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Modeling the interaction between flooding events and economic growth

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ABSTRACT

Recently socio-hydrology models have been proposed to analyze the interplay of community risk-coping culture, flooding damage and economic growth. These models descriptively explain the feedbacks between socio-economic development and natural disasters such as floods. Complementary to these descriptive models, we develop a dynamic optimization model, where the inter-temporal decision of an economic agent interacts with the hydrological system. We assume a standard macro-economic growth model where agents derive utility from consumption and output depends on physical capital that can be accumulated through investment. To this framework we add the occurrence of flooding events which will destroy part of the capital. We identify two specific periodic long term solutions and denote them rich and poor economies. Whereas rich economies can afford to invest in flood defense and therefore avoid flood damage and develop high living standards, poor economies prefer consumption instead of investing in flood defense capital and end up facing flood damages every time the water level rises like e.g. the Mekong delta. Nevertheless, they manage to sustain at least a low level of physical capital. We identify optimal investment strategies and compare simulations with more frequent, more intense and stochastic high water level events.

1. Introduction

Since the beginning of time, people have settled close to rivers and this is still the case nowadays. Rivers enable ways of transport, supply water for industry and agriculture and enhance the quality of living due to lively nature and beautiful scenery. However, living close to rivers also involves the risk of flooding, one of the most devastating natural threats on Earth (Ohl and Tapsell, 2000), whose impact has increased over the past decades in many regions of the world (Dankers et al., 2014, Hall et al., 2014). In order to avoid flood damage, societies have developed projects involving structural defenses (e.g., dams. levees, retention basins) and non-structural measures (e.g., land-planning, insurance, forecasting, see e.g. Kundzewicz, 2002). These investments are costly, but may avoid damage in the future. This is an interesting dynamic trade-off structure which we aim to analyze in a stylized socio-hydrological model that is embedded in a macroeconomic set-up. To account for the dynamic nature of optimal investment strategies, we apply dynamic optimization methods.

Floods and their consequences have been studied with different model approaches: Recent Integrated Assessment Models (IAM) aim to understand the interaction of society and floods (Merz et al., 2014) in a broad context. Climate change leads to more and bigger floods in certain regions Milly et al. (2002). Such models typically do not account for the impact of changes in the environment on economic growth (Estrada et al., 2015). The aim of Agent Based Models (ABM) such as Dawson et al. (2011), Safarzyska et al. (2013) and Li et al. (2015) is to understand the impact of floods on individual behavior. ABMs can provide a qualitative analysis of the consequences of floods on different levels: the individual/micro-level, the aggregated economy/macro-level and the firm level/meso-level. Complementary Input–Output-Models (Hasegawa Ryoji, Koks et al., 2014) provide a quantitative cost–benefit-analysis of case studies. Okuyama (2007) analyzed these model frameworks as well as computational equilibrium models for disasters. A dynamic spatial computable general equilibrium model based on the dynamic structure of a Ramsey growth model was developed by Nakajima et al. (2014) to numerically measure flood damage costs. It displays the dynamic tradeoff between the costs today and future savings, invest-

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ments and consumption. Besides simulation modeling approaches, optimization models have been developed to calculate optimal dike heights (Brekelmans et al., 2012, Chahim et al., 2012, Eijgenraam, 2006). Larger stochastic programming models in water resource management and flood management (Kleywegt et al., 2002, Li et al., 2007, Liu et al., 2014, Needham et al., 2000) only allow optimal solutions for discrete variables and finite time horizon. Moreover, most of these models are linear, have only one control variable, either none or linear constraints and are therefore quite different to the proposed economic growth model in our paper. While existing models on flood management have focused on the analysis at the firm level (e.g. Chahim et al., 2013 and Eijgenraam et al., 2014, who apply impulse control models for optimal dike heightening within an economic cost–benefit decision problem to minimize the sum of the investment and expected damage cost), our model aims to include flood dynamics into a macroeconomic growth model. So far, floods have been rarely analyzed in a macroeconomic model of economic growth considering not only direct and indirect damage costs, but also loss of future potential economic growth through dynamic consumption and investment decisions. In environmental economics this approach is quite common. Economic growth models have been applied to study, e.g., the effect of climate change on long run economic growth (Xepapadeas et al., 2005). More formally, these models commonly postulate that pollution causes economic losses via a damage function that is positively related to an increasing temperature caused by pollution (Millner and Dietz, 2015, Morisugi and Mutoh, 2012, Rezai et al., 2014, Zemel, 2015). Pollution itself is commonly modeled via the flow or stock of emissions. Indeed, emissions and investment in emission abatement have strong analogies to extreme water events (floods, droughts) and investment in abatement (flood defense capital, reservoirs), respectively. It therefore seems an obvious choice to apply this modeling framework also in the context of flood modeling. Similar to the increase in the temperature that underlies the economic damage in climate change models, the water level underlies the occurrence of floodings and hence the economic damage. There is a new research line, socio-hydrology, that deals with such coupled systems. The main thrust of socio-hydrology is to add a new perspective to former models and studies in hydrology by coupling dynamics of human populations, economic growth and general resource availability (Levy et al., 2016, Sivapalan et al., 2012). Socio-hydrology aims at understanding emergent patterns and paradoxes that result from long-term co-evolution of non-linearly coupled human–water systems. Elshafei et al. (2014) and Sivapalan and Blöschl (2015) developed prototype frameworks for socio-hydrology models. Di Baldassarre et al. (2013) and Viglione et al. (2014) developed a socio-hydrology model to explain the feedbacks between settlements close to rivers and flooding events. Di Baldassarre et al. (2015) use the model to capture processes such as the levee effect (e.g., Montz and Tobin, 2008) and the adaptation effect (IPCC, 2012, Mechler and Bouwer, 2014, Penning-Rowsell, 1996), which traditional flood risk models do not include. Pande et al. (2014) were one of the first who added a water related problem to a standard economic model of finitely lived agents, the so-called overlapping-generations model (OLG). In this paper, we build a macro-economic model in the context of floods and use a dynamic optimization model which is a different perspective from the more common descriptive models, simulations and scenario analyses. This is where we regard our model to add to the literature. More specifically, while there exist economic growth models that include the feedback between the environment and economic output, our novel contribution is to add an exogenous time varying water level function and study the resulting optimal path of consumption and investment. Mathematically this poses the challenge that we have to solve a non-autonomous optimization model.

Our model uses the model of Di Baldassarre et al. (2013) and Viglione et al. (2014) as a starting point. Their simulations show that building high levees leads to fewer flooding events with higher impacts which may slow down economic growth. Protecting a settlement by levees can, however, increase the damage to downstream settlement due to the loss of flood retention volume. Furthermore, building levees or any other defense capital will lower flooding probability and may therefore increase the willingness of citizens to build close to the river. If water levels rise higher than the crest of the levees, the physical capital next to the river is destroyed. Since there is a higher physical capital stock next to the river, the flood hits even harder on the economy.

Based on their model set-up we build an economic model to analyze the tradeoffs and feedbacks associated with settlements close to rivers. In the original model, decisions depend on social memory that is accumulated after the experience of flooding events and then decays over time. In our economic model framework memory is captured in the dynamics of the state variables which reflect investment and consumption decisions in the past that are related to flooding events. But also future choices are taken into account. We assume a social planner who decides optimally on investment and consumption to maximize not only current but also long term utility. The concept of utility constitutes a mathematical representation of preferences. Preferences in our model are formed over consumption but may also be influenced by social status (e.g. Fisher and Hof, 2005). We abstract from social status or other forms of social norms and values in our model and our utility function does not change over time to ensure an unambiguous assignment of feedbacks. Moreover we assume that our decision maker represents a social planner whose aim is to maximize the discounted stream of current and future utility of consumption by choosing the time path of investment and consumption and taking into account the dynamics of physical and defense capital. The trade-off for the decision maker is between consumption and investment where the former reduces and the latter augments the capital stock. As typical for economic problems, this trade-off is constrained by the total output, i.e. consumption and investment cannot exceed the output generated. Hence we are facing a standard economic decision problem of optimization under scarce resources.

We assume two types of capital: physical capital and defense capital. Decision makers can invest in physical capital, such as machines, buildings and infrastructure. On the other hand, investments in defense capital can avoid the actual damage of floods and have thereby a positive influence on output. Total output of the economy consequently depends on both capital stocks. We apply a periodic non-autonomous exogenous function to represent the water level. The periodic water function is introduced in Grames et al. (2015). Even though the assumption of non-stochastic flood occurrence is a strong one, we believe that useful insights on the system can still be obtained. Alternatively, we can interpret our water function as approximation of past flood events. Assuming the periodic non-autonomous exogenous function for flood occurrence allows us to solve the dynamic optimization problem, for which we further develop the solution method of Moser et al. (2014) where a similar mathematical problem in the context of renewable energy has been solved.

Including a non-autonomous exogenous deterministic function into a dynamic decision framework over an infinite time horizon requires already quite sophisticated methodologies of optimization and a highly challenging numerical approach. If we would model the water level function stochastically, the long run optimization problem could neither be solved analytically nor numerically. Recent research in that field of stochastic optimization is using much simpler objective and state functions (Nisio, 2015) without such strong nonlinearities as they exist in our model. Climate models include uncertainty in the timing of events (Tsur and Withagen, 2013), where the hazard rate of the event can depend on e.g. a stock of pollution of greenhouse gases (Zemel, 2015). Our exogenous water level