Table of Contents

Go Back

A Dynamic Simulation Model of Beach Sand Replenishment: a Case Study of Santa Barbara, California

David Turbow
Department of Environmental Analysis and Design
270 Social Ecology I
University of California, Irvine
Irvine, CA 92697-7070
Phone (949) 824-5576
Fax (949)824-2056
e-mail: dturbow@uci.edu

Steve Norwick
Department of Environmental Studies and Planning
Sonoma State University, California
Rohnert Park, CA 94928
Phone (707) 664-2485
Fax (707) 664-4202
e-mail: norwick@sonoma.edu

Sajjad Ahmad
Department of Urban and Regional Planning
University of California, Irvine
Phone (949) 824-1879
Fax (949) 824-8286
e-mail: sajjad@uci.edu

ABSTRACT

Sediment deprivation from dam installments contributes to beach erosion yet the underlying physical and economic factors linking them together have traditionally been isolated during regional planning. In order to gain a better understanding of the behavior of a managed beach system, a dynamic simulation model was developed incorporating physical and monetary factors influencing the amount of available beach sand. The Santa Barbara littoral cell was chosen as a case study to evaluate the feasibility of beach preservation goals under scenarios in which annual sand replenishment funding, sand prices, or sediment recovery from behind dams were limiting factors to available beach sand. Sources of model uncertainty included limited information on historical sand replenishment costs and true residence time of sand in the littoral cell. Results indicate that with ample sand replenishment funding and moderate annual sand loss assumed, a beach could be maintained at a desired width for several decades.

Keywords: *beach erosion, coastal processes, sand replenishment, sediment, simulation model*

INTRODUCTION

In this study, policy and management measures related to the costs of replacing sand on eroding beaches were explored using a system dynamics framework. As much as 80% of California's shoreline is actively eroding, removing beaches - tremendous economic assets - at an average rate of four inches, and in some places, several feet per year (FEMA, 1998). Beach erosion poses a continuing challenge to engineers, planners and policy makers because in addition to physical influences beyond human control, such as sea level rise, man-made structures from inland watersheds, especially dams, can deprive beaches of a necessary coarse-grained sediment supply (Willis, 2001).

Coastal rivers and streams are now known to supply up to 90% of the beach sand in California (Griggs, 1987). Unfortunately, the rates and magnitudes of sediment delivery along these channels have been greatly diminished over the past eight decades through land use changes and other barriers to sediment transport, which created a time-delayed need for the beach preservation efforts seen today. For example, more than 1,400 dams in California, many of which were initially designed to provide a reliable supply of water, have prevented a steady supply of sediment from reaching the coast (Jenkin, 1998). The Santa Barbara littoral cell in California was selected as a study site (Figure 1). Fifteen major dams in this littoral cell affect the amount of sediment reaching the actively managed beaches downstream.

Figure 1: Map of Study Site

Sediment accumulation behind dams not only deprives beaches of sand, but also diminishes the storage capacity of reservoirs and causes serious disruptions of the downstream river habitat for plants and fish. Because the average reservoir in the 18 western states of the U.S. has an expected useful life of only 50 years, economic and engineering solutions for restoring downstream environments are a major policy issue.

Artificial beach nourishment, the "soft" solution alternative to, or augmentation of, shoreline armoring projects, refers to the practice of sand replenishment on beaches using dredges and bulldozers. Artificial beach nourishment has been implemented extensively in coastal cities (DNOD, 1977). Sand is typically "piped" in or dredged from offshore sources using funding from coastal cities with help from the State of California. However, the practice of sand replenishment is generally a temporary solution to beach erosion - one likely to become less feasible to coastal cities in the long run due to rising transportation costs and logistic difficulties associated with locating beach sand quality sediment.

The impetus for much coastal erosion policy is that if sand is not replaced on beaches, both private property and lives can be threatened. Beaches boost the economic value of local communities by attracting tourists and benefit coastal residents by increasing property values.

Though it would seem intuitive that a system of accountability for sediment interruption be set in place for California, coastal cities are currently required to apply for limited state funding to prevent beach erosion often associated with federal projects on a site-by-site basis. So historically, property owners and local jurisdictions had to develop individual means to prevent erosion (Fischer, 1990). A draft version of the coastal erosion policy signed by the Governor of the State of California has stressed the need for multi-objective regional approaches towards shoreline protection (Davis, 2001). Similar federal-level coastal erosion policy legislation drafted in the United States would require a systemic approach to beach nourishment. But at present beach nourishment projects are evaluated on a project-by-project basis.

A central premise on which this paper is based is that only loose institutional arrangements are in place to assure sediment delivery to beaches, such that the costs of net sand loss attributable to sediment deprivation from dams are not factored in to the funding equation. Sand replenishment projects designed to offset the loss of beaches often entail incompletely defined economic tradeoffs for coastal cities and the need for beach protection funding can arise rather suddenly. Our purpose is to use a system dynamics methodology to model the key physical and economic factors related to sand supply, so that the feasibility of beach preservation goals can be examined from a regional perspective.

System Dynamics as an approach for modeling complex dynamic systems has been successfully applied to policy analysis and environmental management (Ford, 1999; Sudhir et al., 1997). The use of concepts and applications of the system dynamics approach to address a wide variety of problems have been discussed by several authors (Sterman, 2000; Forrester, 1961; and Coyle, 1996).

System dynamics has become increasingly popular for modeling water resource systems. Palmer (1998) has done extensive work in river basin planning using SD. Keyes and Palmer (1993b) used a SD simulation model for drought studies. Matthias and Frederick (1994) have used SD techniques to model sea-level rise in a coastal area. Fletcher (1998) used system dynamics as a decision support tool for the management of scarce water resources. Simonovic and Fahmy (1999) applied SD to long-term water resources planning and policy analysis for the Nile River Basin. The SD approach has been used to model reservoir operation for flood control (Ahmad and Simonovic, 2000a), to calculate flood damages (Ahmad and Simonovic, 2000b), and to analyze economic aspects of flood management policies (Ahmad and Simonovic, 2000c). Simonovic (2001) used SD to develop a world water model. Ahmad and Simonovic (2001) used SD as a decision support tool to evaluate impacts of flood management policies.

Our model is based on the relationship between sediment delivery to beaches and erosion processes. Rates of coastal sediment delivery (Brownlie and Taylor, 1981) and historic sand yields (Knur, 2001) have been published for portions of the Southern California. Physical oceanographic studies have demonstrated links between climate change and episodic changes in sediment flux on rivers in California (Inman & Jenkins, 1999), and dynamic modeling has been applied to the study of coastline erosion. For example, Ruth and Pieper (1994) simulated the effects of sea level rise in coastal areas of the Eastern United States using a combined dynamic and spatial analytical modeling approach.

METHODS

A sediment budget for the Santa Barbara littoral cell was patterned after Runyan (2001) and Willis (2001). Sand inputs and outputs to the watershed was then simulated over the 150 year time period 1900 to 2050 in a system dynamics framework using STELLA 6.0® Research software from High Performance Systems, Inc. An overview of the model architecture is shown in Figure 2. A 150-year time horizon was set with a time step of one year using Euler integration methodology. The model was loaded with data and run.

DATA AND ASSUMPTIONS

Overview of Study Site and Modeling Approach

The stretch of coastline used in our study extends from Pt. Conception California to Pt. Mugu California and is known to oceanographers as the Santa Barbara Littoral Cell. The cell was assumed to exist in a state of equilibrium before the simulation period, after which the construction of dams perturbed the system. The impacts of fifteen dams upon sediment delivery are modeled singularly for this simulation.

The influence of dams were incorporated into our model as a step function, according to the year they were assumed to be constructed and the degree to which beach sand quality sediment became trapped and precluded from reaching the coast. The year 1940 was chosen as the default year for dam installation in the "dam install" parameter. A model parameter added called "dam remove" referred to either the full decommissioning of a dam, or to methods of sediment bypass, which partially restore sediment supply to the coast.

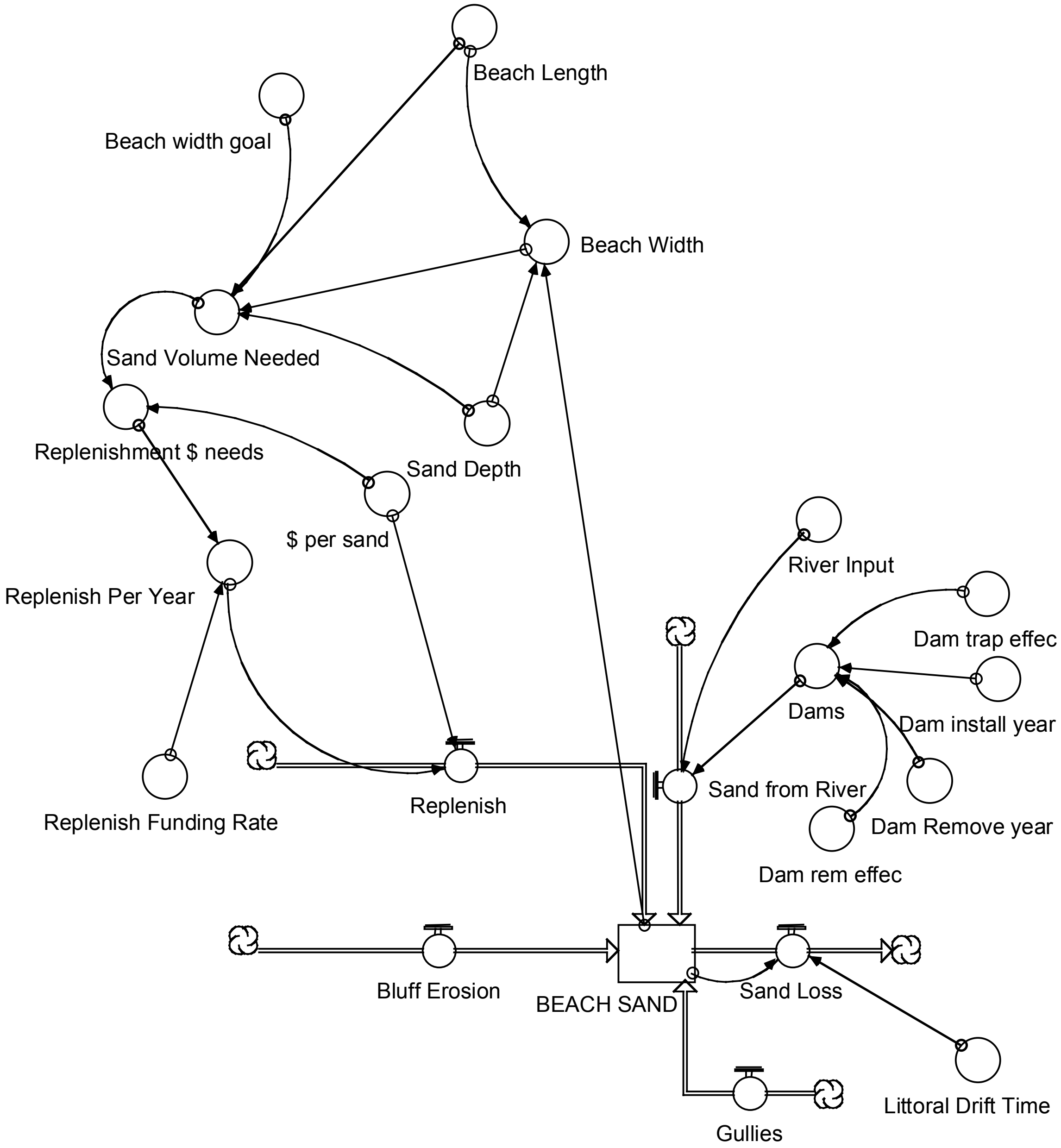

Figure 2: Stock and flow diagram of model structure

The amount of sediment delivery reaching the coastline was modeled using data published by Runyan (2001). The primary exogenous drivers of beach sand delivery were assumed to be river input, cliff sand, littoral drift time, and the influence of dams. No published data are available by which to compare to pre and post-dam sediment loads at stream gauging stations (Willis, 2001). An initial beach length of 140,800 m. was used for the littoral cell and a constant sand depth of 3 meters. Gully erosion was set at zero for the Santa Barbara cell, though it can supply at least 300,000m^3 per year of sediment to other littoral cells in Southern California (Runyan, 2001).

River inputs supplied 3,642,773 m^3 of sand to the Santa Barbara littoral cell per year. The erosion of coastal rocks, or "Bluff Erosion" supplied 11,312 m^3 of sand per year (Runyan, 2001). The rate of river sand reaching the beach was assumed to be dependent upon both littoral drift time (defined in our model as the residence time of sand on the beach in years) and the resistance to flow from dams. The littoral drift time was set at 5.8 years (Runyan 2001), though other estimates of residence time may be required for future examination.

A multiplier used to model the resistance of sand leaving the river from dams could be adjusted at a factor ranging from a value of zero to one. Though dams were constructed as early as the late 19th century and as late as 1976, it was assumed that dams in the littoral cell were constructed in the 1940s - a peak period in the construction of California's dams. The "slider" function in STELLA was used, such that the effects of changing the time of construction could be altered in the simulation period.

Cost estimates of sand replenishment were based on communications with a technical advisor to a long-term state-funded beach restoration project in Santa Barbara, and set at $7 per m^3 (Bailard, 2002). The maximum funding by the state was set at $800,000 per year.

Sand loss was computed as a function of littoral drift time. Replenishment funding needs were defined in our model as the amount of money required to replenish the beach to a width desired by the City, and were assumed to be dependent on both the price of sand and on volume of sand needed. Yearly replenishment funding was computed as a function of the minimum of either the dollars needed, or the replenishment funding rate.

Factors Ignored

The beaches in the watershed were assumed to have been in a state of dynamic equilibrium before human development of the watershed. This is generally believed to be true of California, and the Gulf Coast, but not the Atlantic Coast of the U.S. Stochastic factors influencing the volume of beach sand, such as storm events during the El Niño Southern Oscillation of 1982-1983 and 1997-1998, were ignored.

Apart from the instrumental values of beaches to people, beaches serve as habitat for wildlife such as shorebirds, marine mammals, and invertebrates. We have not considered the environmental or ecological values specifically for this paper.

Scenarios Examined

Three scenarios were examined by employing various assumptions about the conditions and relative influence of input parameters on model output. Each scenario begins with a 50m wide beach. The beach width goal was set at 30 meters for all scenarios, although the average beach width in the littoral cell for 2002 was not used in this simulation.

Scenario 1: Ample Sand Replenishment Funds and Proactive Dam Strategy

This represents a scenario in which there is abundant sand on the beach at the beginning of the simulation and $5 million in funding per year to replace lost sand. Planners heed warnings in the late 1990s that dams are trapping potential beach sand, which might hurt coastal economies, so they decide proactively to undertake a massive cooperative project with state and federal agencies to immediately begin bypassing sediment from behind dams. Sediment once trapped behind dams begins re-flowing in the year 2002, allowing a full 47 years for sediment recovery to occur along the shoreline. The sediment bypass will restore 50% of the previously trapped sediment supply to the shoreline. Unfortunately, the price of sand is rising. Can a beach width goal of 30m still be met if the price of sand should rise from $7 per cubic meter to various levels: $15, $25, and $35 per cubic meter?

Scenario 2: Limited Sand Replenishment Funds and Delayed Sediment Recovery.

In this scenario engineers realize in the late 1930s that dams have deprived the beach of sediment. Smart dams are installed in 1940, which are 50% effective at preventing sediment loss. Policy makers realize that sediment must be restored to the shoreline in order to prevent further loss of property and beaches, so legislation is drafted in the 1990s. A legislative decision in 2002 requires that sediment trapped behind dams must be used to replenish beach sand. However, artificial beach nourishment from offshore dredging is the only current acceptable practice of sand replenishment and so bureaucratic delays in the mobilization of funds preclude any real sediment recovery from behind the dam for another 23 years. The dam is decommissioned in the year 2026, but the recovery of sediment is not as effective as originally projected by engineers. The dam cannot be safely breached and sediment bypass systems only deliver 35% of trapped sediment to streams. To complicate matters, shifting state-level priorities limit state-level sand replenishment funding to $1,000,000 per year. How much money will the city have to request from Sacramento per year to maintain the beach at 30m wide?

Scenario 3: Hands-off Dams

Though it is clear to coastal residents and policy makers alike by the year 2002 that sediment is simply not reaching the beach because of dams, artificial beach nourishment is the only agreed upon measure of sand replenishment to be used. A risk assessment study published by the federal government indicates a slight probability of property damage and risk to human life in downstream should an erected slurry pipe for sediment recovery break along the dam. Public opposition mounts to the federal project and though the dam has outlived its useful water supply purpose by this time, no sediment recovery occurs for the remainder of the simulation period. A shortfall in sand replenishment funding for artificial beach nourishment projects occurs due to state appropriations budget conflicts. At a price of $7 per cubic meter of sand, an immediate determination must be made of how much sand replenishment funding will be necessary per year using only artificial beach nourishment in order to reach the beach width goal of 30m without altering the dam in any way.

RESULTS

Scenario 1

The results of the first scenario indicate that as the price of sand per cubic meter was progressively increased from $7 per cubic meter to $35 per cubic meter, the ability to achieve the beach width goal declined (Figure 3). In each case, the installation of the dam in 1940 severely affected the amount of sand on the beach, but the recovery of trapped sediment from behind the dam after the year 2002 permitted the beach to widen.

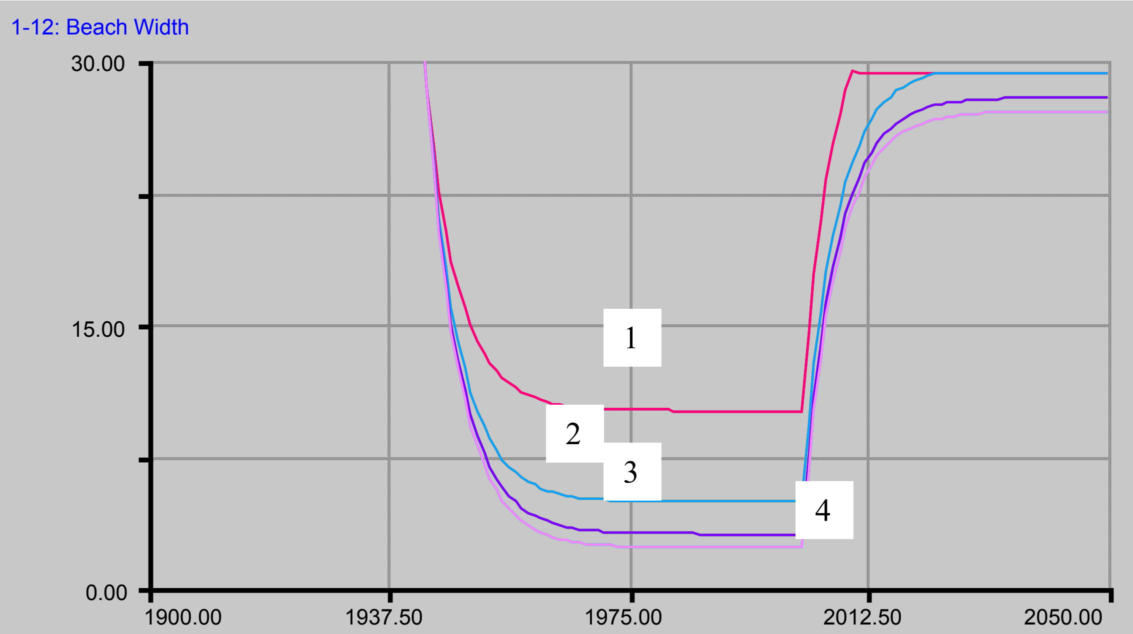

Figure 3: Influence of changing sand price on ability to meet beach width goal

The beach width was reduced to less than 11m under all assumptions about sand price, and in some cases, the beach became reduced to less than 3m by the year 1960 (See Table 1). The effective recovery of sediment from behind the dam after the year 2002 allowed several decades for the beach to widen by at least 20m. The flux in beach sand volume is shown in Figure 4. The results also indicate that a widening of the beach to a 30m goal could be met when the price of sand was \$7 per m^{3} (1), or even raised to \$15 per m^{3} (2), which is partially attributable to the fact that \$5 million dollars in annual sand replenishment funding were provided. When the price of sand was raised above \$25 per m^{3} (3) and \$35 per m^{3} (4), however, the beach width at the end of the simulation period was reduced to a level below 28m.

Table 1: Influence of sand price per cubic meter on beach width

Year	Beach Width (1) \$7 per m^{3}	Beach Width (2) \$15 per m^{3}	Beach Width (3) \$25 per m^{3}	Beach Width (4) \$35 per m^{3}
1900	50.00	50.00	50.00	50.00
1915	50.16	50.16	50.16	50.16
1930	50.17	50.17	50.17	50.17
1945	22.50	21.02	20.44	20.19
1960	10.70	5.68	3.93	3.17
1975	10.01	4.79	2.96	2.18
1990	9.97	4.74	2.91	2.12
2005	20.80	15.57	13.74	12.95
2020	29.29	28.91	27.08	26.30
2035	29.29	29.29	27.86	27.08
Final Beach Width (m)	29.29	29.29	27.91	27.12

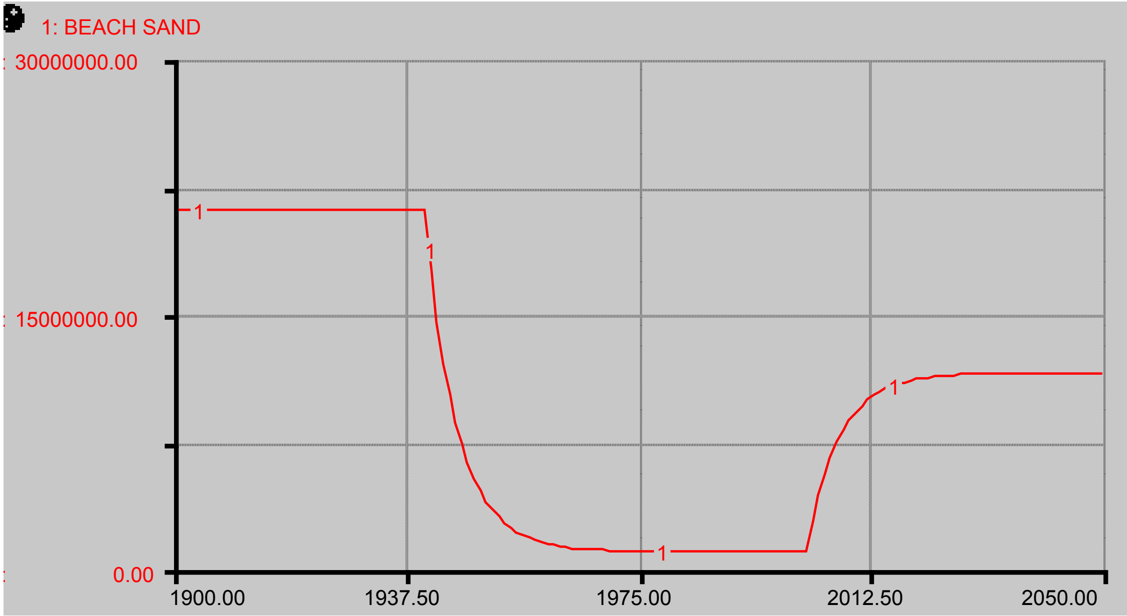

Figure 4: Flux of beach sand volume over time in units of cubic meters

Scenario 2

For Scenario 2, the sediment trapped behind the dam was assumed not to have been recovered until the year 2026, when a sediment bypass system was installed or the dam removed. Results indicated that the amount of sand replenishment funds needed increases greatly from the year 1940 through year 2025, corresponding to the time from which the dam was constructed until the sediment behind it was removed (Figure 5). Though state-level funding has been limited to $1 million per year, sand replenishment needs have exceeded $8 million per year by the early 1970s. Maximum replenishment needs reach a threshold level of approximately $8.4 million per year then drop rapidly towards zero after the dam is removed.

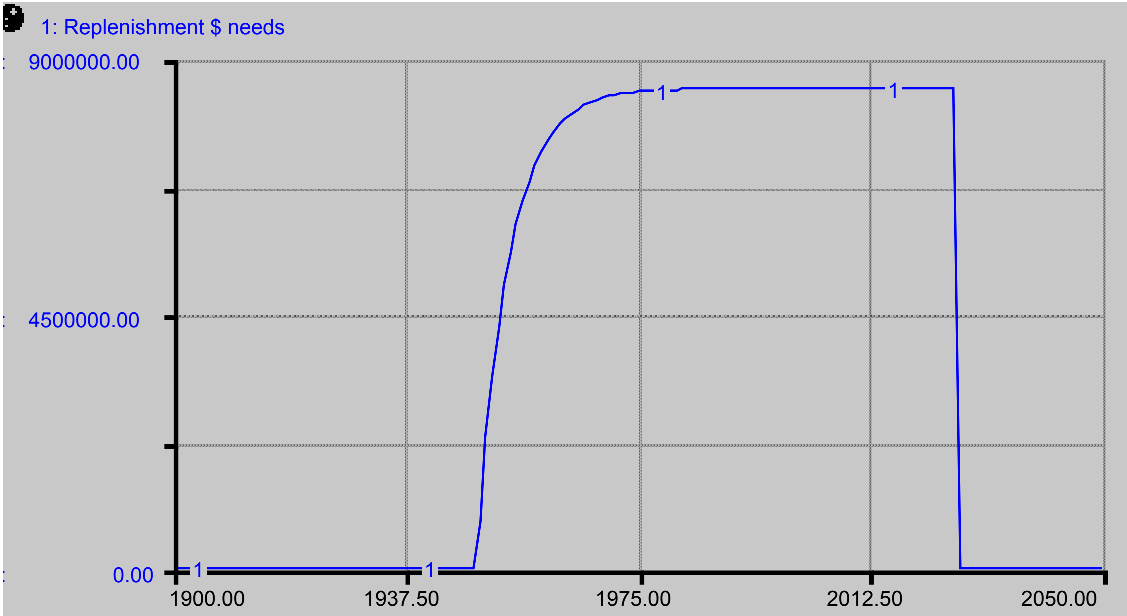

Figure 5: Impact of delayed sediment recovery on sand replenishment funding needs

Scenario 3

Model runs for scenario 3 indicate that the beach width goal of 30m could not be reached until the funding replenishment rate approached $10 million per year (Figure 6). Replenishment funding needs increased rapidly after 1940 when dams were installed and reached asymptotic. Because the dam was not removed in this scenario, replenishment needs did not decrease substantially after the maximum limits were approached.

When annual funding rate was adjusted, the maximum replenishment funding needs were reached in 1945 when the annual replenishment funding rate was set at $10 million per year (Figure 7). When the replenishment funding rate was lowered to $4 million dollars per year, maximum replenishment funding needs were reached 1975.

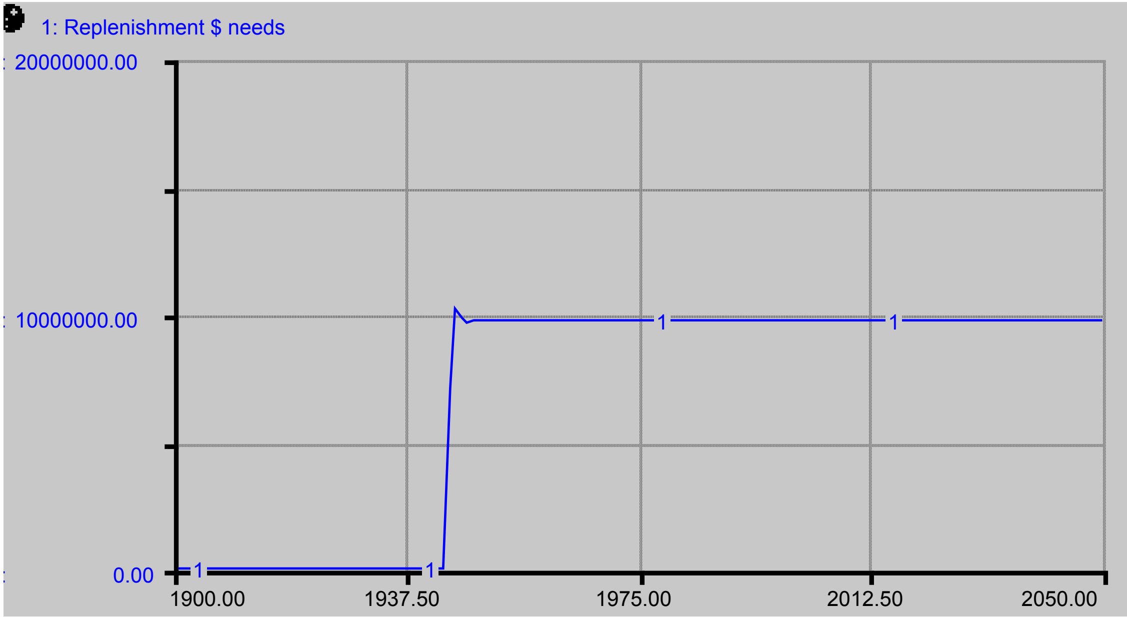

Figure 6: Annual sand replenishment $ needes to meet beach width goal without dam removal.

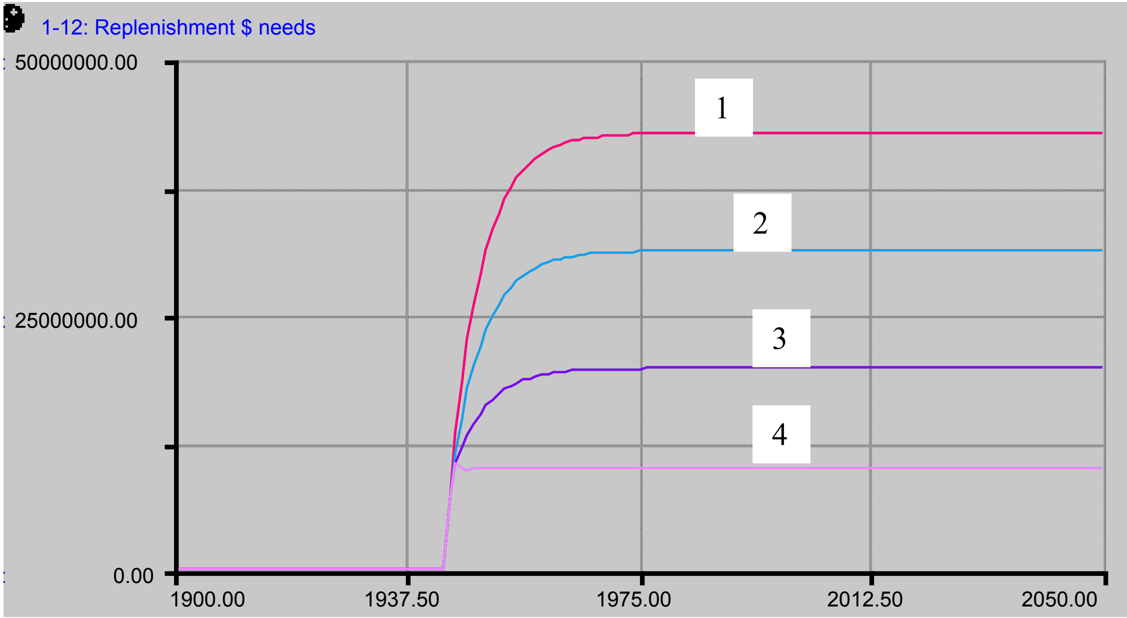

Figure 7: Trends in sand replenishment funding needs with incrementally adjusted sand replenishment funding rate

As shown in Figure 7, when the annual replenishment funding rate was adjusted incrementally from $4 million (1) to $6 million per year (2) to $8 million per year (3) $10 million per year (4), the number of dollars needed to replenish the beach to the width goal of 30m decreased. At $4 million per year of replenishment funding and without removing the dam, $42,860, 245 dollars would have to be spent on replenishment to maintain a goal of 30m (see Table 2). At $6 million per year of funding for sand replenishment, the replenishment funding needs dropped to $31,260,245 to reach the beach width goal. The costs to reach the goal were reduced to $19,660,245 at $8 million dollars per year. Thus, without removing the dam, the city would have to request nearly $20 million in state funding to meet its goal of preserving the beach at the desired width.

Table 2: Influence of annual funding rate adjustments on sand replenishment dollar needs

Years	1: $4 million per year	2: $6 million per year	3: $8 million per year	4: $10 million/yr.
1900	0	0	0	0
1915	0	0	0	0
1930	0	0	0	0
1945	13,257,711	11,257,711	10,167,194	10,167,194
1960	41,128,326	30,089,981	19,104,847	9,714,741
1975	42,758,917	31,191,778	19,627,751	9,714,741
1990	42,854,317	31,256,239	19,658,344	9,714,741
2005	42,859,898	31,260,010	19,660,134	9,714,741
2020	42,860,224	31,260,231	19,660,238	9,714,741
2035	42,860,244	31,260,244	19,660,244	9,714,741
Final	$42,860,245	$31,260,245	$19,660,245	$9,714,741

DISCUSSION

It was demonstrated in this simulation that a beach width goal of 30m could be met by the city given sufficient annual funds for sand replenishment. The results of the first scenario indicate that an increase in sand price indeed affects the ability of the city to meet its beach width goal. But because the beach only narrowed from 30m to 27m in width corresponding to a five-fold increase in the price of sand per cubic meter, the ability of the city to meet its beach width goal does not appear to be highly sensitive to the price of sand. Further, escalating costs of sand reaching $35 per cubic meter may not be a realistic assumption.

The results of Scenario 2 indicate that in the absence of a system of sediment delivery to rivers and streams from behind dams, maintaining a beach of a certain width can lead to rapidly increasing sand replenishment needs. The sediment recovery system was assumed to have only been 35% effective, yet annual funding needs for sand replenishment dropped rapidly after the system was set in place. The rapidly dropping funding requirements may be related to our assumption for this scenario that the smart dams were only 50% effective in trapping sediment.

It was assumed for Scenario 3 that dams could not be removed and that all sand replenishment must come from artificial beach nourishment. Because of sediment deprivation, the annual sand replenishment funding needs increased steadily after the dams had been installed. If a decision had to be made on how much funding to appropriate to beach restoration using only beach nourishment, the beach width goal could only be met if annual funding for sand replenishment exceeded $8 million per year. Thus, it is recommended that the feasibility of sediment recovery be explored in 2002, in order to prevent escalating costs of sand replenishment.

CONCLUSIONS

By making the simplifying assumptions explicit in this simulation, system dynamics can be used to identify strategies by which to defend beach systems against external shocks, such as erosion from sediment deprivation.

One of the limitations to this study is that the current version of our model is spatially aggregated. As more reliable data becomes available on how economic aspects of shoreline management vary spatially within the Santa Barbara littoral cell, the model can be readily spatially disaggregated to enable a more precise analysis of the factors studied.

Further, no stochastic processes were included in this model. During El Niño climatic events, heavy coastal damage from storms can be attributed to a combination of factors including astronomical tides, abnormally high sea levels, and storm-induced waves (Benumof et al. 2000; Flick, 1998; Storlazzi et al., 2000). Although the probability of large episodic storm events were not included in our model, dynamic modeling of policy interventions for large, but rare shocks to systems may turn out to be as important, or even more important than forecasting for "average case" scenarios in the future. To protect beaches and coastal communities, robust state-level policy measures would ideally factor in large margins of uncertainty.

Fischer (1999) asserted that the emphasis placed on evaluating development permitting on a project-by-project basis still takes precedence over strategic planning for coastal hazards. One recommendation for future study would be an in depth exploration of the tradeoffs inherent in managed retreat as a planning measure. Managed retreat, which refers to the practice of inland migration by coastal residents or the relocation of coastal amenities and property resources, may become a more economically feasible option for coastal residents as the sea gradually encroaches upon human habitat. Though preliminary estimates indicate that the costs may be very high for even modest amounts of human relocation, the situation may change over time and is worth examining.

Finally, it should be noted that the decommissioning of dams as it pertains to restoring sediment supply to beaches is a relatively new topic on the regional planning policy table for Californians. A societal determination of equitable cost sharing among local, state, and federal governments for beach nourishment is yet to be made. We hope to have demonstrated through this simulation that the implementation of proactive policy solutions would not only provide flexibility in dealing with beach erosion but also time to adjust to unanticipated surprises related to sand prices and available funding for replenishment.

REFERENCES

Ahmad, S., and Simonovic, S. P., (2000a). Modeling reservoir operations using system dynamics, ASCE Journal of Computing in Civil Engineering, 14(3):190-198.

Ahmad, S., and Simonovic, S. P., (2000b). Dynamic modeling of flood management policies, Proc. of the 18th International Conference of the System Dynamics Society, Sustainability in the Third Millennium, Bergen, Norway.

Ahmad, S., and Simonovic, S. P., (2000c). Analysis of economic and social impacts of flood management policies using system dynamics, Int. Conf. of the American Institute of Hydrology, Atmospheric, Surface and Subsurface Hydrology and Interactions, Research Triangle Park, North Carolina.

Ahmad, S., and Simonovic, S. P., (2001). A decision support tool for evaluation of impacts of flood management policies. AIH J of Hydrological Science and Technology 17(1-4):11-22.

Bailard, J. Ph.d. (2002). Technical Advisor for BEACON. Personal Communication.

Benumof, B.T., Storlazzi, C., Seymour, R.J., and Griggs, G (2000). The Relationship between incident wave energy and sea-cliff erosion rates: San Diego County, California.

Brownlie, W. and Taylor, B. (1981). Sediment Management for the Southern California Mountains, Coastal Plains, and Shoreline, Part C: Coastal Sediment Delivery by Major Rivers in Southern California. California Institute of Technology, Environmental Quality Lab Report No. 17-C, February 1981.

Coyle, R. G., (1996). System dynamics modeling, Chapman and Hall, London, UK.

Davis, G. (2001). Draft policy on coastal erosion: planning and response. Resources Agency of California

(DNOD) (1977). Department of Navigation and Ocean Development, Study of Beach Nourishment along the Southern California Coastline. State of California, California Resources Agency. 149 pages.

FEMA (1998). Federal Emergency Management Agency, "FEMA Winter Storms Update Center". Associated Press. http://www.fema.gov/fema/wsuc.htm

Fischer, D. (1990). Public policy aspects of beach erosion control. American Journal of Economics and Sociology, 49(2) 184-197.

Fischer, D. (1999) Municipal coastal hazard planning: Los Angeles and Orange County city responses, California. Journal of Coastal Research. 15(4) 974-984.

Fletcher, E. J. (1998). The use of system dynamics as a decision support tool for the management of surface water resources. Proc., First Int. Conf. on New Information Technologies for Decision-Making in Civil Engineering, Montreal, Canada, 909-920.

Flick, R. E. (1998) Comparison of California tides, storm surges, and mean sea level during the El Niño winters of 1982-1983 and 1997-1998. Shore and Beach. 66(3) 7-11.

Forrester, J. W., (1961). Industrial dynamics. Pegasus Communications, Inc. Williston, VT.

Griggs (1987). The production, transport, and delivery of coarse-grained sediment by California's coastal streams. Proceedings of Coastal Sediments '87, Volume 2: 1825-1838.

Inman, D. L. and Jenkins, S.A. (1999). Climate change and the episodicity of sediment flux of small California rivers, Journal of Geology, 107: 251-270.

Jenkin, P. (1998). On the edge: Robbed by dams, scoured by seawalls, devoured by winter storms, Ventura county may soon lose one of its most precious resources. http://www.surfing.com/makingwaves2/edge1.htm.

Knur, R. (2001) The Historical Sand Yield from Point Mugu to Santa Monica, California. 2001 PACON Conference Abstract, San Francisco, California.

Runyan, K. (2001) Contributions of Coastal Cliff Erosion to the Beach Sand Budget in California and the Effects of Armoring. Restoring the Beach Science, Policy and Funding, 2001 Annual Conference of California Shore and Beach Preservation Association and California Coastal Coalition San Diego, CA.

Ruth, M. and Pieper, F. (1994). Modeling spatial dynamics of sea-level rise in a coastal area. System Dynamics Review. 10(4): 375-389.

Simonovic, S. P., (2001). World water dynamics: global modeling of water resources, Journal of Environmental Management (in print).

Simonovic, S. P., and Fahmy, H., (1999). A new modeling approach for water resources policy analysis. Water Resources Research, 35(1), 295-304.

Sterman, J. D., (2000). Business Dynamics: Systems thinking and modeling for a complex world, McGraw Hill, NY.

Storlazzi, C., Willis, C. and Griggs, B. (2000). Comparative Impacts of the 1982-1983 and 1997-1998 El Nino Winters on the Central California Coast, Journal of Coastal Research. 16(4) 1022-1036.

Willis, C. (2001). Beach sand delivery by California rivers and human impacts on this system. Restoring the Beach Science, Policy and Funding, 2001 Annual Conference of California Shore and Beach Preservation Association and California Coastal Coalition, San Diego, CA.

ACKNOWLEDGMENTS

The authors would like to thank Cope Willis of the University of California, Santa Cruz for providing critical data used for the physical aspects of our beach erosion model.

Back to the Top