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Using a fuzzy-logic approach to model a reservoir and transfer system under climate change conditions

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Abstract: Embedded in an international project, a management model is developed for assessing climate change impacts on the Water Transfer System in Franconia, Germany. Based on expert knowledge, standard rules operating this system are defined and implemented in a fuzzy-based modelling system. Demands of stakeholders are identified as being core functionalities in the model. First climate change impact assessments were done, driving the management model with outputs from a hydrological model forced by dynamical climate model data.

***Keywords**:* water management, climate change, fuzzy-logic

1 Introduction

The project Q-BIC³ (Quebec Bavarian collaboration on climate change) examines climate change impacts on the operational management of water resources in Bavaria and Québec. The central research question is the analysis of cumulated uncertainties regarding the model chain from global climate models (GCM), regional climate models (RCM), bias correction, downscaling and finally hydrologic models (HyMs) of different complexity and their influence on the regional water management. On the scientific side, partners in this project are the Québec climate impact research consortium OURANOS and the Department of Geography (LMU). The operational side is represented by the Quebec energy company Hydro Québec and regional water authorities (WWA). Acting in between are the state authorities LfU (Bavarian Environmental Agency) and CEHQ (Centre d'expertise hydrique du Québec), providing administrative and scientific supervision and support. In a context of developing adaptation strategies for water management, the LMU has the task to design and implement a prototype of a management model for the Franconian Water Transfer System, capable to a) describe the heavy impact on the natural runoff regimes in the region under present state conditions and b) analyze the impacts of climate change on future operations of the system. This is being assessed in close collaboration with the operators of the system itself. In this case the WWA in Ansbach and LfU act as stakeholders.

2 The system and its stakeholders

The first step for stakeholder participation and integration during the development of a management model for a water transfer system is of course a detailed knowledge of their problems. Influences from third parties on the stakeholders have to be examined and should be also reflected in the model architecture. In the following section, the physical problem is explained and the involved stakeholders are introduced with special regard to their dependencies and responsibilities.

2.1 The Franconian Transfer System

The climate in Bavaria is characterized by a precipitation gradient from South to North with annual values of more than 1000 mm at the edge of the Alps down to 700 mm in the northern part [LfW 1998]. Therefore, rivers in northern Bavaria sometimes suffer under periods of water scarcity, which led to the concept to bring water from the southern Danube, over the European Watershed, to the Main-Rhine catchment (Figure 1). The water transfer system should contribute to a more balanced runoff in rivers in northern Bavaria and improve their water quality. So, from 1975 until 1995 the Franconian Water Transfer System was constructed.
The main objective of this system is to guarantee a minimum runoff at the Regnitz gauge Huettendorf (north of Nuremberg) of 22 m³/s in winter and 27 m³/s in summer. The water transfer in order to fill the reservoirs is possible in two ways:
The first way is to use the reservoir Altmuehlsee with a capacity of 13.8 Mio. m³. Main purpose of this reservoir is to store floodwater of the upper Altmuehl and transfer it via a tunnel (the "Brombach Transfer") into the Large Brombachsee reservoir with a capacity of 136.6 Mio. m³. It has to be mentioned that only floods above a certain threshold are stored. A maximum runoff of 5 m³/s is left in the old Altmuehl channel, which circles the reservoir.
The second way is to pump water at five stations installed at the locks along the Main-Danube shipping channel (the "Channel Transfer"). Each of these stations has five pumps with a single capacity of 7 m³/s. Since only three of these pumps belong to the operator of the transfer system (the other two belong to the channel company) a total capacity of 21 m³/s of water transfer from the Danube to the Rothsee reservoir (with a total capacity of 10 Mio. m³) is possible. Operation of that transfer is preferentially done at night or during weekends. The Rothsee reservoir is designed as a "one week reservoir" and can raise the minimum flow at Huettendorf for about one to two weeks without being refilled. Filling is only possible under the constraint that the runoff of the Danube at gauge Kelheimwinzer is above 147 m³/s. Hence during low flow periods, the Rothsee may run towards the drawdown level, because refilling via the Danube is constrained. In such cases, it is planned that Brombachsee water replaces or at least augments the Rothsee by raising the flow at Huettendorf. This situation mainly occurs during autumn, when water, which is stored mainly during the springtime flood season, is used for that purpose. Annual total transfer is about 25 Mio. m³ for the Brombach Transfer and 125 Mio. m³ for the Channel Transfer.

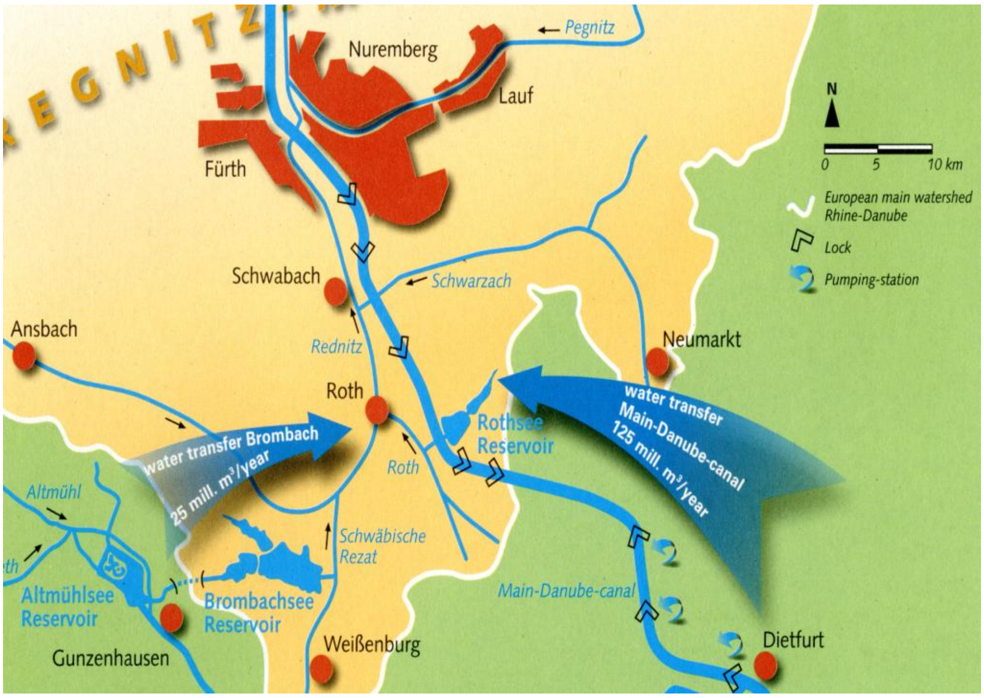

Figure 1. Location of the Franconia Transfer System [WWA Ansbach 2010]

2.2 The active stakeholders

The operation of this system is under the responsibility of the WWA Ansbach and besides its technical and managerial functions, the operation underlies a variety of other interests. First of all, the reservoirs are part of the "Fränkisches Seenland" (Franconia Lake District), which became a very important element of the regions' touristic sector and does provide numerous jobs. For this interest group, a constant lake level and good water quality are important. Secondly, conflicts between economic and ecologic interests (e.g. periodic flooding of downstream areas to assure the ecological functionality of marsh areas versus agricultural productivity issues) led to discussions. And last but not least, transfer water is used for the cooling of power plants situated at the Regnitz [STMLU 2000]. It is obvious that gratifying all interests, while keeping the official guidelines, is a difficult task for the system operators of the WWA.

The official task of LfU is the acquisition and evaluation of environmental data in Bavaria. Based on this, LfU develops goals, strategies and planning for the sustainable use and protection of the environment. The authority can be consulted for recommendations and acts as the regulating authority with respect to environmental fields [LfU 2010]. Relevant for the authority are the regional impacts of climate change on water management issues, hence the scope of LfU duties includes scientific and operational issues. Because of that, regular meetings organized by LfU aim at bringing together regionally acting water authorities with universally thinking scientists.

Identifying both the common and single interests in such meetings is important to gratify the different expectations of all partners. In a first step, the potential capabilities of a management model were identified in cooperation with all participants: a) It should be able to test different operational states of the system that reflect the interests of the local stakeholders for the WWA. b)It should be possible to derive long term adaptation strategies for the LfU by simulating climate change impacts at the regional scale. c) Last but not least, the prototype should be transferable to other managed transfer systems.

3 Methodology and stakeholder involvement

3.1 FranTranS Model – concept, method and technical implementation

As mentioned above, keeping official guidelines can be in opposition to other stakeholder interests. Operators are forced to make decisions from week to week, either balancing all different interests or favor one. The factors, which lead to a certain decision are not always expressed by fixed numbers, often the combination of different circumstances leads to a decision. For example: What should the operator do if it is vacation season and both, Regnitz and Danube, have extreme low flow conditions? Should the operator empty both reservoirs to fulfill the official guidelines and risk an economic harm for the local tourism sector? Or should he violate the guidelines by transferring water? Or should he neglect the minimum flow at Huettendorf? Developing adaptation strategies should cover all these possibilities and for that the model developer has to offer possibilities for the stakeholder defining such strategies in the form of different scenarios. This could be an economic, tourism-friendly or official-guideline scenario. Finding a concept which makes it possible developing such scenarios through discussion and implementing these more verbal statements into mathematical expressions for modeling is important. The fuzzy-logic theory [Zadeh 1965] offer such a possibility. It enables the translation of real values into linguistic expressions (and vice versa). These expressions can be combined to formulate rule sets.

The main concept of the Franconia Water Transfer System Model (FranTranS) is that the different states of all parameters relevant for the operation of the transfer system are explained by fuzzy membership functions (MF). They translate the different states of the system into linguistic expressions (fuzzification). Then, these fuzzy expressions are used to define rules within an if-then bifurcation. The result is

again a linguistic expression, which is translated into a real value (defuzzification) in the end.
For example, different states of the lake level at Rothsee may be: empty, draw down level, below retention water level, operational room, retention water level, highest retention water level and barrier spring. These states are explained by functions that return a possibility value between zero and one for each lake level (Figure 2). The possibility value depends on how a human operator would allocate this state of the lake to an explicit expression. The procedure is repeated for other parameters. Implemented parameters with MFs in the current version of FranTranS are: season, day of the week, lake levels for three reservoirs and runoff at Huettendorf, Kelheimwinzer and the upper Altmuehl. System output is also explained by expressions associated with similar MFs. In the case of the Rothsee, expressions for transfer water are 'one', 'two' or 'three pumps' running to refill the reservoir and e.g. 'is optimal for energy production' as one expression for the discharge. This expression is based on the fact that two turbines with an optimal efficiency between 5 and 6 m³/s are installed at the outlet. Below and above this interval efficiency decreases for hydraulic reasons.
After the system is fully explained by MFs, rule sets can be defined, which have the form:

If lake level of Rothsee is at "operation room" and season is "summer" and day of week is "weekend" and Kelheimwinzer is "above a critical runoff", then channel transfer is "two pumps".

If Huettendorf runoff is a "medium low flow" and lake level of Rothsee is at "retention water level", then discharge of Rothsee is "optimal for energy production".

The technical implementation is done using the graphical user interface of SIMULINK and the Fuzzy Toolbox of MATLAB. It is used to implement a fuzzy controller with the above mentioned MFs and rule sets. Major components in the model are lake objects. These objects consist of simple level-volume relationships converting the lakes' volumes, after the reduction of potential evaporation, into current levels. Another component is an interface for daily runoff data to force the model. This interface allows exchanging input data, e.g. observed runoff or simulated runoff from HyMs forced by climate models or meteorological station data. For current applications simulated runoff from the distributed, process-based hydrological model WaSim-ETH [Jasper and Schulla 2007] is available. All input and computed values communicate with the fuzzy logic control object, which decides how the system is operated at every model time step.

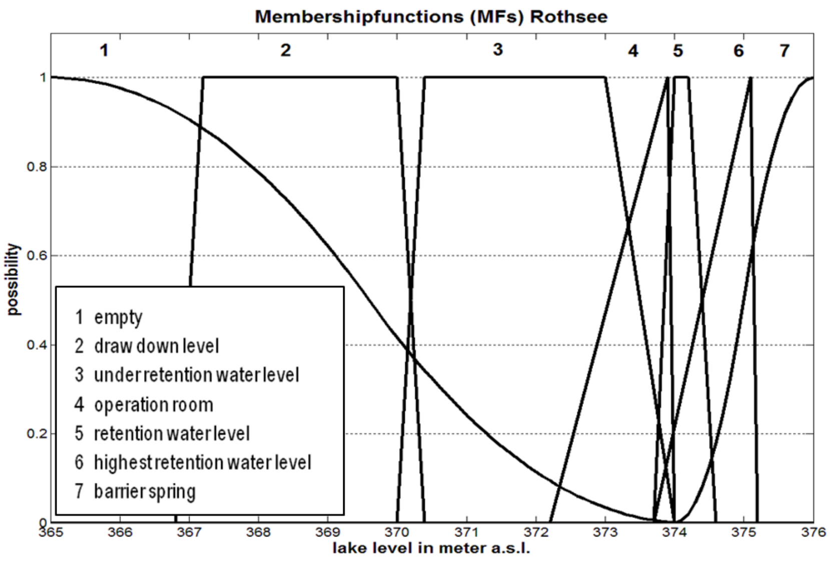

Figure 2: Membership functions for different expressions of Lake Rothsee used in the current version of FranTranS Model

3.2 Stakeholder participation

On the one hand, the daily work of the regional water authority operating the Transfer System in Franconia is far away from complex climate or hydrological models and projections. Major questions in regional water management are e.g. the water quality of the Altmuehlsee, or how to sustain minimum flows at gauge Huettendorf (Regnitz) during dry summers. On the other hand, they are responsible to adapt their system and planning on eventually changing climatic conditions. To do this, they need 'reliable' recommendations for short and midterm planning horizons.

In case of developing FranTranS, the assessment of climate change impacts on runoff, especially on low flow conditions at Huettendorf and Kelheimwinzer, is important. If low flow conditions change in the future, a management model would offer useful information on eventually necessary adaptation strategies for the dam and transfer operation. A first assessment created the foundation for discussions between scientists and stakeholders from WWA Ansbach. The plausibility of future low flow scenarios, and also the capability of a management model to assess adaptation strategies were analyzed.

The null hypothesis for this investigation is: If the management model, using standard rules, could outbalance the uncertainty and/or the climate change impact of the ensemble input data, then no long term adaptation would be necessary. Because of that, the definition of such standard rules must be based on expert knowledge. Of course, there are fixed rules defined in the planning approval, but since it was set up before the system was under real operation, these rules have changed in some details. Hence, the sensitivity or importance of certain management rules can only be identified in close collaboration with the system operator, e.g.:

1. Unusual operation of the system led to measured data, which does not correspond to standard operational rules. E.g. during construction works in the years 2003 and 2006 lake levels were drawn down, so the Brombachsee couldn't be used for maintaining the runoff at Huettendorf. Hence, it is obvious that for direct evaluation the modeller relies on expert knowledge.
2. It is important to identify sensitive standard rules from less sensitive ones. E.g. the Brombachsee should produce one artificial downstream flood during winter. It was suggested from the operator to not include such a rule as it is not sensitive to the yearly management strategy.
3. A constraint for filling the Brombachsee is that the inflow of floods into the Altmuehlsee is restricted by the fact that 5 m³/s must be left in the "old" Altmuehl. Setting this value to 8 m³/s could reduce the nutrient inflush in the reservoir and improve water quality. This will be implemented in a scenario rule set.
4. The more important, yet less complex part of the system are the Rothsee and the Channel Transfer. A constraint implemented in the standard rule set is, that refilling is mainly done during weekends, because energy for pumping the water is cheaper during that time.

Implementing such rules also creates a kind of familiarity on the part of the operator with the model that helps defining scenario rule sets for adaptation strategies.

4. Results

The model performance of FranTraS is exemplified for three use cases: a) an evaluation period 1999 - 2003 for the lake level Brombachsee, b) a case study for summer 2003 where a draw down level of 370 m a.s.l. for Rothsee was reached because of low flow conditions at gauge Kelheimwinzer, and c) a comparison between reference (1971-2000) and scenario (2041-2070) period. Here, a hydro-climatic-model ensemble is used, exposing the FranTranS to a multitude of '2003 situations'.

4.1 Evaluation of lake level Brombachsee

For model evaluation, the period November 1999 until October 2003 is selected to drive FranTranS with two different kinds of datasets: Observed runoff data and modelled runoff with WaSim-ETH driven by station data. Obtained results until November 2001 fit very well with observations. Smaller errors like the missing rise of lake level before May 2001 can be ascribed to uncertainties in the hydrological model, as this phenomenon doesn't appear when FranTranS is operating on observed runoff values. Simulated lake levels for the hydrological year 2002 shows an overestimation. The reason is a missing rule, which limits Brombach transfer in case of exceeding retention water level. This will be part of a further extension of the standard rule set. Yet, a certain standard rule is applied by the model to counteract this deficit: After filling the Brombachsee with flood water from upper Altmuehl, a standard procedure of the operator would be to draw down the level to 409 m a.s.l.. This should assure flood retention space for following floods of the upper Altmuehl. The final evaluation year shows a bigger deviation. Here, in reality, the operator started to decrease the level, because of problems with rising groundwater level around the reservoir which led to the necessity of reconstruction.

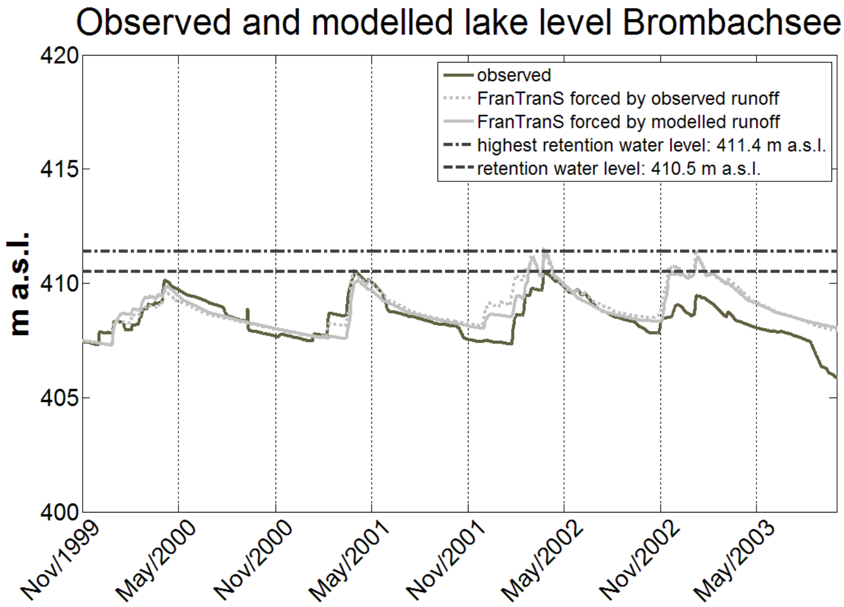

Figure 3. Modeled lake level of Brombachsee. FranTranS driven by observed runoff and runoff simulated with station data

4.2 Case study: summer 2003

Figure 4 shows observations compared with FranTranS forced by modelled runoff for summer 2003. The major question here was to evaluate, whether the model can reproduce, qualitatively and quantitatively, situations when the maximum capacity of the Transfer System is reached. The example shows that the model responds in a plausible range. During May and June, enough water is in the Danube to assure the Rothsee retention water level. In August, no channel transfer was possible for around three weeks and the modelled lake level decrease corresponds to observations in a quantitatively and qualitatively comparable range. Also refilling during September and October, which was still under channel transfer constraints, is simulated qualitatively right but with notable quantitative deficits. A bigger performance problem is shown with the situation in July. Here, the hydrological model simulates runoff very close to the threshold at Kelheimwinzer. Yet in the observed data, two peaks during that period can be found. It should be pointed out that in this case FranTranS responds correctly in stopping channel transfer; thus, the underestimation of channel transfer can be ascribed to the hydrological model.

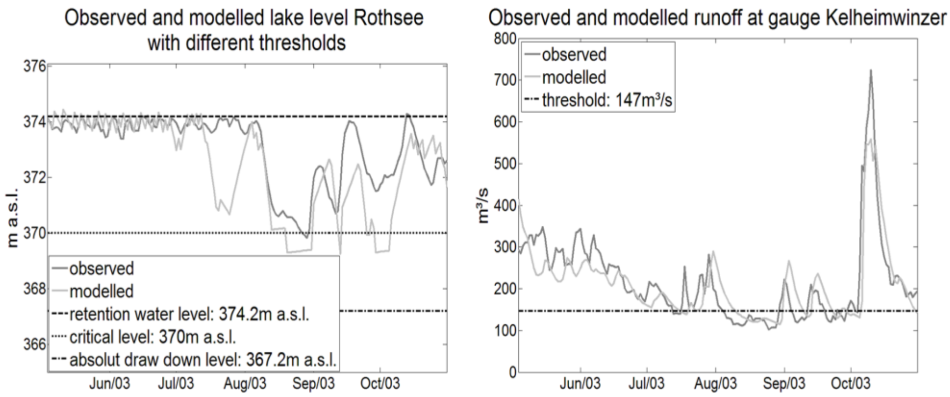

Figure 4. Lake level of Rothsee (left) and runoff at gauge Kelheimwinzer (left) for summer 2003

4.3 Projecting water management operations under climate change conditions

The following example introduces results of FranTranS simulations forced by a hydro-climatic model ensemble for climate change conditions.
A hydro-climatic model ensemble is defined in Q-Bic³ as runoff data derived from hydrological models driven by climate models. In the assessment the hydrological model WaSim [Jasper and Schulla 2007] forced by the RCM RACMO [van Meijgaard 2010] which is driven by three members of the GCM ECHAM5 (WAS-RAC-MBX-ECM) was used. As previously mentioned, a critical lake level of 370 m a.s.l. can be used to mark the low end boundary condition for the system. To query such situations, a hypothetical rule was implemented, setting the discharge to zero when Rothsee is lowered to this critical level. To assess climate change impact, days for every year in the reference and future period with zero discharge are counted and quantiles for both periods (figure 5) are compared. Results show an increase of the median values from 2 to 9 days from reference and future period. The extend of the upper two percentiles are doubled with an increase from 20 to 43 respectively 51 to 90 days for the highest values. Hence the total monthly amount of channel transfer shows a decrease, reflecting this climate change signal. The latter one could also be attributed to a relaxation of low flow situations at gauge Huettendorf, because former assessments show that changes at Huettendorf are very small. Based on such results, scenario rule sets can be developed and FranTranS can be used to test the performance of the water transfer system under enhanced critical conditions. It may then become a very useful tool to examine strategies for adaptation to climate change impacts.

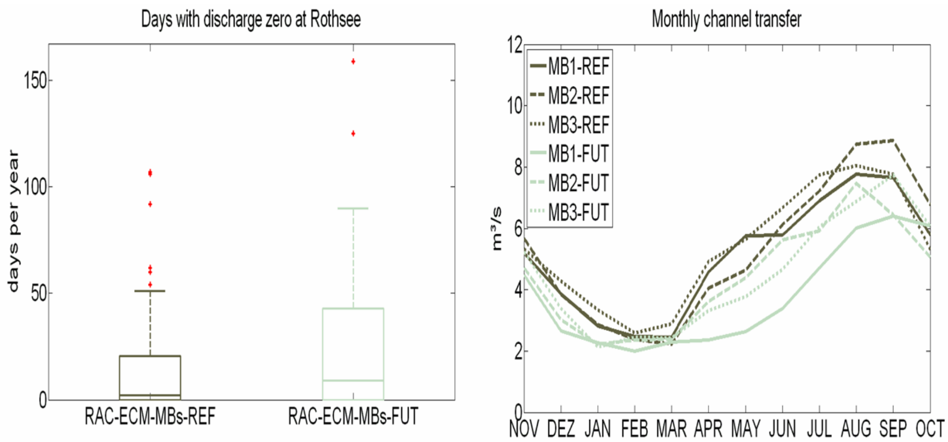

Figure 5. Box plots for days with modeled discharge zero for Rothsee (left) and modeled monthly average of channel transfer (right) for the hydro-climatic ensemble WAS-RAC-MBX-ECM

4.5 Discussion

The three examples show that close participation of the system operator as a major stakeholder is necessary. This is obvious for model validation as outlined in section 4.1. Unusual operation of the reservoirs during construction works and also smaller short term changes in the lake level management (e.g. for building a ramp for disabled people at one of the reservoir beaches) would otherwise lead to a misinterpretation of the model performance. The situation in the summer of 2003 shows another interesting fact: The underestimation of lake levels is not only because of a model error, but it was decided by the operators to use the winter threshold of 22m³/s instead of the summer threshold 27m³/s for gauge Huettendorf. A major question of the stakeholders to the project is, if it is necessary to decrease the thresholds for Huettendorf, as it was done in summer 2003. This could be possible since water quality in the Regnitz has improved since the 1980ies, because better sewage plants have been constructed along its path. An argument for this could be that, as shown in example 4.3, the days when no water can be taken from the Danube to augment low flow at Huettendorf may increase in the future.

5. Outlook and conclusion

The current model version is able to reproduce the current standard operation of the Transfer System in plausible ranges. However, performance deficits still exist; these can be traced back to missing rules and indicate the necessity for further evaluation and to further refine the FranTranS rule set. As some of the reasons for malfunctions have already been identified, they will be eliminated systematically in close cooperation with the operator.

Next to this technical conclusion, a first assessment of potential climate change impacts shows the need to consider the development of adaptation strategies. E.g. an more intense use of the Brombachsee reservoir for low flow augmentation in autumn, since the expected increase of low flow conditions at Kelheimwinzer during autumn will reduce the potential amount of transferable water from the Danube. If it is possible to balance this water deficit with water from the Brombachsee is one example of future FranTranS applications.

Preliminary results indicate that passive strategies might be sufficient, i.e. adapting the operational rules to cope with the changing conditions. Yet, by using and further developing the presented prototype, researchers and stakeholders will collaborate to specify the most useful and applicable concepts for adaptation to climatic and socio-economic changes.

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