# Shoreline Change Projections

In 1962, Bruun was the first to propose a model to describe the relationship between shoreline retreat and sea-level rise (P. Bruun 1962). Being relatively simple to use, as well as the first model of its kind the “Bruun rule” as it is now known was quickly adopted and remains in widespread use. However, our understanding of coastal processes has greatly improved since Bruun first introduced his method and it is now neither the only model available to describe this relationship, nor is it the best model to employ in many circumstances. In 1990 Leatherman described the following four distinct types of models used to predict shoreline change due to sea-level rise, each of which is discussed in further detail in the following text:

1. Historical trend analysis
2. The Bruun rule
3. Sediment budget approaches
4. Dynamic equilibrium models

In addition to the four model types described by Leatherman in 1990, there are also newer types of models in active research and development thanks to advances in computer science, basic coastal science, statistics, and heightened awareness of the potential impacts of future sea levels. Additionally, the following three types of models will also be discussed briefly:

1. Process based models
2. Probabilistic models
3. Integrated coastal systems models

# Historical Trend Extrapolation

Historical trend analysis approaches to projecting future shoreline change, as influenced by varying amounts of potential SLR, involve two main steps. First, observational data is used to develop an empirical relationship between past shoreline recession and SLR. Next, extrapolation of the historical trend is used to predict shoreline change during a future time period. Ashton et al. (2011) altered this method to predict future shoreline erosion of erodible cliff backed coasts by applying a SLR-factor to account for expected changes in the rate of future SLR. The SLR-factor is based on the ratio of projected future SLR rates to historical SLR rates, as well as a component to account for the local geography, geology, and presence of infrastructure. The model presented by Ashton et al. (2011) is the basis for the FEMA Region IX Sea Level Rise pilot study’s analysis of shoreline change in San Francisco (Ashton, Walkden and Dickson 2011).

# The Bruun Rule

The Bruun Rule approach can be described as a 2-dimensional mass balance approach based on the notion that as sea-level rises and sand erodes from the beach-face and dune, and equal amount of sediment is deposited at the beach slope toe offshore. In 2004 Cooper and Pilkey noted the following (Cooper and Pilkey 2004).

“In its simplest form, as it is actually applied, the Bruun Rule states that shoreline erosion caused by sea-level rise is a function of the average slope of the shoreface, which is typically the steepest part of the nearshore profile.”

Due to its simplicity, ease of use, and a lack of easy to apply alternatives, the Bruun Rule remains in widespread use by coastal scientists and engineers, despite growing criticism from researchers in the past decades (Cooper and Pilkey 2004, Stive, Ranasinghe and Cowell 2009, Ranasinghe, Callaghan and Stive 2012). Possibly due to its widespread use, at times the Bruun Rule has been used “rather indiscriminately” outside of its intended applications “without realizing its limitations” (Cooper and Pilkey 2004, P. Bruun 1983). While the Bruun Rule is often applied to coastal problems directly the basic premise, that shoreline change rates with SLR are result of shoreface slope, is just as often incorporated into other models (Cooper and Pilkey 2004).

# Sediment Budget Analysis

Sediment budget approaches can be thought of as a 3-d extension of the Bruun Rule. By considering three dimensions, the long-shore component of sediment transport processes can be described in addition to the cross shore component. However, like the Bruun rule, this method works primarily on the basis of maintaining geometric relationships and doesn’t attempt to describe the basic sediment scale processes which are important to the underlying mechanisms of shoreline change.

# Dynamic Equilibrium Models

Dynamic equilibrium models are based on the idea of an equilibrium profile which was originally described by Fenneman (1902), formulated by Bruun (1962), and further explored by Dean (1977) (S. P. Leatherman 1990). The main assumption of the equilibrium profile is that, based on the hydrodynamic, geologic, and sedimentary conditions present at a given section of coastline, there is an ideal profile shape which is perpetually being approximated, but never reached, by the actual cross-shore and longshore profiles. This type of model includes many well-known examples such as GEOMBEST and GEOMBEST+ (Stopler, List and Thieler 2005, Moore, et al. 2010) . At its core however, this model shares many of the same assumptions underlying the Bruun Rule approach to shoreline change.

# Process Based Models

Process based models predict SLC by simulating the response of a shoreline geometry to a given forcing function based on the underlying physics which govern sediment erosion, deposition, cliff dynamics and overall beach development in the coastal zone. While based on an understanding of the underlying physical processes taking place at the shoreline is an inherent advantage of these models, reproducing these processes in a computer simulation requires intense computational effort and user input (i.e. model setup). This level of effort can be expensive and was up until quite recently, impractical. Unlike the previously mentioned models, process based models don’t define shoreline position based solely on mean sea level (MSL) over time. MSL, wave characteristics, storm surge, the underlying bathymetry, and sediment properties are all inputs of models of this type. However as with the previous examples these models by themselves are deterministic in nature and will produce a single output for a given set of initial conditions and unique forcing function. The XBeach model is an example of a popular and well-known process based model frequently used to examine storm impacts on the coast (Roelvink, et al. 2009).

# Probabilistic Models

Probabilistic models are by definition non-deterministic. These models apply Monte Carlo techniques to forecast a range of possible future shoreline positions including an associated confidence interval based on a large number of model simulations. Input parameters used are in the form of probability distribution functions (PDFs) which describe the statistical and interdependent nature of the variables which govern the problem. This modeling framework/paradigm can be employed with any one or combination of the previously described models.

Currently, there is a growing understanding in the coastal management arena of the need to move away from making policy decisions based on deterministic estimates of shoreline position towards a risk management style coastal planning framework (Stive, Ranasinghe and Cowell 2009, Ranasinghe, Callaghan and Stive 2012, Jongejan, Ranasinghe and Vriling 2011). This risk-based approach to planning requires probabilistic estimates of input parameters including estimates of shoreline erosion (Jongejan, Ranasinghe and Vriling 2011). By taking the probabilistic approach to modeling shoreline-change the option of developing an Economically Optimal Setback Line (EOSL) becomes available to the coastal manager (Jongejan, Ranasinghe and Vriling 2011, Wainwright, et al. 2015). EOSLs provide a robust probabilistic/statistical framework to allow a community to evaluate the potential economic gains associated with building in a coastal area against the risks associated with doing so (Wainwright, et al. 2015).

## Need to edit these two paragraphs

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Despite the

short term risks

depends on availability of historical data to calibrate structural function

limitations of structural models are propagated through this model

This type of model is best suited for quantifying risks due to short-term, storm induced, erosion events. The effects of sea level rise on future shoreline change may also be included in this model. Sea level rise and climate non-stationarity may be explicitly accounted for in the structural model during the simulation of individual erosion events, or the short-term probabilistic shoreline change risk may alternatively be superimposed on separate projections of long-term shoreline change due to SLR. Explicitly including SLR in the structural function should theoretically produce more robust model results, however this method is inherently more complicated than linear superposition of short and long-term erosion risks. Also, the structural function itself must be capable of accepting SLR as an input, which precludes the use of this method with analytical and semi-analytical methods and really demands the use of an advanced process based model. (add citations)

Also, structural function requires significant historical data be available to calibrate shoreline response model to known historical storm impacts on a given shoreline. Not many areas in the world have access to this type of data, however as the body of knowledge surrounding these methods continues to grow it is likely that robust empirical methods of estimating model parameters will become more widespread.

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# Integrated Coastal Systems

Integrated Coastal Systemsapproaches to modeling shoreline change are probably the most complete as well as complex approaches to modeling the coast which is currently being pursued. As the name implies, these models view the coast as an integration of separate sub-systems (inlets, marshes, and open coast, Aeolian transport, etc…) and attempt to model each sub-system simultaneously within an integrated framework. In this framework the separate models are allowed to communicate with one another in a manner analogous to the littoral cells in a sediment budget approach. The difference between these models and a simple sediment budget is that each sub-model is quite detailed and often process based. Conversely, simple sediment budget approaches tend to focus less on modelling the physical processes taking place in each sub-domain of the coastal system and more on tracking the movement of sediment between these systems. The best example of this type of model currently being developed is the iCOASTT project in the United Kingdom, [www.icoasst.net](http://www.icoasst.net), and to some extent certain applications of the Delft3D modelling suite (Nicholls, et al. 2015).

# Region IX Pilot Study

The approach taken in the FEMA Region IX pilot study to estimating shoreline recession is a combination of three of the commonly used approaches to shoreline change modeling described above. The basis of the approach is the utilization of shoreline change model proposed by Ashton et al. (2011) (Ashton, Walkden and Dickson 2011) which defines a SLR factor to describe future vs. historical rates of shoreline change due to SLR. To do this the model assumes that the current shoreline profile is in a state of dynamic equilibrium with the current rate of SLR. By assuming historical shoreline change is due to SLR, the future rate of shoreline change is then defined by the following equation.

(Eq.1)

Where *m* is a factor accounting for the effect of SLR on the erodibility of the coastline, *Rhistoric* is the historic rate of shoreline change due to historic SLR (*SLRhistoric*), and *Rfuture* is the future rate of shoreline change due to future SLR (*SLRfuture*).

In the Region IX study, this basic model was altered to account for the possibility that not all shoreline change is due to SLR (e.g. erosion due to longshore transport) by first separating *Rhistoric* into historic SLC due to SLR, *RSLR\_historic*and historic SLCdue to coastal processes components *RCoast\_historic*. To do this *Rhistoric* was compared to what the rate of shoreline change would be based on recorded SLR assuming a Bruun rule type behavior (*RSLR\_historic*), the difference in the two was taken to be due to local sediment transport effects (*RCoast\_historic*). Projecting SLC forward into the future, *RCoast\_historic* was assumed to remain constant over time (*RCoast\_historic* =*RCoast\_future*) while *RSLR\_future* was found by adjusting *RSLR\_historic* as described in Equation 1.

A total of three of the seven types of shoreline change models discussed have been incorporated into the Region IX model: historic trend analysis (*RCoast\_historic*), the Bruun rule (*RSLR\_historic*), and the dynamic equilibrium approach (Ashton “m” component of SLR factor). Each of these models is based on a certain set of assumptions and by combining the three of them the assumptions of each are incorporated into the resulting model.

# Region IV Pilot Study

Based on the previous discussion and review of different modelling approaches available for examining SLC due to SLR, the modelling approach used in FEMA Region IX was leveraged for a pilot study in FEMA Region IV as well. Due to a lack of cliffs in the low lying and sandy coast present in the Region IV Pilot area, the dynamic equilibrium approach of Ashton collapsed to the Bruun Rule for this application. While the pursuit of incorporating a probabilistic shoreline change model into this method was identified as being highly desirable, it was ultimately not pursued due to constraints on time and budget.

The pursuit of one of the cutting edge probabilistic or integrated coastal systems modelling frameworks for the Region IV study is highly desirable from a purely scientific point of view as these models *should* produce more robust results than those achieved with the other more simple models discussed. However, the very complexity which allows these models to capture the physics of sediment scale processes and statistical robustness which allows a high degree of confidence in their results also means that they are relatively expensive to pursue. Given this, we concluded that use for the FEMA SLR Pilot is impractical at this relatively early stage in the development of these models. The added robustness of these models comes with added complexity and costs in human, data, and technological resources that are currently prohibitive given the budget and scope of the FEMA Pilot Study effort.

There are many benefits to pursuing the existing Region IX modelling framework. These include (but are not limited to):

1. The method is simple, logical, and straight forward with low overhead
2. It supports overall “idea” of the SLR pilot study
3. Building on previous work provides an opportunity improve upon the initial investment in process made by FEMA

However, there are some notable drawbacks to the approach as well including:

1. The Gulf Coast has a complex history of coastal management activities. These human factors will make it harder to separate the component of historical shoreline change rate due to SLR from shoreline change due to other factors such as beach nourishment and shore-hardening.
2. The method inherently relies on the Bruun Rule and its assumptions for its predictions. These assumptions have been shown to not be entirely robust in many cases, however this can be at least partially be accounted for by examining the sensitivity of the model to the choice of input parameters.
3. The value of “m” used in the model and the depth of closure used to define the shoreface should be “fine-tuned” to the local conditions.

# Building on the RIX Work

While the Region IX framework was developed for the West Coast along a relatively unmanaged section of bluff backed coast in Northern California, the proposed application of this method to a completely different coastal environment, a highly managed study area on the Gulf Coast of Florid dominated by barrier island – back bay – inlet processes, will improve the robustness of the FEMA’s efforts to project future shoreline position along the coast of the entire USA. By capturing sources of uncertainty in the modelling effort, examining model sensitivity, and incorporating the effects of shoreline management (beach nourishment and erosion control structures) the original modelling framework will be improved. It should also be possible to improve on the method by incorporating a sediment budget component and adding a decision tree to address coastal management activities.

## Recommended Approach - East Hampton

Separate coast into three main groups which represent the variability of local conditions: bluff-backed coastline, erodible Atlantic facing coastline, and erodible Sound facing coastline.

1. **Bluff-backed Coastline**

Apply Ashton/Region IX framework

(Eq.1)

* 1. Find historic erosion rates (m3/year) (e.g. Buonaiuto and Bokuniewicz 2005)
  2. Apply historic rates to transect profile and translate to a linear rate (m/year)
     1. with confidence range
  3. Apply Ashton SLR factor (future SLR rate/past SLR rate)^m
     1. Use accelerated recession rate and variability in rate to augment sediment budget
  4. Consider possible effects of mass wasting events on oversteepend cliffs
     1. historical observations
     2. geometric/mass balance

1. **Erodible, Non-bluff backed coast**

Split into Atlantic and Northern sections, for each section apply

* 1. Historic SLC rates
     1. Observed trends in historic shorelines
     2. Sediment budget analyses
  2. Project long-term future shoreline
     1. Extrapolate historic trends/sediment budget
     2. Bruun/Equilibrium profile for SLC due to SLR
  3. Project short-term shoreline variability
     1. Monte Carlo Analysis of short-term SLC potential
        1. Calibrate structural model with historic data
           1. Average transect profile shape parameters

especially pre/post storm transects

some available via ACNYMP

* + - * 1. Simulate effects of historic climate record

Good record available for Atlantic Coast

need data for Block Island Sound and Gardiners Bay

* + - * 1. Simulate effects of individual storms

e.g. Sandy

* + - * 1. Grain-size and sediment composition data

Sample from field work

USGS data

* + - 1. Analysis of synthetic climate records
         1. Simulate climate record

statistical tests to validate match of historic record

Basically done, need to summarize, make figures, and record methodology

* + - * 1. Apply climate record to calibrated structural function

Synthetic time-series of shoreline position/erosion data

Summarize as return-period erosion potential

Compare to historic observations

results likely not valid past a 25/30 year return period erosion event

past this timeframe model will over predict erosion (according to examples and experience of Callaghan et al. 2008)

1. **Map projected shoreline erosion/accretion**
   1. Combine sediment budget, Ashton, and Bruun for long term average position
      1. Include confidence bands based on uncertain model inputs
   2. Overlay short-term erosion potential
      1. In bluffed areas this would be potential mass wasting events
      2. In areas with low-lying erodible coast this is the Monte Carlo short-term shoreline erosion potential
   3. Map multiple time-frames
      1. Due to sediment budget, Bruun, and Ashton long-term positions will change
      2. Short-term erosion potential will remain constant across all scenarios

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