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Balancing ecosystem services with energy and food security – assessing trade-offs for reservoir operation and irrigation investment in Kenya's Tana basin

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Abstract

Competition for water between key economic sectors and the environment means agreeing on allocation is challenging. Managing releases from the three major dams in Kenya's Tana River basin with its 4.4 million inhabitants, 567 MW of installed hydropower capacity, 33 000 ha of irrigation and ecologically important wetlands and forests is a pertinent example. This research seeks to identify and help decision-makers visualise reservoir management strategies which result in the best possible (Pareto-optimal) allocation of benefits between sectors. Secondly we seek to show how trade-offs between achievable benefits shift with the implementation of new proposed rice, cotton and biofuel irrigation projects. To identify the Pareto-optimal trade-offs we link a water resources management model to a multi-criteria search algorithm. The decisions or "levers" of the management problem are volume dependent release rules for the three major dams and extent of investment in new irrigation schemes. These decisions are optimised for objectives covering provision of water supply and irrigation, energy generation and maintenance of ecosystem services which underpin tourism and local livelihoods. Visual analytic plots allow decision makers to assess multi-reservoir rule-sets by understanding their impacts on different beneficiaries. Results quantify how economic gains from proposed irrigation schemes trade-off against disturbance of the flow regime which supports ecosystem services. Full implementation of the proposed schemes is shown to be Pareto-optimal, but at high environmental and social cost. The clarity and comprehensiveness of "best-case" trade-off analysis is a useful vantage point from which to tackle the interdependence and complexity of water-energy-food "nexus" challenges.

1 Introduction

Dams necessarily interrupt the natural flow regime of rivers to generate their economic gains, causing environmental and potentially social disruption in the area of inundation and downstream (WCD, 2000; Renofalt et al., 2010; McCully, 2001). Traditionally economic approaches are used to suggest efficient water allocation and management policies (Wilson and Carpenter, 1999; Birol et al., 2006; Winpenny, 1994). Concerns have been raised regarding the ability of economics (Sagoff, 2008, 2011; Steele, 2009; Paton and Bryant, 2012; Abson and Termansen, 2011) and cost benefit analysis tools such as "willingness to pay" (Sagoff, 2000) to assign value to non-market ecosystem goods and services or ensure their sustainability.

Many of the world's rural poor rely on ecosystem services provided by environmental resources. Their vulnerability increases and prospects for economic development reduce with degradation of these resources (Malley et al., 2007; Juana et al., 2012; McCully, 2001). Water and poverty are linked (GWP, 2003); increases in access to irrigation for example, can improve circumstances of economically marginalised groups (Lipton and Litchfield, 2003). Storing water for distribution via engineered infrastructure increases access for those served but may reduce access for users downstream of the storage. "Re-operating" existing dams can increase water available to the rural poor and maintain or improve their ecosystem services at little or no cost to other stakeholders (Richter and Thomas, 2007; Watts et al., 2010; Konrad et al., 2012).

Integrated Water Resources Management (IWRM) (GWP, 2000) is the ideal for addressing complex interactions between water resource uses, incorporating social, economic and ecological goals. Merrey et al. (2005) propose IWRM could better support rural livelihoods by taking a broader perspective, developing interdisciplinary models which integrate physical as well as social variables. In some regions there is a strong water-energy-food security "nexus" implying these components must be managed as a system rather than in isolation (Granit et al., 2012). The exclusive search for water security (Grey and Sadoff, 2007), energy security (Yergin, 2006) or food security (Godfray

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et al., 2010) will cause difficulties where these systems are interlinked as progress in one may stifle the others. Achieving "security" across these sectors requires understanding the trade-offs and synergies between them.

At the limits of a water resource system's utilisation, further gains of one benefit can only result from sacrifice of another. Quantified relationships between these gains and sacrifices are known as Pareto-optimal trade-offs (Cohon, 1978). They can be represented graphically by curves (2-D) or surfaces (3-D) – accepted tools of water management (Loucks et al., 2005). Understanding the form of trade-offs between 4 or more objectives (regarded as "many" objectives, Fleming et al., 2005) can alter decision makers' preferences and avoid the selection of "extreme" management policies which can result from considering smaller numbers of objectives (i.e. ignoring real system complexity) (Kollat et al., 2011). Opportunities can be revealed to achieve win-wins where all parties benefit, or large gains for little or no sacrifice (Hurford et al., 2013).

Where classical multi-objective optimisation (Cohon, 1978; Yeh, 1985) struggles to define trade-off relationships with complex forms or between more than two objectives (Shukla et al., 2005), the most advanced multi-objective evolutionary optimisation algorithms (MOEAs) can simultaneously and reliably define trade-offs between 10 or more objectives (Reed et al., 2013). Classical optimisation requires a priori preferences or weights to be declared for the different objectives so that multiple runs must be carried out with varying weights to define a trade-off curve; this is only practical for a small number of objectives. After a single run, MOEAs allow decision makers to assess a posteriori the relative gains and sacrifices associated with a certain decision or set of decisions before selecting a balance between them (Coello et al., 2007). MOEAs can be coupled to external simulators representing complex non-linear systems, such as those already used by stakeholders to plan their own system. They generate discrete solutions which approximate the continuous Pareto-optimal curve or surface. Non-commensurate (e.g. non-monetary) objectives can be optimised, meaning stakeholder-specific benefit functions can be developed without direct reference to monetary value and optimised alongside traditional economic objectives.

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Several authors (e.g. Kasprzyk et al., 2009; Kollat and Reed, 2007) have demonstrated the use of visual analytics for analysis of trade-offs revealed by MOEA optimisation of water resources problems. Non-optimised information can be added to enhance understanding of the optimised policy implications for different stakeholders. Large datasets (1000's of points) can be analysed in a time-efficient manner facilitating more informed decision-making (Kollat and Reed, 2007; Lotov, 2007)

This paper contributes a many-objective visual trade-off analysis for the multi-reservoir hydropower system known as the Seven Forks project on the Tana River in Kenya. Volume dependent reservoir release curves are optimised for eight objectives covering municipal water provision, ecosystem services, and revenues from hydropower and irrigated agriculture. Introduction of proposed irrigation schemes in the Tana's delta provides a novel approach to investigating the impacts of different investment decisions – by assessing their impact on Pareto-optimal trade-offs.

The case study is outlined in the next section, followed by a description of the methodology before results are presented and discussed then conclusions are drawn.

2 Case study

The Tana is Kenya's longest river and most significant hydropower resource (Fig. 1). The river experiences flood peaks in May and November resulting from the long and short rain seasons respectively.

Currently the five hydropower plants of the Seven Forks project in the Tana basin provide around 70 % of Kenya's electricity. Three plants are associated with storage dams – Masinga, Kiamburu and Kiambere. The other two (Gitaru and Kindaruma) are run-of-river plants with pondages upstream of their dams. Masinga and Kiambere reservoirs also provide water for irrigation and municipal demands. The dams have disrupted the flow regime of the river by augmenting low flows, reducing peak flows and reducing the number of days riparian land is flooded (Maingi and Marsh, 2002). Richter et al. (1996) discuss the importance of hydrological factors in maintaining ecological function.

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The Tana River Delta was recently classified as a protected wetland (Ramsar, 2012), requiring consideration of the sustainability of management practices in terms of both the local ecosystems and livelihoods. This wetland has specific requirements for flow variability which amounts to a major demand for water. In the dry season the delta provides high quality grazing land for large numbers of pastoralists constituting a high value ecosystem service (Davies, 2007).

Protected high biodiversity riverine forests upstream of the delta are home to endemic and endangered species of primates (Karere et al., 2004) and rely on regular floods (Hughes, 1990) and low flows (Kinnaird, 1992) to maintain ecosystem health. Documented flow changes will have a negative impact on these forests (Maingi and Marsh, 2002). The natural variability of flows historically replenished nutrients on riparian agricultural lands and in the delta. Sediments deposited lead to beneficial morphological change. These ecosystem services are under threat from alteration of the flow regime (Emerton, 2005; Leauthaud et al., 2013).

Several large irrigation schemes are planned for the Tana Delta including 20 000 ha of sugar cane, 16 500 ha of cotton and 21 600 ha of irrigated rice. If implemented these schemes could threaten current social and ecological functions of the delta and potentially decrease its value as a tourism resource (Mireri et al., 2008).

3 Methodology

A multi-criteria search (optimisation) algorithm is linked to a water resource management simulator of the basin, to define a set of discrete solutions approximating the Pareto-optimal set. The approach is initially used to reveal trade-offs for the current system (no new irrigation schemes). In a second case new irrigation water demands are introduced to investigate their impact on trade-offs. This will demonstrate how adding irrigation investments impacts the trade-offs that map the social-economic-ecological and engineering performance of the system. Visual analytic plots are built to help understand the trade-offs for each case. This section first describes the features of the

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basin model before explaining how the search algorithm interacts with it and how visual analytic plots help understand results.

3.1 Water resource management simulator

The IRAS-2010 water resources management simulator (Matrosov et al., 2011) is used to model the Tana basin water resources system. Model nodes represent storage reservoirs, run-of-river pondages, abstraction points, demands and flow monitoring locations. Links connect nodes to provide flowpaths representing the main river channel, dam release gates and spillways, hydropower turbines, abstractions and return flows.

Initial reservoir/pondage storages are set at 50 % of their maximum capacity as historical level data were not available. The upstream boundary condition is a 42-year historical (1934–1975) inflow time-series from a point downstream of the dams. This represents pre-dam development conditions and is used as the basis for analysing variations from the natural flow regime. The flow series was disaggregated based on relative flow proportions in Kiptala (2008) into an upstream catchment inflow series and 6 lateral inflow series (Fig. 1). The downstream boundary at the delta does not account for tidal backwater effects restricting river flow. A monthly (30-day) time step is used; water entering the system passes through it within a single time-step making flow routing unnecessary.

In the current water demands case public water supply and irrigation are abstracted from reservoirs taking precedence over hydropower releases. This means the hydropower plant will receive no water until other demands are satisfied. It is necessary to prioritise demands in IRAS-2010 and this approach has little impact while storage is high but best represents the likely results of political pressure under drought conditions. Current demands on the reservoirs for irrigation and municipal supplies are shown in Table A1; proposed additional demands are in Table A2.

Consistent with Kiptala (2008), return flows to the river are a constant 30 % of irrigation abstractions, except for the proposed schemes in the delta. These are assumed to be returned to multiple minor channels flowing to the ocean so not included in flow

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measurements at the delta. It is assumed that no return flows to the Tana occur from public water supply as the major abstraction is for Nairobi which lies outside its basin.

The reservoirs and rivers in this semi-arid region evaporate roughly 2000 mm yr^{-1}. The monthly mean daily evaporation rate for Muguga was increased by 10 % according to maps and data supplied by Dagg et al. (1970) for reservoir evaporation and by 43 % for river channel evaporation in the lowlands.

3.2 Optimisation approach

The IRAS-2010 simulator is linked to a multi-criteria search algorithm (the epsilon dominance non-dominated sorted genetic algorithm-II (ε-NSGAII); Kollat and Reed, 2006; Reed et al., 2013). This combined approach identifies multi-reservoir release policies which achieve Pareto-optimal trade-offs between 8 objectives. Mathematically these trade-offs are only approximately Pareto-optimal but to simplify discussion we refer to them as Pareto-optimal. This section describes interactions between the search algorithm and the model then the optimisation formulation.

3.2.1 Simulation-optimisation interactions

The optimisation algorithm adjusts decision variables within the model to alter its behaviour and simulate the impacts of different operating policies. Variables are selected at the beginning of each simulation and apply for its duration. Impacts are measured in terms of defined objectives for (or benefits from) the system. Over thousands of simulation runs (100 000 in this case, consistent with Kasprzyk et al., 2009), the algorithm iteratively attempts to increase benefits based on objective evaluations of previously simulated policies. Initial policies (sets of variables) are drawn randomly from defined decision variable ranges. The Pareto-optimal "frontier" is revealed as the algorithm finds and explores the performance limits of the system. Results comprise a set of individually unique trade-off solutions and the release policies required to achieve them.

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3.2.2 Decision variables

The decision variables of the optimisation are the release rules of the 3 managed hydropower reservoirs (Masinga, Kiambere and Kiamburu) and (for the 2nd case only), the proportion of each proposed irrigation scheme which is implemented. The other two hydropower stations (Gitaru and Kindaruma) are run-of-river and receive flows limited only by available storage and their maximum turbine flow capacities.

Release rule decision variables comprise 3 plotting coordinates (i.e. 5 values) defining a continuous piecewise linear curve which relates stored volume to release rate (Fig. 2). Reservoir-specific curves dictate the release rate at each simulation time-step. In total 15 decision variables control releases. The releases' range is 0–400 $m^3 s^{-1}$ consistent with Kiptala (2008). The storage variables' range is from dead to maximum storage specific to each reservoir. A single curve is applied throughout the year to represent a conservative approach – release rates are dictated only by current storage volume unaffected by anticipation of a forthcoming rainy season. Information on whether or how forecasts are currently used in Tana reservoir operation was not available in this study. Although irrigation abstractions are directly from the reservoir and prioritised over hydropower releases, they are limited by the release rule.

There are four proposed new irrigation schemes in the delta (Table A2). The proportion of each scheme included in an individual simulation is dictated by a decision variable of range 0–100 %. In the current demands case, these variables are all fixed at 0 %.

3.2.3 Objectives

The impacts of each set of decision variables (operation and development policy) are evaluated with respect to eight objectives and either maximised or minimised by the search algorithm. Objectives are detailed in Appendix B and outlined below.

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Masinga reservoir supplies Nairobi and Kitui and an abstraction from the river downstream of the dams serves small local urban centres. Shortfall in these supplies is minimised by evaluating a municipal deficit objective.

Hydropower revenue is maximised dependent on hydraulic head levels in the associated reservoir or pondage, flow rate through the turbines and timing of releases as bulk energy prices vary though the year. Failure to meet electrical base load or peak demands causes economic losses and can hamper development. A firm energy objective is to maximise the electrical output (GWh) at 90 % reliability over the course of the simulation. Peaking power demands, which typically manifest at the sub-daily timescale are not analysed in this study as they cannot be captured by the monthly model time step. Monthly timescale demand variations are captured by bulk energy prices which fluctuate with demand.

Existing irrigation provision in the basin does not place a strain on water resources as the volume required (Table A1) is small relative to storages and annual flows in the river (Kiptala, 2008). In re-operating the reservoirs however, crop revenues can vary as a result of policies causing irrigation deficits. Agricultural revenue is maximised dependent on minimising crop water deficits during growing seasons. In the proposed demands case it depends also on the selection of crop type, which dictates water requirements and yield response to deficit. A module was added to IRAS-2010 to evaluate crop specific yields and reductions due to irrigation shortfall (Appendix C).

Following Connell's (1979) Intermediate Disturbance Hypothesis (IDH) we assume that river flow variability represented by the natural flow duration curve is most likely to support healthy native ecosystems. Following Gao's (2009) eco-deficit approach, the flow alteration objective is to minimise deviation of the regulated from the natural flow regime. Separate objectives are calculated for deviation at the delta and the riverine forests as proposed demands are abstracted between them causing an unequal impact.

Flood magnitude and timing are components of Richter et al.'s (1996) indicators of hydrological alteration relevant to ecological health. Flood peaks in the Tana basin

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support ecological function and supply agricultural and grazing lands with nutrient rich sediments. Two flood peak objectives are evaluated at the delta; the most important provider of flood related ecosystem services. One objective is evaluated for each of the long and short flood seasons (April–June and November–December respectively) to minimise the difference between the natural and regulated flood peaks.

3.2.4 Problem formulation

Trade-offs are generated for the two cases which share a common problem formulation (Eq. 1–3). Objective functions included in the formulation are detailed in Appendix B. In the current demands case there is no abstraction for proposed irrigation schemes between the locations where f_{flowFOR} and f_{flowDEL} are evaluated, so these objectives have similar values (evaporation causes reductions downstream). Optimisation algorithm parameters are consistent with Kasprzyk et al. (2009).

$$\begin{aligned} F(x) &= \left(f_{\text{mun}}, f_{\text{hydro}}, f_{\text{firm}}, f_{\text{agric}}, f_{\text{flowFOR}}, f_{\text{flowDEL}}, f_{\text{flood}}^{\text{long}}, f_{\text{flood}}^{\text{short}}\right) \\ &\forall \quad x \in \Omega \\ &x = (X_i) \end{aligned} \tag{1}$$

where i is a reservoir, $i \in \{\text{Masinga, Kiamburu, Kiambere}\}$ and X_i represents a reservoir i's release rule. The decision variables being optimised are individual reservoir release rules, where X_i represents reservoir i's release rule for each of the 3 managed reservoirs.

3.2.5 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 broad perspective on the multiple objective performances and operating policies which produced them. Large sets of Pareto-optimal solutions can be analysed in

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plots with high information content facilitating more informed deliberation and decision-making (Kollat and Reed, 2007; Lotov, 2007). The visual analytic plots below aim to help make decisions about the preferred balance of benefits by showing how different societal goals trade-off against each-other. Any selected solution point from the trade-off surface represents the performance achieved for all objectives by a specific set of decision variables (a "policy").

4 Results

This section relates the results of the two optimised cases, starting with the current demands case. Although the computational burden of MOEA optimisation is high, this was mitigated by the use of parallel computing. The two cases presented here each converged using 48 2 GHz processors over 1.75 h.

4.1 Current demands case

This section steps through the construction of a six-dimensional trade-off surface. In the process we highlight the varying impacts on the system of selected policy solutions.

Support of ecological function and ecosystem services is investigated first from the perspective of the three flow related objectives. Trade-offs exist between reduction of the two annual flood peaks (Fig. 3) because water which is released to increase one flood's magnitude is no longer available to increase the other. Flow regime alteration trades off against both flood peak objectives. Greater overall disturbance of the flow regime is required to support flood peaks closer to those occurring naturally. The volume of water released to maintain the highest 20 % of flows can alternatively maintain the lowest 80 % of flows (Fig. 4). The trade-off surface is non-linear incorporating convexities and concavities with respect to the origin (perfect solution). Gain-sacrifice gradients vary across the surface.

Firm energy production is added to the trade-off surface through sizing of the spheres. Larger spheres indicate higher firm energy levels. Hydropower revenue is represented by a colour range applied to the spheres (Fig. 5).

In this and subsequent figures trade-off surfaces are simplified by controlling the resolution at which solutions are displayed. As this reduces the number of solutions shown, decision makers would be asked to choose a preferred region of the surface before all Pareto-optimal points are reintroduced for investigation of detailed solutions. As objectives (dimensions) are added to the surface, the number of solutions included in it increases. An objective's poorest performance can decline further as it is traded off against additional objectives. Maximum flow alteration is increased to 135 in Fig. 5 to accommodate the new surface.

Firm energy trades off against flood peak objectives as it increases when flood water is stored to secure generation during drier periods. It also trades off against the flow alteration objective as relatively constant release provides higher firm energy than natural variability.

Between Policy D and E (Fig. 5) there is a trend for increasing hydropower revenue as flow becomes more natural but flood peaks reduce. Exceptions to this trend result from the limited scope for upstream dam operations to increase revenue without impacting on the flow related objective values controlled by Kiambere – the last hydraulic structure in the system.

Flow alteration is decreased from Policy D to E by releasing water to maintain low flows rather than high flows (Fig. 6). This increases the proportion of flows released through the turbines of the Kiambere hydropower plant because they don't exceed its flow capacity; thereby increasing revenue. The flow duration curve from Policy E departs from the natural curve at the turbine capacity of the Kiambere plant as additional release beyond this magnitude generates no additional revenue.

Policy F brings around 10 % more flow duration within the productive capacity of the Kiambere turbines than Policy E. In addition some of the high flow volume made

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available is released to increase the lowest flows above the natural level (Fig. 6). This more constant flow achieves higher firm energy generation (Fig. 7).

Agricultural revenue is added to the trade-off surface by converting spheres to cones whose orientations indicate its magnitude (Fig. 8). Cones pointing down indicate the lowest revenues; cones pointing up show high revenues. Maximum flow alteration is increased to 195 to accommodate the new surface.

High agricultural revenue depends on both reliable supply (storage) and release rates at the Masinga and Kiambere reservoirs. Storage levels alone are not a predictor of agricultural revenue as without operating rules allowing releases, crops cannot be irrigated. Agricultural revenue trades off against reduction of flood peaks and alteration of the flow regime which can increase storage levels. There is also a trade-off with hydropower revenue, which benefits from some storage but requires higher releases which impact on storage. The maximum mean annual revenue achieved by the optimisation represents no reduction from the maximum possible annual revenue, i.e. there are no irrigation deficits.

4.2 Proposed demands case – implementing irrigation schemes in the delta

Having identified the trade-offs in the system under current water demands, we now compare them with the Pareto set involving a supplemental decision: "what proportions of the proposed irrigation schemes to implement?". Figure 9 shows the trade-off surface combining both cases to highlight the region associated with the introduction of potential irrigation investments. Maximum flow alteration is increased to 1072 and maximum agricultural revenue increased to USD 285 M.

Figure 10 shows the trade-offs between the same metrics as Fig. 8; this shows how ecological flow characteristics trade-off with increased agricultural revenues. New irrigation can lead to a more altered regime.

In the current demands case agricultural revenue could be increased without irrigation development in the delta by reducing the long flood peak magnitude. With the new delta irrigation schemes, the short flood peak is further reduced to provide further

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increases in agricultural revenue, even with increased long flood peaks. The sugar cane crop requires year round irrigation and cotton is irrigated through the short flood season (Table A2).

Whilst it is not possible to generate more hydropower than that obtained in the current demands case, it is possible to maintain generation levels while almost doubling agricultural revenues. When attaining the highest agricultural revenues however, hydropower revenue decreases. Increased agricultural revenues must be traded-off against negative impacts on hydropower revenue, flows, floods and associated ecosystem services.

Figure 11 relates the details of the delta irrigation schemes implemented in Fig. 10, showing the combinations of schemes which achieve different total agricultural revenues. The highest revenues can be gained either with or without cotton cultivation. A high proportion of the rice and sugar schemes must be implemented to maximise revenue.

4.3 How to select a balanced plan?

Exploring trade-offs is insightful, but ultimately the proposed approach is designed to assist with decision-making. Next we demonstrate an approach that could help decision-makers settle on a plan – in our case the combination of a set of reservoir operating rules and a portfolio of new irrigation schemes. This involves (a) filtering the Pareto-front so that only decision-maker-preferred solutions figure there, (b) identifying promising areas of the trade-off curve from which to choose example policies (individual trade-off points) to assess in more detail, and (c) for those example policies look at various objective function performances and decision-variables. This work did not involve decision-makers; here we only describe a proposed approach.

We begin by filtering the Pareto options to arrive at those of primary interest to decision-makers. For our case-study we postulate decision makers will be most interested in solutions that ensure high reliability of municipal supply and therefore filter the trade-off surface to only allow plans with no municipal deficit (Fig. 12). From this

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surface, following step (b) above, we select three promising policies to demonstrate how resulting benefits vary between them.

Finally, following step (c), we generate detailed plots and a table (Table 1) that show the performance in detail of our example policies. For example, Fig. 13 compares the natural with actual flow duration curves resulting from each policy. None of the selected policies are amongst the highest performers in terms of flow alteration, but they deviate from the natural regime in different ways. Policy H generates the most hydropower revenue by favouring release rates close to the turbine capacity of the Kiambere hydropower station. Policy G results in better flow alteration performance at low and high flows, resulting in high firm energy but lower hydropower revenues. Although around 20 % of its highest flows are closer to natural than the others, Policy I results in the greatest alteration of the regime to increase agricultural revenue. The delta irrigation schemes are almost fully implemented (Table 1). Both policies which implement new irrigation schemes result in the delta receiving no water, except return flows from irrigation schemes, for 1–2 % of the time.

Figure 14 illustrates the monthly trends in hydropower production for policies G–I. The highest revenue (Policy H) is achieved by generating more power when the bulk energy price is highest. There are four months where Policy G produces more energy than Policy H however.

5 Discussion

We have demonstrated an approach using many-objective trade-off analysis to help make balanced water management and planning decisions in complex systems with multiple societal benefits. The framework is applied to Kenya's Tana River system with the goal of finding an appropriate set of operating rules for a multi-reservoir system and sizing new irrigation schemes. We report on the approach as a proof of concept as work with decision-makers there has not yet begun. The approach aims to allow decision-makers to visualise the precise trade-offs they face when choosing amongst

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a subset of "best" (Pareto-optimal) strategies identified by a multi-criteria search algorithm. Visual analytics plots allow an interactive and intuitive understanding of the relationships between gains and sacrifices intrinsic to the system. The approach can be considered an alternative form of cost benefit analysis (Chakravarty, 1987), with costs expressed not in financial terms but in terms of sacrifice of other benefits.

The decision-making framework involves two steps. (1) Settling on a framing of the planning decision that is preferred by decision-makers, then (2) probing the trade-offs (Pareto-optimal strategies) to identify a few alternatives to investigate in detail.

The Tana Delta flow regime would be altered by irrigation schemes which withdraw water upstream. The benefit of the proposed approach is that we show the degree of alteration which would occur with the implementation of different scheme sizes. Revenues from the largest irrigated schemes are Pareto-optimal according to the optimisation, but the sacrifice of other benefits to achieve this is high. A limitation of the present work was that irrigation water was assumed to be provided free from source to crop. Had the optimisation included capital and operational costs of supplying irrigation the trade-offs would have been different. Considering further non-water related benefits (e.g. increased local employment) of irrigation schemes could also be included to further elucidate the trade-offs involved. An ensemble analysis considering many plausible future flow series may also alter this assessment if water resources availability changes; uncertainty on future flows and demands was not included in this analysis.

Mean hydropower revenue over the modelled period peaks at around USD 100 M yr^{-1}. This is lower than figures of ~ USD 150 M yr^{-1} stated by Kiptala (2008) whose work used flows from a shorter but wetter period from 1966–1990. The hydrological characteristics of this flow time-series were inconsistent with the 1934–1975 record used here, preventing their combination. Inconsistencies in data relating to hydraulic head ranges at hydropower turbines may also contribute to the discrepancy in power production/revenue between studies. Further work will attempt to resolve these discrepancies on the basis of more accurate survey data.

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A further limitation of this study is the use of proxy objectives for ecosystem services. Local farmers and pastoralists are likely to be better able to describe the relationship between river flows and their livelihoods allowing more specific and accurate benefit functions to be included in our model. This could replace or enhance our assumptions that entirely natural flow regimes are best providers of ecosystem services.

Opportunities exist to implement further hydropower projects on the river. Further work will seek to define the trade-offs inherent in decisions surrounding two or more new hydropower reservoirs which are proposed for the Tana river. Understanding these trade-offs could help design a system (choose which reservoirs to build at which capacity) that best balances system benefits.

We suggest the proposed method can be used for integrated water resources management of systems with a water-energy-food security nexus. Revealing trade-offs between stakeholder-defined metrics could help planners identify solutions that protect livelihoods and the ecosystem services which support them in addition to obtaining good economic returns.

6 Conclusions

A many-objective visual trade-off analysis of the multi-reservoir hydropower system on the Kenyan Tana River quantified the relationships between conflicting system objectives achievable under the best system operating rules and designs. The decisions being optimised were storage-dependent reservoir release rules and extent of new irrigation investments. Decision makers can use the information presented in visual analytic plots to trade-off the various gains and sacrifices according to their preferences. The balance they select is associated with a set of operating rules for the reservoirs which achieve the selected benefits, for a set of hydrological conditions (in our case the historical record). For the case where we consider new irrigation schemes, each Pareto optimal solution on the trade-off plots also corresponds to a specific set of irrigation schemes in the Tana Delta.

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Eight objectives were considered in this study representing benefits to municipalities, a national primate reserve, pastoralists seeking grazing in a protected wetland, riparian farming tribes, the hydropower company and irrigated agriculture. Considering these objectives, full implementation of the proposed irrigation schemes is Pareto-optimal but would involve large sacrifices of non-monetary benefits.

Appendix A

Demand data

This appendix gives demand data relating to the two optimisation cases. Table A1 includes demands applied to both cases. Table A2 gives maximum demands for the four proposed irrigation schemes in the delta.

Appendix B

Objective function details

This appendix presents the mathematical formulation of objective functions used for optimisation. Table B1 details the objectives as they relate to the optimisation before mathematical formulations are presented for each.

B1 Municipal deficit

$$\text{Minimise } f_{\text{mun}} = \frac{1}{Y}\sum_{y=1}^{Y}\left(\sum_{i}\text{Deficit}_y^i\right) \quad i \in \{\text{Nairobi, Kitui, Downstream}\} \qquad \text{(B1)}$$

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where y is the year in the time horizon, Y is the total number of simulated years, i is a municipal demand and Deficit_y^i represents deficit experienced by municipal demand i during year y.

B2 Hydropower revenue

$$\text{Maximise } f_{\text{hydro}} = \frac{1}{Y}\sum_{y=1}^{Y}\left(\sum_i \text{Revenue}_y^i\right) i \in \{\text{Masinga,Kiamburu, Gitaru, Kindaruma,Kiambere}\} \quad \text{(B2)}$$

where y is the year in the time horizon, Y is the total number of simulated years and Revenue_y^i is the revenue generated by the hydropower plant at reservoir/pondage i in year y.

B3 Firm energy

$$\text{Maximise } f_{\text{firm}} = \text{LowGen} \quad \text{(B3)}$$

where LowGen is the 10th percentile value of monthly total energy generation during the 42 yr simulation

B4 Agricultural revenue

$$\text{Maximize } f_{\text{agric}} = \frac{1}{Y}\sum_{y=1}^{Y}\left(\sum_i \text{AgRevenue}_y^i\right) i \in \{\text{Masinga,Kiambere,Delta}\} \quad \text{(B4)}$$

where AgRevenue_y^i is the agricultural revenue associated with irrigation demands in supply region i in year y.

B5 Flow alteration

Two flow alteration objectives are evaluated, but as these share a common formulation a generic form is presented here to avoid duplication.

$$\text{Minimize } f_{\text{flow}} = -\sum_{d}\left(1-\frac{\sum_{t=1}^{\text{TD}}\left(\text{FFC}_t^{\text{u}}-\text{FFC}_t^{r}\right)^2}{\sum_{t=1}^{\text{TD}}\left(\text{FFC}_t^{\text{u}}-\overline{\text{FFC}_d^{\text{u}}}\right)^2}\right)_d \quad d=\{1,2,3,4,5,6,7,8,9,10\} \tag{B5}$$

where d is a decile of the flow duration curve at the objective evaluation site, t is a timestep, TD is the total number of timesteps within decile d, FFC_t^{u} represents the unregulated flow frequency curve value for timestep t, FFC_t^{r} represents the regulated flow frequency curve value for timestep t and $\overline{\text{FFC}_d^{\text{u}}}$ is the mean value of unregulated flow frequency curve in d.

B6 Long flood peak reduction

$$\text{Maximize } f_{\text{flood}}^{\text{long}} = \sum_{y=1}^{Y}\left(\sum_{i}\left|\text{NatFlow}_y^i-\text{ModFlow}_y^i\right|\right) \quad i\in\{\text{April, May, June}\} \tag{B6}$$

where NatFlow_y^i is the natural (observed) flow rate and ModFlow_y^i is the regulated (modelled) flow rate for month i in year y.

B7 Short flood peak reduction

$$\text{Maximize } f_{\text{flood}}^{\text{short}} = \sum_{y=1}^{Y}\left(\sum_{i}\left|\text{NatFlow}_y^i-\text{ModFlow}_y^i\right|\right) \quad i\in\{\text{October,November,December}\} \tag{B7}$$

where NatFlow_y^i is the natural (observed) flow rate and ModFlow_y^i is the regulated (modelled) flow rate for month i in year y.

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Appendix C

Formulation and parameterisation of the crop yield module added to IRAS-2010

This appendix gives details of the crop yield calculation module added to IRAS-2010 in order to evaluate agricultural revenue. The module added is based on work by Doorenbos and Kassam (1979) on crop yield response to water.

Doorenbos and Kassam (1979) developed an equation (C1) relating crop yields to maximum possible yields, actual and maximum evapotranspiration. In order to simplify the calculation we used the ratio of irrigation supplied to irrigation demand as a proxy for the ratio of actual to potential evapotranspiration. We justify this by the statement in Doorenbos and Kassam (1979) (p. 8) that available water supply to the crop controls actual evapotranspiration. It was necessary to assume that the only water received by crops in this region is irrigation. This is reasonable under the semi-arid climate.

$$\left(1 - \frac{Y_a}{Y_x}\right) = K_y \left(1 - \frac{ET_a}{ET_x}\right) \tag{C1}$$

where Y_x and Y_a are the maximum and actual yields, ET_x and ET_a are the maximum and actual evapotranspiration, and K_y is a yield response factor representing the effect of a reduction in evapotranspiration on yield losses.

Yield response factors used to calculate yields in the IRAS-2010 module are shown in Table C1. No response factor for rice was given by Doorenbos and Kassam so it was assumed that yield was directly proportional to water deficit. This was simpler than trying to judge a factor without evidence to support its value.

Supplementary material related to this article is available online at http://www.hydrol-earth-syst-sci-discuss.net/11/1343/2014/hessd-11-1343-2014-supplement.zip.

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Table 1. Objective values and irrigation scheme implementation percentages for selected operating policies from Fig. 12.

Objective	Units	Operating policy H	I	J
Municipal deficit	Mm^3	0.0	0.0	0.0
Hydropower revenue	USD M	88.0	92.7	82.1
Firm energy (90 %)	GWh $month^{-1}$	131.1	105.1	79.9
Agricultural revenue	USD M	121.8	241.4	277.2
Flow regime alteration (Forest)	–	36.4	23.2	49.5
Flow regime alteration (Delta)	–	38.3	134.1	568.8
Long flood peak reduction	$m^3 s^{-1}$	177.3	228.1	179.7
Short flood peak reduction	$m^3 s^{-1}$	77.6	151.3	173.4
Delta irrigation implementation				
Rice (season 1)	%	0	86	100
Rice (season 2)	%	0	98	97
Cotton	%	0	69	31
Sugar cane	%	0	30	100

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Table A1. Non-hydropower demands by month on reservoirs in the Seven Forks project (in $m^3 s^{-1}$) (Kiptala, 2008) applied to both cases.

Reservoir	Masinga			Kiambere
Month	Rice	Horticulture	Municipal (Nairobi &Kitui)	Maize
Jan	17.6	1.3	2.2	3.9
Feb	18.9	0.0	2.2	1.4
Mar	19.7	0.7	2.2	0.0
Apr	0.0	2.3	2.2	0.0
May	0.0	5.0	2.2	2.5
Jun	0.0	5.3	2.2	4.8
Jul	13.8	1.6	2.2	4.3
Aug	13.4	0.0	2.2	1.3
Sep	19.5	1.6	2.2	0.0
Oct	18.7	3.1	2.2	0.7
Nov	0.0	4.3	2.2	1.7
Dec	16.7	3.5	2.2	3.2

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Table A2. Monthly demands for proposed irrigation crops in the Tana Delta (in $m^3\,s^{-1}$) (Kiptala, 2008) applied only in the proposed demands case according to the proportions determined by related decision variables.

	Crop			
Month	Rice Season 1	Rice Season 2	Cotton	Sugarcane
Jan	20.2	0.0	3.3	112.0
Feb	21.8	0.0	0.0	83.5
Mar	22.7	0.0	0.0	29.9
Apr	0.0	0.0	0.0	44.8
May	0.0	0.0	0.0	121.7
Jun	0.0	0.0	0.0	159.7
Jul	0.0	16.0	3.6	156.8
Aug	0.0	15.5	6.3	160.5
Sep	0.0	22.5	10.5	167.4
Oct	0.0	21.5	8.9	143.4
Nov	0.0	0.0	8.4	116.5
Dec	19.3	0.0	8.3	99.3

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Table B1. Objective function goals, results precision, units and comments.

Objective	Function	Goal	Results precision & units	Comments
Municipal deficit	f_{mun}	Minimise	0.25 Mm^3	Evaluated as the sum of deficits during the simulation divided by the number of years to give a mean annual value.
Hydropower revenue	f_{hydro}	Maximise	US$ 1 mil	Total revenue from the five stations according to 2007 bulk energy prices from Kiptala (2008), divided by the years simulated to give mean annual revenue.
Firm energy	f_{firm}	Maximise	1 GWh	
Total agricultural revenue	f_{agric}^{total}	Maximise	US$ 1 mil	Crop yield responses to water deficit (Doorenbos and Kassam, 1979) used to calculate yields. Yields converted to revenues using commodity prices in Kiptala (2008). Objective evaluates whole system for both cases.
Delta Flow alteration Forest Flow alteration	$f_{flowDEL}$ $f_{flowFOR}$	Minimise Minimise	10 10	Evaluated as negative sum of Nash–Sutcliffe efficiencies (Nash and Sutcliffe, 1970) for ten corresponding deciles of natural and regulated flow duration curves. Negative sum is used to make objective more intuitive, i.e. ecosystem benefits are preserved by minimising, rather than maximising flow regime alteration. Theoretical range of objective is -10 to ∞, although physical limits mean value unlikely to approach ∞.
Long flood peak reduction Short flood peak reduction	f_{flood}^{long} f_{flood}^{short}	Minimise Minimise	10 $m^3 s^{-1}$ 10 $m^3 s^{-1}$	Flooding results from controlled releases through dam gates and uncontrolled releases over the dam spillways. Objectives are controlled by the operation of the downstream most dam, Kiambere although upstream dam operations affect water available at Kiambere. Evaluated as absolute sum of differences between flows for the whole simulation.

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Table C1. Yield response factors for crops proposed for delta irrigation schemes (based on Doorenbos and Kassam, 1979).

Crop	Yield response factor
Rice	1.0
Maize	1.25
Cotton	0.85
Sugar cane	1.2

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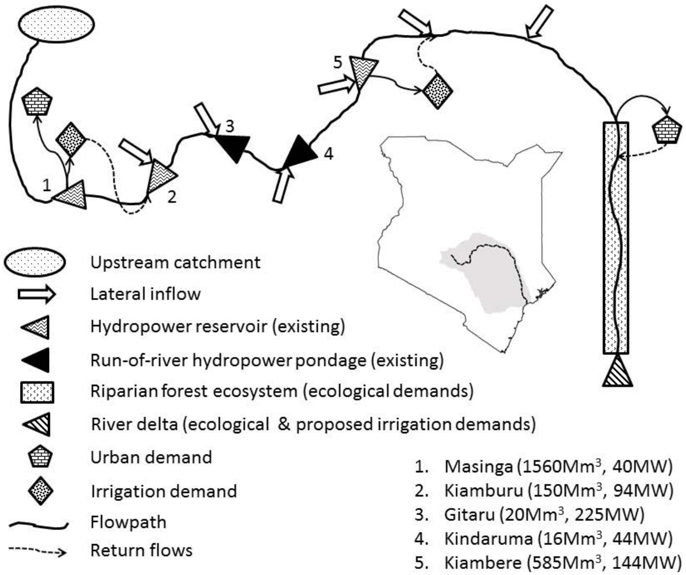

Fig. 1. Tana River basin schematic. Inset map shows the location of river and catchment within Kenya.

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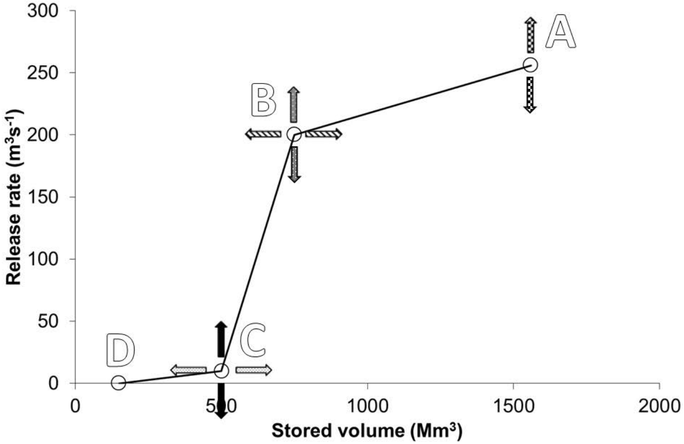

Fig. 2. Reservoir release rule (hedging) curves as represented by the IRAS-2010 model. Each patterned pair of opposing arrows represents an optimisation decision variable. Point D is the dead storage of the reservoir. Point A represents the controlled release when the reservoir is full. B and C points can be varied in two dimensions for hedging. In total 5 decision variables define each reservoir's release rule.

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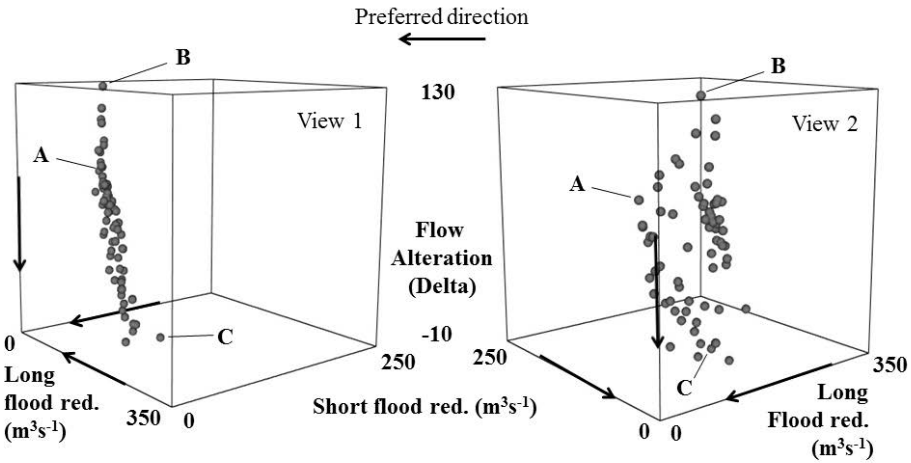

Fig. 3. Two views of the trade-off surface between flow related objectives. Flow regime alteration decreases as flood peaks are reduced allowing lower flows to be maintained closer to the natural regime. Three policies are highlighted and referred to in the text and subsequent figures. A 3-D animation of this plot is available in online Supplement.

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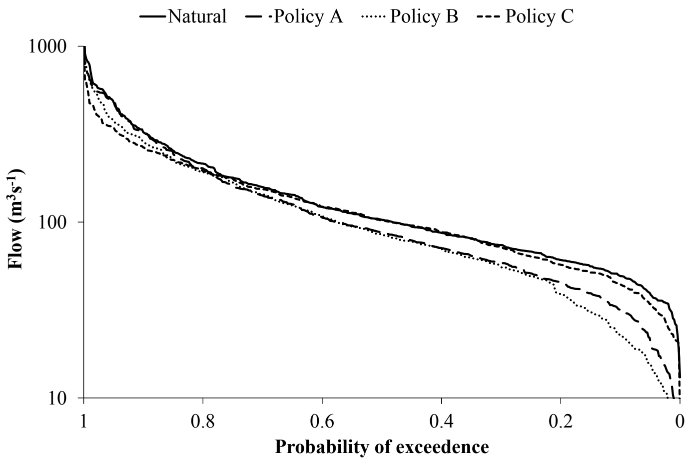

Fig. 4. Comparison of the flow duration curves resulting from Policies A, B and C of Fig. 3. Policy C allows around 20 % of highest flows to diverge from the natural curve to augment lower flows, maintaining them closer to the natural regime. Policy A achieves the reverse.

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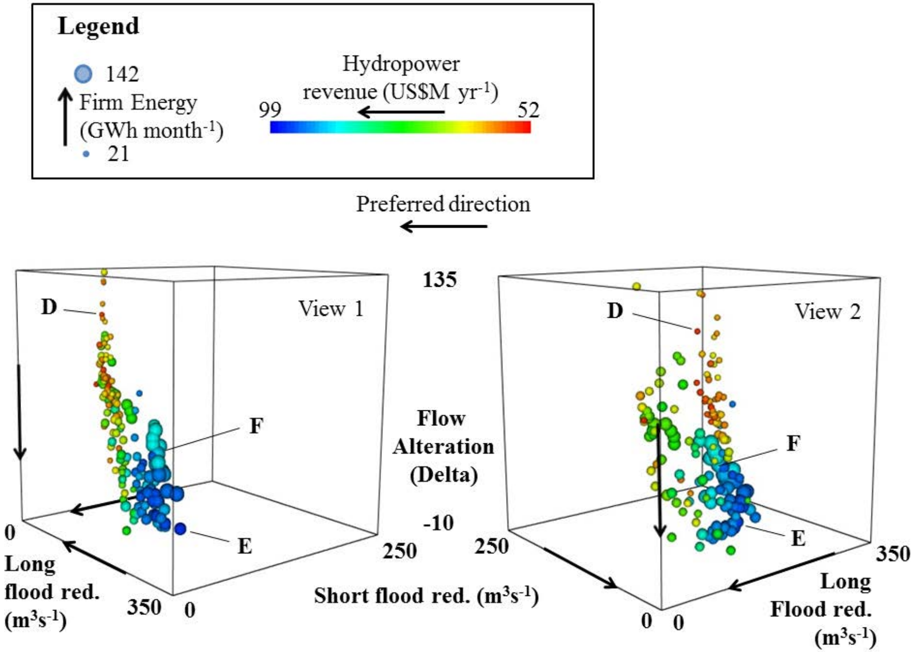

Fig. 5. The same trade-off surface as Fig. 3 with firm energy added using sphere size and hydropower revenue shown with colour. Larger spheres indicate higher firm energy; blue spheres mean high revenues. Three policies (D, E, F) illustrate trends across the surface. Moving from D to E, hydropower revenue increases as flood peaks are reduced but flow regime alteration becomes less pronounced. From E to F long flood peaks are increased as a result of higher storage levels increasing uncontrolled releases and flow regime alteration is increased to conserve water for firm energy generation.

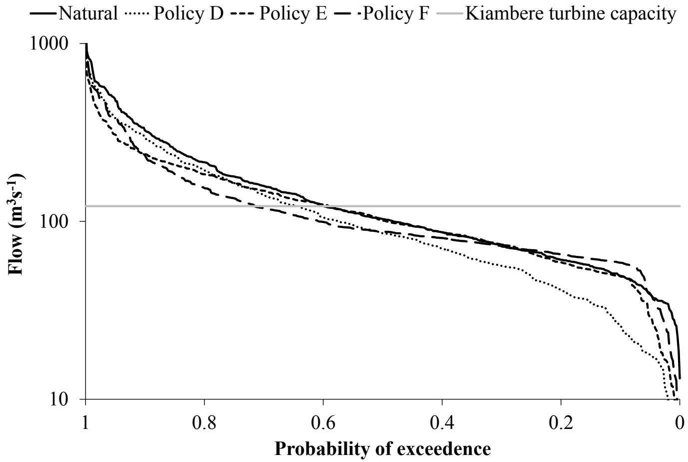

Fig. 6. Comparison of the natural flow duration curve with those resulting from the 3 selected policies of Fig. 5. Lower flows are increased by sacrificing higher flows as we move across the trade-off surface in Fig. 5 from Policy D to E. This results in 79 % higher hydropower revenue. The Policy E curve departs from the natural curve at the turbine flow (i.e. productive) capacity of the Kiambere plant. Policy F brings around 10 % more flows within the productive capacity at Kiambere than Policy E and increases low flows above the natural regime.

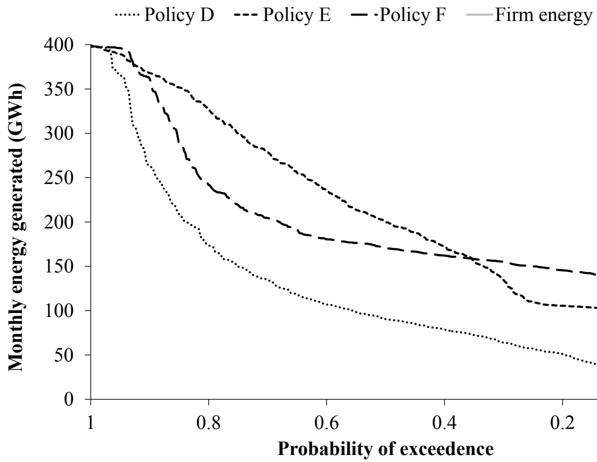

Fig. 7. Energy generation implications of the three policies labelled in Fig. 5. Firm energy is the level of generation which can be provided with 90 % reliability. Policy F best sustains energy generation to achieve firm energy 326 % higher than Policy D and 37 % higher than Policy E.

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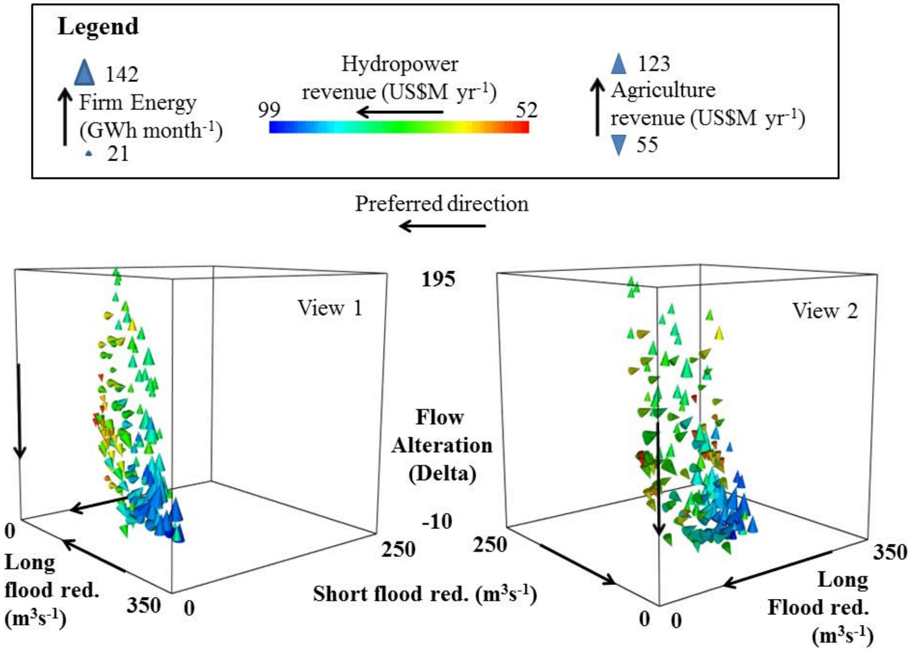

Fig. 8. The same trade-off surface as Fig. 5 with cones replacing spheres. Their orientation shows agriculture revenue from lowest (pointing down) to highest (pointing up). Agriculture revenues trade-off against flood peak objectives and correlate with firm energy, except at the highest agricultural revenues, where there is a trade-off.

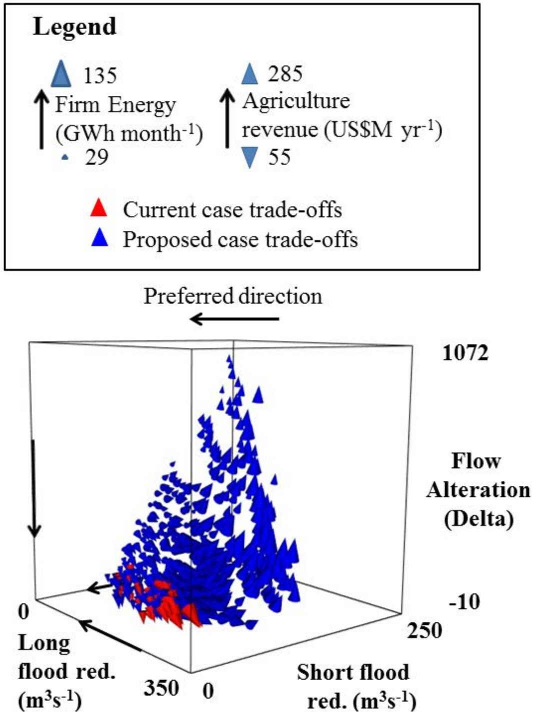

Fig. 9. Trade-off surface of the combined current and proposed demands cases (blue cones show system performance when irrigation schemes can be expanded). Some proposed demands solutions dominate the current demands solutions reducing their representation on the surface. This figure shows how trade-offs achievable by the best system operating rules change once irrigation investments are considered.

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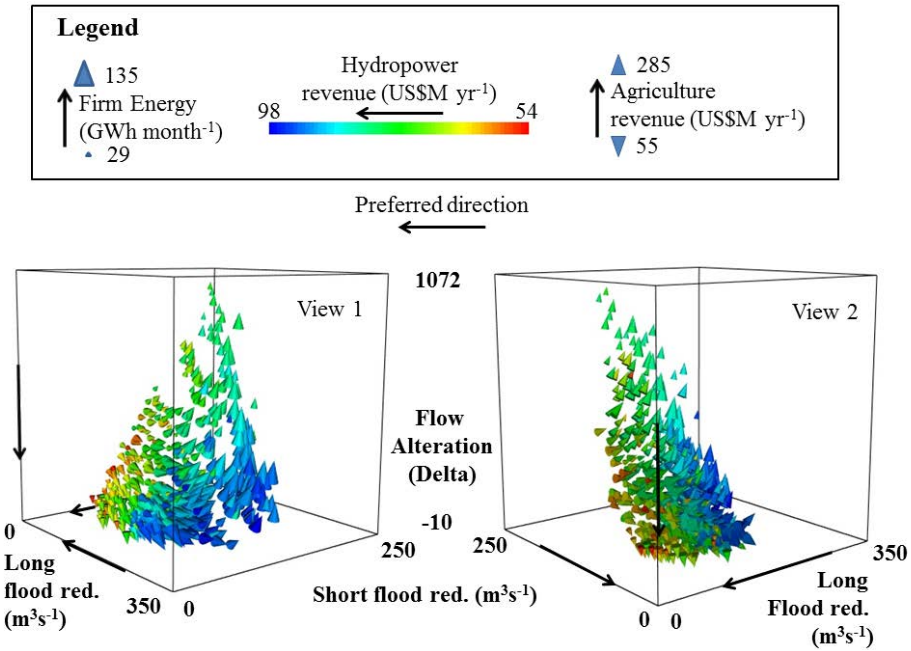

Fig. 10. The same trade-off surface as Fig. 8 but with different extents of irrigation scheme implementation. Maximum agricultural revenue more than doubles but maximum flow alteration increases by 5.5 times. Increased agricultural revenue correlates with greater disturbance of the natural water environment. A 3-D animation of this plot is available in online Supplement.

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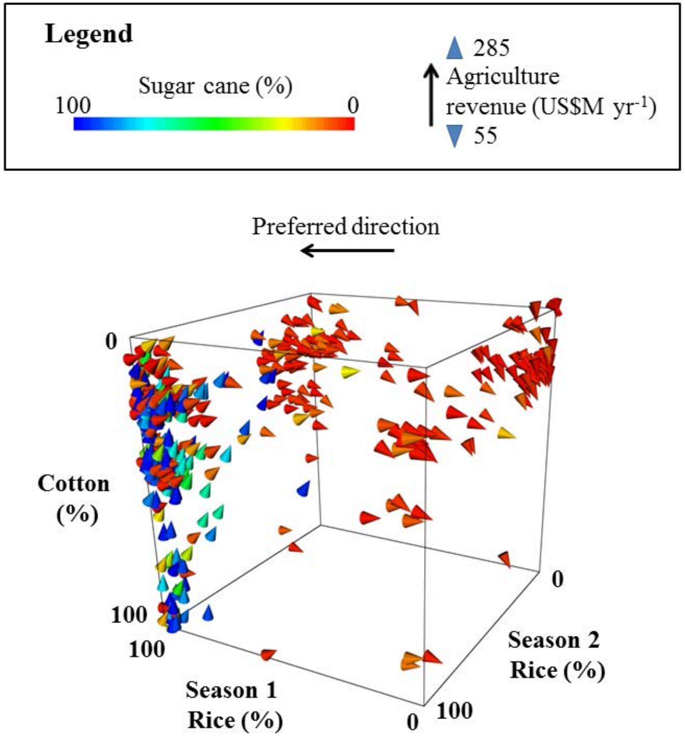

Fig. 11. 3-D (non-trade-off) plot showing the relationship between irrigation scheme selection and agricultural revenue. The solution points are the same as those shown in Fig. 10. High revenues can be achieved with or without the implementation of the cotton scheme. A high proportion of all other schemes must be implemented to achieve maximum revenue however.

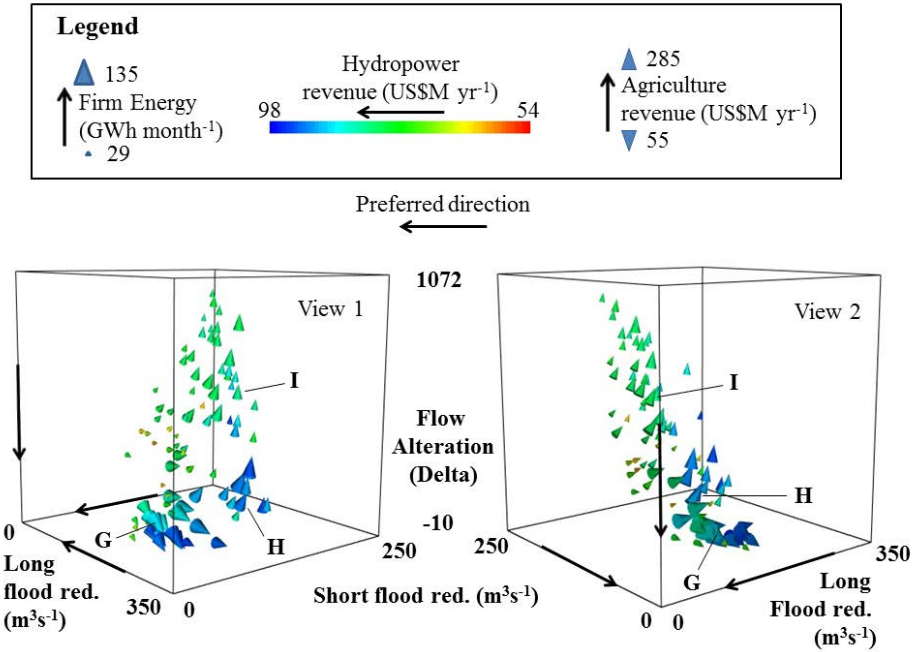

Fig. 12. The same trade-off surface as Fig. 10 but restricted to reservoir rules which result in no municipal deficits considering historical data. Such "brushing" of trade-off plots allow stakeholders to focus on system designs that interest them. Three policies are selected for discussion. A 3-D animation of this plot is available in online Supplement.

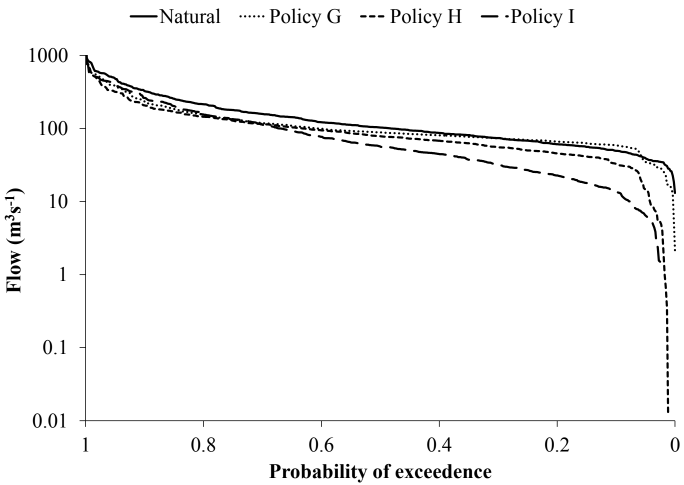

Fig. 13. Comparison of the flow duration curves for the three selected operating policies showing the implications of the flow alteration values in Table 1. The Policy G flow regime is closest to natural conditions at both low and mid-range flows, but high flows are sacrificed to increase firm energy. Policies H and I result in the river not reaching the ocean for 1–2 % of the time.

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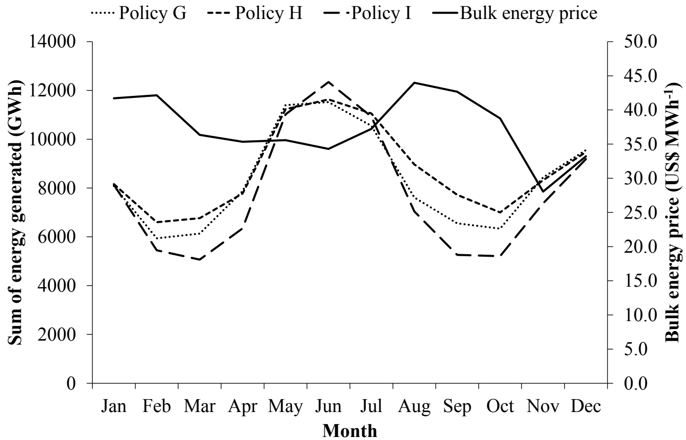

Fig. 14. Plot of the total energy generation for each of three selected policies from Fig. 12 alongside the monthly bulk energy price. Higher hydropower revenue (Policy H) is achieved by generating high levels of power in months (August–October) when the bulk energy price is highest.