Rain events and their effect on effluent quality studied at a full scale activated sludge treatment plant

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Abstract The effect of rain events on effluent quality dynamics was studied at a full scale activated sludge wastewater treatment plant which has a process solution incorporating pre-denitrification in activated sludge with post-nitrification in trickling filters. The incoming wastewater flow varies significantly due to a combined sewer system. Changed flow conditions have an impact on the whole treatment process since the recirculation to the trickling filters is set by the hydraulic limitations of the secondary settlers. Apart from causing different hydraulic conditions in the plant, increased flow due to rain or snow-melting, changes the properties of the incoming wastewater which affects process performance and effluent quality, especially the particle removal efficiency. A comprehensive set of on-line and laboratory data were collected and analysed to assess the impact of rain events on the plant performance.

Keywords Activated sludge; effluent quality; floc stability; nitrogen removal; phosphorus removal; rain events

Introduction

Wastewater treatment plants based on the activated process are subjected to transient operating conditions. The hydraulic loading varies significantly due to diurnal variations and to inflow and infiltration due to rain events. At different flows, the composition of the wastewater varies due to dilution with stormwater or a varying load of domestic wastewater but also due to changed physical, chemical and biological processes in the sewer system (Warith et al., 1998). Depending on the preceding dry weather flow, different amounts of built-up sediments can be brought to the treatment plant during rain events (Larsen et al., 1998). Apart from containing organic matter they can act as a carrier material for toxic compounds such as heavy metals and synthetic organics (El Samrani et al., 2004). The wastewater qualities and properties will affect biological processes such as nitrification, denitrification and degradation of organic material, by supplying different amounts or qualities of electron donors or acceptors, but can also affect the physical properties of the sludge flocs or particles in the water. Furthermore, changed hydraulic conditions can affect the effluent quality due to disturbances propagating through the system such as altered sludge concentration in the activated sludge tanks or changed hydraulic conditions through the secondary settlers. Depending on the settling properties of the sludge flocs, the secondary settlers can handle different hydraulic loading rates.

The flocculation and adsorption of particles and colloids from the wastewater is a crucial parameter for the effluent quality. Weakened floc stability can lead to increased suspended solids concentrations in the effluent wastewater. Sludge flocs have a complex
composition where the main components are bacterial cells embedded in a polymeric network of extracellular polymeric substances (EPS) (Frølund et al., 1996). The EPS are highly charged polymers which interact with water and ions in the water phase and determine the surface charge of the flocs (Keiding et al., 2001, Mikkelsen and Keiding, 2002). The attachment of small floc components (e.g. bacterial cells) or adsorbed particles from the wastewater is dependent on the surface properties which can change quickly. Several mechanisms have been suggested as being involved in the floc formation and they all include different interaction forces between surfaces. The main mechanisms are: the polymer bridging model, where the negatively charged groups of the EPS are bound together by divalent and/or trivalent cations to form networks into which other floc components can attach (Bruus et al., 1992; Nielsen and Keiding, 1998); and the colloidal interaction model where the interactions of the floc components can be described by the DLVO theory in which the electrical double layers around colloids interact (Hermansson, 1999). Changes in wastewater parameters such as ionic strength or ionic composition, temperature, availability of organic material or changes in pH may quickly change the ability for particles to attach or detach from the larger flocs (Zita and Hermansson, 1994; Hermansson, 1999). The microbial activity, which is affected by parameters such as temperature and substrate loading, may also have an effect on the floc stability (Wilen et al., 2000).

The Rya WWTP is designed for biological nitrogen removal utilizing pre-denitrification in a non-nitrifying activated sludge system and post-nitrification in a trickling filter (Balmér et al., 1998) (Figure 1). Phosphorus is removed by chemical precipitation with ferrous sulphate. The plant is operated at low solids retention time (SRT), 2–4 days. The plant serves about 771,000 pe and flows range from 175,000 to 1425,000 m³/d with an average daily flow of about 350,000 m³/d. The nitrified stream is mixed with the recycled activated sludge stream (Q_RAS) for deoxygenation after which it is mixed with the primary settled wastewater and led into the anoxic part of the activated sludge reactors for denitrification, thus utilizing the carbon available in the influent. When the flow of primary settled water (Q_PS) changes, the recycling over the trickling filter (Q_TR) is adjusted so that the flow to the secondary settler (Q_SED = Q_PS + Q_TR) is kept as close as possible to their maximal capacity. The recycle activated sludge flow (Q_RAS) is kept rather constant. The plant experiences periods with poor clarification and/or poor settling properties (Wilen et al., 2004). When the settling capacity of the secondary settlers is exceeded some wastewater is bypassed after primary treatment (Q_bp). This has severe consequences for the future stricter phosphorus discharge limits (0.3 mg P/l and 10 mg N/l). More nitrogen removal can be achieved by increasing the recycle to the trickling filters and more phosphorus removal is obtained by decreasing the discharge of particulates. Since the secondary settlers are constantly operated at or near their maximum capacity, minor differences in sludge properties have an impact on effluent turbidity.
The aim of this study was to assess the impact of flow condition changes due to rain events on effluent quality. The primary settled wastewater composition at different hydraulic conditions was characterised and the influence it has on different processes in the plant was assessed and related to the effluent quality.

Materials and methods
Acquisition of process data. On-line historical data (6 minutes or hourly average values) of flow, pH, conductivity, temperature, turbidity, oxidation reduction potential, dissolved oxygen, sludge concentrations, etc. for different locations, as well as routine daily laboratory analyses of suspended solids (SS), COD, phosphorus, phosphate, nitrate/nitrite and ammonium in influent and effluent were used. Data over 2.5 years was investigated in detail (2003–2005).

Results and discussion
The quality of the wastewater changes with the wastewater discharge and flow conditions in the sewer system. The change in some parameters is simply due to dilution of the wastewater with stormwater and inflow and infiltration of groundwater. For other parameters the change is more complex and related to altered physical, chemical and biological processes in the sewer system (Seidl et al., 1998). During rain events, settled particles and organic compounds can be transported to the treatment plant and affect the treatment process. When looking at daily average values, the concentration of COD, phosphorus, suspended solids and ammonium decreased with flow, whereas the mass flow into the plant increased slightly (Figure 2a–f). On the contrary the concentration of nitrate/nitrite in the influent water was generally very low but increased at higher flows (Figure 2e, f). The oxidation reduction potential of the incoming wastewater to this plant was generally higher at high flows indicating that the wastewater contains more oxygen at high flows compared to low flows (Mattsson, 1997). Thus the biological processes occurring in the sewer are more aerobic at high flows and more anaerobic at low flows which has an impact on the wastewater properties. Wastewater conductivity generally decreased with increased flow (Figure 2g). If a 14 day average dry weather flow (approximately for flows lower than 4 m$^3$/s) temperature, is subtracted from the wastewater temperature, an estimation of the decrease in temperature, as a result of stormwater entering the sewer can be estimated. From Figure 2h it can be seen that at flows above 4 m$^3$/s the temperature drops with increasing flow by up to about 3.5 °C.

The change in mass flow of both total and dissolved COD, will give higher organic loading of the sludge (F/M ratio) during higher incoming flows (Figure 3a). It is difficult to determine how this will affect the biological processes in the activated sludge tanks. In several studies it has been observed that higher organic loading rates might lead to decreased EPS production which can give weaker flocs (Eriksson et al., 1992). Higher organic loading can also lead to increased sludge production and suspended bacterial growth. Furthermore, due to the operational strategy, the ratio between the mass flow of COD and nitrate entering the activated sludge tanks was lower at low flows (Figure 3b). This leads to a shortage of carbon and ethanol is dosed on these occasions. At high incoming flows the decreased recirculation over the trickling filters leads to a lower mass flow of nitrate returned to the anoxic zones for denitrification (data not shown). Hence, with regard to nitrogen removal, the plant is limited by the hydraulic capacity of the secondary settlers at high influent flows, whereas it is limited by the carbon source at low flows.

All changes in wastewater properties will affect the different processes in the treatment plant and ultimately the effluent quality. Due to the recirculation over the trickling filters, the flow through the activated sludge system was kept relatively constant and this
gave fairly constant concentrations of COD and total phosphorus in the effluent (Figure 4a,c), irrespective of the incoming flow. Similar observations can be made for the nitrate/nitrite concentration. The concentration of dissolved phosphorus and phosphate in the effluent decreased with increased incoming flow (Figure 4e). A similar trend was observed for ammonium. The mass flows of the different parameters in the effluent increased with flow (Figure b,d,f). These results show that mainly the effluent particle content is increased at higher flows.

The phosphorus removal is mainly determined by the solids–liquid separation properties of the activated sludge, whereas the phosphate removal is determined by the efficiency of the precipitation process. Since the concentration of total phosphorus is closely related to the suspended solids concentration, the production of a clear effluent is crucial. The changes in clarification properties follow a seasonal pattern with generally better properties during the summer. In spite of a large variation in the data, the effluent
turbidity is generally higher at high flows of primary settled wastewater (Figure 5a). Similar observations can be made for effluent total COD and phosphorus concentrations. High flow due to rain or snow melting is more common during the winter months with some occasional large summer rains. The hydraulic conditions in the secondary settlers are also crucial but large variations in influent flow are normally compensated by changed recirculation from the trickling filters, thus keeping a constant flow through the secondary settlers. The variation in turbidity caused by hydraulic effects has been found to be relatively small (Wileń et al., 2004) which is also seen in Fig 5b where no correlation between $Q_{sed}$ and effluent turbidity could be found. This indicated that the increase in effluent turbidity is mainly caused by the change in wastewater properties.

Figure 3 (a) Organic loading expressed as $F/M$ ratio; and (b) COD(tot)/NO$_3$-N ratio at different flows of primary settled wastewater

Figure 4 Change in effluent quality at different flow conditions (a) conc. COD; (b) mass flow COD; (c) conc. P(tot) and SS; (d) mass flow P(tot) and SS; (e) conc. P(tot) and phosphate (dissolved) and (f) Mass flow of P(tot) and phosphate (dissolved)
Due to seasonal and other variations in process performance it is important to look at individual rain events during more limited periods of time. During rain events, the wastewater characteristics change. Two periods (about 2 weeks each) with a few rain events are shown in Figure 6a,b. There is a clear relationship between influent flow, water temperature, influent conductivity and effluent turbidity. The water temperature in the treatment plant changes as a result of the incoming water temperature and it takes about one hydraulic retention time (HRT $= 5–10$ h) before it has reached a similar temperature as the influent water. The influent conductivity decreases at the same time as the flow increases. An increase in effluent turbidity can be observed about one HRT after the increase in flow has occurred. The effluent conductivity has similar values as the influent conductivity but it is more stable and the values follow a similar pattern but delayed with about one HRT (Figure 6b). The change in effluent turbidity is not always proportional to the flow rate or conductivity but follows a similar pattern. This is probably due to differences in the characteristics of the sludge flocs which is a rather variable parameter. Turbidity is generally lower during summer than winter.

A typical large summer rain event is shown in Figure 7. The inflow ($Q_{in}$) increased from 2.5 to 9.5 m$^3$/s in about 7 h. Some influent had to by-pass ($Q_{bp}$) secondary treatment due to hydraulic limitations of the secondary settlers. The flow through the settlers ($Q_{sed}$) was increased slightly from 7.3 to 8.3 m$^3$/s. As the water flow increased, the temperature

![Figure 5](https://iwaponline.com/wst/article-pdf/54/10/201/431056/201.pdf)

**Figure 5** Correlation between (a) effluent turbidity and primary settled flow; and (b) effluent turbidity and $Q_{sed}$

![Figure 6](https://iwaponline.com/wst/article-pdf/54/10/201/431056/201.pdf)

**Figure 6** Two periods with several smaller and larger rain events: (a) November 2003; (b) July 2004
dropped to 17.2 from 18.2–18.9°C. There was a delay in the temperature drop in relation to flow. Changes in influent conditions have to propagate through the plant before the effect on the effluent quality can be observed. Due to the recirculation flows and deviations from plug flow through activated sludge tanks, the actual hydraulic retention time deviates from the theoretical. After the rain it takes several hours before the temperature has increased again. The first peak in effluent turbidity comes 5 h (equal to one HRT) after the flow has started to increase and could be due to eroded sediments from the sewer entering the plant with either toxic compounds or an extra load of particles that are not adsorbed to the flocs. This is also about one HRT after the decrease in influent conductivity. As the rain continued, the effluent turbidity gradually increased until a few very large peaks occurred. The turbidity is generally 3–5 mg/l during the summer and the increase caused by this rain event is comparatively high due to washout after the settlers are overloaded. The drop in temperature could have different effects on the floc stability such as decreasing the microbial activity or decreasing the viscosity of the water which makes the aggregation and settling process less efficient at the same time as the flocs are subjected to higher shear forces. Decreased conductivity is the result of lower ionic strength of the wastewater. According to the DLVO theory for colloidal stability, lower ionic strength leads to a larger electrostatic repulsion between floc constituents or particles in the wastewater, hence giving poorer aggregation (Hermansson, 1999).

Conclusions
- During rain events the composition and quality of the incoming wastewater changes which has an impact on the treatment performance mainly through altered colloidal properties of the activated sludge flocs leading to higher effluent turbidity.
- Due to the process configuration of the WWTP the impact of influent wastewater quality variations during a rain event can be separated from the effect of higher hydraulic loading on secondary settlers.
- At this WWTP, the changes also affect both the nitrification and denitrification due changes in both hydraulic conditions and wastewater composition.

References


