FLOOD CONTROL AT MULTIPURPOSE RESERVOIRS CONSIDERING DOWNSTREAM HAZARDS AND WATER QUALITY

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Model-based reservoir management systems are indispensable for determining an optimal water resources management in river basins with multipurpose reservoirs. A recently developed management system will be described, using evolutionary algorithms to optimize both event-based and long-term operation of a reservoir system concerning multiple objectives with different units of measurement (Money, Dimensions, Ecology). The result are sets of so-called *Pareto* optimal solutions which represent the most useful compromises and can serve as a transparent information base for decision-making. In order to improve the ecological performance of multipurpose reservoirs, a dynamic operating scheme is implemented, which ensures that reservoir releases correspond to natural flow variability as far as possible. In addition water quality problems during the flood discharge and the release from selected layers of the water body will be discussed in brief.

INTRODUCTION

Multipurpose reservoirs play an important role in the low mountain regions of Germany as well as other European countries. They serve for flood protection, drinking water supply, low flow regulation for downstream reaches during dry seasons, hydropower generation and recreation. At the same time, most dams change the downstream flow regime of the impounded river which is affecting the variety of riverine ecosystems considerably (*Poff* et al., 1997).

Therefore it is necessary to find and optimize operating rules for both, the normal as well as for the flood event based operation while at the same time attempts are made to achieve an ecologically and water quality oriented reservoir operation.

METHODOLOGY

In the past several investigations have examined methods to optimize reservoir policy decisions (*Labadie*, 2004; *Yeh*, 1985). The use of evolutionary algorithms (EA) for optimizing reservoir operation has been gaining in popularity since the 1990s (e.g. *Oliveira & Loucks*, 1997; *Sharif & Wardlaw*, 2000; *Lohr*, 2001; *Ndiritu*, 2005; *Chen* et al., 2007; *Kim* et al., 2006). This trend is also due to advances in computer science, as evolutionary algorithms tend to be computationally intensive.

A main prerequisite is the precipitation forecast for the watershed with an appropriate resolution in space and time. In this study the rainfall-runoff processes and reservoir operation are simulated using the model BlueM.Sim. This river basin model is also 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).

The multi-objective optimization problem (MOP) has multiple 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 ($x=x_1,\ldots,x_N$). 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 (Fig. 1).

To solve this MOP, a state-of-the-art Multi-Objective Evolution Strategy algorithm (MOES, *Muschalla* 2008) is used. This 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 *Pareto*-optimal set of solutions can be visualized using a so called scatter plot matrix showing all $n\cdot(n-1)/2$ possible combinations of the objective functions each with a two-dimensional projection of the points of the approximated *Pareto*-front in the n-dimensional solution space.

The software can be used to find optimal *long-term* operating rules (normal operation) as well as optimal *short-term* operating rules in case of flood events including precipitation forecasts (flood control, flood routing).

The financial inundation damage downstream to minimize is quantified by means of stage-damage-relations for considered river sections. The water profiles are calculated with a hydrodynamic model (e.g. HEC-RAS, MIKE 11). Then the resulting water levels are merged with the digital terrain model and the types of land use. For each partial area the specific damages are found using appropriate stage-discharge-functions. Later these damages are summed up to yield the total discharge-damage-function.

The dam safety can be expressed by the minimum freeboard remaining during the flood event. The objective for the freeboard value is the required calculated value.

The release of good quality water from the deep layers (hypolimnion) during the flood control causes a worsening of the water availability so that the objective function of the discharge should become a minimum too.

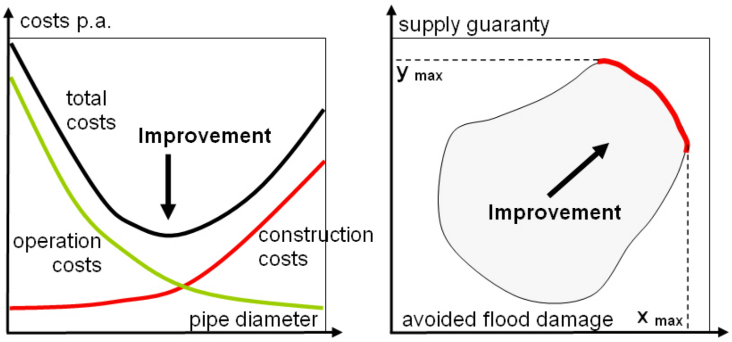

Figure 1 Two methods of optimization (here for only two objective functions): top: total costs/benefit, bottom: *Pareto* optimization

LONG TERM OPTIMIZATION

Dams have several environmental impacts on the impounded rivers (*Bunn & Arthington* 2002; *Collier* et al. 1996; *Ligon* et al. 1995; *Nilsson & Berggren* 2000; *Petts* 1984; *World Commission on Dams* WCD 2000). First of all, a reach of a flowing river is converted into an impounded reservoir, thus fundamentally changing the immediate environment of the dam. Secondly, dams act as a barrier between upstream and downstream reaches, inhibiting both the movement of species as well as the transport of sediment, nutrients and organic matter. Third, dams have an affect the water quality (temperature, suspended matter, sediment, dissolved oxygen, concentration of other dissolved materials). Finally, with few exceptions (*Willmitzer* 2002), most dams seriously alter the flow regime of the downstream river, which has an effect on a large variety of riverine ecosystem aspects (*Poff* et al. 1997, 2007). In this paper special emphasis is given to the ecological aspects, which demand dynamic, inflow controlled operational rules (dynamic controlled normal operation). The dam-induced hydrologic alteration should remain low.

The degree of alteration of the natural flow regime by reservoir operation can be evaluated by means of the Indicators of Hydrologic Alteration (= IHA, *Richter* et al. 1996). The IHA method is based on 32 biologically relevant hydrologic attributes, that are arranged in fife groups of the flow regime (quantity, time, frequency, duration and rate of alteration) to characterize the hydrologic variation during the year statistically. Hence the objective functions for the normal operation are the IHA-parameters of the flowing water without the influence of the impoundment. Due to the purpose of any dam this objective will never be fully achieved. Therefore the "Range of Variability Approach" (RVA, *Richter* et al. 1997) will be used, to define a range of variability for each of the IHA parameters as a provisional operation objective. This approach comes from the ecology of waters which attaches a great importance to the hydrologic variability as a "master variable" when conserving aquatic ecosystems (*Poff* et al. 1997).

In order to improve the ecological performance of the reservoir system, the currently used static operating rules are replaced by dynamic, inflow-driven operating rules and are then optimized with regard to multiple objectives. A time step of one day is used for the long-term simulations.

The reduction of dam-induced hydrologic changes can serve as an interim goal and as a starting point for an adaptive management process before comprehensive ecosystem research results are available (*Richter* et al. 1997). To achieve this it is advantageous to make reservoir releases dependent on the reservoir inflow. This ensures that the existing variability in the natural flow regime is also reflected in the tail water and avoids the necessity of having to reproduce a natural flow regime artificially by linking the discharge from the reservoir Q_{out} to the current reservoir inflow Q_{in} by a factor f_{dyn} being a function of the current storage volume S. The general goal of reservoir operations regarding the storage volume is to keep the normal operating level. 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 downstream reach). When the reservoir storage level falls below the normal water level, outflows should be reduced so as to fill the reservoir again, and above the normal water level the outflow will be increased.

The dynamic operating rules as described above were implemented in the simulation model BlueM.Sim and compared with the existing operation. The multi-objective optimization problem (in this study) can at least be described by objective functions that minimize the deviation of the actual water level from the operation level, that maximize the supply water level and that minimize the hydrologic alteration (as a function of the IHA parameters).

SHORT TERM OPTIMIZATION

In the case of a flood event short-term operation rules come into effect and override the long-term operating rules. For the short-term operation a time step of one hour has been used here to describe the processes with sufficient accuracy. *Froehlich* et al. 2008 used the BlueM.Opt programme to optimize short-term operating rules assuming one single precipitation forecast. However, in reality the actual precipitation always deviates from the temporal and spatial precipitation forecast. Most of the world's major operational weather prediction facilities commonly use ensemble weather prediction and provide warnings of heavy or prolonged rainfall for river basins or special warning regions. An ensemble forecast makes it possible to include a bundle of representative samples of possible future states into the optimization. In this work, an ensemble forecast is approximated by a simple stochastic rainfall generator to show the potential of the proposed optimization method. A future step would be to use real ensemble forecasts from e.g. a national weather service.

The used stochastic spatial rainfall generator started with 6-h-intervals and refined them into 1-h-intervals in a second step. By means of the related precipitation-runoff model the flood hydrographs with the appropriate peaks will be generated. The detailed procedure has been described e.g. by *Dittmann* et. al. 2009.

Because valuable water could be released through the bottom outlet in order to reduce the reservoir level, the short-term operating rules also affect water supply safety and water quality. The objective is to minimize the sum of the reservoir releases through the bottom outlets because the water withdrawn from the deep layers (hypolimnion) is often of higher quality (lower temperature, less eutrophication) than the surface water of the epilimnion (warm, algae, floating matter – Fig. 2).

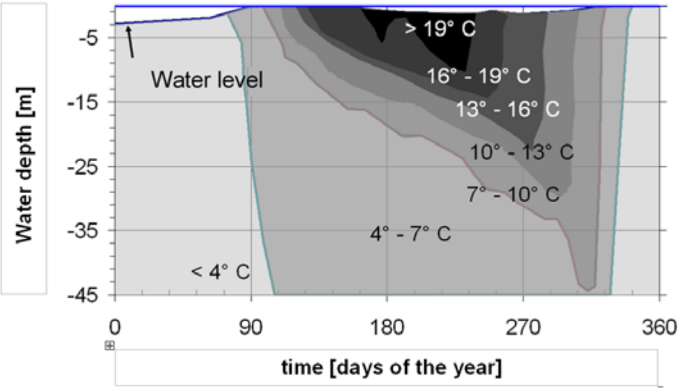

Figure 2 Seasonal water temperature distribution in a reservoir depending from the depth

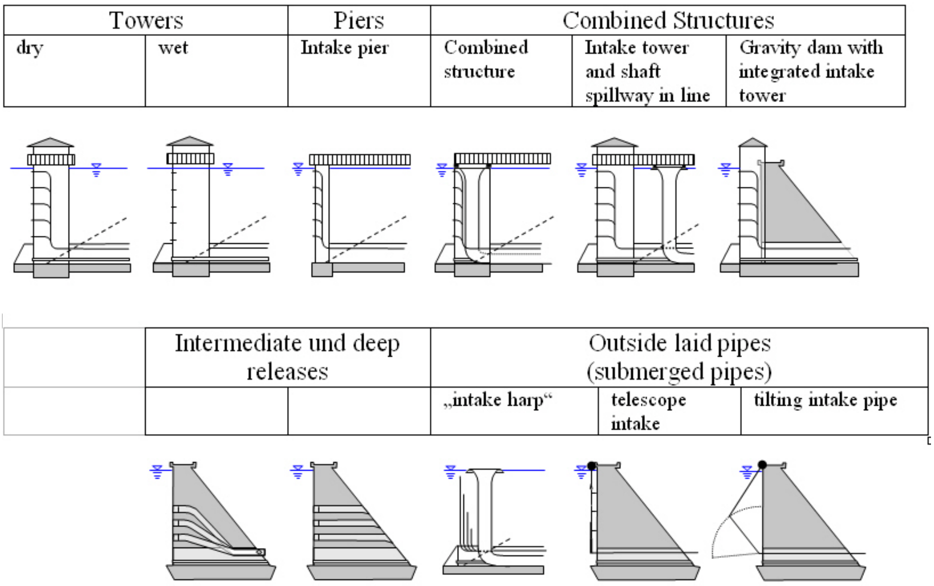

Figure 3 Overview of several types of staggered reservoir intake openings

The reservoir operating rule responsible for keeping the flood retention volume empty can be replaced by a time-dependent release curve and be subjected to optimization. The maximum releases are limited by the hydraulic capacity of the outlets.

QUALITY ORIENTATED DISCHARGE

In the past the focus of quality-oriented reservoir management was mainly directed to the long-term operation. Recently is has begun to play a more important role also with respect to the short-term operation, especially for the predischarge to increase the free storage space to catch the upcoming flood. In this case the water should be released from low quality layers of the impounded water body. This requires a series of inlets at different levels. Fig. 3 gives an overview of several types of staggered intake openings.

The main problem is that these intake devices are in general designed for relatively low flow velocities (1 - 3 m/s) and relatively low flow discharges. To enable a considerable contribution to the flood routing higher discharges and consequently higher velocities are needed. As the intake pipes are equipped with many valves and bends higher velocities could cause cavitation. This will be increased by flow separation with reduced cross sections and local vortexes and turbulence. Recently in several cases a redesign of intake devices at dam s has been carried out to make higher flow rates possible. These included larger diameters, smother bends, less bends, reposition of valves to the end of pipe, symmetrical to the approaching flow (*Pohl, Martin* 2009).

CASE STUDY

The Weisseritz River Basin including parts of the city of Dresden is located in the low mountain ranges of Saxony, Germany and equipped with three multipurpose reservoirs.

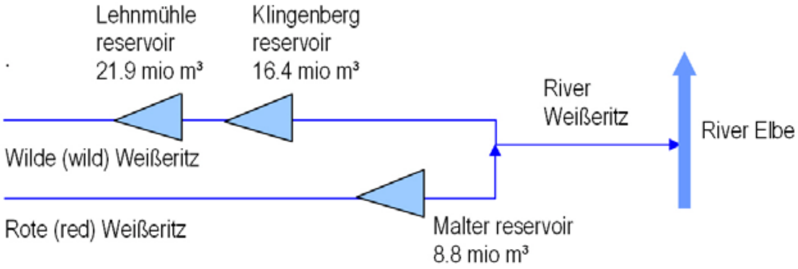

Figure 4 Schematic view of the reservoir system; maximum storage capacities are indicated.

The system has two serial und one parallel situated reservoirs that serve for tap water, flood protection, recreation and water power generation. Within the optimization system, hydropower generation is not considered here.

The **long-term evaluation** of the objective functions for each parameter set was carried out by simulating a time period of 39 years, using recorded inflows, with a time-step of 24 hours. Figure 5 shows a set of 50 *Pareto*-optimal solutions attained after 5,000 simulation runs, depicted in a (four-dimensional solution space) scatter plot matrix.

It can be seen that the ecological performance Z_{dyn4} and the water supply Z_{dyn3} (3rd line, 3rd column) are clearly competing objectives, while some of the other objectives seem to have lower correlations versus each other. For the sake of comparison with the status quo, solution no. 4528 has been selected, which provides the largest amount of water supply with $(Z_{dyn})_3$ = - 0,84 m³/s, which is close to the status quo with $\overline{Q_{ext}}$ = - 0,87 m³/s, but yields one of the lowest ecological performance values among the solution set. However, even in this – from an ecological viewpoint suboptimal – solution, the dynamic operating rule results in a downstream regime that resembles that of the inflow much more closely; in particular, many of the flow peaks occurring in the inflow also occur in the tail water.

While providing more fluctuation in reservoir releases, the dynamic reservoir operating rule on the other hand causes less fluctuation in reservoir storage levels, as can be seen in Fig. 6.

The result of the **short-term** multi-objective optimization is a set of *Pareto*-optimal solutions in the n-dimensional space shown in the scatter plot matrix in Figure 7. Each individual solution represents one possible trade-off between the objectives. The prioritization between the objectives is left up to the decision-maker. To validate the selected solutions, a further 77 rainfall samples are simulated. Additionally, two conventional operating strategies comprising a maximum release from the bottom outlet starting from the beginning of the simulation period are considered. Strategy S1 comprises a maximum release only of the reservoir Malter and strategy S2 comprises parallel maximum releases of the reservoirs Malter and Klingenberg.

Exemplarily four flood control strategies are compared in table 1 which can be regarded to be an optimum each (part of the *Pareto* front). Despite this they are different. E. g. L2 causes less damages downstream and less discharge of good water but provides also less freeboard and thus higher loading to the barrage.

The presented method for optimizing short-time operating policies is computationally extensive. The *Pareto*-front was sufficiently approximated after 10 hours of CPU-time on a Xeon 3.6 GHz computer. Thus the method is of only limited benefit for real any time optimization but could be used to create a database of robust operating policies. Such a database would contain different pre-optimized operating strategies categorized by initial storage of the reservoirs, initial soil moisture of the river basin and the forecasted length and amount of precipitation.

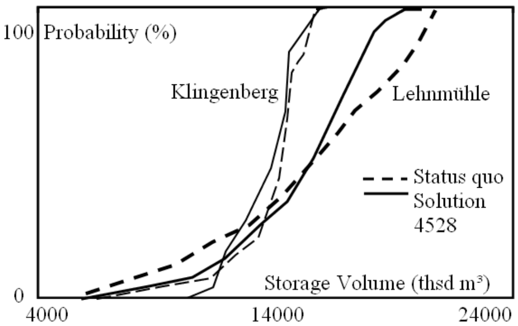

Figure 6.

Cumulative probability distribution of reservoir storage levels (comparison between solution 4528 and the status quo).

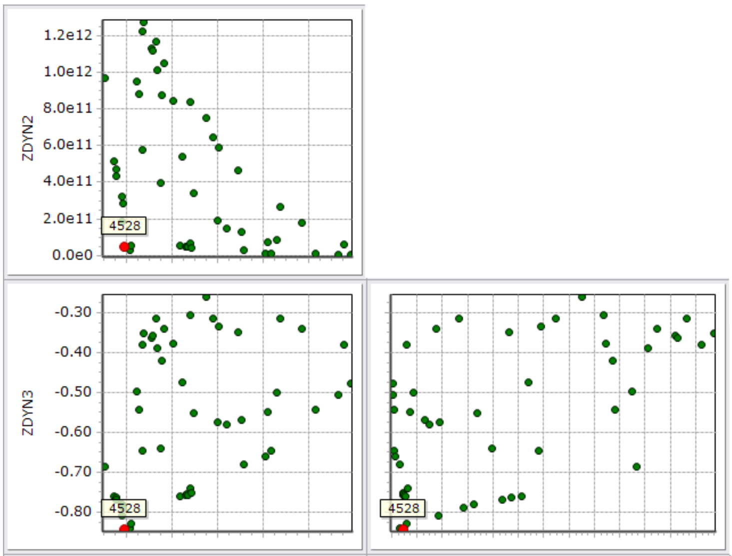
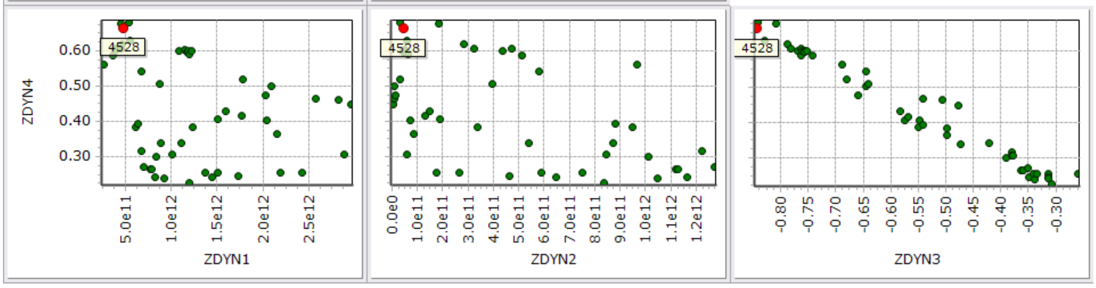

Figure 5. Depiction of 50 *Pareto*-optimal solutions in a scatter plot matrix. Each individual diagram represents one of the possible two-dimensional projections of the four-dimensional solution space. Solution no. 4528 has been marked. ZDYN1 and ZDYN2 are the sums of the squared storage volume differences of the reservoirs Lehnmühle and Klingenberg to their respective target storage levels (normal operation level), ZDYN3 is the average withdrawal for water supply and ZDYN4 is calculated using IHA parameters.

CONCLUSIONS

On the basis of the rainfall prediction the multi-objective optimization provides a multitude of alternative operation strategies with the most effective trade-offs. This enables the reservoir operator or owner to select the best strategy from his point of view. Likewise the presented method can be used for adaptive control purposes that allows updating the control procedure on the basis of updated forecasts.

The procedure can be understood as an integrated approach, that brings together a series of models (precipitation forecast, precipitation-runoff, freeboard, reservoir release, downstream water profiles, stage-damage, DTM) to establish a complex optimization and decision support system. This enables a multi-objective analysis and optimization of river basins with multipurpose reservoirs.

The described multi-objective optimization algorithm can be used for optimizing reservoir operation regarding both event-based as well as normal long-term operations. The result of the optimization is a set of most effective compromises between the target objectives, which exposes conflicting objectives and allows for transparent decision-making.

The described dynamic operating rule on the one hand produces less fluctuation in reservoir storage levels, and on the other hand results in a downstream regime that more closely resembles that of the inflow. From an ecological viewpoint, these both are positive effects. In the case study presented here, these effects could only be achieved in conjunction with a small reduction in water supply provisions.

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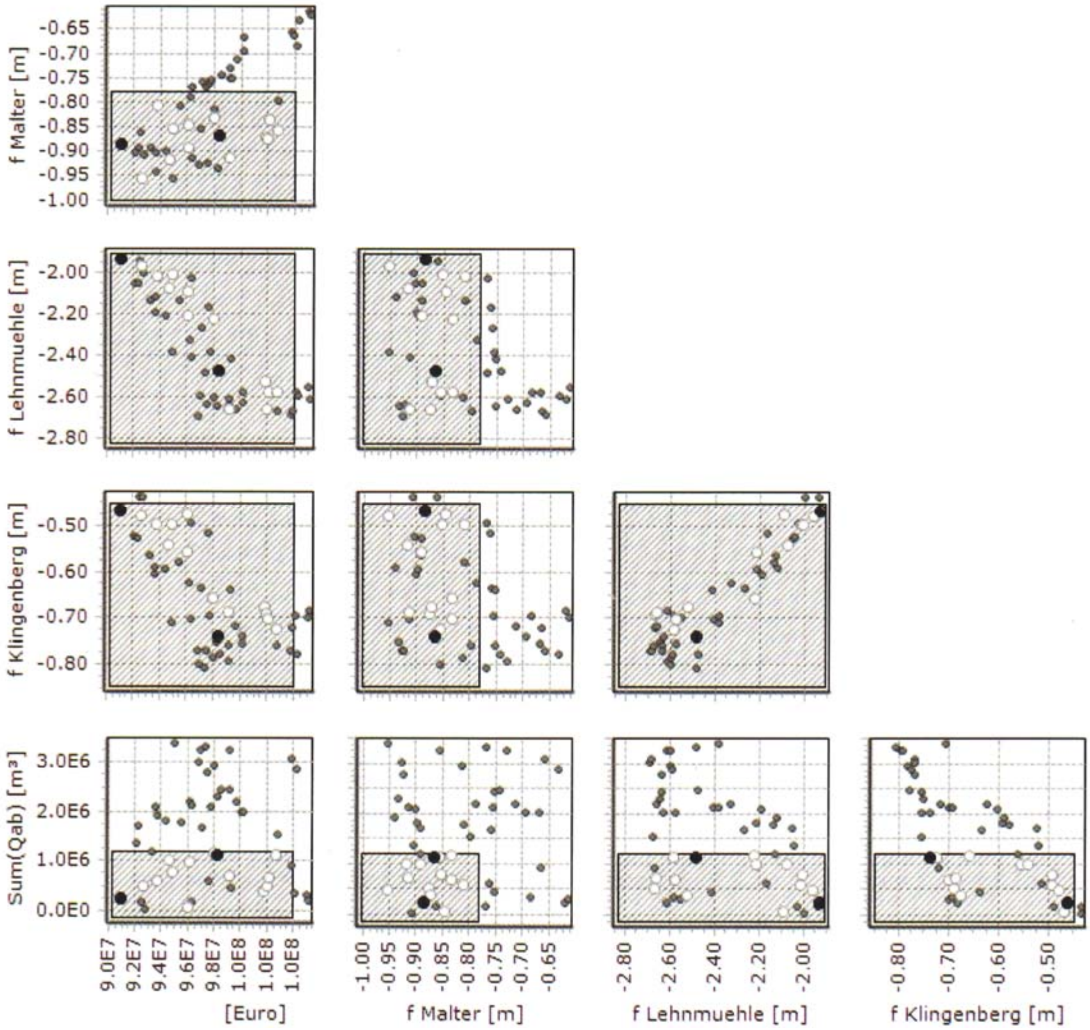

Figure 7 Scatter plot matrix: set of *Pareto*-optimal solutions. The grey dots are the solutions of the five-dimensional *Pareto*-front. The marked dots represent the selected solutions L1 and L2. *Z1* [Euro²] is the squared damage, *f* [m] the freeboards (and with this the safety of the barrages) of the reservoirs Malter, Lehnmühle and Klingenberg respectively and *SumQab* [m^3] is the volume of the bottom outlet releases of the reservoir Klingenberg. The solutions in the hatched areas can improve the status quo.

Table 1: Results and comparison of different operation strategies.

	calculated	**Status quo**	**S1**	**S2**	**L1**	**L2**
Damage [Mio. Euro]	-	104,0	95,0	95,0	98,3	91,0
Freeboard Malter [m]	0,57	0,78	0,95	0,95	0,87	0,88
Freeboard Lehnmühle [m]	0,79	1,91	1,91	1,91	2,48	1,93
Freeboard Klingenberg [m]	0,61	0,45	0,45	0,51	0,74	0,47
ΣQ_{ab} Kling. [Mio. m³]	-	1,2	1,2	2,5	1,1	0,2

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