Choosing metrics that matter – quantifying performance to help address reservoir operation challenges in Kenya's Tana basin

ANTHONY P. HURFORD[1,2] & JULIEN J. HAROU[2]
1 HR Wallingford, Howbery Park, Benson Lane, Wallingford OX10 8BA, UK
a.hurford@hrwallingford.com
2 University College London, Department of Civil Environmental and Geomatic Engineering, Chadwick Building, Gower Street, London WC1E 6BT, UK

Abstract A system of five hydropower plants on Kenya's Tana River (the Seven Forks project) currently provides three-quarters of Kenya's electricity. Operating the hydropower dams to support economic development without reducing hydropower generation, water supplies or ecological function is a challenge. We developed a range of performance metrics within an open-source water resources simulator (IRAS-2010) to help gauge success in this effort. Modifying reservoir operating rules enhances performance in particular metrics but lowers others, demonstrating the existence of trade-offs. Financial benefits of hydropower generation and agriculture are assessed alongside non-monetary benefits accruing from a natural flow regime. Pre-dam development flow time-series are used to represent both the range of hydrological conditions experienced in the basin and the ecological flow requirements. The maximum-to-minimum ratio of individual performance metrics varies from 1.75 to ∞ (where zero is the best performance) suggesting different operating rules lead to a wide range of performances.

Key words Tana River; Kenya; economic development; ecosystem services; hydropower; performance metrics; IRAS-2010; reservoir operating rules; trade-offs

INTRODUCTION

Water resources management is a complex challenge with numerous interactions and feedback between natural and engineered systems (Reed & Kasprzyk, 2009; Lund, 2012). Construction and operation of dams necessarily interrupt the natural flow regime of rivers, harnessing the resource for economic gain. This economic gain comes at the price of disruption downstream through for example, reduced flood peaks, reduced sediment and nutrient loads, changed chemical composition and temperature of river water, altered flow variability, ecological or geomorphological change or combinations of the above and more (WCD, 2000, Renofalt *et al.*, 2010). The cost-benefit analyses historically used to assess proposed dam building projects often discounted or ignored the non-economic supply of goods from common resources and likely impacts on the livelihoods of the poorest people (McCully, 2001; GWP, 2003). There is potential to decrease disruption downstream by changing dam operations taking into account previously ignored benefits (Richter & Thomas, 2007; Watts *et al.*, 2010; Konrad *et al.*, 2012).

Many of the world's poorest people rely on ecosystem services provided by common environmental resources for their livelihoods. Change in these resources can increase the vulnerability of these people and reduce their prospects for economic development (Malley *et al.*, 2007; Juana *et al.*, 2012). The global push for sustainable development requires consideration of and attempts to reduce or eliminate these broader negative impacts on people and the environment which supports them.

Modelling can be used with stakeholders in a participatory framework to enhance water management and reservoir operation (Welp, 2001; Skoulikaris *et al.*, 2009; Voinov & Bousquet 2010). It is important that the value range of model metrics effectively differentiate between the outcomes of different management decisions. We propose seven such metrics for the modelling of the Tana River basin in Kenya. These metrics represent traditional water supply, hydropower and irrigation benefits as well as the ecosystem services the river provides, both directly by flooding agricultural land with nutrient rich sediments and indirectly through the maintenance of diverse ecosystems.

CASE STUDY

The Tana is Kenya's longest river and most significant hydropower resource (Fig. 1). The river receives runoff from Mount Kenya and the Aberdare mountain range upstream, and from ephemeral streams in the semi-arid lowlands. The river flow has 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. The associated reservoirs provide water for irrigation and municipal demands, but the dams have necessarily disrupted the flow regime of the river (Maingi & Marsh, 2002).

The Tana River delta was recently classified under Ramsar (2012) as a protected wetland, 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 seasons the delta provides high quality grazing land for large numbers of pastoralists, constituting a high value ecosystem service (Davies, 2007).

Two other smaller protected forest areas upstream of the delta are also reliant on regular floods (Hughes, 1990) and low flows (Kinnaird, 1992) to maintain their biodiversity and ecosystem health. The same natural variability of flows historically replenished nutrients on agricultural lands along the river and in the delta. and deposited sediments leading to beneficial morphological change. These ecosystem services are under threat from the alteration of the flow regime. Richter *et al*. (1996) discuss the importance of various factors in maintaining ecological function.

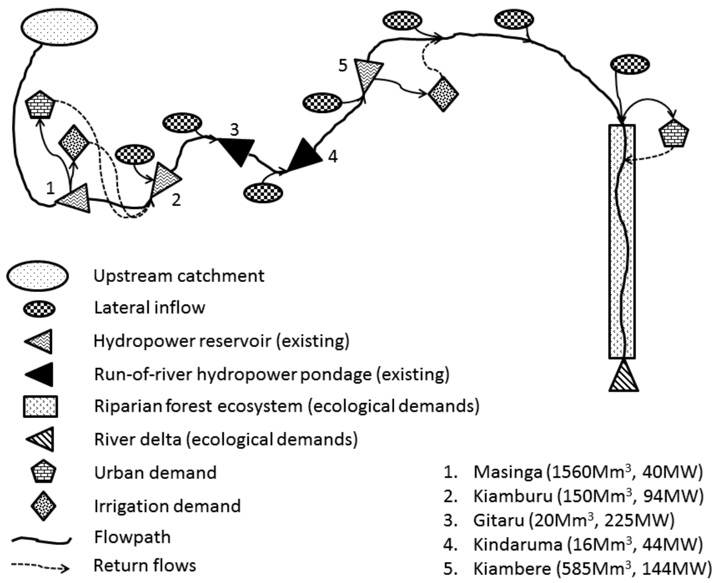

Fig. 1 Tana River basin schematic showing features of interest to this study – features are listed by symbol and reservoir names and storage/hydropower capacities are numbered.

METHODOLOGY

The open source IRAS-2010 generalized water resource simulator (Matrosov *et al.*, 2011) was used to create a model of the main features of the Tana River and Seven Forks system. The model is comprised of nodes and links, with reservoir nodes being assigned an annual release rule curve which dictates the release rate according to the volume stored (Fig. 2). Run-of-river pondage dams were assumed to release the maximum possible flow into the associated hydropower plant without control, unless additionally spilling over the top of the dam. All storages were modelled with an outlet representing the dam spillway in addition to an outlet to a hydropower plant.

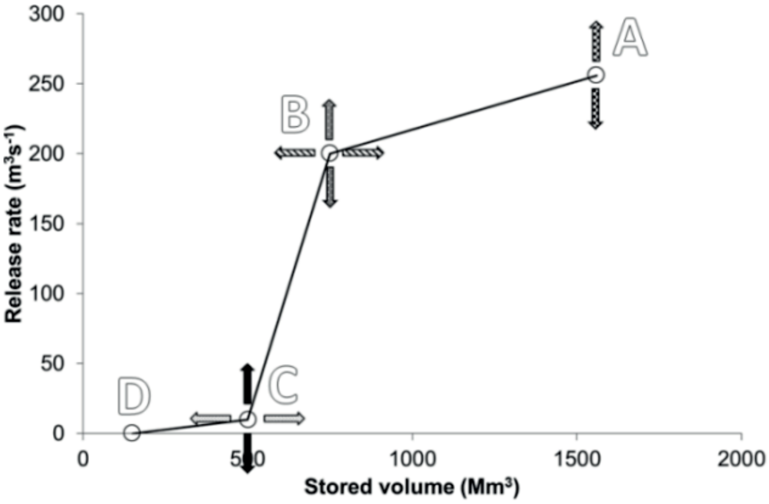

Fig. 2 Reservoir release rule curves used in the IRAS-2010 Tana basin model. Each patterned pair of opposing arrows represents a variable. Point D is the dead storage of the reservoir. Point A represents the controlled release when the reservoir is full. B and C points can be varied in two dimensions for hedging. In total five variables define each reservoir's release rule.

Table 1 Non-hydropower demands by month on reservoirs in the Seven Forks project (in m^3 s^{-1}).

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

Hydropower output is determined for all five existing power stations at each model timestep and the total resulting revenue calculated using 2007 monthly bulk energy prices (Kiptala, 2008).

River abstractions for public water supply and irrigation are taken from reservoirs and take precedence over hydropower generation. Demands on the reservoirs for irrigation and municipal supplies are shown in Table 1. This means that the hydropower plant will receive no water until other demands are satisfied. While this might not be realistic under normal circumstances, it is likely to be more representative of political pressures when stocks are depleted.

Return flows from irrigation systems to the river are assumed to be a constant 30% of the abstraction. It was assumed that no return flows to the Tana occur from public water supply as the major abstraction is for Nairobi which lies outside the Tana basin.

Observed monthly flow time-series (1934–1975) were obtained for Garissa, downstream of the Seven Forks project. Upstream catchment and lateral inflow (see Fig. 1) time-series were disaggregated from the Garissa data using the relative proportions in Kiptala (2008). Monthly timesteps were used in the IRAS-2010 Tana model.

The reservoirs and rivers in this semi-arid region are subject to significant evaporative demands. The monthly mean daily evaporation rate for Muguga was increased by 10% according to maps and data supplied by Dagg *et al.* (1970) to apply to the reservoirs and again by 30% for river channel evaporation in the lowlands.

Bathymetric data were not available, so assumptions were made regarding the depth–storage relationships of the reservoirs and pondages.

Performance metrics

Performance of the municipal water supply provided from the Masinga reservoir (to Nairobi and Kitui) and by abstraction from the river downstream of the dams is captured by the mean annual municipal deficit in millions of m^3. The metric values can also be processed into reliability of supply as a proportion of the total demand.

The hydropower generation in the basin was measured by calculating the total revenue from the five stations, according to 2007 bulk energy prices (Kiptala, 2008). This metric captures the impacts of higher energy prices when there is more demand for water but supply is limited. The units are mean annual millions of US Dollars of income generated.

Resource efficiency is increasingly of interest and hydropower is starting to come under scrutiny (Demeke, 2012). We used a water footprint metric to provide a relative measure of the hydropower water "efficiency" resulting from different operating strategies. The units are m^3 of water evaporated per MW of electricity generated.

The productivity of irrigation schemes for which data were available is captured through an economic metric. We used FAO research on crop yield responses to water deficit (Doorenbos & Kassam, 1979) to calculate reductions in crop yields due to growing season irrigation deficits. Crop yields were converted to economic values using commodity prices quoted by Kiptala (2008). Units are mean annual millions of US Dollars of income generated.

The major ecological demands for flow in the basin are the riverine forests of the lower Tana of which two areas are designated as national parks, and the Tana Delta Ramsar wetland. Following Connell's (1979) Intermediate Disturbance Hypothesis (IDH) we assume that the 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, we developed a performance metric comparing the natural and regulated flow duration curves. The pre-dam building flow record is assumed to represent the natural flow duration curve. The Flow alteration metric is computed as the sum of Nash-Sutcliffe efficiencies (Nash & Sutcliffe, 1970) for 10 corresponding deciles of the natural and regulated curves at the outlet of the basin. The theoretical range of the metric is 10 to $-\infty$, although physical limits mean its value is unlikely to approach $-\infty$.

Flood peaks are important in the Tana basin both for ecological function and for flooding of agricultural lands with nutrient rich sediments. We include a metric for each of the long and short flood seasons, quantifying the difference between the mean natural and modified flood peaks. This is calculated over three months for each flood peak – April, May, June and October, November, December. The metric is the sum of absolute differences between the mean natural and regulated flow for each month. Units are m^3s^{-1}.

Model runs

Six operating strategies, represented by different reservoir release rule curves, were developed to favour each of the performance metrics separately. Strategies were named according to the metric enhanced. The Agricultural yield strategy also represents reduction of municipal deficit as both are improved by the same operating strategy, which maintains storage in the Masinga reservoir.

RESULTS

The numerical results for each operating strategy and performance metric are shown in Table 2. There is considerable variation in the performance of all metrics, with the maximum-to-minimum ratio ranging from 1.75 to ∞ (where zero is the best performance).

The implications of flow duration difference values are depicted in Fig. 3. The Flow alteration strategy matches the majority of the natural curve well, although sacrifices some variation from the natural regime at both high and low flows. It also matches the Short floods curve well at high flows. Both Long and Short floods curves sacrifice performance at low flows while prioritising different magnitudes of flow at the upper end. We can also observe how the middle range of flows, which are best for generating hydropower, are matched well with the natural curve, while low and high flows are sacrificed to maintain hydraulic head in the reservoirs.

Table 2 Performance metric results for each of the six operating strategies, named by the metric enhanced.

Reservoir operating strategy	Long floods	Flow alteration	Short floods	Agric. yield	Hydro–power	Water footprint
Mean annual municipal deficit (Mm^3)	17.9	12.9	10.8	0.0	10.7	18.2
Mean annual hydropower revenue (US$mil)	48.0	86.1	77.3	77.0	94.1	62.9
Water footprint of power (m^3/MW)	6.4	3.5	6.2	7.0	4.9	2.3
Mean annual crop revenues (US$mil)	56.4	69.6	76.7	113.5	96.1	55.7
Flow duration difference (–)	–117.5	–2.0	–27.6	–220.8	–39.1	–120.9
Long floods peak difference (m^3s^{-1})	67.0	272.5	179.4	119.5	226.2	149.4
Short floods peak difference (m^3s^{-1})	85.4	113.2	65.9	110.3	84.7	115.6

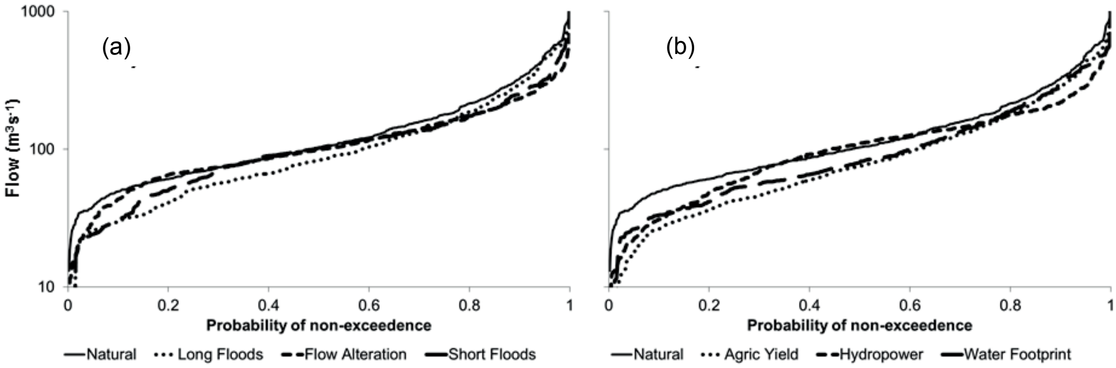

Fig. 3 Comparison of flow duration curves for the six reservoir operating strategies, separated into two groups for easier viewing: (a) flow related strategies, (b) hydropower and agriculture related strategies.

DISCUSSION

The results give some indication of the trade-offs inherent in the system. For example, we can see by how much flow alteration might need to increase to eliminate municipal deficit or how much the water footprint increases with hydropower revenue.

As the Masinga reservoir is by far the largest in the Seven Forks project, its surface evaporation is the greatest. The storage in this reservoir therefore accounts for the majority of differences in the water footprint of hydropower production. The Masinga hydropower plant has the lowest capacity so hydropower revenue increases with release of water to downstream plants. This reservoir also serves the majority of municipal and irrigation demands which however require storage to be maintained in conflict with the releases for hydropower. We can see that where storage is maintained for the best irrigation and municipal supply benefits, the water footprint of hydropower is the highest. There are clear trade-offs to be considered regarding the operation of this reservoir. The Kiambere reservoir also provides irrigation water (requiring storage) while having the second largest hydropower plant at 144 MW (requiring release), so there are also trade-offs here.

Analysis of the flow duration curves shows that all the strategies employed here have negative effects on low flows with sacrifices in performance of all metrics except the water footprint necessary to achieve the least negative flow alteration. Again, trade-offs are apparent. The highest flows under all strategies are likely to be due to spills as the highest controlled release was limited to 400 m^3s^{-1}. This means storing water at the time of high inflows helps generate high outflows.

These metrics appear useful in differentiating performance in key areas for the Tana basin and highlighting the inherent system trade-offs. Future work will build on these metrics and attempt multi-criteria optimisation of reservoir release rules.

REFERENCES

Dagg, M., Woodhead, T. & Rijks, D. A. (1970) Evaporation in East Africa. *International Association of Scientific Hydrology. Bulletin,* 15(1), 61-67.

Davies, J. (2007) Total Economic Valuation of Kenyan Pastoralism.

Demeke, T. A. (2012) *Hydropower "Water Footprint" – does hydropower consume water ?* UNESCO-IHE.

Doorenbos, J. & Kassam, A. H. (1979) *Yield response to water, Irrigation and Drainage Paper 33.* Food and Agriculture Organization of the United Nations, Rome.

Gao, Y. X., R. M. Vogel, C. N. Kroll, N. L. Poff & J. D. Olden (2009) Development of representative indicators of hydrologic alteration. *Journal of Hydrology,* 374(1–2), 136–147.

GWP (2003) Poverty Reduction and IWRM. In: *TEC Background Papers, No. 8.* (ed. by T. Committee). Global Water Partership, Sweden.

Hughes, F. M. R. (1990) The influence of flooding regimes on forest distribution and composition in the Tana River floodplain, Kenya. *Journal of Applied Ecology* 27(2), 475–491.

Juana, J. S., Mangadi, K. T. & Strzepek, K. M. (2012) The socio-economic impacts of climate change on water resources in South Africa. *Water International* 37(3), 265–278.

Kinnaird, M. F. (1992) Phenology of flowering and fruiting of an east-african riverine forest ecosystem. *Biotropica,* 24(2), 187–194.

Kiptala, J. K. (2008) Intersectoral Allocation in the Tana River Basin (Kenya). *Institute for Water Education.* UNESCO-IHE, Delft.

Konrad, C. P., Warner, A. &Higgins, J. V. (2012) Evaluating dam re-operation for freshwater conservation in the sustainable rivers project. *River Research and Applications* 28(6), 777–792.

Lund, J. R. (2012) Provoking more productive discussion of wicked problems. *Journal of Water Resources Planning and Management-Asce* 138(3), 193–195.

Maingi, J. K. & Marsh, S. E. (2002) Quantifying hydrologic impacts following dam construction along the Tana River, Kenya. *Journal of Arid Environments* 50(1), 53–79.

Malley, Z. J. U., Taeb, M., Matsumoto, T., & Takeya, H. (2007) Environmental change and vulnerability in the Usangu plain, southwestern Tanzania: Implications for sustainable development. *International Journal of Sustainable Development and World Ecology* 14(2), 145–159.

Matrosov, E. S., Harou, J. J. & Loucks, D. P. (2011) A computationally efficient open-source water resource system simulator – Application to London and the Thames Basin. *Environmental Modelling & Software,* 26(12), 1599–1610.

McCully, P. (2001) *Silenced Rivers: The Ecology and Politics of Large Dams.* Zed Books Ltd, London.

Ramsar (2012) Tana River Delta added to the Ramsar List. http://www.ramsar.org/cda/en/ramsar-news-archives-2012-kenya-tana/main/ramsar/1-26-45-520%5E25948_4000_0__ (accessed 09 July 2013).

Reed, P. M. & Kasprzyk, J. (2009) Water Resources Management: The Myth, the Wicked, and the Future. *Journal of Water Resources Planning and Management-Asce* 135(6), 411–413.

Renofalt, B. M., Jansson, R. & Nilsson, C. (2010) Effects of hydropower generation and opportunities for environmental flow management in Swedish riverine ecosystems. *Freshwater Biology* 55(1), 49–67.

Richter, B. D., Baumgartner, J. V., Powell, J. & Braun, D. P. (1996) A method for assessing hydrologic alteration within ecosystems. *Conservation Biology* 10(4), 1163–1174.

Richter, B. D. & Thomas, G. A. (2007) Restoring environmental flows by modifying dam operations. *Ecology and Society* 12(1).

Skoulikaris, C., Ganoulis, J. & Monget, J. M. (2009) Integrated modelling of a new dam: a case study from the "HELP" Mesta/Nestos River. In: *18th World Imacs Congress and Modsim09 International Congress on Modelling and Simulation: Interfacing Modelling and Simulation with Mathematical and Computational Sciences*, 4050–4056.

Voinov, A. & Bousquet, F. (2010) Modelling with stakeholders. *Environmental Modelling & Software* 25(11), 1268–1281.

Watts, R. J., Ryder, D. S., Allan C. & Commens S. (2010) Using river-scale experiments to inform variable releases from large dams: a case study of emergent adaptive management. *Marine and Freshwater Research* 61(7), 786–797.

WCD (2000) *Dams and Development: A New Framework for Decision-Making: Report of the World Commission on Dams.* Earthscan Publications, London.

Welp, M. (2001) The use of decision support tools in participatory river basin management. *Physics and Chemistry of the Earth Part B-Hydrology Oceans and Atmosphere,* 26(7–8), 535–539.