Computers & Geosciences 53 (2013) 30–38

Contents lists available at SciVerse ScienceDirect

Computers & Geosciences

journal homepage: www.elsevier.com/locate/cageo

Progress in coupling models of human and coastal landscape change

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ARTICLE INFO

Article history:
Received 8 March 2011
Received in revised form
9 September 2011
Accepted 12 October 2011
Available online 9 November 2011

Keywords:
Coupled modeling
Coupled human/natural systems
Coastline change
Coastal economics
Beach nourishment

ABSTRACT

Humans are increasingly altering the Earth's surface, and affecting processes that shape and reshape landscapes. In many cases, humans are reacting to landscape-change processes that represent natural hazards. Thus, the landscape is reacting to humans who are reacting to the landscape. When the timescales for landscape change are comparable to those of human dynamics, human and 'natural' components of developed environments are dynamically coupled—necessitating coupling models of human and physical/biological processes to study either environmental change or human responses. Here we focus on a case study coupling models of coastal economics and physical coastline change. In this modeling, coastline change results from patterns of wave-driven sediment transport and sea-level rise, and shoreline stabilization decisions are based on the benefits of wide beaches (capitalized into property values) balanced against the costs of stabilization. This interdisciplinary modeling highlights points that may apply to other coupled human/natural systems. First, climate change, by accelerating the rates of landscape change, tends to strengthen the coupling with human dynamics. In our case study, both increasing sea-level-rise rates and changing storm patterns tend to increase shoreline change rates, which can induce more vigorous shoreline stabilization efforts. However, property values can fall dramatically as erosion rates and stabilization costs rise, which can also lead to the abandonment of expensive stabilization methods as shoreline change rates increase. Second, socio-economic change can also strengthen the human/landscape coupling. Changing costs of shoreline stabilization can alter stabilization decisions, which in turn alters patterns of coastline change. The coupled modeling illuminates the long-range effects of localized shoreline stabilization efforts; communities arrayed along a coastline are unwittingly affecting each other's erosion rates, and therefore each other's economies. Our coupled modeling experiments show that spatial distributions of property values and erosion rates can jointly affect economic outcomes, resource allocation between communities, and patterns of shoreline change. These findings raise questions about coastal management strategies, and efficient and equitable allocation of scarce resources among coastal communities.

1. Introduction

In the past, researchers studying the processes that shape the Earth's surface most often looked for pristine landscapes in nature—environments in which the physical and/or biological processes proceed without the complicating influence of human manipulations. However, human modifications of landscapes, and of the processes that change landscapes, have become so ubiquitous that opportunities for analyzing pristine landscapes are limited. To understand the evolution of much of the planet's surface, Earth-surface-process studies increasingly need to address the human component of the system (e.g. Haff, 2003; Werner and McNamara, 2007).

Addressing the human component often requires more than just superimposing a model of human effects on some representation of a 'natural' system. Human actions and landscape change do not necessarily act independently but are often coupled in feedback loops. Feedbacks occur because (1) many human actions are explicit reactions to landscape changes or to the processes that shape landscapes in the long term (e.g. arresting river bank or shoreline erosion, or trying to affect the course of debris flows that threaten alpine infrastructure and lives) and (2) human manipulations often affect future landscape changes. Humans react to landscape-change processes that are in part functions of human actions.

Such couplings range from being local in time and space—flood control levees on a river lead to increased flooding and

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0098-3004/$ - see front matter
doi:10.1016/j.cageo.2011.10.010

increased need for flood control immediately downstream (Criss and Shock, 2001), and to less local and less obvious—a dam constructed at one point along a river course will ultimately cause a wave of erosion to propagate downstream. The longer the timescale considered the longer the distance over which the local human manipulation will affect riverine environments, human habitation, and use of these environments. Similarly, land use changes in mountainous environments that affect vegetation will ultimately change the shape of the landscape on the mountain-range scale (Collins et al., 2004; Istanbulluoglu and Bras, 2005). When thinking about large-scale landscape features such as mountain ranges and major river systems, the timescales of landscape change are often very long compared to those of human dynamics. In such cases, human actions might come and go so quickly that the landscape reactions to each one are insignificant—they are dynamically uncoupled from the human disturbances.

On the other hand, when the timescales for human dynamics and landscape change are closer together, the coupling between the two can be strong (Werner and McNamara, 2007). In such cases, the recursive adjustments of humans to landscapes and vice versa can lead to the emergence of phenomena that would be impossible to anticipate by studying either the physical landscape or human components in isolation (e.g. McNamara and Werner, 2008; Magliocca et al., 2011).

On sandy coastlines, large-scale changes can occur relatively rapidly. Shorelines and barrier islands can shift as much as a kilometer in the cross-shore direction over decades (e.g. Dean and Perlin, 1977), and the plan-view shape of a coastline can adjust over human timescales even on spatial scales of a hundred kilometers (Slott et al., 2006). McNamara and Werner (2008) coupled a numerical model of barrier island evolution to resort community development and found the emergence of temporal and spatial cycles of island stability and economic expansion alternating with periods of rapid island migration and property loss. The cycles arose neither from the patterns of forcing (sea level rise and storm statistics were constant) nor from the dynamics of either human or landscape components alone, but from the feedbacks between them.

Here we present a case study involving shoreline erosion and the plan-view evolution of a sandy coastline, which further illustrates that in a tightly coupled human/landscape system, we cannot understand either the human dynamics or the physical/biological system separately. This model-coupling endeavor also illustrates the synergistic benefits to multiple disciplines that result from thoroughly interdisciplinary interactions between researchers who ordinarily study the component parts separately. Rather than pasting together models developed independently within the respective disciplines, a deliberate melding of human and landscape processes in numerical models generates new insights about coupled human and coastal landscape change.

In a numerical model addressing how patterns of wave-driven alongshore sediment transport shape coastlines, experiments have shown that even one localized shoreline-stabilization project, when maintained for decades, can affect coastline evolution over surprisingly long distances. Erosion rates change up to 100 km away. Those early experiments, described briefly in Section 2 below, lacked human dynamics; the shoreline stabilization was assumed to occur perpetually at one location in the form of beach nourishment, which adds sand to the nearshore system at a long-term rate sufficient to counteract erosion locally. However, beach nourishment is an expensive endeavor. Not all coastal communities choose to spend resources in this way, and communities that employ nourishment at one time may not maintain the practice forever as the costs and/or perceived benefits change. Thus, addressing how a developed coastline evolves requires a model of human dynamics. In Section 3, we outline economic models that characterize the costs and benefits of beach nourishment and the resulting decision calculus of individual communities. The costs of nourishment depend in part on erosion rates that might change over time and are tied to the physical system. The benefits reflect increased property values (or avoided property losses) from wider (narrower) beaches. These economic models, in combination with the coastline change models, suggest that coastal property values depend strongly on how the coastline evolves. Section 4 illustrates how coastline evolution in turn depends on the distribution of coastal property values. Thus, fully coupled modeling is required to investigate the behaviors of either the human or landscape components of the system in this case.

Our case study illustrates two other points that are also likely to apply more broadly. Climate change, by accelerating landscape change, accentuates the coupling between humans and the environments they inhabit. In our case, the intensified coupling arises because both increased rates of sea-level rise and changing storm climates tend to increase shoreline erosion rates. These increases tighten the connections between shoreline changes in different locations even when they are far apart in space. Similarly, changes in socio-economic conditions can accentuate human/landscape coupling by accelerating changes in the patterns of land use and landscape manipulations. In our case, changes in the cost of nourishment (possibly related to dwindling resources of suitable sand for nourishment) precipitate abrupt changes in coastal economies and therefore patterns of coastline change.

Our coupled coastline/economic modeling endeavor includes many facets, ranging from projects involving a little bit of economics integrated into landscape change models, to those involving a little bit of geomorphology woven into economics models, to more complete coupling involving increasingly complex economic and coastline-change components. We will outline examples of each after some of the background motivating this work.

2. Background: large-scale coastline morphodynamics

Gradients in wave-driven alongshore sediment transport play a key role in shaping sandy coastlines, especially on spatial scales of kilometers and greater (e.g. Komar, 1998; Lazarus and Murray, 2007; Lazarus et al., 2011). Where net alongshore transport (averaged over timescales of years or longer) brings more sediment into a stretch of coast than it takes out, the convergence of sediment transport tends to produce a seaward progradation of the shoreline. On the other hand, a divergence of transport tends to drive shoreline erosion. This conservation of nearshore sediment is expressed by

$$\frac{\partial \eta(x,t)}{\partial t} = -\frac{1}{D}\frac{\partial Q_s(x,t)}{\partial x}, \tag{1}$$

where η is the cross-shore shoreline position, x is the alongshore coordinate (Fig. 1), Q_s is the alongshore sediment flux (m^3/day), and D is the water depth (m) to which cross-shore wave-driven transport processes redistribute sediment over the seabed (plus the height of the beach, or dunes if any are present).

Alongshore sediment transport results from the combined action of breaking waves, which entrain sandy sediment, and a subtle alongshore current that advects the suspended sediment. Breaking waves deliver momentum into the nearshore water, and the alongshore component of that momentum flux drives the alongshore current. The strength of the current is related to the rate at which waves deliver alongshore momentum into the surf