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Causal Loop Analysis of coastal geomorphological systems

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ABSTRACT

As geomorphologists embrace ever more sophisticated theoretical frameworks that shift from simple notions of evolution towards single steady equilibria to recognise the possibility of multiple response pathways and outcomes, morphodynamic modellers are facing the problem of how to keep track of an ever-greater number of system feedbacks. Within coastal geomorphology, capturing these feedbacks is critically important, especially as the focus of activity shifts from reductionist models founded on sediment transport fundamentals to more synthesist ones intended to resolve emergent behaviours at decadal to centennial scales. This paper addresses the challenge of mapping the feedback structure of processes controlling geomorphic system behaviour with reference to illustrative applications of Causal Loop Analysis at two study cases: (1) the erosion–accretion behaviour of graded (mixed) sediment beds, and (2) the local alongshore sediment fluxes of sand-rich shorelines. These case study examples are chosen on account of their central role in the quantitative modelling of geomorphological futures and as they illustrate different types of causation. Causal loop diagrams, a form of directed graph, are used to distil the feedback structure to reveal, in advance of more quantitative modelling, multi-response pathways and multiple outcomes. In the case of graded sediment bed, up to three different outcomes (no response, and two disequilibrium states) can be derived from a simple qualitative stability analysis. For the sand-rich local shoreline behaviour case, two fundamentally different responses of the shoreline (diffusive and anti-diffusive), triggered by small changes of the shoreline cross-shore position, can be inferred purely through analysis of the causal pathways. Explicit depiction of feedback-structure diagrams is beneficial when developing numerical models to explore coastal morphological futures. By explicitly mapping the feedbacks included and neglected within a model, the modeller can readily assess if critical feedback loops are included.

1. Introduction

Feedbacks and emergent behaviours in geomorphology have been long recognised (Schumm and Lichty, 1965; Schumm, 1991) but it has been in recent decades when views of change, disturbance, response and recovery have expanded considerably (Phillips, 2009): conceptual frameworks emphasizing single-path, single-outcome trajectories of change have been supplemented – not replaced – by multi-path, multi-outcome perspectives. In this context, Phillips (2009) argues that any attempt to explore change and response studies should seek to identify potential feedbacks, determine their signs, and assess their relative importance. This is especially important when studying coastal systems in which a broad range of feedback mechanisms drives the system's evolution. A feedback is a change to a component of the system that causes a knock-on effect that further alters the original change. A positive feedback amplifies the initial change. For example as waves erode the cliff, granular material will be released, which may abraid the shore platform, resulting in even more cliff erosion. Negative feedbacks have the opposite effect of the initial change. For example, as the shore platform is eroding it becomes wider and gentler diminishing the rate of mass wasting for the same given offshore wave energy flux. Identifying these feedbacks is the first step towards establishing their relevance at the spatial scales of geomorphological models (Lane, 2013). As an ever-greater number of feedbacks are identified and appreciated, the need to map them into a coherent framework is needed. Techniques for the formal assessment of the main feedbacks between coastal geomorphology and the drivers of change (i.e. climatic variability and human interventions) assist geomorphological modellers to

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explore how that variability might change during the 21st century and what this might mean for geomorphic processes, landforms and entire landscapes.

The concept of feedbacks has proved helpful in the idealized model domain, but extrapolation to the real world is complicated (i.e. Klocke et al., 2013). In geomorphology examples of qualitative stability assessment of the system based on the feedback loop structure go back to at least the early 1980s (Slingerland, 1981; Phillips, 2006). The stability of the system (or conditions under which it is stable) can be determined if historical reconstructions or field observations identify the key system components and the positive, negligible, or negative links between them. This often takes the form of a directed graph, network model, or box-and-arrow diagram (Capobianco et al., 1999; Townend, 2003) (Fig. 1). These can be translated into an interaction matrix, and the stability may be determined based only on a qualitative (+, −, 0) assessment. Payo et al. (2014) have taken this qualitative analysis forward by showing how the strength (i.e. not only the sign) of a single feedback loop (e.g. the cliff toe energy depletion feedback loop) can be assessed by reasoning on the current understanding of its causal pathway. Payo et al. (2014) used directed graphs (i.e. Lane, 2000) but limited their analysis to the main processes that control the morphodynamics of cliff and shore platforms.

In this work, we extend the use of directed graphs to two different case studies: (1) processes that control the erosion–deposition behaviour of graded beds, and (2) processes that control the local alongshore sediment transport fluxes of sand-rich shorelines. These case studies are selected because they are illustrative of how directed graphs can be used to capture different types of causation, and because of their central role in the quantitative modelling of geomorphological futures. When modelling geomorphological futures at decadal and longer timescales, the modeller is likely to make informed decisions about how to numerically model the fundamentally different behaviour of mixed sediments versus uniformly graded ones. Le Hir et al. (2011) noted the need for any morphodynamic model of mixed sediment to add an active layer concept to deal with the erosion of the different fractions. Explanations of shoreline behaviours not captured by a purely diffusive 1-line approach (Ashton et al., 2001; Van den Berg et al., 2011), and attempts to unify the quantitative modelling of a graded beach has been published elsewhere (van Rijn et al., 2007). However, to the authors' knowledge, no attempt to synthesize the feedback structure of these case studies in a unified way has yet been presented.

This manuscript is organised in four main sections. In Section 2, we present the rationale for this study and define the symbolic convention adopted in this work. The feedback structures for each of the study cases are presented in Sections 3 and 4. To conclude, we highlight the benefits and limitations of our advocated qualitative modelling approach.

2. Methodology

Of the varied representational approaches within the field of systems dynamics two predominate: Causal Loop Diagrams (CLDs) and Stock and Flow Diagrams (Lane, 2000). CLDs are a broad representations of the variables and feedback structure while, in contrast, Stock and Flow Diagrams are more detailed, discriminating both state and flow variables. These two forms are fairly standardised and while their benefits and limitations are generally understood (Morecroft, 1982), the preference for one over the other is still contested (Lane, 2000); both conventions have been used in the past for conceptualizing decadal to centennial coastal system dynamics (Fig. 1). For example, Townend (2003) used stock/flow system diagrams to represent coast and estuarine system behaviour and Capobianco et al. (1999) proposed the use of CLDs to assess the impact of sea-level rise on estuaries and adjacent coasts. From a model development perspective, it might be argued that stock and flow diagrams provide more information to guide the organisation and structure of model code developed from them. Here, however, we are interested in the identification of the feedback loop structure, and the use of directed graphs is favoured. While the most relevant literature at which the conceptualization presented here is built upon is cited, the authors acknowledge that is not possible to cite the entire significant body of literature.

Fig. 2 shows the symbolic convention used in this work. The hierarchy of levels is captured by a cluster of variables at each level (c.f. Phillips, 2012). The terms 'local' and 'global' are used in the broadest sense to refer to scale finer, shorter and more detailed, or coarser, longer and broader, respectively, than the scale of observation. The term 'scale' is also used in a broad sense, encompassing both spatial and temporal resolution and position within a hierarchy. For the sake of clarity, a minimal set of symbols is used to capture causality and feedback loop structure. This includes:

- Two types of variables: (1) state variables (stocks, levels, attributes) (e.g., beach width, dune volume, sea level, sediment size, threshold wind velocity for initiating sediment transport), and (2) rate variables (underlined) (flows) (e.g. rate of shoreline change, sediment transport rate).
- Positive (+), negative (−) or influence (+/−) links. Links connect two variables (e.g. X → Y) and represent the answer to the question if X increases, would Y increase or decrease compared to what it would otherwise have been? Links are positive if dy/dx > 0 or negative if dy/dx < 0. When the answer is not known or ambiguous it is represented as an influence link.
- Causal pathways. We can reason about the influence of one variable on another variable indirectly connected to it by examining the

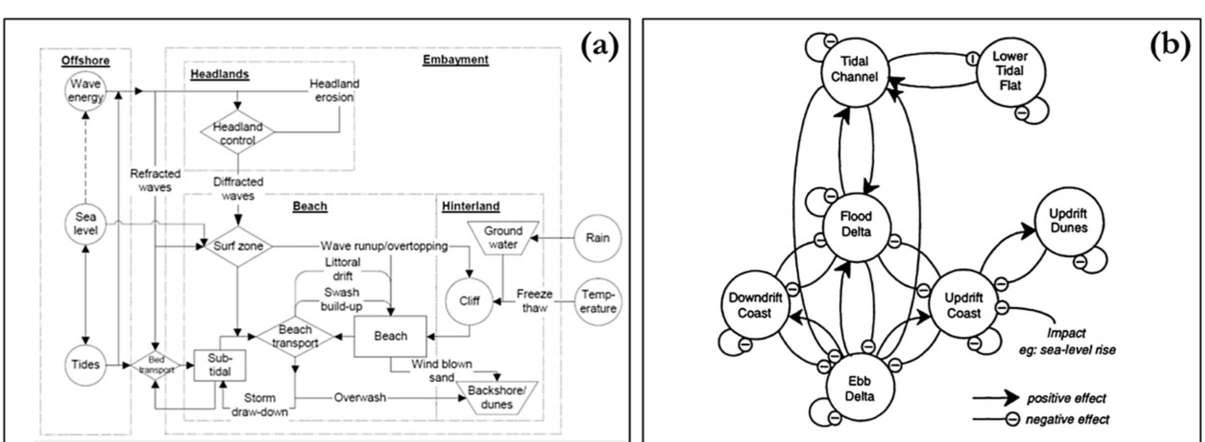

Fig. 1. Examples of how stock and flow and causal loop diagrams have been used to represent coastal system functioning and behaviour for different purposes. (a) Stock and flow diagram of an embayment (Townend, 2003) and (b) causal loop diagram of the impact of sea-level rise on an inlet or lagoon entrance (Capobianco et al., 1999).