AN ECONOMICS-DRIVEN APPROACH FOR OPTIMIZING WATER USE IN TRANSBOUNDARY RIVER BASINS

N.D. Riegels[1], T. Siegfried[2], S.J. Pereira Cardenal[1], R.A. Jensen[3], and P. Bauer-Gottwein[1]

[1]*Department of Environmental Engineering, Technical University of Denmark, 2800 Kgs. Lyngby, Denmark*
[2]*Earth Institute, Columbia University, New York, NY, USA*
[3]*DHI Water Environment Health, Agern Allé 5, 2970 Hørsholm, Denmark*

E-mail: ndr@env.dtu.dk

In most economics-driven approaches to optimizing water use at the river basin scale, the system is modelled deterministically with the goal of maximizing overall benefits. However, actual operation and allocation decisions must be made under hydrologic and economic uncertainty. In addition, river basins often cross political boundaries, and different states may not be motivated to cooperate so as to maximize basin-scale benefits. Even within states, competing agents such as irrigation districts, municipal water agencies, and large industrial users may not have incentives to cooperate to realize efficiency gains identified in basin-level studies. River basin-scale studies also suffer from oversimplification due to the difficulties of modelling detailed hydrologic processes over large scales. Such studies often do not offer meaningful guidance for real-world decision making.

The Syr Darya River basin in Central Asia is a classic example of a transboundary river basin in which basin-wide efficiency gains identified in optimization studies have not been sufficient to induce cooperative management of the river. The river was extensively developed for hydropower and irrigation under the Soviet regime with significant environmental consequences, including the desiccation of the Aral Sea. Since the downfall of the Soviet Union, the river now flows through three countries between its source in the Tien Shan mountain range and the Aral Sea. The most upstream country, Kyrgyzstan, controls a series of reservoirs constructed during Soviet times that have considerable leverage over the downstream flow regime. Kyrgyzstan's objectives regarding the operation of these reservoirs frequently put it at odds with the downstream riparians, Uzbekistan and Kazakhstan. Kyrgyzstan prefers to conserve flows during the peak runoff season in the spring and summer in order to maximize energy generation during the winter, when power for heating is at a premium. Conversely, Uzbekistan and Kazakhstan depend on summer releases to provide flows for irrigation agriculture which, in the case of Uzbekistan, comprises more than 50% of GDP. Despite interstate efforts to manage the river, the countries have not been able to resolve their conflicting goals and management of the river continues to be a source of conflict.

This paper presents an economics-based approach for river basin-scale optimization that combines a detailed hydrologic model with an economic valuation tool to estimate the costs and benefits of different water allocation plans. The modelling approach is used as the basis for a multi-objective optimization tool to map the feasible allocation space and the associated Pareto hyper-surface that identifies efficient spatiotemporal allocation sets as well as tradeoffs across various water users.

In a second step, the dynamic feedback between decision-making agents themselves and an inherently uncertain environment is studied. Agents with decision-making control over water allocation such as countries, irrigation districts, and municipalities are represented by reinforcement learning agents. This approach emphasizes learning by agents from their continuous interaction with other agents and the environment. It provides a convenient framework for the solution of the problem of dynamic decision-making in a mixed cooperative/non-cooperative environment. Different institutional setups and incentive systems will be studied to identify reasonable ways to reach desirable allocation outcomes. Preliminary results from an application to the Syr Darya case are presented and discussed.

Details of the approach are outlined below.

Hydrological Model

A semi-distributed, node-based river basin mass balance model has been developed for the Syr Darya River Basin. The hydrographic network and sub-catchment discretization are based on the global topography dataset from the SRTM (shuttle radar topography) mission. The model is driven with remotely sensed precipitation estimates, which are be benchmarked against in-situ station data. Temperature and potential ET fields are be derived from ECMWF global reanalysis datasets (Molteni et al. 1996).

Water users are grouped into five use categories: irrigated agriculture, urban/domestic use, industry, hydropower, and ecosystems. Irrigation water requirements are estimated using FAO guidelines (Allen et al. 1998). Domestic demand is estimated using population density data from the LandScan project (Dobson et al. 2000). Water demands from industrial users are estimated using estimates of the water intensity of various production processes following the approach suggested by Vassolo and Doll (2005). Hydropower demands are not modeled explicitly but marginal values of hydropower production are included in the optimization framework driving the water allocation process. Ecosystem demands are estimated using an approach suggested by Loucks (2006) in which ecosystem performance metrics are linked to hydrologic attributes.

Valuation Approach

Water demands are represented using marginal benefit and marginal cost functions that estimate the costs and benefits of each increment of water use; total net benefits are then estimated by integration of marginal value curves for given water use levels.

For domestic/urban users, marginal benefit curves are developed using observed water use data following an approach suggested by Griffin (2006). Observed water use data are assumed to give a snapshot of the marginal value of water use and price/use data are combined with elasticity estimates to develop demand curves assuming constant elasticity (for a meta-analysis of price elasticities, see Dalhuisen et al. 2003). These curves are assumed to give marginal values of water at various water use levels and are integrated to approximate total benefits.

Marginal benefits of irrigation water use are estimated based on crop areas, maximum yields, irrigation water requirements, and crop producer prices. Water shortage impacts on crop yields are estimated using FAO guidelines (Allen et al. 1998).

Marginal benefits of industrial water use are estimated assuming that industries shift to more expensive but efficient water conservation processes in order to maintain full production during shortages. The added expense of using conserving processes is then subtracted from total benefits.

Marginal benefits of hydropower are estimated using current energy prices and standard assumptions for hydropower energy generation.

Ecosystem benefits are monetized using an approach outlined by Korsgaard (2006) in which hydrological attributes are linked to ecosystem services, which are in turn linked to economic values. The ecosystem valuation approach focuses on important wetland areas in the Syr Darya delta. Wetland ecosystem service values are estimated using standard methods from the wetland valuation literature as outlined by Brander et al. (2006).

Costs are estimated for all water use categories and subtracted from benefits to estimate net benefits. For all water users, water supply costs are estimated. Water supply costs are not the same as user costs (i.e., the amounts paid by users to water suppliers) but instead represent the costs of providing water supply. For irrigation and industry users, non-water input costs such as fertilizer and labor costs are also included in net benefit estimates.

Optimization and Trade-off Analysis

A multi-objective decision support tool is developed to map the feasible allocation policy space where an allocation policy is understood as a set of rules for each stakeholder that defines where to allocate how much groundwater and/or surface water at which time. The tool also identifies efficient solutions for which there exist no better ones in the Pareto-sense.

The tool uses multi-objective evolutionary optimization algorithms with the ability to handle complex simulation-optimization models (e.g. Siegfried and Kinzelbach 2006). These algorithms perform policy searches stochastically under evolutionary selection pressure where the performance of individual policies is estimated by mapping from the allocation space to the objective space using economic valuation framework outlined above. The separation of the problem-dependent modeling part from the optimizer allows for an efficient implementation (e.g. Bleuler et al. 2003 and Siegfried et al. 2008).

Strategic Analysis and Institutional Design

A simulation-optimization approach such as the one presented above assumes pre-commitment by individual agents and stakeholders and unconditional compliance on each side. While this can help determine attainable gains and tradeoffs from efficient management, such *hardwired* policies do not account for dynamic feedback between agents themselves or between agents and their environments (e.g. due to climate change etc.). In reality, we are dealing with an out-of-equilibrium multi-agent system, where there is neither global knowledge nor global control, but rather continuous strategic interaction between decision making agents. This sort of strategic interaction, where agents are constantly adapting to other agents and the environment, cannot be studied using a multi-objective optimization approach (e.g. Abul et al. 2000).

To address this problem, we use a novel agent-based water resources management framework to study the decision making behavior of individual water users under different institutional setups. It borrows heavily from game theory and seeks to identify strategies, moves, or allocations consistent with the interests of individual agents operating within institutional constraints—given the strategies, moves, and allocations that rival agents might choose (Arthur 2006).

We assume that each decision making unit can be represented by a reinforcement learning agent which has to solve a Markov decision process (see Puterman 2005 on the latter). Reinforcement learning is an approach to artificial intelligence that emphasizes learning by the individual agent from its continuous interaction with the environment so as to maximize benefits. The approach provides a convenient framework for the solution of the problem of dynamic, decentralized decision-making under uncertainty in a mixed cooperative / non-cooperative environment (e.g. Hu and Wellman 2004).

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