Flow control by prediction of water demand

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ABSTRACT

The production rate of drinking water treatment plants in the Netherlands is currently often directly related to the level in the clear water reservoir. This results in many production rate changes, and the daily peak demands are not completely levelled off in the clear water reservoir. A recently developed control algorithm, based on an adaptive demand prediction, can achieve a more stable production pattern with a minimum of flow changes. The implementation of the algorithm at several treatment plants has led to a significant optimisation of the treatment process. A more stable treatment process leads to better clear water quality and to less energy consumption. A future combination of a control algorithm and a qualitative model opens up the possibilities for further optimisation of the treatment process and to a consistent clear water quality.

Key words | drinking water demand prediction, modelling, optimisation, real-time control

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INTRODUCTION

The control of the main elements of the drinking water infrastructure, such as treatment plants, pumping stations and reservoirs, is often based on relatively simple control rules (or manually). For example the level in the clear water reservoir often directly controls the production rate of a treatment plant: if the level is high, the production rate is decreased or reduced to zero; if the level is low, (additional) pumps are switched on.

This article focuses on the operational control, typically on a 24 h scale, of the main elements of the drinking water infrastructure (plants, reservoirs, pumping stations), and not on the real-time control of individual elements (like pumps, valves, etc.).

Despite the on-going innovation in the fields of process automation and information and communication technology, the primary control is still based on the same techniques that were used several decades ago. This is understandable because these techniques have proved to be adequate and very reliable over a long period of time. As Dutch law holds the manager of a drinking water company personally responsible for the supply of water of good quality under sufficient pressure to the customers, reliability has always been an important issue.

However, society is changing, and also demands on the drinking water companies are changing. Not only is the continuous supply of water of good quality important, but also aspects like customer satisfaction, environmental impact, efficiency, etc. have become important. This development is intensified by the recent benchmark of drinking water companies in the Netherlands. The benchmark is an incentive for the drinking water companies to improve efficiency, for example by minimising energy consumption or costs in drinking water production and distribution.

One of the promising methods to reduce energy consumption in the production and distribution of drinking water is to improve the operational control of the main elements. This improvement of control can be achieved by using demand prediction.

WATER DEMAND

People and industry generate water demand. By studying the demand of a supply area, a lot can be learned about the people living in the area or about the type of housing in the area. One can look at, or predict, demand over various time scales:

- long-term: 5 to 20 years (calculation units: million m^3/year);
- medium-term: 1 year (calculation units: m^3/day);
- short-term: 1 day to 1 week (calculation units: m^3/h);
- ultra short-term: real-time to 1 h (calculation units: m^3/sec).

Long-term demand

Long-term demand prediction is needed for the planning and realisation of new infrastructure. Based on long-term demand prediction the point in time can be determined at which the existing infrastructure will not suffice for predicted demand. To avoid this happening, a number of years before this point in time the construction of a new treatment plant, reservoir or pipe should start.

Long-term demand prediction is usually based on the planned construction of new city districts or other housing and sociological aspects, such as the number of persons per household, the water use per person, etc. However, actions of the water company also play a role, like campaigns for reducing leakage or water saving campaigns for customers.

Medium-term demand

The medium-term is about the demand in the forthcoming period of approximately 1 year. Not only is the total amount (m^3/year) an important figure, but also the distribution of the demand over the year and the predicted peak demand (m^3/day) are important. In Figure 1, the daily demands over 1 year and 1 month are shown for both a province and a village. To be able to compare the curves, not the daily demand (m^3/day), but the daily demand factors (–) are shown. The graphs show that there are obvious differences between a small area (Limburg village) and a bigger area (Northern Holland province):

- the peak demand is higher in small areas;
- the day-to-day variation is bigger in small areas;

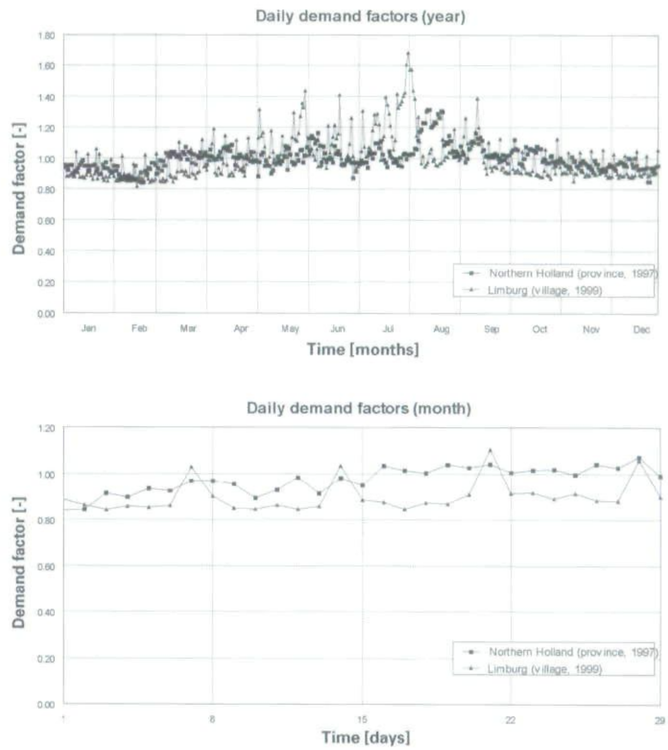
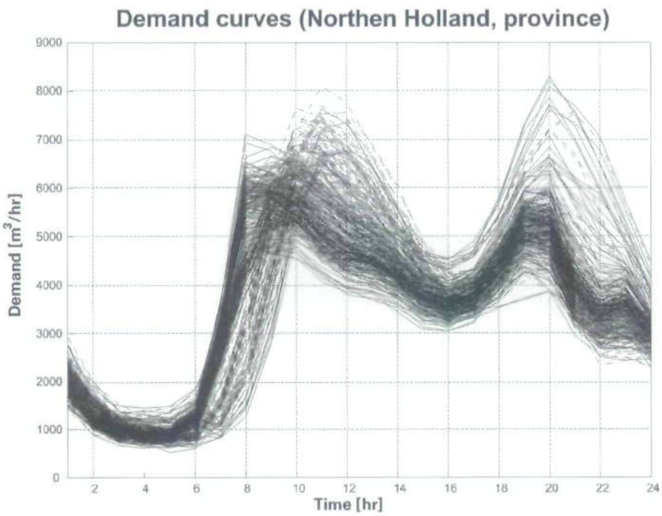


Figure 1 | Daily demand factors (=daily demand/average daily demand of 1 year) on a 1-year and 1-month time scale of a province and a village. Both charts show the difference between a small village (higher peaks, distinct weekly pattern) and a province (lower peaks, less day-to-day variation).

- periods of high demand are not always at the same time (in Northern Holland in 1997 in August; in Limburg in 1999 in July);
- the weekly pattern is more distinct in small areas.

A medium-term demand prediction can be used to make strategic choices about the use of the existing infrastructure in the forthcoming period of approximately 1 year. If the sum of the production capacities and the abstraction permits of the treatment plants in the area are bigger than predicted demand for the next year, various divisions can be made in the use of the treatment plants. For example, the optimal division can be to use the entire capacity of the treatment plant with the lowest operational costs.

Not only can strategic choices on a yearly basis be made, choices for a shorter period of time, like high demand periods, can also be optimised.



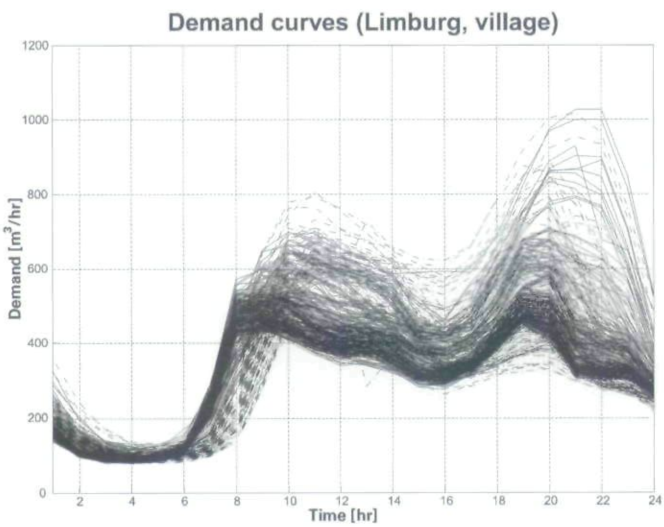


Figure 2 | Daily demand curves of 1 year (365 curves) plotted on a 24-h scale of a province and a village. The graphs show that the variation in demand is relatively small. The variation in a village is, however, bigger than in a province, especially during the evening peak demand (between 18.00 and 24.00 h).

Short-term demand

The short-term is about the demand in the coming days or week, in which typically the hour-to-hour demand is considered. On this time scale the daily demand patterns are important. In Figure 2 the daily demand patterns of 1 year (365 curves) are plotted on a 24-h scale of both a province and a village. The demand patterns on Saturdays (dashed lines) and Sundays (dashed dotted lines) are clearly different from the patterns on weekdays (other lines). Because people sleep late on Saturdays, and especially on Sundays, the increase in demand in the morning starts 1 or 2 h later. And, surprisingly, the peak hour demand in average demand situations of both considered demand files do not occur on weekdays but on Saturdays (Northern Holland) and Sundays (Limburg) at about 11.00 h.

The figure shows that the demand patterns of most days are very much alike. In particular, the variation in demand during the night and early morning is very low. The variation in a small area (Limburg, village), however, is bigger than the variation in a bigger area (Northern Holland, province). The biggest variation in demand occurs during the second demand 'bulge', approximately between 18.00 and 24.00 h, on peak demand days. In this period a lot of customers use extra water to sprinkle their garden. The peak hour demand on peak demand days doesn't occur at 11.00 in the morning, but between 8.00 and 10.00 in the evening. The so-called 'sprinkle-bulge' can require a tremendous extra amount of water to be supplied, as can be seen in the demand curves of Limburg (Figure 2).

Ultra short-term demand

The ultra short-term is about the demand in the forthcoming minutes or hour. This can be seen as the sum of 'real-time' flows of all pumping stations, reservoirs and water towers. This demand can be very capricious, because (theoretically) each individual water use can be seen, although in practice only the individual use of very large consumers can be seen.

However, when many small consumers all behave similarly as a group, an extraordinary demand pattern can observed. In Figure 3, the demand before, during and after an important soccer game during the world championship in 1998 is shown. Over 5 million people watched this game, which is more than one third of the Dutch population. Dramatic increases in demand of over 50% in 1 min after the first half and after the end of the game occurred. These increases are caused by use of the toilet. After the tension of the game, some tension needs to be released . . .

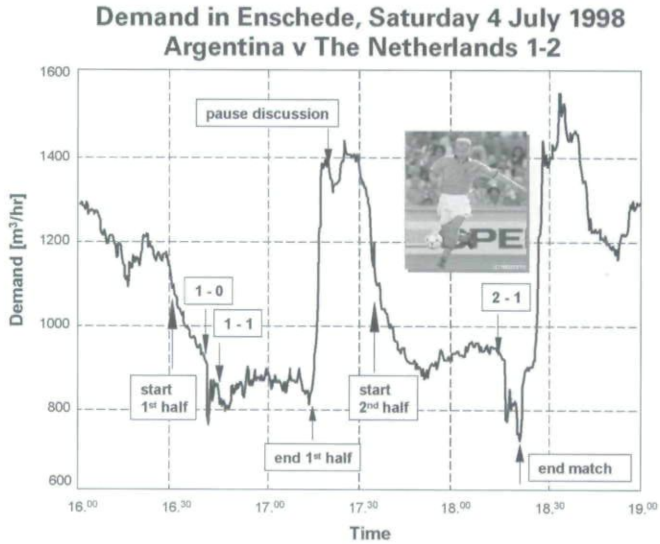


Figure 3 | Demand during a soccer game in the world championship in 1998. During the game extreme demand variations occur in the ultra short-term. For example, right after the finish of the first half, the demand rises from 800 to 1400 m^3/h within only 1 or 2 min.

it's obvious that such a demand pattern is very hard to predict.

However the average hourly demands during the game hardly differ from the demands in normal situations. This means that dramatic effects on the ultra short-term have virtually no effect on the short-term demand.

Water demand: conclusions

As noted at the beginning of this section, people generate water demand. The examples of demand on various time scales point out the influences of human behaviour on water demand. The water demand during an important soccer game indicates that human behaviour and water demand in the ultra short-term can be very unpredictable. However, in the short- and medium-term, the behaviour and thus the water demand are fairly predictable. The following aspects in the short-term water use of western (or at least Dutch) society are identified:

- the daily demand (m^3/day) is characterised by a weekly pattern and changes quite gradually (Figure 1);
- the daily demand curve ($24 \times m^3/h$) is characteristic for each day of the week, and Saturdays and Sundays differ from weekdays;
- on peak demand days an extra 'sprinkle' demand in the evening (between 18.00 and 24.00 h) is added to the 'normal' demand.

These observations are true for all analysed supply areas. The day-of-the-week demand factors and the day-of-the-week demand curves are, however, unique for each supply area and can differ greatly from each other for various supply areas.

SHORT-TERM WATER DEMAND PREDICTION

Straightforward prediction

Based on the observed typical aspects of water demand, a relatively simple prediction algorithm was developed. The algorithm consists of three steps:

1. Prediction of the daily demand. Based on the demand of the previous 48 h and *day-of-the-week demand factors*, the daily demand for the next 48 h is calculated.
2. Prediction of hour-to-hour demand. The predicted daily demand is multiplied by *demand curve(s)* to predict the demand for each of the next 48 h.
3. Prediction 'sprinkle demand'. Based on the observed extra demand during the 'sprinkle hours' on the previous day, an extra 'sprinkle demand' for the next 48 h is predicted.

The prediction is updated every hour so that the most recent (previous) demand figures are used. As can be seen from the three steps, only the previous demand and a limited number of factors and curves are used to predict the water demand. No other input such as weather observation or even weather prediction is used. This means that the algorithm only needs the actual demand (m^3/h) in the distribution area to predict the demand. The actual demand is the sum of all pump flows of pumping stations in the supply area. For the implementation of the algorithm in a supply area with only one treatment plant, only

Table 1 | Demand errors for simple prediction algorithm per day and per hour

	Day		Hour	
	Average	95%	Average	95%
Northern Holland (province, 1997)	2.3%	<6.2%	6.2%	<14.2%
Limburg (village, 1999)	3.8%	<11.1%	6.9%	<14.2%

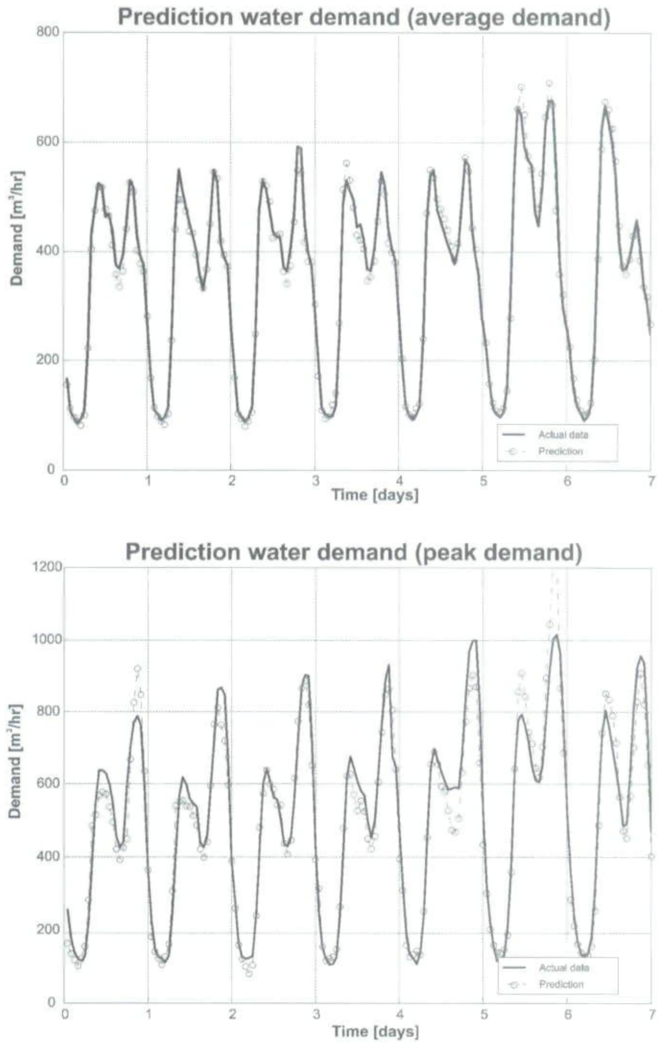


Figure 4 | Examples of the results of a simple demand prediction algorithm for the next 48 h. The graphs show that the prediction error during average demand is very small. The peak water demand shows more variation and is therefore harder to predict. Nevertheless, the prediction errors are relatively small.

the measurement of the distribution pump flow is needed. Because this flow is always measured at pumping stations and used for real-time control of pumps, the measurement is always available and moreover the reliability of the measurement is very high. This fact contributes to the reliability of this type of demand prediction.

'Adaptive' demand prediction

When active, the data of the demand in the supply area are collected. By analysing these data the algorithm learns the *day-of-the-week factors* (used in step 1) and the daily demand patterns for the different days of the week (used in step 2). In less than a month more than 90% of the typical demand patterns and factors in the considered supply area is collected. The used patterns and factors in the demand prediction are always up-to-date, because gradual changes in demand patterns are automatically picked up.

Accuracy

Despite the straightforward formulae used, the accuracy of the prediction is fairly high, thanks to predictability of the demand and the adaptive curves and factors of the algorithm. The prediction errors are shown in Table 1.

As the examples in the section about demand demonstrated, the variations in demand in larger areas are smaller than the variations in a small village. This also results in smaller prediction errors in the prediction of demand of a province (Northern Holland) versus the prediction of demand in a village (Limburg). In Figure 4, the actual and the predicted demands during an average week and during an extreme week in Limburg are shown.

Advanced demand prediction

The relatively simple demand prediction formula enables quick implementation. More advanced demand prediction, such as prediction based on neural networks (Aafjes, 1993), needs data analysis of the demand patterns in the distribution area for at least 2 years. If no distribution data are available, no demand prediction can be established. Another issue is that advanced demand prediction uses meteorological data, like (predicted) temperature, rain and evaporation. The relatively simple demand prediction doesn't need this information, so no manual input or data communication is needed.

The accuracy of advanced demand prediction will be higher. Nevertheless certain occurrences, such as a burst pipe or fire fighting, simply can't be foreseen by even the most advanced demand prediction. For this reason the control algorithm, which determines the production rate based on the demand prediction, must be able to cope with extreme prediction errors. The robustness of the control algorithm is much more important than the accuracy of the demand prediction.

FLOW CONTROL BASED ON PREDICTION OF WATER DEMAND

Aim of flow control

Based on prediction of the demand, the production rate of a treatment plant and the intake and pump flow of reservoirs in a supply area can be optimised. The most important function of clear water reservoirs (both at treatment plants and in the field) in the Netherlands is to level out the daily fluctuation in the demand pattern. In most systems in the Netherlands, the total reservoir volume in a distribution system is just enough to level out the demand pattern in the highest demand period. The available amount of storage normally equals about 25% of the daily demand of the peak day. Figure 5 shows a typical demand pattern and the level in the clear water reservoir at constant production.

The main goal of flow control is to establish a constant production rate at a treatment plant by using the available storage volume in reservoirs. The possibilities of saving energy costs are comparatively small in the Netherlands, because there are very few high reservoirs. This limits the options to make use of the cheaper energy during the night.

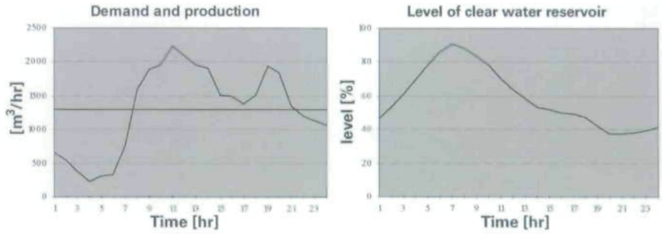


Figure 5 | Levelling out daily fluctuations in demand pattern.

Benefits of a constant production rate

A constant production rate can be achieved by using the clear water reservoir efficiently. A constant production rate has several advantages:

- A constant flow through sand filters gives the best filtration results. Filtration research has proved that turbidity peaks in the clear water occur after a production rate change.
- The use of wells with an inferior raw water quality can be avoided.
- By continuously using the same wells, the raw water quality will be more constant, which results in a more constant clear water quality.
- Optimal process conditions (such as doses, bypass flows, etc.) can be better achieved (Keuning *et al.*, 1998).
- Hydraulic losses, and thereby energy consumption, are minimised.
- Peak energy use will be lower, and in general relatively more cheap energy available during the night will be used. This will result in a lower energy bill.

Establishing a constant production rate

Currently used control algorithms are not at all capable of establishing the desired constant level of production. It often occurs that the production in treatment plants is completely switched off during the night and is significantly higher than the average demand during the day.

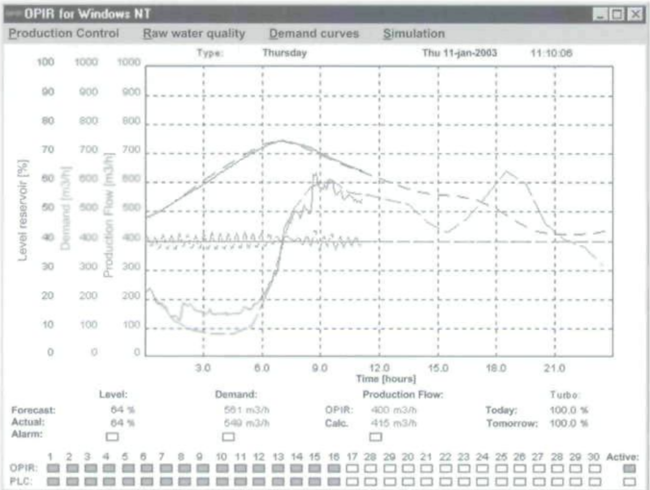


Figure 6 | User interface of OPIR. The chart shows forecasted and actual measured data of the demand, the production flow (constant value), and the level in the reservoir on a 24-h time scale.

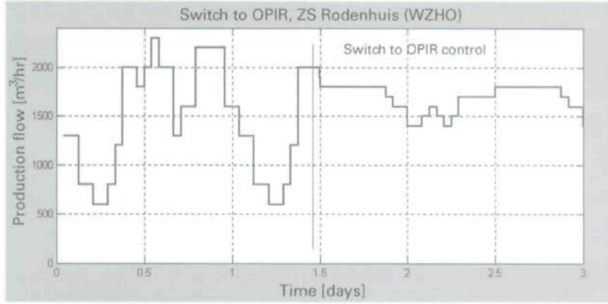


Figure 7 | Switch to OPIR at the Rodenhuis treatment plant.

To establish a constant production level a control algorithm was developed called OPIR, Optimised Production by Intelligent contRol. Based on a prediction of the demand pattern for the coming 48 h, and the actual, maximum and minimum allowed levels in the clear water reservoir, the algorithm determines the required production. The algorithm determines the optimal production rates for the next 48 h, whereby the volume in the clear water reservoir is most efficiently used. It is essential is to adapt the production rate as soon as possible, to avoid a bigger flow change, and so a less constant production, in the future.

Figure 6 shows the user interface of OPIR, in which the demand, production rate and level in the reservoir are shown on a 24 h scale.

IMPLEMENTATION

First implementation of advanced production control in the Netherlands

In January 1996 the first advanced production control algorithm was implemented at a drinking water treatment plant in the Netherlands. At the treatment plant 'Helden' ($12{,}000\ m^3/day$) of the Drinking Water Company of Limburg (WML), the implemented control algorithm automatically determined the number of raw water wells switched on, without any intervention by the operator. The reason for the implementation of the model was to optimise the quality of the purified water. The optimisation could be achieved by a constant production rate, with a minimum number of flow changes.

After these satisfactory results the algorithm was also implemented at the Beegden treatment plant ($22{,}000\ m^3/day$) of WML in 1996, and at the Reijerwaard treatment plant ($16{,}000\ m^3/day$) and in 1998 at the Rodenhuis treatment plant ($60{,}000\ m^3/day$) of the Drinking Water Company South Holland East (WZHO). The implementation of OPIR at the Reijerwaard has led to a significantly better quality of the clear water in terms of hardness and turbidity (Keuning *et al.*, 1998) and a spectacular drop in the number of failures. The switch to OPIR at the Rodenhuis treatment plant has led to a reduction in the energy costs of about 10%. The switch is monitored and results are shown in Figure 7.

Both WML and WZHO have decided to implement OPIR at all major treatment plants and reservoirs. It is currently used to control eight locations and in the next few years it will be used to control another number of locations.

Implementation on a standard PC

The control algorithm is a stand-alone application that runs on any standard Windows-NT computer. When implementing the control algorithm, a connection between the standard PC and the existing PLC is made. The algorithm obtains all the required information (distribution flow, level in clear water reservoir, actual status of wells, reservoirs and pumps, etc.) from the PLC. After determining the optimal operation of the treatment plant, the PC 'tells' the PLC which raw water wells to switch on. The wells are switched on or off by the PLC.

To reduce the (small) chance of failure, the conventional control of the treatment plant is present as a backup. If the PC, the communication with the PC or the algorithm breaks down, the PLC automatically switches to the conventional control. The plant will keep on functioning albeit in a less optimal way.

FURTHER OPTIMISATION: CONNECTING QUANTITY AND QUALITY MODELS

By achieving a constant production rate with an intelligent control algorithm and off-line optimisation of the process conditions with a quality model, a great deal of improvement in the treatment process could be made. The next step in optimising the drinking water treatment process is to make a connection between the quantitative and the qualitative models. Based on the production rate prediction calculated by the control algorithm and raw water quality parameters of individual wells, an average raw water quality prediction for the next 48 h can be made. This can be used as input for the quality model which can then calculate optimal process conditions for the predicted production rate and raw water quality.

Moreover, the times for backwashing of rapid filters can be calculated based on the iron load of the raw water and the built-up iron quantity in the rapid filters. Unfavourable times for backwashing a filter (because of required production rate or capacity of a backwash water treatment unit) can be avoided by bringing forward or postponing the backwashing of the considered filter(s).

CONCLUSION

Considerable knowledge about water demand and recognition of typical demand patterns were translated in a water demand prediction algorithm. The water demand prediction was subsequently used to determine the optimal control of the drinking water infrastructure in the supply area. Both the prediction algorithm and the production control algorithm are implemented at drinking water treatment plants on standard computers.

By using standard computers in the control of drinking water treatment plants more advanced control of the plant is possible. After optimising the quantitative control of the plant (constant production rate with an intelligent control algorithm), the possibilities of qualitative optimisation are now being investigated.

The aim in the optimisation is no longer a constant production rate, but a constant production *quality*. This constant quality can be established by on-line quality modelling based on a production rate prediction.

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