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Development of a software tool for rapid, reproducible, and stakeholder-friendly dynamic coupling of system dynamics and physically-based models

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A B S T R A C T

System Dynamics (SD) modeling is well adapted to developing participatory environmental models. However, SD models are ill-suited for complex physical (e.g., groundwater) processes, and existing methods to couple them with physically-based models tend to be complex and inflexible. We here present *Tinamit*, a novel tool to couple SD and physically-based models in a rapid, reproducible, and stakeholder-friendly manner. *Tinamit* requires only a few lines of Python code to couple and simulate models (or, with its interface, no coding at all), which is expected to make model coupling more accessible to stakeholders and allow them to continue developing coupled models after the end of a funded project. We use *Tinamit* to couple a SD-based farmer economics model from Pakistan with a soil salinity model (SAHYSMOD) and analyze the trade-offs of various policies, of which canal lining with subsidies seemed promising. Such results cannot be readily obtained from either model alone.

1. Introduction

Effective environmental management, and in particular water resources management, requires holistic impact assessment tools that can assist in the deep understanding of environmental system processes, including biophysics and socioeconomics and their complex interactions over time (Jakeman and Letcher, 2003). However, many available tools either represent only one aspect of environmental systems, or encompass individual models for each of the system processes which are loosely connected through their final outputs and inputs (e.g., Schmitz et al., 2009). Using such models with partial representation of system processes can be problematic, particularly to evaluate long-term impacts of policy decisions on the entire system performance (Pahl-Wostl, 2007). While some joint socioeconomic-environmental models have been developed by researchers, stakeholder participation is difficult to achieve given the complexity of most modelling approaches (e.g., Akhtar et al., 2013; Elshafei et al., 2014). One way to overcome this challenge is to couple participatory-built socioeconomic models developed in a stakeholder-friendly framework with physically-based models in such a way that the models exchange data at runtime. Such model linkage enables the exploration of the dynamic relationships among various system elements, as well as the complex behavior that emerges from such interactions, while retaining stakeholder inputs and viewpoints (e.g., Inam et al., 2017b).

System dynamics (SD) (Forrester, 1961) is one of the promising approaches for modelling socioeconomic processes that allows for holistic environmental impact assessments due to its intuitiveness and capability to integrate various viewpoints, disciplines and processes (Winz et al., 2009; Kelly et al., 2013). SD is of particular interest in participatory model building as it allows stakeholders to create models of the environmental systems they work with through a highly visual interface (Stave, 2003; Simonovic, 2009). Mirchi et al. (2012) has conducted a review of the application of SD in understanding physical system processes and policy making, as

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well as participatory water resource modeling. SD has been widely used for integrated water resource modeling and management (e.g., Ahmad and Simonovic, 2004; Madani and Mariño, 2009; Butler and Adamowski, 2015; Hassanzadeh et al., 2012; Sahin et al., 2015). In particular, SD has been used to link socioeconomic and hydrological models in one platform, including the work of Cockerill et al. (2006), Langsdale et al. (2009) and Sušnik et al. (2012). Although SD is a useful approach to develop socioeconomic models and elicit stakeholder participation (e.g., Winz et al., 2009; Langsdale et al., 2007, 2009), the representation of physically-based systems in the SD environment is rather challenging and time-intensive. For one, simple representations of dynamic and non-linear relationships among biophysical system variables in a SD environment might inaccurately represent the overall system behavior (Prodanovic and Simonovic, 2010); in addition, the complexity of most detailed physical models (such as SWAT (SWAT, 2017), DSSAT (Jones et al., 2003; Hoogenboom et al., 2015), etc.) renders their translation into the SD interface infeasible, especially when these models are frequently updated by a third party.

Coupling SD-based models of socioeconomic systems with existing physically-based models of the environment (e.g., cropping models such as DSSAT, CropSyst (Stöckle et al., 2003) and APSIM (Keating et al., 2003), or hydrological models such as SWAT and SAHYSMOD) is therefore a promising method for obtaining the "best of both worlds" by allowing for the integration of physically-based models into participatory SD-based projects. This allows stakeholders to indirectly access the predictive power of physically-based models through the intuitive SD modelling interface. The exchange of data on internal (and, potentially, output) variables between individual models at runtime effectively allows for the simulation of the larger system as if it were represented by one overall, integrated model. Furthermore, such model coupling becomes a highly time-effective way of reusing freely available physically-based models, as it eliminates the need to construct and test the accuracy of models of physical processes in the SD environment (which, in addition, may not be feasible for all physical processes).

Common approaches to couple separate models include: 1) scripting (e.g., Peck et al., 2014), 2) spreadsheet databases (e.g., Inam et al., 2017a), 3) model translation (e.g., Prodanovic and Simonovic, 2010), and 4) wrapper models (e.g., Shrestha et al., 2013); these approaches, however, have for the most part been developed in the context of linking two physically-based models and are ill-suited for participatory modelling. There is therefore a lack of intuitive, flexible and stakeholder-accessible tools and methodologies for coupling SD and physically-based models. General model coupling frameworks have been developed for other purposes (such as the recent work of Belete et al. (2017) to couple models in different platforms) and have been shown to significantly reduce the workload necessary for future coupled model development. However, no such framework or tool currently exists to couple SD and physically-based models.

This article will i) discuss the benefits and drawbacks of current methods with regards to coupling SD models with physically-based models in the context of a participatory modelling process (Section 2), ii) present a novel software coupling tool, *Tinamit*, to implement flexible, rapid, and stakeholder-friendly model coupling (Sections 1 and 3), and iii) provide an example of *Tinamit's* application to coupling a stakeholder-build SD farming model with a physically-based soil salinity model (Section 4). The coupled model is used to analyze the reciprocal impacts of the physically-based and socioeconomic subcomponents of the agricultural system on each other and to test the potential of various policy options for sustainable soil salinity management. Finally, Section 5 elaborates on the benefits and limitations of *Tinamit* and outlines future research directions, followed by general conclusions in Section 6.

2. Current methods for model coupling

2.1. Scripting

Scripting refers to the use of a computer code, written in a separate language (e.g., Python or Visual Basic) as a "linking" program that externally controls both models to be linked, running each one for the desired time step and then, within the linking program itself, managing the exchange of input and output data between the two models. For instance, the scripting approach has been used to couple a Vensim SD model of hospital system resilience during a natural emergency with ArcGIS (Peck et al., 2014), by Rosenzweig and Hodges (2011) to couple hydrodynamic and oil spill models, and by Akhtar et al. (2013) to connect a Vensim global systems model (ANEMI) with a MATLAB model-optimizing program (though, strictly speaking, the latter is not an example of coupling two models *per se*, but rather of connecting a model with an external optimizer).

2.2. Spreadsheets

The use of computer spreadsheets (in particular Excel) offers another opportunity to control the execution of and data exchange between physical models and SD-based socioeconomic models. In this case, a Visual Basic language macro is written into the Excel file, which then controls the execution of each model. Outputs from one model are copied into the cells of the Excel sheet and are available for export as input data into the other model (Inam et al., 2017a).

2.3. Model translation

Not as much a coupling method as a "brute force" approach, model translation refers to the translation of one or both of the individual models into a common programming language. Nonetheless, this approach is rather common in the modelling field, including Prodanovic and Simonovic's translation of a SD-based socioeconomic and a physically-based model representing the Upper Thames watershed into the Java programming language, from which the integrated model could be run (Prodanovic and Simonovic, 2010), and Cai et al.'s (2003) development of a joint economic-agricultural-hydrologic model within a single programming language framework.

2.4. Wrapper models

A final option for coupling models is to develop "wrapper models", which involves the development of a computer program to "wrap around" each model to be coupled and manage the execution of each and the exchange of data between the two. OpenMI is such a modelling framework that has been used to couple different physically-based models (Gregersen et al., 2007). Examples include coupling a rural soil and water model (SWAT) to an urban water runoff model (Shrestha et al., 2013); combining urban runoff and storm sewer models (Liao et al., 2012); and integrating economic, agricultural, and groundwater models in a study of the impacts of water-use policies in sustainable management of the Ogallala Aquifer of the United States (Bulatewicz et al., 2010).

2.5. Coupling with system dynamics models

While these methods are quite adequate for linking physically-