Using Simulation for Optimising Biological Nutrients Removal Design in Wastewater Treatment Plants

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At the moment, in Romania, high investments are made in developing or rehabilitation of wastewater treatment plants. Design of a new plant is usually made based on the national design standards. Sometimes the wastewater treatment processes are designed for a much higher capacity than the current necessities and therefore they don't lead to the desired efficiency. The aim of this paper is to evaluate different nutrient removal configuration on order to identify the optimal solution for a certain wastewater treatment plant and to evaluate the different designed configurations. Alternative systems were evaluated in order to identify the one with the highest removal efficiency and lowest costs.

Keywords: wastewater, simulation, biological nutrients removal

The rising concentration of harmful nutrient compounds – specifically nitrogen and phosphorus – in municipal wastewater treatment plant discharge causes cultural eutrophication (nutrient enrichment due to human activities) in surface waters. Summer algal blooms are a familiar example of this eutrophication and can present problems for ecosystems and people alike: low dissolved oxygen, fish kills, murky water and depletion of desirable flora and fauna.

As Romania declared the entire territory as a sensitive area, the water quality parameters before discharge in natural streams have to comply strict limitations. The main limiting factors for municipal wastewater treatment plants effluents are the total phosphorous and total nitrogen, with concentration values of 2 and respectively 15 mg/L [1], for equivalent populations of lower than 100000 inhabitants.

Because conventional biological processes designed to meet secondary treatment effluent standards typically do not remove total nitrogen and total phosphorus to the extent needed to protect receiving waters, wastewater treatment facilities are increasingly being required to implement processes that reduce effluent nutrient concentrations to safe levels [2]. This can be a challenge for existing wastewater treatment plants because it usually involves major process modifications to a plant, such as splitting aeration basins into anaerobic and/or anoxic zones, which reduces the aerobic volume and limits nitrification capacity[3].

Total effluent nitrogen comprises ammonia, nitrate, particulate organic nitrogen, and soluble organic nitrogen. The biological processes that primarily remove nitrogen are nitrification and denitrification [4]. During nitrification ammonia is oxidized to nitrite by one group of autotrophic bacteria, most commonly Nitrosomonas [5]. Nitrite is then oxidized to nitrate by another autotrophic bacteria group, the most common being Nitrobacter.

Denitrification involves the biological reduction of nitrate to nitric oxide, nitrous oxide, and nitrogen gas [6]. Both heterotrophic and autotrophic bacteria are capable of denitrification. The most common and widely distributed denitrifying bacteria are Pseudomonas species, which can use hydrogen, methanol, carbohydrates, organic acids, alcohols, benzoates, and other aromatic compounds for denitrification [5].

In BNR (Biological Nutrients Removal) systems, nitrification is the controlling reaction because ammonia oxidizing bacteria lack functional diversity, have stringent growth requirements, and are sensitive to environmental conditions [4, 6, 7]. Note that nitrification by itself does not totally remove nitrogen from wastewater. Rather, denitrification is needed to convert the oxidized form of nitrogen (nitrate) to nitrogen gas [8]. Nitrification occurs in the presence of oxygen under aerobic conditions, and denitrification occurs in the absence of oxygen under anoxic conditions [9].

Total effluent phosphorus comprises soluble and particulate phosphorus. Particulate phosphorus can be removed from wastewater through solids removal. To achieve low effluent concentrations, the soluble fraction of phosphorus must also be targeted. That phosphorous fraction is removed by one of two mechanisms: microbial uptake or chemical precipitation.

Biological phosphorus removal relies on phosphorus uptake by aerobic heterotrophs capable of storing orthophosphate in excess of their biological growth requirements [10].

Phosphorus can also be removed from wastewater through chemical precipitation. Chemical precipitation primarily uses aluminum and iron salts coagulants or lime to form chemical flocs with phosphorus. These flocs are then settled out to remove phosphorus from the wastewater [11,12]. However, compared to biological removal of phosphorus, chemical processes have higher operating costs, produce more sludge, and result in added chemicals in sludge [5]. When P_T (total phosphorus) levels close to 0.1 mg/L are needed, a combination of biological and chemical processes may be less costly than either process by itself.

Experimental part

Simulation study

The paper shows the results obtained for a treatment plant that processes the wastewater collected by a combined sewerage system and comprises a modular mechanical stage, biological reactors for advanced treatment and a sludge processing stage.

The design parameters that were considered can be seen in the table 1.

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Q [m³/day]	1970
BOD [mg/l]	309
COD [mg/l]	618
TSS [mg/l]	412
TKN [mg/l]	62
P_T [mg/l]	18

Table 1
WASTEWATER LOADING

The following notations are made: Q – daily wastewater flowrate; BOD – biological oxygen demand; COD – chemical oxygen demand; TSS – total suspended solids; N_T – total nitrogen; P_T – total phosphorus.

Several biological nutrients removal processes were evaluated by using CAPDET, software for Wastewater treatment plants design and cost estimation. The studied configurations were as follows:

- Biological nitrogen removal
- Biological nutrients removal- 2 and 3/5 Stages
- Pre and Post denitrification

For each studied case the results were evaluated and the operational costs were compared.

Result and discussions

Case 1 - Biological nitrogen removal

The designed case- suspended growth nitrification system is similar to activated sludge systems. The solids retention time is longer than the one in carbon oxidation systems due to the reduced growth rates of nitrifiers compared to heterotrophic microorganisms. This configuration includes an unaerated stage ahead of an aerobic reactor, as can be seen in figure 1. Sludge is recycled at the beginning of the unaerated stage.

Fig. 1. Biological nitrogen removal process schematics

The design led to an anoxic volume of 1870m³ and an aerobic volume of 2800m³. The average internal pumping rate resulted of 985 m³/day while the average sludge recycle resulted of 657 m³/day. Two circular clarifiers with a cumulated surface area of 100 m² resulted as necessary. An excess sludge flow of 70 m³/days evacuated from the two clarifiers.

Denitrification processes

Discharge of ammonia nitrogen to receiving water causes the reduction of the dissolved oxygen contents as the ammonia is oxidized to nitrate. During the nitrification process used in most of the wastewater treatment plants converts ammonia nitrogen to nitrate nitrogen prior to discharge. In certain cases, nitrate nitrogen can cause eutrophication of the water bodies and thus a denitrification system must be used. During this biological process nitrate nitrogen is converted to gaseous nitrogen. There are two main configurations for the biological denitrification systems- with the anoxic reactor situated before the aerobic tank (pre-denitrification) and the second one, where the anoxic tank is situated afterwards the aeration processes (post-denitrification). Both configurations were evaluated and the resulting configurations can be seen in figure 2.

The Pre-denitrification design (Case 2) led to an anoxic tank with a volume of 324 m³ and an two aerobic bioreactors having a cumulated volume of 2800 m³. The anoxic hydraulic retention time was of 3.95 h, while the aerobic one was 34.1 h. The average internal nitrates pumping rate resulted of 6150 m³/day and the average sludge recycle was 657 m³/day. Two circular clarifiers with a cumulated surface area of 97 m² were necessary, with an excess sludge flow of 68 m³/day that had to be evacuated from the two clarifiers.

In the case of the Post-denitrification configuration (Case 3), the two anoxic tanks had a total volume of 141 m³ and the four aerobic tanks had a cumulated volume of 2800 m³. The aerobic tank hydraulic retention time resulted similar to Case 2, while the anoxic one resulted of 1.7 h. As a difference from Case 2, the anoxic hydraulic retention time is within the normal range, as identified in previous studies [2]. The methanol required is of 139 kg/day.

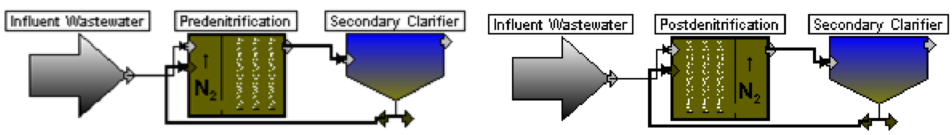
Biological nutrient removal-2 Stage and 3/5 Stages

Biological nutrients removal envisages excess Phosphorous removal from the wastewater, in addition to Nitrogen removal. The two stage biological nutrient removal consists of an unaerated and an aerobic stage, with sludge recycled from the secondary clarifier to the unaerated tank. Although the schemes seem similar to the classical nitrogen removal process, in order to obtain a high quality effluent, the microbial community is enriched in the biological stage with polyphosphate accumulating organisms [13].

The 3 stage Biological nutrient removal (BNR) configuration consists of an anaerobic tank, followed by anoxic and aerobic stages. The system has an internal nitrate recycle from the aerobic bioreactor to the anoxic one and also sludge recycle from the clarifier to the anaerobic tank. The modified Bardenpho configuration – the 5 stage BNR has a first reactor similar to the previous one but in order to increase the nutrients removal two other reactors are added- an anoxic stage to increase the denitrification capacity and an aerobic one for effluent polishing [14].

The 2 and 3 and 5 Stages biological nutrient removal configurations were evaluated and the resulting configurations can be seen in figure 3.

The 2-stage biological nutrient removal design led to tanks volumes of 123 m³ for the anoxic ones and aerobic bioreactors with a cumulated volume of 2800 m³ in two parallel lines, each having one anoxic cell and two aerobic ones. The aerobic SRT (sludge retention time) resulted greater than 7 days, leading to uncertainties referring to the possibility that the system nitrifies, because the air flow was estimated assuming complete nitrification. The influent TKN/BOD ratio, lower than 0.15, suggests insufficient BOD for denitrification, thus a third stage for denitrification or additional carbon source may be needed.



a) b)

Fig. 2.Biological nitrogen removal processes. a) Pre-denitrification, b) Post-denitrification

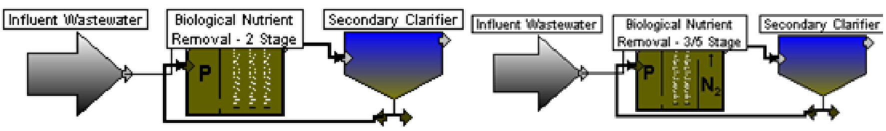


Fig. 3. Biological nutrient removal-2 Stage (a) and 3/5 Stages (b)

Table 2
EFFLUENT PARAMETERS FOR THE DESIGNED CASES

Parameter	Influent	Effluent					
		Biological Nitrogen Removal	Pre-Denitrification	Post-Denitrification	Biological Nutrient removal – 2 Stages	Biological Nutrient removal – 3 Stages	Biological Nutrient removal - 5 Stages
Flow [m^3/d]	1970	1900	1900	1900	1900	1900	1900
SS [g/m^3]	412	20	20	20	20	20	20
BOD [g/m^3]	309	3.78	3.78	6.78	3,78	3,78	3,78
COD [g/m^3]	618	22.5	22.5	22.5	22,5	22,5	22,5
TKN [gN/m^3]	62	2.24	2.24	2.24	1,3	2,24	2,24
P_T [gP/m^3]	18	13.4	13.4	13.4	1,18	1	1

The excess sludge flow was of 68 m^3/day. The sludge recycle rate resulted identical to the previous studied cases.

When designing the 3 stages biological nutrients removal, with coarse bubbles air diffusion system, the influent BOD/P_T ratio resulted too small and thus the anaerobic tank was not calculated and was considered unnecessary. The total volume of the reactors resulted of 739 m_3, with an anoxic volume of 82.1 m^3. Considering the limiting HRT in the aerobic stage, the SS was recalculated. Influent BOD to P_T ratio suggested the need for chemical precipitation for bio-P removal. The maximum anoxic HRT of one hour was used. The aerobic-anoxic internal recycle was designed for a 300% rate.

For the 5 stages biological nutrients removal process, fine-bubble aeration was considered. Due to the BOD/TP ratio no anaerobic tank was designed. The total reactors volume resulted of 1640 m^3, with an anoxic global volume of 575 m^3. The internal recycle ratio resulted of 191%, while a sludge flow of 1970 m^3 was returned daily to the anoxic stage.

The effluent quality parameters for all the studied cases can be seen in table 2.

As can be seen, maintaining similar parameters for the influent, sludge recycle, solids concentration in the biological stages etc., led to identical outflow values for all the studied cases, as well as identical solids concentration in the effluent. The solids concentration in the effluent complies in all cases the Romanian legal requirement, of at most 35 mg/L [1].

Important BOD and COD removal rates were obtained- of roughly 98%.

As can be seen in table 2, all the designs led to proper BOD and COD removal rates. When it comes to TKN, in all six cases the legislation requirements are fulfilled, fact that's not similar in the case of P_T. The Romanian legislation

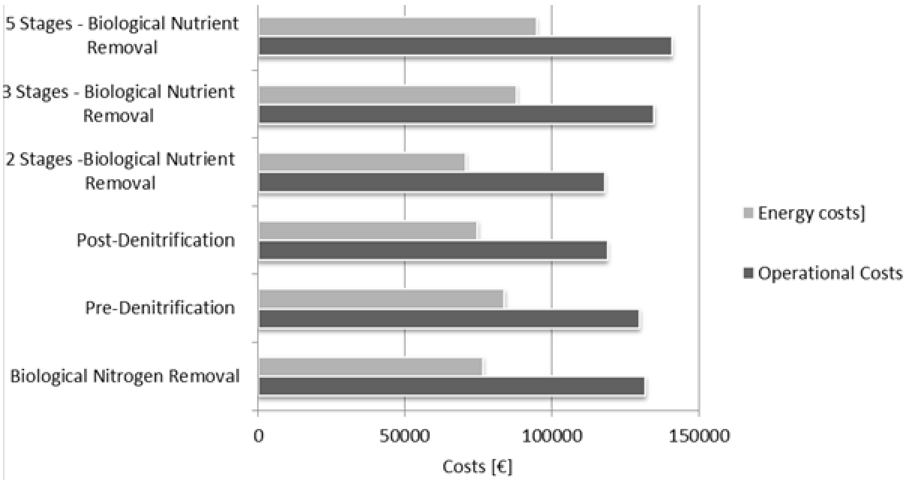


Fig. 4. Energy and Operational costs for the designed cases

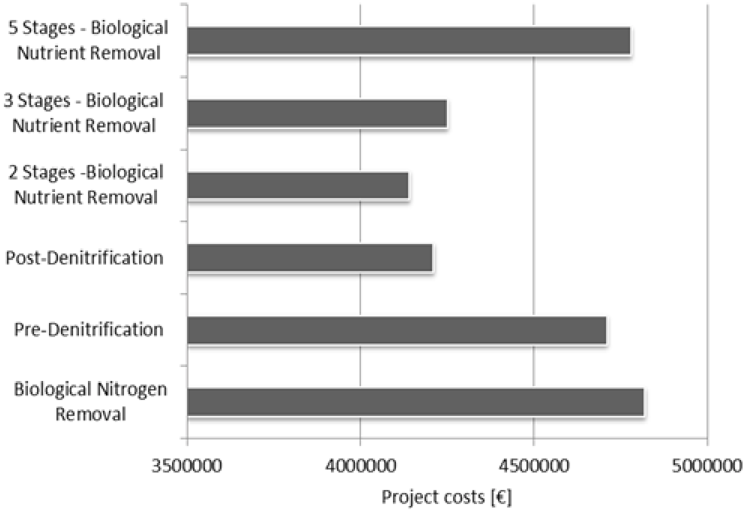


Fig. 5. Project costs for the designed cases

requires effluent concentration of 1(2) mg/L P_T value that was only found in the case of the 3/5 Biological nutrients removal processes.

The operational costs, with a highlight on the energy consumption, can be seen in figure 4 and the total project costs are shown in figure 5.

The highest project cost was obtained for the Biological Nitrogen removal configuration, mainly due to the high biological tank values. The projects in all cases consist only in the biological stage of the wastewater treatment plant and are reported to the CapdetWorks Database. The aim of presenting this data is showing the difference between various configurations costs. The lowest project cost was the one for the 2-Stages Biological Nutrient Removal process, having the price lower with an estimate 15%. As can be seen in table 2, none of the two configurations fulfil the Phosphorous removal requirements, thus leading the need for evaluating the other cases.

From a Project cost to Phosphorous removal point of view, the optimal solution is the 2 Stages Biological Nutrient Removal Process. This case also led to the lowest energy and operational costs. The Phosphorous concentration in the effluent is slightly higher in this case than the other ones, but is still fulfils the national legislation requirements.

Conclusions

Most wastewater treatment plants operators in Romania are at the moment looking for solutions for eliminating the high nutrients concentrations from the water stream before it's restitution to the natural courses. Sometimes only biological treatment is not enough to obtain an effluent that complies the legislation limits regarding nutrients concentration. It is necessary to introduce chemical addition to the treatment process in order to obtain the desired phosphorous concentration. Chemical addition, if not properly operated and designed can lead to reduction of the efficiency of the biological wastewater treatment stage, and therefore, reduction of the global wastewater treatment efficiency. The lowest energy costs were obtained in the 2-Stages Biological Nutrient Removal configuration's case, being the case that also had the most reduced operational cost. Similar values when it comes to costs were identified in the Post denitrification case, with a difference in the operational costs of less than 1%. For the studied wastewater inflow the optimal solution resulted as being the 2-Stages Biological Nutrient Removal configuration, mainly due to the increased pollutants removal rates when compared to Post-denitrification system.

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