# Future Shoreline Change Projections

It is well understood that an effect of increasing sea-level rise (SLR) will be the erosion of unprotected coastlines throughout the world (P. Bruun 1962). This is, and will continue to be, a problem for much of the world’s population which lives near the coast as well as the infrastructure which they rely on. In order to mitigate the negative consequences of changing shoreline position due to SLR on human lives, property, and infrastructure it is necessary to understand not only *that* sea-level rise affects coastline position, but also *how* SLR will effect local shorelines over time.

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 (S. Leatherman 1979), 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

***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 into the future is then used to predict shoreline change during a given time period. The method may be altered by applying a SLR-factor to account for changes in SLR rate. This SLR-factor is typically a rule of thumb based on the ratio of projected future SLR rates to historical SLR rates and engineering judgment taking into account the local geography, geology, and infrastructure. Aston et al. 2011 present an example of this type of model, which is also 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*** 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.”

Despite growing criticism in the past decade or more, due to its simplicity, ease of use, and lack of simple alternatives the Bruun Rule remains widely adopted and in use by coastal scientists and engineers (Cooper and Pilkey 2004, Stive, Ranasinghe and Cowell 2009, Ranasinghe, Callaghan and Stive 2012). At times it has been used “rather indiscriminately without realizing its limitations” in applications Bruun himself would advise against (Cooper and Pilkey 2004, P. Bruun 1983). While the Bruun rule is often applied to coastal problems directly, its basic premise of shoreline change rates being a result of shoreface slope is just as often incorporated into other models (Cooper and Pilkey 2004).

***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*** 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.

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. Here we will briefly discuss three of these model types: process based models, probabilistic models, and integrated coastal systems models.

***Process based models*** predict SLC by simulating the response of a model shoreline 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. This level of computational 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*** are by definition non-deterministic and 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 allow a community or individual to weigh the potential economic gains associated with building in a coastal area against the risks associated with doing so within a robust probabilistic/statistical framework (Wainwright, et al. 2015).

***Integrated Coastal Systems*** approaches 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 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.

***Recommended Approach***

Based on the previous discussion and review of different modelling approaches available for examining SLC due to SLR, it is recommended for the Region IV study the work produced earlier in Region IX be leveraged for the current study’s goals. 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. I was therefore concluded that, especially at this still early stage in the development of these models, the use of either of these models is currently impractical. 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 pilot study.

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.
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.

# References

Ashton, Andrew D., Mike J.A. Walkden, and Mark E. Dickson. 2011. "Equilibrium responses of cliffed coasts to changes in the rate of sea level rise." *Marine Geology* 284 (1): 217-229.

Bruun, P. 1962. "Sea-level rise as a cause of shore erosion." *Journal of the Waterways and Harbors Division* (The American Society of Civil Engineers) 88: 117-130.

Bruun, Per. 1983. "Review of conditions for uses of the Bruun Rule of erosion." *Coastal Engineering* (7): 77-89.

Cooper, J. Andrew G., and Orrin H. Pilkey. 2004. "Sea-level rise and shoreline retreat: time to abandon the Bruun Rule." *Global and Planetary Change* 43 (3): 157-171.

Dean, Robert George. 1977. "Equilibrium beach profiles: US Atlantic and Gulf coasts." Department of Civil Engineering and College of Marine Studies, University of Delaware, Newark, DE.

Fenneman, Nevin Melancthon. 1902. "Development of the profile of equilibrium of the subaqueous shore terrace." *The Journal of Geology* 10 (1): 1-32.

Jongejan, R.B., R. Ranasinghe, and J.K. Vriling. 2011. "A risk-informed approach to coastal zone management." *Australian Journal of Civil Engineering* 9 (1): 47.

Leatherman, S.P. 1979. "Barrier dune systems: a reassessment." *Sedimentary Geology* 24 (1): 1-16.

Leatherman, Stephen P. 1990. "Modelling shore response to sea-level rise on sedimentary coasts." *Progress in Physical Geography* 14 (4): 447-464.

Moore, Laura J., Jeffrey H. List, S. Jeffress Williams, and David Stolper. 2010. "Complexities in barrier island response to sea level rise: Insights from numerical model experiments, North Carolina Outer Banks." *Journal of Geophysical Research: Earth Surface* 115 (F3).

Nicholls, Robert J., Jon French, Helene Burningham, Barend van Maanen, Andres Payo, James Sutherland, Mike Walkden, et al. 2015. "Improving decadal coastal geomorphic predictions: An overview of the iCOASST Project." *The Proceedings of Cosastal Sediments 2015.* San Diego, CA.

Ranasinghe, Roshanka, David Callaghan, and Marcel J.F. Stive. 2012. "Estimating coastal recession due to sea level rise: beyond the Bruun rule." *Climatic Change* 110 (3-4): 561-574.

Roelvink, Dano, Ad Reniers, Ap van Dongeren, Jaap van Thiel de Vries, Robert McCall, and Jamie Lescinski. 2009. "Modelling storm impacts on beaches, dunes and barrier islands." *Coastal Engineering* 56: 113-1152.

Stive, Marcel J.F., Roshanka Ranasinghe, and Peter J. Cowell. 2009. "Sea Level Rise and Coastal Erosion." In *Handbook of coastal and ocean engineering*, 1023-1038. World Scientific.

Stopler, David, Jeffrey H List, and E. Robert Thieler. 2005. "Simulating the evolution of coastal morphology and stratigraphy with a new morphlogical-behaviour model (GEOMBEST)." *Marine Geology* 218 (1): 17-36.

Wainwright, D.J., R. Ranasinghe, D.P. Callaghan, C.D. Woodroffe, R. Jongejan, A.J. Dougherty, K. Rogers, and P.J. Cowell. 2015. "Moving from deterministic towards probabilistic coastal hazard and risk assessment: Development of a modelling framework and application to Narrabeen Beach, New South Wales, Australia." *Coastal Engineering* 96: 92-99.

# Appendix A. Relevant literature

Table 1 Works of interest for modelling coastal erosion and its effects.

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| ***Source*** | ***Model Type*** | ***Notable for*** |
| T. R. Anderson, C. H. Fletcher, M. M. Barbee, N. L. Frazer and B. M. Romine, "Doubling of coastal erosion under rising sea level by mid-century in Hawaii," *Natural Hazards,* 2015. | Probabilistic / Historic Trend |  |
| A. D. Ashton, M. J. Walkden and M. E. Dickson, "Equilibrium responses of cliffed coasts to changes in the rate of sea level rise," *Marine Geology,* vol. 284, no. 1, pp. 217-229, 2011. | Historic Trend /  Equilibrium Profile |  |
| BakerAECOM, "FEMA Region IX - Sea Level Rise Pilot Study," NA, San Francisco, CA, 2015. | Bruun /  Historic Trend /  Equilibrium Profile |  |
| P. Bruun, "Sea-level rise as a cause of shore erosion," *Journal of the Waterways and Harbors Division,* vol. 88, pp. 117-130, 1962. | Bruun | Origin of “Bruun Rule” |
| P. Bruun, "Review of conditions for uses of the Bruun Rule of erosion," *Coastal Engineering,* no. 7, pp. 77-89, 1983. | Bruun | Explicitly lays out shortcomings of the Bruun Rule as perceived by Bruun himself. |
| D. Callaghan, P. Nielsen, A. Short and R. Ranasinghe, "Statistical simulation of a wave climate and extreme beach erosion," *Coastal Engineering,* vol. 55, no. 5, pp. 375-390, 2008. | Probabilistic | Joint Probability Method |
| D. P. Callaghan, R. Ranasinghe and D. Roelvink, "Probabilistic estimation of storm erosion using analytical, semi-empirical, and process based storm erosion models," *Coastal Engineering,* no. 82, pp. 64-75, 2013. | Probabilistic | Review of the effects of 3 types of structural functions on model results. |
| S. E. Chang and M. Shinozuka, "Measuring improvements in the disaster resilience of communities," *Earthquake Spectra,* vol. 20, no. 3, pp. 739-755, 2004. | Probabilistic | Examines how recovery measures post-disaster can actually increase resiliency |
| M. Chu, J. Guzman, R. Munoz-Carpena, G. Kiker and I. Linkov, "A simplified approach for simulating changes in beach habitat due to the combined effects of long-term sea level rise, storm erosion, and nourishment," *Environmental Modelling & Software,* vol. 52, pp. 111-120, 2014. |  |  |
| C. Coelho, M. Lima and F. Veloso-Gomes, "Relationship between cross-shore active profile and one-line shoreline evolution models performance," *Journal of Coastal Research,* pp. 2107-2112, 2013. |  |  |
| J. A. G. Cooper and O. H. Pilkey, "Sea-level rise and shoreline retreat: time to abandon the Bruun Rule," *Global and Planetary Change,* vol. 43, no. 3, pp. 157-171, 2004. | Bruun Rule | Scathing Critique |
| P. J. Cowell, P. S. Roy and R. A. Jones, "Shoreface translation model: Computer simulation of coastal-sand-body response to sea level rise," *Mathematics and Computers in Simulation,* vol. 33, pp. 603-608, 1992. | Equilibrium profile |  |
| P. J. Cowell, B. G. Thorn, R. A. Jones, C. H. Everts and D. Simanovic, "Management of uncertainty in predicting climate-change impacts on beaches," *Journal of Coastal Research,* vol. 22, no. 1, pp. 232-245, 2006. |  | Managing uncertainty |
| M. Davidson, R. Lewis and I. Turner, "Forecasting seasonal to multi-year shoreline change," *Coastal Engineering,* vol. 57, no. 6, pp. 620-629, 2010. | Probabilistic | Simple Monte Carlo Implementation  Wave Climate via Borgman 1991 |
| R. G. Dean, "Equilibrium beach profiles: US Atlantic and Gulf coasts," Newark, DE, 1977. | Equilibrium Profile |  |
| N. M. Fenneman, "Development of the profile of equilibrium of the subaqueous shore terrace," *The Journal of Geology,* vol. 10, no. 1, pp. 1-32, 1902. | Equilibrium Profile | Proto-Bruun Rule |
| J. R. Houston and R. G. Dean, "Shoreline change on the East Coast of Florida," *Journal of Coastal Research,* vol. 30, no. 4, pp. 647-660, 2014. |  |  |
| M. Jara, M. Gonzalez and R. Medina, "Shoreline evolution model from a dynamic equilibrium beach profile," *Coastal Engineering,* vol. 99, pp. 1-14, 2015 | Equilibrium profile | Variable depth of closure |
| R. Jongejan, R. Ranasinghe and J. Vriling, "A risk-informed approach to coastal zone management," *Australian Journal of Civil Engineering,* vol. 9, no. 1, p. 47, 2011. | Probabilistic | Economically optimal setback lines |
| D. L. Kriebel and R. G. Dean, "Numerical simulation of time-dependent beach and dune erosion," *Coastal Engineering,* vol. 9, pp. 221-245, 1985. |  |  |
| D. L. Kriebel and R. G. Dean, "Convolution method for time-dependent beach-profile response," *J. Waterway, Port, Coastal, Ocean Eng.,* vol. 119, no. 2, pp. 204-226, 1993. |  |  |
| A. Kroon, M. Larson, I. Möller, H. Yokoki, G. Rozynski, J. Cox and P. Larroude, "Statistical analysis of coastal geomorphological data sets over seasonal to decadal time scales," *Coastal Engineering,* vol. 55, pp. 581-600, 2008. |  |  |
| M. Larson, L. Erikson and H. Hanson, "An analytical model to predict dune erosion due to wave impact," *Coastal Engineering,* vol. 51, pp. 675-696, 2004. |  |  |
| S. Leatherman, "Barrier dune systems: a reassessment," *Sedimentary Geology,* vol. 24, no. 1, pp. 1-16, 1979. |  |  |
| S. P. Leatherman, "Modelling shore response to sea-level rise on sedimentary coasts," *Progress in Physical Geography,* vol. 14, no. 4, pp. 447-464, 1990. | Review of model types |  |
| F. Li, P. van Gelder, J. Vrijling, D. Callaghan, R. Jongejan and R. Ranasinghe, "Probabilistic estimation of coastal dune erosion and recession by statistical simulation of storm events," *Applied Ocean Research,* vol. 47, pp. 53-62, 2014. | Probabilistic | Economically Optimal Setback Lines (EOSL) |
| F. Li, P. Van Gelder, R. B. Jongejan, R. Ranasinghe and D. P. Callaghan, "Land-use strategies for coastal erosion zone based on a risk-informed approach," [Online]. Available: http://waterbouw.tudelft.nl/fileadmin/Faculteit/CiTG/Over\_de\_faculteit/Afdelingen/Afdeling\_Waterbouwkunde/sectie\_waterbouwkunde/people/personal/gelder/publications/papers/doc/9th\_IPW\_FanLi\_Land-use\_strategies\_for\_coastal\_erosion\_zone\_based\_on\_a\_risk-infor. [Accessed 9 December 2015]. | Probabilistic | EOSL |
| M. C. Little, R. M. Horton, R. E. Kopp, M. Oppenheimer, G. A. Vecchi and G. Villarini, "Joint projections of US East Coast sea level and storm surge," *Nature Climate Change,* 2015. |  |  |
| J. Lorenzo-Trueba and A. D. Ashton, "Rollover, drowning, and discontinuous retreat: Distinct modes of barrier response to sea-level rise arising from a simple morphodynamic model," *Journal of Geophysical Research: Earth Surface,* vol. 119, no. 4, pp. 779-801, 2014. |  |  |
| R. Masetti, S. Fagherazzi and A. Montanari, "Application of a barrier island translation model to the millennial-scale evolution of Sand Key, Florida," *Continental Shelf Research,* vol. 28, no. 9, pp. 1116-1126, 2008. |  | Same geographical area as Region IV study |
| J. K. Miller and R. G. Dean, "A simple new shoreline change model," *Coastal Engineering,* vol. 51, no. 7, pp. 531-556, 2004. |  |  |
| J. K. Miller and R. G. Dean, "Shoreline variability via empirical orthogonal function analysis: Part I temporal and spatial characteristics," *Coastal Engineering,* vol. 54, no. 2, pp. 111-131, 2007. |  |  |
| J. K. Miller and R. G. Dean, "Shoreline variability via empirical orthogonal function analysis: Part II relationship to nearshore conditions," *Coastal Engineering,* vol. 54, no. 2, pp. 133-150, 2007. |  |  |
| T. L. Miller, R. A. Morton, A. H. Sallenger and L. J. Moore, "National Assessment of Shoreline Change: Part 1. Historical Shoreline Changes and Associated Coastal Land Loss along the U.S. Gulf of Mexico," Washington DC, 2004. |  |  |
| L. J. Moore, J. H. List, S. J. Williams and D. Stolper, "Complexities in barrier island response to sea level rise: Insights from numerical model experiments, North Carolina Outer Banks," *Journal of Geophysical Research: Earth Surface,* vol. 115, no. F3, 2010. |  |  |
| G. Muraleedharan, A. D. Rao, P. G. Kurup, N. Unnikrishnan Nair and M. Sinha, "Modified Weibull distribution for maximum and significant wave heigh simulation and prediction," *Coastal Engineering,* vol. 54, pp. 630-638, 2007. |  |  |
| R. J. Nicholls, J. French, H. Burningham, B. van Maanen, A. Payo, J. Sutherland, M. Walkden, G. Thornhill, J. Brown, F. Luxford, J. Simm, D. E. Reeve, J. W. Hall, A. Souza and P. K. Stansby, "Improving decadal coastal geomorphic predictions: An overview of the iCOASST Project," in *The Proceedings of Cosastal Sediments 2015*, San Diego, CA, 2015. | Integrated Coastal Systems | iCOASST |
| D. Pender and H. Karunarathna, "Modeling beach profile evolution - A statistical-process based approach," in *Proceedings of the 33rd Conference on Coastal Engineering*, Santander, Spain, 2012 | Probabilistic |  |
| D. Pender and H. Karunarathna, "A statistical-process based approach for modelling beach profile variability," *Coastal Engineering,* vol. 81, pp. 19-29, 2013. | Probabilistic |  |
| D. Pender, D. P. Callaghan and H. Karunarathna, "An evaluation of methods available for quantifying extreme beach erosion," *Journal of Ocean Engineering and Marine Energy,* vol. 1, no. 1, pp. 31-43, 2015. | Review | Overview of methods for predicting extreme beach erosion. |
| R. Ranasinghe, D. Callaghan and M. J. Stive, "Estimating coastal recession due to sea level rise: beyond the Bruun rule," *Climatic Change,* vol. 110, no. 3-4, pp. 561-574, 2012. | Probabilistic |  |
| R. Ranasinghe, R. B. Jongejan, D. Callaghan and H. Vrijling, "An innovative approach to determine economically optimal coastal setback lines for risk informed coastal zone management," in *8th International Conference on Coastal and Port Engineering in Developing Countries*, Chennai, India, 2012. | Probabilistic | EOSL |
| J. Rosati, R. Dean and T. Walton, "The modified Bruun Rule extended for landward transport," *Marine Geology,* vol. 340, pp. 71-81, 2013. | Bruun Rule-type |  |
| P. Ruggiero, M. Buijsman, G. M. Kaminsky and G. Gelfenbaum, "Modeling the effects of wave climate and sediment supply variability on large-scale shoreline change," *Marine Geology,* vol. 273, no. 1, pp. 127-140, 2010. | quasi-probabilistic/  sediment budget | Importance of sediment supply and non-stationary wave climate |
| K. D. Splinter, M. A. Davidson, I. L. Turner and T. Beuzen, "Estimating shoreline response in a changing wave climate," in *Proceedings of the 34th Confernence on Coastal Engineering*, Seoul, Korea, 2014. |  | *ShoreFor* model/  effects of non-stationary wave climate |
| M. J. Stive, R. Ranasinghe and P. J. Cowell, "Sea Level Rise and Coastal Erosion," in *Handbook of coastal and ocean engineering*, World Scientific, 2009, pp. 1023-1038. |  |  |
| D. Stopler, J. H. List and E. R. Thieler, "Simulating the evolution of coastal morphology and stratigraphy with a new morphlogical-behaviour model (GEOMBEST)," *Marine Geology,* vol. 218, no. 1, pp. 17-36, 2005. | Equilibrium Profile | Geombest |
| R. C. Thomas and A. E. Frey, "Shoreline change modeling using one-line models: General model comparison and literature review," US Army Corps of Engineers, Washington, DC, 2013. | Analytical | Review |
| K. E. Townsend, R. C. Thomas and A. E. Frey, "Shoreline change modeling using one-line models: Application and comparison of GenCade Unibest, and Litpack," US Army Corps of Engineers, Washington, DC, 2014. | Analytical | Review |
| D. Wainwright, R. Ranasinghe, D. Callaghan, C. Woodroffe, R. Jongejan, A. Dougherty, K. Rogers and P. Cowell, "Moving from deterministic towards probabilistic coastal hazard and risk assessment: Development of a modelling framework and application to Narrabeen Beach, New South Wales, Australia," *Coastal Engineering,* vol. 96, pp. 92-99, 2015. | Proabilistic | Combine long- and short-term erosion effects. Use these to develop EOSLs. |
| D. Walters, L. J. Moore, O. D. Vinent, S. Faherazzi and G. Mariotti, "Interactions between barrier islands and backbarrier marshes affect island system response to sea level rise: Insights from a coupled model," *Journal of Geophysical Research: Earth Surface,* vol. 119, no. 9, pp. 2013-2031, 2014. | Equilibrium Profile | Develop GEOMBEST+\  Capture interaction between barrier island and backbarrier marsh |
| C. D. Woodroffe, P. J. Cowell, D. P. Callaghan, R. Ranasinghe, R. Jongejan, D. J. Wainwright, S. J. Barry, K. Rogers and A. J. Dougherty, "Approaches to risk assessment on Australian coasts: A model framework for assessing risk and adaptation to climate change on Australian coasts," National Climate Change Adaptation Research Facility, Gold Coast, 2012. | Probabilistic | Comprehensive |