Commissioning of the new water line of the Central wastewater treatment plant in Prague and its impact on the operation of the existing water line

J. Wanner, J. Rosický, J. Kovařík, M. Srb, M. Lánský and P. Sýkora

ABSTRACT

This paper describes the commissioning of the new water line (NWL) of the Central wastewater treatment plant in Prague and also the gradual reduction of the existing water line (EWL) loading. Concerning the NWL, the gradual start-up of the process without inoculation will be described. As to the EWL, the presentation describes the adaptation of the EWL operation to the relatively quick reduction of loading to approximately 35%.

Key words | activated sludge, nitrogen removal, operation, process start-up, WWTP commissioning

J. Wanner (corresponding author)
Vysoká škola chemicko-technologická v Praze,
Technická 5,
166 28 Praha 6,
Czech Republic
E-mail: *jiri.wanner@vscht.cz*

J. Rosický
J. Kovařík
Pražská vodohospodářská společnost a.s.,
Žatecká 110/2,
110 00 Praha 1,
Czech Republic

M. Srb
M. Lánský
P. Sýkora
Pražské vodovody a kanalizace, a.s.,
Ke Kablu 971,
102 00 Praha 10,
Czech Republic

HIGHLIGHTS

- Prague Central WWTP is the largest municipal WWTP in the Czech Republic using the *in situ* bioaugmentation of nitrification.
- The capacity of the plant was recently upgraded by building a new water line which is operated in parallel to the existing water line.
- The start-up of the new activated sludge system was done without any sludge inoculation.
- The new water line helped gradually to reduce the loading of the existing water line.

INTRODUCTION

The existing Central wastewater treatment plant (CWWTP) was built on Cisarsky Island during the 1960s as a conventional mechanical-biological wastewater treatment plant with a single-stage biological process, with capacity of the mechanical stage 4.5 m^3/s and of the biological stage 2.5 m^3/s. Since its construction the existing water line (EWL) capacity had been repeatedly extended. The hydraulic capacity was increased to average flow 6.0 m^3/s and maximum daily flow $Q_d = 7$ m^3/s. The development of wastewater treatment in Prague in the past 20 years includes two major upgrades of the technological water line. Reconstructions in 1995–1997 and 1999–2000 increased the total capacity to 7.0 m^3/s and secured conditions for full nitrification by building a regeneration zone with bioaugmentation of nitrification (Wanner *et al.* 2009). The main intent of regeneration is to increase sludge mass in the system together with sludge retention time and thus provide better conditions for a stable nitrification process. In 2002–2003 another major reconstruction of the whole CWWTP was required due to a great flood in August 2002. However, in spite of these measures, the EWL only reached approximately 66.3% efficiency of nitrogen removal with total nitrogen (N_{tot}) effluent concentration of 21.8 mg/l (both average value for 2017) and consequently it was not able to reach efficiency of nitrogen removal and effluent limits required by EC Directive 91/271/EEC (CEC 1991).

In 2004 the City Council decided the future conception of wastewater treatment in Prague. The main idea was to divide the wastewater treatment into two plants – one part was to be treated at the EWL and the rest at the so-called

doi: 10.2166/wst.2020.575

'new water line' (NWL) which was to be built on the undeveloped area available in the southern part of Cisarsky Island (Kos *et al.* 2015). The NWL was put into operation in September 2018.

The main goals of the building of the NWL and reducing the load towards the EWL described in this paper were (see also Table 1):

1. To reach the limit defined by the discharge permit for the year-average concentration of total nitrogen in the outlet, 10 mg/l, at the NWL. The limit of the total nitrogen concentration is based on best available technique limits defined in the Czech Government Act No. 401/2015 Coll.
2. To reach the limit defined by Council Directive 91/271/EEC concerning urban wastewater treatment for the year-average removal efficiency of total nitrogen in the outlet of 70–80% at the EWL. Even after reduction of load it would be impossible to reach the concentration limit of 10 mg/l total nitrogen suggested in the Council Directive 91/271/EEC without large refurbishment of the EWL. That is why the EWL discharge permit also does not require this strict concentration limit for total nitrogen.
3. To fulfill all other limits defined by the discharge permits of both lines.

METHODS

Description of EWL

Technological arrangement of the EWL consists of conventional technological parts: fine screens, grit chamber, eight circular primary settling tanks with possible chemical precipitation to reduce chemical oxygen demand (COD) concentration, eight aeration basins and 12 secondary circular settling tanks. Each aeration basin is divided into nine sections with adjustable anoxic zone volume. All zones are equipped with fine-bubble aeration; there are no zones with mechanical mixing. The anoxic zones are adjusted by reducing the air distribution in selected sections so that the air serves only for mixing of activated sludge and not for providing oxic conditions. Phosphorus is removed by chemical precipitation.

A flowscheme of the EWL and nominal technical data are summarized in Figure 1.

Sludge management processes the sludge resulting from mixing of primary sludge with biological sludge, both of them from the EWL and NWL. The mixed sludge is pumped into two-stage digester tanks operated under thermophilic conditions ($6 \times 4{,}350\ m^3 + 6 \times 4{,}550\ m^3$). The digested sludge is dewatered on centrifuges.

Table 1 | Inflow and outflow water quality from EWL and NWL

	COD	BOD	Suspended solids	$N\text{-}NH_4$	$N\text{-}NO_3$	$N\text{-}NO_2$	Inorganic nitrogen	Total nitrogen	Total phosphorus
Average concentration in inlet (mg/l)									
EWL 2017	692	268	362	35.3	0.6	0.2	35.7	65.0	7.6
EWL 2019	739	270	381	37.4	0.4	0.1	37.7	64.3	8.4
NWL 2019	1,098	412	552	41.2	0.2	0.1	41.3	74.2	9.4
Average concentration in outlet (mg/l)									
EWL 2017	34.8	6.2	9.2	9.4	8.0	1.6	18.9	21.9	0.7
EWL 2019	32.4	5.5	7.0	4.9	8.8	0.1	13.9	16.0	1.0
NWL 2019	24.6	2.1	6.5	0.3	6.5	0.0	6.7	8.1	0.7
Average treatment efficiency									
EWL 2017	95%	98%	97%	73%	x	x	47%	66%	91%
EWL 2019	96%	98%	98%	87%	x	x	63%	75%	88%
NWL 2019	98%	99%	99%	99%	x	x	84%	89%	93%
Target values (mg/l or % where noted)									
NWL permit	55	15	20	x	x	x	x	10	0.8
EWL permit	60	15	20	10	x	x	x	75%	1.0
91/271/EEC	125	25	35	x	x	x	x	10 (70–80%)	1.0

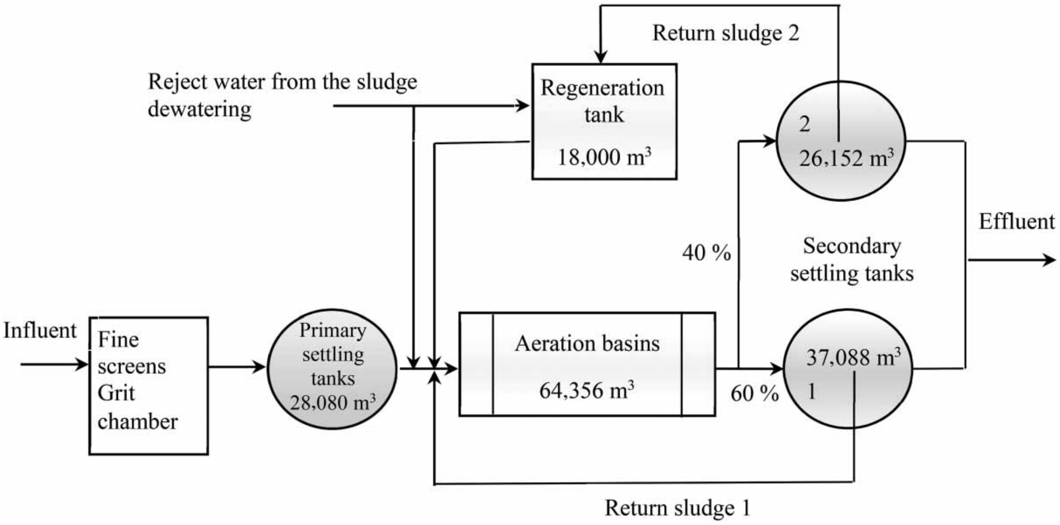

Figure 1 | Flowscheme of Prague WWTP EWL.

Description of NWL

The NWL is a mechanical-biological wastewater treatment plant (WWTP) with chemical phosphorus precipitation of treated wastewater. The complete design was subject to space limitation because the whole plant was to be completely covered.

The reasons for completely covering the plant were total flood protection and immediate restart after floods and requirements of aesthetical appearance of the site near Prague's historical centre. A flowscheme of the NWL and nominal technical data are summarized in Figure 2.

After screening, the wastewater is mechanically pre treated in lamella sedimentation tanks Densadeg 4D with integrated sand and grease removal. Biological treatment of wastewater is carried out in four identical activated sludge process lines. Each line consist of a three-stage cascade activated sludge process – ALPHA, which is an activated sludge technology with three anoxic/oxic zones in series. The oxic zones are constructed as carousel tanks. The inflow is distributed to individual anoxic zones in a ratio of 39:33:28. External substrate can be dosed to denitrification sections. The regeneration zone is common for two lines. Mixed liquor from activated sludge process tanks is led to 40 rectangular clarifiers. Return sludge is subjected to oxic regeneration (Kos *et al.* 1992). The regeneration zone is also supplied with reject water (centrate) for *in situ* bioaugmentation of nitrification. Chemical phosphorus removal is carried out as post-precipitation at the third stage of treatment in lamella sedimentation tanks Densadeg

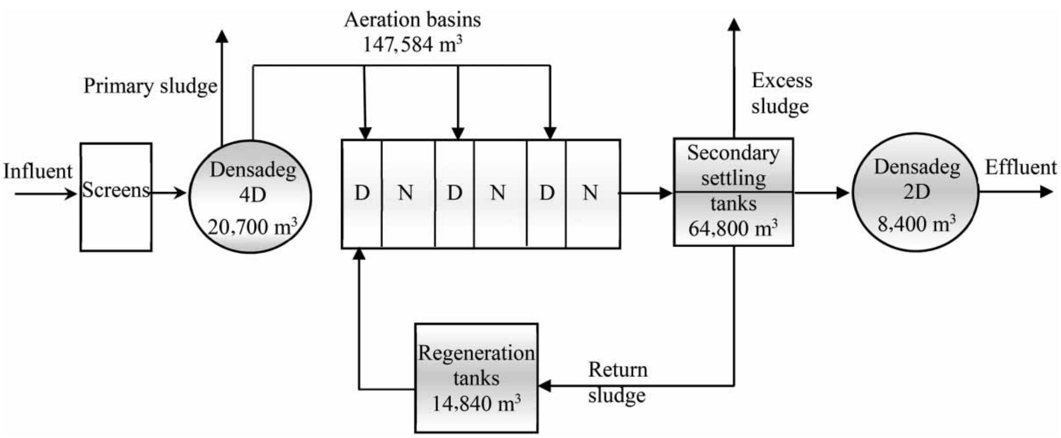

Figure 2 | Flowscheme of Prague WWTP NW. D: denitrification; N: nitrification.

2D. A mixture of primary and tertiary sludge is thickened in gravity thickeners; excess biological sludge is pre-thickened in gravity thickener Drainis Turbo and thickened by centrifuges. All thickened sludge is pumped together with separated grease to the sludge management unit of the EWL for further processing.

In situ bioaugmentation

Both lines of CWWTP are equipped with a regeneration tank. At the EWL, there is one regeneration tank divided into four sections, of which the first three sections have an adjustable oxic/anoxic mode. At the NWL, there are two regeneration tanks (common for two activated sludge process lines each) divided into four sections, of which two sections have an adjustable oxic/anoxic mode. Activated sludge in the regeneration tank has higher mixed liquor suspended solids, which reduces the demands on the total volume of this reactor, in which nitrifying bacteria are cultivated by so-called *in situ* bioaugmentation. A stream of reject water (centrate), with average concentration of ammonia nitrogen of 1,197 mg/l, obtained by dewatering of the anaerobic sludge serves as a nitrification culture substrate (Novák & Havrlíková 2003). Despite the fact that at the EWL only a part of returned activated sludge (approximately 35%) comes through the regeneration tank, it has proved its effectiveness here and even at other WWTPs in the Czech Republic (Krhůtková *et al.* 2006). It is used for all return sludge at the NWL.

RESULTS AND DISCUSSION

Start of the operation of NWL

The volume of NWL activated sludge tanks is 162,424 m^3; therefore the inoculation of the process with activated sludge would require excessive transportation measures. To avoid this it was decided to start the process without inoculation. In order to fulfil limits determined for the start-up period, the whole activated sludge process was not put in operation at once but by individual parallel activated sludge systems (four in total) with gradual increase of treated water volumes. At the same time it was necessary to reach the concentration of sludge required for nitrogen removal in the first 100 days in order to fulfil the N_{tot} 10 mg/l limit required by the local water authority from the 101st day of operation. The total sludge amount (expressed as total suspended solids: TSS) in the activated sludge system was calculated from the sludge mass balance for an ideal batch reactor (Weber 1972) described by the equation:

$$m_{n+1} = m_n + \Delta BOD_5 \cdot Y_{OBS} - m_{n,\text{TSS, outflow}}$$

where m_{n+1} is sludge mass in the system in day $n+1$, m_n is sludge mass in the system in day n, ΔBOD_5 is mass of organic matter expressed as 5-day biochemical oxygen demand (BOD_5) removed per day, $m_{n,\text{TSS, outflow}}$ is mass of sludge removed by leak of sludge to outflow.

The Y_{OBS} (observed biomass yield) equation is defined according to Czech standard ČSN 75 6401 (2014):

$$Y_{OBS} = 0.6 \cdot \left(\frac{c_{\text{TSS, inflow}}}{c_{\text{BOD5, inflow}}}\right) + 1 - \left(\frac{0.0432 \cdot 1.072^{(T-15)}}{\frac{1}{\text{SRT}} + 0.08 \cdot 1.072^{(T-15)}}\right),$$

where $c_{\text{TSS, inflow}}$ is concentration of TSS in the inflow, $c_{\text{BOD5, inflow}}$ is concentration of total BOD_5 in the inflow, T is temperature and SRT is a solids retention time.

SRT was replaced by the number of days in operation based on our assumption. The procedure of the start-up process started with all the activated sludge process tanks filled with river water used for previous water tightness tests. The procedure began with filling up the first activated sludge process line of the total of four with mechanically pretreated wastewater and start of aeration. In the first days the growth of sludge was slower than expected because it took approximately 4 days to replace river water with wastewater. The calculations carried out for the fifth day already reached a full agreement with the real data and after approximately 1 month of operation the growth of sludge exceeded the calculated rate. After 40 days the sludge concentration reached almost 2 g/l (Figure 3) which was the target concentration to put the second activation line in operation. For start-up of the second line, inoculum from first line was used. It was possible to pump sludge to the next aeration tank as inoculum. Ammonia uptake rate was measured for the first time after 30 days of operation with measured ammonia uptake rate = 4.31 mg/g.h and full nitrification was reached after 58 days (Figure 4) when the sludge concentration was 3.61 g/l.

Figure 4 also displays how $N\text{-}NO_3$ concentration in outflow increased in accordance with the decrease of $N\text{-}NH_4$ concentration until November 2018 because of full aeration

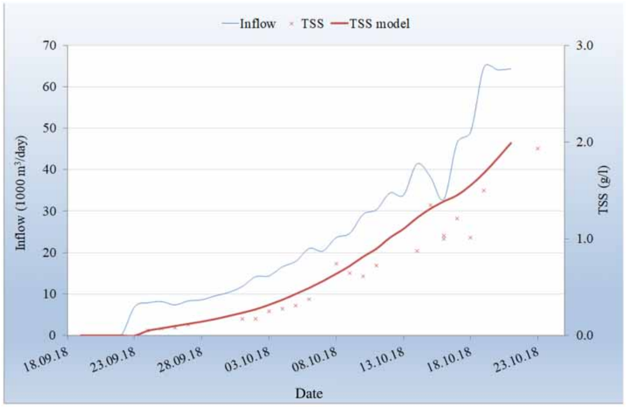

Figure 3 | Treated water volume and TSS concentration of activated sludge – NWL.

of all nitrification sections with a dissolved oxygen (DO) setpoint 4.0 mg/l. In order to fulfil the target N_{tot} limit of 10 mg/l it was necessary to implement periodic aeration of the nitrification section, which led to fast decrease of $N\text{-}NO_3$ concentration from 13.9 mg/l in late October to 6–8 mg/l in December 2018. The denitrification sections had been anoxic all the time. In this experimental period the intermittent aeration was not controlled by an automated system and aeration was turned on and off manually every 4 hours with DO setpoint 3, 2.5 and 2 mg/l in oxic sections 1, 2 and 3 respectively. This led to a wrong set-up during the end of December 2018, when the intermittent aeration mode was accidentally switched off and aeration ran continuously for 2 days and consequently outflow $N\text{-}NO_3$ concentration immediately rose from 10 to 18 mg/l. Although this episode was unwanted, it repeatedly proved the importance of intermittent aeration and its precise control.

During January it became clear that the intermittent aeration control strategy with fixed length of phases was not optimal, because it did not respond to variable load of the plant during the day. The peak of concentration of $N\text{-}NH_4^+$ in inflow and also peak of hydraulic load around 2 p.m. caused overloading of nitrification sections leading to higher concentration of ammonia of around 5–7 mg/l in outflow from the activated sludge tank (Figure 5). To avoid nitrification overloading, intermittent aeration with variable ratio of oxic and anoxic times was introduced. Duration of anoxic phase was adjustable from 0 to 540 minutes per day, divided across six oxic/anoxic periods. One period lasted for 4 hours in total. Usually the anoxic condition took place for 20 to 35% of one period. Oxic part of each period was set with final DO concentration 2 mg/l in all three oxic zones. This led to additional decrease in $N\text{-}NO_3$ concentration in the NWL outflow in February 2019 (Figure 4).

An important part of the NWL start-up strategy was the approach to processing the centrate generated in the sludge management unit of the EWL. Because the sludge management unit processes sludge from both lines, the produced centrate has to be divided between both lines for processing. As the NWL start-up took place without inoculation, the processing of centrate at the NWL began 73 days after start of operation. The volume of processed centrate gradually increased from 160 m^3 at the end of November to ultimate processing of 57% of centrate production, i.e. 1,300 m^3 per day at the end of December. The effect of centrate introduction on concentration of nitrogen forms in the effluent was negligible and nitrification rate gradually increased from 2.21 to 5.60 mg/g.h during 8 months, which is comparable to published values for other systems with bioaugmentation (Pospíšil *et al.* 2015). The issue of centrate processing is closely connected with methanol dosing. Methanol as an external carbon source has been dosed to all

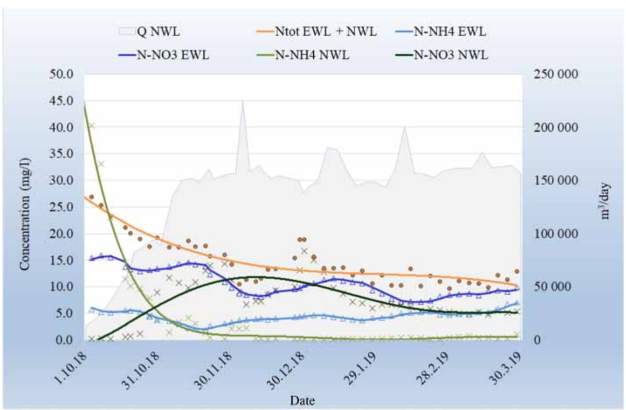

Figure 4 | CWWTP Prague nitrogen removal after the NWL start-up (concentration of outflow parameters).

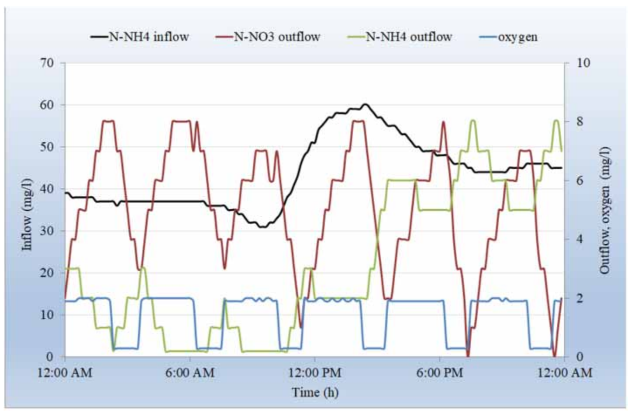

Figure 5 | Intermittent aeration variations during the day.

anoxic zones from January 2019. The need for methanol as an external carbon source was due to a stoichiometric limitation of organic matter in the influent. We have also performed the bioavailability test and only 10% of COD is readily biodegradable, instead of the common 15–20% (Henze *et al.* 1994), and available for denitrification. The initial set-up of methanol dosing control with constant dose 6 tons/day led to relatively high consumption of approximately 1 kg of external COD for 1 kg N-NO_3 removed. In May 2019 optimization of methanol dosing according to the current load was introduced which led to a decrease of consumption to 0.25 kg COD/N-NO_3 in September with almost no effect on total nitrogen removal efficiency (Figure 6). The external dosage of organic substrate is comparable or higher to doses of methanol in full-scale reported in literature (Nyberg *et al.* 1992; Ginige *et al.* 2009).

Effect of the operation of NWL on the EWL

The impact of the NWL start-up in September–December 2019 on operation of the EWL was characterized by gradual decrease of treated wastewater inflow to approximately 42% (from 260,000 to 110,000 m^3/day) over 3 months, with a large drop at the end of October. The strategy of the operator was to retain maximum capacity of the treatment process in case of possible failure of the NWL. However, this was no longer feasible after reduction of flow to approximately 50%. The reduction of load changed the activated sludge process from medium loaded (sludge loading $BOD_5 = 0.25$ kg/kg.day) to low loaded (sludge loading $BOD_5 = 0.13$ kg/kg.day) conditions (Palm *et al.* 1980).

As the amount of wastewater pumped to the EWL was dynamically changing after the NWL was put into operation, a number of effective system settings and

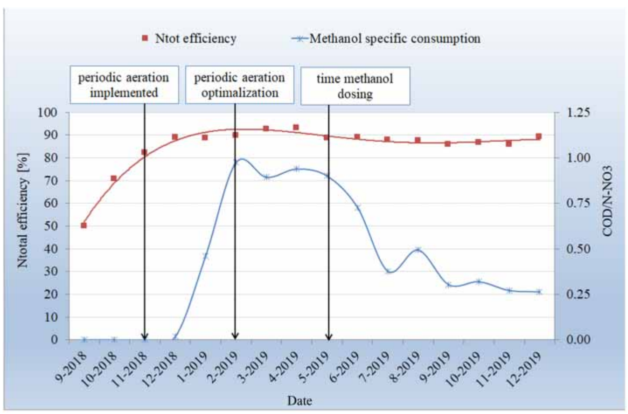

Figure 6 | Effect of methanol dose optimization on nitrogen removal efficiency.

modifications of the EWL line technology were necessary to implement. Operation of the grit chamber was changed in the means of aeration and number of operated chambers. The aeration was reduced to avoid mixing energy being too high and consequent outflow of sand from the chamber. During dry periods, only three grit chambers out of the original six are being operated during dry weather flow. During rain events the full capacity is used. The entire precipitation (coagulant and flocculant dosing) at the front of primary settling tanks, originally introduced to reduce organic load of the activated sludge process, was cancelled to provide more organic carbon for the denitrification process. Four primary settling tanks and two secondary settling tanks were shut down due to 42% reduction of hydraulic load. The four primary settling tanks were shut down to reduce organic carbon removal prior to the activated sludge process to provide more organic carbon for denitrification. The reduction of number of secondary settling tanks in operation was introduced to reduce hydraulic retention time of the sludge in the tanks to avoid anaerobic conditions and consequent release of biologically bound phosphorus. The start-up of the NWL also brought a change of maximum required flow to be treated at the EWL from 8.1 to 4.1 m^3/s. This avoided peak overload of secondary settling tanks and mitigated the risk of sudden rise of the sludge blanket. Consequently the dosing of flocculant into secondary settling tanks was no longer necessary.

The most demanding process in terms of optimization was nitrogen removal. The EWL gradually shifted from a state of overloaded treatment plant with a lack of oxygen and subsequent problematic nitrification to a state with excess oxygen and problematic denitrification. In order to control the process under rapid inflow changes, a simplified mathematical model of the EWL was created for continuous control of the activated sludge process. The model is based on a combination of contact times in individual sections of the activated sludge system with denitrification and nitrification rates measured in kinetic tests. It allows determination of the degree of degradation of nitrogen in the individual sections and, on that basis, determination of the optimal ratio and arrangement of the oxic and anoxic sections in the system. Based on this model, the volume of anoxic zone in the activated sludge tank was gradually increased, until anoxic zones represented a larger part of the tank volume (first, second, third, eighth and ninth sections of all tanks). In addition, most of the regeneration tank was operated as anoxic (first, second and fourth sections) as shown in Figure 7.

The use of the eighth and ninth sections of the activated sludge tank for post-denitrification was intended to at least partially compensate for the absence of internal recirculation. However, the benefit of post-denitrification was limited by the fact that the denitrification zones are not equipped with mixers, but are mixed by fine-bubble aeration. It led to the input of oxygen into the mixed liquor and made it impossible to provide fully anoxic conditions in the denitrification zones. For tank utilization before and after NWL start-up see Table 2. Air supply for aeration had changed from the continuous operation of three blowers (total airflow 140,000 Nm^3/h; 2.6 Nm^3/m^3 h of aerated sections) to operation of only one blower (airflow between 36,000 and 50,000 Nm^3/h; 1.15–1.60 Nm^3/m^3 h of aerated sections).

Despite all modifications the denitrification process was not optimal as shown in Figure 4 for the January 2019 results. For further increase of nitrogen removal efficiency, introduction of intermittent aeration was considered. Unfortunately, the design of blowers in combination with the dimensioning of the distribution network did not allow that. Finally, the blower was modified by decreasing the minimal airflow from 36,000 to 16,000 Nm^3/h. This modification allowed simultaneous denitrification in aerated sections and reduced oxygen input into the post-denitrification sections of the activated sludge tank. The $N\text{-}NH_4$ and $N\text{-}NO_3$ data sets in Figure 4 show that for the EWL the optimal total nitrogen removal is reached when nitrate concentration is approximately 9–10 mg/l. Unfortunately, such decrease of nitrates concentration is possible only with low DO concentration limiting nitrification and consequently increasing the ammonia concentration to approximately 4–5 mg/l.

Table 2 | Utilization of tanks at EWL before and after NWL start-up

	Before NWL start-up		**After NWL start-up**	
Primary settling tanks (m^3)	28,080			
Used volume (m^3)	24,570		14,040	
Used volume (%)	88%		50%	
Contact time (h)	2.3		3.1	
Secondary settling tanks 1 (m^3)	37,088			
Used volume (m^3)	37,088		27,816	
Used volume (%)	100%		75%	
Contact time (h)	2.6		2.6	
Secondary settling tanks 2 (m^3)	26,152			
Used volume (m^3)	26,152		26,152	
Used volume (%)	100%		100%	
Contact time (h)	2.9		4.3	
Activated sludge tank (m^3)	64,356			
	Anox	**Ox**	**Anox**	**Ox**
Used volume (m^3)	7,151	57,205	35,753	28,603
Used volume (%)	11%	89%	56%	44%
Contact time (h)	0.31	2.45	2.09	1.68
Regeneration tank (m^3)	18,000			
Used volume (m^3)	8,640	9,360	12,960	5,040
Used volume (%)	48%	52%	72%	28%
Contact time (h)	2.00	2.17	3.00	1.17

The main drawback of the EWL thus remains as the supply of easily biodegradable substrate. The concentration of filtered COD at the inlet to the denitrification zone of

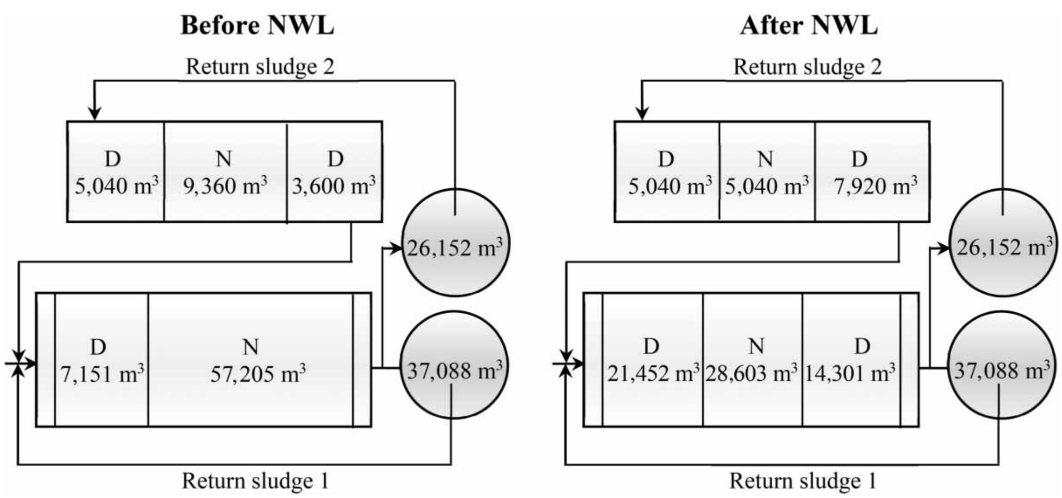

Figure 7 | Usage of D-N sections of activated tank before and after NWL. D: denitrification; N: nitrification.

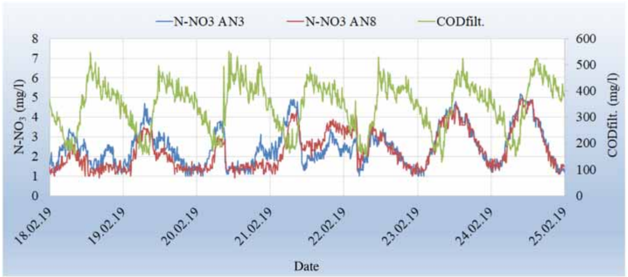

Figure 8 | N-NO_3 concentration in the outlet of aeration basin depending on chemical oxygen demand in filtrate ($COD_{filt.}$).

the activated sludge tank decreases significantly in some parts of the day, resulting in the reduction of denitrification rate. This leads to the penetration of nitrates through the denitrification section into the following sections (Figure 8), where the nitrate removal efficiency by simultaneous denitrification or post-denitrification is significantly lower due to the low denitrification rates with endogenous substrate.

The EWL is not equipped with dosing of external substrate into the denitrification sections of the activated sludge tank; the dosage of external substrate is possible only to the last anoxic part of the regeneration zone.

CONCLUSIONS

The CWWTP of the City of Prague was built in the 1960s employing a conventional, BOD_5 removal activated sludge process. In spite of several upgrades including, inter alia, the introduction of sludge regeneration zone with *in situ* bioaugmentation of nitrification, the overloaded plant was not able to remove enough nitrogen to meet limits corresponding with the EU Urban Wastewater Directive. Therefore the City of Prague decided to divide the treatment process between two plants – one part of wastewater is treated at the original plant (now called the EWL) and the rest is treated at the new plant (NWL), built in the same location and completed in the autumn of 2018. The sludge handling facility is common for both water lines and generated centrate is split between the lines for processing in bioaugmentation regeneration zones.

The activated sludge system of the NWL was not inoculated, but sludge was developed in the plant by gradual increase of treated water volumes. After 52 days of trial operation the target state of the NWL was reached and the plant started to meet the effluent limits.

The launch of the NWL resulted in a dynamically changing situation regarding the amount of wastewater treated on the EWL in relation to the daily increasing amount of wastewater pumped to the NWL. The operator reacted mainly by stopping chemical pre-precipitation and by the reduction of operated primary settling tanks to provide enough substrate for denitrification. Further major adjustment was extension of anoxic zones both in aeration basins and regeneration tank. The decrease in load led to an improvement of the nitrification process, but at the same time to deterioration of the denitrification process due to excess air in aeration basins and lack of organic substrate, in spite of made adjustments. Therefore the aeration control system was adjusted to maintain simultaneous nitrification and denitrification. Together with accepted measures this resulted in reaching almost complete nitrification and approximately 75% efficiency of total nitrogen removal in the January–December 2019 period.

The main goals of the building of the NWL and reducing the load towards the EWL introduced at the introduction of this paper were fulfilled (see also Table 1).

1. The limit defined by the discharge permit for year-average concentration of total nitrogen in the outlet, 10 mg/l, was reached at the NWL with 2019 year-average of 8.1 mg/l total nitrogen.
2. The limit defined by Council Directive 91/271/EEC concerning urban wastewater treatment for year-average removal efficiency of total nitrogen in the outlet of 70–80% was reached at the EWL with 2019 removal efficiency for total nitrogen of 75%.
3. All other limits defined by the discharge permits of both lines were fulfilled (see Table 1).

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

CEC (Council of the European Communities) 1991 Council Directive 91/271/EEC of 21 May 1991 concerning urban waste-water treatment. *Official Journal of the European Communities L* **135**, 30 May 1991, 40–52.

ČSN 75 6401 2014 *Čistírny Odpadních vod pro Ekvivalentní Počet Obyvatel (EO) Větší než 500 (Czech Standard 75 6401 Wastewater Treatment Plants for Total Number of Inhabitants and Population Equivalents (PE) more than 500)*. Český normalizační institut, Praha.

Ginige, M. P., Bowyer, J. C. & Foley, L. 2009 A comparative study of methanol as a supplementary carbon source for enhancing denitrification in primary and secondary anoxic zones. *Biodegradation* **20**, 221. doi:10.1007/s10532-008-9215-1.

Henze, M., Kristensen, G. H. & Strube, R. 1994 Rate-capacity characterization of wastewater for nutrient removal process. *Water Science and Technology* **29**, 7. doi:10.2166/wst.1994.0318.

Kos, M., Wanner, J., Šorm, I. & Grau, P. 1992 R-D-N activated sludge process. *Water Science and Technology* **25**, 4–5. DOI: 10.2166/wst.1992.0490.

Kos, M., Mucha, A., Wanner, J. & Žejdlík, P. 2015 General reconstruction and extension of the CWWTP Prague. In *Proceedings 12th IWA Specialised Conference on Design, Operation and Economics of Large Wastewater Treatment Plants, 6–9 September, Prague*.

Krhůtková, O., Novák, L., Pachmanová, L., Benáková, A., Wanner, J. & Kos, M. 2006 In situ bioaugmentation of nitrification in the regeneration zone: practical application and experiences at full-scale plants. *Water Science and Technology* **53**, 12. doi:10.2166/wst.2006.404.

Novák, L. & Havrlíková, D. 2003 Performance intensification of Prague wastewater treatment plant. In: *Proceedings 9th IWA Specialised Conference on Design, Operation and Economics of Large Wastewater Treatment Plants, 1–4 September, Prague*.

Nyberg, U., Aspegren, H., Andersson, B., la Cour Jansen, J. & Villadsen, I. S. 1992 Full-scale application of nitrogen removal with methanol as carbon source. *Water Science and Technology* **26**. doi:10.2166/wst.1992.0549.

Palm, J. C., Jenkins, D. & Parker, D. S. 1980 Relationship between organic loading, dissolved oxygen concentration and sludge settleability in the completely-mixed activated sludge process. *Journal Water Pollution Control Federation* **52**, 10. doi:10.2307/25040913.

Pospíšil, V., Kelbich, P., Chovancová, L., Martínek, F., Pečenka, M., Růžičková, I. & Wanner, J. 2015 Study of regeneration zone in WWTP Liberec and WWTP Plzeň. In: *Proceedings 12th IWA Specialised Conference on Design, Operation and Economics of Large Wastewater Treatment Plants*, *September 6–9*, *Prague*.

Wanner, J., Kos, M. & Novák, L. 2009 Intensification of Prague central WWTP – ten years of practical experiences with the in-situ bioaugmentation nitrification method. *Water Practice and Technology* **4**, 1. doi:10.2166/WPT.2009.016.

Weber Jr., W. J. 1972 *Physicochemical Processes for Water Quality Control*. Wiley-Interscience. doi:10.1002/aic.690190245.

First received 29 September 2020; accepted in revised form 20 November 2020. Available online 7 December 2020