

A MANAGEMENT SYSTEM FOR OPTIMIZING OPERATING RULES OF MULTIPURPOSE RESERVOIRS ALLOWING FOR BOTH EXTREME FLOODS AND ECOLOGICAL PERFORMANCE

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ABSTRACT: An important tool for investigating the effects of reservoir operation is a model-based management system for river basins comprising all reservoirs, including their specific operating rules affecting the downstream reaches, as well as the entire river network. For the optimization of operating rules of multipurpose reservoirs an assessment system is introduced. The assessment system covers (I) hydraulic and hydrological risks along the downstream river reach, (II) safety of dams, (III) reliability of water supply and (IV) ecological performance. A new dynamic long-term operating rule is introduced where the reservoir releases depend on the reservoir inflow. The operating rules are optimized using evolutionary algorithms. Results show that the long-term dynamic operating rule is superior to the static operating rule of the status quo. The management system is also utilized in real-time simulation for adjusting short-term operating rules during critical flood events. The result of this multi-objective optimization problem is a set of solutions with different degrees of trade-off between the objectives (a so called Pareto-front). These results help to improve the decision making of the authorities and lead to more comprehensibility.

Key Words: multipurpose reservoirs, hydraulic risk, safety of dams, environmental flows, evolutionary algorithms

1. INTRODUCTION

Dams in the low mountain ranges of Germany and other European countries play an important role in providing flood protection for downstream areas. Most of the German multipurpose reservoirs serve drinking water supply as well. Other utilizations are low flow regulation for downstream reaches during dry seasons, hydropower generation and recreation. The different purposes of reservoirs are often competing (e.g. drinking water supply versus flood protection), in other cases, they are complementary. To meet all the different purposes, integrated management systems are required, covering both long- and short-term operating rules.

This paper aims at presenting a set of tools allowing for the optimization of operating rules for multipurpose reservoirs, primarily with regard to the mitigation of flood risks while at the same time

attempting to achieve an ecologically oriented reservoir operation, which is especially significant with regard to the implementation of the European Water Framework Directive (EU, 2000), and of course the sustainment or, where possible, the improvement of any other utilizations.

In order to evaluate a set of operating rules concerning different objectives of the optimization problem, the reservoir – or system of reservoirs – is modelled using a reservoir operation model. Simulations of the reservoir operation then provide information on how a particular set of operating rules performs with regard to each objective. Short-term and long-term operating rules are optimized using a multi objective evolutionary algorithm to determine a Pareto optimal set of solutions. The optimization of the short-term operating rules requires a detailed and preferably long precipitation forecast. The optimized long-term operating rules affect the flood risk primarily by altering the initial reservoir water levels.

Within a case study the management system is applied to the Weisseritz River Basin, located in the low mountain ranges of eastern Germany which is equipped with three multipurpose reservoirs. The reservoir system Lehmuehle-Klingenberg is a serial system and is mainly used for water supply and flood protection. The reservoir Malter is situated in parallel to the reservoir system Lehmuehle-Klingenberg and is mainly used for recreation, hydropower production and flood protection.

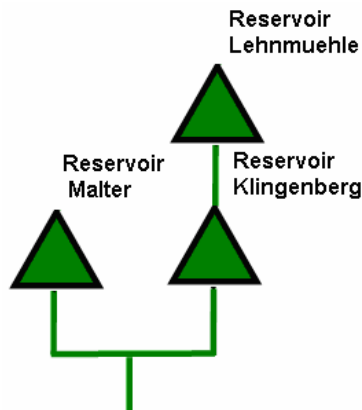


Figure 1: Schematic view of the reservoir system.

2. APPROACH

2.1 Reservoir simulation

The reservoirs and their operation are simulated using the software TALSIM (Ostrowski et al., 2000). This river basin model is capable of simulating complex reservoir operating rules and also comprises conceptual rainfall-runoff and channel routing modules. In the model, operating rules are defined as relationships between system states and reservoir releases. Both linear and non-linear relationships are possible, as well as the definition of reservoir zones (Lohr, 2001). This allows for the modeling of very complex operating rules.

We distinguish between long-term operating rules that govern a reservoir's operation in general and short-term operating rules that come into effect and override the long-term operating rules in the case of a flood event. To model the hydrological processes sufficiently a time step size of one hour is used for the short-term simulation and a time step size of one day is used for the long-term simulation.

2.2 Reservoir operating rules of the status quo

The downstream reservoir's releases depend on the actual storage volume:

$$[1] Q_{out} = \begin{cases} Q_{in} & (S > S_{target} \wedge Q_{in} < Q_{max}) \vee (S < S_{min}) \\ Q_{max} & S > S_{target} \wedge Q_{in} \geq Q_{max} \\ Q_{min} & S \leq S_{target} \end{cases}$$

where S [m^3] is the actual storage volume, S_{target} [m^3] is the reservoir target level, Q_{out} [m^3/s] is the reservoir release, Q_{in} [m^3/s] is the inflow to the reservoir, Q_{max} [m^3/s] is the maximum total discharge of the outlets and spillways, Q_{min} [m^3/s] is a constant minimum flow and S_{min} [m^3] is the minimum operating volume.

The water supply of the reservoir system Lehmuehle-Klingenberg is determined by three supply levels ($S_I - S_{III}$) which are specific for each month and ensure a future deficit probability of 99 %.

$$[2] Q_{ext} = \begin{cases} Q_{ext,99\%,SI} & S_{tot} \geq S_I(M) \\ Q_{ext,99\%,SII} & S_I(M) \geq S_{tot} \geq S_{II}(M) \\ Q_{ext,99\%,SIII} & S_{II}(M) \geq S_{tot} \geq S_{III}(M) \\ 0.0m^3/s & S_{tot} \leq S_{min} \end{cases}$$

where $Q_{ext,99\%,SI-III}$ [m^3/s] is the water supply release, S_{tot} [m^3] is the total actual storage volume of the reservoir system Lehmuehle-Klingenberg, S_{max} [m^3] is the maximum storage volume and M is the month.

2.3 Multi-objective optimization

A multi-objective optimization problem (MOP) has a number of objective functions which are to be minimized or maximized. The decision variables within a lower and an upper bound constitute a decision variable space. A solution x is a vector of N decision variables ($x=x_1, \dots, x_N$). The objective functions constitute a multidimensional space called the objective function space. A solution x is called Pareto-optimal when there is no solution x' that will improve at least one objective function value without worsening at least one other objective function value.

To solve the MOP, a state-of-the-art Multi-Objective Evolution Strategy MOES (Muschalla, 2008) is used. The selected optimization algorithm, which is based on the concept of domination and Pareto optimality, allows the evaluation of a multitude of objectives and constraints simultaneously. To facilitate the simulation-based evaluation of the objectives mentioned above, the optimization algorithm and the employed simulation model are coupled in a common software shell, providing fully automatic interfaces between the optimization and simulation tools.

The software can be used to find optimal long-term operating rules as well as optimal short-term operating rules in case of flood events including precipitation forecasts.

2.4 Target objectives for optimization

(I) The risk caused by inundation is evaluated using discharge-damage functions. Lateral inflow from sub catchments downstream is considered within the optimization system in order to evaluate the total effects of the reservoir operating rules in terms of inundation. Thus the river system is already divided into sections determined by the distributed rainfall-runoff modeling. The water levels of these predefined river sections are simulated using the one dimensional hydrodynamic model HEC-RAS. The computed water surfaces for each river section are exported to HEC-GeoRAS, where they are intersected with digital

elevation and land use data. Depending on the inundation depth and the land use, damage functions are applied and totaled in order to determine an integral relationship between discharge and damage. Generalized damage functions for each kind of land use are applied. Square functions are used where the damage D depends on the inundation height h_i , scaled by a factor f depending on the type of land use, e.g. for areas with buildings.

$$[3] D = f \cdot \sqrt{h_i}$$

Agricultural and infrastructural damages are considered with specific monetary values per inundation area.

The hydraulic safety of dams depends mainly on the required freeboard, which is influenced by meteorological factors like the wind velocity, duration, direction and reservoir specific factors like the fetch, the shape of the water surface, the reservoir geometry and the construction of the dam crest. Both the wind setup, caused by wind stress on the water surface and leading to a vertical rise of the still water level at the face of the dam and wave run-up being the elevation above the stillwater level to which water from a specific wave will run up on the dam slope have to be assessed in order to be able to parameterize dam safety. The wind setup h_{wi} can be computed using the frequently used Zuider Zee formula. The non breaking run-up R_{nb} of non-breaking waves can e.g. be calculated according to Pocklington (1921):

$$[4] R_{nb} = H \cdot \sqrt{\frac{\pi}{2\alpha}}$$

where 2α is the amplitude at an antinode of a standing wave in deep water and H the wave height. The irregular run-up $R_{irregular}$ of breaking waves can be estimated from DVWK 1997:

$$[5] R_{irregular} = k_R \cdot \sqrt{\overline{H} \cdot \overline{L}} \cdot \sin \beta$$

where k_R is the roughness, \overline{H} the average wave height, \overline{L} the average wave length and β the slope angle. The total freeboard f is obtained as follows:

$$[6] f = R + h_{wi}$$

(III) The security of water supply provision from a reservoir is evaluated by considering the average reservoir releases. Within the long-term optimization the objective is to maintain $Q_{ext,99\%,SI}$.

During a flood event, the short-term operating rules cause valuable water to be released through the bottom outlet in order to reduce the reservoir level. Thus short-term operating rules also affect water supply security, especially the actual water supply.

(IV) Dams have a multitude of negative environmental impacts (Collier et al., 1996; Nilsson et al., 2000; Bunn et al., 2002). With few exceptions (Willmitzer, 2002), most dams profoundly alter the flow regime of the river on which they are built, which has a damaging effect on a large variety of riverine ecosystem aspects (Poff et al., 1997). The degree to which a natural flow regime is modified by reservoir operations is assessed using the Indicators of Hydrologic Alteration (IHA) (Richter et al., 1996). For this, long-term hydrographs of a 'natural' flow regime (either recorded or simulated) are compared to the flow regime produced as a result of reservoir operations in order to calculate the 'Hydrologic Alteration' for each of the 32 IHA Parameters. The Range of Variability Approach (RVA) is then used to define a range of variation in each of the 32 IHA parameters as initial flow management targets. This approach is based on the aquatic ecology theory concerning the critical role of hydrologic variability, and associated characteristics of timing, frequency, duration, and rates of change in sustaining aquatic eco-systems (Richter et al., 1997).

Reducing the loss of water from the hypolimnion in case of a flood event besides actual water supply concerns also covers ecological concerns due to cold water pollution downstream (Lugg, 1999).

3. SHORT-TERM OPTIMIZATION USING PRECIPITATION FORECAST

The operating rules of the status quo (equation 1) might be suitable in general but if a forecast of the temporal and spatial distribution of precipitation within the river basin is available, the reservoir releases can be optimized using MOES. Assuming a “perfect” precipitation forecast, the fixed operating rules can be replaced by time-dependent releases Q_{out} which are to be optimized. Optimizing every single time step would lead to a large number of decision variables and cause long computation times. For this reason, the releases are approximated by release intervals $i=(i_1, \dots, i_{ni})$ whose duration d_i and quantity $Q_{out,i}$ are subjected to the multi-objective optimization. $Q_{out,i}$ is optimized directly and d_i is calculated by $d_i=t_{i+1}-t_i$ whereas t_i is subjected to the optimization. As t_1 and t_{ni} are given due to the simulation period $ni-1$ decision variables are to be optimized in terms of d_i and ni in terms of $Q_{out,i}$. This lead to the following number of decision variables:

$$[7] N = 2 \cdot ni - 1.$$

In addition to the precipitation forecast, a wind speed forecast is used to calculate freeboard ensuring sufficient dam safety. The required freeboard is used as a constraint within the optimization process in order to reduce the objective function space. The short term optimization problem comprises the following target objectives: (I+II+III) minimize the water level in each reservoir, (IV) minimize the total monetary damage downstream from the reservoirs and (V) minimize the loss of hypolimnion water from the reservoir Klingenberg due to releases through the bottom outlet.

An exemplary optimization using three release intervals for each reservoir is carried out for an extreme flood event in the Weisseritz river-basin based on a flood event in August 2002. The rainfall took 48 h. The simulation and optimization starts at the time when the rainfall event begins. 72 h of the event is simulated and optimized. It is assumed that the entire spatial and temporal distribution of the precipitation is known. The required freeboards for each dam are calculated assuming maximum wind velocities of up to 20 m/s. The resulting freeboards are shown in table 1. 3000 simulation were carried out in about 30 min of CPU time on a 3.00 GHz Pentium 4 processor resulting in a Pareto-optimal set of solutions (Figure 2). The Pareto-optimal set of solutions enables the user to validate possible solutions a posteriori. As there does not exist any functional relationship between some target objectives no clear 2D-Pareto-Front from the five dimensional objective function space can be projected (e.g. bottom outlet release of Klingenberg and Water level Z of Malter). In Figure 2, two examples are selected (solutions $x = 1132$ and $x = 1965$). Though solution $x = 1132$ results in lower damages than solution $x = 1965$, the small freeboard at reservoir Klingenberg does not match the dam safety requirements. If dam safety was the primary objective, the user would select operating strategy $x = 1965$. If the dams are not at risk due to high structural safety the user could select solution $x = 1132$ which causes less damage downstream. According to other consideration the user may select one different solution.

Table 1: Results of example solutions $x = 1132$ and $x = 1965$.

x	Damage [Mio. Euro]	Bottom outlet release [Mio. m ³]	freeboard f		
			Malter [m]	Lehnmuehle [m]	Klingenberg [m]
1132	69.5	9.4	0.68	1.74	0.15
1965	79.4	12.4	0.65	0.88	0.68
		required:	0.57	0.79	0.61

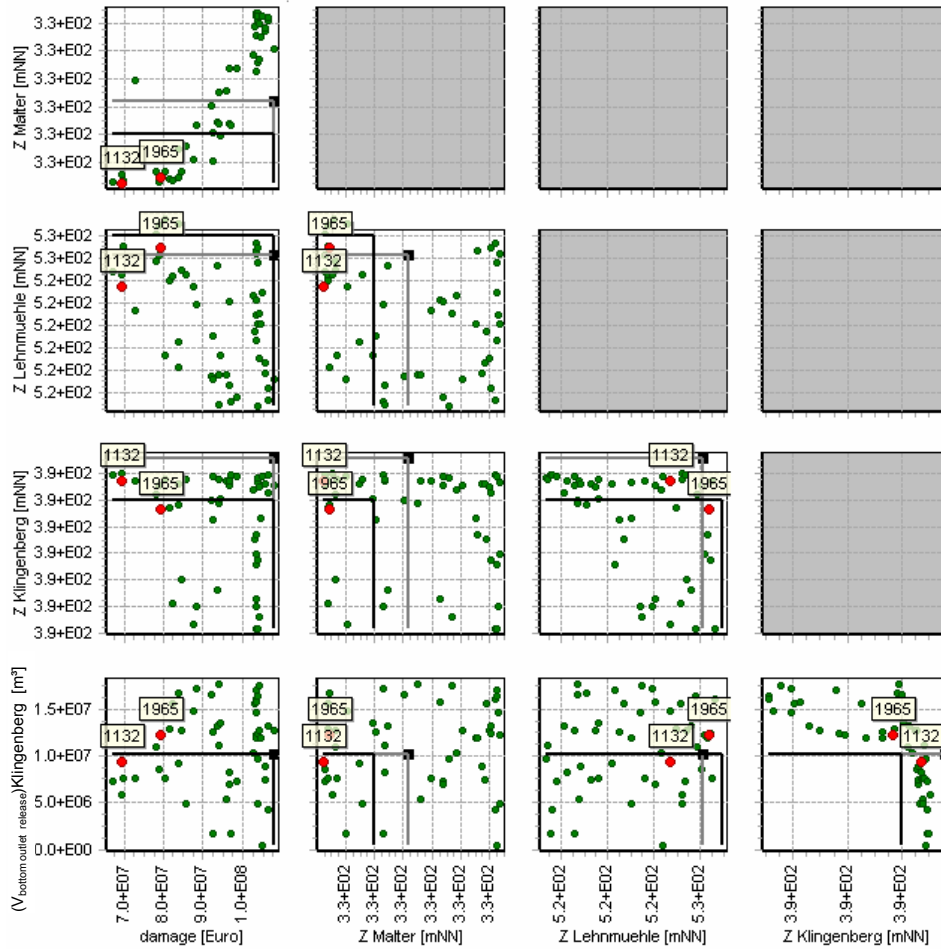


Figure 2: Scatterplot-matrix: set of Pareto-optimal solutions. The black lines mark the critical freeboard for ensuring dam safety. The grey lines and the black square mark the results from simulations of the status quo. The selected solution should be left below the black square to ensure sufficient dam safety.

4. LONG-TERM OPTIMIZATION

In order to improve the ecological performance of a dam (in terms of hydrologic alteration), it is advantageous to make reservoir releases dependent on the inflow into the reservoir, which in the case of the reservoir system Lehmuehle-Klingenberg can be regarded as a natural flow regime. This ensures that the existing variability in the natural flow regime is also reflected in the tailwater and avoids the necessity of having to reproduce a natural flow regime artificially.

For this, a dynamic operating rule was developed which links the discharge from the reservoir Q_{out} to the actual reservoir inflow Q_{in} by a multiplication factor F . This factor F is a function of the actual storage volume S . The general goal of reservoir operations regarding the storage volume is to keep the water level at the top of the normal operating zone, i.e. at the flood guide level S_{target} . When this storage level is reached, outflows should be equal to inflows minus any flows extracted from the system Q_{ext} (e.g. for water supply). An additional constraint is that releases should not exceed the permitted maximum discharge Q_{max} (in most cases this will be the no-damage discharge for the tailwater). Below this storage level, outflows should be reduced so as to fill the reservoir again, and above this level, outflows should be increased so as to lower the reservoir level again to the flood guide level S_{target} . This concept is illustrated in Figure 3.

$$[8] \quad Q_{out} = \begin{cases} Q_{in} \cdot F(s) - Q_{ext} & Q_{in} \cdot F(s) - Q_{ext} < Q_{max} \\ Q_{max} & Q_{in} \cdot F(s) - Q_{ext} \geq Q_{max} \end{cases}$$

The dynamic operating rule is defined by the function $F(S)$, which in its simplest form can be described using only two variables (one for the value of F when the storage volume reaches the dead storage, and one for the value of $F(S_{target})$).

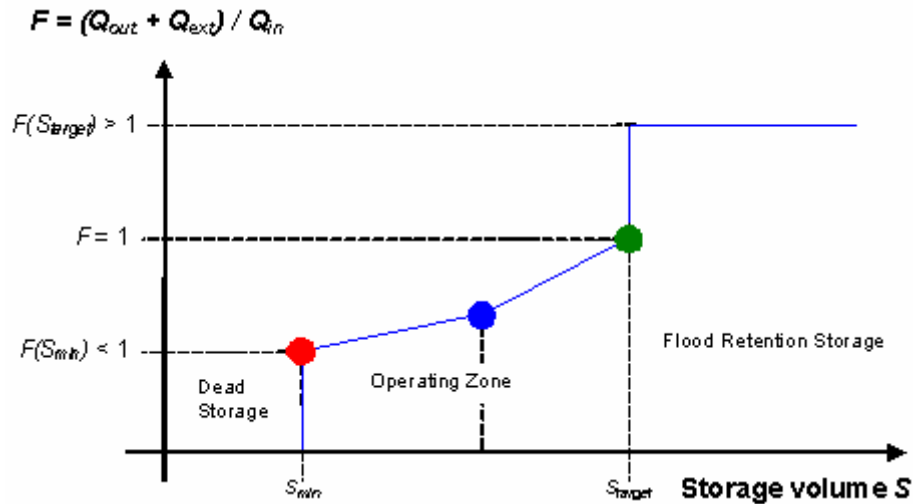


Figure 3: General concept of a dynamic operating rule for minimizing dam-induced hydrologic alteration.

For the optimization, the function $F(S)$ is approximated by supporting points with linear interpolation which yield three decision variables for each reservoir. Four objective functions are defined: (I+II) minimize the deviation from S_{target} for each reservoir, (III) minimize the difference to $Q_{ext,99\%,SI}$ (water supply) and (IV) maximize ecological dam performance (IHA parameters). The dead storage volumes are used as constraints.

The results of the simulation of the reservoir system Lehmuehle-Klingenberg over a 13-year period using such a dynamic operating rule can be depicted in a scatterplot matrix (Figure 4). The lower a value the better it is. It can be seen that ecological performance (IHA) and water supply ($d(Q_{ext,99\%,SI})$) are clearly competing objectives. The user can choose a solution which meets his demands a posteriori. Solution $x = 90$ leads to a lower ecological performance than solution $x = 464$ but ensures a better water supply safety. But compared to the status quo (black square in Figure 4) even solution $x = 90$ with lower ecological performance in relation to the optimization result improves the variability in reservoir releases and therefore the ecological performance.

In terms of flood risk-related objectives, both exemplary solutions result in lower storage levels over time, so more flood retention storage volume is available while at the same time the water supply safety is increased (Figure 5). Solution $x = 464$ for example, enlarges the flood retention storage volume by about 5 million m^3 .

These results show that the long-term dynamic operating rule is superior to the static operating rule of the status quo in all objectives.

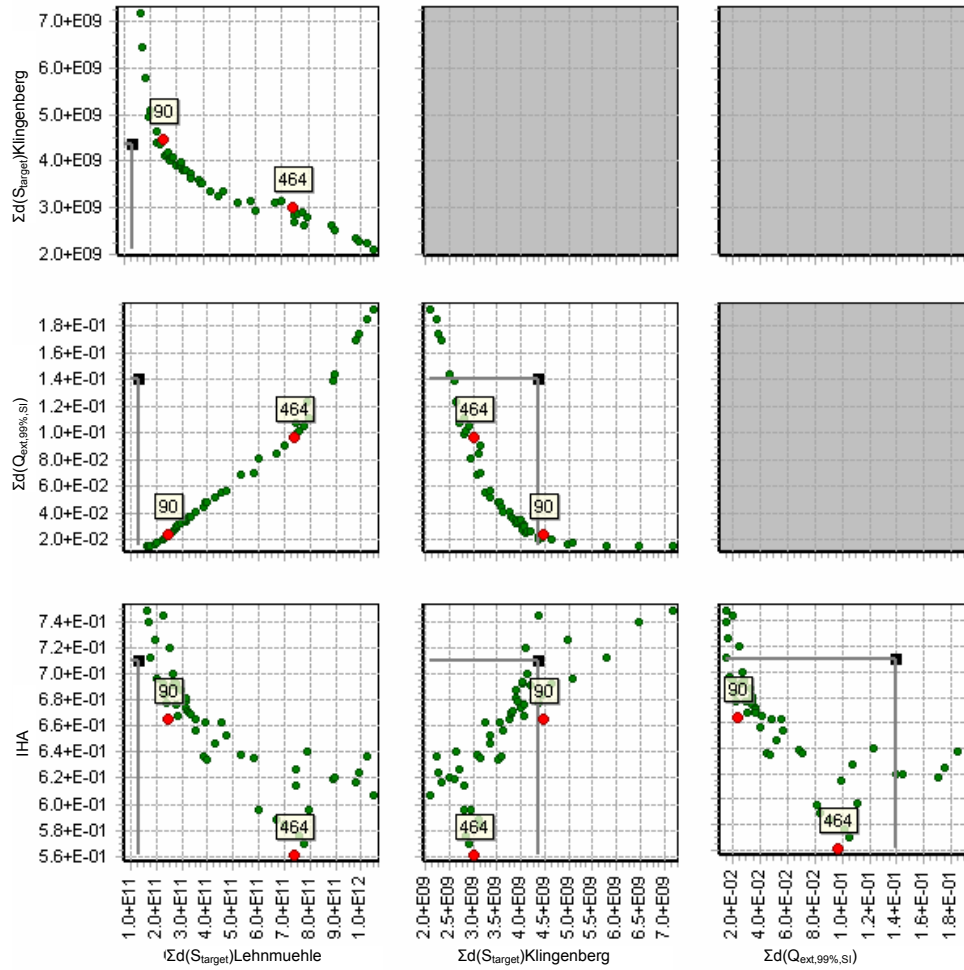


Figure 4: Relationship between four reservoir management objectives - water supply ($\Sigma d(Q_{ext,99\%,SI})$), ecological performance (IHA) and the deviation to S_{target} at each reservoir. Two solutions are marked ($x = 90$ and $x = 464$). The grey lines and the black square mark the results from simulation of the status quo.

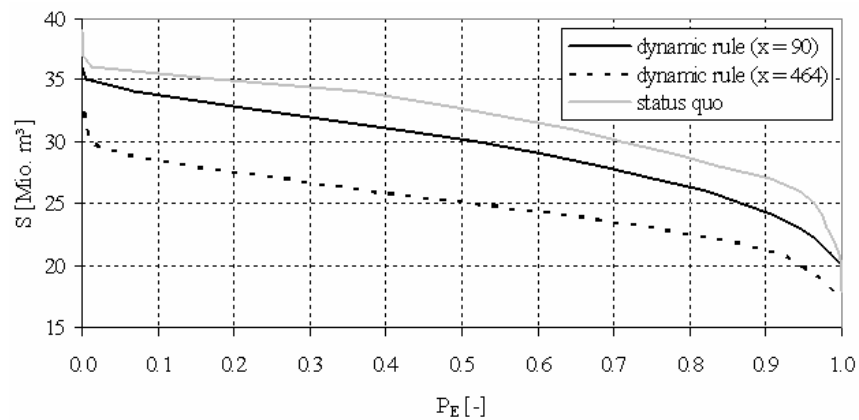


Figure 5: Comparison of exceedance probability P_E curves of reservoir storage volume of the reservoir system Lehnmuehle-Klingenberg.

5. CONCLUSIONS

Applying an evolution strategy to the multi-objective optimization problem with competing purposes of a multipurpose reservoir lead to a Pareto optimal set of solutions from which a user can select one solution by weighting the objective functions a posteriori. This method can be used as a management and decision support system to optimize short- and long-term operating rules. The optimization of the short-term operating rules requires a detailed precipitation forecast.

As the example results show, the presented method can achieve significant improvements in dam performance regarding ecology, water supply and flood protection.

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