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Are engineered river bifurcations susceptible to tipping?

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1. Introduction

Typically the time scale of river response to change of the controls (i.e., flow duration curve, sediment flux, and sea level) is of the order of decades to centuries. Understanding temporal change and, in particular, abrupt change in channel response is increasingly important in engineered river systems, as abrupt change may negatively affect flood risk, navigation, and freshwater supply. The analysis of abrupt change in engineered systems with a bifurcation (i.e., a single channel splitting into two branches or bifurcates) is complicated by the fact that insight and measured data on the partitioning of water and sediment over the bifurcates are typically lacking. Our objective is to provide insight on whether observed abrupt change of the Pannerden bifurcation in the upper Rhine delta (Netherlands) may be associated with tipping.

2. Theoretical framework

Tipping theory originates from the analysis of dynamical systems. Tipping occurs when the system is forced outside the domain of attraction of one stable equilibrium, and into the domain of attraction of another. We follow Ashwin et al. (2012) and distinguish between bifurcation tipping (where bifurcation refers to a 'mathematical bifurcation') versus noise-induced tipping. In bifurcation tipping, the forcing is a parameter change that makes the system state switch to a region with a different number or characteristics of equilibrium states. This parameter is called the bifurcation parameter. Noise-induced tipping is a system evolving from one stable equilibrium towards another without transitioning to a region with different characteristics of the equilibrium states.

3. Results

Here the dynamical system is a one-dimensional river network where one channel transporting gravel and sand splits into two bifurcates. Although we do not exclude the possibility of noise-induced tipping, we limit ourselves to an example of bifurcation tipping. The partitioning of gravel and sand over the branches is governed by nodal point coefficients that act as bifurcation parameters. We assume that these nodal point coefficients change due to subsequent peak flows that are associated with sudden sediment deposition and change in flow depth in one of the bifurcates (Chowdhury et al., under review).

We adopt the Schielen and Blom (2018) schematic model of a bifurcating river system with sand and gravel transported as bed material load. They found that the (k_g, k_s)-parameter space (k_g and k_s being the nodal point coefficients for gravel and sand) can be divided into three regions with different characteristics of stable and unstable solutions. We visualize the mechanism of bifurcation tipping in the phase planes that are associated with the different regions (Figure 1). Here, the system tips from a situation where both branches are open (left figure, solid blue dot, with nonzero values for a_1 and a_2 denoting the flow depth in the two bifurcates) to a state where one branch is closed (right-hand figure, solid red dot, with either a_1=0 or a_2=0, indicating that the flow depth in one branch is zero). The green lines visualize the tipping trajectory, associated with and without a sudden change in flow depth.

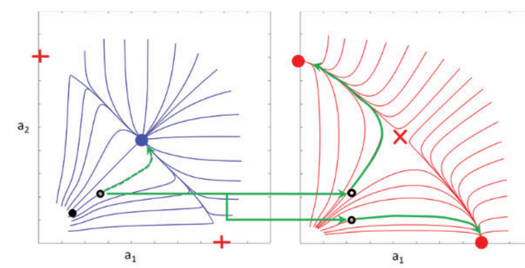

Figure 1. Example of bifurcation tipping: river system transitioning from two open bifurcates to a system with one closed bifurcate.

3. Conclusions

We provide an example of how peak flows leading to sudden flow depth change in one bifurcate may lead to tipping of the bifurcating river system.

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