Real Time Control and Operation of drinking water Networks: A Case Study at the Syndicat des Eaux du Sud Koerich

A. Cornelissen[2], T. Levy[1], G. Schutz[2], N. Ney[1], D. Fiorelli[3]

[1]Syndicat des Eaux du Sud Koerich, Fockemillen, L-8386, Koerich, LuxembourgO
[2]RTC4Water s.a.r.l, 9, av. des Hauts-Fournaux, L-4362 Esch-Sur-Alzette (Belval), Luxembourg
[3]Luxembourg Institute of Science and Technology (LIST),5, avenue des Hauts-Fourneaux, 4362 Esch-sur-Alzette, Luxembourg

ABSTRACT

Real Time Control (RTC) systems in potable water supply have the potential to use existing infrastructure (basins and pipes) in a more efficiently manner. Advantages include: an improvement in the water quality by reducing stand-times in basins, constant flow control into the distribution system and the ability to deal with water supply shortages or high water consumption in a much more efficient way. This paper will investigate the potential of these advantages based on an initial assessment of the water distribution system of the Syndicat des Eaux du Sud Koerich (SES) in the south of Luxembourg. This assessment is performed based on little data and a knowledge of the network. Currently the syndicate has one large storage basin and 36 smaller distribution basins on a communal level. The paper will focus on: the benefits RTC4Water's real time control system can have on the individual communal basins, the increase in overall autonomy, the decrease in daily capacity and the decrease in flow variations and associated pressure fluctuations.

1.0 INTRODUCTION

1.1 Description of the current system

The entire Syndicat des Eaux du Sud Koerich (SES) system is relative complex and consists of spring catchments, deep wells, pumping stations, disinfection plants, water storage tanks, pipelines and additional installations [1,2]. Included are 28 kilometres of water mains that conduct water from the source to the pumping stations and 185 km water mains for carriage and distribution to the local storage reservoirs. In addition, the water systems of the 22 member municipalities must be considered. These communities are: Bertrange, Bettembourg, Differdange, Dippach, Dudelange, Esch-sur-Alzette, Frisange, Garnich, Käerjeng, Kayl, Koerich, Leudelange, Mamer, Mondercange, Pétange, Reckange-sur-Mess, Roeser, Rumelange, Sanem, Schifflange, Septfontaines and Steinfort. Furthermore, there are a number of large industrial customers in the area, such as the group Arcelor Mittal, a steel manufacturer.

A schematic of the distribution system is given in Figure 1. The system of catchments and wells that supplies almost half of the water needed is not shown here. However, this volume is relatively constant (and for the purpose of this study considered a constant). From figure 1 it can be observed that the central storage basin(s) Rebierg plays a dominant role. Currently this is the only reservoir that is controlled by operators and used to absorb the effects of high customer demand or an exceedance of the reserved daily capacity (RDC).

1.2 The Reserved Daily Capacity

The Reserved Daily Capacity (RDC) is a restriction places on consumers by the SEBES[3], the water producer in Luxembourg[4]. In essence each of SEBES's costumers reserves a certain daily capacity in m^3/day at the start of each year. If the customer exceeds this RDC, even for one day, the monetary penalties for this are severe, since the producer then essentially has to supply the necessary infrastructure to deal with this demand. This results in customers reserving more water than they normally need to avoid these penalties. However, this practice also encourages the use of reservoirs to adsorb daily peak demands.

Photo 1: The Esch-sur-Sûre dam from which the SEBES abstracts drinking water for Luxembourg

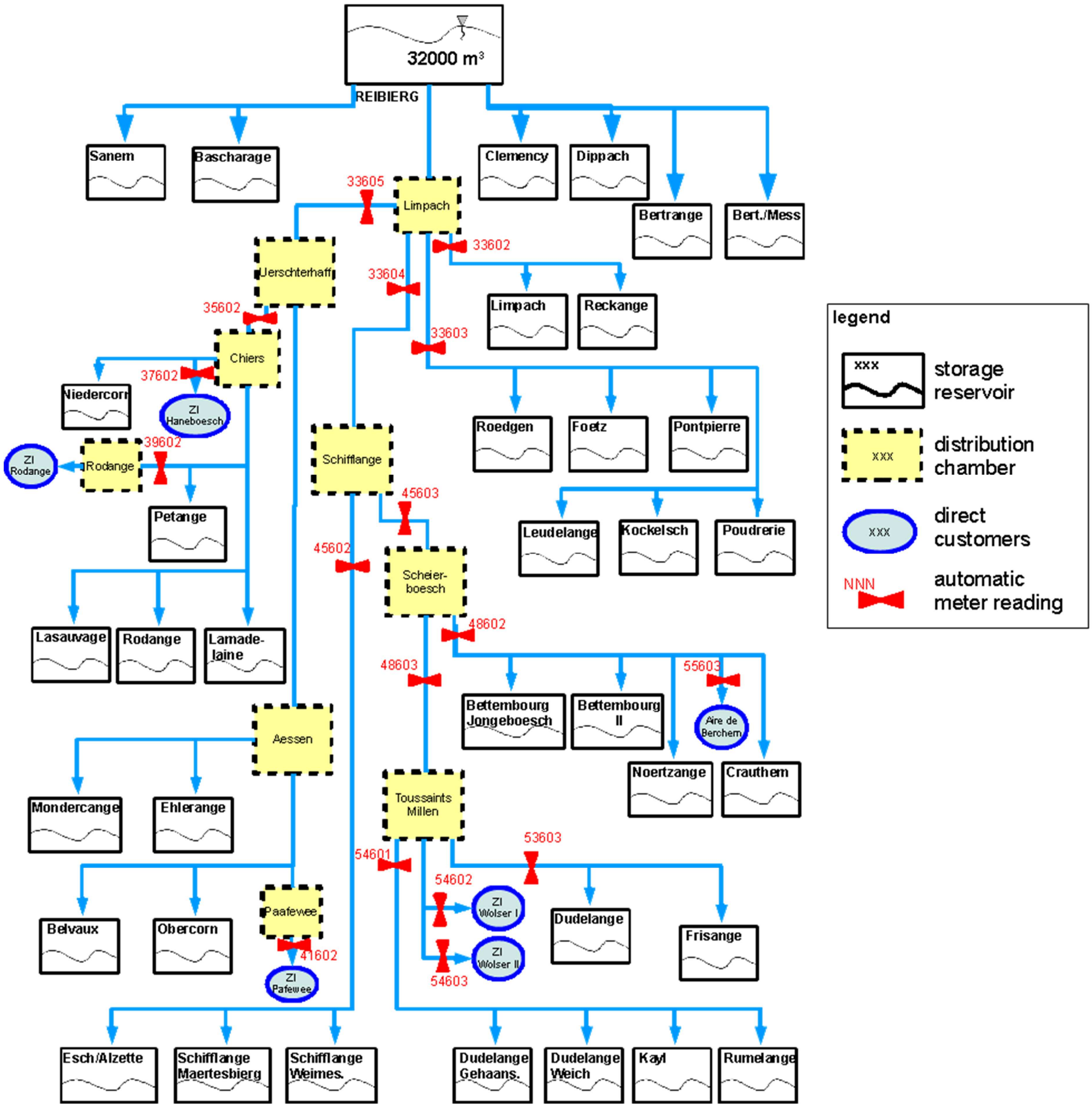


Figure 1: Schematic of the overall SES distribution system

1.3 Operation of the current system

As mentioned above, in the SES distribution system, only the Rebierg reservoir(s) are currently used to absorb periods with high demand and/or flow. The remainder of the reservoirs are operated with a simple control strategy that basically means that these tanks currently can be considered to be full at all times, clearly with the exception of tanks with very low autonomies.

Parts of the SES network are characterized by large fluctuations in demand. The typical daily demand profile resulting from residential areas is further exacerbated by large industrial users which are in many cases directly connected to the network (without a basin). These fluctuations have in the past required the installation of substantial piping, which enabled the SES to deliver large amounts of water in a short time. However, the resulting transient high flow rates are undesirable because these can result in significant pressure fluctuations and pressure surges in the network.

In July 2015 Luxembourg experienced a prolonged drought period just before the summer holidays, which resulted in the Reiberg reservoir being stretched to the limits and the system was very close to needing to exceed the reserved daily capacity in order to maintain supply.

1.4 Aim of the study

The aim of this study is to analyse the potential for optimization through the use of a real-time regulation to reduce the required daily capacity and/or increase the autonomy of the system. Thus using the existing infrastructure in a more efficient manner, only adding measurement and control systems such as flow and level measurements, flow control and a local controller (PLC) at each basin as well as a central global controller at a central point. Daily capacity and autonomy are opposing constraints as will be discussed in detail later in this paper. Another aim is to evaluate a potential reduction in peak flows and investigate if an increase in water quality through reduced residence times in low demand periods.

1.4 Real Time Control

The Real Time Control system as produced by RTC4Water is essentially a merging of three technologies: Model Predictive Control (MPC), Distributed Control Theory (DCT) and Self Adapting Network (SAN) technology. The DTC and SAN part of the technology are used to increase the overall resilience of the control system (failure recovery and network reconfiguration due to faults or maintenance) and will not be further discussed here. The MPC system has been extensively described in previous publications of some of the Authors [5-9]. However, a short description of the process for constructing a RTC controller is given below:

The process consists of the development of a simulation environment of the client network, from which subsequently a simplified predictive model is derived. Together with a control strategy, which is formulated depending on client preferences, a real time controller is then produced. This controller works together with the client's Supervisory Control And Data Acquisition (SCADA) system to optimise the network. The individual steps are the following:

1. Information acquisition–understanding of the structure and function of the current system, including meta data, plans, archive data to identify the constraints and system dynamics of the network
2. Understanding the needs of the customer which are then translated into the objectives and subsequently in an objective function
3. Develop a simulation environment to identify and calibrate the system model, which is a plug flow/mass-balance model.
4. Develop a control strategy where an objective function, fall back strategies and emergency strategies are defined
5. Build the controller, the RTC4Water controller builds a problem description every 15 minutes based on the past, present and future anticipated situation as well as the objective function. The controller then solves this problem (which is always possible, since the simplified model only allows linear elements) and implements the resulting set-points.
6. Determine the real time data requirements for control and, where necessary, install these.
7. Deploy, test and monitor the Global Predictive Control (GPC) instance

There are a number of statements that can be made about the effect of the RTC4Water's Real Time Control which can be helpful in initially understanding the functioning of such a system:

1. The Real Time Control allows the distributed storage in the system to work together because RTC distributes the available water depending on the current (and future predicted) demand, this means that:
   a. The (virtual) effect is that it is conceptually possible to transfer water from one basin to another (although in reality this is clearly not the case)
   b. All basins aim to maintain the same autonomy (at the end of each day)
   c. Distributed storage can be virtually added together to virtually act together as one large storage reservoir
2. Real Time Control maintains an overall better water quality because the controller aims to maintain a fixed residence time in each Basin (Normally 2 days or 48 hours)
3. Clearly statement 1 and 2 are not in alignment, however, in practice this behaviour is possible because a situation of low flow (high residence times) and high flow (risk of exceeding the RDC) do, in reality, not occur together in a distribution system. Although, even if they would occur, the system is still stable and finds the best solution. However, normally the transfer from a low flow scenario to a high flow scenario in a water distribution system is normally gradual and the controller is able to make a smooth transition from the one to the other

1.5 Definitions

- Design Autonomy Basin (DAB) = Time in days where a basin has enough water to supply its consumers if the inflow would be 0.
- Design Autonomy System (DAS) = Time in days where a water distribution system has enough water to supply its consumers if the inflow would be 0 and the water distribution is ideal.
- Operational Autonomy Basin (OAB)=Time in days where a basin has enough water to supply its customers at a specified daily inflow:
  - The OAB under normal circumstances (Inflow-Outflow >=0) is ∞
  - If the Inflow(system)-Outflow(system)<0, the operational autonomy is the (Inflow-Outflow)/storage capacity if for that basin: Qmax(in)>>Qmax(out).
- Operational Autonomy System (OAS)=Time in days where a water distribution system has enough water to supply its customers at the daily inflow:
  - The OAB under normal circumstances (Inflow-Outflow >=0) is ∞
  - If the Inflow(system)-Outflow(system)<0, the operational autonomy is the (Inflow-Outflow)/total storage capacity if for all basins: Qmax(in)>>Qmax(out) and all basins reduce their Operational Autonomy simultaneously.
- Theoretically achievable Daily Capacity (TADC) = Is the daily capacity if a water distribution system is considered to have an unlimited storage capacity, a theoretically achievable daily capacity can be calculated by dividing the total yearly consumption by the number of days in a year.
- Validated Maximum Demand Day (VMDD) is the day where the amount of water consumed is larger than all other days for which there is data. However, the data for this day needs to be validated to ensure that there are no abnormal events leading to the high figure such as a fire or a pipe burst.
- Operational Autonomy of a basin at the Validated Maximum Demand Day (OABVMDD)
- Operational Autonomy of the system at the Validated Maximum Demand Day (OASVMDD)

2.0 EXPERIMENTAL

Two datasets were compiled with the available infrastructure, since no real data acquisition system for the basins is currently in place this data is infrequent and currently does not allow the building of a controller:

1. The first dataset contains weekly flows for each basin in 2015. The data was evaluated and outliers removed. A table was created to include all basins with their storage volumes (metadata), the design flow (metadata), the average design retention time (Volume / design flow), the average flow (data), the minimum daily inflow (data), the maximum daily inflow (data), the number of data points received for the basin, the average retention time in days (data), the minimum retention time in days (data), and the maximum retention time in days (data). Furthermore, totals were calculated.

2. The second dataset contained hourly flow data from the 9 distribution sumps (see Figure 1) in the system. This data was collated into daily flow data. Furthermore, using this data, average daily flow profiles were estimated for each basin.

3.0 RESULTS AND DISCUSSION

3.1 Theoretically achievable Daily Capacity

The yearly outflow for the complete SES system in 2015 was 12,891,378 m3 or 12,891 Ml, therefore the TADC is 35,319 m3/day or 35 ML/day for the complete system. However, the total inflow from SEBES was only 6,945,000 m3 (53% of the total, the rest is supplied by SES sources) and the TADC here is 19,027 m3/day or 19 Ml/day (the current SES Reserved Daily Capacity is 32600 m^3/day). However, this theoretical situation is currently not feasible and also not desirable because of a need for very large reservoirs with high stand-times resulting in a reduced water quality. In reality there is a trade-off between daily capacity, autonomy and quality. However, the TADC is useful as a starting point for setting the RDC.

The current storage capacity used for managing the daily capacity or maintaining autonomy is the Rebierg reservoir which has a storage volume of 32000 m3. The calculated autonomies here are:

Table 1: Autonomies of the Rebierg Reservoir(s)

Autonomies Rebierg Reservoir(s)	**At Average Flow** 35319 m3/day	**At VMDD** 53130 m3/day	**Notes**
Design Autonomy Basin (DAB)	0.90 days or 21:45 hours	0.60 days or 14:30 hours	
Operational Autonomy Basin (OAS)	∞	10.3 days	**keeping daily capacity SEBES of 32600, total inflow of 17430 from other sources**

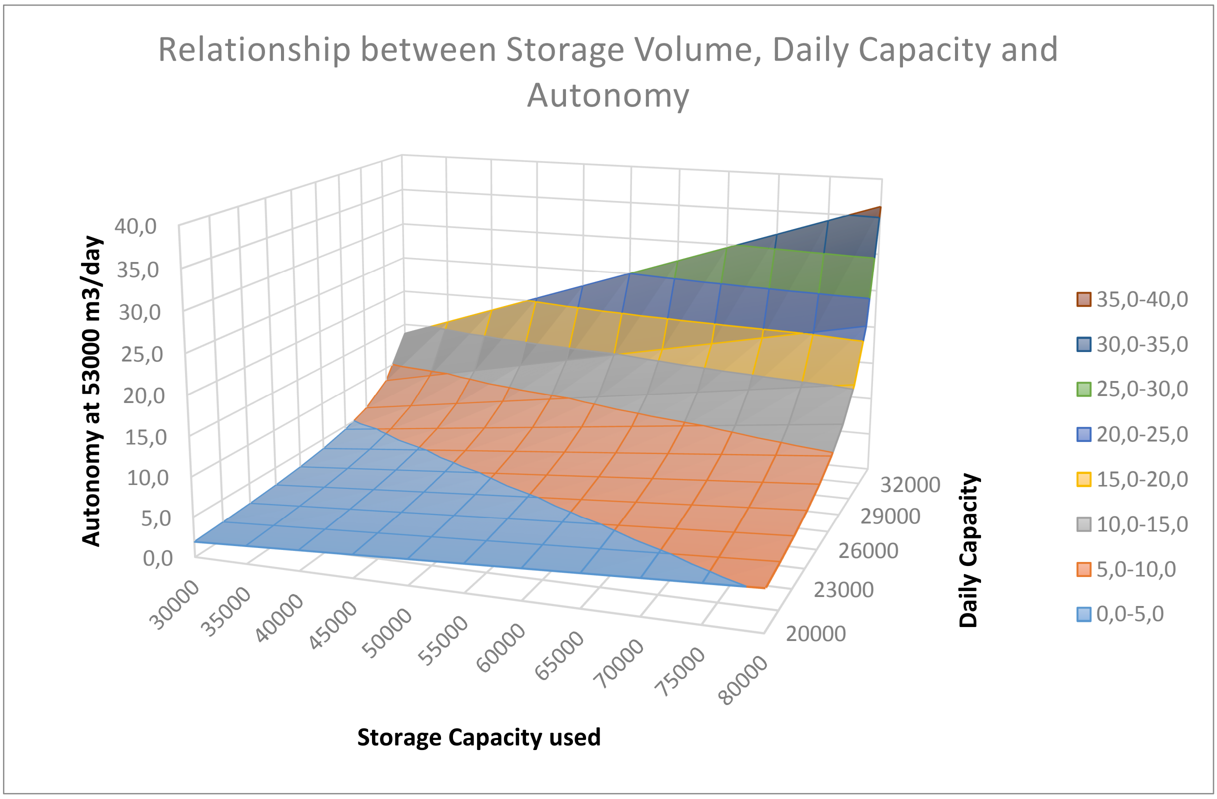
The capacity of all other reservoirs added together is 59345 m3, which gives a total available storage volume, including the Rebierg reservoir(s) of 59345+32000 = 91345 m3.

Photo 2: The high level section of the Rebierg reservoir

Therefore, the total theoretically available autonomy increase is 91345/32000= 2.85 times. This means that if the Rebierg storage gives an autonomy of 10.3 days, then theoretically, using the total storage volume an autonomy of 29.4 days is achievable. However, often a fire reserve of around 20% of the total volume of a basin is required. Therefore, many basins are not allowed to empty below 20% of its total volume. This reduces the potential increase to ((59345*0.8)+32000)/32000=2.48 times or 25.5 days. This is also a hypothetical scenario: in practice the actual system needs to be modelled and tested to see where any difficult point in the network are and in how far the overall volume can be used as assumed in the ideal case.

3.2 Trade-off between Reserved Daily Capacity and System Autonomy

As already mentioned there is a trade-off between the Reserved Daily Capacity and the System Autonomy. The higher the Reserved Daily Capacity, the longer the operational autonomy remains ∞ with rising demand and the longer the System Autonomy once the daily demand exceeds the RDC (assuming the system does not take-in more water than the RDC). This relationship can be observed in Graph 1, where the Controlled Storage Capacity, the Reserved Daily Capacity (RDC) and the resulting Autonomy are shown. This graph shows that it is in essence possible to come close to the Theoretically Achievable Daily Capacity (TADC) of 19000 m^3/day if 80,000 m^3 of storage volume is available for control. At a RDC of 20,000 there is an autonomy of 5 days at OASVMDD. More realistic would be to maintain 10 days of autonomy: this would result in a RDC of 28,000 m^3 with all current existing volume controlled.



Graph 1: The relationship between the Controlled Storage Capacity, the Reserved Daily Capacity (RDC) and the resulting Autonomy

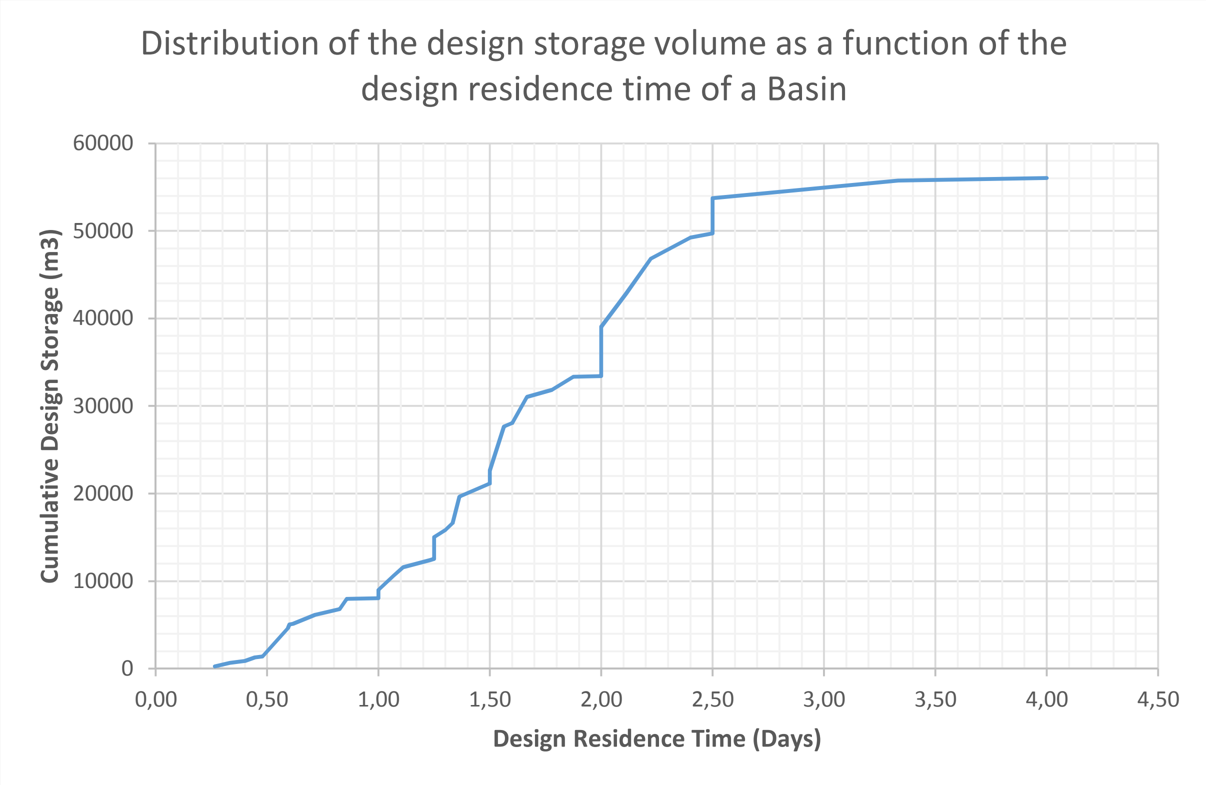
3.3 Basin Autonomy, Daily Reserved Capacity and System stability

It is clear that a basin with a very high autonomy (> 2 days) can effectively contribute to the overall storage volume. What is not so clear is that a basin with a low autonomy (<1 day) can contribute to the overall autonomy. In control terms this is however no big problem as long as the possible inflow of the basin is much higher than the outflow. In practice there are limitations to this approach: there is essentially a cost of basins with low autonomies to the overall stability of the control system and its ability to reach its objectives at days' end (Even more of an impact have the direct consumers). Furthermore, the physical capabilities of the system determine if a certain volume can effectively contribute to the overall (virtual) volume controlled. Examples are: Opening and closing speed and maximum frequency of valves, pipe diameters, pipe lengths and pump dimensions. Hence the need to build and closely examine a software model of the distribution system.

Graph 2 shows the distribution of the available storage which is currently not controlled as a function of the residence time at the design flow.

3.4 Control strategies

Because, normally, it takes time to change a system from no, or simple control to RTC, there are several strategies that can be imagined to get the biggest benefit during the alterations required:



Graph 2: The relationship between the Design Residence Time in Days and the Cumulative Design Storage Volume

Strategy 1: Focus on increasing the controlled storage volume

A cost effective increase in the overall autonomy and/or a decrease in the Reserved Daily Capacity can most easily be achieved by first controlling the basins with the largest volume.

Strategy 2: Stability Increase

Another strategy is to increase the stability of the system by controlling the basins with the highest autonomies first. This will increase the stability of the system because these basins can be easily filled during low system flow and low demand conditions (filling will be interrupted during high demand).

Strategy 3: distribute controlled volumes evenly across the network

Clearly, there is no point in having severe flow fluctuation in one part of the network and a nice smooth flow in another. It makes therefore a lot of sense to distribute controlled reservoirs evenly across the network.

Strategy 4: Problem Removal

The SES distribution system is build-up of a number of branches. It is conceivable that one of these branches results in the majority of problems that a network is experiencing. A valid strategy therefore would be to control a “problem” branch in its entirety first. The Branch Clemency, Dippbach, Bertrange has in the meantime be identified as such a “problem” branch, because under certain conditions there are hydraulic problems in providing enough water to the reservoir at the end of this branch (Bertrange Mess).

Combined overall strategy:

In this case it is possible to combine the four strategies outlined above in one single strategy: First eliminate any problem areas (Clemency branch), followed by the control of large reservoirs with high autonomies. Identified are the reservoirs Bertrange (4000 m^3, 2.5 days), Belvaux (4000 m^3, 2.2 days), Marmer (3800 m^3, 2.11 days) and Bettenbourg (3400 m^3, 2 days). These four tanks would add 15,200 m^3 to the controlled storage volume, virtually doubling the controlled storage.

3.5 Limitations

As already mentioned, there will be limitations in the network that will in turn limit the efficiency of a RTC system. These can only be identified by the availability of considerable more data than currently at the disposal of the researchers. In addition, a simulation model of the system will have to be developed to fully explore these restrictions and (partly or fully) remediate these by optimisation of the controller. It is therefore necessary to implement the measurement systems as a priority.

4.0 CONCLUSIONS

In this paper the capabilities of an RTC system have been outlined and the ideas developed that make it possible to perform a first assessment of the effects an RTC approach can have on a water distribution system. This is useful because often there is very little data available on the detailed performance of a particular system. However, using the methodology outlined, at least some indications can be developed on how such a control system can perform.

5.0 REFERENCES

1. www.ses-eau.lu
2. Distribution of drinking water in the grand-duchy of luxembourg – the challenge to mix water of different chemical and physical properties, Tom LEVY, Dipl.Ing, Technical Manager Syndicat des Eaux du Sud – Koerich (G.-D. Luxembourg), CEOCOR 2012
3. www.sebes.lu
4. www.eau.public.lu/eau_potable/production_distribution_responsabilites
5. Fiorelli D., Schutz G. : "Conduite optimale de réseaux de bassins" , in proceedings of the Sixième Conférence Internationale Francophone d'Automatique, CIFA 2010, Nancy, France, 2-4 juin 2010
6. Fiorelli D., Schutz G., Meyers J. : "Application of an optimal predictive controller for a small drinking water network in Luxembourg" , in proceedings of the Eleventh International Conference on Computing and Control for the Water Industry, CCWI 2011, Exeter, England, 5-7 September 2011
7. Schutz G., Fiorelli D. : A pilot implementation in Wormeldange. Cahier scientifique. Revue technique luxembourgeoise. No 2 pp 20–23 2012
8. Fiorelli D., Schutz G., Metla N., and Meyers J. : Application of an optimal predictive controller for a small water distribution network in Luxembourg. Journal of Hydroinformatics Vol 15 No 3 pp 625–633 © IWA Publishing 2013 <doi:10.2166/hydro.2012.117>
9. Benallouch M., Schutz G., Fiorelli D., Boutayeb M.,: H8 model predictive control for discrete-time switched linear systems with application to drinking water supply network. Journal of Process Control, International Federation of Automatic Control, 24 (6), pp.924-938, 2014 <10.1016/j.jprocont.2014.04.008>