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Modeling water allocating institutions based on Multiple Optimization Problems with Equilibrium Constraints

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ABSTRACT

Hydro-economic river basin models (HERBM) based on mathematical programming are conventionally formulated as explicit 'aggregate optimization' problems with a single, aggregate objective function. Often unintended, this format implicitly assumes that decisions on water allocation are made via central planning or functioning markets such as to maximize social welfare. In the absence of perfect water markets, however, individually optimal decisions by water users will differ from the social optimum. Classical aggregate HERBMs cannot simulate that situation and thus might be unable to describe existing institutions governing access to water and produce biased results for alternative ones. We propose a new solution format for HERBMs, based on Multiple Optimization Problems with Equilibrium Constraints (MOPEC), which allows, inter alia, to express spatial externalities resulting from asymmetric access to water use. This new problem format, as opposed to commonly used linear (LP) or non-linear programming (NLP) approaches, enables the simultaneous simulation of numerous 'independent optimization' decisions by multiple water users while maintaining physical interdependences based on water use and flow in the river basin. We show that the alternative problem format allows formulating HERBMs that yield more realistic results when comparing different water management institutions.

1. Introduction

There is growing awareness that availability of water and its efficient management will become one of the key questions of the 21st century (Chartres and Varma, 2011). Decision makers increasingly demand scientific support in integrated water resource management (IWRM), where 'integrated' purports to relevant aspects from domains such as hydrology, ecology, engineering and economics and thus an interdisciplinary approach. Scientific analysis and simulation in the context of IRWM is predominantly based on integrated river basin/catchment modeling. Kragt et al. (2011) distinguish between hydro-ecological models, economic valuation models and (economic) optimization models, the sub-class preferred by resource economics and best termed hydro-economic models (Harou et al., 2009). In this study we focus on alternative designs of hydro-economic models at the river basin or catchment scale, which we will further denote as HERBM (hydro-economic river basin models) in accordance with Wang et al. (2008).

An often discussed issue in IWRM on the basin scale is that of an appropriate institutional design (Livingston, 1995) to improve resource allocation resulting from unregulated use of water or inefficient assignments of water use rights. These inefficiencies often arise from individual water withdrawal decisions based solely on private use costs, possibly reducing water availability for economically more efficient users. As a consequence, private use costs might deviate from basin-wide social opportunity costs and lead to inefficient water allocation among users (Barbier, 2003). The institutional response usually consists of a mixture of administrative approaches like water charges or assignment of water use rights, and market-based approaches such as establishing tradability of water use rights, often burdened with high transaction costs (Livingston, 1995). The economic assessment of these water management institutions and tools is often carried out on the basis of simulations with HERBMs that are based on linear (LP) or non-linear (NLP) mathematical optimization. This study argues that these optimization formats might deliver unrealistic results for water allocation in river basins if individual agents compete for water use and are not subject to central planning or participants in a perfectly functioning water market. Instead, we suggest the application of MOPEC (Multiple Optimization Problems with Equilibrium Constraints, Ferris and Wets, 2013) which allows us to

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physically couple optimization problems of numerous agents with market-based approaches, a setup that is, as we will argue, difficult or simply impossible to implement in a standard NLP or LP format based on the optimizing of an overall social welfare criterion.

The rest of the paper is organized as follows. Section 2 discusses the current state-of-the-art in hydro-economic river basin modeling. Section 3 provides an introduction to MOPEC, its integration into the GAMS software package, and existing applications. Section 4 presents our problem setting – several firms positioned along a water distribution system competing for water use – and presents algebraic formulations and solution algorithms to evaluate a range of typical institutional designs related to water use proposed and analyzed in the literature. Subsequently, we develop a small numerical example and apply the proposed solutions to highlight differences in the results between the two principal optimization formats. Finally, we apply our settings to an example with 500 agents. The GAMS code used to generate the results is appended to this study.

2. State of the art and pitfalls in hydro-economic basin modeling

2.1. Examples of current HERBMs

Hydro-economic models, according to Harou et al. (2009), represent hydrologic, engineering, environmental and economic aspects of spatially differentiated regional water resource systems "within a coherent framework". The term 'coherent framework' means that in hydro-economic models, all water resources and flows have to be valued by a common denominator (or *monetized*) in order to allow for a comparison of their utility among competing uses. Valuation, ideally, should include costs of water supply and both the market and non-market utility of water uses. It thereby simplifies a multi-objective management problem – designing a strategy which considers tradeoffs in all relevant economic, social and environmental aspects related to the water uses under consideration – into a single-objective optimization problem. By this, Harou et al. (2009) claim that hydro-economic models basically are constrained numerical optimization problems, a view supported by Booker et al. (2012). The inclusion of a willingness to pay by water users distinguishes true hydro-economic models from so-called integrated water management models where water demand by users is exogenous and not driven by economic considerations (cf. Qin et al., 2011).

Although driven by an economic criterion, current HERBMs provide considerable detail of the hydrological and bio-physical relationships (e.g. hydrological details of conjunctive use of water or water-crop yield relations) and are used as both a) planning models for optimal water allocation, and b) evaluation tools by water institutions for water pricing, water use rights, water trade, planned water allocation, and physical infrastructure. For an early, but still representative example, see Guise and Flinn (1970) who apply a linear programming (LP) model to a river basin in south-eastern Australia and test the effect of water pricing on allocative efficiency. More recent examples are non-linear integrated river basin models for the Maipo river in Chile (Rosegrant et al., 2000), the Jordan Valley (Doppler et al., 2002; water pricing), and the Drâa Valley in Southern Morocco (Heidecke and Kuhn, 2008), where water pricing options under conjunctive use of water resources are evaluated. Peña-Haro et al. (2011) provide a supply-side example that addresses optimal water allocation under uncertainty in hydraulic conductivity, while observing environmental constraints. Coupling of programming-based HERBMs with other models such as crop growth models is common. Wang et al. (2008) use a HERBM together with an irrigation planning model and a model simulating cooperative games for water allocation planning in the South Saskatchewan River Basin which uses a multi-criteria objective function.

2.2. The problem with 'aggregate optimization'

Most current models for water allocation in river basins are formulated as linear (LP) or nonlinear optimization problems (NLP) (cf. Brouwer and Hofkes, 2008) that allocate water among users, uses, locations, and points in time so that an *aggregate* social welfare criterion is maximized (we will call this format '*aggregate optimization*' AO).[1] The welfare measure is typically based on profits or utility of the different water users. Additional objectives such as equity or sustainability can be accounted for in the objective function or the model constraints. Regardless of the explicit or implicit composition of the objective to be maximized or minimized, this formulation of the problem tacitly assumes that agents will allocate water and other resources between them such as to maximize a joint, aggregate welfare criterion.[2]

On the contrary, our starting assumption is that each agent optimizes her individual welfare independently while being influenced by other user's decisions who withdraw water from the same common resource. For example, upstream users will continue to extract water as long as this is feasible, permitted, and increases their individual welfare. This might be considered excessive use from a societal viewpoint, since their water use may reduce aggregate welfare, because water availability for more valuable downstream uses (e.g. by more efficient firms) might be reduced. In the following we will show cases where the AO format violates the abovementioned starting assumption, and discuss the consequences.

The AO solution format is appropriate as long as interactions between agents and competition for resources can be interpreted in a competitive market paradigm. That includes the case where formal or informal non-tradable property rights restrict individual water use *and* the sum of these rights does not exceed the total available water. In these cases, the individual optimal strategy coincides with the point where the sum of producers' and consumers' surplus is maximized and represents an economic welfare optimum. Under these specific assumptions, it does not matter if we maximize that social welfare criterion or simulate interactions based on optimal strategies of the individual agents; this provides the foundation for using the AO format in price endogenous economic simulation models (cf. Takayama and Judge, 1971). Instead of the Takayama-Judge inspired interpretation of AO as the outcome of competitive markets, the AO approach can be alternatively viewed as a central planning model aimed at maximizing aggregate welfare. This particularity makes the institutional interpretation of AO-HERBMs somewhat ambiguous, as it is not clear whether they provide the results of planning or market processes.

HERBMs based on the AO problem format presuppose that the water institutions providing the rules and incentives necessary for perfect cooperation among the decision makers are already established and functional. This implies that binding contracts about water use between agents can be successfully made, that

[1] Conradie and Hoag (2004) provide an overview on mathematical programming models used for the estimation of marginal-value-based irrigation water charges.

[2] For instance, Mahan et al. (2002) describe their HERBM application as '[…] utilizing a nonlinear programming model that maximizes conventionally defined social welfare (consumers' plus producers' surplus) while observing essential institutional and hydrologic structures, we quantify the short-run efficiency gains (over one growing season) from reallocating scarce surface water. Such reallocations would be consistent with basin-wide policy reforms implementing perfectly functioning water markets'.