continue the strategy of mega-nourishment for the Dutch coast. This panoramic view from 2012 was taken from the dunes on the landward side of the Sand Engine, looking toward the sea.*

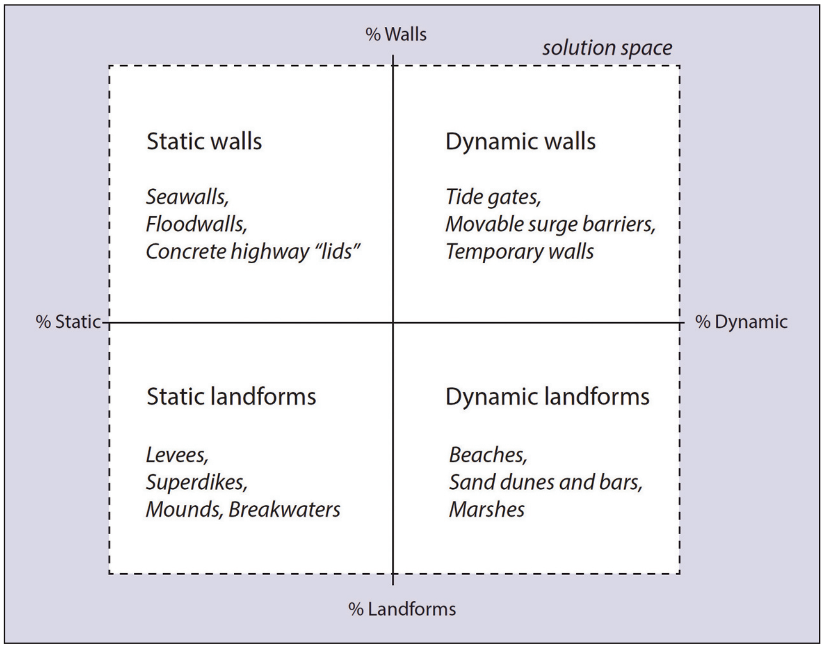

Figure 5. *Illustration of the typology as four ideal types that establish gradients of similarity to the ideal, defining four quadrants of a solution space. The vertical axis is defined by the percentage of the physical infrastructure proposal that uses walls versus landforms; the horizontal axis is defined by the percentage of design components that are dynamic versus static. This version of the diagram can be used to generate a wide range of alternative structural and non-structural proposals.*

may not provide a consistent level of function over time and space (flood protection levels, for instance, may vary in specific locations during different stages of erosion and accretion; Stevens *et al.* 2014), they may successfully deliver multiple benefits, including habitat, recreation, and other ecosystem services. These dynamic landforms may also be easier to build in phases as sea levels continue to rise. Because they are made of loose material, it may be possible to enlarge them without replacing the original structure, as future conditions require a higher or wider structure (SPUR 2012; Clevenger *et al.* 2014).

These four simple types – static and dynamic walls, and static and dynamic landforms – represent ideals; actual built or proposed structures can "mapped" onto gradients that are defined by similarity to these four ideal types. Figure 5 represents the typology as a solution space for an optimization problem with four quadrants. Gradients that represent similarity to the ideal types in the "corners" of this diagram are defined using both the percentage of walls versus landforms contained in a specific infrastructure project or proposal, and the percentage of fixed versus dynamic components.

Identifying coastal infrastructure strategies appropriate for specific contexts

The intent of the typology is to represent the range of choices that *could* be applied, but the selection of the specific types of infrastructure that *should* be applied requires a review of the specific context. The most important of these contextual issues is the fragility or robustness of the adjacent landscape, given that alternative strategies offer different levels of protection over time and space.

If the area inland of the coastal infrastructure is *vulnerable*, meaning that failure of the infrastructure could easily result in loss of human lives, extreme property damage, or the destruction of unique and sensitive ecosystems, then the infrastructure strategy must be robust to prevent such consequences (eg Sterr 2008). Alternatively, the landscape adjacent to the infrastructure could be *resilient* to disturbances, in the sense that it is able to recover from a given range of frequency and intensity of events, such as flooding (Barroca *et al.* 2015).

A third alternative is that the adjacent land uses or ecosystems might be designed to be *adaptive* in themselves, so that they will not be greatly affected by an event that overtops or results in the temporary failure of a coastal protective structure (Restemeyer *et al.* 2015). This more robust strategy would provide substantial benefits in other areas, such as ecosystem support and recreation, because the infrastructure investment does not need to be utilized solely to produce a very high reliability of protection from flood events. This type of infrastructure has been characterized as "safe-to-fail" (as opposed to "fail-safe") although the "failure" in this case refers to a temporary loss of some functionality, rather than a catastrophic or permanent loss of all functional capacity (Lister 2007). One example is the use of wide wetland/beach/dune complexes in shore zones to protect urban districts or critical habitat areas from inundation in most – though not all – weather events, while simultaneously providing more land area for coastal ecosystems and more opportunities for recreation (van Slobbe *et al.* 2013). Figure 6 illustrates these strategic choices in the pairing of infrastructure with urban districts that represent different levels of vulnerability due to the design characteristics of their roads and buildings.

■ Applying the typology

Application to decision making: San Francisco Bay

A useful typology of coastal infrastructure strategies is one that can serve as a heuristic tool in planning and policy making, meaning that it allows for a more thorough exploration of a set of solutions and the generation of a complete range of alternatives within a defined set of variables. Application of the typology can provide insights into whether some strategies may be overlooked or pre-judged without adequate consideration, since many coastal planning efforts will give less attention to certain quadrants of the typology than to others. For example, civil engineers who are more familiar with levees and floodwalls may ignore wetland and beach strategies as viable alternatives.

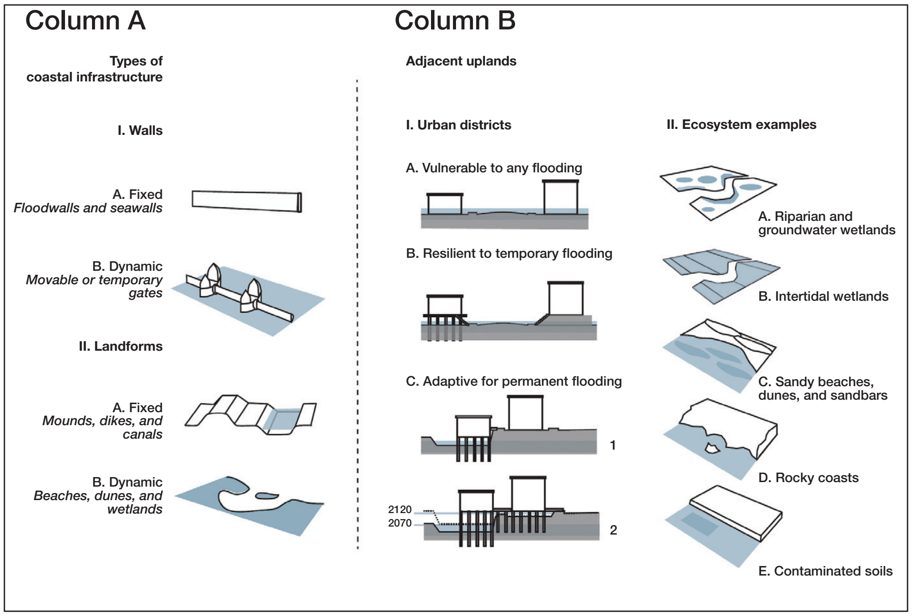

Figure 6. *The four basic infrastructure types can be paired with adjacent land uses and landscapes, including urban districts and ecosystems (eg wetlands, rocky shores, sandy beaches, contaminated soils). The typology is a heuristic, meaning that it enables a user to generate many alternative pairings as a way of studying options, rather than producing a single pairing between Column A and Column B.*

The process of planning coastal infrastructure in the US is described in Part 5, Chapter 1 of the USACE's *Coastal Engineering Manual* (Housley and Thompson 2008). This publication notes that a wide range of different alternatives should be considered during a "reconnaissance" planning stage, and that selected alternatives should be examined in greater detail through a feasibility study. However, the description of structural and non-structural infrastructure designs is unbalanced, providing greater detail in defining structural types than non-structural types. The USACE manual uses a flow chart to describe the coastal infrastructure planning process, which includes 11 standard alternatives (from "do nothing", to non-structural options such as marshes, to structural options including breakwaters and seawalls; see Figure V-1-1 in Housley and Thompson 2008). This list of alternatives does not distinguish between dynamic strategies that move mechanically (eg a movable storm-surge barrier) or function as a result of change over time (eg "sacrificial" beaches, which are designed to erode as they supply sediment to areas farther down the coast), and static strategies that are maintained exactly as they were initially built and are fixed in space (eg a permanent floodwall). Moreover, although the manual includes information about non-structural options, it does not identify specific examples as it does for the structural options.

Unlike the standard USACE manual, the typology described here provides equal consideration to the structural, non-structural, dynamic, and static categories of coastal infrastructure designs; this allows a broader assessment of alternatives without pre-judgment of whether one specific subset of alternatives is more feasible than another. The typology is simple in that it uses only four ideal types to describe an inclusive solution space and can be used to generate alternatives by exploring options from the four quadrants of the typology diagram (Figure 5), but it can also be used to categorize actual proposals and built projects – planners can describe examples in a specific region by plotting actual projects on the diagram. By measuring the percentage of the proposed project's length along the shoreline that would be dedicated to each of the ideal types, a specific built or proposed project can be assigned a location within the diagram. Some projects will contain elements that overlap along the shore, requiring two points to be used to represent a single project within the diagram; for instance, an earthen levee with an additional floodwall on top would require two points to represent both the static landform (the levee) and the static wall (the floodwall). The diagram's simplicity also means that it should be limited to use in what the USACE refers to as the "reconnaissance" stage of reviewing a broad set of alternative proposals. It is also limited to biophysical adaptation strategies, and does not address specific opportunities for re-aligning coastal development by a combination of removing structures in some locations and adding new structures in others.

Recent planning efforts in the San Francisco Bay region of California illustrate how the typology presented here might be applied, and the insights it can offer. The San Francisco Bay Commission for Development and Conservation (BCDC) was created in 1965 to regulate the artificial shoreline position of the bay, after decades of urban fill deposition. BCDC has assumed a coordinating role in planning for adaptation to sea-level rise in the region. In 2009, BCDC organized an international competition to generate design proposals for sea-level rise adaptation projects in the San Francisco Bay area, with five bay-centered entries selected as winners by an independent jury. A review of those winning entries reveals that all but one included "wall" proposals (including the construction of a dynamic barrier under the Golden Gate Bridge; a series of permanent or temporary barriers separating smaller bays or critical urban sites, such as airports, from the main bay; a light installation that would represent the location of needed barriers along the shore).

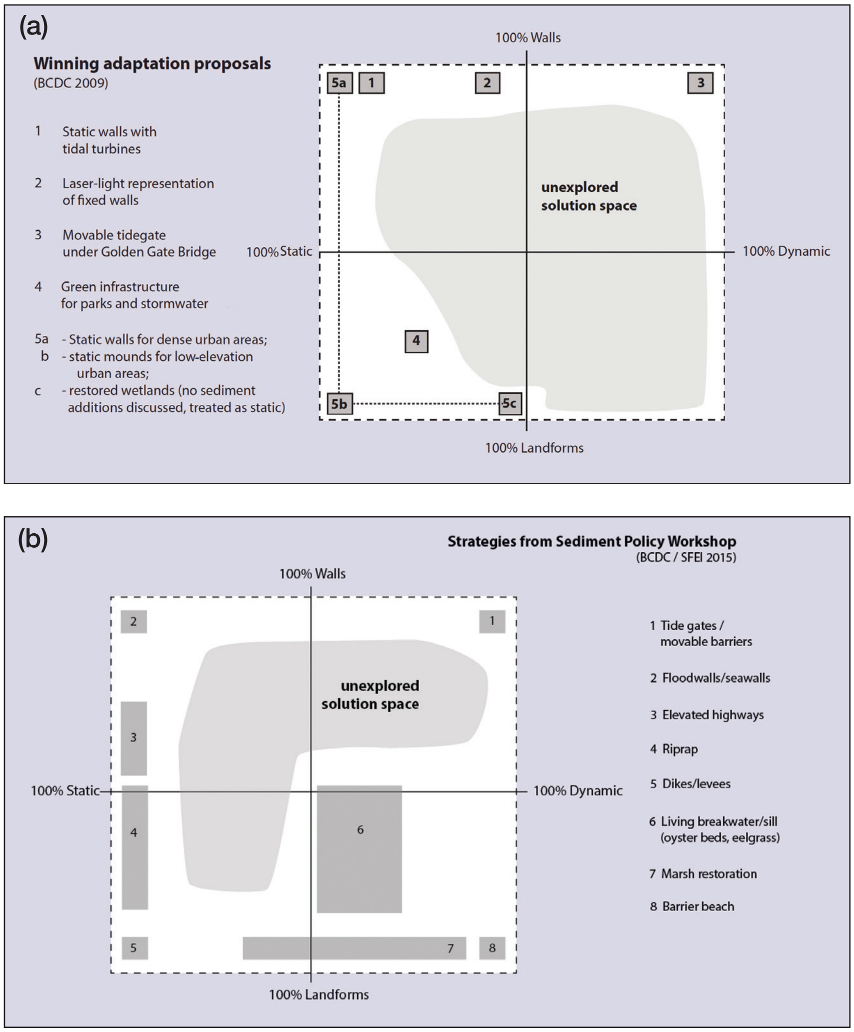

Figure 7. *The typology can also be used to "map" specific proposals within the four quadrants, based on the percentage of the shore that is occupied by each of the four ideal types (static and dynamic walls and landforms). This can reveal the areas of the diagram's solution space that might be unexplored: for example, in a case where non-structural alternatives, such as a wetland or an oyster reef, are not included. Different regional approaches or different eras in time can be compared side-by-side using the diagram as a map of specific alternatives. The dashed line represents the concept of a solution space, which contains voids that depict unexplored alternatives. (a) BCDC's Rising Tides competition winners (BCDC 2009). The six winning proposals are mapped onto the diagram with approximate positions, since specific lengths of shore were not specified for each design. As the diagram shows, dynamic landforms were not well-explored. (b) BCDC's Bay Policies workshop, exploring alternatives for adaptation (SFEI 2015). Specific dimensions were not proposed at the workshop, but ranges were discussed and are used to represent the proposals within the diagram, extending their shapes. Mixes of dynamic walls and landforms were not as frequently discussed as "pure" strategies.*

Three of the winning entries also included proposals for expanding marsh edges at locations where marshes or salt ponds already exist, to be supported by reconfigured regional water systems of various kinds. None of the entries recognized that intertidal wetlands are at risk of submergence and collapse.

The winning proposals can be mapped onto a diagram defined by the four types included in the typology described in this paper, where the criteria for inclusion in categories are represented as gradients rather than discrete thresholds. This diagram reveals that the category of "dynamic landforms" as coastal infrastructure strategies is empty (see Figure 7a). Static landforms appeared in the proposals, as did movable and static walls. The absence of proposals in the fourth quadrant of the typology diagram, which includes dynamic landforms such as marshes and beaches, suggests that there is potential in exploring other options for coastal infrastructure.

The dynamic landform options include sandbars, beaches, dunes, and wetlands, all of which could provide ecosystem services, including flood protection. Interestingly, none of the 2009 competition-winning alternatives considered the option of pairing coastal infrastructure of any kind with floodable urban districts, or took into account the likelihood that many coastal wetlands will be lost to higher sea levels. The critical relationships between coastal infrastructure choices and adjacent land areas went unexplored, aside from proposals to raise the elevation of some coastal areas.

In contrast, in preparation for a spring 2015 workshop sponsored by BCDC, staff from the San Francisco Estuary Institute (SFEI) developed a list of alternatives for coastal infrastructure that were intended for application along different segments of the bay shoreline (SFEI 2015). That list of alternatives, when mapped onto the same typology diagram, produces a different pattern within the solution space represented by the four quadrants (Figure 7b). This reveals a shift in strategy toward dynamic landforms, including beaches, dunes, and marshes, that are expected to grow with managed nourishment over time. Dynamic walls, such as tide gates, were considered but were not developed as proposals by the participants at the workshop. Static walls, such as seawalls and reinforced concrete "lid" structures that would allow urban development to expand over existing highways and connect to the future shoreline from a higher elevation, were also included.

The use of this typology reveals that the emphasis in May 2015 was quite different than that in 2009, perhaps because of SFEI's knowledge about the effects that movable barriers would have on tidal wetlands, as well as about their potential costs and feasibility. The reasons for the change in priorities are not stated explicitly in the BCDC/SFEI workshop materials, but guidance to the workshop participants stated that "strategies should maximize nature-based adaptation solutions where appropriate" (Case Study 1.1 in SFEI 2015). Recent adaptation proposals for Ocean Beach in San Francisco (SPUR 2012) and the Metropolitan Transportation Commission (Clevenger *et al*. 2014) that pre-dated the 2015 workshop also made dynamic landforms a priority as strategies for coastal infrastructure, suggesting that the region may be developing a preference for multi-benefit strategies that provide both protection and habitat.

Discussions at BCDC's 2015 workshop also considered the relative vulnerability of adjacent land areas to increased flooding, including both wetlands and urban districts. Workshop participants were encouraged to promote equitable solutions that increase resilience in communities" and "restore and enhance diversity of Bay ecosystems and wildlife" (Case Study 1.1 in SFEI 2015). The relative vulnerability of shore zone ecosystems and urban land areas was reflected in participants' choices about the need for different levels of robustness in the coastal infrastructure that would be paired with those land areas. The option of creating floodable urban development areas, such as those that exist in Hamburg, Germany, or in London (see Greater London Authority, London [England] and Mayor of London 2008; Clevenger *et al*. 2014), was also discussed. This change represents a considerable shift in strategy from the 2009 competition results.

■ Conclusion

Over the next century and beyond, policy makers, planners, and ecologists will likely be forced to deal with major changes in coastal ecosystems and coastal communities. A simple typology of coastal infrastructure strategies based on long-term historical models in coastal engineering can be used to support both the analysis and generation of a complete range of alternative proposals for adaptation to sea-level rise. Specifically, the omission of some strategies and emphasis on others is evident when sets of alternatives are represented in a typological solution space. Important questions remain about the dynamics of specific coastal systems, which need to be understood before shore zones can be classified in ways that would allow a rational match to be made between infrastructure strategies and natural processes. Similarly, classifications of the vulnerability of land areas that will be subject to more frequent flooding in the future must evolve with greater sophistication to facilitate the matching process between infrastructure choices and the social, biological, and physical conditions of urban districts and ecosystems.

Proposals for coastal infrastructure as adaptations to sea-level rise are shifting toward the inclusion of a wider range of options, with a greater interest in using dynamic landforms as engineered components of infrastructure. The financial cost of all of these adaptation proposals is high (Jonkman *et al*. 2013), and there will be intense competition for future funding. Policy makers, planners, and ecologists need ways to explain these choices to the public that will help them understand the range of alternative strategies, and increase public support for both long- and short-term investments that may help to sustain coastal ecosystems and urban districts under new climate regimes.

■ Acknowledgements

I thank the consulting engineers who educated me about engineering practices, and the public agency leaders who included me in strategy discussions. Without the opportunity to learn from both private consultants and public agency staff grappling with storm surges and sea-level rise, I would have been unable to develop the typology described here.

■ References

Aarninkof SGJ, van Dalfsen JA, Mulder JPM, and Rijks D. 2010. Sustainable development of nourished shorelines: innovations in project design and realisation. In: Proceedings of the PIANC MMX Congress 2010. Liverpool, UK: Waterman.

Aerts JCJH, Wouter Botzen WJ, Bowman M, *et al*. (Eds). 2011. Climate adaptation and flood risk in coastal cities. Amsterdam, the Netherlands: Earthscan Climate.

Arcadis. 2014. Coastal green infrastructure research plan for New York City. A report prepared for the Hudson River Estuary Program, New York State Department of Environmental Conservation. Amsterdam, the Netherlands: Arcadis. www.dec.ny.gov/docs/remediation_hudson_pdf/cginyc.pdf. Viewed 12 Oct 2015.

Barroca B, Becue V, Serre D, and Balsells M. 2015. Making urban flood resilience more operational: current practice. *P I Civil Eng – Wat M* **168**: 57–65.

Barton ME, Brown S, and Nicholls RJ. 2014. Shoreline response of eroding soft cliffs due to hard defences. *P I Civil Eng – Mar En* **167**: 3–14.

BCDC (San Francisco Bay Commission on Development and Conservation). 2009. Rising Tides Competition. www.risingtidescompetition.com/risingtides/Home.html. Viewed 12 Oct 2015.

Beach D. 2003. Coastal sprawl: the effects of urban design on aquatic ecosystems in the United States. Philadelphia, PA: The Pew Charitable Trusts.

Biging G, Radke J, and Lee JH. 2012. Impacts of predicted sea level rise and extreme storm events on the transportation infrastructure in the San Francisco Bay region. CEC-500-2012-040. Sacramento, CA: California Energy Commission.

Blackman DJ. 1982. Ancient harbors in the Mediterranean. *Int J Naut Archaeol* **11**: 79–104, 185–211.

Borges LMS. 2014. Biodegradation of wood exposed in the marine environment: evaluation of the hazard posed by marine woodborers in fifteen European sites. *Int Biodeter Biodegr* **96**: 97–104.

Bridges TS, Wagner PA, Burks-Copes KA, *et al*. 2015. Use of natural and nature-based features for coastal resilience. Washington, DC: US Army Corps of Engineers. www.nad.usace.

army.mil/Portals/40/docs/NACCS/NNBF%20FINAL.pdf. Viewed 12 Oct 2015.

Bruun P. 2005. Recent developments in shipping ports and terminals. *J Coastal Res* **S46**: 1–21.

Bulleri F and Chapman MG. 2010. The introduction of coastal infrastructure as a driver of change in marine environments. *J Appl Ecol* **47**: 26–35.

Burcharth HF, Lykke Andersen T, and Lara JL. 2014. Upgrade of coastal defence structures against increased loadings caused by climate change: a first methodological approach. *Coast Eng* **87**: 112–21.

Charlier RH, Chaineuxt MCP, and Morcos S. 2005. Panorama of the history of coastal protection. *J Coastal Res* **21**: 79–111.

Chernoff H and Moses LE. 1959. Elementary decision theory. New York, NY: John Wiley and Sons.

Clevenger C, Feng T, LaClair J, *et al.* 2014. Climate change and extreme weather adaptation options for transportation assets in the Bay Area: pilot project. San Francisco, CA: Metropolitan Transportation Commission.

Doty DH and Glick WH. 1994. Typologies as a unique form of theory building: toward improved understanding and modeling. *Acad Manage Rev* **19**: 230.

Eelkema M, Wang ZB, Hibma A, and Stive MJF. 2013. Morphological effects of the Eastern Scheldt storm surge barrier on the ebb-tidal delta. *Coast Eng J* **55**: 1350010.

Flood JF and Cahoon LB. 2011. Risks to coastal wastewater collection systems from sea-level rise and climate change. *J Coastal Res* **274**: 652–60.

Gedan KB, Silliman BR, and Bertness MD. 2009. Centuries of human-driven change in salt marsh ecosystems. *Annu Rev Mar Sci* **1**: 117–41.

Giannico G and Souder J. 2005. Tide gates in the Pacific Northwest: operation, types and environmental effects. Corvallis, OR: Oregon Sea Grant. Research Paper ORESU-T-05-001.

Greater London Authority, London (England) and Mayor of London. 2008. East London green grid framework: London plan (consolidated with alterations since 2004) supplementary planning guidance. London, UK: Greater London Authority.

Henry T. 1855. Natural history of Pliny the Elder. London, UK: HG Bohn.

Hill K. 2011. Climate-resilient urban waterfronts. In: Aerts J, Botzen W, Bowman M, *et al.* (Eds). Climate adaptation and flood risk in coastal cities. London, UK: Routledge.

Housley J and Thompson E. 2008. Planning and design process. In: Coastal engineering manual. Washington, DC: US Army Corps of Engineers.

Jennerjahn TC and Mitchell SB. 2013. Pressures, stresses, shocks and trends in estuarine ecosystems – an introduction and synthesis. *Estuar Coast Shelf Sci* **130**: 1–8.

Johnston A, Slovinsky P, and Yates KL. 2014. Assessing the vulnerability of coastal infrastructure to sea level rise using multi-criteria analysis in Scarborough, Maine (USA). *Ocean Coast Manage* **95**: 176–88.

Jonkman SN, Hillen MM, Nicholls RJ, *et al.* 2013. Costs of adapting coastal defences to sea-level rise – new estimates and their implications. *J Coast Res* **290**: 1212–26.

Kadiri M, Ahmadian R, Bockelmann-Evans B, *et al.* 2012. A review of the potential water quality impacts of tidal renewable energy systems. *Renew Sust Energ Rev* **16**: 329–41.

Lister N-M. 2007. Sustainable large parks: ecological design or designer ecology? In: Czerniak J and Hargreaves G (Eds). Large parks. Princeton, NJ: Princeton Architectural Press.

Louters T, Mulder JPM, Postma R, and Hallie FP. 1991. Changes in coastal morphological processes due to the closure of tidal inlets in the SW Netherlands. *J Coast Res* **7**: 635–52.

Mattheus CR, Rodriguez AB, McKee BA, and Currin CA. 2010. Impact of land-use change and hard structures on the evolution of fringing marsh shorelines. *Estuar Coast Shelf Sci* **88**: 365–76.

Mees HLP, Dijk J, van Soest D, *et al.* 2014. A method for the deliberate and deliberative selection of policy instrument mixes for climate change adaptation. *Ecol Soc* **19**: 58.

Morris RKA. 2013. Geomorphological analogues for large estuarine engineering projects: a case study of barrages, causeways and tidal energy projects. *Ocean Coast Manage* **79**: 52–61.

Nordstrom KF. 2014. Living with shore protection structures: a review. *Estuar Coast Shelf Sci* **150**: 11–23.

Perkol-Finkel S, Ferrario F, Nicotera V, and Airoldi L. 2012. Conservation challenges in urban seascapes: promoting the growth of threatened species on coastal infrastructures. *J Appl Ecol* **49**: 1457–66.

Pilkey OH and Dixon KL. 1996. The Corps and the shore. Washington, DC: Island Press.

Reeder T and Ranger N. 2011. How do you adapt in an uncertain world? Lessons from the Thames Estuary 2100 project. Washington, DC: World Resources Institute.

Reid RL. 2013. Defending New Orleans. *Civil Eng* **83**: 43–83.

Restemeyer B, Woltjer J, and van den Brink M. 2015. A strategy-based framework for assessing the flood resilience of cities – a Hamburg case study. *Planning Theor Pract* **16**: 45–62.

Ruiz GM, Fofonoff PW, Carlton JT, *et al.* 2000. Invasion of coastal marine communities in North America: apparent patterns, processes, and biases. *Annu Rev Ecol Syst* **31**: 481–531.

Schifter I, González-Macías C, Salazar-Coria L, and González-Lozano C. 2011. Pollution in estuarine and bay sediments at a refinery complex located on the Mexican Pacific Ocean. *Int J Environ Stud* **68**: 83–106.

Sekovski I, Newton A, and Dennison WC. 2012. Megacities in the coastal zone: using a driver–pressure–state–impact–response framework to address complex environmental problems. *Estuar Coast Shelf Sci* **96**: 48–59.

SFEI (San Francisco Estuary Institute). 2015. Case Study 1.1, BCDC Policies for a Rising Bay Project. San Francisco, CA: SFEI.

SPUR. 2012. Ocean beach master plan. San Francisco, CA: SPUR.

Sterr H. 2008. Assessment of vulnerability and adaptation to sea-level rise for the coastal zone of Germany. *J Coastal Res* **242**: 380–93.

Stevens R, Hill K, Burgess N, and Grady A. 2014. New beach designs as urban adaptation to sea level rise. *Landscape Res Rec* **1**: 176–87.

Stive MJF, de Schipper MA, Luijendijk AP, *et al.* 2013. A new alternative to saving our beaches from sea-level rise: the Sand Engine. *J Coastal Res* **290**: 1001–08.

Tallet P and Marouard G. 2014. The Harbor of Khufu on the Red Sea Coast at Wadi al-Jarf, Egypt. *Near East Archaeol* **77**: 4–14.

Van de Ven GP. 1993. Man-made lowlands: a history of water management and land reclamation in the Netherlands. Utrecht, the Netherlands: Matrijs.

VanKoningsveld M, Mulder JPM, Stive MJF, *et al.* 2008. Living with sea-level rise and climate change: a case study of the Netherlands. *J Coastal Res* **242**: 367–79.

van Slobbe E, de Vriend HJ, Aarninkhof S, *et al.* 2013. Building with nature: in search of resilient storm surge protection strategies. *Nat Hazards* **66**: 1461–80.