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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

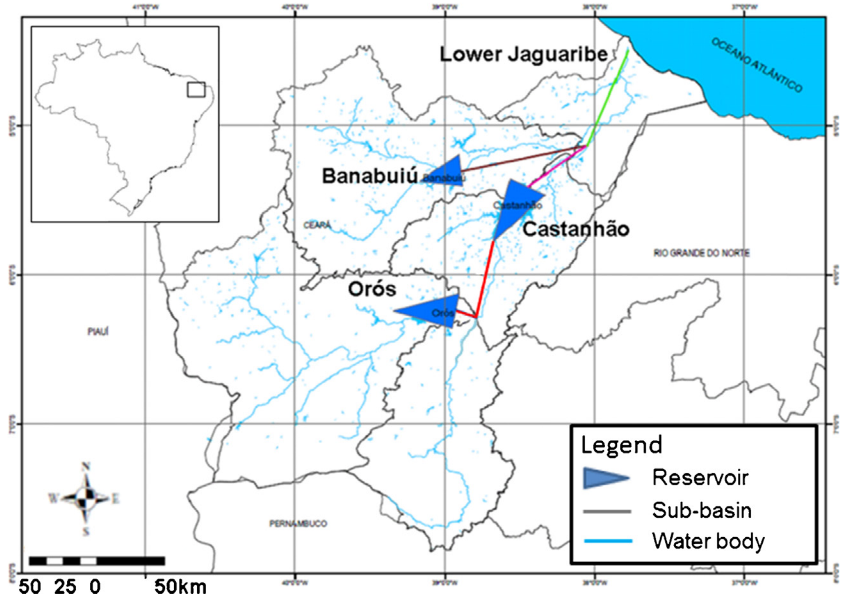

Fig. 1 – Five Jaguaribe sub-basins overlaid with a schematic of the major water resources system (inset: location in Brazil): three large reservoirs and four major perennialised river reaches (coloured). Large font represents four modelled supply regions (map from Mendiondo, pers. comm.).

modelling of the impacts on reservoir levels of a limited number of release scenarios form the basis of negotiation and eventually consensus about the subsequent season's releases. The primary conflict in negotiations is between users who benefit from water retention (high storage levels) and those who benefit from regular releases. Current policy dictates that 30 months of municipal supply must be guaranteed from the date of negotiation (Sankarasubramanian et al., 2009).

3. Methodology

We formulate the water management problem of the Jaguaribe basin by representing it with a water resource management simulator. Decision variables within the simulator represent management policies and objective functions measure the performance of different policies. The model is linked to an optimisation algorithm which explores the performance 'space' by varying the decision variable values, revealing approximately Pareto-optimal trade-offs. In other words, the simulator tracks several performance metrics throughout the river basin which allow the optimisation algorithm to search for solutions where the only way to further improve one objective causes loss of performance in other objectives. Rather than resulting in a single optimal solution, this method provides trade-off curves or surfaces which show which decisions lead to the best balanced system performances.

3.1. *Water resource system simulation*

The open-source IRAS-2010 water resources management simulator (Matrosov et al., 2011) is used to simulate the Jaguaribe basin. IRAS-2010 was selected due to its appropriate level of complexity and adaptability and its computational efficiency. Model run times can be kept to the order of seconds; in our study this meant 25,000 model runs executed by the optimisation algorithm took 1.5 h using a 16 processor cluster. The sections below describe how the model is parameterised and how system performance is measured.

3.1.1. *Jaguaribe basin model*

The river network model comprises 119 reservoir and abstraction nodes connected by 174 river, abstraction and return flow links. Initial reservoir storages are set at mean January levels over the 2002–2010 period. The upstream boundary condition is a 90-year historical (1911–2000) inflow time-series for each reservoir. The downstream boundary is an unrestricted outflow node – not accounting for tidal influence. A monthly (30-day) time step is used so flow entering a river reach passes through it within a time-step, removing the need for flow routing.

Transmission losses are estimated as 0.6% of discharge per km (Rêgo, 2001). Return flows are based on information provided by de Araújo (Personal communication) based on measurements in a Middle Jaguaribe river (Rêgo, 2001). Evaporation is accounted for using monthly mean daily evaporation rates applied to each reservoir.

3.1.2. *Demands*

A water demand prioritisation feature of IRAS-2010 is used to ensure the model allocates water realistically when availability is limited. As water flows down the river the model ensures water is allocated according to user-defined priorities. The priority of demand sectors is municipal, livestock, industry, irrigation then aquaculture. Aggregated monthly demand data from abstraction license data, account for both fixed and varying demands in each sector.

Transfer to Fortaleza is prioritised equally with Municipal demands in the Castanhão and Lower Jaguaribe supply areas, but the Trabalhador transfer canal from the Lower Jaguaribe is not prioritised owing to its low capacity and hydraulic gradient which make it ineffective as a transfer to Fortaleza. Demand volumes by supply region and sector are provided in Hurford et al. (2012).

3.2. *Performance metrics*

This section describes the sixteen metrics used to quantify system performance under different management policies. It was not possible to engage stakeholders in metric development at this stage. Some of these metrics are used as optimisation objective functions (Section 3.3.2). Each time the simulator is executed to evaluate an operating policy, scores produced for each metric used as an objective function allow the optimisation algorithm to search for the best policies.

System water 'losses' are calculated as the sum of mean annual evaporative loss from all three reservoirs plus uncontrolled releases (also a surrogate for flood protection) from the Castanhão and Banabuiú reservoirs. Uncontrolled releases from Orós reservoir are captured by Castanhão reservoir and therefore not lost to the system.

Hydropower deficit is calculated as the mean annual number of months when the hydropower generation potential at Castanhão reservoir falls below 100% of capacity.

In months when storage in all three reservoirs is below 25% of their maximum capacity, it is considered that there are no good fisheries for poor itinerant fishermen (based on AZCOL classification in Hardy (1995)). Fisheries deficit is defined as the mean annual number of months with poor fisheries in all three reservoirs.

Land availability for farmers of the reservoir floodplain (Vazanteiros) is represented by the mean annual proportion of the maximum land available when the growing season begins (based on van Oel et al. (2008)). It is summed across all three reservoirs. Land availability depends on low enough reservoir levels so that fertile land is exposed, but high enough levels that this land can be irrigated by pumping from the reservoir. The optimum is at 2/3 of reservoir capacity, meaning retention benefits the poorest farmers.

Agricultural deficit is assessed for the four supply regions separately to enable considering the trade-offs between them. Owing to the prioritisation of allocations, aquaculture demand allocation will be reduced to zero before agriculture loses any of its allocation. The metric is calculated as the mean annual volumetric deficit from the 90% level of supply reliability (supply/demand). An aggregated metric – the sum of regional deficits – is also calculated to allow higher level (more aggregated) trade-offs to be explored.

There is concern that the altered flow regime at the mouth of the Jaguaribe river negatively impacts estuarine ecosystems and by implication ecosystem services. Mangrove intrusion on agricultural land and declines in economically important crab and fish populations are of particular note (Marins and Lacerda, 2007). Following Connell's (1979) intermediate disturbance hypothesis (IDH) we assume that the river flow variability represented by the unregulated (naturalised) flow frequency curve is most likely to support healthy native ecosystems. Accounting for Gao et al.'s (2009) eco-surplus and eco-deficit approach, we use a flow alteration metric which assesses the deviation of the regulated flow from the unregulated flow frequency curve. Flow alteration is assessed seasonally to correspond with the temporal resolution of reservoir release rules.

Two flow alteration metrics are computed (one for each season – wet/dry) as the negative sum of Nash–Sutcliffe efficiencies (Nash and Sutcliffe, 1970) for ten corresponding deciles of the regulated and unregulated curves, at the outlet of the basin (the location of concern for Marins and Lacerda, 2007). The negative sum is used to make the metric more intuitive – it is desirable to minimise flow alteration, rather than maximise it. Deciles are used to avoid favouring any particular range (*e.g.* high flows) at the expense of others. The range of the metric is -10 to infinity, although physical limits mean the value is unlikely to approach infinity. Perfectly matching curves give -10. An aggregated metric – the sum of seasonal alterations – is calculated to allow higher level trade-offs to be explored.

The simulation model registers the minimum volume of municipal reserves reached during each 90-year simulation and converts this to an equivalent duration of municipal supply, accounting also for evaporation. This quantifies the security of municipal supply provided by any management policy because a drought can theoretically begin at any moment – impacts are likely to be greater, the lower the reserves at that time. This index helps evaluate the consequences of relaxing the current policy guaranteeing 30 months of municipal supply. This metric is calculated for each reservoir; Lower Jaguaribe municipal demand being divided between Castanhão and Banabuiú proportional to storage capacity. An aggregated metric – the sum across all reservoirs – is calculated to allow higher level trade-offs to be explored.

3.3. *Optimisation model formulation*

The search for the best management policies and performance trade-offs is facilitated by connecting the water management simulator to a multi-objective search (optimisation) algorithm. The IRAS-2010 simulator is linked *via* a C++ wrapper to the Epsilon Dominance Non-dominated Sorted Genetic Algorithm-II (ε-NSGAII) (Kollat and Reed, 2006; Reed et al., 2013). The optimisation formulation is described in Appendix A, Section 3.3.1 describes the decision variables used to represent different management policies and Section 3.3.2 describes the objective functions used to assess performance of each policy.

3.3.1. *Decision variables*

The decision variables optimised are release (hedging) rules for the individual reservoirs, together representing a management policy. To limit the complexity of the optimisation problem, and considering the current biannual negotiation process, we chose to separate wet season (January–June) and dry season (July–December) rules per reservoir. The release rules can be visualised as piece-wise linear curves leading to 21 decision variables (Fig. 2).

3.3.2. *Objective functions*

Ten of the sixteen performance metrics (Section 3.2) are used as objective functions (*i.e.*, to direct the optimisation algorithm's search for the best management policies). The other six metrics provide additional information when visualising

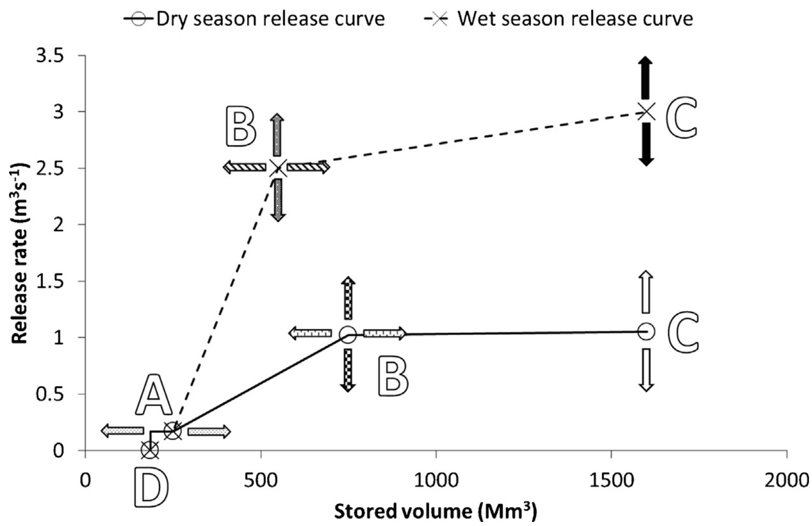

Fig. 2 – Seasonal release rule (hedging) curves as represented by the IRAS-2010 Jaguaribe model. Each patterned pair of opposing arrows represents an optimisation decision variable. Point D is the dead storage of the reservoir. Point A is the storage level at which releases are restricted to municipal supply. B points can be varied in two dimensions for hedging. C points represent the controlled release when the reservoir is full. In total 7 decision variables define each reservoir's release rule.

trade-offs. The precision of objective function results is specified to provide meaningful differentiation between management policy outcomes. There would be little gained from comparing 0.1 months of difference in hydropower deficit, for example. Metrics, goals and results precision are listed in Table 1; objective function equations are detailed in Appendix A.

3.3.3. *Optimisation verification and parameters*

Evolutionary optimisation algorithms begin with a random draw of decision variable values. To ensure the optimisation worked well, a random seed (RS) analysis can be undertaken to check that different start points finish with the same optima. We carried out a 50 RS analysis which confirmed results from the single seed analysis (original optimisation) satisfactorily represent the whole trade-off surface.

Optimisation parameters for the ε-NSGAII followed Kasprzyk et al. (2009).

3.3.4. *Visual analytics*

We use visual analytics (Keim et al., 2008) to interactively explore the trade-offs between competing objectives, and add analytical and non-optimised information to the trade-off surface to highlight information about the results. Visual analytics provide a holistic picture of the multiple measures of performance and the policies which led to them. It allows large datasets (1000's of points) to be analysed in a time-efficient and visually appealing manner facilitating more informed decision-making (Kollat and Reed, 2007; Lotov, 2007). The visual analytic plots crafted below aim to help make *a posteriori* decisions about the preferred balance of benefits considering the various trade-offs (Coello et al., 2007). Any selected point from the trade-off surface represents the performance achieved for all metrics by a specific set of reservoir control rules (policy).

4. Results

4.1. *Pareto-optimal trade-offs*

A Pareto-optimal trade-off (Cohon, 1978) occurs where no further performance gains can be achieved in any one objective, without reducing performance in one or more of

Table 1 – Performance metrics and their objective functions, goals and results precision.

Performance metric	Objective function (Appendix A)	Goal	Result units and precision
Evaporative/spill losses	f_{losses}	Minimise	50 Mm^3
Hydropower deficit	f_{hydro}	Minimise	1 month
Fisheries deficit	f_{fish}	Minimise	1 month
Land availability	f_{land}	Maximise	0.02
Agricultural deficit – Orós	$f_{agr}^{Orós}$	Minimise	0.05 Mm^3
Agricultural deficit – Castanhão	$f_{agr}^{Castanhão}$	Minimise	0.1 Mm^3
Agricultural deficit – Banabuiú	$f_{agr}^{Banabuiú}$	Minimise	0.1 Mm^3
Agricultural deficit – lower Jaguaribe	$f_{agr}^{Lower\ Jaguaribe}$	Minimise	0.025 Mm^3
Flow alteration – wet season	f_{flow}^{wet}	Minimise	2.5
Flow alteration – dry season	f_{flow}^{dry}	Minimise	2.5

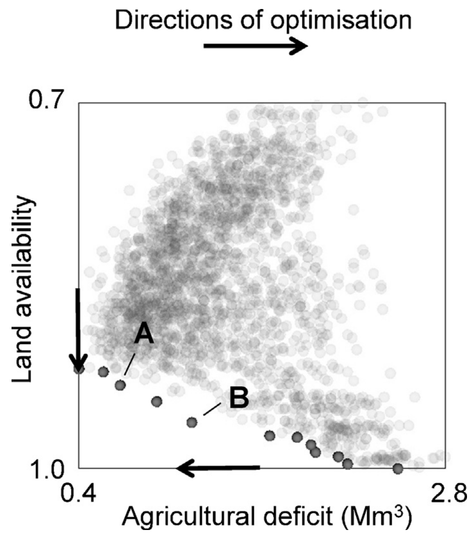

Fig. 3 – Solid (non-dominated) solution points show the Pareto-optimal trade-off between land availability and aggregated agricultural deficit. Dominated solution points are greyed out. Arrows show the direction of improved performance (optimisation). Each point represents the performance achieved when simulating one release rule policy for the three reservoirs.

the others. A trade-off curve can be approximated by discrete solution points between two axes. The trade-off curve represents the 'non-dominated set' of solutions, meaning that other (dominated) solutions are available but all are outperformed by one or more of the non-dominated results. Fig. 3 illustrates these concepts using two example solutions within a trade-off curve: solution A performs better for agriculture deficit, while B performs better for land availability (both are Pareto-optimal). Land availability and agricultural deficit represent conflicting objectives therefore a decision (a 'trade-off') must be made about how much to sacrifice performance in one to improve performance in the other. In our case each solution on the trade-off curve represents the set of release rules (management policy) for the reservoirs which achieves the respective benefits. Evolutionary algorithms are heuristic search methods that approximate the Pareto surface without ever reaching it in an absolute mathematical sense. Formally therefore, the trade-offs are 'Pareto-approximate' although we refer to them subsequently as 'Pareto-optimal' to simplify the discussion.

4.2. *Retention-release*

The first trade-off we investigate is between retention (storage) and release (Fig. 3): the key conflict of reservoir management in the Jaguaribe basin. A balance must be struck between the two and this balance has implications for all stakeholders. In Fig. 3 and all subsequent figures, the aggregate agricultural deficit metric (benefiting from release) is used to show high-level trade-offs, except where aggregation is addressed in Section 4.7. Land availability (benefiting from retention, see Section 3.2) also represents fisheries deficit as the two metrics are correlated (not conflicting). Dominated solutions are not shown in subsequent figures to simplify illustration of trade-offs.

4.3. *Flow regime alteration*

The storage of water to allow perennially flowing rivers even during the dry season interrupts natural flow regimes (see Section 3.2). Fig. 4 shows the same trade-off as Fig. 3 but with a third axis showing the flow alteration metric. In three dimensions, rather than a trade-off curve we now have a trade-off surface which allows visualising how performance across all three metrics is distributed for the best reservoir management policies. Fig. 4 shows as land availability increases (benefit), flow alteration increases (disbenefit). The lowest agricultural deficits (benefit) are in the mid-range of flow alteration benefits. At high flow alteration (poor ecological performance), decreasing flow alteration initially improves agricultural deficits but at around 500 further ecological improvement causes loss of agricultural benefits.

It is worth recalling from Section 3.2 that the flow alteration metric represents not only purely ecological interests, but also impacts on the ecosystem services of the Jaguaribe estuary.

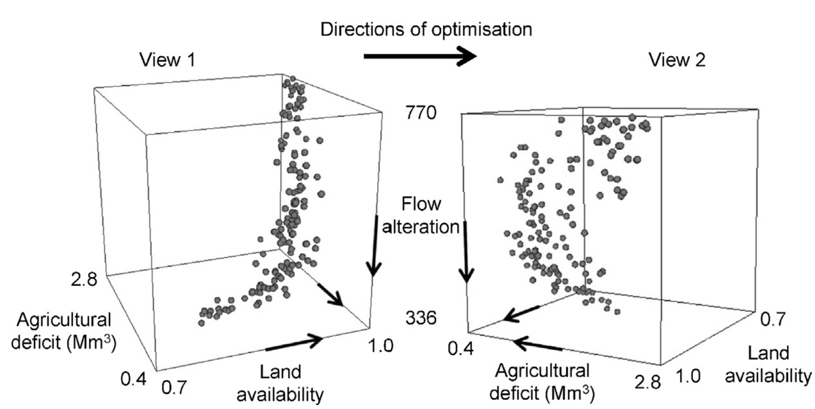

Fig. 4 – Trade-off curve from Fig. 3 expanded into a trade-off surface by also considering the flow alteration metric (vertical axis). Both panels show the same surface; two angles are used to aid orientation. As the number of axes (dimensions) increases, so the number of points comprising the trade-off surface increases. The animation available in Appendix B supplementary data (online version) helps illustrate the shape of this trade-off surface.

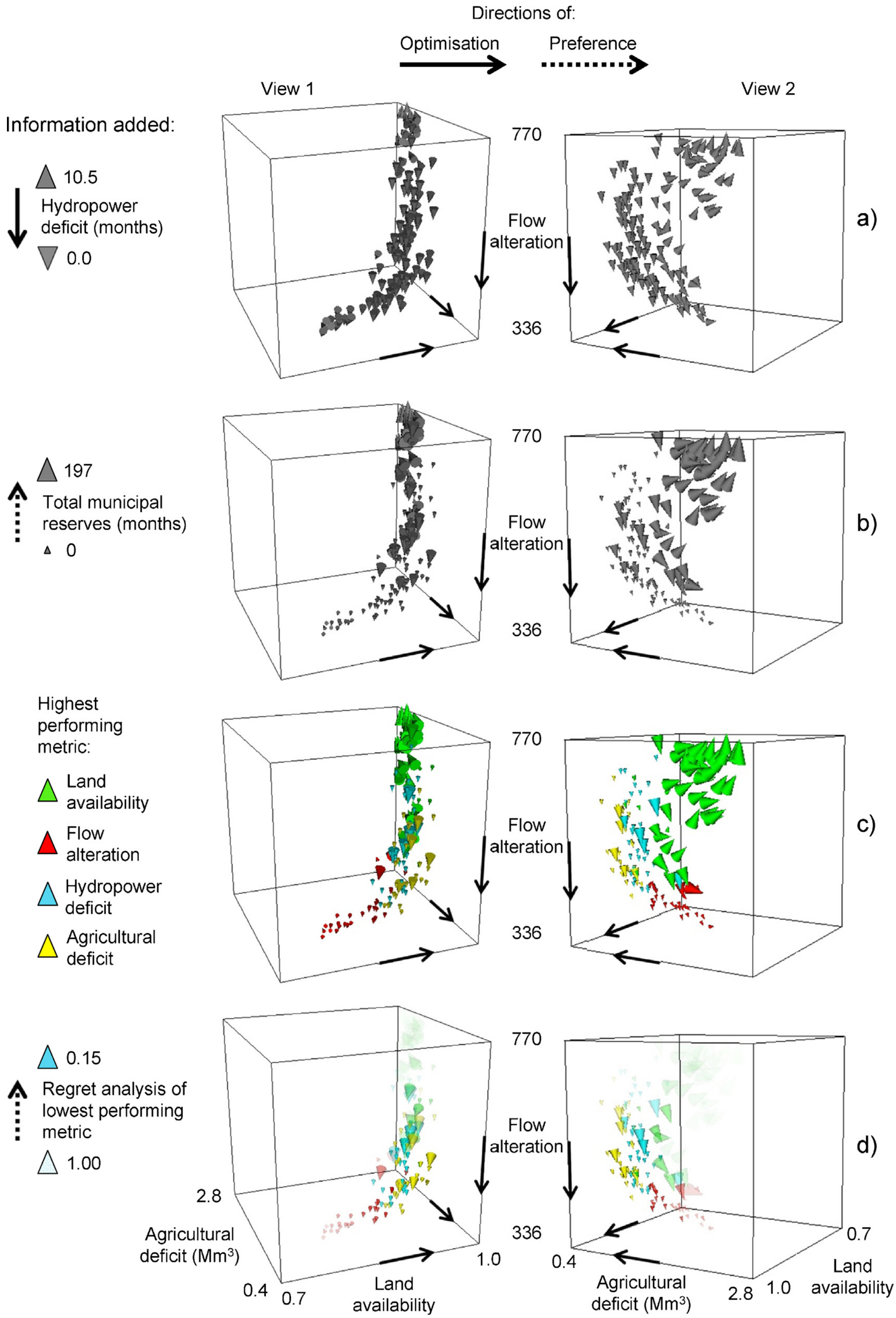

Fig. 5 – Progressive addition of information to the trade-off surface from Fig. 4. The *x*- and *y*-axis are labelled only in the bottom panel (d) for simplicity but apply to all panels. Initially a fourth optimisation dimension is added to show hydropower performance (a), then visual effects are used to illustrate further features of the solutions, (b) the minimum total municipal reserves reached, (c) the region of the trade-off surface where each metric performs best, and (d) gradation of regret to emphasise where best performing compromises are likely to be. The animation available in Appendix B supplementary data (online version) helps illustrate the shape of the trade-off surface in 5(c).

Trade-offs between flow alteration and land availability therefore imply trade-offs between the support of upstream and downstream livelihoods.

4.4. *Expanding the trade-off surface*

In Fig. 5(a) the optimised hydropower deficit metric is displayed (using cone orientation, where up is high deficit and down is no deficit) on the same trade-off surface displayed in Fig. 4. Two viewing angles (left and right panels) are displayed to enhance visualisation. This is consistent with maximising hydropower production by balancing high reservoir storage (hydraulic head) with releases to drive turbines. Fig. 5(b) shows the municipal reserves using cone size, where large cones indicate large reserves and small cones small reserves. Municipal reserves increase with land availability and flow alteration, *i.e.*, retention rather than release. Fig. 5(c) uses colours to highlight which metric performs best for each solution. Regions of high performance for different metrics become apparent in the objective space. In Fig. 5(d) transparency is used to highlight the solutions likely to constitute high performing compromises, using regret analysis (Savage, 1954). Low regret solutions are opaque while high regret solutions are transparent.

Regret (*R*) quantifies how much a policy's (*s*) performance (*P*) deviates from the performance of the best-performing policy (*s*′) in each performance metric (*c*), for the same set of input parameters (inflow time series) (*j*) and is normalised by the range between the best and worst-performing (*s*″) policies (Eq. (1)). The best performing result has a Regret of 0 and the worst performing a Regret of 1.

$$R_c(s, j) = \frac{|P_c(s', j) - P_c(s, j)|}{|P_c(s', j) - P_c(s'', j)|} \qquad (1)$$

4.5. *Investigating details of selected Pareto-optimal operating rule sets*

Five points representing specific interesting management policies were selected from the trade-off surface of Fig. 5 to demonstrate their reservoir storage, release rule and flow regime implications. The best performing policy was selected for each metric plus one example 'compromise' policy. The location of each point is highlighted on the trade-off surface in Fig. 6.

4.6. *Reservoir storage levels*

Fig. 7 shows how the 5 selected reservoir operating rule sets impact monthly reservoir storage levels (as percentage of full capacity). Retention and river regulation is minimised in Fig. 7(a) to preserve the unregulated flow regime. Conversely, Fig. 7(e) shows storage maximised around the best level for land availability, which also means fisheries deficit is low. Fig. 7(d) illustrates a known (Lund and Guzman, 1999) policy for reservoirs in series supporting hydropower generation – Orós storage is sacrificed to maintain hydraulic head for generation at Castanhão. Fig. 7(b) and (c) represents balances between release and retention to increase dependability of supply; in (b) to minimise agricultural deficit and in (c) to balance all the objectives.

4.7. *Aggregated metrics*

The agricultural deficit and flow alteration metrics used to define the trade-off surface in Figs. 4 and 5 were aggregated. Visual analytics allow us to examine the trade-off within these aggregations and consider the balance between the component metrics. Should a particular region of the sub-trade-off curve/surface be preferred, this can inform constraining the surface in Fig. 6 during a decision-making process. Fig. 8 for example, shows the selected rule set locations within the context of the disaggregated agricultural deficit trade-off. This shows how much less than optimal performance must be accepted in these metrics in order to achieve high performance in other metrics or the example compromise rule set.

4.8. *Release rules*

As described in Section 4.1, the solutions comprise a set of reservoir release rules of the form shown in Fig. 2. Fig. 9 illustrates the five selected rule sets (policies) in the same form. The rule curves demonstrate the conflict between Pro-poor and Eco-flow policies as curve shapes are almost mirror

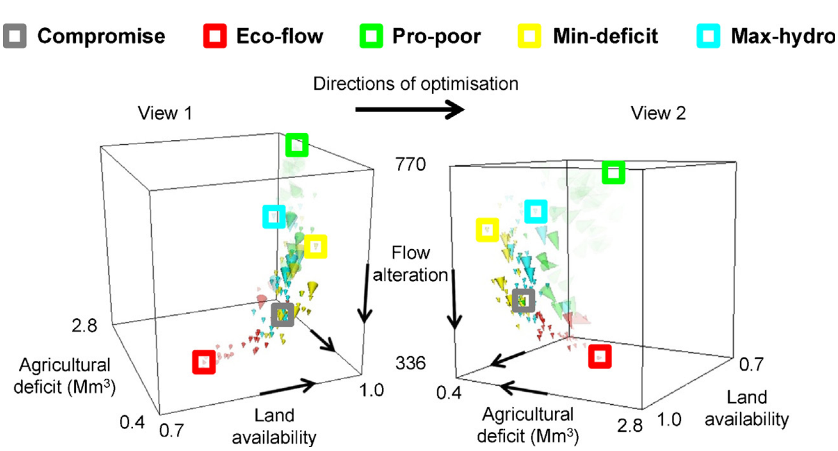

Fig. 6 – The trade-off surface from Fig. 5(d) with coloured boxes highlighting the location of selected policies. The policies span the whole trade-off surface so they help to understand the implications as release rules change across the surface.

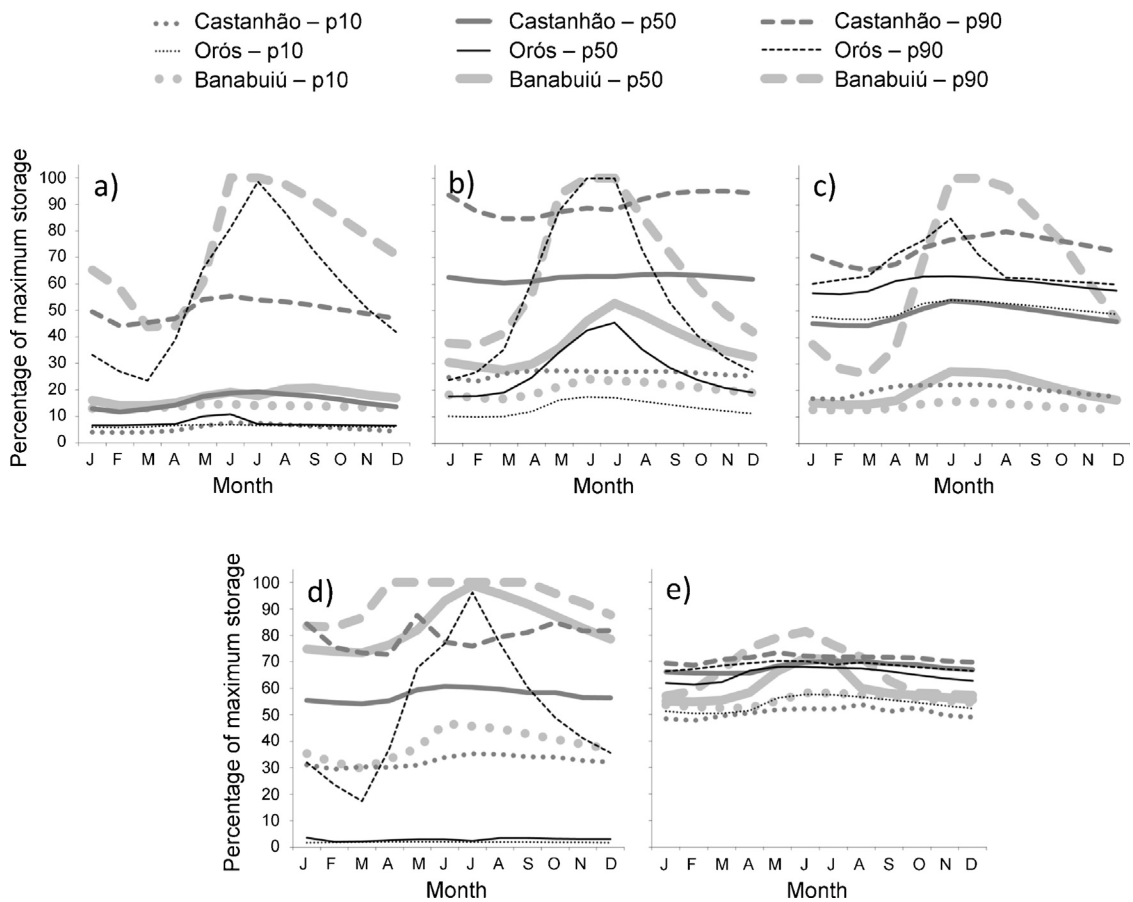

Fig. 7 – Average reservoir storage profiles over the 90-year simulation period for selected release rule sets; (a) Eco-flow, (b) Min-deficit, (c) Compromise, (d) Max-hydro, and (e) Pro-poor. The range of storage generated by each rule set is indicated by 10th, 50th and 90th percentile plots; colour tones and line thickness differentiate between reservoirs.

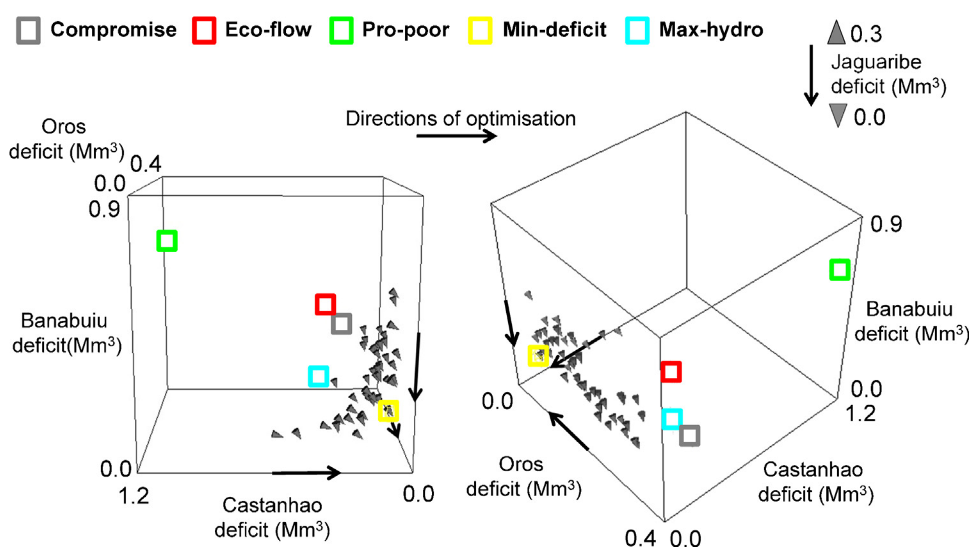

Fig. 8 – Trade-off between regional agricultural deficits. Coloured boxes highlight the location of selected policies. This shows how less than optimal agricultural deficits in some regions must be accepted in order to achieve high performance (green, red, blue) or the example compromise rule set (grey). (For interpretation of the references to color in this legend, the reader is referred to the web version of the article.)

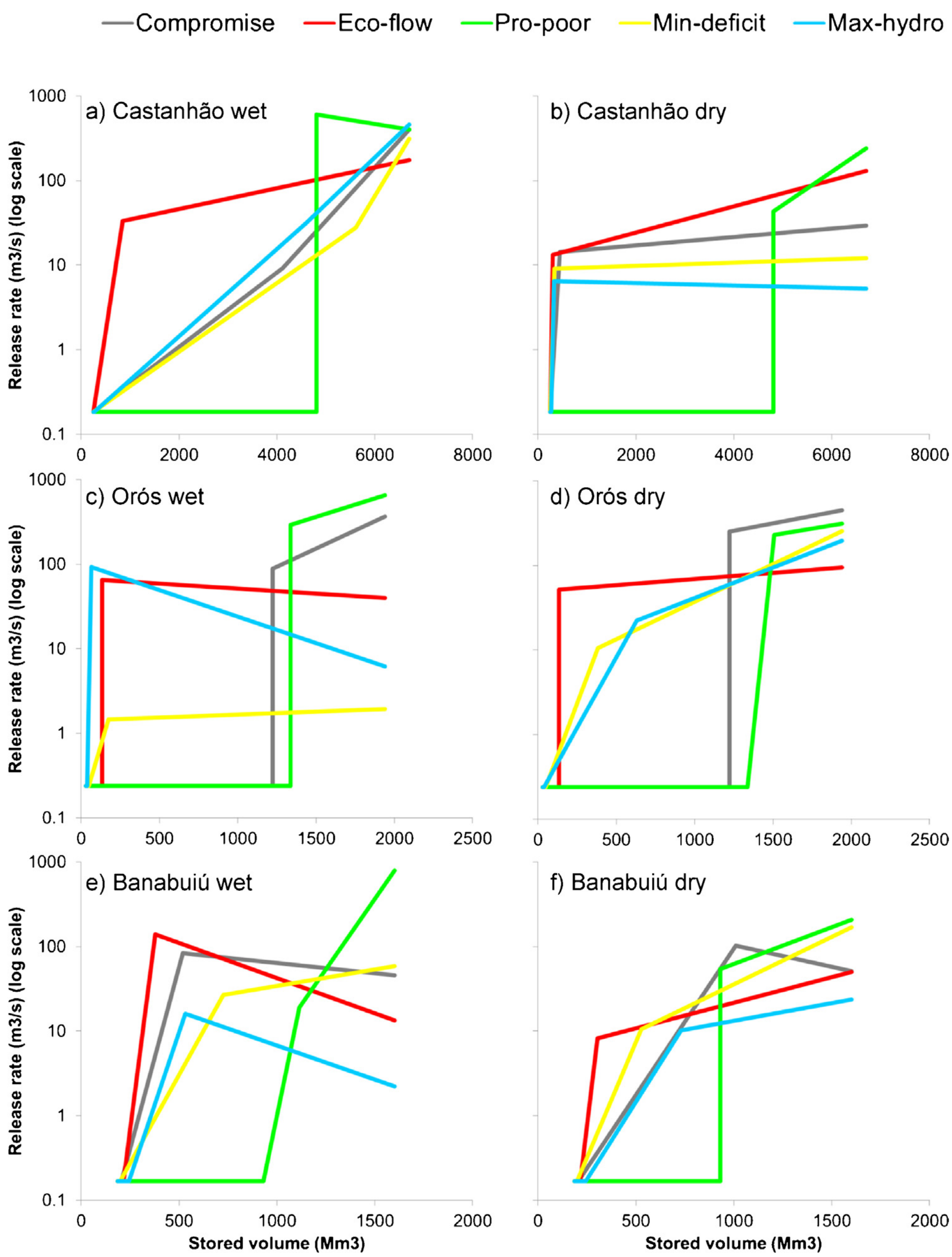

Fig. 9 – Seasonal release rule sets for each reservoir (NB: *x*-axis changes according to reservoir storage capacity).

images of each other – Pro-poor favours retention while Eco-flow favours release. These points also lie at opposite ends of the trade-off surface (Fig. 6). Other policies balance or mimic the two extremes, to varying degrees, seasonally to achieve their respective high or balanced performance.

4.9. *Flow alteration*

Examining flow frequency curves (Fig. 10) resulting from each selected release rule set helps understand flow alteration metric optimisation. Fig. 10 shows how different regions of the unregulated curve are affected by particular release rule sets. These plots help decide how far regulated flows should be allowed to stray from unregulated (natural) flows. The gap between regulated and unregulated curves in the wet season (Fig. 10(a)) represents the volume stored – it is not possible to achieve natural flow conditions and at the same time store water. Regulated flows are closer to the natural regime in the dry season (Fig. 10(b)) as the flows are an order of magnitude lower than in the wet season. Less water needs to be released to meet these flows, with less impact on storage.

Further data pertaining to the requirements for maintaining perennial flows would allow constraining the optimisation within particular limits.

4.10. *Comparing optimised to current operation*

Comparison of optimised solutions with observed reservoir releases is limited by the fact that the reservoirs were built at

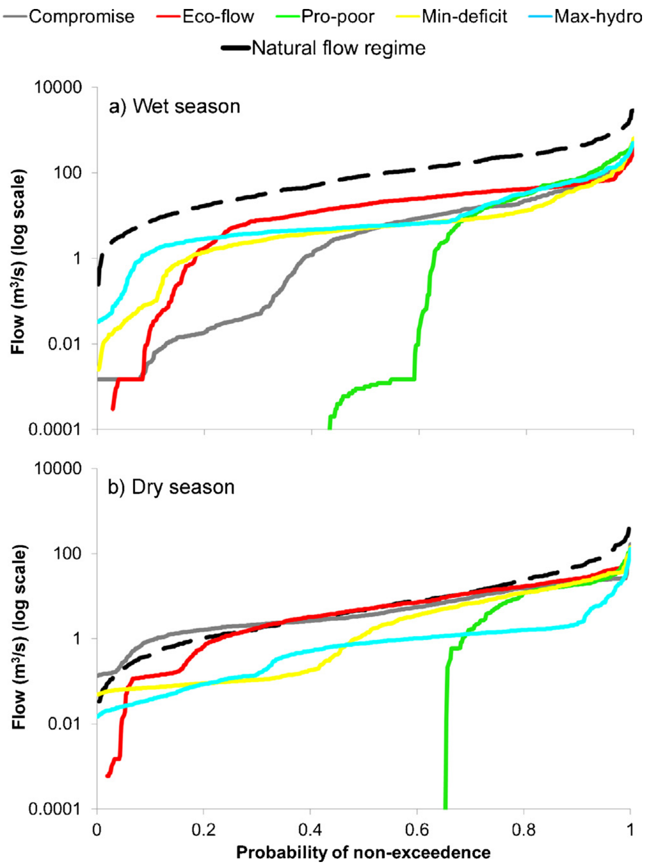

Fig. 10 – Unregulated (natural) basin outlet flow frequency curve compared to results of selected release rule sets. Flow frequency curves provide the probability that a given flow will not be exceeded. Flow is zero where lines do not contact the y-axis.

different times. There are only 7 years of observed conditions when all reservoirs are active and have accomplished their fill-up period. Inflow data were not available to us for modelling this period, so it is not possible to account for the hydrological validity of the comparisons made here. Nevertheless Fig. 11 shows marked differences between reservoir storages implied by the example optimised release rule set and observed storages resulting from both recent negotiated releases and those before the construction of the Castanhão reservoir.

Comparison of observed dry season release data for 1998–2010 (Orós and Banabuiú) and 2002–2010 (Castanhão), with dry season releases resulting from the optimised Compromise release rule set shows the Castanhão releases are similar although greater for the optimised rules, but substantial differences are apparent between releases for the other two reservoirs – release rates varying more widely with the optimised rules. The same example optimised rules increase median land availability performance over that calculated from observed reservoir levels by 25%.

5. Discussion

The rich information revealed by visual analytic plots of Pareto-optimal solutions allows stakeholders to understand environmental management conflicts in an intuitive way. Considering many benefits in a single visualisation helps maintain a broad perspective in comparing policies. It is more difficult to ignore the benefits available to poor and marginalised groups when they are explicitly represented alongside traditional measures of economic performance. We hypothesise that this type of information lends itself well to group decision-making such as that currently used in the Jaguaribe basin and could supplement current analysis outputs considered during reservoir release negotiation.

We have shown how performance varies across the Pareto-optimal surfaces for different objectives. We considered the details of high level trade-offs with aggregated metrics and showed for example the implications for reservoir levels and seasonal flow regimes (Figs. 7 and 10). Once a decision is made about the balance between benefits, the approach quickly can provide information about the policy (release rule set in our case) required to achieve the selected balance.

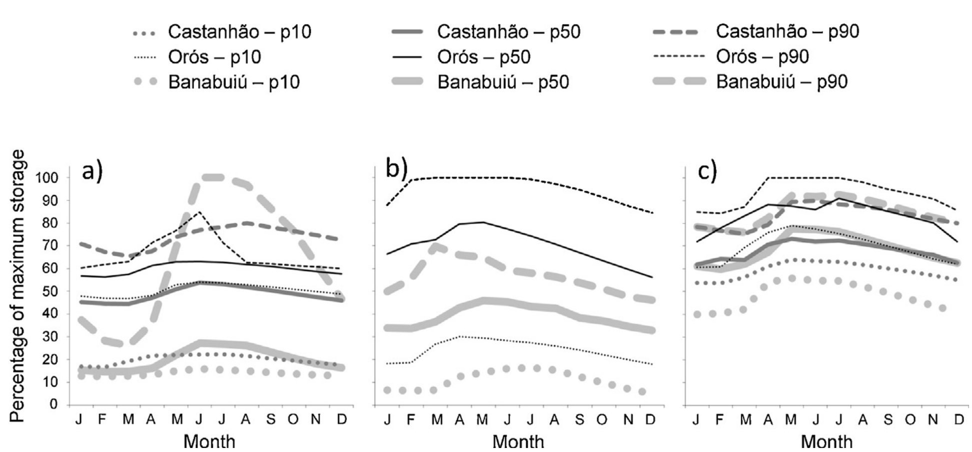

Fig. 11 – Reservoir storages for (a) the optimised compromise release rule set simulated using 1911–2000 flows, (b) the 1968–2004 observed Orós and Banabuiú reservoirs pre-Castanhão construction, and (c) and observed 2004–2011 reservoir storages. Storages (b) and (c) show the impact of the Castanhão reservoir construction and also suggest different priorities in management than those represented in (a).

It is important when optimising to carefully consider the spatial and temporal resolution of objective functions. This can help avoid compensation effects whereby one region or time period has high benefits to "subsidise" low benefits in other regions or time periods. This may or may not be acceptable in real management decisions and is the reason for using seasonal flow alteration and regional agricultural deficit metrics. Even so, we see compensation effects in the example Compromise policy; agricultural deficit in the Oros region is allowed to be high at times to keep Oros reservoir water levels high to enhance fisheries and land availability there. In this case the disaggregated trade-off (Fig. 8) can be used to help apportion deficits between the four regions.

Current releases appear from Fig. 11 and additional analysis to be more conservative than the example optimised releases generated by us, favouring storage over release. Available release data (COGERH, 2011) suggest that releases are often lower than those agreed to during negotiations. The reasons for this are unclear, but regional water manager risk-aversion could be a factor. It is also possible that the 7-year period is insufficient to compare optimised and current management owing to lack of sufficient hydrological variability in that period. Land availability increases suggest optimised rules can simultaneously increase benefits dependent on both storage and release.

Demonstrating the advantages of Pareto-optimal solutions may be difficult in developing country contexts where data are scarce against which to either calibrate and verify models or to compare benefits. We hypothesise that stakeholders who trust the environmental system simulator and who develop their own benefit functions in shared vision modelling approaches are more likely to support the balanced solutions output by our approach. The case study described here is deterministic; an explicitly stochastic analysis may be more appropriate for management where climate change impacts are relevant over the time-scale considered in the decisions.

6. Conclusions

We have applied a multi-criteria framework for optimising the management of a shared resource system explicitly considering the benefits of multiple groups including livelihood objectives. The framework links a water management simulator to a many-objective optimisation algorithm. Because the system simulator outputs several performance metrics the end result is not a single prescriptive 'optimal solution' but rather a diverse set of (approximately) Pareto-optimal reservoir operation policies where each solution is 'best' given a unique set of preferences. No 'weights' or 'priorities' must be elicited *a priori* from users of this approach; the approach is an *a posteriori* one which results in Pareto-optimal trade-off curves or surfaces which encapsulate the trade-offs implicit in the best performing decisions. Water managers can assess policies and their impacts without having to decide and declare how much they value the different metrics of performance. This is important in environmental management 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*.

The generated trade-off curves or surfaces are comprised of individual Pareto-optimal points which represent the modelled performance of one operating policy (in our case study: wet and dry season rules for each of the 3 reservoirs). The trade-offs are displayed using visual analytic tools that allow interactive exploration of solutions by stakeholders.

This approach was applied to a reservoir management problem in NE Brazil. In that system 3 reservoirs are managed to support local municipal demand, agriculture, aquaculture and industry as well as an inter-basin transfer to a growing metropolis. Groups of poor farmers and fishermen are marginalised in the current negotiated release process. Using plots of reservoir storage levels and flow frequency we illustrated the real world effects of different optimised reservoir release rule policies. We hypothesized that benefits to marginalised social groups are less likely to be neglected if they are plotted in trade-off curves alongside traditional measures such as irrigated agricultural and hydropower production. Many-objective optimisation supported by advanced visualisation can help diverse groups of stakeholders select consensual policies for complex shared environmental resource systems.

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Appendix A

This appendix details the mathematical optimisation formulation and objective functions used for optimisation, as described in Section 3.3.2 and Table 1.

A.1. *Optimisation formulation*

$$\begin{aligned} &F(x) = (f_{\text{losses}}, f_{\text{hydro}}, f_{\text{fish}}, f_{\text{land}}, f^{J}_{\text{agr}}, f^{S}_{\text{flow}}) \\ &\forall x \in \Omega \\ &x = (X^{s}_{i}) \end{aligned} \quad \text{(A.1)}$$

where j is a supply region and $\boldsymbol{j}, \in \{$**Orós**, **Castanhão**, **Banabuiú**, **Lower Jaguaribe**$\}$, s is a season and $\mathbf{s} \in \{$**wet season**, **dry season**$\}$, i is a reservoir and i ∈ Orós, Castanhão, Banabuiú.

$\mathbf{X^S_i}$ represents a reservoir i's release rule during season s.

The decision variables being optimised are individual reservoir release rules, where $\mathbf{X^S_i}$ represents reservoir i's release rule during season s for each of the 3 large regional reservoirs.

A.2. Losses objective

$$\text{Minimise} \quad f_{\text{losses}} = \frac{1}{Y}\sum_{y=1}^{Y}\left(\sum_{j} Spill_y^j + \sum_{i} Evap_y^i\right) \qquad (A.2)$$
$$i \in \{\text{Orós}, \text{Castanhão}, \text{Banabuiú}\}$$
$$j \in \{\text{Castanhão}, \text{Banabuiú}\}$$

where y is the year in the time horizon, Y is the total number of simulated years, i and j are reservoirs, $\boldsymbol{Evap_y^i}$ represents the evaporative losses from reservoir i in year y, and $\boldsymbol{Spill_y^j}$ represents spills from reservoir j during year y.

A.3. Hydropower deficit objective

$$\text{Minimize} \quad f_{\text{hydro}} = \frac{1}{Y}\sum_{y=1}^{Y} HDM_y \qquad (A.3)$$

where HDM_y is the number of months in year y when there is the hydropower deficit.

A.4. Fisheries deficit objective

$$\text{Minimize} \quad f_{\text{fish}} = \frac{1}{Y}\sum_{y=1}^{Y} FUM_y \qquad (A.4)$$

where FUM_y is the number of months in year y when the fisheries underperform.

A.5. Land availability objective

$$\text{Minimize} \quad f_{\text{land}} = \frac{1}{Y}\sum_{y=1}^{Y}\sum_{i} AL_y^i \qquad (A.5)$$

where $\boldsymbol{AL_y^i}$ is the available land in the floodplain of reservoir i in year y.

A.6. Agricultural deficit objective

$$\text{Minimize} \quad f_{\text{agr}}^j = \frac{1}{Y}\sum_{y=1}^{Y} AD_y^j \qquad (A.6)$$

where $\boldsymbol{AD_y^j}$ is the deficit in supply region j in year y. An additional aggregated metric – the sum of regional agricultural deficits at each timestep – is not itself optimised, but is used for analysis unless explicitly stated otherwise.

A.7. Flow alteration objective

$$\text{Minimized} \quad f_{\text{flow}}^s = -\sum_{d}\left(1 - \frac{\sum_{t=1}^{TD}(FFC_t^u - FFC_t^r)^2}{\sum_{t=1}^{TD}(FFC_t^u - \overline{FFC}_d^u)^2}\right)_d^s \qquad (A.7)$$
$$d = \{1, 2, 3, 4, 5, 6, 7, 8, 9, 10\}$$

where d is a decile of the flow frequency curve, t is a timestep, TD is the total number of timesteps within decile $\boldsymbol{d}$, $\boldsymbol{FFC_t^u}$ represents the unregulated flow frequency curve value for timestep $\boldsymbol{t}$, $\boldsymbol{FFC_t^r}$ represents the regulated flow frequency curve value for timestep t and $\boldsymbol{\overline{FFC}_d^u}$ is the mean value of unregulated flow frequency curve in d. s represents a season, *i.e.* the flow alteration is calculated separately for each season. An additional aggregated metric – the sum of seasonal flow alterations – is not itself optimised, but is used for analysis unless explicitly stated otherwise.

Appendix B. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.envsci.2013.10.003. Supplementary data consist of 3D animations of Figure 4 and Figure 5c to provide a clearer understanding of the trade-offs across the surface.

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