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Using many-objective trade-off analysis to help dams promote economic development, protect the poor and enhance ecological health☆

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ABSTRACT

Allocating water to different uses implies trading off the benefits perceived by different sectors. This paper demonstrates how visualising the trade-offs implied by the best performing water management options helps balance water use benefits and find sustainable solutions. The approach consists of linking a water resources model that can simulate many management policies and track diverse measures of system performance, to a many-objective evolutionary optimisation algorithm. This generates the set of Pareto-optimal management alternatives for several simultaneous objectives. The relative performance of these efficient management alternatives is then visualised as trade-off curves or surfaces using visual analytic plots. Visually assessing trade-offs between benefits helps select policies that achieve a decision-maker-selected balance between different metrics of system performance. We apply this approach to a multi-reservoir water resource system in Brazil's semi-arid Jaguaribe basin where current water allocation procedures favour sectors with greater political power and technical knowledge. The case study identifies promising reservoir operating policies by exploring trade-offs between economic, ecological and livelihood benefits as well as traditional hydropower generation, irrigation and water supply. Results show optimised policies can increase allocations to downstream uses while increasing median land availability for the poorest farmers by 25%.

1. Introduction

Water resources management has been described as a ‘wicked’ class of planning problem (Liebman, 1976; Lund, 2012; Reed and Kasprzyk, 2009) with difficult to predict “waves of repercussions” (Rittel and Webber, 1973) resulting from the complex interactions between social, environmental and economic impacts. The need to consider multiple concurrent and sometimes conflicting objectives is a salient feature of water resource management (Reed et al., 2013). Visually displaying trade-offs between these objectives can play a useful role in solving wicked problems because it helps stakeholders assess how non-commensurate goals relate.

In reservoir systems, livelihood factors such as ecological and social impacts are often considered after monetisable

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benefits from sectors like irrigation and hydropower, if at all (GWP, 2003; McCully, 2001). Political conflict can result where poor or marginalised groups are not involved in decision-making processes, jeopardising the sustainability of benefits (McCully, 2001; Nguyen-Khoa and Smith, 2004; WCD, 2000). Methods which combine scientific and local knowledge to consider the inherently complex impacts of any policy show promise for more sustainable management of environmental resources (Bryant, 1998).

Stakeholder participation in managing reservoirs can mitigate conflict and ensure wider societal knowledge and objectives are considered (Johnsson and Kemper, 2005; Poff et al., 2003; Roncoli et al., 2009; Uphoff and Wijayaratna, 2000). Some participatory approaches overlook the trade-offs inherent in water management decisions, however (Kallis et al., 2006). Explicitly considering trade-offs between many objectives can help avoid negative impacts of human decision biases in complex planning problems (Brill et al., 1982). Many-objective problems are those considering 4 or more objectives (Reed et al., 2013). Considering fewer objectives can lead to "cognitive myopia" (Hogarth, 1981), where the diversity of possible solutions is unrealistically constrained, or lead to "cognitive hysteresis" (Gettys and Fisher, 1979), where preconceptions about the nature of a problem are reinforced by lack of new insight. Kollat et al. (2011) show that increasing the number of objectives considered can change decision makers' preferences about system performance.

Trade-off curves or surfaces representing Pareto-optimal relationships between conflicting management objectives are a recognised tool of water management (Loucks et al., 2005). Their form elucidates the degree of sacrifice of one benefit required for gain of other benefits. Pareto-optimal solutions are those which cannot be improved for any one of the benefits considered, without disadvantaging one or more of the others. Trade-offs were illustrated numerically (Haimes and Hall, 1974) or with simple visualisations (Loucks, 2006; Ryu et al., 2009) until the advent of advanced visual analytic tools (Keim et al., 2008) allowed multiple dimensions (objectives) and richer information to be explored in a more intuitive way. These tools have recently been applied to the results of many-objective water resources planning and management optimisations (Kasprzyk et al., 2009; Kollat and Reed, 2006; Matrosov et al., Subject to minor revisions; Reed and Kollat, 2012).

A large body of literature considers the optimisation of reservoir planning and operation. Linear programming, non-linear programming, dynamic programming and their variants are classical methods of single or multiple objective optimisation, though they require pre-assigned (*a priori*) weights or procedures to combine objectives (Cohon, 1978; Yeh, 1985). With these methods the water system model must be embedded in the mathematical programme which typically requires simplifying assumptions to represent the non-linear features common in water resources systems. The challenges of identifying Pareto-optimal trade-offs with complex forms or more than 2 objectives using classical multi-objective methods (Shukla et al., 2005) has limited their application to real-world problems (Bhaskar et al., 2000). Shukla et al. (2005) contrasted these classical methods with a multi-objective evolutionary algorithm (MOEA) continuing to perform well as trade-off complexity and number of objectives increased.

Multi-objective evolutionary algorithms (MOEAs) (Coello et al., 2007) are heuristic search techniques which perform thousands of simulations to 'evolve' the best policies for the given objectives. As the algorithm can be separated from the simulation model, trusted existing simulators can be used in the optimisation. Optimisation using MOEAs is attractive because preferences about performance objectives need not be expressed *a priori* through weightings. This is significant because the desirability of any given level of benefit depends to some extent on the sacrifice required to achieve it; this cannot be known *a priori*. Preference decisions are made after trade-offs are revealed, representing an *a posteriori* approach (Coello et al., 2007). MOEA optimisation has been under development for two decades and can now consider up to 10 objectives in some cases. Reed et al. (2013) review the state-of-the-art.

MOEAs have been used to optimise reservoir rules (continuous storage-release relationships) (Shiau, 2009) and reservoir operating rule curves (target storage levels throughout the year) (Chang et al., 2005). Ecological and economic objectives have been optimised simultaneously using MOEAs (Suen and Eheart, 2006). This paper contributes an MOEA trade-off analysis for multi-reservoir system operation and water allocation considering novel livelihood-related objectives alongside traditional economic objectives (irrigation, hydropower, and water supply). Trade-offs between benefits are explored using visual analytics and impacts of optimised reservoir operating policies are examined for a three-reservoir system in NE Brazil's Jaguaribe basin.

The next section describes the case study, followed by a methods description in Section 3. Results are described in Section 4 with discussion and conclusions following in Sections 5 and 6.

2. Jaguaribe basin case study

The state of Ceará in north east Brazil is semi-arid with annual average rainfall between 400 (interior) and 1200 mm (coast). Ceará's largest city Fortaleza is expanding with a water transfer from the nearby Jaguaribe basin to meet its growing needs. At 610 km the Jaguaribe river is the world's longest naturally dry river which although now perennialised, historically ran dry for up to 18 months during severe droughts; at worst killing thousands of people (Taddei, 2005). Flow variations are extreme and evaporative losses are significant. The basin's three largest reservoirs are Castanhão (6700 Mm^3), Orós (1940 Mm^3) and Banabuiú (1601 Mm^3), totalling over 75% of the basin's storage capacity (Fig. 1). Reservoir operation is a critical issue as a large population of rural poor depend on surface water for their livelihoods (reservoir dependent fisheries and agriculture).

A biannual participatory negotiation of reservoir releases, based on current storage, occurs for the three reservoirs individually. Its effectiveness in empowering vulnerable groups is still questioned (Broad et al., 2007; Johnsson and Kemper, 2005; Taddei, 2011) as poorer stakeholders such as farmers and fishermen are often under-represented or marginalised in the negotiation and relatively ineffective compared to the politically powerful and technically knowledgeable (Taddei, 2005). Results of the water utility's