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A Sea Level Rise Simulator for Coastal Communities

Bradd Libby, Alexander Flesjø Christiansen
DNV GL, Høvik, Norway

Abstract

Climate change-induced sea level rise and its associated affects (like increased flooding frequency, severity and duration) are already affecting the San Francisco Bay Area and other coastal urban areas around the world. Our simulations show that possible responses to these threats have complex and interconnected effects on the city's and surrounding region's ecological, structural, socioeconomic and governance systems. We developed a simulator that provides a 'learning laboratory' to investigate the impact of sea level rise on a small portion of the San Francisco Bay Area. Users are encouraged to use the simulator in a group setting, collectively deciding on future actions before seeing the simulated results and then using open dialogue to build collective understanding of the causal connections between the various sub-systems. In this example, we apply the simulator to the San Francisco Bay Area but the simulator can be applied to many other coastal areas.

Introduction

This paper explores how climate change driven sea level rise (SLR) and its associated flooding are affecting the dynamic interaction between the ecological, structural, socioeconomic and governance system of coastal urban areas and influence the human reaction to these changes in the decades to come. The San Francisco Bay Area is the model case.

The San Francisco Bay Area, home to Silicon Valley, is a global powerhouse for innovation. Many of the world's leading high-tech companies and thousands of startup companies are located in the region (see Figure 1). Historically, much of the Bay's shoreline has consisted of low-lying marshes, but extensive urbanization around the southern part of the Bay and the development of rich farmland in the North, both of which have largely been near the water's edge, have reduced the marsh area by 90% compared to its natural historical extent. The constraint by local development means that further increases in average sea level are likely to result in additional loss of marsh area rather than the migration of marshes.

Some of the region's most valuable and critical resources are located at the shoreline, including San Francisco and Oakland airports, key highways and bridges, corporate headquarter buildings, electrical infrastructure, and all of the regional wastewater treatment plants. Options for responding to the risks posed by sea level rise are limited: defend land against indundation, adapt to periodic flooding, retreat from high-risk areas, or accept the loss of valuable assets.

Figure 1: Schematic map of the San Francisco Bay Area. Homes, the campuses of high-tech companies, critical transport links, utility infrastructure and other assets converge near the shoreline marshes.

The waters of the Bay are interconnected. Hydrological simulations conducted at the University of California at Berkeley indicate that hardening of the coastal infrastructure in the southern portion of the Bay will increase tidal variation in the northern Bay, potentially threatening the levees that protect low-lying farmland and rapidly-growing urban areas with catastrophic failure, a potential situation Wired magazine has dubbed "Calfornia's Katrina" [Holleman, 2014].

Even if the levees keep standing, one foot of SLR will profoundly affect water quality. A 2008 report by the Public Policy Institute of California says: "With a three-foot sea level rise, salinity would greatly increase the cost of drinking water treatment and Delta water may be unsuitable for agricultural irrigation." [Lund, 2008] Nearly 30 million people in California get their drinking water from the north bay delta.

In the densely urbanized parts of the San Francisco peninsula and areas around the Bay, tens of billions of dollars of property are threatened by rising seas. Numerous initiatives are underway to deal with the effects. In 2016 a regional ballot measure imposed a per-parcel tax on property owners around the Bay that is expected to raise $500 million dollars over 20 years for marsh restoration efforts. [Sommer, 2016] Both private and public organizations have been involved in coastal modification and flood control projects. As well, the City of San Francisco, which only constitutes a portion of the San Francisco Bay region in both population and land area, announced funding in early 2017 for a 'Rebuild by Design' competition based on the one held in the New York City area after Superstorm Sandy but focused on SLR.

To bring diverse stakeholders together, we developed a simulator that provides a ‘learning laboratory’ to investigate the impact of sea level rise on a small portion of the San Francisco Bay Area. In developing this simulator, we consulted officials in local city and county governments, the US Federal government, academics at multiple leading institutions in the region, business executives, and local residents.

Our simulator considers the interconnected effects of rising sea levels from multiple perspectives, the mutual impact of the environment, coastal infrastructure, socioeconomics, and regional governance. Multiple scenarios are possible, ranging from sea level rise with no adaptive actions taken, to simulations with adaptive actions of ‘hard’ infrastructure like building seawalls and levees, to cultivating ‘green’ infrastructure solutions, reconstructing lost marsh areas, establishing easement zones, and other possible policy measures. Users are encouraged to use the simulator in a group setting, collectively deciding on future actions before seeing the simulated results and then using open dialogue to build collective understanding of the causal connections between the ecological, structural, socioeconomic and governance systems.

Background

The tide gauge of the Bay is the oldest continuously operating station in the Western Hemisphere and the water there has shown a nearly linear increase in average level, totalling approximately 20 cm (8 inches) in the 20th century. But with accelerating climate change, future estimates project an exponential rate of rise, resulting in up to 140 cm (55 inches) of change by the year 2100, or maybe significantly more. Projections done in 2012 by the National Research Council suggest the “most likely” scenario is average tides 36 inches higher than today’s level by the year 2100.

A primary source of uncertainty is the extent to which the so-called ice albedo feedback loop will affect future sea levels. The ice sheets of Greenland naturally have a high reflectance, or albedo, sending more than half of the incoming solar energy back into space. Liquid water, in contrast, absorbs more than 90% of incoming energy. As ice sheets warm, meltwater puddles on the surface, forming regions that absorb significantly more solar energy than the underlying frozen ice sheet. This helps to trap more incoming energy, resulting in more melting of ice. Uncertainty concerning this feedback loop is a large portion of the uncertainty in the overall future average sea level increase.

In addition to changes in the average sea level, the sea level in the San Francisco Bay is constantly in flux due to tides and meteorological effects like the El Niño Southern Oscillation (ENSO). Rainfall in the Bay Area is strongly seasonal, falling mostly in December through February and very little at other times of the year, there are also annual extremes called 'King Tides'. A rising sea will result in more frequent and more extreme high tides and storm surges, but there is a lack of knowledge regarding how this rising sea level will affect the frequency and severity of indundation events.

Much about the dynamics of sea level rise is nonintuitive. For example, a 2011 bill before the House of Representatives in North Carolina would have required the state government to base estimates of future sea level rise only on observed (linear) historical data, amounting to about 20-30 cm in SLR per century, rather than scientific calculations (which suggest about 100 cm or more in rise). “Rates of sea-level rise may be extrapolated linearly to estimate future rates of rise but shall not include scenarios of accelerated rates of sea-level rise." [General Assembly of North Carolina, 2012]

Though the lawmakers proposing the bill presumably thought that a 20 cm linear rise was a less-aggressive estimate than a 100 cm exponential rise, plotting the two paths on the same chart, as seen in Figure 3, shows that for most of the time, the smaller linear increase actually assumes a higher sea level than the larger exponential rise.

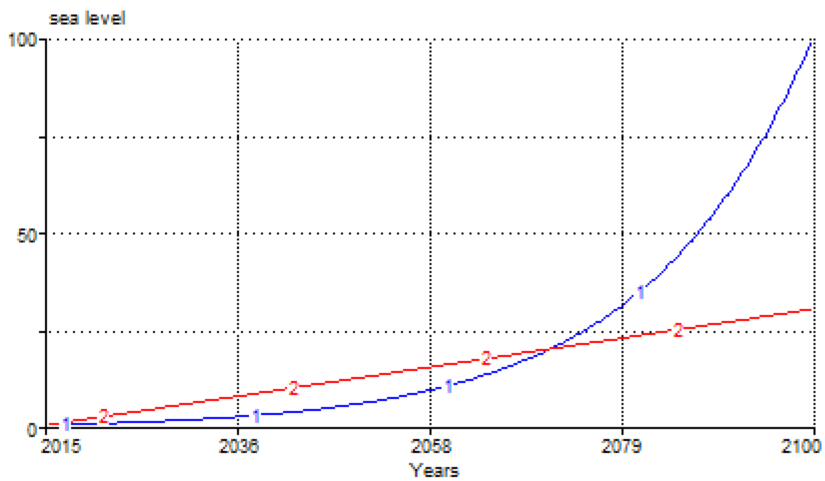

Figure 2: Comparison of 100 cm exponential rise (blue) in sea level to 30 cm in linear rise (red). A more-modest linear increase assumes higher sea levels for most of the comgin century compared to a more-aggressive exponential rate of sea level rise.

Numerous modeling, simulation, data analysis, mapping and visualization efforts deal with various aspects of the interconnections between climate change, sea level rise, flooding events, coastal defences, transport and utility infrastructure, socioeconomics, urban development and governance issues.

The United States Geological Survey (USGS) developed the Wetland Accretion Rate Model for Ecosystem Resilience (WARMER) to model rates of marsh accretion and degradation. [Swanson, 2013] This model has been applied to marshes in the San Francisco Bay Area to study spatial changes in marsh morphology with future sea level rise [USGS, 2013]. System Dynamics has also been used to study the spatial dynamics marshland development. [Ruth, 1994] Game theoretic studies have examined the interplay between cooperation and competition in the construction of levee systems [Hui, 2016]. Even Forrester's classic work Urban Dynamics was used as the basis for one version of the

Our model draws on works like these, but necessarily reduces spatial and 3-D models to single stock variables, limits the structure to key feedback connections, and simplifies some relationships. Key sectors of the model are described in the next section.

Model

The model presented in this work considers changes in a geographical slice of urban area near the Bay, starting at the shore and progressing inland, over the period 2015 to 2100. In order, the segments depicted in the inset of Figure 1, of land are:

(1) marshes
(2) coastal protective infrastructure (e.g., levees)
(3) urban land vulnerable to flooding
(4) urban land that is less-vulnerable to flooding

The model sectors consider four perspectives: ecological system, the structural system, the socioeconomic system and the governance system. Possible actions by users are related to the construction of infrastructure, management of natural habitats, and selection of public policies, the extent and timing of which profoundly affect the urban coastal area's response to the threat of sea level rise. The objective is to minimize the total financial cost to the region, considering both the costs of action and the costs of inaction. These costs are both direct (e.g, the cost of flooding damage and the expense of constructing infrastructure) and indirect (e.g., the cost of lost productivity and the lack of attraction of new businesses), and arise from the numerous interacting feedback loops, some of which contain lengthy delays and non-intuitive behaviors.

Figure 3 depicts some of the causal relationships identified in each of the four perspectives, as well as some exogenous inputs and key outputs.

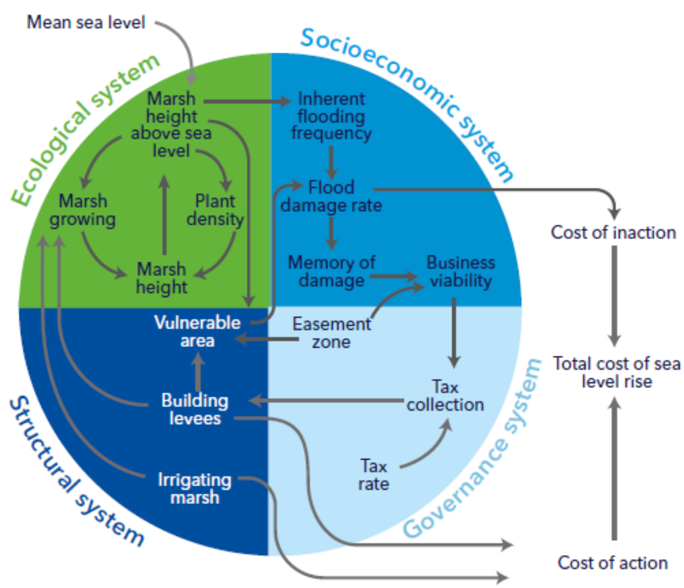

Figure 3: Causal connection diagram of some factors relevant to sea level rise in the Bay Area

We refer to the four-perspective approach as the Systems & Urban Resilience Framework, or SURF.

Several sea level rise scenarios are included in the model, driven by parameters that affect the rate and ultimate amount of rise. Sea level rise is treated as exogenous to the model and its behavior can be chosen by the user to increase linearly, to increase exponentially, or to increase in a manner that is a blended average of a linear and an exponential increase.

The model is illustrated in Figure 4 below.

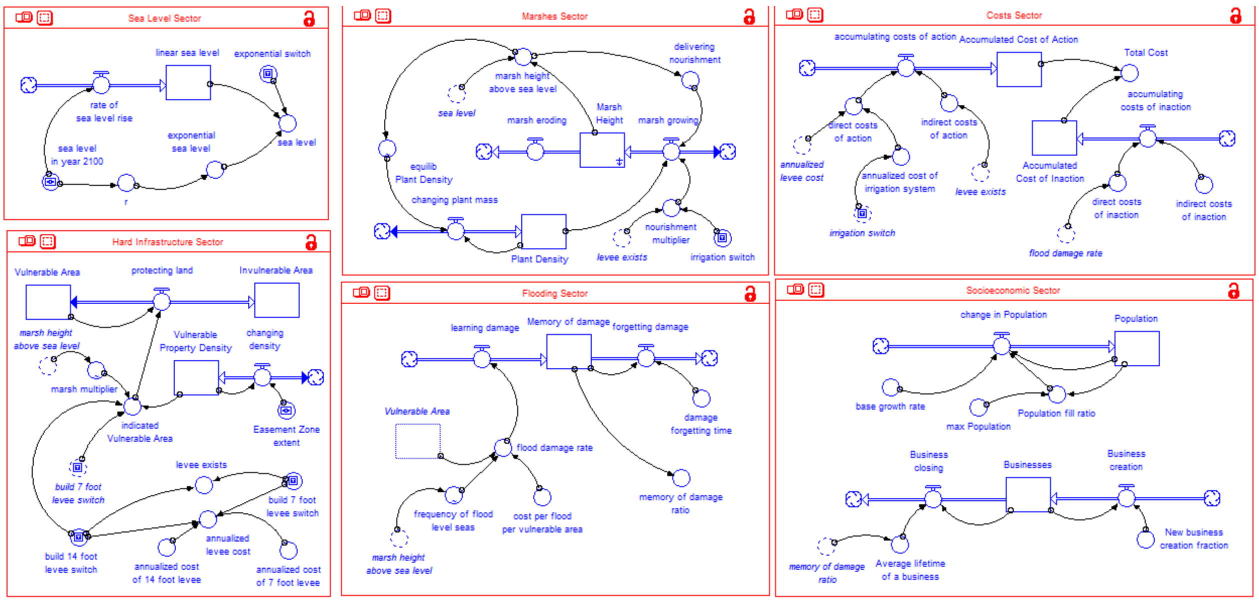

Figure 4: Stock-and-flow diagram of the Baytown model

Governance system

The user's objective during the simulation is intended to be, although not constrained to, minimize the total combined cost ('Total Cost') of action and of inaction regarding sea level rise. Direct costs of action include those associated with construction and maintenance of flood protection systems.

Not acting on the threat posed by rising sea levels also can carry direct costs, primarily due to increased frequency, intensity and duration of flooding. The rate at which flood damage occurs ('*flood damage rate*') is determined in the Flooding Sector, described below.

Both sets of costs, the costs of action and the costs of inaction, are tabulated throughout the simulation through independent stock variables.

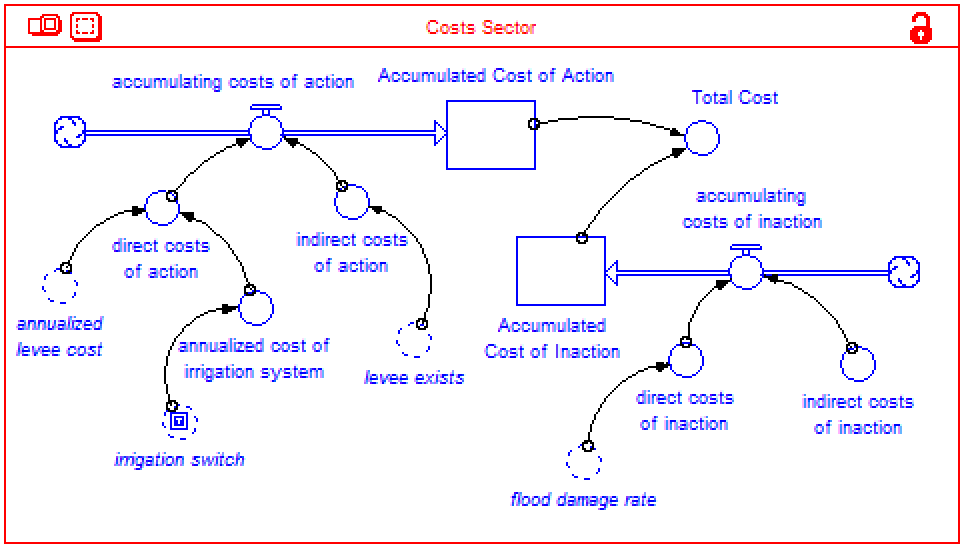

Figure 4: Stock-and-flow diagram of the Costs sector

Ecological System

Marshes are dynamic ecosystems that can change in height, shift location with a changing shoreline, and change in composition of biota over long periods of time according to local environmental conditions. Marsh environments are defined by and rely on frequent inundation by salt water. The heart of a marsh consists of land that is submerged and exposed on the twice-daily basis corresponding to the tides. This land is dominated by plants that have adapted to the brackish salinity of this unique environment and the insects, birds and other animals that depend on these plants. In lower-lying land that is submerged more often and for longer periods of time, the plant life cannot survive, and therefore these regions revert to mudflats.

In the model, the height of the marsh relative to a fixed reference elevation is represented by a single stock. The marsh suffers erosion at a fixed rate (‘*marsh eroding*’). The rate of accumulation of new material in the marsh depends on the rate of delivery of sediment (‘*delivering nourishment*’) and the relative proportion of sediment that is captured by the marsh, which is assumed proportional to the density of plant life (‘*Plant Density*’).

The dynamics of the marsh elevation are governed by two feedback loops, both of which depend on the relative height of the marsh above sea level (‘*marsh height above sea level*’). If the marsh height above sea level decreases, the equilibrium plant density (‘*equilib Plant Density*’) also decreases due to increased inundation with brackish water.

If the marsh height above sea level increases, the rate at which sediment is delivered ('*delivering nourishment*') decreases. This constitutes a balancing feedback loop that constrains marsh growth when the marsh grows too high, but also which promotes marsh growth if the marsh level falls. In a recent report, the USGS estimated the rate of sediment accumulation as a function of the marsh elevation relative to the average sea level for several marshes around the San Francisco Bay [USGS, 2013].

Each tidal cycle brings sediments, a portion of which are trapped by the plants in the marsh. Measurements conducted by the United States Geological Survey (USGS) suggest that the rate of organic matter accumulation in a marsh peaks when the marsh elevation is close to the average sea level [USGS, 2013] and decreases as the marsh elevation becomes higher or lower than the average sea level. The functions used in this work were taken from the USGS's study of the Laumeister marsh, a section of wetlands located in Palo Alto.

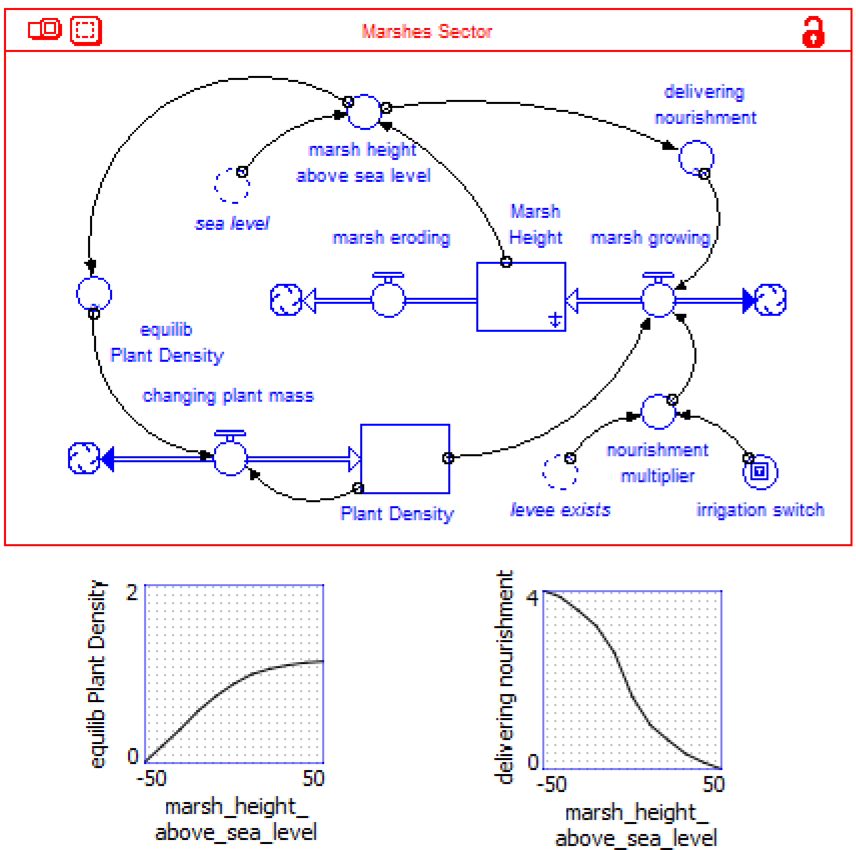

Figure 5: Stock-and-flow diagram of the marsh sector (top) and graphs of the two non-linear functions that appear in this sector (bottom)

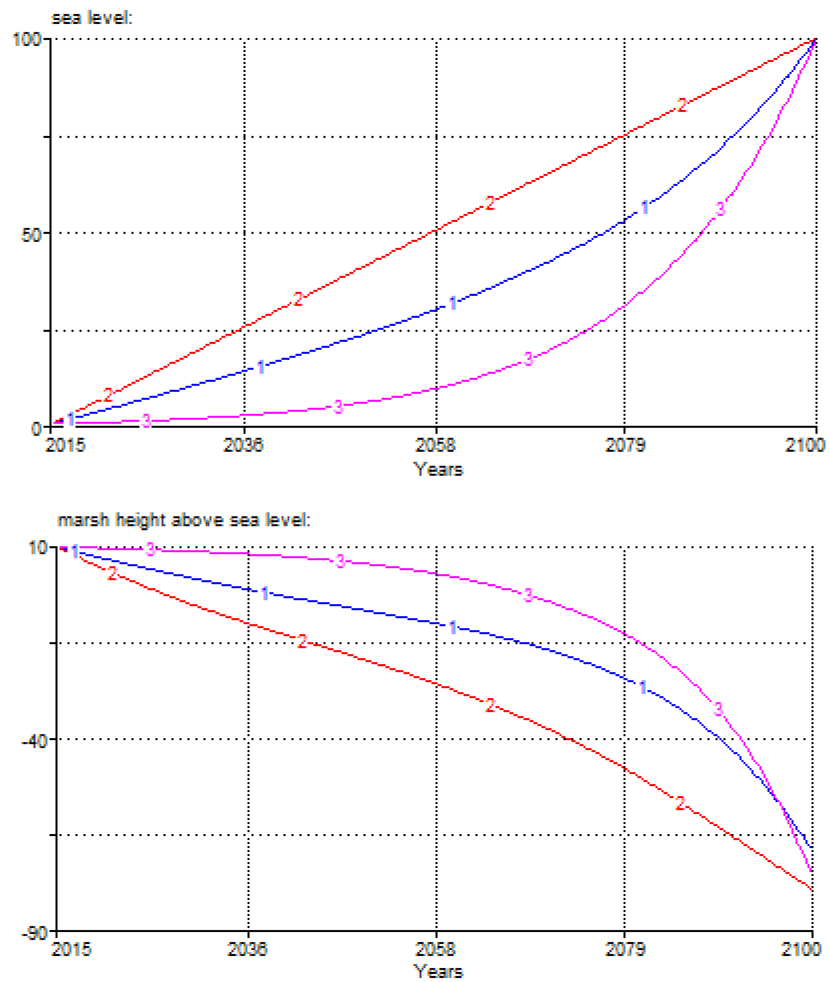

Figure 6: Graph of 'sea level' (top) and 'marsh height above sea level' (bottom) for the cases of linear rise (red), exponential rise (magenta) and a 50/50 hybrid of linear and exponential rise (blue), each of which reaches 100 cm by the year 2100.

Figure 6 depicts simulations of the response of the marsh sector to a linear increase (red line), exponential increase (magenta line), and 50/50 hybrid (blue line) of the linear and exponential increase in sea level. All three of the sea level rises result in an increase of 100 cm by the year 2100, with the linear increase beingg the highest at all times, the exponential increase being the lowest, and the hybrid case being in-between the two previous cases.

Interestingly, the values of the 'marsh height above sea level' (bottom graph) in the year 2100 are the lowest for the linear case (red line), highest for the hybrid case (blue line) and in-between for the exponential sea level rise (magenta line).

Structural System

In the model, urbanized area is divided into two stocks connected by a bi-flow: vulnerable area and less-vulnerable area, corresponding roughly to land that is within the 100-year floodplain and land that is not. The chang in the '*marsh height above sea level*' affects the long-term vulnerable area (refered to as the '*indicated Vulnerable Area*'). Building levees affects the indicated vulnerable area, as well as the annualized cost of maintaing the levees ('*annualized levee cost*').

Within the more-vulnerable land, the density of development ('*Vulnerable Property Density*') is affected by the extent to which the user declares the coastal property off-limits to development ('*Easement Zone extent*').

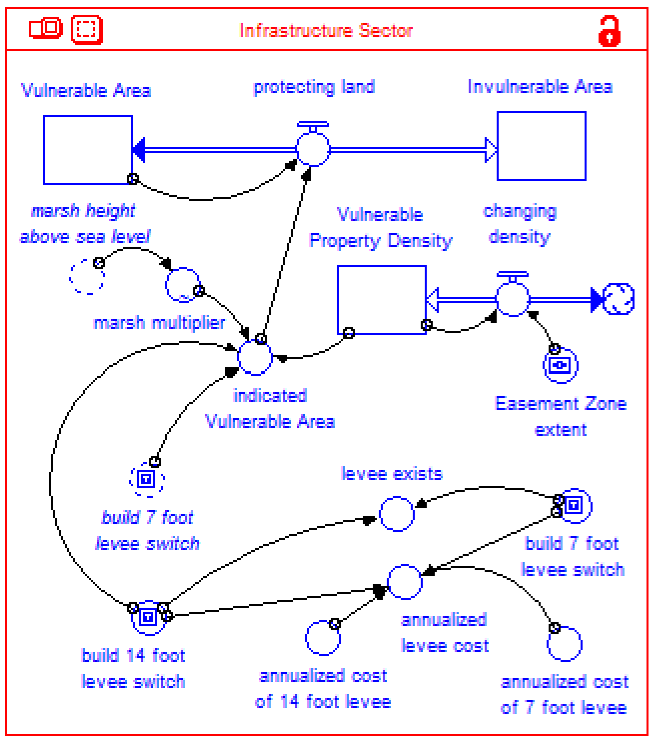

Figure 7: Stock-and-flow diagram of the infrastructure sector

One policy option for coastal adaptation is to declare the most-vulnerable area to be an easement zone and therefore off-limits to further development. Shoreline adaptation land trusts (SALT) are a legal concept whereby an owner of coastal property would be allowed to use (but not sell) their land and would no longer be required to pay taxes [Englander, 2015]. In the model, this is represented by a fixed portion of the difference between the vulnerable property density and its equilibrium value (1 – '*Easement Zone extent*') being eliminated per year.

Flooding Sector

Figure 8 depicts the Flooding Sector, the primary purpose of which is to convert the 'flood damage rate', determined from the vulnerable area, '*cost per flood per vulnerable area*', and frequency of flooding into a ratio of memory of the rate of damage ('*memory of damage ratio*'), which is the ratio of the memory of the rate of damage to its initial value at the beginning of the simulation.

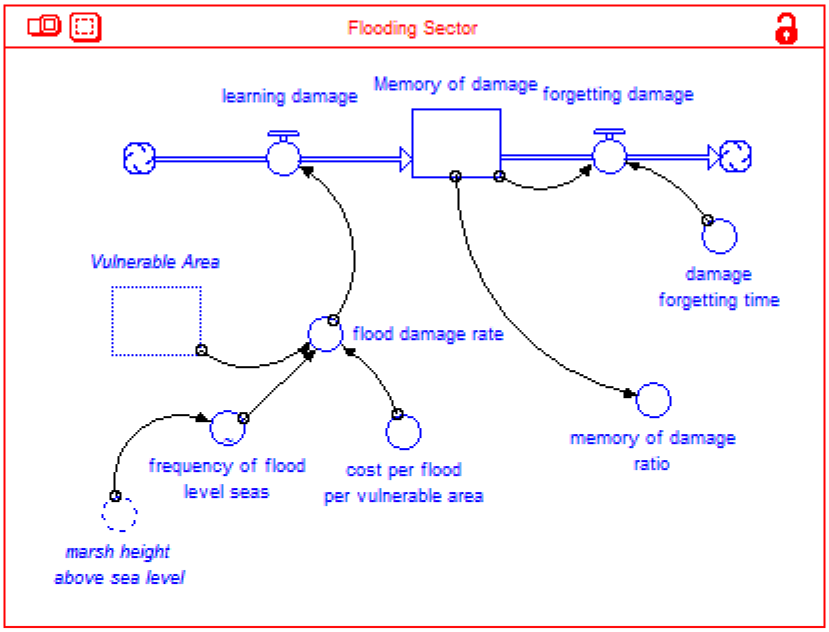

Figure 8: Stock-and-flow diagram of the Flooding Sector

A quantitative model developed recently by the Potsdam Institute for Climate Impact Research suggests that the rate of rise of costs associated with sea level related flooding is greater than linear [Boettle, 2016]. For example, a 10-inch sea level rise in Copenhagen by 2050 would result in four times as much damage per year as a 4-inch rise. The authors of the study claim that the model is applicable to any coastal city around the world.

The rate of degradation of the memory of damage ('*forgetting damage*') is treated as a fixed percentage of the stock of '*Memory of damage*'.

Socioeconomic Sector

The socioeconomics of the Bay Area are too complex an issue to treat in any realistic and dignified manner and therefore have been simplified for the purposes of this 'learning laboratory' simulator. During the modeling effort a strong preference was given in developing this 'learning laboratory' environment to using formulations that were as simple as possible, even excessively so, to make the model dynamics as easy to describe as possible to non-SD participants.

Many of the cities of the Bay Area have officially published estimates of future population levels, which are necessary for planning purposes. In one version of this simulator, a table function simply displays the official future population estimates to the user as a reminder of the values. In the version shown in Figure 9 below, future population levels follow an S-shaped behavior pattern as a result of a positive feedback loop driven by a '*base growth rate*' being constrained by a negative feedback mechanism reducing the growth rate as the *Population* reaches a pre-programmed maximum level ('*max Population*').

The number of *Businesses* is tracked by a single stock which are created by a first-order positive feedback loop and whose average lifetime ('*Average lifetime of a business*') depends on the memory of recent impacts of flooding ('*memory of damage ratio*'), a proxy for insurance rates and other restrictions that make business continuation a more difficult prospect in an area strongly affected by sea level rise.

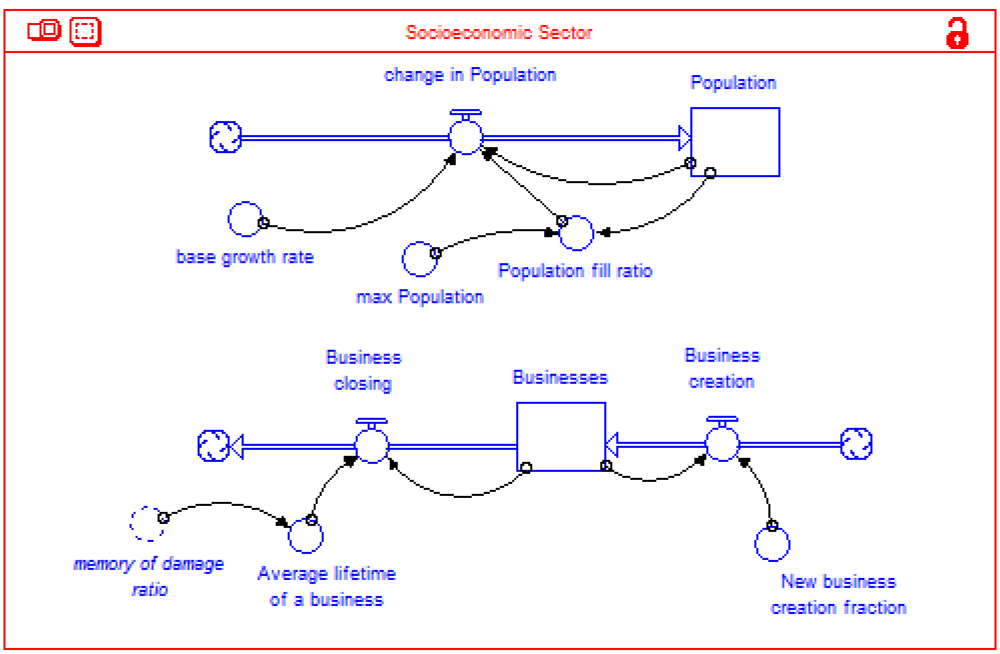

Figure 9: Stock-and-flow diagram of the Socioeconomic Sector

Exploring Resilience Strategies

The figure below depicts a screenshot of the interface for the ‘Baytown Sea Level Rise Simulator, showing three runs where the user has set different policies. The simulator is designed for use in a group setting such as in a conference room where it can be projected onto a wall and the participants, preferably from different aspects of business, academia, government and civil society, can work together to play out the consquences of their decisions and then to build a shared understanding of why the model structure generated those behaviors.

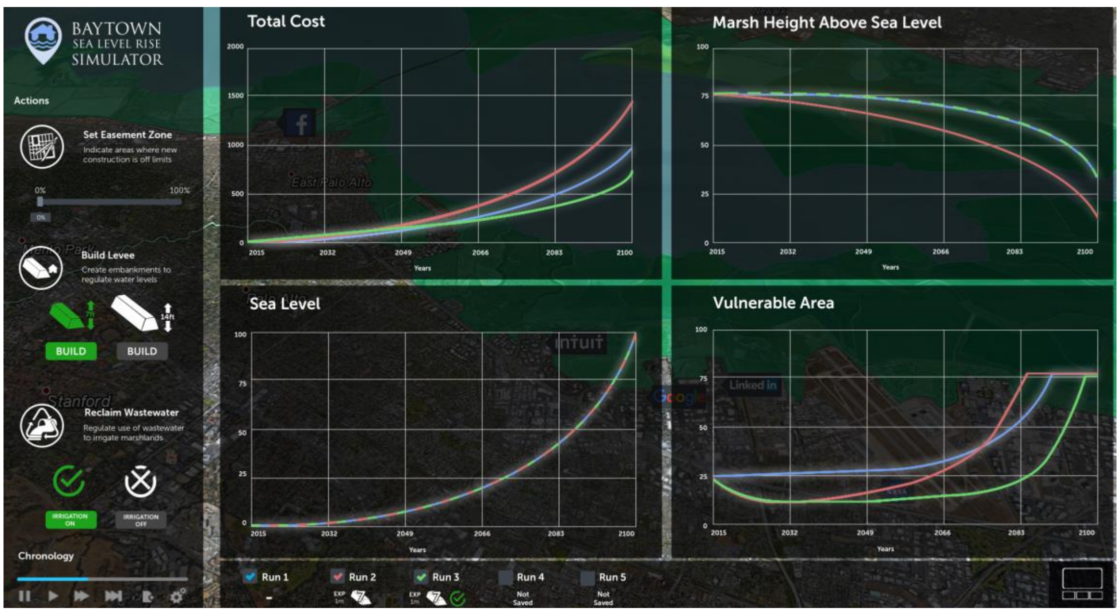

Figure 10: Screenshot of the interface for the ‘Baytown Sea Level Rise Simulator’

The specific results depend on parameters which are set prior to running the simulations and on the policy choices and their timing during the simulation runs. Of course, due to delays in the system and feedback loops, some policy effects can play out over long time-scales and some policy choices that have short-term benefits can be detrimental in the long run. The policies that minimize the total cost to the system are not obvious and, during use of the simulator, it is not clear whether the total cost is even the best metric by which to judge the performance of the system.

By examining various possible policies and adjusting their timing and extent, users can identify those responses to sea level rise that help to maintain and build regional resilience to climate change.

Conclusion

In this paper we describe the creation of a System Dynamics-based simulator that considers the effects of sea level rise on the local ecological, structural, socioeconomic and governance systems in the San Francisco Bay area.

There are a large number of climate change adaptation initiatives in California. However, the institutional landscape for climate change adaptation is very fragmented and coordination is often not optimal. Consequently, it is difficult to integrate the planning effort at the state level on a city level. The need exists for bringing together academia and practitioners from government and private sectors to work across disciplines and silos to co-create systems solutions for climate change resilience.

The Silicon Valley Sea Level Rise ('Baytown') simulator could potentially be used by specialists and the wider community, in public meetings, or hosted on a public website. The parameters in the simulator are adjustable for a given portion of the Bay Area and therefore the simulator can, in principle, be altered to apply to other places in the world where coastal urban areas interact with a natural environment in complex and dynamic ways. The model can also be modified to take into account other climate change related issues like groundwater availability and quality, and the urban heat island effect.

The model currently only considers a single segment of urban land, but is being extended to consider multiple segments, each of which can have different model parameters and each of which can be subjected to different policy options, but each of which also mutually affect and are affected by the other urban segments.

In the coming decades, we will see a rapid pace of migration, demographic changes, and continued economic growth in coastal urban areas. Technological progress like automation, artificial intelligence, the 'Internet of Things' will require businesses, public entities, and citizens to change. Simulators like this could be instrumental in promoting cooperation among disparate elements of society.

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