

ANALYSIS AND BALANCE OF PHOSPHOROUS REMOVAL FROM WASTEWATER AT URBAN WASTEWATER TREATMENT PLANT

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Abstract: Phosphorus is a major substance that is needed especially for agricultural production or for the industry. At the same time it is an important component of wastewater. At present, the waste management priority is recycling and this requirement is also transferred to wastewater treatment plants. Substances in wastewater can be recovered and utilized. In Europe (in Germany and Austria already legally binding), access to phosphorus-containing sewage treatment is changing. This paper dealt with the issue of phosphorus on the sewage treatment plant in Nitra. There are several industrial areas in Nitra where record major producers in phosphorus production in sewage. The new wastewater treatment plant is built as a mechanical-biological wastewater treatment plant with simultaneous nitrification and denitrification, sludge regeneration, an anaerobic zone for biological phosphorus removal at the beginning of the process and chemical phosphorus precipitation. The sludge management is anaerobic sludge stabilization with heating and mechanical dewatering of stabilized sludge and gas management. The aim of the work was to document the phosphorus balance in all parts of the wastewater treatment plant - from the inflow of raw water to the outflow of purified water and the production of excess sludge. Balancing quantities in the wastewater treatment plant treatment processes provide information where efficient phosphorus recovery could be possible. The mean daily value of P tot is approximately 122.3 kg/day of these two sources. The mean daily value of P tot is approximately 122.3 kg/day of these two sources. There are also two outflows - drainage of cleaned water to the recipient - the river Nitra - 9.9 kg Ptot/day and Ptot content in sewage sludge - about 120.3 kg Ptot/day - total 130.2 kg Ptot/day.

Keywords: Wastewater, Biological treatment, Phosphorus, Balance, Water quality, Sewage sludge

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1. Introduction

The current depletion and loss of phosphorus (P) at each stage of its life cycle contribute to worries about future stocks as well as it concerns about water and soil pollution in the EU and around the world [1]. An increased phosphorus demand for food (over 90% of P is used up as fertilizer and feed additive), as well as uneconomical phosphorus management and the reports of shrinking P stocks in the available rocks, contributes to the increasingly frequent debate [2]. The phosphorus stock is now estimated to be about 300 billion tones, and the availability of the phosphorus-containing rocks will also depend on its price. At present, almost the entire EU is dependent on phosphorus imports from the countries with its own growing consumption (Morocco, China, USA), with the EU showing a huge phosphorus consumption (1 kg P/inhabitant/year) [3], [4].

In Europe (in Germany and Austria already legally binding), access to phosphorus-containing sewage treatment is changing, and more recycling of the substances is being promoted that is the case with the conventional waste management [5].

The potential of recovered phosphorus in the EU should be up to 300,000 tones/year [3]. Recycling can be done from the two positions. Either the sewage sludge will continue to be used on the soil (either directly or after composting), and then the recycling of the substantial part P removed from the wastewater is realized already traditionally (the main task will be the optimal realization) [6]. The second possibility is that the sewage sludge will not be used in the soil and then to obtain P recycling from wastewater and sewage sludge lines during the special processes is necessary [7].

At Waste Water Treatment Plan (WWTP) with a capacity of more than 10,000 inhabitants, P removal is obligatory. In Slovakia to these WWTPs are connected with approx. 2.5 million inhabitants.

The sources of phosphorus in wastewater are different. Most phosphorus comes from detergents and human excrements, phosphorus in food and other organic substances [8].

One inhabitant produces approx. 1.8 g P/day. If 80% P is removed from the sewage treatment plant and if sludge is used on the agricultural land, recycling of 3.6 tones P/day or 1300 t/year might be possible [9].

To recycle even more P, it is necessary to have additional P precipitation in the tertiary treatment stage, in water from dewatered sludge or directly in activated sludge processes. In this case, there are still reserves of max. up to 2.3 tones P/day or 800 t/year [8].

At the present time, there exist a large number of phosphorus removal technologies, some of them are applied at a large industrial scale and some exist only on a theoretical basis or on a laboratory scale.

In all cases, however, the phosphorus is converted into an insoluble solid phase. This fraction may be an insoluble inorganic salt, activated sludge biomass, or the biomass of artificial wetlands. In all cases, however, the phosphorus is converted into an insoluble solid phase. Today in modern projects it would be converted as well into the biomass of the cultivated algae [10].

The insoluble phosphates are simply landfilled, incinerated, or used as a fertilizer, as long as from the mixture are removed pathogens and toxic compounds [11].

The technologies used for the separation and recycling of phosphorus from wastewater include chemical precipitation with iron, aluminium and calcium salts; increased phosphorus removal by incorporating phosphorus into biomass; crystallization of calcium phosphate on crystallization cores, crystallization of the structure of struvite - composition of Magnesium, Ammonia and Phosphate (MAP) ($\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$) [12]. Less commonly used technologies include the use of sludge itself through a variety of other stabilization, hygienisation and composting or granulation processes; the filtration before which the phosphorus has been converted into a solid phase; absorption where minerals (hydroxylapatite, vivianite and others) are formed by sorbents. Indirect removal of P is also possible through constructed wetlands; ion exchange process into struvite form; magnetic removal of phosphorus by magnetite crystallization; electrocoagulation; incorporation into biomass of bacteria, algae, macrophytes and other modern technologies (bacterial precipitation of phosphates, application of nanotechnologies and others) [13].

Each WWTP, therefore, requires a completely individual approach deciding on the proper configuration and dimensioning, depending on the required sewage system parameters, the quality of the wastewater, the application of the mechanical pre-treatment system for wastewater and the method of disposal of the water from sewage sludge dewatering [8].

In the 2017, a thematic issue for the World Water Day - Wastewater - The Untapped Resource was announced through the United Nations. The aim of the analysis in the published document was not only to deal with water scarcity and the use of wastewater as an alternative source of water but also of sources of substances in wastewater [14]. These are organic substances, nutrients (N, P) and other important macro and microelements. The phosphorus and nitrogen and energy recovery can add substantial new worth streams to increase the proposition of cost balance [15]. Today an increasing number of potentially cost-effective chances for extracting useful resources from the treated wastewater are known, and nitrogen and phosphorus that can be converted into fertilizer [16].

The use of wastewater will reduce a load of nature with pollutants. It will reduce the potential threat of water by eutrophication, contamination or saprobisation. The importance of wastewater recycling at the WWTP focuses on two basic solutions - the use of organic matter and the recovery of phosphorus [17].

2. Material and method

2.1. Material

This research dealt with the issue of phosphorus on the sewage treatment plant in Nitra. There are several industrial areas in Nitra where recorded major producers of phosphorus were dumping in sewage. Within the short time, an important multinational car manufacturing company will be put into operation, which will be a potentially significant producer of wastewater rich in other characteristic compounds as well as polyphosphates that are relatively difficult to degrade in the conventional biological WWTP processes.

Nitra - Dolné Krškany WWTP is one of the largest wastewater treatment plants in Slovakia. The operator of The Western Slovakia Water Company is a joint-stock company. The wastewater from the city of Nitra and its suburban areas is collected at Nitra wastewater treatment plant. The number of connected peoples represents approx. 77 000 inhabitants. The original old WWTP was built in 1968 for 89,000 Equivalent Inhabitants (EI). It was a mechanical-biological treatment with medium load activation, followed by anaerobic stabilization of primary and excess sludge and its dewatering on the sludge fields. Because of the lack of hydraulic capacity of the secondary treatment - activated sludge -and the lack of efficiency of biological nutrient removal, reconstruction or construction of a new WWTP was necessary.

The new WWTP was completed in 2006 for the projected capacity of 175,450 EI with the possibility of expansion to the resulting 230,000 EI after the completion of activation tanks and settling tank. The new WWTP is built as a mechanical-biological WWTP with simultaneous nitrification and denitrification, sludge regeneration, an anaerobic zone for biological phosphorus removal at the beginning of the process and chemical phosphorus precipitation. The sludge management is anaerobic sludge stabilization with heating and mechanical dewatering of the stabilized sludge, gas management with the possibility of energy recovery of the produced biogas in the cogeneration units and the combustion boilers. The recipient is the Nitra river in the river kilometer 52.5 (Fig. 1). The basic design parameters of the new WWTP are in Table I - Table III.



Fig. 1. Location of the WWTP Nitra in Slovakia and view at WWTP objects
(Photo: Lukac, 2015)

The research will focus on the flow (circular, balance) of phosphorus by individual stages of Nitra WWTP, especially in qualitative and the quantitative indicators in the form of phosphorus phosphor ($P-PO^4$) and the total phosphorus (P_{tot}). As a part of the treatment process, phosphorus is incorporated into the activated sludge biomass, either simultaneously or in the process of enhanced biological phosphorus removal, followed by chemical removal with the chemical precipitants. They are the aluminium or iron salts which, after precipitation, settle in the sedimentation tank together with the microorganisms in the biological treatment.

Table I

Design parameters for new WWTP in Nitra

<i>Inflow</i>		
average dry-weather daily inflow Q_{24}	36 300 m ³ /d	420.1 l/s
maximal dry-weather daily inflow Q_d	44 660 m ³ /d	516.9 l/s
maximal hourly dry-weather daily inflow Q_h	2 833 m ³ /h	786.9 l/s
Wet weather maximum daily inflow		1500 l/s

Table II

Average daily mass loads at new WWTP in Nitra

BOD ₅	290 mg/l	10 527 kg/day
COD _{Cr}	470 mg/l	17 061 kg/day
SS ₁₀₅	310 mg/l	11 253 kg/day
N-NH ₄	23 mg/l	834.9 kg/day
N _{org.}	7 mg/l	254.1 kg/day
N _{tot.}	30 mg/l	1 089 kg/day
P _{tot.}	5 mg/l	181.5 kg/day

Table III

Water management permission for new WWTP in Nitra

<i>Water management permission č. 2008/00880 Outflow</i>			
<i>maximal hourly dry-weather daily outflow Q_h</i>	<i>average dry-weather daily outflow Q_{24}</i>	<i>average dry-weather daily outflow Q_{24}</i>	<i>average dry-weather yearly outflow Q_{24}</i>
660 l/s	400 l/s	34 560 m ³ /day	11 890 000 m ³ /year

Certainly, part of the phosphorus is transported to the recipient in the treated effluent, presently is not possible to achieve zero phosphorus outflows in the discharged wastewater with the conventional biological purification.

2.2. Methods

Many parameters have the impact on the capacity of P-accumulation, like retention time of anaerobic and aerobic/anoxic phases, or physical-chemical characteristics of wastewater such as pH, temperature, fatty acid structure, NH₄⁺, K⁺, Na⁺, Mg²⁺, Ca²⁺, PO₄³⁻, SO₄²⁻ and other metal ion concentrations [18].

The P storage compounds can be mineral or organic and accumulation depends on the type of microorganism. A specific microbiota, phosphate accumulating organisms (PAOs), stores phosphate as polyphosphate. Biochemically activated sludge also contains bacteria capable of increasing phosphorus accumulation in the cells. These organisms are collectively referred to as poly-P (polyphosphate accumulating or also polyphosphate) consequential predominantly from the genus *Acinobacter* [19].

Orthophosphate compounds with low-solubility are the simplest forms of phosphorus accumulation. Some archaea can precipitate $\text{MgPO}_4\text{OH}\cdot 4\text{H}_2\text{O}$ (*Halobacterium salinarium*).

These strains concentrate P from water solution in the period of their growth phase. *Brevibacteria* can also store P as $\text{NH}_4\text{MgPO}_4\cdot 6\text{H}_2\text{O}$ in cells of organisms. Cyanobacteria accumulate P in their covers, combined with Ca ions. The storage of P as the organic compounds is another type of storage. Acids are synthesized by bacteria and composed of different types of polyols with phosphodiester bonds. These molecules are used by microorganism as phosphate reserve [20], [21].

Phosphorus is about 1-3% of the dry weight of a bacterium. The phosphorus content is approximately one-fifth of the nitrogen content of the bacteria. The actual phosphorus content may vary from one-seventh to one-third of the nitrogen content depending upon environmental conditions [22].

Commonly used technology for P removal chemical precipitation with Al^{3+} or Fe^{3+} , makes phosphorus recycling more difficult, compared to biological phosphorus removal. These metals form insoluble P precipitates are poorly utilized by plants when applied to agricultural soil as fertilizer [23]. If P is removed by precipitation with Al^{3+} or Fe^{3+} , it needs to be converted to a more plant-available form using wet chemical or thermochemical technologies [24]. Biological P removal is more amenable to P recycling because P is accumulated by sludge microorganisms in the form of polyphosphate (poly P), which can be further recovered as soluble P for recycling [25].

The residual concentrations of P_{tot} are limited by the summation of orthophosphate and inorganic phosphorus (up to 0.1 mg/l in dissolved form and 1-2% in suspended solids). The precipitation of P-PO_4^{4-} is very often effective and can reach the concentration below 0.1 mg/l [26].

At the WWTP in Nitra, for phosphorus removal is used ferrous sulphate. The amount of sulfate is dosed in the range of 30-35 l/hour depending on the wastewater flow (Fig. 2).



Fig. 2. The distribution chamber with the precipitant application for phosphorus
(Photo: Jurik, 2017)

The object of the biological reactor consists of 4 circular activation tanks, 61.0 m long, 13.10 m wide, each of the tanks is divided into two channels with a width of 6.40 m.

The activated sludge process can be controlled in three ways:

1. Spatial segregation of nitri/denitri processes - practically impossible to achieve in practice - the oxygen concentration is almost the same in the whole volume;
2. Time-shift for nitri/denitri processes - Use in case of malfunction of operating sensors - Specification of the exact duration of nitri and denitri and regular rotation;
3. Controls from operating probes - the values from the operating measurement points (for ammonia and nitrate) are relatively simple logarithmic relation, where minimal and maximum concentrations are determined using hysteresis, in the space bounded by two curves a space for nitrification is defined, respectively. The air blower operation is controlled by frequency converter controllers by an oxygen probe in addition to the logarithmic relationship, the nitrite and denitrification times are limited by type of control, both the minimum and maximum of nitrification and denitrification times.

Characteristics of the removal of pollution in activated sludge process at Nitra wastewater treatment plant:

- stored sludge in the biological reactor approx. 72,670 kg;
- sludge concentration 4.3 - 4.7 g/l;
- reclaimed sludge concentration 7.5-8.0 g/l;
- volume of sedimentation sludge in 30 min - 750-850 ml/l;
- sludge index - 150-200 ml/g;
- age of sludge - 29 days;
- residence time - 15.5 hours;
- volume bulk density - $0.31 \text{ kg/m}^3 \cdot \text{day}^{-1}$;
- sludge load - $0.057 \text{ kg/kg} \cdot \text{day}$;
- specific dry sludge production - $0.6 \text{ kg/kg} \cdot \text{day}^{-1}$.

3. Results and discussion

The aim of the work was to document the phosphorus balance in all parts of the wastewater treatment plant - from the inflow of raw water to the outflow of purified water and the production of excess sludge. Balancing quantities in WWTP treatment processes is providing information, where efficient phosphorus recovery could be possible. The basis of the balance was based on the comparison of input and output quantities at WWTP. The input is a wastewater flow from the city through the sewer system and the wastewater from the cesspits (*Fig. 3*).

The mean daily input value of P_{tot} is approximately 122.3 kg/day from these two sources. There are two outflows streams - flow of treated water to the recipient - the Nitra river - $9.0559 \text{ kg } P_{\text{tot}}/\text{day}$ and P_{tot} content in sewage sludge - about $120.3 \text{ kg } P_{\text{tot}}/\text{day}$ - total $130.2 \text{ kg } P_{\text{tot}}/\text{day}$.

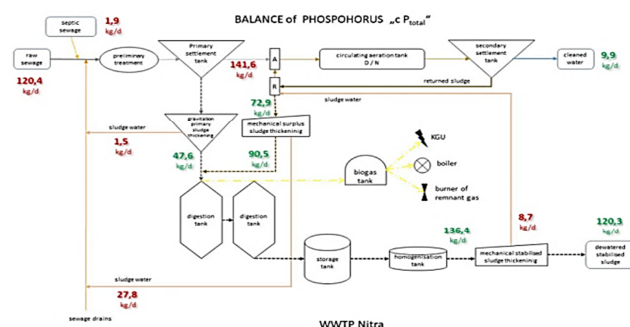


Fig. 3. Schematic sketch of phosphorus concentrations in WWTP objects

Comparing both values, it was found out that there were no equal values between inputs and outputs. There were also obtained data from measurements on individual components of the WWTP and a trial to find out how to specify the balance better.

Therefore, the values for primary sedimentation and the return water data from dewatering sludge coming into the WWTP inlet were added. The amount of phosphorus in water from sludge dewatering is 23.3 kg/day. Then it is changed the input quantity to 145.6 kg/day.

The concentration measurements at WWTPs were also made at other important points, but also after this data complement the quantity balance at the input and the output even after refinement not failed to reach the same value.

That is why in the next few months the analysis will be done at new available locations where measurements can be made. Significantly, the new technology of WWTP in Nitra has a substantial impact on the runoff concentrations and hence on the quality of water in the Nitra river (Fig. 4).

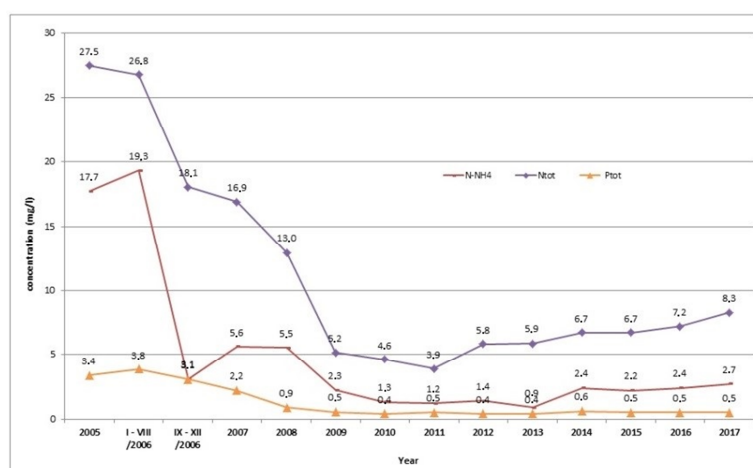


Fig. 4. Outflow concentrations in the treated water before and after reconstruction of WWTP Nitra

4. Conclusion

The aim of the research was to evaluate the balance of phosphorus conversion in individual parts of the treatment plant.

Knowing all the processes of phosphorus conversion in the treatment plant requires more time-consuming research. The preliminary results published in the present paper are satisfactory. An important problem is the comparison of the values in wastewater and parts of phosphorus accumulated in sewage sludge. The sludge age in WWTPs is 29 days and its processing is even up to months. The balance results will not always be equivalent to both input and output. Outputs are in results from different times. Water is flowing out after some hours; sludge is produced after some days. Interest also focuses on the content and species composition of microorganisms that accumulate phosphorus.

The influence of discharged phosphorus on the Nitra river basin is considerably smaller than the limit values set by the legislation in force in the Slovak Republic as well as in the EU.

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