IntegTa: a procedure for integrative management of dammed raw water reservoirs for drinking water production and their lower reaches

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ABSTRACT

Dammed water reservoirs for drinking water production with their catchment areas and rivers downstream represent dynamic systems that change constantly and are subject to many influences. An optimized management considering and weighing up the various demands on raw water reservoirs (long-term storage for drinking water supply, flood control, ecological state of the rivers downstream, energy production, nature conservation and recreational uses) against each other is therefore very difficult. Thus, an optimal reservoir management has to take into account scenarios of possibly occurring external influences and to permit predictions of prospective raw water qualities, respectively. Furthermore, the impact of short and long term changes in raw water quality on subordinate processes should be considered. This approach was followed in the work presented here, as there currently is no tool available to predict and evaluate the impacts of raw water reservoir management strategies integratively. The strategy supported by the newly developed decision support procedure takes into account all aspects from water quality, flood control and drinking water treatment to environmental quality downstream the reservoir. Furthermore, possible extreme events or changes of boundary conditions (e.g. climate change) can be considered.

Key words | decision support procedure, drinking water, ecological state, EU water framework directive (WFD), integrative modeling, management of dammed reservoirs, water quality

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NOMENCLATURE

A_e (km^2)	catchment area
DOC (mg/L)	dissolved organic carbon
DW	drinking water
DWT	drinking water treatment
moG	meters over ground
N	nitrogen
O$_2$	oxygen
P	phosphorus
Q_{in} (L/s; m^3/s)	inflow

Q_m (L/s; m^3/s)	average flow rate	
Q_{max} (L/s; m^3/s)	maximum flow rate	
Q_{out} (L/s; m^3/s)	outflow	
Ref	reference scenario being based on mere quantity optimization	
Sc1	scenario 1	
Sc2	scenario 2	
Sc3	scenario 3	
TOC (mg/L)	total organic carbon	
WFD	Water Framework Directive	

INTRODUCTION

The management of multipurpose raw water reservoirs has to take into account numerous potential conflicts of interest. The optimum mode of operation for one purpose is possibly suboptimal for another. For example, maximum flood protection will be achieved at low reservoir fill levels (large flood storage) but the best raw water quality, however, can be expected in the completely filled reservoir, which is allowed to flow over. Also, the discharge from the reservoir affects the ecological state in the downstream river reaches. This in turn can result in conflicts with the requirements and objectives of the EU Water Framework Directive (WFD) (European Commission 2000). According to the WFD, most of rhithral and potamal rivers beneath dams will not achieve a "good status" or "good potential", respectively, until 2015 (Richter & Völker 2010). In spite of good water quality in the flowing water with high ecological potential, interacting processes between surface water, river bed and hyporheic interstitial can be interfered by reservoir discharge. Possible consequence of unnatural inflow is a functional loss of the hyporheic interstitial over long passages for the interstitial being a fundamental habitat for aquatic communities, especially benthic invertebrates and gravel spawn fish species (Borchardt & Pusch 2009; Saenger & Zanke 2009). Therefore, the main difficulty in the management of drinking water reservoirs is to find management strategies that will harmonize all demands.

For that reason, a decision support procedure was developed to help dam administrators optimize their reservoir management decisions. It provides possibilities for comparative assessments in particular decision-making

scenarios: for example, of the amount of water that should be discharged, when and from what depth, so that enough water remains available in dry seasons; ensuring that there is enough capacity available in periods of intense rain so that possible flooding in settlements below a dam can be avoided; ensuring that captured raw water can be converted into safe potable water cost-efficiently using existing water treatment plants; and that the lower reaches remain in a natural and ecologically sound condition.

The decision support procedure that was developed in the course of this project consists of a number of modules. The modules include model based mathematical descriptions and stochastic analysis of the processes and inter-relations of the subsystems of a raw water reservoir system: raw water quality and quantity, drinking water treatment and ecological state of the lower reaches. The linking of these modules offers the possibility to predict consequences of different management strategies (level and amount of discharge for drinking water production, discharge to the lower reaches) in interaction with external factors (catchment area management, hydrological and climatical factors) on the particular subsystems (Figure 1) to find optimal reservoir management strategies for current or prospective incidents using defined target values and limits as input data.

MATERIALS AND METHODS

The reservoir system investigated comprised the reservoirs Klingenberg and Lehnmühle including their tributaries and pipelines (Figure 2). The field work was primarily done at these reservoirs, which are situated in the south-eastern low mountain range of the state of Saxony, Germany.

To optimize the operation rules for quantity related reservoir management, objective functions describing optimal management were set up. In this case, the guarantee of drinking water supply, dam safety and the protection of downstream sites have been the main objectives. Flood protection downstream is achieved by keeping maximum and minimum tolerable discharges. By setting up the reservoir system (Figure 2), the objective functions describing inflow to the reservoir and the water level of the reservoir as function of inflow and outflow were available. In order to generate inflow as a function of time during
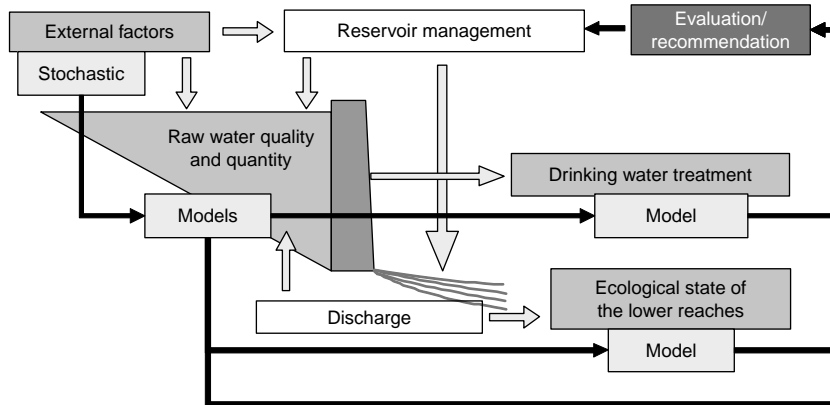
Figure 1 │ Subsystem interactions and data flows considered in the decision support procedure.

the year, data from past precipitation-drainage-events and measured inflows to the reservoir were subjected to pattern recognition. From that, 100 scenarios were generated stochastically covering a period of 100 years each to describe typical inflow events. With that all components were available to apply quantity optimization using evolutionary strategy. As a parameter for the evolutionary strategy, the operating rules as relationships between discharges and selected state variables are considered, for example, in the simplest case, a relationship between discharge and reservoir volume. The rules themselves are described as "if-then-functions".
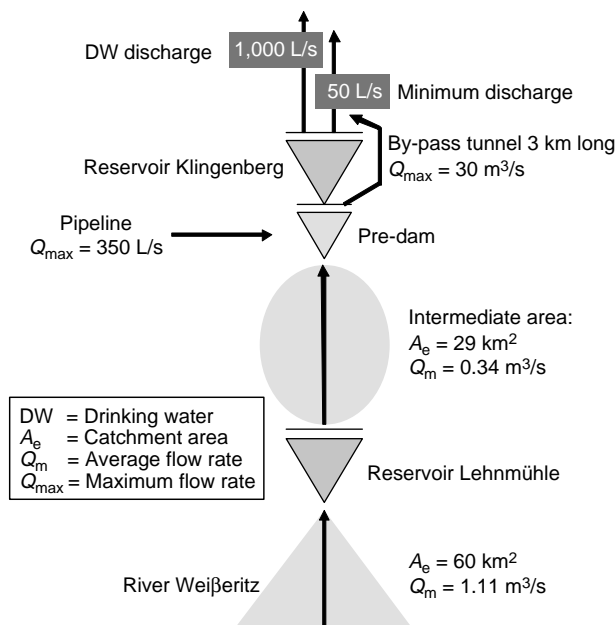

Figure 2 │ Reservoir system investigated.

The integration of water quantity and water quality management was performed using the computer program TALSIM, which was developed by SYDRO Consult GmbH. Within this work the program TALSIM was extended to be able to include the quality parameters and to adopt the quantity based operation strategy according to the quality-related criteria (Rolinski *et al.* 2007).

To estimate effects of different management strategies on water quality (at optimum quantity-management), the coupled physical-ecological model SALMO-HR (Figure 3) was used for deterministic predictions. The model SALMO-HR is a vertically resolved one-dimensional hydrophysical-ecological model for lakes and reservoirs (Petzoldt *et al.* 2005; Rolinski *et al.* 2005; Rolinski *et al.* 2008). In comparison to other models its equations and parameters are formulated in a rather generalized manner, so that site-specific calibration can be avoided or is limited to few site-specific parameters only (e.g. fish stock, light extinction, sediment-P-disposal). The model consists of the ecological sub-model SALMO-1D developed at Technische Universität Dresden and the hydrophysical k-ε-model LAKE of the Institute IAMARIS e. V. The current version of SALMO-HR simulates the seasonal development of temperature, stratification and turbulence (physical components) as well as the concentrations of phosphorus, nitrogen, phytoplankton (3 groups), zooplankton, oxygen, DOC (incl. humic substances) and suspended matter (4 particle classes).

Extreme hydrological events, e.g. extreme floods or severe drawdowns of the storage level, can substantially deteriorate the water quality and may even result in a malfunction of drinking water treatment. Therefore, inflow
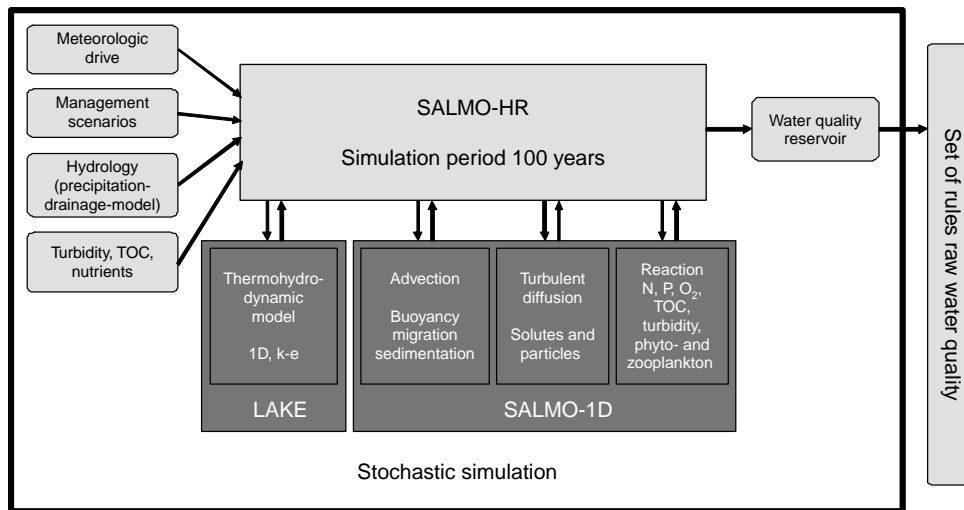
Figure 3 │ Schematic representation of the coupled physical-ecological model SALMO-HR.

and in-lake distribution of pollutants were investigated in order to develop dam-specific as well as general standards to complete the optimization rules for the management of dammed drinking water reservoirs in both water quantity and quality aspects. Special attention was paid to turbidity caused by floods and the characteristics of suspended particulate matter. The field work was primarily done at the reservoir system shown in Figure 2. Besides general water quality data, flux, concentration, size distribution and settling velocity of particles as well as fractions of dissolved natural organic matter were determined. Data already available were additionally used. Empiric models were used to describe the development of turbidity within the raw water reservoirs due to inflow and sedimentation of particles. Considering statistical probabilities, a procedure was developed and implemented in spreadsheet-form that allows for the determination of the minimum storage capacity and minimum hypolimnion volume of stratified reservoirs at the beginning of the summer stratification needed to ensure basic raw water quality and quantity requirements.

To model the impact of management strategies on river water quality downstream the reservoir, at first investigations at river sections of the lower reaches were performed to predict water quality by means of oxygen conditions and nutrient concentrations in the flowing water and the hyporheic interstitial as well as to investigate the influence of reservoir discharge on benthic invertebrates.

In the catchment area the following characteristics were investigated at three sampling sites in the flowing water and the hyporheic interstitial: oxygen, temperature, pH-value, conductivity, nitrogen, phosphorus, DOC and pressure variability. The interactions between surface and pore water of the sediment were investigated with the temperature method. In doing so, conclusions on the functionality of the hyporheic interstitial could be drawn because of decelerated temperature exchange between surface and pore waters: vertical infiltration rates, reaction potential, detrital drive and mass transfer between the flowing water and the hyporheic interstitial in dependence of discharge. Results of the water quality characteristics were compared with thresholds of chemical and physico-chemical variables by LAWA (2007) to estimate the ecological state of water bodies according to WFD. Oxygen concentrations in the surface water were modeled according to different scenarios to predict water quality for specific management strategies. Benthic invertebrates were sampled in spring 2007 and 2008 according to standardized methods (Haase *et al.* 2004; Hering *et al.* 2004; Sundermann *et al.* 2008). In doing so, biological attributes of benthic invertebrates (e.g. taxonomic or functional composition) were selected to identify possible effects of unnatural inflow to aquatic community.

To assess the impact of water quality on drinking water treatment, coagulation filtration experiments were planned according to factorial design and carried out at pilot scale. Treatment performance and costs were described as

a function of organic load and turbidity. Required information had to be determined with maximum accuracy from as few as possible experiments. Using the method of factorial design, simultaneous variation and investigation of all variables within a single experimental plan was possible (Montgomery 2005). Thus, distinction of significant from insignificant variables as well as identification of relationships and optimum values could be achieved. Treatment performance can be measured as filter run time until breakthrough, head loss, coagulant demand, acid/base demand for pH-adjustment, backwash water demand and sludge produced. As a result of the experiments governed by factorial design and the application of an optimization algorithm, optimum treatment parameters (pH, coagulant dosage and filter velocity) can be determined for each combination of organic load and turbidity. Then, with these optimized treatment parameters, specific treatment costs can be determined. As a result, expected treatment costs for optimized treatment of each expected raw water quality can be calculated (Slavik *et al.* 2010).

RESULTS

Development of the decision support procedure

Figure 4 shows the required flow of information and data between the particular modules of the joint *IntegTa* project

being the basis for developing the decision support procedure. Starting point is a mere quantity optimization of raw water reservoir management strategies with its results (Q_{in}, Q_{out}, storage level) serving as input data for the simulations of dammed reservoir water quality and directly entering the all-up evaluation. Within the module "Simulation water quality dammed reservoirs" additional rules considering quantity management at extreme situations is also regarded. The results of these simulations are used as input data for the calculations within the modules "Simulation drinking water treatment" and "Simulation water quality rivers downstream" and directly contribute to the all-up evaluation of the results. The all-up evaluation is finally completed by the treatment cost indicators being determined within the drinking water treatment module and by the water quality indicators of the rivers downstream.

To optimize quantity related reservoir management, objective functions were set up within the module "Simulation water quantity" as described before to guarantee drinking water supply, dam safety and the protection of downstream sites. Using these objective functions and the stochastically generated inflow loads operation rules can be defined to optimize quantity management for the reservoir system investigated. On the basis of these operation rules relationships between the inflow to the reservoir, the discharges (drinking water treatment, rivers downstream) and the resulting storage level can be described.
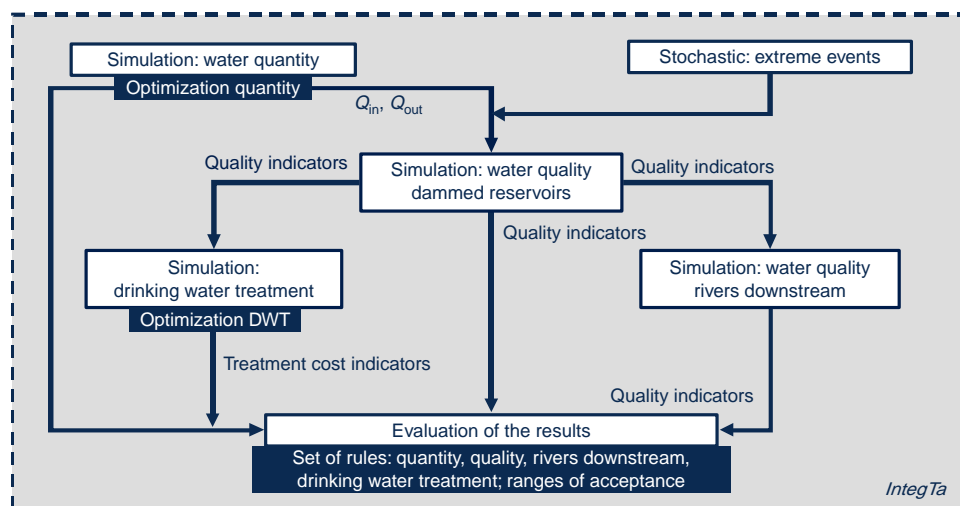

Figure 4 │ Flow of information and data between the modules of the decision support procedure.

The results of the quantity related calculations serve as input data for the simulations of raw water quality.

In the quality-related optimization, investigation results of inflow and in-lake distribution of pollutants during extreme hydrological events (e.g. extreme floods or severe draw-downs of the storage level) are also taken into account. Using stochastic simulations to determine the minimum storage capacity and minimum hypolimnion volume in dependence of raw water quality and in-lake flow conditions, additional rules for quantity management were developed.

The consecutive reservoir water quality simulation is using these boundary conditions and gives information under which constellations of the inflow, the reservoir storage and the discharge etc. quality-related problems can occur. Moreover, scenario based modeling shows how quality problems can be prevented by changing the height of raw water intake for drinking water production and/or discharge to the river, respectively. The stochastically generated time series from the water quantity management model were used as hydrological input data and complemented with meteorological records and empirically derived import concentrations (nutrients, humic substances, particles). Subsequently, indicators for the quality of raw water and ecological impacts on the downstream reaches of the discharge were determined using these simulation results. The comparison of different variants of operational reservoir management on the basis of simulated scenarios allows objectifying management decisions, which guarantee a best possible raw water quality for drinking water production and good ecological conditions downstream.

The quality simulation of the lower reaches shows under which constellation of the discharge quality-related problems occur downstream and whether and if necessary how those can be reduced by changes in discharge. By using a model describing transport and transformation processes, especially the oxygen conditions in the flowing water and the hyporheic interstitial in dependence of different
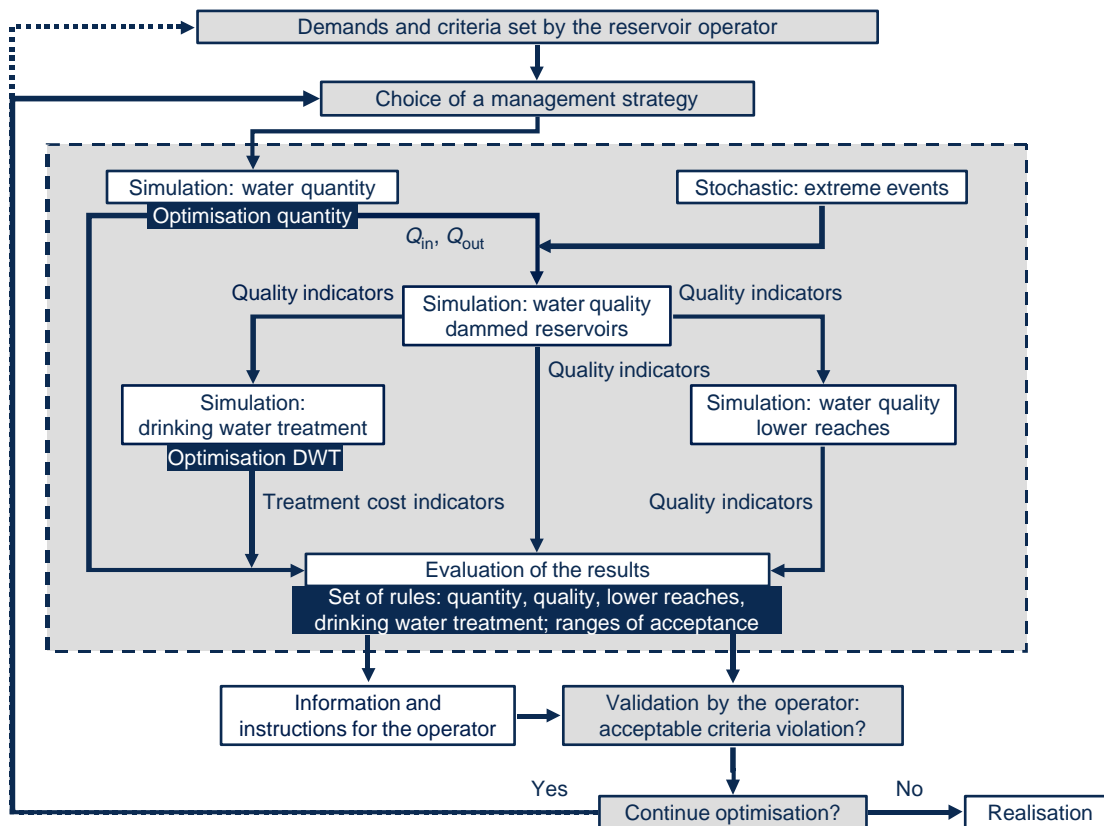

Figure 5 │ Functional principle of the developed decision support procedure, DWT = drinking water treatment, Q_{in} = inflow, Q_{out} = outflow.

reservoir management strategies, river water quality can be predicted. As a result these simulations provide indicators for the quality of raw water being discharged to the lower reaches.

To simulate impacts of different raw water qualities on drinking water treatment, a model was developed to optimize drinking water treatment which takes into account short-, mid- and long-term factors impacting raw water quality (Slavik & Uhl 2007, 2009; Slavik *et al.* 2010). To assess the impact of water quality resulting from reservoir management on drinking water treatment, at first analyses of historical quality data and treatment performance during extreme events were carried out. Furthermore, extensive series of experiments using pilot-scale filter plants were run, planned and evaluated by factorial design. Input parameters for simulation of drinking water treatment are TOC and turbidity, obtained from the water quality module. Based on the results of data analysis and pilot investigations and the model developed herewith, optimum treatment parameters (filter velocity, coagulant dosage, pH-value) are determined for minimum costs per m^3 drinking water produced. To evaluate drinking water treatment within the framework of the decision support procedure, treatment cost indicators can be set by the user.

An overall evaluation of the simulation results is done within the framework of the decision support procedure (Figure 5). For evaluation, at first the user has to define quality and treatment cost indicators and ranges of acceptance as well. After running the combined models, subsequently the user of the decision support procedure has to decide whether a possible violation of the chosen criteria is acceptable or not. Furthermore, the decision on continuing the optimization has to be made. An optimization and
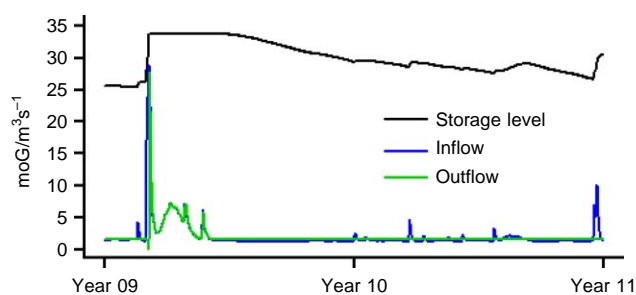

Figure 6 │ Relationship between inflow, outflow and storage level as result of a quantity related optimization exemplarily shown for two years of a time series.
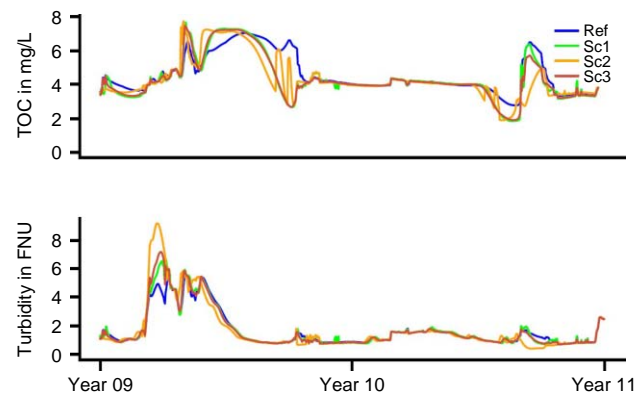

Figure 7 │ Development of the TOC-concentration and the turbidity in the raw water reservoir during two generated years for the scenarios 1 to 3 (Sc1, Sc2 and Sc3) compared to a mere quantity optimized reservoir management strategy (Ref).

iteration cycle is finished on decision of the user if a management strategy is found which ideally fulfills the quality and quantity-related objectives as well as the demands on drinking water treatment efficiency or rather shows least possible deviation. Furthermore, the user will get information and instructions for the operation and management of a raw water reservoir. Otherwise, a new management strategy has to be chosen to start the optimization and iteration cycle again.

Application of the decision support procedure

Applying the new developed decision support procedure to a certain dammed reservoir system it becomes now possible to simulate the effects of reservoir management strategies on water quantity and quality, drinking water treatment and river water quality, provided that objective functions describing the relation between inflow minus outflow and fill level are given, time series of meteorological events are generated stochastically and relations for transport of particles (turbidity) and organic matter (TOC) to the reservoir are available.

To show the effect of water quantity management on raw water quality three basic scenarios were defined. In the first two scenarios it was assumed, that hypolimnic abstraction is taken from the deepest (scenario 1) or the highest (scenario 2) possible outlet. Alternatively, it was assumed that epilimnic water is abstracted to the downstream reaches and raw water is taken from a medium
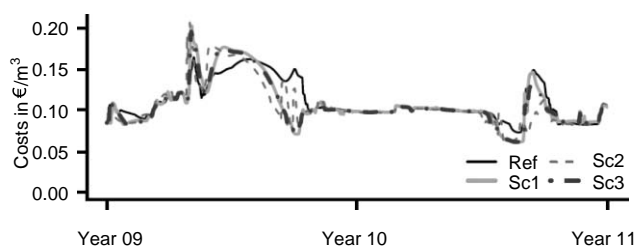
Figure 8 | Development of specific costs (in Euro per m³) of drinking water treatment by coagulation-filtration during two generated years for the scenarios 1 to 3 (Sc1, Sc2 and Sc3) compared to a mere quantity optimized management strategy (Ref).

hypolimnic outlet (scenario 3). For these scenarios, the development of water quality parameters and their effects on drinking water treatment costs and the ecological state of the river downstream the reservoir can be described.

On the basis of the quantity optimization, operation rules relationships between the inflow to the reservoir, the discharges (drinking water treatment, rivers downstream) and the resulting storage level can be described. Figure 6 exemplifies the results of two generated years out of a centennial hydrograph curve.

Using the results of the quantity related calculations, the simulations of raw water quality can be performed. The water quality model is able to reproduce seasonal dynamics of the reservoir water reasonably well, especially

particulate substances, physical variables (e.g. temperature) and phytoplankton. For this seasonal dynamic is also decisive for raw water quality, the TOC-concentration was aggregated with a monthly resolution. As a result the development of raw water quality parameters in the dammed reservoir can be simulated, exemplarily shown in Figure 7, for the TOC-concentration and the turbidity for two generated years.

The effects of the development of the water quality parameters on drinking water treatment costs and the ecological state of the river downstream the reservoir are shown in Figures 8 and 9. According to Figure 8, the abstraction level effects the specific costs for drinking water treatment. Furthermore, the unnatural inflow by discharging water from a reservoir to the lower reaches effects water quality variables there. Figure 9 shows the development of the oxygen concentration development based on modeling by River Water Quality Model No. 1 (Reichert *et al.* 2001) for scenario 1.

For the example shown in Figure 9 the oxygen concentration in the flowing water can fall below the assessment value for a "good ecological state". The oxygen concentration in the sediment hardly achieves a "good ecological state". This in turn can have an effect on the functional and taxonomic composition within these river
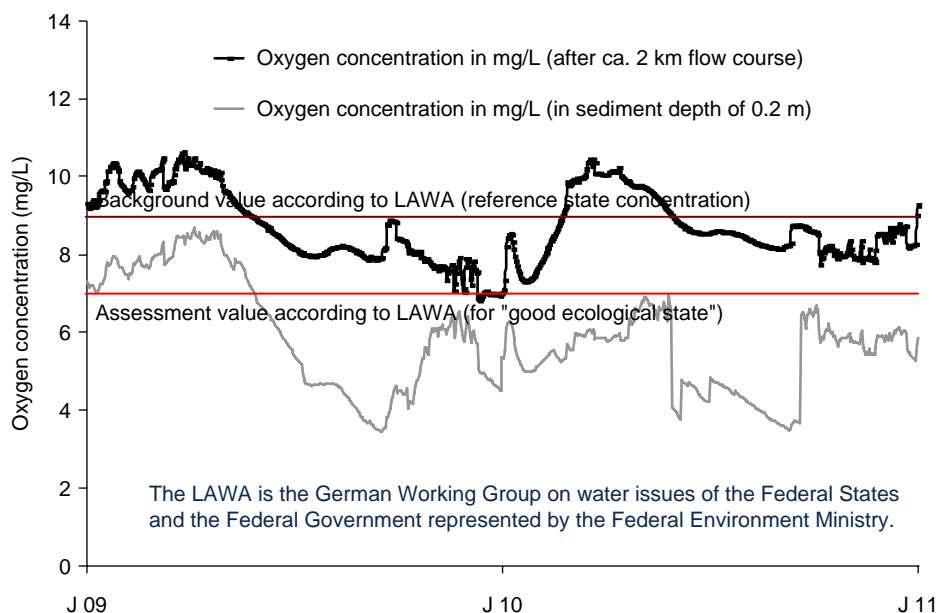

Figure 9 | Model-based oxygen concentration in the flowing water and in sediment, calculated for scenario 1 for two generated years, compared to the background and assessment value according to LAWA (2007).

sections that are affected by reservoir discharge. Consequently, the abstraction level is of special importance for water quality and the ecological state in the lower reaches.

By defining criteria and ranges of acceptance for supply guarantee, water quality and treatment costs an all-up evaluation of the simulation results can be performed. In this evaluation verification can be done with respect to the violation or fulfillment of these criteria and ranges of acceptance. In doing so, an evaluation of the chosen management strategy is possible. The result is a set of precise formulated management rules for raw water reservoirs, for example describing

- at which conditions how much has to be discharged from the reservoir,
- which discharge level has to be chosen,
- how discharge to the lower reaches has to be performed and
- which choice of treatment parameters is ideal for drinking water production.

CONCLUSIONS

The complete system of a raw water reservoir for drinking water production with its catchment area, the river downstream and the drinking water treatment plants is very complex and dynamic. With increasing demands and external pressures such as climate change, future management of drinking water reservoirs should not only be based on water management plans and the operator's experience anymore. Decisions based on experience are highly valuable. However, new, eventually better solutions have to be searched for. Until now there is no tool available for integrative evaluation of raw water reservoir management strategies, meaning to consider water quality and flood protection as well as efficient drinking water treatment and the ecological state of the rivers downstream. Furthermore, the impact of extreme events and long-term changes (e.g. due to climate change) has to be taken into consideration.

Within the scope of the work described here a decision support procedure for integrative management of multi-purpose raw water reservoirs for drinking water production was developed for the first time taking into account all aspects from flood protection as well as water quality and

drinking water treatment to the point of ecological quality of the rivers downstream and all the conflicts involved. The decision support procedure was developed on the basis of linking and partly coupling of models describing the processes and interrelations in the subsystems/modules raw water quality and quantity, extreme events, drinking water treatment and ecological state of the rivers downstream the reservoir. Within the modules water quantity and raw water quality already existing software tools were developed further with respect to the intended purposes of this project and interlinked. The results of the water quantity and quality simulations serve as data basis for the calculations to optimize treatment efficiency for drinking water production as well as to describe transport and transformation processes in the lower reaches. By combining all simulation results and by setting up demands and criteria for raw water reservoir operation users of this decision support procedure will be able to simulate and to evaluate the complex consequences of different management strategies and flood protection demands on reservoir water quantity and quality, drinking water treatment and river water quality.

REFERENCES

Borchardt, D. & Pusch, M. 2009 An integrative, interdisciplinary research approach for the identification of patterns, processes and bottleneck functions of the hyporheic zone of running waters. Editorial. In: Borchardt, D. & Pusch, M. (eds) *Advances in Limnology*, (Vol. 61). E. Schweizerbart'sche Verlagbuchhandlung, Stuttgart, pp. 67–85.

European Commission 2000 Official Journal L 327, 22.12.2000, pp. 1, Directive 2000/60/EC (EU Water Framework Directive).

Haase, P., Lohse, S., Pauls, S., Schindehütte, K., Sundermann, A., Rolauffs, P. & Hering, D. 2004 Assessing streams in Germany with benthic invertebrates: development of a practical standardised protocol for macroinvertebrate sampling and sorting. *Limnologica* **34**(4), 349–365.

Hering, D., Meier, C., Rawer-Jost, C., Feld, C. K., Biss, R., Zenker, A., Sundermann, A., Lohse, S. & Böhmer, J. 2004 Assessing streams in Germany with benthic invertebrates: selection of candidate metrics. *Limnologica* **34**(4), 398–415.

LAWA−Länderarbeitsgemeinschaft Wasser AO 2007 Rahmenkonzeption Monitoring. Teil B−Bewertungsgrundlagen und Monitoring. Arbeitspapier II Hintergrund- und Orientierungswerte für physikalisch-chemische Komponenten. Stand 07.03.2007.

Montgomery, D. C. 2005 *Design and Analysis of Experiments*, 6th edition. John Wiley, New York.

Petzoldt, T., Rolinski, S., Rinke, K., König, M., Baumert, H. Z. & Benndorf, J. 2005 SALMO: Die ökologische Komponente des gekoppelten Modells. *Wasserwirtschaft* **95**(5), 28–33.

Reichert, P., Borchardt, D., Henze, M., Rauch, W., Shanahan, P., Somlyody, L. & Vanrolleghem, P. A. 2001 *River Water Quality Model No. 1, Scientific & Technical Report No. 12*, IWA Publishing, London. 144pp.

Richter, S. & Völker, J. 2010 *Results of the First River Basin Management Plans 2009 in Germany*. Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, Bonn (In press).

Rolinski, S., Petzoldt, T., Baumert, H. Z., Bigalke, K., Horn, H. & Benndorf, J. 2005 Das physikalisch-ökologisch gekoppelte Talsperrenmodell. *Wasserwirtschaft* **95**(5), 34–38.

Rolinski, S., Petzoldt, T., Hillert, K., Paul, L. & Benndorf, J. 2007 Linking water quality to water quantity: integration of disturbance variables into the management strategies of drinking water reservoirs, In: *American Geophysical Union Fall Meeting*, abstract B51B-0378, San Francisco/USA, 12/2007.

Rolinski, S., Petzoldt, T. & Benndorf, J. 2008 Nutrients, Weather, Food Web: What do we need to model Trophic Change? In: *Proceedings of the Workshop 'Perspectives of lake modeling towards predicting reaction to trophic change', Kompetenzzentrum Wasser Berlin Publication Series*, 9, 30–37, ISBN 978-3-9811684-3-3.

Saenger, N. & Zanke, C. E. 2009 A depth-oriented view of hydraulic exchange patterns between surface water and the hyporheic zone: analysis of field experiments at the River Lahn, Germany. In: Borchardt, D. & Pusch, M. (eds) *Advances in Limnology*, (Vol. 61). E. Schweizerbart'sche Verlagbuchhandlung, Stuttgart, pp. 67–85.

Slavik, I. & Uhl, W. 2007 Optimizing water treatment to respond to quality changes due to reservoir management and climate change, In: *Proc. Am. Water Works Ass. 'Water Quality Technology Conference'*, Charlotte/USA, November 4–8.

Slavik, I. & Uhl, W. 2009 Analysing water quality changes due to reservoir management and climate change for optimization of drinking water treatment. *Water Sci. Technol. Water Supply* **9**(1), 99–105.

Slavik, I., Skibinski, B., Watzlawik, S. & Uhl, W. 2010 Beschreibung von Einflüssen der Wasserqualität auf den Aufwand für die Trinkwasseraufbereitung–ein statistisches Modell. In: *Proc. Wasser 2010–Jahrestagung der Wasserchemischen Gesellschaft*, Bayreuth, May 10–12.

Sundermann, A., Pauls, S. U., Clarke, R. T. & Haase, P. 2008 Within-stream variability of benthic invertebrate samples and EU water framework directive assessment results. *Fundam. Appl. Limnol. (Arch. Hydrobiol.)* **173**, 21–34.