AN AEOLIAN TRANSPORT MODEL FOR THE SELECTION OF DUNE RESTORATION ALTERNATIVES

A Thesis

by

JAMES CLAYTON BELL

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2005

Major Subject: Geology

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Approved by:

Chair of Committee,	Christopher C. Mathewson
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ABSTRACT

An Aeolian Transport Model for the Selection
of Dune Restoration Alternatives. (December 2005)
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The landfall of hurricane Claudette in 2003 damaged and eroded most Texas coastal counties. The residents of Pointe San Luis on the west end of Galveston Island, Texas lost their protective dune front and experienced significant shoreline erosion. Following the storm, the Pointe San Luis Property Owner's Association contacted Texas A&M University to design a dune restoration strategy. The greatest natural contributor to dune reconstruction is the available sand delivered by aeolian transport. During the course of the study it became apparent that no model or software existed capable of demonstrating the effectiveness of available dune restoration alternatives. Building Beach©, a coastal aeolian sand transport simulator, was developed in response to this need. Based on discrete dynamics and requiring a minimum of technical input, the software allows coastal property owners, consultants, and coastal developers to graphically model the effectiveness of several dune restoration options including sand fence, planted vegetation, geo-textiles, and other solid protective barriers. The graphical output of Building Beach© enables the user to compare approximations of the performance of different restoration strategies to select the most effective option for a particular beach.

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INTRODUCTION

On July 15th 2003, Hurricane Claudette made landfall at Port O'Connor, Texas, damaging and eroding the shoreline in most south Texas coastal counties. The powerful landfall of hurricanes strip away dune stabilizing vegetation, move massive quantities of sand landward, and create breaches in continuous dune ridges allowing subsequent storms to flood the back dune region (Mathewson, 1987). The residents of Pointe San Luis, on the west end of Galveston Island, Texas, experienced the loss of the majority of their protective foredune line, and the erosion of the already narrow beach. Immediately following the storm, the Pointe San Luis Home Owner's Association began to search for alternatives to rebuild the eroded dune front and reestablish protection for their property. Several factors had to be considered. Any measure taken to reestablish the foredune ridge must be designed to withstand continuous attack by waves and high winds, or built with the intention of sacrificing the structure to the next large storm. In addition, the method chosen must consider the post-storm morphology of the shore, continually acting natural processes, and the identification of weak areas where future storms may breach (Mathewson, 1987).

Any techniques chosen must also consider impacts to beach use and availability. In 2004, tourism to the Texas Gulf Coast generated approximately $7.5 billion in revenue for the State of Texas, coastal communities, and businesses (Texas Tourism Office, 2004). Keeping Texas beaches attractive to tourists seeking recreation is a high priority. However, what attracts visitors to beaches seems somewhat paradoxical.

This thesis follows the style of *Environmental & Engineering Geoscience.*

In a recent survey of Polish coastal tourists and inhabitants, people indicated that they desired a natural looking beach, but responded unfavorably to inconvenient access and lack of immediate services, such as parking, lodging, and restaurants (Jeddrzejczak, 2004). Of course, in order to provide full services, storm protection for these facilities is necessary; but the installation of some protective measures destroys the tourist's and resident's aesthetic perception of a "natural" beach. Tragically, while the value of protective foredunes is appreciated by researchers and planners, it is not always true of municipalities where active recreation and ocean views are priority. Any dune restoration strategy must take into account the economic, ecological, and aesthetic preferences desired, as well as the hazard protection required.

COASTAL PROTECTION

Currently, many methods are commonly utilized to reconstruct post-storm dunes. The most often seen method for the rapid reconstruction of coastal protection is the installation of a solid linear barrier seaward of property, such as a seawall, scraping the beach to create a sand wall, geotextile tube core dunes, or groins. In most instances, the installation of seawalls and groins are reserved for shorelines in need of significant protection, where the natural beach environment and ecology is sacrificed for the safety of the public, such as the beaches in front of the city of Galveston, Texas. These beaches preserve nothing of the initial natural ecology, and completely recreate a beach geomorphology to best serve the protection of the city.

Geotextile tube core dunes, or “geotubes” have performed very well along the Texas coast, preventing or minimizing storm induced erosion and landward property damage. Although these structures provide immediate storm protection, it comes at a great financial and ecological cost. The installation of a geotube requires a significant initial investment, and continuous maintenance. Though fairly resistant, geotubes in place on 8 miles of Galveston Island, at a cost of $3.5 million, suffered numerous tears, partial deflations, scour, and wash overs during Hurricane Claudette (Heilman, 2003). Also, a geotube requires constant attention to detect tears and ruptures caused by vandalism, wildlife activity, and natural processes.

Similarly, sand walls constructed by scraping the beach creates an immediate protective barrier, and at a much smaller cost, but at a beach sand cost which can increase the risk of coastal erosion. However, sand walls are even more susceptible to erosion by natural processes and lower energy seasonal storms, and require much more maintenance and attention. The raking of beaches prevents new plant colonization and disturbances created by burrowing animals that can trap sand and nutrients (Nordstrom, 2000). It is most important to note, that while these often utilized methods create an immediate barrier, once in place they can only degrade. Natural processes cause the eventual failure of these structures. Any blown sand stopped by the structure is merely redirected down the longshore component of the wind direction, resulting in no new dune growth and no additional protection.

Alternatively, permeable barriers such as sand fence, vegetation, and even recycled Christmas trees have been used to rebuild protective foredunes. Though these options do not create immediate storm protection, they optimize natural processes to trap sand and continuously encourage rapid dune creation and growth. Sand fencing is extremely effective and inexpensive, often constructed of materials that would otherwise be discarded, such as wooden pallets. A study conducted on Santa Rosa Island, Florida, following Hurricane Opal in 1995 by Miller et.al. (2001) showed that sand fencing was crucial to the rehabilitation of wash over sites in the foredune line, regardless of its configuration or material. Planting vegetation for foredune reconstruction can be as effective as sand fencing. Any species selected for this purpose must be tolerant of the shore's climate, saline conditions, and possess a root structure capable of stabilizing developing dunes (Dahl, 1977). Along the Texas Gulf Coast, sea oats and Bitter panicum have both been used to rehabilitate dunes with great success, as well as adding to the local ecology and aesthetics. Finally, once a year there is a surplus of discarded

Christmas trees available for use in dune restoration. These discarded trees are very effective at capturing windblown sand, and as biodegradable protective barriers, they provide a source of nutrients for colonizing vegetation (Barnett, 1989). It is not surprising then, that a combination of these methods, such as the use of both sand fence and planted vegetation would yield even greater results. A study conducted on Timabalier Island, Louisiana over three years concluded that in combination, sand fencing and vegetation could build significant foredunes, even in a sediment deficient environment (Mendelssohn, 1991).

It is important to note that none of these dune restoration alternatives are meant or designed to prevent shoreline erosion. Sand dunes and barriers offer protection from severe storms by providing a source of sediment to dissipate energy, but cannot prevent long term erosion of the shoreline.

Commercial and government software programs exist that attempt to model sediment transport as described by the intricate physics of particle motion and fluid mechanics. However, the strong non-linearity and difficulty of reconciling and modeling the fluid dynamics of wind over an irregular surface, saltation of particles, and the avalanching of grains by gravity, accurately tracking dune field evolution by aeolian processes has been described as “practically impossible” (Bishop, 2002). In addition, current sediment transport software programs either require membership or affiliation with a government or consulting agency, are expensive, and extremely technical. They require an intimate understanding of sedimentary processes and the input of data often not available to the lay person. What is needed is a simulator that can model the common approaches and combinations of approaches as accurately as possible while minimizing the detailed input required and associated cost.

BUILDING BEACH©

Building Beach©, an aeolian sand transport simulator, was developed in response to this need for a simple program designed for non-technical use. The software contains twenty different simulators, each modeling a unique dune restoration option with fully adjustable parameters regarding beach morphology and sand transport. Building Beach© is based on the concept of discrete dynamics in which simplified rules, not based on detailed physical processes govern sand transport, reflect observations of reality. The model illustrates the transport of discrete units of sand through an approximated beach environment in an attempt to demonstrate the fate and transport of aeolian beach sand.

The model considers discrete blocks of sand being transported by wind in a 100x100 cell two-dimensional lattice. Each block represents the average quantity of sand transported by wind under the assumed average wind condition. The movement and behavior of these blocks are governed by three simple algorithms, “Fall”, “Slip”, and “Stack”. (Figure 1.)

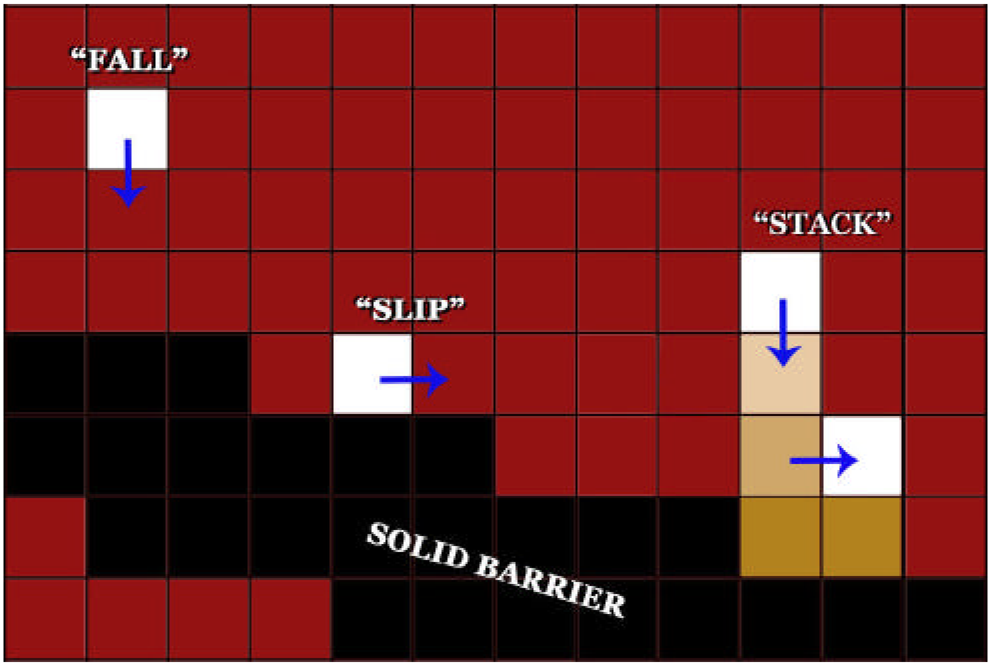


Figure 1. Motion of sand units in Building Beach©.

Under "Fall", a sand block with open space below it will advance into the empty cell each timestep, until it encounters a barrier of some kind. Upon encountering a solid barrier, the sand unit is prevented from continuing in the direction of transport. Instead, the unit is now moved by the force of the wind deflected by the solid barrier, as defined by "Slip". If a permeable barrier is encountered, the sand unit is allowed to proceed through the barrier as determined by the properties of that barrier, which are discussed later.

Sand transport is governed by "Slip" when the cell below a unit of sand is occupied by a barrier. In this case, the block of sand is then transported not by the prevailing wind conditions, but by the estimated component of the wind vector deflected by the barrier. (Figure 2.) Under "Fall" the rate of sand transport is always 1 cell/timestep. To account for the reduced magnitude of the component of the deflected wind, “Slip” defines motion along the barrier at a rate of (1/n) cells/timestep, where n is dependent on the orientation of the barrier relative to the wind front. For example, a barrier at an angle of 20° relative to the wind front will have a deflected component of approximately 30% of the “Fall” transport rate, so n ˜ 3. This results in an approximate “Slip” transport rate of 0.33 cells/timstep. However, a sand unit cannot move a fraction of a cell in the discrete lattice. Sand units may only move an integer number of cells every timestep, so under “Slip” the block of sand will migrate down the barrier at a rate of 1 cell every three timesteps. A greater the angle between the barrier and the windfront will result in a larger deflected wind component, and a more rapid rate of “Slip”.

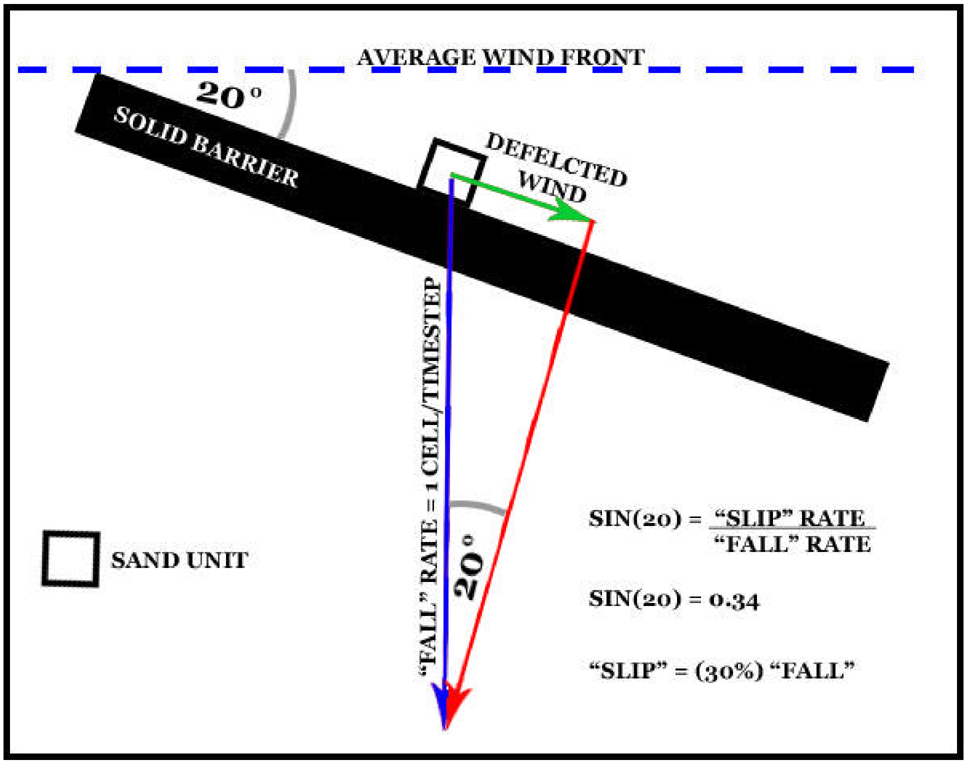


Figure 2. Determination of “Slip” rate based on ANGLE.

Under the “Stack” algorithm, blocks of sand are allowed to stack on top of each other up to a reference height of four units. This reference height represents the maximum height to which a sand dune can grow under the prevailing wind conditions. The sand blocks have undefined dimensions of length, width, and height, in size, and do not attempt to quantify the height of accumulated sand in the model. Sand blocks are also allowed to un-stack in the horizontal direction under the “Slip” algorithm, under the assumption that the horizontal component of the deflected wind is never strong enough to move more than one block. However, stacks of sand are not allowed to un-stack in the vertical direction, because the magnitude of the prevailing wind may be strong enough to transport multiple blocks in one timestep. Building Beach© assumes that the average wind velocity is all times powerful enough to transport a stack of sand four units high as a collective unit.

Building Beach© utilizes two types of barriers to sand transport to emulate dune restoration alternatives; Solid barriers and permeable barriers. Solid barriers are defined in the model as cells that cannot be occupied by discrete sand blocks. These barriers are meant to represent such features as geotextile tubes, sand walls, and other impermeable structures. On encountering a solid barrier, a sand block governed by “Fall” is halted and becomes governed by “Slip”. All solid barriers in the models are defined as having a width of five cells, except for solid groins, which have an width of two cells.

Permeable barriers trap some sand blocks, and allow some to pass through. A permeable barrier is defined in the model as a zone of cells in which each cell can be either defined as being solid or open space. Each cell within the zone is first assigned a random number between 0 and 1. Then based on the user defined trapping efficiency, each cell is defined as either solid or open. For example, given a trapping efficiency of 70%, all cells in the permeable zone with an assigned random number value equal or less than 0.7 would be then defined as solid, and all other cells defined as open space. This process repeats and regenerates the zone every timestep, meaning that each cell within the permeable barrier zone is solid 70% of the time on average. In this way, any permeable barrier can be modeled with any given trapping efficiency, enabling the user to model sand fence, planted vegetation, natural dunes, hay bales, and even Christmas trees. The layout of permeable barriers in Building Beach© can be modeled in three ways; as linear features such as sand fence, as perpendicular linear features such as sand fence groins, and as rectangular patches or thick linear features such as planted patches of vegetation. Building Beach© combines these options into twenty different beach layout simulators, each with adjustable orientations and sand input rates.

APPLYING THE MODEL

Applying the model to the Pointe San Luis, or any beach, requires the user to input parameters specific to that location. After opening the program Building Beach©, the user is first shown the Main Menu. The Main Menu offers the user three choices regarding the morphology of their beach; Solid Barrier, No Protection, or Natural Dunes. (Figure 3.)

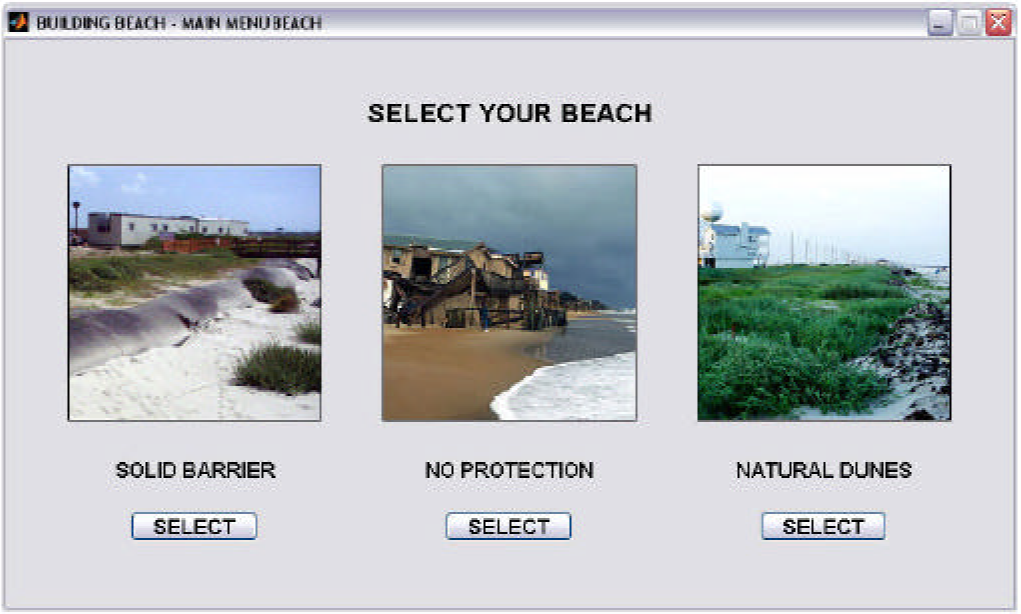


Figure 3. Main Menu of Building Beach©.

The Solid Barrier selection directs the user to a submenu containing simulators which all include an impermeable barrier. The No Protection selection directs the user to a submenu containing simulators which only include non-natural permeable barriers such as sand fence and planted vegetation. The Natural Dunes selection directs the user to a submenu where combinations of non-natural permeable barriers are modeled in conjunction with natural dunes. The Pointe San Luis has a narrow strip of natural dunes in front of the developed property, so the Natural Dunes option should be selected. The user is then directed to a submenu where dune restorations options may be selected from a pop-up menu. (Figure 4.) A preview image of the selected options is generated and displayed to the right of the pop-up menu.

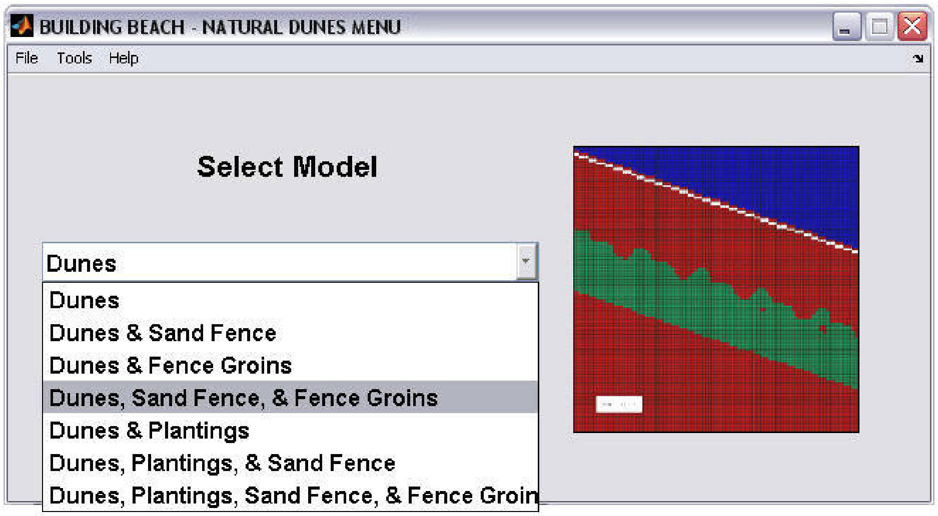


Figure 4. Submenu of Building Beach (Natural Dunes).

All of the models presented by the Natural Dunes Submenu will require the same input parameters to define the morphology and layout of the beach at Pointe San Luis. These input parameters are described in Table 1.

Table 1. *Input parameters required for simulation.*

INPUT PARAMETER	DESCRIPTION
ANGLE	Angle between the average wind front and the beach orientation
BEACH WIDTH	Normalized width of the beach relative to the grid
DUNE TRAPPING	Trapping efficiency of the natural dunes
DUNE WIDTH	Normalized width of the dunes relative to the grid
DUNE FREQUENCY	A coefficient determining the sinuosity of the dune front
DUNE IRREGULARITY	A coefficient determining the shape of the dune front
SAND INPUT	Defines periodic pulses of sand introduced to the system.

The ANGLE parameter is defined in the model as the angle between the average wind front and the shoreline. (Figure 5.) The orientation of the shoreline is easily obtained using a compass, map, or air photograph. The average wind direction can be obtained from many sources, including the National Weather Service or the National Oceanic and Atmospheric Administration (NOAA). It is important to note that Building Beach© requires the orientation of the average wind front, which is perpendicular to the average wind direction. The orientation of the shoreline at Pointe San Luis is N 50° E and the average wind direction is approximately N 60° W (Wind front orientation of N 30° E), giving an input value of 20° for ANGLE. Building Beach© is capable of modeling ANGLE values from 0° to 45°.

Figure 5. Determination of ANGLE parameter.

The Parameters of BEACH WIDTH and DUNE WIDTH are easily acquired from air photographs or site surveys. In the model, these parameters have undefined units of length, and are entered relative to each other. For example, from the air photograph (Figure 6.), it is shown that the DUNE WIDTH is 27% of the BEACH WIDTH. The user controls the scale of the model domain by their choice of input values for these parameters. For example, a chosen BEACH WIDTH value of 30 cells would result in a DUNE WIDTH value of approximately 8 cells.

Figure 6. Determination of DUNE WIDTH & BEACH WIDTH parameters.

The DUNE FREQUENCY and DUNE IRREGULARITY parameters are determined by the user by adjusting the given parameters in the model, and pressing the Preview/Reset button until the desired dune front shape is reached. The shape of the dune front for Pointe San Luis is linear, with small perturbations. Building Beach© uses a trigonometric expression to describe the shape of the dune line, and every cell below this line is defined as being part of the natural dune.

The function determining the shape of the dune line follows. The coefficients are defined in Table 2.

```
if (i)<(((100-BW))  -(j*((theta)))+(DI*sin(j*DF)*cos(i*DF)))&...
   ((i)>((100-BW-DW)-j*((theta))))
                         S(i,j)=dune;
end
```

Table 2 *Dune line function coefficients.*

Coefficient	Model Definition
i	i th row
j	j th row
BW	BEACH WIDTH
DW	DUNE WIDTH
DI	DUNE IRREGULARITY
DF	DUNE FREQUENCY

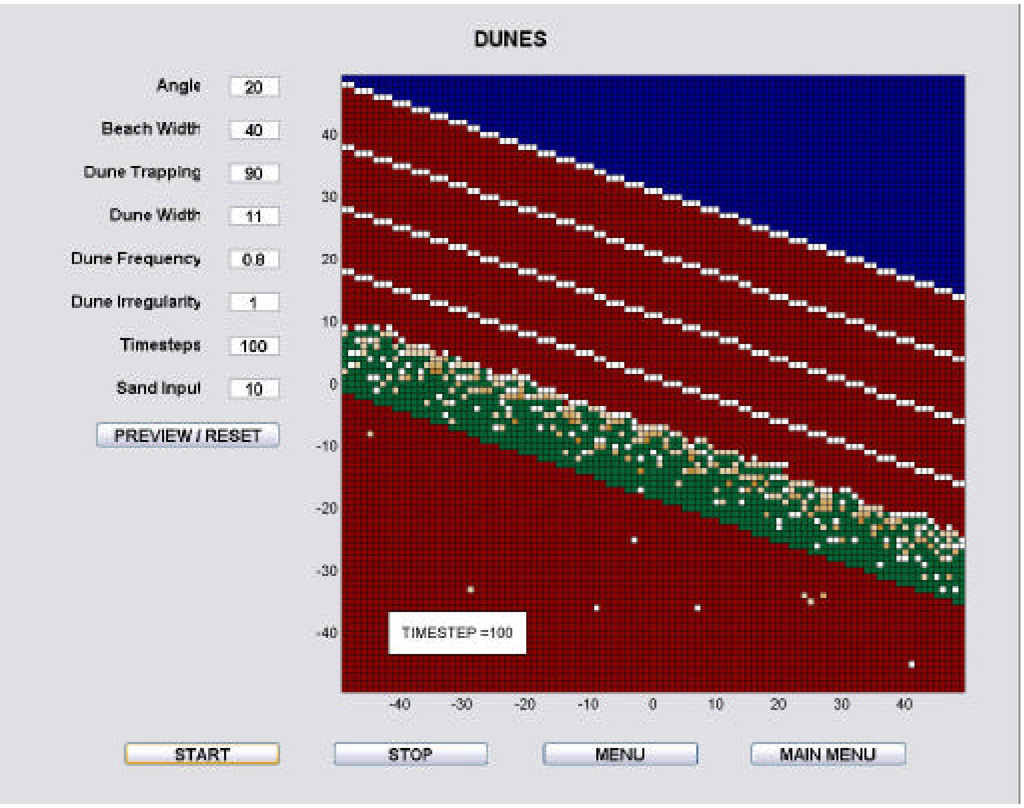
In this function, the DF coefficient describes the periodic shape of the dune line, and the DI coefficient determines the magnitude of the maxima and minima. For this scenario, a DUNE FREQUENCY value of 0.8, and a DUNE IRREGULARITY value of 1 seem to accurately reflect the actual shape of the dune front. Building Beach© accepts DUNE FREQUENCY values between 0 and 1, and DUNE IRREGULARITY values between 0 and 10. These values should be chosen to reflect the appropriate scale chosen by the user in the selection of the DUNE WIDTH and BEACH WIDTH parameters. (Figure 7.)

Figure 7. Illustration of dune line from aerial photograph.

The DUNE TRAPPING parameter describes the trapping efficiency of the natural dunes in order to model them as a permeable barrier. For the small dune field on Pointe San Luis, a trapping efficiency of 90% was estimated based on the observed quantity of sand permeating the vegetated dunes, the density of dune vegetation, and the slope of the dune crest.

Finally, a SAND INPUT value must be entered by the user to define the average amount of sand entering the system. Building Beach© approximates the influx of wind blown sand into the system by introducing pulses of sand units, instead of continuous sand input. The input given for this parameter defines the periodic pulses of sand introduced to the system. For example, a SAND INPUT value of 12 generates a pulse of sand entering the system every 12 timesteps. A value between 5 and 10 describes a large quantity of sand moving through the system, a value between 10 and 15 describes a moderate amount of sand, and a value between 15 and 20 describes very little sand. It is estimated that the beach at Pointe San Luis has a low/moderate amount of sand entering the system on average, so a SAND INPUT value of 10 was chosen.

Now that all the necessary input parameters for Pointe San Luis have been determined, they can be used to model different dune restoration options, such as sand fence, planted vegetation, combinations of restoration options, or no action. Below the model output for the current condition of Pointe San Luis after 100 timesteps is shown. (Figure 8.)



DUNES

Angle 20
Beach Width 40
Dune Trapping 90
Dune Width 11
Dune Frequency 0.8
Dune Irregularity 1
Timesteps 100
Sand Input 10

TIMESTEP =100

Figure 8. Results of Dunes model after 100 timesteps.

The graphical output of each simulator may be saved as a .jpeg image by using the File -> Save as Image option. This command automatically saves the generated output as an image file, including the user defined input, within a folder named "SAVED_IMAGES" contained inside the Building Beach© software package. After the image has been saved, a small window is displayed alerting the user. After saving all desired simulations, the user may then graphically compare the generated images to determine the appropriate or best dune restoration option for the beach in question. In the example shown in Figure 9, simulation output of natural dunes and the combination of natural dunes, sand fence, and planted vegetation are compared. The comparison of these two models shows that the combination of natural dunes, sand fence, and planted vegetation is more effective at capturing sand over the period of 100 timesteps.

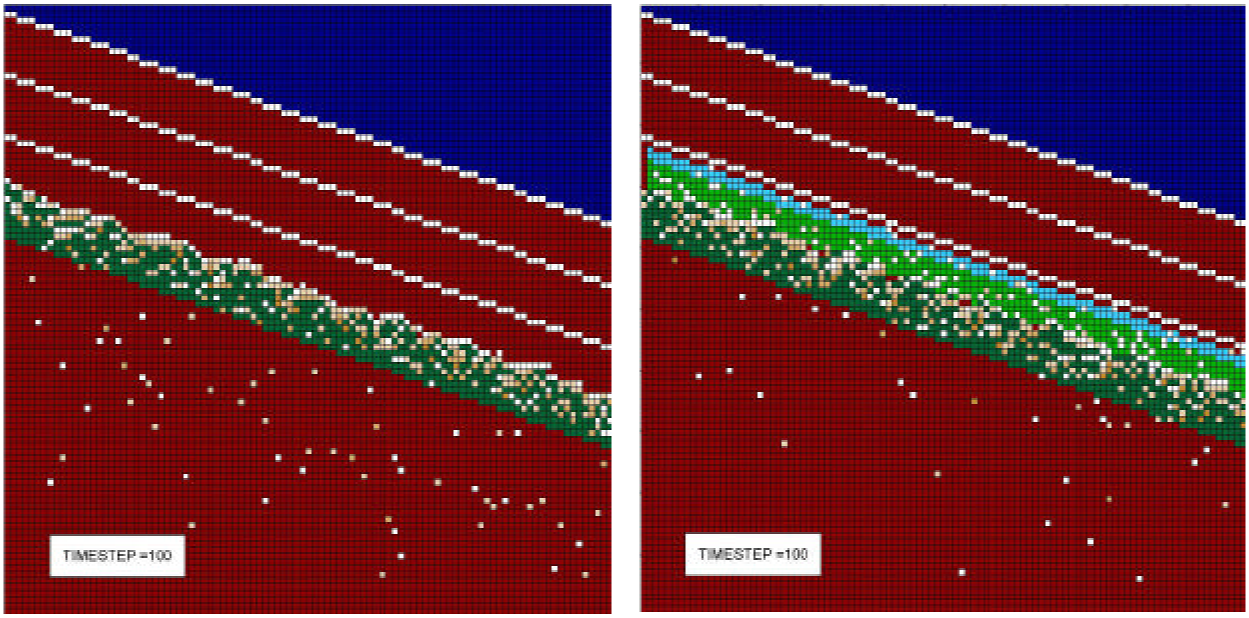


Figure 9. Simulation outputs compared. Left: Natural dunes. Right: Natural dunes, plantings, and sand fence.

Documentation for Building Beach© is included, in the form of a website contained within the software. The site offers examples, step by step instructions, and definitions of all model parameters. The help file is accessed from the Help menu, and uses a browser detector to open the documentation web page with the user's default browser.

DISCUSSION AND CONCLUSIONS

The benefits of simple and readily available software like Building Beach© are extensive. It allows coastal home owners and property managers to assess and compare available dune restoration options easily, without requiring technical skills and difficult to obtain data. The semi-qualitative nature and graphics generated by Building Beach© allow the software to be applied to virtually any beach on Earth, simulating twenty combinations of dune restoration alternatives, with fully adjustable user input. In addition, to make Building Beach© accessible to the public, it is currently available for free download from http://www.claytonbell.net as both MatLab code and as a Windows executable program.

In order for the software to be applicable to many locations, many assumptions were made. Building Beach© assumes that for any beach modeled, there exists an infinite supply of sand available for transport by wind, with the rate at which sand enters the system determined by the SAND INPUT parameter. The model does not consider colonization and stabilization of dunes by vegetation, shoreline erosion, changes in wind direction or magnitude, or storm frequency and effects. To include these factors in the scope of the simulator would require the quantifying of their respective rates relative to the prevailing sediment transport rate. This would also require the addition of technical input parameters such as particle density and grain size analysis, historic shoreline erosion rates, and rates of growth and survival of specific coastal plant species. The incorporation of additional coastal processes would result in a more powerful, yet more complicated software package that would either be beyond the ability of the non-technical user, or only applicable to a few locations where input values were readily available.

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