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Screening reservoir systems by considering the efficient trade-offs—informing infrastructure investment decisions on the Blue Nile

Robel T Geressu[1,2] and Julien J Harou[2,1,3]

1   Department of Civil, Environmental and Geomatic Engineering, University College London, Chadwick Building, Gower Street, London, WC1E 6BT, UK
2   School of Mechanical, Aerospace and Civil Engineering, The University of Manchester George Begg Building, Sackville Street, Manchester, M13 9PL, UK
3   Author to whom any correspondence should be addressed.

E-mail: robel.geressu.12@ucl.ac.uk and julien.harou@manchester.ac.uk

Abstract

Multi-reservoir system planners should consider how new dams impact downstream reservoirs and the potential contribution of each component to coordinated management. We propose an optimized multi-criteria screening approach to identify best performing designs, i.e., the selection, size and operating rules of new reservoirs within multi-reservoir systems. Reservoir release operating rules and storage sizes are optimized concurrently for each separate infrastructure design under consideration. Outputs reveal system trade-offs using multi-dimensional scatter plots where each point represents an approximately Pareto-optimal design. The method is applied to proposed Blue Nile River reservoirs in Ethiopia, where trade-offs between total and firm energy output, aggregate storage and downstream irrigation and energy provision for the best performing designs are evaluated. This proof-of concept study shows that recommended Blue Nile system designs would depend on whether monthly firm energy or annual energy is prioritized. 39 TWh/yr of energy potential is available from the proposed Blue Nile reservoirs. The results show that depending on the amount of energy deemed sufficient, the current maximum capacities of the planned reservoirs could be larger than they need to be. The method can also be used to inform which of the proposed reservoir type and their storage sizes would allow for the highest downstream benefits to Sudan in different objectives of upstream operating objectives (i.e., operated to maximize either average annual energy or firm energy). The proposed approach identifies the most promising system designs, reveals how they imply different trade-offs between metrics of system performance, and helps system planners asses the sensitivity of overall performance to the design parameters of component reservoirs.

1. Introduction

Sufficient and reliable energy supplies are a prerequisite for attracting investments and bolstering local industry in developing countries (Dunkerley and Ramsay 1982, Bartle 2002, Javadi *et al* 2013, Kenfack *et al* 2014, Zhu *et al* 2014). Many developing countries are ill-equipped to meet growing energy demands and suffer from frequent service interruptions (Pode 2013, Alfaro and Miller 2014, Dugoua and Urpelainen 2014). Energy security is therefore at the forefront of development agendas of many governments who, despite the high initial capital cost, would like to investigate future hydropower investments (Bartle 2002, Kaygusuz 2004, Arsano and Tamrat 2005, Porrua *et al* 2009). New reservoirs are frequently challenged however for their high costs (Ansar *et al* 2014) or inappropriately balanced benefits (Bird and Wallace 2001, Sneddon and Fox 2008). Many researchers have focused on how to operate hydropower reservoirs to meet multiple objectives including ecological ones (e.g., Petersson

et al 2007, Jager and Smith 2008, Renofalt *et al* 2010, Mirumachi and Torriti 2012). In this paper we focus on the design and operation of reservoir systems to meet multiple conflicting societal objectives.

Various methods have been used for designing cost-effective reservoir system interventions in the last decades. Klemes (1979), Lall and Miller (1988), Eastman and Revelle (1973) contributed early methods for design of single purpose standalone reservoirs. Often reservoirs are planned jointly so multi-reservoir system design, i.e., identifying the combinations of reservoirs, their capacities and operating rules, should maximize overall system performance and meet different requirements. This task is difficult to handle with conventional simulation modeling because invariably too many possible combinations of assets and their coordinated operation rules need to be considered (Khaliquzzaman and Chander 1997). This led researchers early on to attempt using optimization to search for good multi-reservoir system designs (Houck and Cohon 1978, Lall and Miller 1988, Sinha and Bischof 1998). Stedinger *et al* (1983) reviews different early optimization-based screening models.

The above-mentioned studies design for a single system objective whereas real multi-reservoir systems seek to maximize reliable and total energy output whilst considering other needs such as flood prevention, minimizing water losses and other downstream impacts. Ko *et al* (1992) proposed multi-reservoir system design optimization considering multiple objectives. That study and others like it use linear programing which requires significant simplification for large water resource systems or nonlinear programming that may be unreliable at achieving global optima (Yeh 1985, Labadie 2004). Labadie (2004) and Rogers and Fiering (1986) cite lack of confidence in the assumptions and structure of many water resource optimization models for their relatively modest real-world use. Some authors opine that operating rules should be expressed such that they are usable by operators who have limited foresight of the future (Li *et al* 2014).

Water resources problem formulations can lead to models with non-convex and/or discontinuous functions which are difficult to handle with traditional mathematical programming methods (Labadie 2004). Approaches that link simulation models with heuristic global search methods such as evolutionary algorithms (Deb *et al* 2002, Coello 2007) are well suited to handle nonlinearity associated with operating rule design (Thorne *et al* 2003, Sechi and Sulis 2009, Vamvakeridou-Lyroudia *et al* 2010, Hurford and Harou 2014). Evolutionary algorithms have been demonstrated to be effective for water resources optimization involving non-convex and discontinuous functions (Castelletti *et al* 2008, Nicklow *et al* 2010, Reed *et al* 2012, 2013, Maier *et al* 2014). Anghileri *et al* (2013), Arena *et al* (2010) and Giuliani *et al* (2014) used multi objective evolutionary algorithms to refine operating policies of reservoir systems. Matrosov *et al* (2015) reveal Pareto-approximate portfolios of infrastructure and demand management options but assume pre-set operating rules.

Multi-reservoir system design should consider the potential for coordinated operation of reservoirs. Mortazavi *et al* (2013) identify the failure to optimize operating rules jointly with infrastructure options as a limitation of existing design methods. The approach proposed here screens designs by considering the interdependency of infrastructure and its operation. We do this by simultaneously optimizing asset selection, size (capacity) and reservoir operating rules to balance multiple objectives. The method suggests the required increase in reservoir capacities for gaining particular increases in benefits (i.e., energy, reliability, irrigation water supply). The approach fulfils decision-makers' desire to see the critical factors that affect various objectives. In transboundary systems where full coordination may not be feasible, selecting designs that lead to acceptable downstream benefits while being operated to maximize upstream benefits is desirable.

The proposed approach is applied to suggest which combinations of new Ethiopian Blue Nile reservoirs, are most efficient and what the relevant trade-offs between system goals are. 'Efficient' is used in a Pareto-optimality sense (the set of solutions which cannot be further improved in any one metric without simultaneously reducing performance in others) rather than a monetized sense where multiple performance objectives would need to be commensurable. The approach proposed in this paper is a 'weightless' multi-criteria approach. This approach is an '*aposteriori*' or generate-first-choose-later approach (Herman *et al* 2014), where there is no need to provide weights or priorities for objectives *apriori*. The multi-objective optimization approach works for any number of objectives, typically up to 10, (Nicklow *et al* 2010, Reed *et al* 2013) which can be monetary or not. We optimize proposed upstream Blue Nile multi-reservoir system design considering Ethiopian hydropower and storage size of reservoirs. We show that specific groupings of reservoirs perform better in firm and/or total annual energy than individual reservoirs for similar aggregate storage size. Impacts of optimized infrastructure choices on downstream assets are demonstrated via visual analytic trade-off scatter plots which help explore and understand the information contained in Pareto-approximate solution sets (Vitiello *et al* 2012, Fu *et al* 2013, Reed and Kollat 2013).

The next section describes the case-study context and is followed by a description of the problem formulation. These are followed by results, discussion and conclusion sections.

2. The Nile context

The Blue Nile is one of the largest basins in Ethiopia, covering 35% of its land mass. The narrow gorges in the upper part of the Blue Nile harbor large hydropower potential. However because of disputes in water use rights in the Nile basin and lack of capacity for Ethiopia to self-finance the large projects (Amer *et al* 2005, Arsano and Tamrat 2005, Cascao 2008) the basin remains under-developed.

In Sudan, two multipurpose dams are used to serve three large irrigation sites and generate hydropower. The river is highly seasonal and annually variable (Block and Rajagopalan 2007) with frequent flooding and occasional droughts. Goor *et al* (2010) argue implementation of the proposed hydropower reservoirs in Ethiopia and consequent regulation of the flow could boost irrigation production and hydropower in Sudan. Regardless, in the Nile basin as a whole, there is concern about the potential impacts of new upstream storage (Swain 2011).

The Grand Ethiopian Renaissance dam currently under construction is located downstream of all of the other potential dam sites in Ethiopia (see figure 1). The dam if fully completed as planned with 6000 MW installed capacity, would impound a 62 BCM (Billion cubic meters) reservoir which will have a full supply level of 640 masl (meters above sea level). This reservoir, referred to in this study as GERD, would inundate the site of the proposed Mandaya dam, but would still allow an alternative reservoir named 'Upper Mandaya'. A smaller design with 620 masl full supply level (see table 1) at the site of GERD, which we will refer to as Border dam, would allow the implementation of Mandaya dam. Further upstream, the Beko Abo High can be implemented instead of the most upstream proposed dam site, Karadobi, or the smallest of the proposed dams, Beko Abo Low, could simultaneously exist with Karadobi. The Border dam design is not actively being considered (Jeuland and Whittington 2014) but it is included here to demonstrate the proposed approach. Mutually exclusive reservoir designs are given in table 1.

The Blue Nile reservoirs would provide benefits through regulation of the river for irrigation purposes (Goor *et al* 2010) and by providing energy (Whittington *et al* 2014). This study contributes to the Blue Nile infrastructure literature by exploring what combinations of new Ethiopian reservoirs, their storage sizes and

operating rules, would perform best considering several performance metrics. We also investigate what new reservoir system designs, optimized for Ethiopian benefits, would most benefit Sudan irrigation and hydropower interests. The minimization of total Ethiopian storage capacity is included as one of the optimized objectives in an attempt to represent the potential interests of Nile stakeholders wishing to minimize the water and land footprint of the dams. This informs planners about how much hydropower production would be lost in the best case (assuming an optimized system) for historical flows if they were to opt for less stored water.

This study aims to show how impacts of the dam system (including some downstream impacts) depend on design parameters of the Ethiopian dams. The approach is applied to a proof of concept evaluation of proposed Blue Nile reservoirs in Ethiopia. Results of this study are intended to demonstrate the method but not to be taken as prescriptive recommendations.

3. Methods

We employ a heuristic optimization approach where a search algorithm (Kollat and Reed 2006, Reed *et al* 2012) is coupled with a simulation model of the water resources system (Matrosov *et al* 2011). The water system simulation model representing the Blue Nile includes 3 irrigation demand, 9 reservoir node and 16 junction nodes and 13 links representing river reaches. The system model was built using the interactive river-aquifer simulation system 2010 ('IRAS-2010') described by Matrosov *et al* (2011).

3.1. Many-objective optimization formulation
The problem is formulated as a seven-objective optimization problem with 2 existing reservoirs and 7 proposed reservoir designs. The objectives are evaluated by simulating the system monthly using 50 years of monthly historical flow data. The objectives include minimizing the storage size of new infrastructures, maximizing firm monthly and average annual energy generation from the proposed dams and maximizing energy generation and minimizing water supply deficit for irrigation served from the existing 2 reservoir system. Minimizing the number of reservoirs is also included as an objective to consider possible preferences for a simpler system design. Decision variables include the activation of new reservoirs, their

Table 1. Parameters of dam projects.

Reservoir	Mutually exclusive with	MaxStorage (MCM)	Installed capacity (MW)
Beko Abo High	Karadobi, BekoAboLow	31 692	1940
Beko Abo Low	BekoAboHigh	1751	935
Border (FSL 620)	GERD	34 970	2400
GERD (FSL 640)	Border dam	62 930	6000
Karadobi	BekoAboHigh	40 200	1600
Mandaya	UpperMandaya	48 088	2000
Upper Mandaya	Mandaya	27 702	1700

Figure 1. Locations of proposed reservoirs in Ethiopia and existing dams in downstream Sudan.
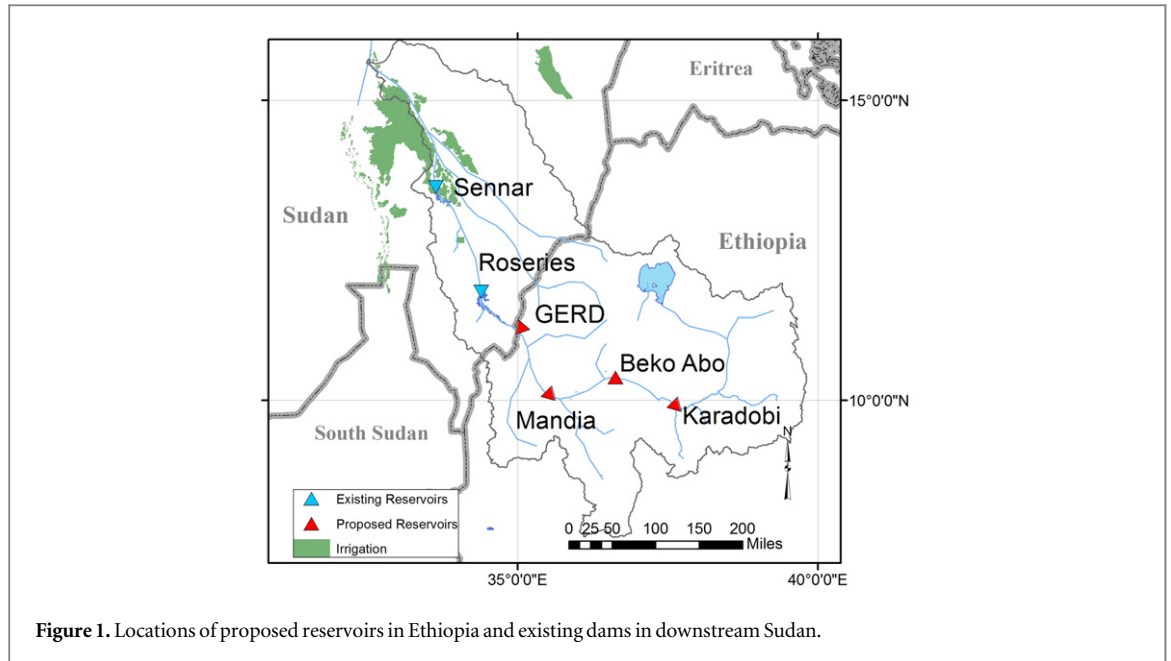
storage capacity and reservoir release rule parameters. The multi objective problem is formulated as:

$$\text{Minimize } F_x = \left(f_{\text{Sc}}, \, -f_{\text{FEE}}, \, -f_{\text{AAE}}, \right.$$
$$\left. -f_{\text{AAS}}, f_{\text{IDS}}, \, -f_{\text{No Re S}} \right) \quad (1)$$
$$\forall \, x \in \Omega,$$
$$X = \left(Y_i, \; \text{Cap}_i, \; \text{Op}_i, \; \text{Op}_j \right), \quad (2)$$
$$Y_i = \{0, \; 1\} \; \forall \, i \in \text{RES}.$$

Subject to $Y_i + Y_k < 2 \; \forall \, i, \; k \in m_t$.

Where RES is the set of all reservoirs given in table 1, while $m_t \subset$ RES are the sets of mutually exclusive designs given in rows in the table.

Where

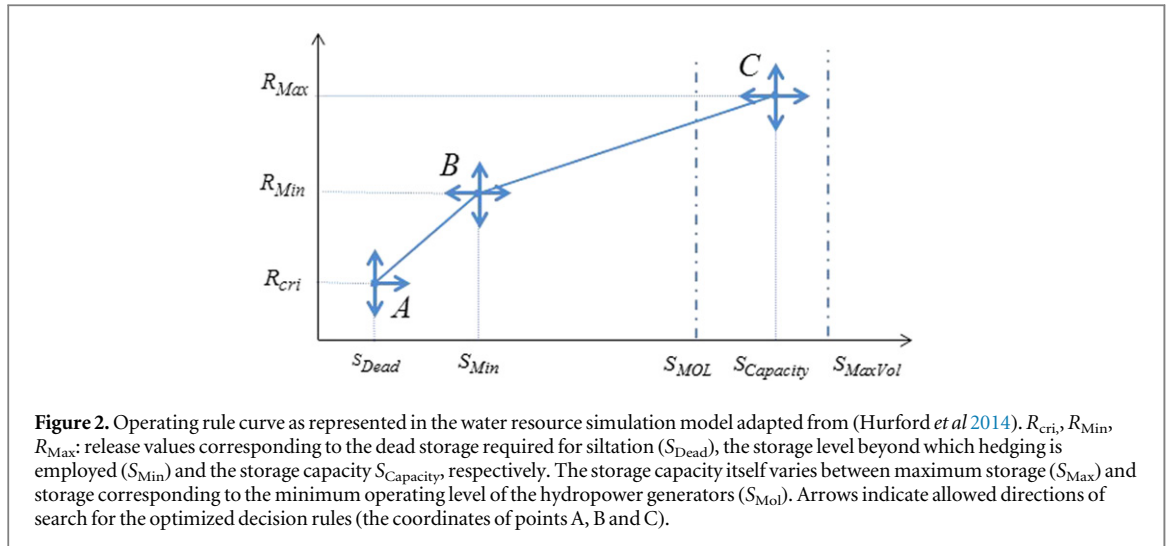|		
F_x	=	Objective function
f_{SC}	=	Aggregate storage capacity of reservoirs in the multi-reservoir system
f_{FEE}	=	Reliability of the energy output, measured as the monthly energy generation exceeded 95% of the time. The objective is to maximize the minimum monthly energy generation from all time steps (months) in the simulation.
f_{AAE}	=	The average annual energy generation from the combined Blue Nile dams in Ethiopia
f_{AAS}	=	Average annual energy generation from the Roseires and Sennar dams combined
f_{IDS}	=	Average annual Irrigation water supply deficit in the Blue Nile schemes in Sudan
f_{NoRes}	=	Number of reservoirs
m_t		Sets of mutually exclusive designs (columns 1 and 2 in table 1) over which logical constraints are set.
i, j		Notations refereeing to proposed and existing dams respectively
Y_i		Decision to activate reservoir i
Cap_i		Storage capacity of reservoir i
Op_i, Op_j		Operation rule parameters of proposed and existing reservoirs respectively

We aim to answer the question, what combinations of assets perform well for the historical flow record. The storage capacity (S_{cap}) varies between maximum storage (S_{Max}) and storage corresponding to the minimum operating level of the hydropower generators (S_{Mol}). The study does not consider the future progression of time, and discounting is not used. The storage size is used as a rough proxy for capital costs.

Because upstream reservoirs alter flow regimes, downstream reservoirs operating rules may need to change if dams are built upstream. With simultaneous design and operating rule optimization, the selection of reservoirs and their release rules are jointly considered by the search algorithm to increase performance. The proposed approach identifies high performing designs of multi-reservoir systems assuming optimally coordinated operations formulated as a piecewise linear curve for each reservoir (figure 2). Reservoir designs where the storage sizes are optimized are compared with those for which the storage sizes are assumed fixed to demonstrate the impact of concurrent optimization in achieving efficient investment portfolios.

3.2. Computational details

The optimization is conducted using a many-objective evolutionary algorithm which have proved popular in water system applications (Labadie 2004, Reed *et al* 2013). We employ the Epsilon-Dominance Non-dominated Sorted Genetic Algorithm II (Kollat and Reed 2006, Tang *et al* 2006) linked to the water impact model via a wrapper code.

The ε-NSGAII generates its initial random population of decision variables by exploiting uniform random sampling within the user specified ranges. These

Figure 2. Operating rule curve as represented in the water resource simulation model adapted from (Hurford *et al* 2014). R_{cri}, R_{Min}, R_{Max}: release values corresponding to the dead storage required for siltation (S_{Dead}), the storage level beyond which hedging is employed (S_{Min}) and the storage capacity $S_{Capacity}$, respectively. The storage capacity itself varies between maximum storage (S_{Max}) and storage corresponding to the minimum operating level of the hydropower generators (S_{Mol}). Arrows indicate allowed directions of search for the optimized decision rules (the coordinates of points A, B and C).

variables are then passed as input variables to the water resources simulator which evaluates the performance of the system. The performance information is passed back to the ε-NSGAII algorithm which evaluates the fitness of the decision variables to produce the next generation of decision variables. We ran the algorithm (parameters given in table A1) for 50 000 function evaluations based on a visual assessment convergence and time-varying diversity of the evolving solutions. To ensure the final solutions are not influenced by the randomly generated initial populations we ran the algorithm 5 times with different seed values. The results from each run are then sorted together to provide the best overall reference set (Kollat *et al* 2008). The proposed multi-objective system design analysis provides Pareto-approximate sets of designs for which no objective can be further improved without deterioration in at least one other objective (Reed *et al* 2012) (i.e., the 'non-dominated' set of infrastructure portfolios). Heuristic search results cannot be mathematically proven to be Pareto-optimal hence the term 'Pareto-approximate' (Datta *et al* 2008). Visual analytic trade-off plots (Vitiello *et al* 2012, Reed and Kollat 2013) are used to present the results.

3.3. Data

We use a publicly available database of proposed Blue Nile reservoirs and their characteristics collected by the Nile Basin Initiative (NBI-ENTRO 2015). Water demand patterns assumed for the three irrigation sites served by the Roseires and Sennar reservoirs in the Blue Nile in Sudan are given in figure A1 in the appendix. A 50 year monthly stream flow data set is used to simulate the performance of reservoir designs. Because information on methods used for filling gaps, and estimating ungauged catchments is not accessible (Block and Strzepek 2010, Alan 2012, NBI-ENTRO 2015), results are only indicative and intended to demonstrate the methodology but not to be taken as prescriptive recommendations.

4. Results

Analysis results consist of trade-off curves built of Pareto-approximate designs; each design consists of existing reservoirs and one or more new reservoirs, their storage capacities, and operating rules. The 'efficient' designs cannot be further improved in any dimension without deterioration of at least one other objective (Olenik and Haimes 1979, Mavrotas and Florios 2013).
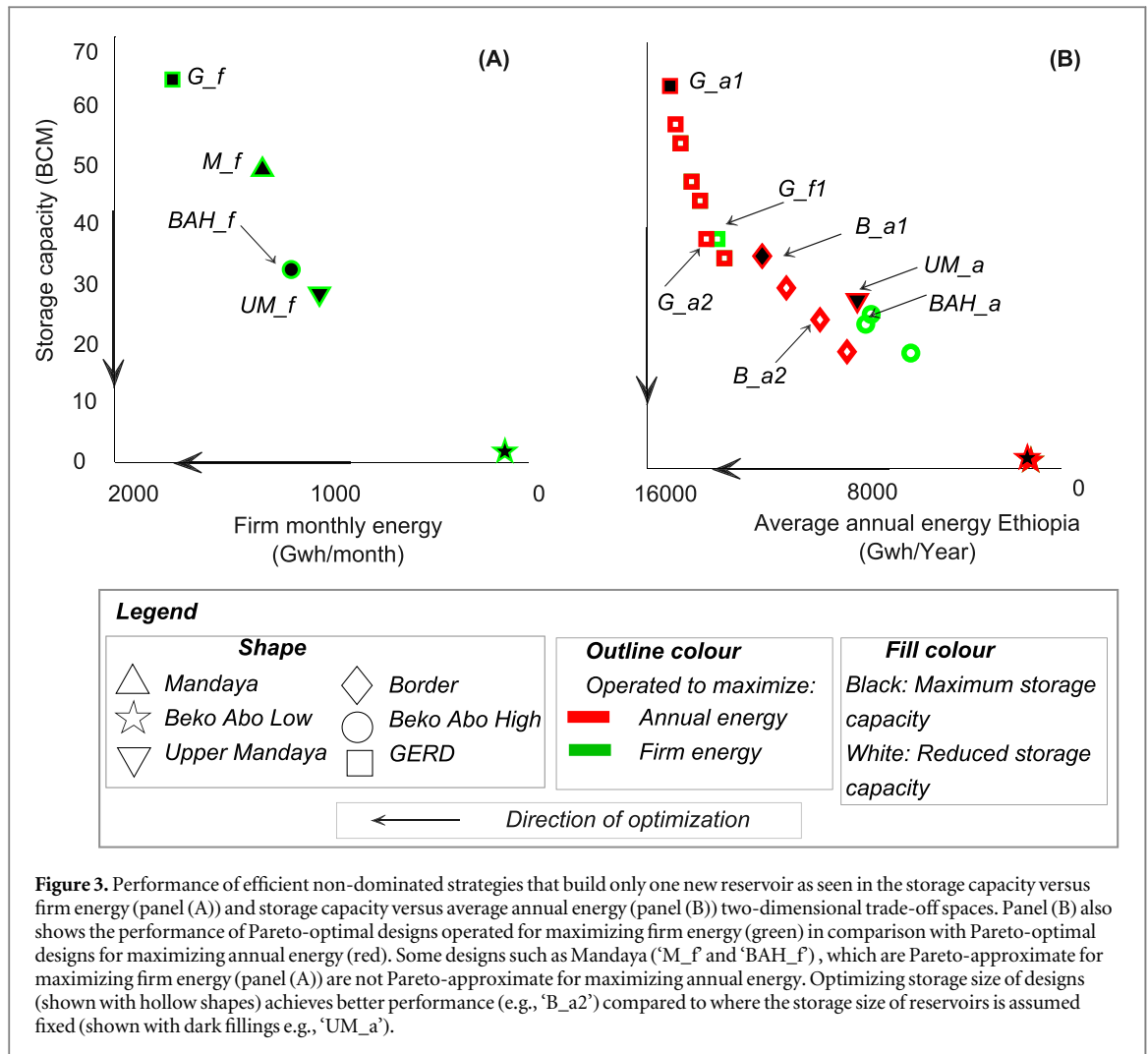
In the following sections, we present non-dominated designs of proposed individual new reservoirs (section 4.1) and of multi-reservoir system designs (4.2) considering multiple performance metrics. Reservoir operating rules for the different Pareto-approximate reservoir configurations are discussed in section 4.3. Finally, section 4.4 investigates the downstream impact of designs that are Pareto-approximate in upstream objectives.

4.1. Single dam strategy

This section presents performance of non-dominated designs of single new dams using different operational strategies, e.g., maximizing average annual energy or firm monthly energy generation.

The points with darkened fills in figure 3 show performance of proposed reservoirs without storage capacity optimization, i.e., $Cap_i = CapMax_i$. For a reservoir with a given storage capacity, operating rule parameters (which are decision variables) can be chosen to maximize the firm energy (panel (A)) at a cost of the average annual energy (red colored shapes in figure 3 panel (B)) and vice-versa.

Panel (B) shows that when operating rule parameters are chosen to maximize annual energy, the GERD works well over a wide range of capacities. Although a GERD design with intermediate storage capacity performs better when maximizing annual energy (in panel (B)), it is inferior to Mandaya and Beko Abo High dam designs (in panel (A)) if the

Figure 3. Performance of efficient non-dominated strategies that build only one new reservoir as seen in the storage capacity versus firm energy (panel (A)) and storage capacity versus average annual energy (panel (B)) two-dimensional trade-off spaces. Panel (B) also shows the performance of Pareto-optimal designs operated for maximizing firm energy (green) in comparison with Pareto-optimal designs for maximizing annual energy (red). Some designs such as Mandaya ('M_f' and 'BAH_f') , which are Pareto-approximate for maximizing firm energy (panel (A)) are not Pareto-approximate for maximizing annual energy. Optimizing storage size of designs (shown with hollow shapes) achieves better performance (e.g., 'B_a2') compared to where the storage size of reservoirs is assumed fixed (shown with dark fillings e.g., 'UM_a').

objective is to maximize firm energy. Therefore, if firm energy is preferred and a storage capacity of 48 or 30 BCM are chosen for other reasons as the upper storage limit, Mandaya and Beko Abo High dam respectively would be better choices than the GERD.
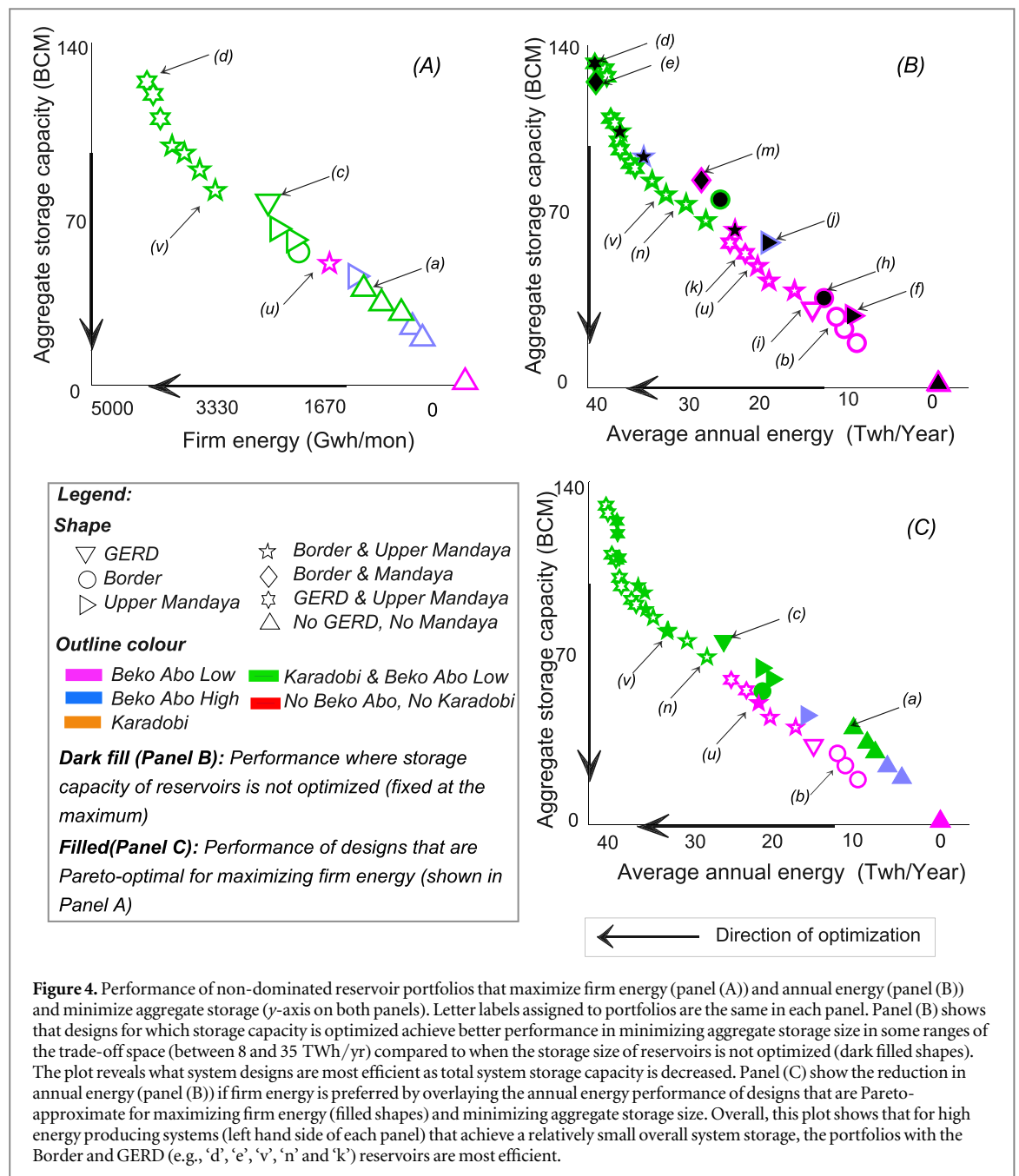
4.2. Multi-reservoir systems

Figure 4 shows designs that include more than one reservoir on the firm energy versus the total combined storage capacity (panel (A)) and energy generation versus total combined storage capacity trade-off (panel (B)).

A 4-reservoir system of GERD, UpperMandaya, Karadobi and Beko Abo Low ('d' in panel (B)) achieve the highest average annual energy generation capacity of more than 39 TWh/yr, an alternative 4-reservoir system with Border dam, Mandaya, Karadobi and Beko Abo Low ('e') being the next largest. Labels 'c' and 'n' in figure 4 show alternative designs recommended (for similar aggregate storage sizes) when maximizing firm energy (label 'c') and for maximizing annual energy (label 'n'). Some portfolios (e.g. designs 'u' and 'v') do well in both annual energy and firm energy whereas other designs (e.g. labeled 'a', 'b, 'c') only do well in one of these.

Stakeholders may prefer reservoir systems with smaller aggregate storage capacity as these would leave lower local environmental footprint and could translate to a lower cost. Fewer reservoirs could also be preferable (e.g. easier to implement, quicker onset of benefits). Pareto approximate portfolios that minimize the number of reservoirs are shown in figure 5.

Figure 5 shows the relationship of the optimal sizes of the alternative Border and GERD dams (circles and squares respectively in panel (B)) with the overall energy generation capacity of the system. The plots show Border dam with reduced storage size is Pareto-approximate in most combinations (lighter circles) that do not constrain the number of reservoirs. The optimal size of the Border dam depends on which upstream reservoirs are implemented, with reductions to its size improving overall performance (i.e., lighter colored circles approach the ideal solution, e.g. 'q', 'x', 'y'). The GERD designs with current storage size (figure 5 label 'o') is dominated by two ('p') or three reservoirs ('q') i.e., with less aggregate storage size and higher energy generation. However, the current design of the GERD (with 100% of its stated storage size) is Pareto-approximate for plans that aim to minimize

Figure 4. Performance of non-dominated reservoir portfolios that maximize firm energy (panel (A)) and annual energy (panel (B)) and minimize aggregate storage (*y*-axis on both panels). Letter labels assigned to portfolios are the same in each panel. Panel (B) shows that designs for which storage capacity is optimized achieve better performance in minimizing aggregate storage size in some ranges of the trade-off space (between 8 and 35 TWh/yr) compared to when the storage size of reservoirs is not optimized (dark filled shapes). The plot reveals what system designs are most efficient as total system storage capacity is decreased. Panel (C) show the reduction in annual energy (panel (B)) if firm energy is preferred by overlaying the annual energy performance of designs that are Pareto-approximate for maximizing firm energy (filled shapes) and minimizing aggregate storage size. Overall, this plot shows that for high energy producing systems (left hand side of each panel) that achieve a relatively small overall system storage, the portfolios with the Border and GERD (e.g., 'd', 'e', 'v', 'n' and 'k') reservoirs are most efficient.

number of reservoirs such as one ('o'), two ('r') and three ('s') reservoir systems.

4.3. Operating rules

In this section we show how optimized reservoir operating rules change depending on system configurations using GERD as an example. Figure 6 panel (A) displays storage and release relationships over the full simulation period for GERD reservoir.

Upstream regulation when reservoirs are added (e.g., Beko Abo High, Upper Mandaya) allows the GERD to function with less variation and a high storage level (green star, orang circle and magenta triangle) compared to the standalone GERD (blue square in figure 6 panel (A)).

Figure 6 panel (B) shows monthly energy generation from GERD for annual energy maximizing operations as a standalone ('o') and in coordinated operation with upstream dams ('r', 's', and 'd' in figure 5). Both the minimum energy that may be required to be guaranteed as firm energy (to be generated close to 95%–100% of the time) and the highest monthly energy (e.g., available only 5% to 20% of the time) are improved with addition of upstream reservoirs.

4.4. Downstream impact of proposed reservoirs

In this section, we investigate the impact of upstream Pareto-approximate designs identified in figure 3 on the Sudanese system. Figure 7 shows the highest
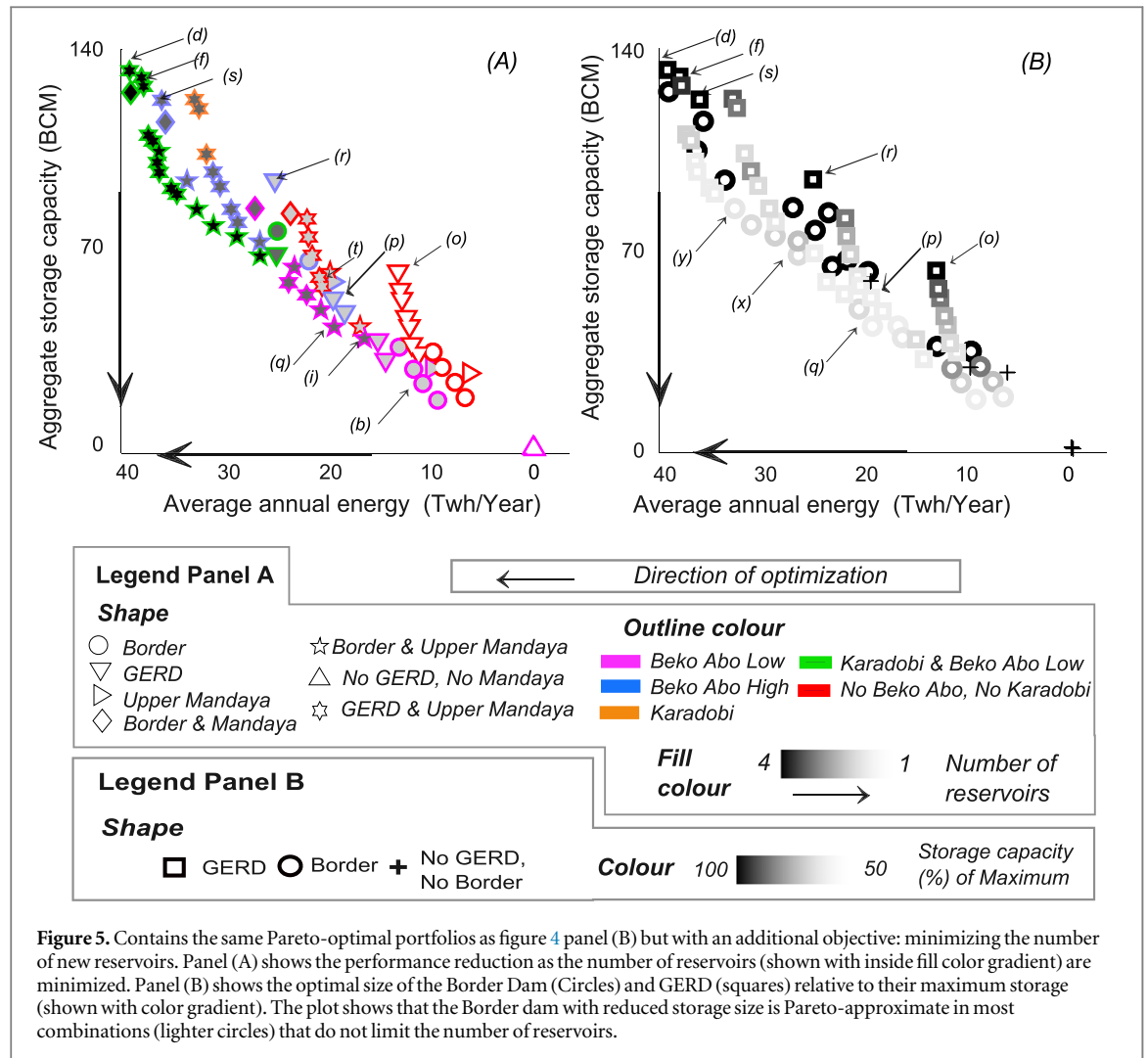
Figure 5. Contains the same Pareto-optimal portfolios as figure 4 panel (B) but with an additional objective: minimizing the number of new reservoirs. Panel (A) shows the performance reduction as the number of reservoirs (shown with inside fill color gradient) are minimized. Panel (B) shows the optimal size of the Border Dam (Circles) and GERD (squares) relative to their maximum storage (shown with color gradient). The plot shows that the Border dam with reduced storage size is Pareto-approximate in most combinations (lighter circles) that do not limit the number of reservoirs.

achievable performance of the two existing Sudanese reservoirs with designs (i.e., reservoirs, storage capacity and operating rules) that are Pareto-approximate for Ethiopian objectives of maximizing firm and annual energy at least storage capacity.
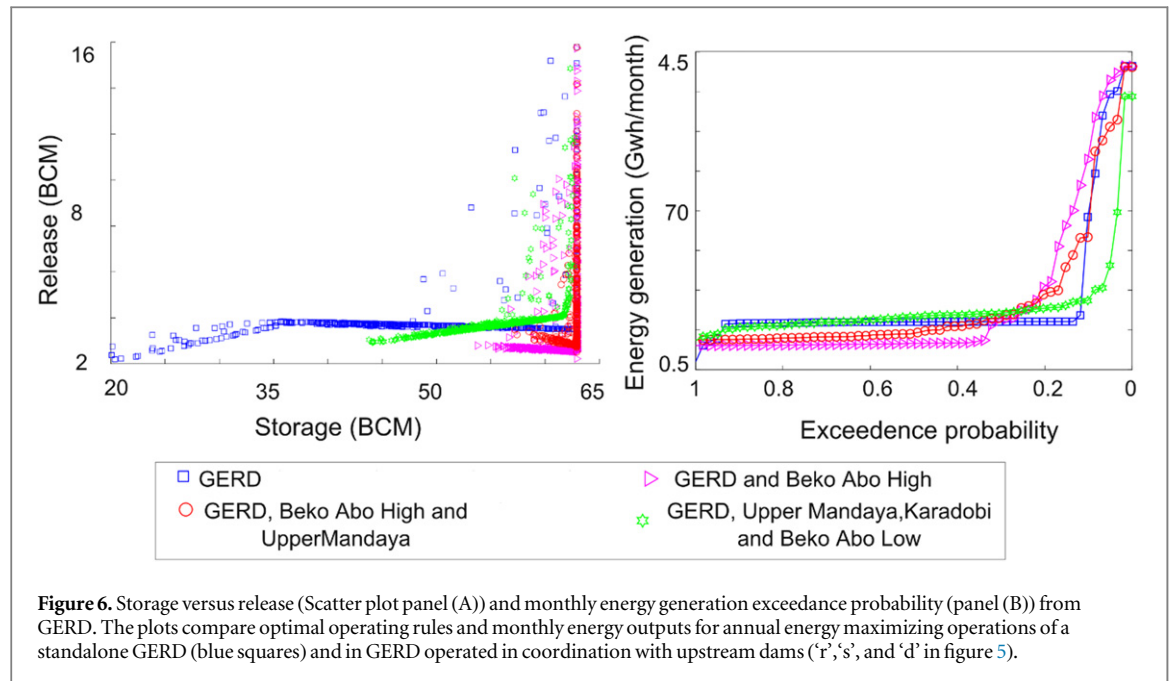
Figure 7 shows the average irrigation water supply deficit for a simulation period of 50 years. Downstream system performance (in Sudan) is affected by what single reservoir is built upstream (shown with shapes), its size (labels) and its operating strategy (color). For each portfolio plotted in figure 7, the operating rules of the two Sudanese reservoirs, Roseires and Sennar, are optimized to adjust to the new hydrologic conditions each upstream system design implies. Although the downstream system performance is improved under most designs, a large storage (shown with % of maximums storage capacity), Mandaya and GERD operated for firm energy (green upright triangle and square respectively near origin) and Upper Mandaya operated to maximize annual energy (red triangle pointing downwards near origin of figure 7) are most favorable to Sudanese system performance.

5. Discussion

5.1. Screening new reservoirs within the Blue Nile multi-reservoir system

A multi-criteria approach to screening proposed new reservoirs within multi-reservoir systems is proposed and applied to the Blue Nile multi-reservoir portfolio design problem. The method reveals the trade-offs in management objectives that the most promising (Pareto-approximate) system designs (incorporating new and existing dams, their sizes and their operating rules) imply. High performing designs which achieve the most efficient trade-offs between conflicting objectives are revealed visually. The mapping of assets in performance space, e.g., figures 3–5, summarize which asset combinations achieve what performance providing valuable insights to system planners.

The results show the combinations of assets that work best together vary throughout the performance space. Figures 3 and 4 were used to assess which subset of designs are Pareto-approximate revealing how certain assets do well under several sets of objectives (e.g. designs 'u' and 'v' in figure 4) whilst others not as well (e.g. design 'a', 'b, 'c in figure 4).

Figure 6. Storage versus release (Scatter plot panel (A)) and monthly energy generation exceedance probability (panel (B)) from GERD. The plots compare optimal operating rules and monthly energy outputs for annual energy maximizing operations of a standalone GERD (blue squares) and in GERD operated in coordination with upstream dams ('r','s', and 'd' in figure 5).

Reliability measures for hydropower systems can be difficult to commensurate with cost and benefit measures. Designs that have the highest average annual and firm monthly energy generating capacity are in general desirable. However, those efficient in maximizing annual energy do not necessarily perform best for maximizing firm energy output. Incorporating energy reliability, a non-monetary metric of interest to system planners, shows how multi-objective analysis helps reveal practical designs with complex combinations of monetary and non-monetary benefits.

Investment costs and costs associated with the downstream impact of projects often are accrued by different stakeholders. Due to ongoing disputes over Nile water use rights, selecting designs on the aggregated net benefits, i.e., total benefits estimated from energy generation, capital costs and costs incurred by downstream users (reduction in benefits due to upstream intervention) may be difficult. In reservoir systems required to meet a number of conflicting objectives held by upstream and downstream system owners, explicit consideration of all major stakeholder objectives help identify potential compromise designs and the trade-offs in benefits these designs imply. Visual assessment of trade-offs can facilitate stakeholder deliberations post optimization, meaning weights are not required as in 'apriori' multi-criteria analysis. Many-objective optimization as shown here allows planners to visually assess important trade-offs where stakeholder preferences are evolving. Learning and exploring about benefits and negative impacts of new investments help different parties assess new designs, compromise on their benefit distribution and hopefully agree upon an acceptable way forward. Considering multiple goals and their trade-offs explicitly
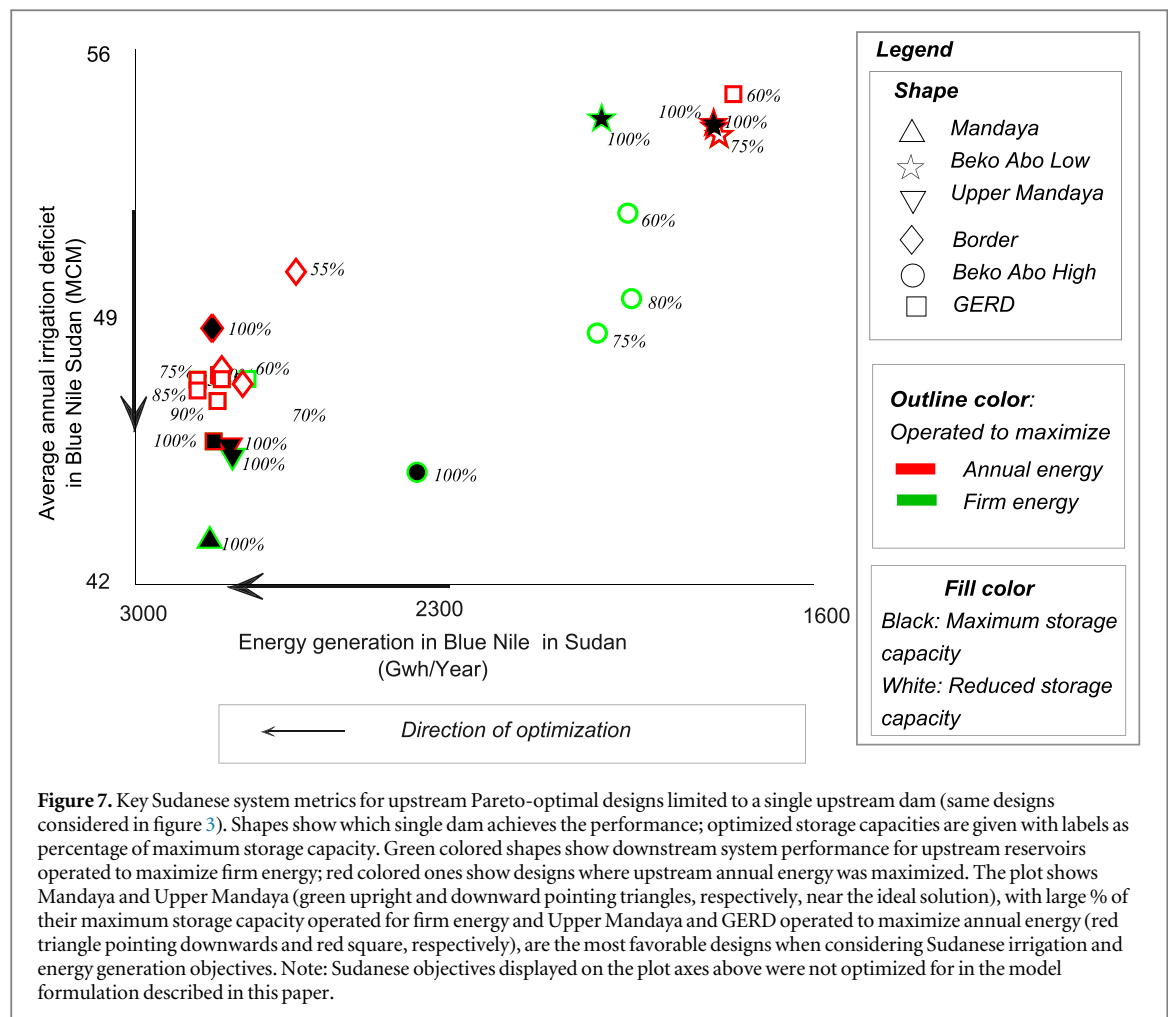
and simultaneously in system planning can provide valuable assistance in the decision making process (Kasprzyk *et al* 2009).

Figure 4 shows jointly optimizing reservoir capacities and operating rules achieves better performing designs than only optimizing the coordination of rules. Figures 5 and 6 demonstrated that optimal storage size and optimal operating rules for a reservoir depend on the portfolio of reservoirs included in any particular design. Plots like figures 5 and 7 that show the performance trade-offs of new dams as their storage capacity is reduced could be of interest to those arguing for larger or smaller reservoirs. Results show assessing new reservoirs considering their coordination with existing and other new assets enables effective screening of new reservoir designs.

5.2. Implications for Blue Nile infrastructure development

Given our current data and modeling assumptions, results argue that multiple reservoirs achieve better results at lower aggregate storage capacity. The current GERD design is not Pareto-approximate for maximizing energy generation for the least storage capacity possible (figure 4 panel (B)) but it is Pareto-approximate with regard to maximizing energy generation while minimizing number of reservoirs (figure 5 panel (A)). GERD only requires one dam to achieve the benefits rather than two or three as the nearby more efficient portfolios do. If several dams could be built at once, it would be advantageous to build a combination of reservoirs rather than a single reservoir with equivalent storage size, if not, GERD is an efficient alternative for the benefits considered in this study.

Storage-size-optimized designs (hollow shapes in figure 4) perform better in energy generation

Figure 7. Key Sudanese system metrics for upstream Pareto-optimal designs limited to a single upstream dam (same designs considered in figure 3). Shapes show which single dam achieves the performance; optimized storage capacities are given with labels as percentage of maximum storage capacity. Green colored shapes show downstream system performance for upstream reservoirs operated to maximize firm energy; red colored ones show designs where upstream annual energy was maximized. The plot shows Mandaya and Upper Mandaya (green upright and downward pointing triangles, respectively, near the ideal solution), with large % of their maximum storage capacity operated for firm energy and Upper Mandaya and GERD operated to maximize annual energy (red triangle pointing downwards and red square, respectively), are the most favorable designs when considering Sudanese irrigation and energy generation objectives. Note: Sudanese objectives displayed on the plot axes above were not optimized for in the model formulation described in this paper.

compared to those at maximum capacity for which only operating rules are optimized (shapes with dark outline in figure 4) in some ranges of the trade-off space. Results show if constructing more than one dam was possible at the same time and Border dam were to be selected, less than its maximal storage would have been efficient up to 35 TWh/yr (e.g., 'v' on panel (B) in figure 4). Outside of this range, the maximum storage size designs of each reservoir are most efficient. Figure 5 panel (B) presents system designs for which storage size of the downstream most reservoirs GERD and Border dam are optimized (shown with color and shape).The maximum storage size of the GERD is efficient in all ranges where the number of reservoirs is purposely limited. Although reducing the storage size of GERD leads to Pareto-approximate designs (e.g., label 'q' in figure 5 panel (B)) at lower ranges of energy generation capacity. This would limit future expansion potential (e.g., 'd','s','r' in figure 5) and performance in designs aiming to minimize the number of reservoirs as it would involve, for example, constructing the GERD and the Beko Abo High ('p') with reduced storage size.

Figure 6 panels (B) shows that the reliability of energy output from the GERD will be improved with addition of upstream reservoirs. Figure 7 showed

downstream irrigation deficits and hydropower production in Sudan given different optimized standalone Ethiopian reservoirs. Sudan's benefits depend on upstream reservoir storage capacities and operations (i.e., whether they maximize firm or total annual energy). Figure 7 showed the Mandaya design would perform better than all alternative single dam designs from the Sudanese perspective including Border dam if it was to be operated for firm energy. The current GERD design performs best if it is to be operated to maximize annual energy. The results also show reducing the storage size of the GERD reduces the irrigation water supply performance. Coordinated multi-purpose operation of Ethiopian reservoirs could potentially further improve performance of the downstream system. However the potential collaborative use of the Ethiopian and Sudanese and other downstream reservoirs is out of scope for this study which limits itself to predicting the best performance achievable in Sudan when the Ethiopian system is operated to either maximize annual or firm energy.

Study assumptions and limitations discussed next strongly impact the results. At it currently stands, the analysis results can be summarized as follows. A four-reservoir system, either with GERD or Border dam, can generate more than 39 TWh/yr. If a total energy

generation capacity of less than 35 TWh/yr is acceptable, Border dam is in the efficient asset mix in lieu of GERD. Although once it has been filled a two-reservoir system (e.g., GERD and Beko Abo High) achieves higher energy production with a lesser aggregate storage capacity than a standalone GERD, the current GERD-only design is the best possible one-reservoir system design given the objectives and assumptions considered in this study. Furthermore, if operated to maximize annual energy, the current GERD design (with 95% to 100% of the proposed storage capacity) enables the highest levels of downstream Sudanese benefits assuming Sudan would change its reservoir operations to adapt to the new upstream development.

5.3. Limitations and future work

Recent papers explore climate change impacts on the economic feasibility of the projects and the impact on the downstream system that filling and operating of these reservoirs entails (Block and Strzepek 2010, Jeuland and Whittington 2014, King and Block 2014). Here our focus was on optimizaing joint operations and investments over the historical period to investigate potentially promising investment portfolios. This study focuses on a trade-off analysis of alternative designs and leaves the consideration of uncertainty of filling periods and the long-term impacts of climate change or other supply/demand changes for future work. The study is deterministic, the assets are evaluated over one hydrological time-series (the historical one) rather than multiple plausible futures. Also, as discussed in section 5.2, this paper does not consider possible inter-country collaboration; all plots maximize benefits from the country where the dams are located (in this case Ethiopia). This study only modeled Blue Nile impacts.

The study assesses the storage size requirements assuming fixed installed power capacities. An aggregate net benefit maximizing objective considering variation in cost and installed power capacities with storage size, peaking power demand and the cost of delay in onset of benefits could provide more decision relevant information. The study uses monthly time steps. The firm energy metric used in this study represents the seasonal and inter annual variation of monthly energy generated. Incorporating other short-term performance metrics such as energy supply reliability considering the daily and hourly demand distribution which are of interest to system planners could reveal more insights on the design problem.

Only benefits along the Blue Nile and for few major irrigation sites in Sudan are considered. The impact/benefit of regulation on other important dams on the Main Nile (Merowe and Aswan) and impacts of Ethiopian dams on Egypt are not assessed in this proof of concept study. The study also ignores possible changes of cropping patterns in Sudan, i.e., the change in magnitude and/or timing of seasonal irrigation demand with the availability of more regulated flow from Ethiopian dams. Finally in this study reservoirs use one operating policy, the standard linear operating policy. The operating rules are assumed to be fixed throughout the time horizon and do not vary when basin conditions change as they might with real operators. More complex rules that change with environmental conditions could likely attain better performance and hence might change the systems designs recommended within this study.

6. Conclusions

Increasingly new reservoirs will be built within existing multi-reservoir systems with significant stakeholder preferences and complex distributions of diverse system benefits. Evaluating future designs based on aggregating all benefits will in many situations not be helpful; it will be more helpful for planners to evaluate various stakeholder defined goals and track the implications of various infrastructure investments on these. A screening method is proposed that simultaneously optimizes the operation and sizing of reservoirs when searching for promising multi-reservoir system configurations. The approach works by linking a water resource system simulator of existing and new reservoirs to a multi-criteria heuristic search optimization algorithm. The approach works for any number of objectives and ideally are defined through repeated consultation with stakeholders and/or decision-makers to ensure appropriate investment criteria are being used. Outputs include the set of approximately Pareto-optimal systems designs which can be viewed in customized scatter plots showing how different objectives trade-off for the most efficient designs and how proposed assets map to performance space. The approach is designed such that it can serve a single organization's planning or potentially aid negotiations on future reservoir development between different stakeholder groups (e.g. upstream and downstream).

The approach is applied to a proof of concept evaluation of proposed Blue Nile reservoirs in Ethiopia. Proposed system designs were obtained via minimizing aggregate storage capacity whilst maximizing monthly firm energy and total energy production. The method was used to identify those Ethiopian reservoirs and their capacities that achieve the greatest firm or total annual energy production at least aggregate system storage. This study could benefit from a more thorough analysis of the impact of the new upstream interventions on the many downstream Nile water uses. The type and number of objectives considered in this study and assumptions are preliminary and changeable.

The proposed approach for screening efficient system designs allows the analyst to present decision makers with a wide range of designs and the trade-offs they imply to inform deliberation.
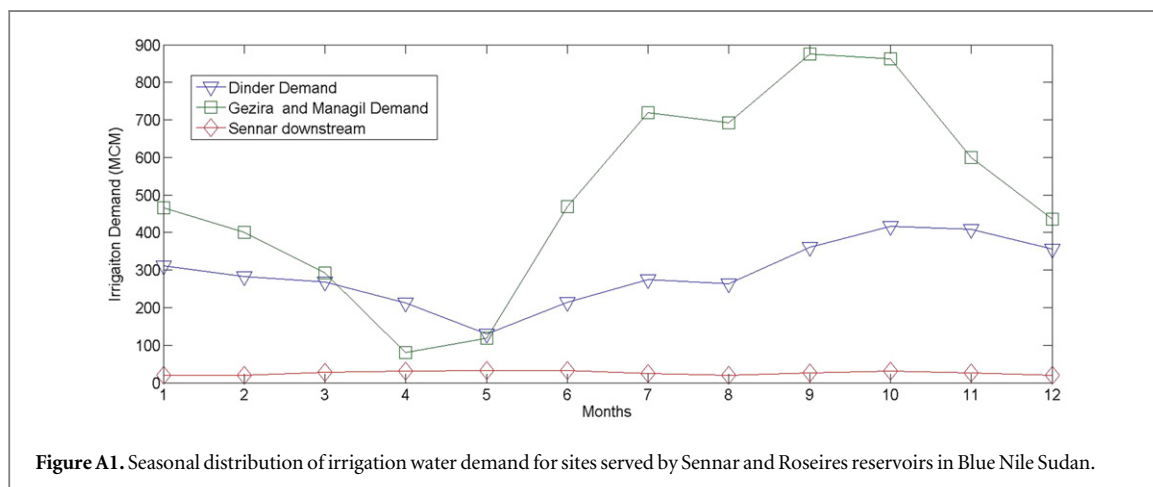
Appendix A

Figure A1. Seasonal distribution of irrigation water demand for sites served by Sennar and Roseires reservoirs in Blue Nile Sudan.

Table A1. Algorithm parameter and objective epsilon values used in the case study.

Algorithm parameters	Value	Objective	Epsilon
Initial population size	24	f_{Sc}	5000
Population scaling factor (for injection)	0.25	f_{FEE}	50
Number of generations per run	250	f_{AAE}	100
Probability of crossover	1.0	f_{AAS}	200
Probability of mutation	0.05	f_{IDS}	5000
Distribution index for SBX crossover	15	f_{NoRes}	1
Distribution index for poly-nomial mutation	20		

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