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Regime shifts under forcing of non-stationary attractors: Conceptual model and case studies in hydrologic systems

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ABSTRACT

We present here a conceptual model and analysis of complex systems using hypothetical cases of regime shifts resulting from temporal non-stationarity in attractor strengths, and then present selected published cases to illustrate such regime shifts in hydrologic systems (shallow aquatic ecosystems; water table shifts; soil salinization). Complex systems are dynamic and can exist in two or more stable states (or regimes). Temporal variations in state variables occur in response to fluctuations in external forcing, which are modulated by interactions among internal processes. Combined effects of external forcing and non-stationary strengths of alternative attractors can lead to shifts from original to alternate regimes. In systems with bi-stable states, when the strengths of two competing attractors are constant in time, or are non-stationary but change in a linear fashion, regime shifts are found to be temporally stationary and only controlled by the characteristics of the external forcing. However, when attractor strengths change in time non-linearly or vary stochastically, regime shifts in complex systems are characterized by non-stationary probability density functions (*pdfs*). We briefly discuss implications and challenges to prediction and management of hydrologic complex systems.

1. Introduction

A *regime* is a region in state-space in which a complex system retains the same attributes such as structure, functions, and feedbacks. An *attractor* refers to a stable equilibrium state and the basin of attraction, which is equivalent to a regime, defines the state-space region in which initial conditions will tend to move towards the attractor (Walker et al., 2004). Complex systems often possess more than one attractor between which repellers (or unstable equilibrium state) exist as a boundary for the basins of attraction (Scheffer, 2009). Regime shift occurs when the system crosses such repellers. Dynamics of the system will be governed by completely different processes in an alternative regime (Scheffer et al., 2001). Regime shifts are often driven by external stochastic events or drivers. Stochastic events, characterized by fast variables, cause regime shifts by pushing the complex system toward alternate regime across the repeller. External drivers, characterized by slow variables, also can cause regime shifts by gradually changing the size of the regimes (Walker et al., 2012). When an external driver reaches a critical value, which is known as bifurcation point, the original regime disappears and only the alternative regime remains (Lenton, 2013; May, 1977; Scheffer et al., 2001). Thus, the complex system ends up being in an alternate regime because that is the only regime existing under the new conditions as changed by the external driver(s). Here, both external drivers and stochastic events are referred to as *external forcing(s)*.

Considering groundwater quality as state variable, clean (potable) and contaminated (non-potable) groundwater are two bi-stable states (regimes) of an aquifer. Successive loads of

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contaminants can lead to a regime shift, when the contaminant loading rates exceed the natural attenuation rate. Natural attenuation capacity serves as the negative feedback to maintain the groundwater quality within the original potable regime. Once in a contaminated non-potable regime, aquifer biogeochemical conditions change (e.g., redox potential decreases due to lack of oxygen), and different negative feedbacks now dominate, and the aquifer persists in the contaminated regime, even after some management practices are introduced to lower the contaminant loading rate below the level that contributed to the regime shift. The contaminated aquifer returns to the potable regime only when the biogeochemical conditions (negative feedbacks) are restored.

While external forcings are often direct causes for regime shifts, changes in internal system dynamics, which forms the size and shape of regimes, can also bring about regime shifts (Hastings and Wysham, 2010; Scheffer et al., 2001). A regime can be defined by two geometric features of the attraction basin: (1) width (or latitude), which characterizes how far a system state is allowed to move before it crosses a repeller; and (2) depth (or resistance), which characterizes how difficult is for the system state to be moved from its attractor, or how fast a disturbed system state can return to the attractor (Walker et al., 2004). In the following discussion, we integrate these two characteristics of a regime in a single term, *attractor strength*.

Typically, two competing forcings are identified in human-nature coupled complex systems: (1) persistent natural forcing (e.g., hydro-climatic forcing) under which the system evolves through self-reorganization; and (2) anthropogenic forcing (e.g., land-use changes) that involves utilization of natural resources to maximize socio-economic services but with a loss of other ecosystem services. Depending on the relative strength of forcing, state variables of a complex system may remain in the current regime, or move toward alternate regimes. Complex systems can also oscillate between alternate regimes in a cyclic way (van Nes et al., 2007) or flip between alternate regimes in highly stochastic systems (Scheffer et al., 2012). Nonetheless, all of these phenomena occur because of multi-stability, which is a consequence of multiple competing forcings that shape the stability landscape inherent to the complex system.

Human-impact gradients and ecosystem alterations over time and space can be observed in many parts of the world at multiple scales (Scheffer et al., 2001). Interesting cases of ecological regime shifts, often undesirable and sometimes irrevocable, occur along these impact gradients when anthropogenic forcing, combined with natural forcing, eventually propels the ecosystem out of its current regime. Furthermore, for a given ecosystem, multiple natural (e.g., rainfall, temperature, nutrient availability, etc.) and anthropogenic (e.g., irrigation; urbanization; climate change, etc.) forcings exhibit stochastic temporal fluctuations. Such stochastic drivers control the temporal trajectories of the ecosystems, displacing it from an attractor.

Current literature on regime shifts of complex systems is focused on a deterministic perspective; that is, the attractors are assumed to be stationary, with their "strength" changing slowly with the changes in drivers (see Rockström et al. (2009), for example). In such cases, regime shifts between the two attractors occur at known bifurcation points (Scheffer and Carpenter, 2003). However, complex natural systems are often characterized by non-stationary responses to external and internal forcing (i.e., contingent on initial conditions), and non-linear positive and negative feedbacks (Hastings and Wysham, 2010), all of which make the attractors to be non-stationary and the response of the systems, including regimes shifts, to be non-stationary.

We examine here complex system dynamics in which the attractors are non-stationary, in that their strengths change in time, either in a deterministic manner or even more interestingly changes are defined by some stochastic processes. Many cases of interest are, in fact, represented by such non-stationarity, as will be illustrated with some minimalistic hypothetical models, and also with few case studies using hydrologic systems (e.g., vadose zone and aquifers) which (1) are subject to anthropogenic forcing (e.g., land use and land cover changes) and natural forcing (e.g., precipitation; evapotranspiration); and (2) can have at least two or more regimes and shifts under both external forcing and internal changes.

2. Conceptual model

2.1. Regime shifts

Consider regime shifts in a complex system with two competing attractors, which are characterized by mean strength μ_A and μ_B, and with respective variances of σ_A^2 and σ_B^2. Note that we assume the system condition is within the range of multiple regimes. For a bi-stable system, the two regimes *A* and *B* are separated by a transition zone, which is a heterogeneous hybrid space of *A* and *B* and includes the repeller (see Fig. 1). A system in the either regime *A* or *B* is assumed to have homogeneous system attributes, and maintains its crucial forms and functions. We identify *A* as the original regime (e.g., a pristine forest, a wetland or an uncontaminated aquifer), where ecologically healthy functions exist with minimal or no human interventions, and let *B* as an alternate regime, where structure and functions are dramatically altered as a result of human intentions. The system state, while in either regime *A* or *B*, fluctuates around the mean value with some variance, but tends to return to the mean because of negative feedbacks with a characteristic reverting rate. The system state does have some probability of entering the transition zone, and eventually shifts to an alternate regime. A similar process describes the transition from regime *B* to *A*; thus, in this analysis we assume that regime shifts between *A* and *B* are revocable.

Once the system state is in the transition zone, the reverting rate that drives the system state back to the original regime *A* diminishes with the increasing counter-balancing force from the alternate attractor in regime *B*. This phenomenon is equivalent to a critical slowing down in dynamic systems theory (Scheffer et al., 2009). In this transition zone, whether the net feedback rate is negative or positive is determined by the vector sum of two attracting strengths. By using this analogy, we define a *tipping point* as where the vector sum equals zero, and *thresholds* as the boundaries within which two attractors co-exist. Generally, tipping points have been referred to as bifurcation points which have often been treated as a deterministic critical value of a known external driver (or control parameter).

2.2. Non-stationary attractors

We argue here that regime shifts do not always happen in a deterministic fashion, at a fixed value of the control parameter