Evolution of a wastewater treatment plant challenges traditional design concepts

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ABSTRACT

Traditional design and upgrade concepts for wastewater treatment plants (WWTPs) are based on the forecasting of load parameters over a period of 25–40 years. This approach is adequate as long as the environment of a WWTP is stable or predictable over this long time period. However, these conditions are usually not met, as the catchment area, discharge requirements, available technology and institutional conditions of a WWTP may change drastically over time. The complexity and consequences of these dynamics are shown exemplarily in a case study analyzing the historical development of a plant from the initial planning steps to the current date. We conclude that the dynamics and complexity of the wastewater system makes reliable predictions impossible, and therefore question the current design and upgrade approach. Instead, we propose to improve the planning and design of wastewater infrastructures through methodologies that systematically account for future uncertainty, like, e.g. scenario planning.

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1. Introduction

Professionals working in the field of urban wastewater are often confronted with the disappointing fact that carefully researched measures do not lead to the desired results. The reason for this can often be attributed to unforeseeable social, economical and legal changes.

Nevertheless, consciousness of the long-term dynamics in wastewater systems and its importance is not widespread among practitioners and decision makers (Beck and Cummings, 1996). Because of this lack of consciousness, structures are designed or upgraded under the assumption that future changes can be taken into account through forecasts. This is highly questionable given the pace of changes and their uncertain consequences on the operation of wastewater structures. The long planning phase and the long operational lifespan of wastewater structures only add to this dilemma.

In this paper, we assert that the current design and upgrading practice for wastewater structures is unsuitable in view of the unpredictability of future developments. This uncertainty results from the long-term dynamics and complexity of the wastewater system as well as the long planning and operational life of wastewater structures. Moreover, current design procedures can be of such rigidity that they hinder future adjustments (Vanrolleghem et al., 1996). To prove this assertion, we analyze the historical development of an exemplary wastewater treatment plant (WWTP) and its surrounding environment from the initial planning to the current date. The interactions between the evolution of the pollutant loads (phosphorus, chemical oxygen demand (COD)) from the catchment, the development of the plant's capacity and changes in environmental standards are emphasized. From the results of our analysis we deduce weaknesses in the way we typically handle long-term future
uncertainty and propose scenario planning as an alternative approach.

To be able to understand the development of a WWTP through time, it is first necessary to apprehend the system in which it is embedded.

A WWTP is part of an urban water system, which consists of a catchment area (households, industry, roads, etc.), a sewer system and a receiving water. As shown in Fig. 1, these so called sub-systems of an urban wastewater system are subject to multiple and often complicated interactions. Additionally, they influence and are influenced by legal and socio-economical factors, e.g. new legislation concerning receiving water, public acceptance, saving measures, etc. The various types of interactions and feedback loops within this socio-technical system make it difficult to understand how single actions affect the entire system (Geldof, 1995). Load dynamics and operational changes in a WWTP can therefore only be explained by considering the development of each subsystem and their interactions.

For the sake of simplicity, we regard the catchment area and the sewer system as one sub-system.

2. Case study

In this case study, we analyze the historical development of the WWTP Werdhölzli, located in Zurich, Switzerland. With an influent load corresponding to approximately 600,000 person equivalents (p.e.), it is the largest treatment plant in the country.

The planning and design phase of the plant started in 1972 and lasted until 1981. The nitrification and filtration performance of the plant were based on extensive pilot tests conducted during this phase (see Gujer, 1977; Gujer and Boller, 1978). The design loads were established in a comprehensive study in 1976 (Zurich Civil Engineering Office, 1976) using the available information about past and expected future trends in water consumption and pollutant concentration. After 4 years of construction the plant went into operation in 1985.

Originally designed as a two-step plant (see Fig. 2), the WWTP has undergone many important changes in the time elapsed since it started operation, an overview of which is given in Table 1. How and why these changes occurred can only be explained under consideration of the dynamics of the entire wastewater system since the 1970s.

The dynamics of the wastewater system is characterized by the dynamics of its sub-systems and their mutual relationships. In the following sections we will therefore first analyze important developments concerning the catchment area and the environmental standards. Thereafter, we will show how these developments affected the WWTP.

2.1. Developments in the catchment area

The characteristics of the catchment area can change substantially during the long time span between the initial planning and the beginning of operation of a WWTP (i.e. 13 years for Werdhölzli). Changes continue occurring during the
operational life of a plant. As seen in Fig. 3, the city of Zurich has experienced strong changes in population size, amount of industry and water consumption since the initial planning phase in 1972.

Between 1970 and 2000, Zurich’s population decreased by 21% (see Fig. 3). Since 1998, efforts are being undertaken to reverse this negative trend (Urban development of the city of Zurich, 2004).

As can be seen in Fig. 3, the city of Zurich has experienced an employment shift from the second sector (processing of goods) into the tertiary sector (services). This shift is due to structural changes in the Swiss economy that started in the second half of the 1960s and led to the closing, relocating, restructuring or outsourcing of the activities of several companies. As a consequence, industry in Zurich has been decreasing ever since (Bretschger and Klaus, 1998).

Water consumption in the catchment area reached its highest value in 1973 (see Fig. 3). Since then, consumption has been dropping as a result of water saving measures and the above mentioned economical shifts from industrial to service-related activities (Urban development of the city of Zurich, 2004).

| Table 1 – Significant changes in operation and performance of WWTP Werdhölzli since 1985 (operation start) |
|--------------------------------------------------|--------------------------------------------------|--------------------------------------------------|
| 1985                                             | 2003                                             |
| Infrastructure                                    | Two-step plant                                   | One step                                         |
| Activated sludge concentration                    | 2.5–3 kg TSS/m³                                   | 3.8–4.5 kg TSS/m³                                 |
| Treatment processes                               | Nitrification                                    | Nitrification and denitrification                 |
| Wastewater treated                                | Approx. 80% of Zurich’s wastewater               | All wastewater from Zurich and de-icing wastewater from the airport |

Fig. 3 – Development of population, industry (employees working in the second and tertiary sector) and water consumption in the city of Zurich for the time span between 1970 and 2003 (Zurich’s statistics agency et al.). The design values (dashed lines) are included for comparison (Zurich Civil Engineering Office, 1976). Planning and design of the plant was done between 1972 and 1981. Operation started in 1985.
In addition to these developments, changes in drainage concepts and optimization measures in the wastewater system also had an effect on the catchment area:

The drainage concept of the city of Zurich underwent a re-orientation in the mid-1980s. The forceful drainage of all natural water (e.g. rain water, small streams) from the urban area was no longer considered advisable (AWEL, 2003; Rauch et al., 2001). Whenever possible, rain water is kept out of the sewer system and unpolluted extraneous water is removed. As seen in Table 2, the extraneous water flow has decreased by approx. 30% since 1985. Reductions of at least the same order of magnitude are expected to have occurred due to restorations of the sewer system (AWEL, 2003). The amount of rainwater entering the combined sewer system of Zurich is being reduced through increased local infiltration (Rauch et al., 2001).

Until 2001 Zurich operated two WWTPs. To reduce overall costs the operation of the WWTP Glatt was stopped in November 2001 and the wastewater was re-directed to Werdhölzli. This increased the treated p.e. from approx. 500,000 to approx. 600,000.

2.2. Development of the environmental standards

Legal environmental standards develop through time due to new scientific insight and changing societal demands. They influence the performance of a WWTP directly (e.g. new performance requirements due to legal changes) or indirectly (e.g. requirements of water saving technologies).

Important changes in environmental standards in Switzerland since 1985 (operation start) include the coming into force of a phosphate ban for detergents in 1986 and a regulation to reduce total nitrogen load in the effluent of WWTPs in the Rhine watershed. The former had a substantial effect on the phosphorous content of the influent, while the latter required upgrading of the WWTP Werdhölzli for denitrification.

2.3. Development of the WWTP

As mentioned before, developments in the catchment area and in the environmental standards can lead to substantial changes of the incoming load and in the operation of a plant. Interestingly, this is not unidirectional as developments in the plant can also lead to changes within the catchment, which again have consequences for the plant. This feedback loop and the different interactions have in time lead to several changes within the WWTP Werdhölzli, an overview of which is given in Table 3. A detailed account on the cause-and-effect chain shows how complex the impacts of load changes and alterations of environmental standards can be.

2.3.1. Effect of changes in the environmental standards

The phosphate ban in detergents (1986) led to an abrupt decrease in the phosphorous load to be treated by Swiss WWTPs (Siegrist and Boller, 1999). This decrease was also observed in Werdhölzli. The phosphorous load measured in the past 14 years has remained constant at approx. 0.7 t/d, well below the design load of 2.2 t/d. The decrease of the phosphorus load led to a reduction of the sludge production from chemical phosphorus precipitation of approx. 10 t TS/d. This is equivalent to an aerated volume of around 12,000 m³ (or 20% of the main nitrifying stage) considering the operational conditions at the time and the design parameters.

In 1985, the plant was built as a two-stage treatment plant consisting of one fully aerated pre-step (8900 m³) and a main nitrifying stage (60,000 m³). The decrease in sludge production resulting from the phosphorus load reduction made it

<table>
<thead>
<tr>
<th>Date</th>
<th>Main process development</th>
</tr>
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<tbody>
<tr>
<td>1985</td>
<td>Start of operation of the WWTP Werdhölzli in two-step mode</td>
</tr>
<tr>
<td>1989</td>
<td>Stop of operation of aerated pre-step, operation of the plant in single-step mode</td>
</tr>
<tr>
<td>1993–1997</td>
<td>Gradual installation of anoxic zones in the existing activated sludge tanks (28% of total volume)</td>
</tr>
<tr>
<td>1994–1998</td>
<td>Optimization of the denitrification (reduction of oxygen input and increase of denitrifying sludge blanket in the secondary clarifier)</td>
</tr>
<tr>
<td>1996</td>
<td>Reduction of the maximum allowed storm water flow from 9 to 6 m³/s. This allowed for an increase in activated sludge concentration from 3 to 4.5 kgTSS/m³ (maximum possible concentration)</td>
</tr>
<tr>
<td>2001</td>
<td>Stop of operation of the WWTP Glatt (approx. 100,000 p.e.) in Zurich’s north. This wastewater is now treated by the WWTP Werdhölzli</td>
</tr>
<tr>
<td>2002</td>
<td>Treatment of the de-icing wastewater from the airport</td>
</tr>
</tbody>
</table>

Table 2 – Estimated extraneous water flow in combined sewers by categories in 1985 and 2003 in the city of Zurich (AWEL 2003)

<table>
<thead>
<tr>
<th>Estimated extraneous water flow in combined sewers (l/s)</th>
<th>1985</th>
<th>2003</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring and stream water</td>
<td>250</td>
<td>85</td>
</tr>
<tr>
<td>Fountains</td>
<td>65</td>
<td>45</td>
</tr>
<tr>
<td>Cooling water</td>
<td>103</td>
<td>88</td>
</tr>
<tr>
<td>Seepage water, intruding groundwater</td>
<td>450</td>
<td>385</td>
</tr>
<tr>
<td>Total</td>
<td>868</td>
<td>603</td>
</tr>
</tbody>
</table>
possible to take the pre-step out of operation in 1989 and hence to save operation costs.

The expected introduction of legal restrictions regarding nitrogen elimination required the installation of a denitrifying stage. This was accomplished between 1993 and 1997 by gradually separating anoxic zones from the total activated sludge volume. At the same time measures to optimize denitrification were conducted (see Table 3). The partition led to the desired nitrogen elimination, but it also implied a decrease of the COD-based operational capacity of the plant (Fig. 4, left). This operational capacity is an indicator of the COD load that the plant is able to treat under the prevailing operational conditions. It is a function of the activated sludge concentration, the available aerated volume and the minimal required aerobic sludge retention time for full nitrification.

2.3.2. Effect of changes in the catchment area

The mean annual inflow to the WWTP was well below the maximum expected dry weather flow of the plant until 1996 (see Fig. 4, right). This overcapacity was the consequence of an unforeseen strong decrease in wastewater flow during the past 30 years due to a decline in water consumption, and measures reducing the amount of extraneous water and rain water in the sewer system. The maximum expected dry weather flow was therefore lowered in 1996.

The decrease of the maximum expected dry weather flow allowed an increase of the suspended solids concentration from approx. 2.75 to 4.5 kg TSS/m³. As seen in Fig. 4, right, the plant is currently operated at approx. 3.8 kg TSS/m³.

The increase of the suspended solids concentration led to a rise of the plants operational capacity compensating the capacity loss caused by the installation of anoxic zones (compare Fig. 5).

The COD load has been decreasing since the mid-1990s (compare Fig. 5) because of important load contributors (e.g. dairy, breweries and meat processing enterprises) shutting down production in the catchment area. The closing down of the WWTP Glatt and the diversion of its wastewater to the WWTP Werdhölzli in 2001 briefly attenuated the COD load decline.

The COD decrease and the simultaneous increase of the operational suspended solids concentration has led to a growing deviation between operational capacity and incoming load (Fig. 5). This difference is a measure of the capacity reserve of the plant.

2.3.3. Feedback from the WWTP

The presence of capacity reserves in the WWTP Werdhölzli encouraged the merging of the catchment areas of Werdhölzli and Glatt in 2001. This increased the incoming load to WWTP Werdhölzli from approx. 500,000 p.e. to an estimated 600,000 p.e., leading to a reduction of the capacity reserves of the plant (see Fig. 5). In other words, a decision based on the available reserves of the plant had an effect on the load to be treated and hence on the available reserves. This feedback or back-coupling could be observed again in the additional treatment of de-icing wastewater.

In 2002, the WWTP Werdhölzli began treating the de-icing wastewater from Zurich’s airport, consisting of highly concentrated organic compounds. The consequential rise in the COD load can be observed in Fig. 5. Once again, it was the recognition of available capacity reserves which led to this step. An additional incentive was the enhancement of
the denitrification rate through the addition of easily degradable COD.

3. Discussion

In this paper, we analyzed the long-term dynamics in the development of a WWTP. The analysis was based on the reconstruction of the historical cause-and-effect chain that led to changes in the plant. We observed strong operational and performance changes, despite the fact that the analyzed time span is only a fraction of the life expectancy of a plant. These operational and performance changes were the consequence of developments in the catchment area and in environmental law influencing the WWTP and a feedback between the plant and these sub-systems. These interactions and feedbacks led to an extreme dynamic development of the investigated WWTP.

The developments in the catchment area and in the environmental standards resulted in a better performance of the plant while retaining a certain amount of capacity reserves. This performance increase was achieved without costly structural alterations. Only relatively modest costs for the installation of volume partitions and additional aeration were necessary.

The development, however, could have been entirely different. Population could have increased strongly over the same period or a highly polluting industrial enterprise could have started operation in the catchment area. Such an expansive development is just as conceivable as the one which actually took place. As seen in this case study, future uncertainty in wastewater systems is very high due to the complexity and dynamics of the system.

WWTPs are typically constructed to be long living and considered as rather static, future uncertainty is hardly considered during the planning and design of a plant: We plan and design infrastructure in the wastewater sector based on forecasts (see e.g. Tchobanoglous and Metcalf & Eddy (Boston), 2003; Qasim, 1999), as if we knew what to expect in the future. This has important consequences for the operational life of a plant. An unfulfilled forecast will lead to an over- or undersized plant. While the former produces unnecessary capital and operational costs, the latter can require expensive upgrades of the plant in order to meet environmental standards. These environmental standards, on the other hand, can also change over time, posing new demands on the WWTP. As this possibility is usually not considered during the design phase, plants are seldom built to facilitate future upgrading, which as a consequence may be very costly.

Fig. 5 – Yearly average COD load measured after the primary clarifier versus the calculated COD capacity of the plant (dashed line). Important events leading to changes of the load and capacity are also displayed. The difference between the two lines is a measure for the capacity reserve of the plant.
What are the alternatives? More accurate forecasts would require the modeling of the whole wastewater system, a complicated and probably impossible task. Instead, we need to identify the range of future uncertainty and design our plants accordingly. The WWTP Werdhölzli would probably have been designed quite differently if the possibility of a strong decline in the COD load would have been considered in its early planning phases. This development, like the reduction of inflow and the introduction of more constructive environmental regulations was not unthinkable at the time of design. Today, we lack approaches that acknowledge the relevance and unpredictability of such developments. We are therefore in need of methodologies capable of systematic identification of the relevant factors influencing the long-term development of a WWTP, their interactions and possible future developments.

A systematic approach for characterizing long-term future uncertainty is scenario planning (Schoemaker, 1995; Schnaars, 1987), which has been gaining attention in the field of wastewater management as a tool for guiding future-oriented decisions (see Lienert et al., 2006; Semadeni-Davies et al., 2005). The central idea of scenario planning is to consider a variety of possible futures that include many of the important uncertainties in the system rather than to focus on the accurate prediction of a single outcome (Peterson et al., 2003). Scenario planning is used in business and policy contexts when the relevant time frame is extremely long and the uncertainty about the relevant factors and their interactions is high (Ringland, 2002). This applies for the operational life of WWTPs, which makes scenario planning a promising option for dealing with the complexity and dynamics of the system. However, research still has to be conducted to demonstrate how and to what extent scenario planning can be applied to our field.

Not analyzed in this paper is the role of changes in management and organizational structures on the development of a WWTP. The WWTP Werdhölzli, for example, underwent a drastic reorientation and restructuring in the year 2000. It is now managed as a private enterprise providing a service and the command structure is now flat and process oriented. This has reduced the decision time and established clear competencies and responsibilities among the plant operators.

It is not clear yet to what degree management and organizational structures can encourage the recognition and use of capacity reserves or facilitate the implementation of measures leading to performance improvements. The role of management and organizational structures in the ability of a WWTP to react to changes is still an unanswered question.

The WWTP Werdhölzli was chosen as a case study because the duration and extent of its planning appears to be representative for a plant of its size.

It may be argued that our findings are strongly case specific. It is true that the dynamics observed in this case study are not representative for all WWTPs. However, we expect all WWTPs and most wastewater structures, to be subject to a certain degree of dynamics, as they are all integrated in socio-technical systems. The variety and complexity of the dynamics does not contradict but rather support the general conclusion of this study.

4. Conclusions

The historical analysis conducted in this study shows the extreme dynamics which WWTPs are subject to during their operational life. The details of these dynamics are unpredictable because of the complexity of the wastewater system. As a consequence, a design approach based on a fixed demanded performance and incoming load is not sufficient. This holds true especially in view of the longevity of wastewater structures and the long period of time elapsing between the planning of a measure and its realization. We therefore need new approaches for characterizing long-term future uncertainty. This requirement is emphasized by the increased cost pressure on wastewater infrastructure and future challenges (e.g. micropollutants and pathogens).

In the future uncertainty about long-term developments should systematically be considered to improve the way we plan and design structures in urban wastewater systems. We consider scenario planning to be a possibility to account for this uncertainty, but research is still needed concerning the applicability of the methodology in our field.

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