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Towards an optimal integrated reservoir system management for the Awash River Basin, Ethiopia

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Abstract. Recently, the Kessem-Tendaho project is completed to bring about socioeconomic development and growth in the Awash River Basin, Ethiopia. To support the reservoir Koka two new reservoirs where completed with extensive infrastructure for irrigation projects. The conflicting management goals of energy production at three hydropower stations and basin wide water supply for various sites require an integrated reservoir system management for best socioeconomic benefits. To satisfy the multi-purpose nature of the reservoir system a multi-objective parameterization-simulation-optimization model is developed. Different Pareto-optimal trade-off solutions between water supply and hydro-power generation are provided for two scenarios, i) recent conditions and ii) future planned increases for Tendaho and Upper Awash Irrigation projects. Reservoir performance is assessed by i) rule curves with a high degree of freedom; this allows for best performance, but may result in rules curves to variable for real word operation; ii) smooth rule curves, obtained by artificial neuronal networks. The results show a small performance penalty for the smooth rule curves.

1 Introduction

Recently, the Kessem-Tendaho Project is completed to bring about socioeconomic development and growth in the Awash River Basin, Ethiopia. To support the existing Koka reservoir two new reservoirs where completed together with extensive infrastructure for irrigation projects. Besides the basin wide supply of water of municipal water, irrigation water for various agricultural sites and sugar cane plantations, the reservoirs are also responsible for flood protection. Hydropower production is a critical factor for the local economy. Koka reservoir provides hydropower through hydro-power station Awash I and supports the hydro-power stations Awash II and III. Development plans project an increase of 40,000ha in Tendaho Irrigation project and expansion of upper Awash irrigation site by two fold.

For maximum socioeconomic gains an integrated reservoir system management is crucial. To achieve this, optimal operational policies for all reservoirs are needed. Mathematical optimization models are used widely in water resources management to provide operational policies for optimal integrated reservoir management (Loucks et al., 1981). To account for multi-purpose nature of the Awash River Basin reservoir system a multi-objective parametrization-simulation-optimization model is developed in this study. In a reservoir management simulation model is coupled to an optimization algorithm to iteratively search for better operational policies. The advantages of PSO over other common optimization techniques are discussed in Koutsoyiannis and Economou (2003).

Yibeltal (2013) analysed the water audit of Awash Basin using WEAP model on the basis of three different scenarios (Expansion of irrigation area, improvement of irrigation and Climate change). Berhe et al. (2013) assessed the water allocation for future development scenarios in a modelling study using MODSIM model (Labadie, 2007). The authors concluded that the irrigation level of 2005 will be sustainable up to year 2028. Additional storage at or upstream of Koka Dam may be necessary due to sedimentation in 2038. However hydropower production is modelled on purely opportunistic basis, because releases from the reservoir respond only to irrigation demands.

This study is a first step to provide optimal rule curves for an integrated management of the reservoir system for possible compromises between energy production and basin wide water supply for, i) recent conditions and ii) the planned increase of 40,000ha in Tendaho Irrigation project and expansion of upper Awash irrigation site by two fold. Sustainability is assessed in two steps. The maximum performance of the reservoir system is assessed with curves with a high degree of freedom. This allows for best performance, but results in non-smooth monthly rule curves which are not favoured by reservoir operators. Therefore also smoothness constrained rule curves are optimized by using a surrogate function. Possible losses of reservoir system performance are analyzed.

2 Material and Methods

2.1 Awash River Basin

Awash River basin is one of the twelve basins in Ethiopia. The basin has a total catchment area of 110,000 km^2 and total length of 1200 km. The Awash River originates from a high plateau, which is the central Ethiopian Highland with an elevation up to 3000 m.a.s.l..

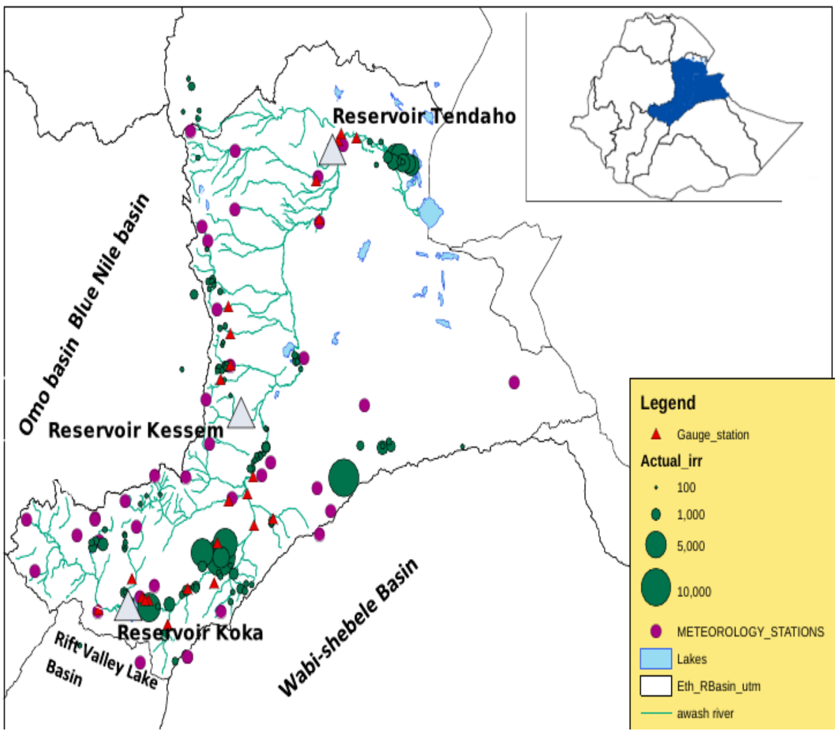

Figure 1: Map of Awash River Basin (adopted from Gebretsadik, 2015)

It descends in the Rift Valley after passing Koka Reservoir and flows into at Lake at 250 m.a.s.l near the border of Ethiopia (Figure 1). Awash River has 15 important tributaries which significantly contribute for the flow of the main course.

The land use is dominated by exposed rock with about 34.9 % followed by cultivated land of about 27 % and open shrub land (20.9%). The seasonal distribution of rainfall with two distinct rainy periods is caused by a shifting of the Inter Tropical Convergence Zone. The March to May season is the main rainfall season yielding 100-200 mm per month, followed by a lesser rainfall season in October to December with 100mm per month. More detail about the basin give Berhe et al. (2013).

2.2 Setup of the parameterization-Simulation-Optimization Model

For all reservoirs upper rule curves define the top of conservation storage zones and lower rule curves define the top of buffer storage zones. Important reservoir characteristics are summarized in Table 1. The given buffer zone for reservoir Koka is a lower constraint and the actual buffer zone may be greater after optimization. Also all conservation zones are subject to optimization and change due to optimization; here the upper constraints are given. Storage above the conservation zone is designated for flood protection.

Table 1: Important reservoir characteristics, (*) denotes upper constraint and (**) denotes lower constraint for optimization

Reservoir	Dead zone (10^6 m^3)	Buffer zone (10^6 m^3)	Conservation zone (10^6 m^3)	Total storage (10^6 m^3)
Koka	8	300*	1000*	1186
Kessem	200	200	500*	800
Tendaho	364	364.6	1610*	1860

Awash I hydropower station, located at Koka reservoir houses three units with 14.4 MW capacity. Average and firm production of hydropower are 110 GWh per annum and 80 GWh per annum respectively. Awash II and Awash III run-of-river hydropower stations are located 25 km and 28 km of the Koka dam. Both stations feature an installed capacity of 34MW. The regulated turbine flow is restricted to 40 m^3s^{-1}. Reservoir Koka serves water for energy production only from the conservation zone; water in the buffer zone is preserved for supply of irrigation and municipal demands.

Several problems arise from an unsatisfactory data basis. Almost no data is available to model the hydrological characteristics of the Gedabbesa swamp, which has high influence in the water allocation (Berhe et al., 2013). Therefore, Gedabbesa swamp is modelled as follows: Average monthly patterns for losses to the swamp and returns from the swamp are calculated from gauging stations upstream and downstream of the swamp. In the model all flow exists at node 702 and the difference between the monthly pattern of losses and the flow to node 702 is returned at node 703. Additional mean monthly returns enter at node 701. Similarly, little data is available for Lake Abe, the terminal lake of Awash River.

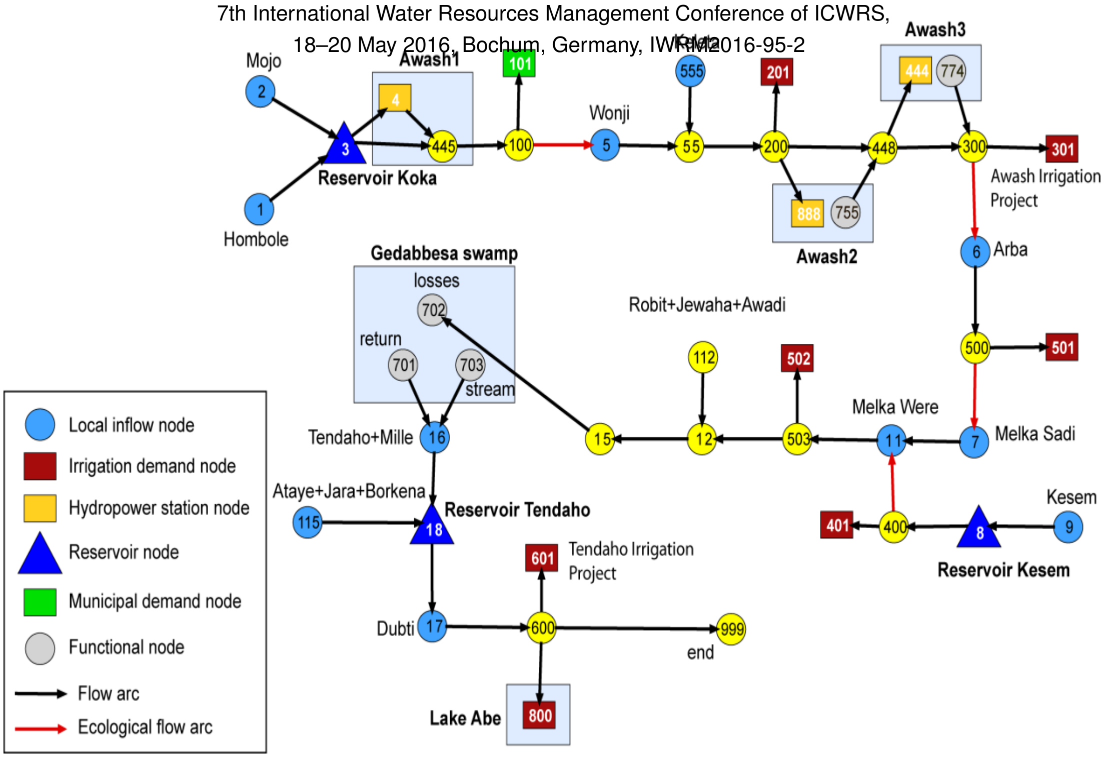

Figure 2: Schematic representation of Awash Basin multi-reservoir system in OASIS.

The evaporation from Lake Abe is estimated with the Penman equation for the average sea surface area (Gebretsadik, 2015). The monthly evaporation is set as a demand to account for sustainability.

For PSO, in this study we link the multi-objective evolution strategy MO-CM-ES (Igel et al. 2007) to the OASIS reservoir simulation model (Hydrologics, 2009). OASIS distributes the water optimally of each time step using mixed-integer linear programming. Figure 2 gives an overview about the implementation of the multi-reservoir system in OASIS. Functional features are coded in the OCL language of OASIS. For the simulation of reservoir management 21 years data (1981-2001) is used in this study. Irrigation demands for the demand nodes in the model and the evaporation rates and the seepage losses for the reservoirs which are taken from Gebretsadik (2015).

3 Problem formulation

The competing management goals of water supply for irrigation projects, municipal, ecology and the production of hydropower in the Awash river basin requires the formulation of two objective functions. Objective function F_1 minimizes the sum of all deficits over all demands

$$\min(F_1) = \min\left\{\sum_{t=1}^{240}\left(D_{\mathrm{Mun},t} + D_{\mathrm{Irr},t} + D_{\mathrm{Eco},t}\right)\right\}, \quad (1)$$

where for each time step t, $D_{\mathrm{Irr},t}$ is the sum of all deficits in the supply for all irrigation projects, $D_{\mathrm{Mun},t}$ is the deficit in municipal supply and $D_{\mathrm{Eco},t}$ is the sum of all deficits in ecological minimum flow support for all nodes as given in Figure 2. Objective function F_2 maximizes the energy production of the three hydropower stations in the basin

$$\max(F_2) = -1 \cdot \min\left\{\sum_{t=1}^{240}\left(-E_{\mathrm{Awash1},t} - E_{\mathrm{Awash2},t} - E_{\mathrm{Awash3},t}\right)\right\}, \quad (2)$$

where $E_{\mathrm{Awash1},t}$ is the energy production at hydropower unit Awash1 and $E_{\mathrm{Awash2},t}$ and $E_{\mathrm{Awash3},t}$ at units Awash2 and Awash3, respectively. The produced energy is calculated as $E = \eta\, g\rho Q_{\mathrm{T}} H$ (MWh), with efficiency of $\eta = 0.9$ (-) for all units, turbine flows Q_{T} (m^3s^{-1}) for all units is given by OASIS model, as is the head H (m) for Awash1. For Awash2 and Awash3 run of river units the head is fixed at 60m.

The models are considered which vary in the formulation of the rule curves. In model MOD1 the lower rule curve of reservoir Koka is kept constant. For model MOD2 this lower rule is seasonally variable. Decision variables for MOD1 and MOD2 are the storage control volumes. An unconstraint and bounded formulation from Müller (2014) is used. Smooth variable rule curves for MOD3 are obtained by formulating the rule curves with an artificial neuronal network

$$Z_s^k = \alpha_{1,l\cdot k} + \sum_{n=1}^{2}\left\{\alpha_{2,k\cdot n} \cdot \mathrm{tansig}\left(\alpha_{3,k\cdot n} \cdot \sin(T) + \alpha_{4,k\cdot n} \cdot \cos(T) + \alpha_{5,k\cdot n}\right)\right\} \quad (3)$$

$$\forall (s = 1, \ldots, 12; l = 1, \ldots, 5; k = 1, \ldots, 4),$$

subject to $Z^{\mathrm{buffer}} \geq Z_s^{k=1} \geq Z_s^{k=2} \geq Z^{\mathrm{cons}}$ (for Koka reservoir) and $Z^{\mathrm{buffer}} \leq Z_s^k \leq Z^{\mathrm{cons}}$ (else). $Z_{s,l}^k$ is a storage control volume from: k=1 the upper rule curve or k=2 the lower rule curve of reservoir Koka or for k=3 and k=4 the upper rule curves for reservoirs Kessem and Tendaho. $s = 1, \ldots, 12$ enumerates the months of a year and the decision variables are hyperparameter α. Constraints for the buffer zone Z^{buffer} and conservation zone are given in Table 1. T codes the cyclostationarity and runs from $-\pi$ to $+\pi$ for $s = 1, \ldots, 12$. The approach follows Castelletti et al. (2012), who use artificial neuronal networks for operational rules in a different context. The decision variables sets are evaluated by simulation model OASIS, which handles all physical constraints like maximum flows and mass conservation.

4 Results and Discussion

Optimization runs for the three models where conducted with 60000 model evaluations and a population size of 48 each. The resulting Pareto-Fronts are depicted in Figure 3a for recent conditions and in Figure 3b for the future development plan.

With nearly no deficits under recent conditions and 440 GWh per annum energy production, MOD1 performs best when preference is set to minimizing deficits (Objective F_1). The rule curve (RC) behind this solution is unique (Figure 3a, lower part), because of the size of the conservation zone in May. For the high energy production preference up to 442 GWh per annum, the performance of the reservoir under constant lower (MOD1) and varying lower (MOD2) RCs is similar. The size buffer zone of reservoir Koka is zero m^3 for all solutions of MOD1, MOD2 reserves water for demands especially in January, August, October and December.

For reservoir Tendaho MOD3 proposes a draw down period from March to April and refill in July for low deficits. Surprisingly, RCs for high energy production require an empty reservoir Tendaho. MOD1 and MOD2 prefer a lower storage throughout the year and only a major fill in July; this reduces evaporation losses and support from upstream reservoirs. The

RCs from all models show the same general course; yet, MOD2 produces the most variable RCs with several draw downs and refills.

Under future development plans no model dominates the others in overall performance, but the models cover different spaces of the Pareto-space. This might be due to the formulation of the RCs or an optimization related problem. In general, deficits under increases demands can be as low as $2 \cdot 10^6$ m^3 when energy production is reduced to 424 GWh per annum. In general, the energy production decreases in average about 3 % under future plans. For reservoir Koka higher storages are proposed from January to April for MOD3. RCs for Kessem reservoir are much smoother for MOD3 in comparison to MOD1. The same shapes of RCs are evident for MOD1 and MOD3, MOD2 proposes an additional refill in August.

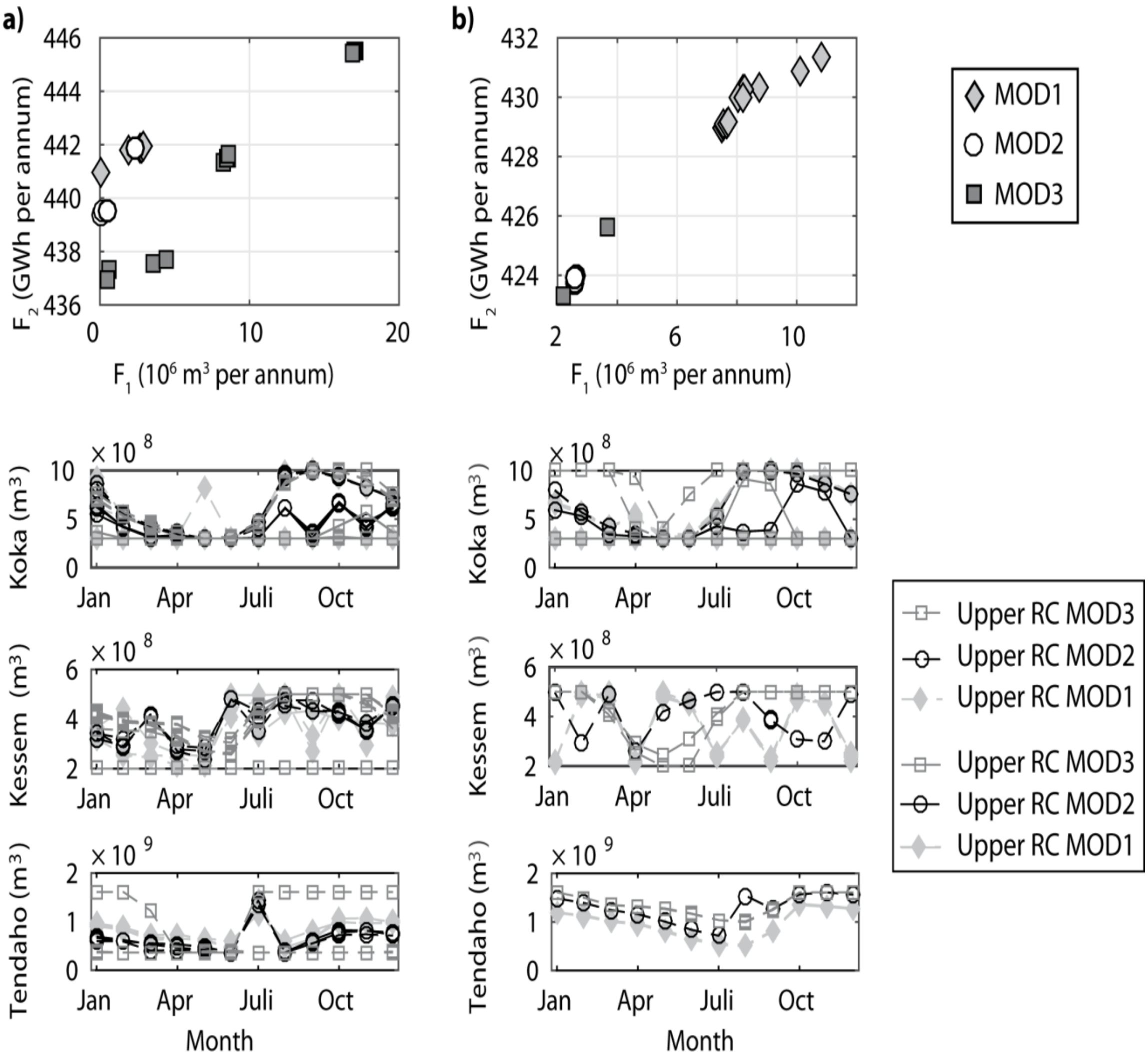

Figure 3: Pareto-Fronts and rule curves for (a) recent conditions and (b) the development plan.

5 Conclusion

An integrated reservoir management for the multi-reservoir system in the Awash River Basin is needed to maximize socioeconomic benefits. Multi-objective optimization is carried out for conflicting management goals of energy production and basin wide water supply. Future development plans for expansion in irrigation sites are considered. Reservoir performance is assessed by rule curves with a high degree of freedom and smooth rule curves, obtained by artificial neuronal networks. For recent conditions the smoothness constraint rule curves cause a performance penalty in the reservoir management. Under the development plans this cannot be observed. However, the trade-offs under both scenarios and for all considered models are huge in terms of deficit, while relative gains in energy performance are negligible. Therefore the decision maker may choose his preferred management by special consideration of the underlying rule curves.

It is advised to conduct studies to enhance understanding of Gabeddesa Swamp. Additionally shortcomings in the model, like missing translation times for water routing and irrigation efficiencies need to be addressed.

6 Literature

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