Model-based evaluation of a trickling filter facility upgrade to biological nutrient removal

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Abstract

This article presents the feasibility evaluation and preliminary design of a wastewater treatment plant upgrade supported by simulation. The existing facility was based on trickling filters, and the objective of the upgrade was to achieve nutrients removal. The proposed solution modifies the existing primary clarifier to host an anaerobic-anoxic suspended growth reactor, which is an alternative that, to our knowledge, has not been proposed or explored so far. The trickling filters would remain as aerobic reactors. In this study, the novel treatment scheme has been assessed for the first time, through model simulations. The modified treatment train was simulated, showing that the anoxic zone is able to denitrify satisfactorily achieving the required effluent nitrogen concentration. However, to promote biological phosphorus removal, an additional aerobic zone combined with a bypass of activated sludge from the anoxic zone to the first trickling filter is needed, in order to provide aerobic conditions to the phosphate accumulating organisms. Several combinations of additional aerobic volume and sludge bypass flowrate were found to successfully achieve both nitrogen and phosphorus removal, using the existing facilities without the need for new reactors neither implementing modifications that could put the trickling filters' physical integrity at risk. The novel treatment scheme could be applied in other cases with similar flowsheet in the same context.

Keywords: trickling filter retrofitting; modeling and simulation; anaerobic-anoxic biological reactor; nitrogen removal; enhanced biological phosphorus removal; integrated process

1. Introduction

Nitrogen and phosphorus are the main nutrient elements discharged along with wastewaters, whose presence in the receiving water bodies significantly contributes to eutrophication. The need for nutrient removal is pursued by stringent regulation for the protection of water bodies, such as Directive 91/271/EEC in Europe. In addition, due to the reviews of the water quality objectives, there is an increased number of areas being declared as sensitive to eutrophication which, therefore, require nitrogen and phosphorus removal from wastewater before it is discharged into such areas (European Union, 1991; European Union, 2000). This fact implicates a need for upgrades or retrofits of a significant number of wastewater treatment plants (WWTP) for nutrient removal. Conventional configurations for biological nutrient removal (BNR) require anaerobic and anoxic compartments, in addition to aerobic ones, which must be large enough to establish nitrification. This results in a substantial increase in the complexity of wastewater treatment configurations when compared to those needed for organic matter removal only.

Facilities based on trickling filters (TF) have been widely used in many countries for organic matter removal. TFs' inherent advantages include operational simplicity, resistance to toxic and shock loads, and low energy requirements (Daigger and Boltz, 2011). These features make TF facilities suitable for small and medium-sized communities, as the case presented in this paper. Many TF facilities have been upgraded because they have become undersized due to increasing influent loadings. Generally, these upgrades consist on incorporating suspended growth reactors, giving place to combined or coupled processes, such as the TF/solids contact (TF/SC) and the roughing filter/activated sludge (RF/AS) (Harrison, 2017). However, those processes are inherently aerobic processes, facing only organic matter removal and in some cases nitrification. Examples and studies about TF/SC and RF/AS processes are presented in Harrison et al. (1984), Harrison and Lum (1994) and Harrison (2017).

For total nitrogen removal, facilities must be upgraded for denitrification as well, which can be achieved by means of pre or post-anoxic suspended growth or biofilm reactors (Mehlhart, 1994). Vanhooren et al. (2003) observed that at high organic loading rates with insufficient oxygen supply to the biofilm, denitrification could be induced in TFs by providing the biofilm with external nitrate. Indeed, several full-scale case studies have been reported in the literature using TFs for denitrification. Dorias and Baumann (1994) reported three cases in Germany where TFs were modified for denitrification: the TFs were covered and the aeration openings were impounded. Successful results are presented, comparable to those obtained by pre-anoxic denitrification in the activated sludge process. Nasr et al. (2000) presented the upgrade of the WWTP of Salisbury (Maryland), in which a TF was flooded to provide anoxic conditions for denitrification. The preliminary tests results were successful, however, due to the lack of backwashing and air scour, the biofilm grew excessively and the desired denitrification performance was not achieved. Eventually, when the anoxic TF was drained to take it out-of-service, the media support collapsed due to the biofilm weight without the buoyant force of water in the tank. Manzano et al. (2018) presented the upgrade of a medium-sized WWTP in southern England, where a pre-denitrification submerged anoxic filter was installed downstream the primary settling and prior to the TFs. Different operational strategies were studied, achieving successful nitrogen removal. In a different approach, Dai et al. (2013) integrated pre-anoxic denitrification in a primary settling tank to enhance nitrogen removal in a TF facility. By recycling the nitrified effluent from the TF to the primary settling tank, an improvement of nitrogen removal was achieved through denitrification in the activated settling tank.

Regarding phosphorus removal, biological processes are preferred over chemical ones, due to the lower operational cost. Indeed, the application of innovative processes for chemical phosphorus removal from TF effluents, such as electrocoagulation, has shown not to be a feasible alternative to conventional processes (Stafford et al., 2014). Therefore, additional anaerobic tanks are needed for enhanced biological phosphorus removal (EBPR). Moreover, alternate anaerobic-aerobic/anoxic conditions are required to promote the growth of phosphate accumulating organisms (PAO), responsible for EBPR. Few studies have been found that address both nitrogen and phosphorus biological removal at full-scale TF facilities. Most of them have proposed the extension of the TF process with additional anaerobic, anoxic and aerobic activated sludge tanks (Christensen, 1991; Morgan et al., 1999) or converting the TFs into suspended growth reactors (Dichtl et al., 1994).

In the case study presented in this paper, the objective of the upgrading is to achieve nitrogen and phosphorus effluent standards, and the primary constraint for the process selection is the limited available space. It should also be considered that the WWTP serves a medium-sized community of fewer than 20,000 inhabitants, so that alternatives involving low investment and operating costs would be prioritized. In this framework, a number of alternatives were proposed and preliminarily analyzed in order to upgrade the existing facility to nutrient removal. The first alternative, consisting of post-anoxic denitrification in biofilters and chemical precipitation of phosphorus, corresponds to conventional and consolidated technology and makes it possible to reach a good quality effluent. However, the main drawbacks of this alternative are the implementation of an additional post-treatment, and the need for an external carbon source and chemical addition for denitrification and phosphorus precipitation, respectively. These facts would imply a high investment and operational cost.

Another alternative was pre-anoxic denitrification, which could be carried out in the first TF or in the primary clarifier. Those possibilities do not require an external carbon source addition and do not imply the construction of new tanks or reactors for nitrogen removal, but, as a drawback, phosphorus should be removed by chemical precipitation. In order to avoid the use of chemicals, and therefore reduce the operational cost, a plant extension including anaerobic suspended growth reactors was proposed, in order to provide alternating anaerobic-aerobic/anoxic conditions to promote the growth of PAO.

Specifically, the ultimate alternative proposed consists of a modification of the existing primary clarifier to host an anaerobic-anoxic sludge blanket reactor. The main goals of this alternative are to achieve BNR (i.e. no need for chemicals and low sludge production) and to reuse the existing facilities (i.e. no need for construction of new tanks or reactors). These goals entail a low investment and operational cost compared to conventional upgrade alternatives. In spite of the apparent suitability of such a process there is no literature in the state-of-the-art reporting similar configurations. The possibility of reusing primary clarifiers and converting them into activated anaerobic-anoxic reactors for biological removal is an alternative that, to our knowledge, has not been proposed or explored so far in attempts to upgrade TF facilities. In addition, the proposed modification is inspired in a patent of the authors (Tejero et al., 2010) that allows combining anaerobic-anoxic zones and clarifying functionality in the same reactor, which would cover the aforementioned proposed goals. If feasible, the proposed configuration could be applied in many other cases with similar flowsheet in the same context. Nonetheless, the hypothesis of achieving the proposed goals with the conversion of the primary clarifier to an anaerobic-anoxic reactor should be tested prior to full-scale implementation. A model-based approach is proposed for the feasibility evaluation and preliminary design of the facility upgrade. The capabilities of mathematical models for assessing and comparing different alternatives have proven their usefulness to make decisions about existing facilities' retrofits (Hvala et al., 2002; Mucha and Mikosz, 2016). Model simulations have been shown to be useful for the design, optimization and upgrading of WWTP, aiding to estimate the optimal design configuration, reactor sizes and operational strategies, and providing an estimation of the expected response (Daigger and Nolasco, 1995; Salem et al., 2002; Seco et al., 2004; Guerrero et al., 2011; Chen et al., 2018;

Kroiss and Klager, 2018). Furthermore, modeling is of particular interest in BNR processes due to the large number of interacting phenomena.

The objective of this paper is to assess the feasibility and to preliminarily design and optimize a novel process for the retrofitting of an existing TF WWTP to BNR, by means of mathematical model simulations. This study is a required preliminary step prior to the real full-scale implementation, in order to assess the feasibility of the proposed solution, avoiding or reducing the risk and uncertainty of classical and conventional design procedures. The configuration of this novel process consists of an anaerobic-anoxic sludge blanket reactor, hosted in the existing primary clarifier, followed by the existing TFs and clarifiers.

2. Methodology

2.1. Case study

The existing WWTP began operations in 2005. It serves a Spanish community with a population of approximately 15,000 inhabitants, discharging into the Ebro river basin. The wastewater treatment scheme, consisting of a two-stage TF process with intermediate clarification, is shown in Figure 1. The process consists of pretreatment (5-mm screening and grit removal), primary clarification, first stage TF, intermediate clarification, second stage TF and secondary clarification. The TFs are filled with a random plastic media type (specific surface area 100 m^2 m^{-3}; void space 95%), occupying a volume of 3,181 m^3 in each filter. The three clarifiers (primary, intermediate and secondary) are identical, with an individual volume of 1,823 m^3.

The influent and effluent annual average available data are summarized in Table 1. These values, provided by the public company Navarra de Infraestructuras Locales S.A. (NILSA, Gobierno de Navarra), were obtained from the operation of the WWTP during a whole year. Satisfactory organic matter removal and nitrification were achieved, while denitrification and phosphorus removal did not occur. The new discharge permit requires both nitrogen and phosphorus removal with an annual average effluent TN and TP concentration of 15 mg L^{-1} and 2 mg L^{-1}, respectively, according to European regulation Directive 91/271/EEC, for treatment plants of less than 100,000 population equivalent discharging into sensitive areas.

2.2. Process description

The proposed configuration is based on the reuse of the existing primary clarifier to accommodate an anaerobic-anoxic sludge blanket reactor, as depicted in Figure 2(A). The overall proposed treatment scheme, shown in Figure 2(B), claims that both nitrogen and phosphorus biological removal using the existing facilities avoids the construction of new tanks or reactors, does not require an external carbon source or chemicals addition, and does not imply modifications that could put the TFs' physical integrity at risk.

At first glance, the primary clarifier volume, with an average hydraulic retention time (HRT) of 8.4 h, seems to be large enough to hold the anaerobic and anoxic zones. The anaerobic-anoxic modified primary clarifier (MPC) would provide the environmental conditions needed for phosphate release and denitrification (with its corresponding uptake of organic matter), while the existing TFs would provide the aerobic stage for the removal of remaining organic matter, phosphate uptake and nitrification. Mainly, the first TF is aimed at organic matter removal and phosphate uptake, operating as a hybrid process (biofilm and suspended biomass coexisting in the same reactor), while the second filter is aimed at nitrification.

Coupling the existing TFs with a suspended biomass reactor (the MPC) leads to an integrated process. It has the additional advantage of enabling separate control of both the slower-growing nitrifying biomass, which usually prefers to reside on biofilms, and the faster-growing heterotrophic biomass including denitrifiers and PAO, which would reside in the suspended activated sludge. This feature facilitates the optimization of simultaneous nitrogen and phosphorus removal processes (Onnis-Hayden et al., 2011).

The modification of the primary clarifier is based on an anaerobic-anoxic sludge blanket reactor for BNR, named AnoxAn, which was proposed by Tejero et al. (2010). The AnoxAn reactor was conceived with the objective of unifying the anaerobic and anoxic zones of a wastewater treatment process for BNR in a single reactor, aimed at achieving high compactness and efficiency. A clarification zone at the top of the reactor avoids the escape of large amounts of biomass, thus promoting high sludge concentration in a sludge blanket type reactor. Moreover, simultaneous denitrification and phosphate uptake could be achieved. Overall, the AnoxAn configuration claims anaerobic phosphate release, anoxic denitrification and phosphate uptake in a single reactor. Its hydrodynamic and biological feasibility was demonstrated in an upflow AnoxAn prototype (Díez-Montero et al., 2015; Díez-Montero et al., 2016).

However, in this case study, due to the shape and dimensions of the primary clarifier (26 m diameter and 3.0 m depth), a concentric configuration was proposed instead of a vertically compartmentalized upflow reactor, which in addition is expected to provide a simplification of the hydrodynamic behavior. The primary clarifier modification can be implemented by means of a cylindrical inner wall dividing the clarifier into two different zones: (i) central anaerobic zone with a volume of 800 m^3, and (ii) outer anoxic zone with a volume of 1,013 m^3. The influent wastewater is fed into the anaerobic zone, where it is mixed with activated sludge recycled from the anoxic zone (anoxic recycle, AR). A submersible mixer would provide mixing in the anaerobic zone, and the mixed liquor would flow to the anoxic zone through openings in the upper part of the cylindrical inner wall. A nitrate rich stream recycled from the second TF (nitrate recycle, NR) would enter the anoxic zone together with the sludge recycled from the intermediate clarifier (return activated sludge, RAS), where submersible mixers provide intermittent mixing. The effluent would then be withdrawn through submerged outlet tubes. Underneath the outlet tubes, a set of lamellas would be assembled to provide a final clarification zone. The intermittent mixing in the anoxic zone would, therefore, cause settling cycles, which together with the lamellas, would aid to reduce the amount of biomass escaping from the MPC.

Inside the MPC, the biomass would alternate anaerobic and anoxic environmental conditions, so that denitrifying PAO would be promoted. Furthermore, a certain amount of activated sludge would be bypassed (sludge bypass, SB) from the anoxic zone to the first stage TF in order to provide aerobic conditions to the PAO and enhance the phosphorus removal efficiency. The simulated SB, expressed as a percentage of the influent flowrate, covered a range from 0 to 50%.

Finally, the inclusion of an aerobic zone in the MPC has also been considered, correspondingly reducing the available anoxic volume. This additional aerobic volume would be needed to improve the EBPR and to achieve the desired phosphorus removal efficiency. The aeration could be performed in a specific volume of the anoxic zone, by means of submerged air diffusers, therefore reducing the actual anoxic volume. Several aerobic volumes (AV) have been simulated, from 100 m^3 to 800 m^3 (accordingly reducing the anoxic volume), which correspond to 9.8% to 78.2% of the original anoxic volume. Besides, aeration could be carried out continuously or intermittently, depending on the oxygen demand. Therefore, the process would provide flexibility to control the addition of electron acceptors depending on influent characteristics.

2.3. Mathematical model

A model of the current secondary treatment WWTP was implemented in BioWin Process Simulator v4.0 (EnviroSim Associates Ltd., Ontario, Canada), as shown in Figure 3(A). The biological processes were described according to the BioWin General Model (ASDM), which has fifty state variables and sixty process expressions, including ordinary heterotrophic biomass activity under aerobic and anoxic conditions, nitrification (ammonium oxidation and nitrite oxidation), and enhanced biological phosphorus removal. For details on parameters description and process expressions, the reader is referred to the BioWin user manual (freely available on the internet).

A TF process flowsheet element is included in BioWin v4.0, which can be configured for various media packing types and characteristics. In the model, the depth of the TF is divided into three equal layers to simulate oxygen levels and removal gradients from top to bottom. The biofilm model used in BioWin is a 1D model as described by Wanner and Reichert (1996) and Reichert and Wanner (1997). For details on fundamental equations, the reader is referred to those documents. The settling tanks were implemented as ideal clarifiers. The influent wastewater characteristics were adopted from the available data, including total and soluble COD, TN, NH_4-N, NO_3-N, NO_2-N, TP and TSS. Further fractionation of the influent characteristics was obtained using the BioWin default parameters.

In this case study, typical municipal wastewater with negligible industrial contribution is treated in the WWTP, and the environmental conditions are not extreme. Within this context, it was expected that the default model parameters would not need to be significantly modified. Nonetheless, steady-state simulation results were compared with the annual average operational results of the WWTP shown in Table 1. Some model parameters were adjusted in order to improve the agreement between predicted results (simulations) and operating results in the existing secondary treatment, based on a trial and error method as in Simsek et al. (2012). Afterwards, the model was modified to represent the proposed upgrade for BNR, as shown in Figure 3(B), without modifying the model parameters neither the influent wastewater characteristics. In order to represent the physical upgrades, the primary clarifier was divided into two chambers to host the anaerobic and anoxic zones, or three chambers to host also the aerobic one. A final settling tank was included at the end of the MPC, to represent the clarification zone. The AR from the anoxic to the anaerobic zone and the NR from the second TF to the anoxic zone were set to 2 and 3 times the influent flowrate, respectively, while the RAS from the intermediate clarifier to the anoxic zone flowrate was set equal to the SB. The excess sludge waste was adjusted in order to achieve suitable biomass concentration in the MPC in the simulations, compared to conventional activated sludge systems, not exceeding TSS concentration of approximately 3 g L^{-1}. The biomass concentration in the MPC was kept reasonably similar in all the simulations, allowing to compare the different scenarios under similar conditions.

A set of steady-state simulations has been performed covering a range of different configurations and operational conditions: Run001-Run011 for different SB; Run101-Run188 for different combinations of additional aerobic volume (AV) and SB; and Run201-Run207 for different dissolved oxygen (DO) concentration in the additional aerobic zone, as shown in Table 2.

3. Results and Discussion

3.1. Simulation of the current WWTP

The steady-state effluent quality predicted by the model with the default values of the model parameters was slightly better compared to the effluent quality observed during operation of the WWTP. Therefore, five model parameters were adjusted in order to fit the real plant behavior: ammonium oxidizing bacteria maximum specific growth rate and half-saturation coefficient, ordinary heterotrophic organisms anoxic yield, phosphorus content in biomass, and phosphorus content in the endogenous residue, as shown in Table 3. Through this parameters adjustment, the model nitrifying and denitrifying activities and the biological phosphate uptake were reduced. Therefore, the adjusted model avoids overly optimistic simulation results, being on the safe side. Being aware that it cannot be considered a complete model calibration, the simulated effluent matched pretty well the real average effluent concentrations. The acceptance criteria were a difference lower than 5 mg L^{-1} for TSS, 10% for total and soluble COD, and 1 mg L^{-1} for NT, NH_4-N, NO_3-N, TP, as proposed in Water Environment Federation (2013). Default values of the biofilm model (number of biofilm layers, liquid boundary layer thickness, and attachment and detachment parameters) were kept unchanged, since there were no experimental data to adjust them and the simulation results fulfilled the acceptance criteria.

3.2. Performance of the anaerobic-anoxic modified primary clarifier with sludge bypass to the first trickling filter

The adjusted model was used to simulate the modified WWTP. It should be pointed out that the modified treatment train includes suspended growth reactors, but since there are not real operating results with suspended biomass, it has not been possible to calibrate the model parameters for such biomass. The proposed treatment train has not been implemented in the existing secondary treatment WWTP. Therefore, no experimental data regarding the novel treatment train are available. The previously adjusted parameters have been used in order to avoid overly optimistic results, remaining on the conservative side and keeping the uncertainty within the limits to provide trustworthy results.

The overall effluent quality obtained with the modified treatment train is displayed in Table 4, along with the MPC effluent nitrate concentration and the TSS concentration in the hybrid TF, and in the anaerobic and anoxic zones of the MPC. Satisfactory nitrogen removal was achieved with effluent TN concentration lower than 15 mgN L^{-1} in all of the simulated scenarios. Nitrate concentration in the MPC effluent resulted in being negligible ($<$ 0.1 mgN L^{-1}), confirming that pre-anoxic denitrification performed successfully in the MPC, which could be attributed to a sufficiently high anoxic HRT (4.7 h) with moderate suspended sludge concentration (up to 2,869 mgTSS L^{-1}). However, increasing the bypass of biomass from the anoxic zone to the first stage TF resulted in an increase of the effluent TN concentration. Effluent ammonium concentration rose from 2.9 mgN L^{-1} (Run001) to 6.6 mgN L^{-1} (Run011), denoting that nitrification was adversely affected. For this reason, configurations with SB above 50% of the influent flowrate were not simulated.

The lower nitrification efficiency obtained for higher SB is attributed to the increasing particulate and soluble COD concentration in the nitrifying TF influent (second stage TF). The importance of maintaining low influent suspended solids and biodegradable organic matter to achieve good performance in nitrifying TFs has been previously reported (Parker et al., 1989; Parker et al., 1995; Mofokeng et al., 2009; Dai et al., 2013). In these investigations, it has been suggested that the influence of influent biodegradable organic matter on nitrification is due to the development of a heterotrophic population, which competes with the nitrifiers for oxygen, thereby reducing nitrification rates. For instance, Parket et al. (1989) and Mofokeng et al. (2009) reported that influent biodegradable soluble COD concentration higher than 30 mg L^{-1} could promote such competition. The simulations showed that the influent biodegradable soluble COD to the nitrifying TF (second stage) ranged from 33.9 mg L^{-1} (Run001) to 38.5 mg L^{-1} (Run011), which are slightly higher than the threshold reported by Parker et al. (1989) and Mofokeng et al. (2009). The organic loading rate to the nitrifying TF was increased compared to the one obtained with the existing WWTP flowsheet. Such an increase, regarding biodegradable soluble COD loading rate, ranged from 2.5 (Run001) to 3.9 (Run011) times the loading rate in the existing WWTP, which was detrimental to nitrification. In addition, the BOD_5 and TKN volumetric loading rates recommended by the German standard for the dimensioning of TFs with nitrification were exceeded in the second stage TF in runs with SB above 15% (Run005-Run011), confirming the inability to perform successful nitrification (DWA, 2001). According to this standard, the dimensioning of trickling filters should sum the volumes corresponding to organic matter removal and nitrification, obtained with the relevant parameters 0.4 $kgBOD_5\ m^{-3}\ d^{-1}$ and 0.1 $kgTKN\ m^{-3}\ d^{-1}$, respectively.

Regarding phosphorus removal, the desired effluent TP concentration was not achieved in any simulation and was not improved by increasing SB. Negligible phosphate release in the anaerobic zone (results not shown) confirmed that EBPR would not take place. It is considered that the influent wastewater was not carbon deficient, according to the high C/N ratio (COD/TN=14), and the aforementioned excessive organic loading rate, so that the inability to achieve EBPR was attributed to the short HRT under aerobic conditions in the hybrid TF (first stage). Taking into account that the volume of water in a TF corresponds only to a thin layer trickling over the support media and the biofilm, the actual residence time of wastewater (and suspended biomass) in TFs is relatively low compared to other types of hybrid processes. For instance, the HRT in integrated fixed film activated sludge (IFAS) reactors corresponds to the total volume of the reactor, which is in the range of hours.

3.3. Performance of the anaerobic-anoxic modified primary clarifier with additional aeration and sludge bypass to the first trickling filter

In order to increase the aerobic HRT for the suspended growth biomass, an additional aerobic reactor should be included in the treatment train. Due to the large size of the primary clarifier and the excellent denitrification capability shown in the aforementioned simulations, the use of a section of the anoxic zone of the MPC to provide aerobic conditions is proposed. In order to represent the aerobic zone, an additional aerobic reactor has been included in the model next to the anoxic one, with a DO concentration of 2.0 mg L^{-1}. This alternative has been assessed in combination with the SB previously discussed. A range of combinations (AV – SB) was analyzed. Three-dimensional surface plots of the effluent TN and TP concentrations for each combination of AV and SB are shown in Figure 4. It can be observed that most of the scenarios analyzed fulfill the required effluent quality. The effluent TN, NH_4-N, NO_3-N and TP concentrations, NO_3-N concentration in the MPC effluent, and TSS concentration in the anaerobic zone, anoxic zone and hybrid (first stage) TF, for each simulation (Run101-Run188), can be found in Supplementary Information (Table S1).

Excellent nitrogen removal was obtained, with an effluent TN concentration lower than 15 mgN L^{-1} in all of the simulated scenarios. However, the extent of nitrification and denitrification varied depending on the AV – SB combination. Without the additional aerobic zone, it was previously discussed how nitrification was deteriorated as the SB was increased, due to an excessive organic loading into the nitrifying TF (second stage). This issue was improved by including an aerobic zone in the anoxic zone of the MPC, where a certain amount of organic matter was removed. An AV as small as 100 m^3 (corresponding to 9.8% of the original anoxic volume) was enough to reduce the biodegradable soluble COD loading rate into the nitrifying TF by 25.5% compared to the simulations without AV, as well as to fulfill the BOD_5 and TKN volumetric loading rates recommended by the German standard for dimensioning of TFs with nitrification (DWA, 2001). Larger AV volumes provided higher organic loading decreases. Furthermore, it was observed that an aerobic volume higher than 48.9% of the original anoxic volume had an adverse effect on denitrification, thereby increasing the nitrate concentration in the MPC effluent (up to 4.3 mgN L^{-1}) and the TN concentration in the overall effluent (up to 11.7 mgN L^{-1}). In such scenarios, denitrification was not complete, which was attributed to the reduced anoxic volume wherein the aerobic zone replaced more than 48.9% of the original anoxic volume. Under the conditions of the present case study, the minimum anoxic volume that guarantees suitable denitrification is 523 m^3, which provides an HRT of 2.4 h and corresponds to an aerobic occupancy of 48.9% of the original anoxic volume. Therefore, the implementation of large aerobic volumes is not recommended on account of the fact that the TN effluent quality is slightly deteriorated due to the reduction of denitrification ability.

Regarding phosphorus removal, effluent TP concentration exceeded 2 mgP L^{-1} in several runs, all of them characterized by low AV and/or low SB. This indicates that EBPR could not be achieved by means of only SB or only AV. When no additional AV was implemented, the EBPR failure was attributed to the reduced aerobic HRT provided for suspended biomass in the TF. On the other hand, when an excessively large AV was added, the increasing nitrate concentration in the anoxic zone due to incomplete denitrification led to nitrate recycle into the anaerobic zone, hampering or avoiding the occurrence of EBPR. Nonetheless, excellent phosphorus removal was achieved by the combination of AV and SB. The effluent TP concentration was reduced as both the AV and the SB were increased, and eventually, most of the scenarios analyzed provided an effluent TP concentration below 2 mgP L^{-1}. This effluent TP concentration came along with significant phosphate release in the anaerobic zone (results not shown), thus confirming the occurrence of EBPR, which was attributed to the increase of the aerobic HRT for suspended biomass, provided by the combination of the hybrid TF (first stage) and the additional AV included in the MPC.

Overall, a broad range of combinations of AV and SB was found to fulfill the required removal of both nitrogen and phosphorus (effluent TN and TP below 15 mgN L^{-1} and 2 mgP L^{-1}, respectively) using the existing facilities, without the construction of new tanks or reactors. This range is depicted in green in Figure 5. Moreover, there is an optimal range of combinations AV – SB able to achieve more restrictive requirements (effluent TN and TP below 10 mgN L^{-1} and 1 mgP L^{-1}, respectively), which is displayed in light green in Figure 5. In addition, biomass concentration in the anoxic/aerobic zone ranged between 2,475 and 3,107 mgTSS L^{-1}, which appears to be moderate enough to allow for a final clarification of the MPC effluent.

Finally, in order to optimize the aeration in the additional aerobic volume, further simulations have been performed reducing the DO concentration in the aerobic zone from 2.0 mg L^{-1} to 0.01 mg L^{-1} (Run201-207). The configuration implemented in Run140 (39.1% of AV and 30% of SB) has been selected as one of the optimal solutions and has been used as the basis for the following simulations. Results are depicted in Figure 6.

Excluding the simulations with 0.02 and 0.01 mg L^{-1}, it was observed that the effluent TN and TP concentrations were similar to those obtained with DO concentration of 2.0 mg L^{-1}. BNR performed successfully with DO concentration as low as 0.1 mg L^{-1}, while it was deteriorated when the DO was further reduced due to the loss of nitrification and the reduction of PAO activity, similarly to the simulations without aerobic zone. These results imply that the aerobic reactor could be operated with low DO concentration and support the viability of including the aerobic zone inside the anoxic zone by means of intermittent aeration of a partial volume of the anoxic zone. The DO concentration could be controlled to a low set point during the aeration period, thereby allowing oxygen transfer efficiency to be optimized and the energy requirement reduced, therefore reducing the operational cost of the additional aerobic zone.

4. Conclusions

The upgrading of an existing secondary treatment TF WWTP to achieve BNR is proposed and assessed through model simulations. The proposal is based on the modification of the existing primary clarifier to host an anaerobic-anoxic sludge blanket reactor, and therefore to provide the conditions required for BNR. By means of this facility upgrade, BNR resulted feasible by using the existing facilities in the current WWTP, without the addition of any new tanks neither implementing modifications that could put the TFs' physical integrity at risk. The proposed treatment train upgrade would be advantageous from the economic point of view, reducing both the investment and operational cost compared to conventional upgrade alternatives.

Nitrogen removal was successfully achieved in all the simulated scenarios, with TN effluent concentration below 15 mgN L^{-1}. The anoxic zone in the modified primary clarifier performed satisfactorily, and proper denitrification was maintained reducing the anoxic HRT up to 2.4 h. Further reduction of the anoxic volume led to incomplete denitrification.

Biological phosphorus removal was not achieved by solely alternating anaerobic and anoxic conditions. A reduction of the anoxic volume to host an additional aerobic zone in the same modified primary clarifier, in combination with the bypassing activated sludge from the anoxic zone to the first stage TF, in order to provide aerobic conditions to the PAO biomass, was found to achieve EBPR successfully. Several combinations of aerobic volume – sludge bypass obtained a TP effluent concentration below 2 mg L^{-1}, while maintaining excellent nitrogen removal. Furthermore, there is an optimal range of combinations of aerobic volume and sludge bypass able to achieve more restrictive requirements (effluent TN and TP below 10 mgN L^{-1} and 1 mgP L^{-1}, respectively).

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Figure captions:

Figure 1 - Wastewater treatment scheme of the existing WWTP

Figure 2 - (A) Primary settling tank modification to anaerobic-anoxic sludge blanket reactor, and (B) Wastewater treatment scheme of the WWTP upgrading for BNR

Figure 3 - BioWin flowsheet of: (A) the existing WWTP; and (B) the modified treatment train

Figure 4 - Simulated effluent TN (left) and TP (right) concentration for each combination of aerobic volume (AV) and sludge bypass (SB)

Figure 5 - Range of simulated combinations of aerobic volume and sludge bypass fulfilling the required effluent quality (green, TN < 15 mgN L^{-1} and TP < 2 mgP L^{-1}) and more restringing requirements (light green, TN < 10 mgN L^{-1} and TP < 1 mgP L^{-1})

Figure 6 - Simulated overall effluent TN, NH_4-N and TP concentration, MPC effluent NO_3-N concentration, and PO_4-P concentration in the anaerobic zone, versus DO concentration in the aerobic zone

Table 1 - Existing WWTP influent and effluent flow and concentration (annual average)

	Influent	Effluent
Flow rate (m^3 day^{-1})	5239	
Total COD (mg L^{-1})	524	43
Soluble COD (mg L^{-1})	204	32
TN (mg L^{-1})	37.3	24.7
NH_4-N (mg L^{-1})	21	0.6
NO_3-N (mg L^{-1})	0.1	21.3
NO_2-N (mg L^{-1})	0.0	0.4
TP (mg L^{-1})	4.7	3.2
TSS (mg L^{-1})	267	7

COD = Chemical Oxygen Demand; TN = Total Nitrogen;
TP = Total Phosphorus; TSS = Total Suspended Solids

Table 2 - Set of simulations performed to assess the feasibility of the modified WWTP and preliminary design and optimize the MPC

Run	SB (% of influent flowrate)	AV (% of anoxic volume)	DO in aerobic fraction of MPC (mg L^{-1})
001-011	0-50	0	-
101-188	0-50	9.8-78.2	2
201-207	30	39.1	0.01-2

SB = Sludge Bypass; AV = Aerobic Volume; DO = Dissolved Oxygen

Table 3 - Model parameters adjustment

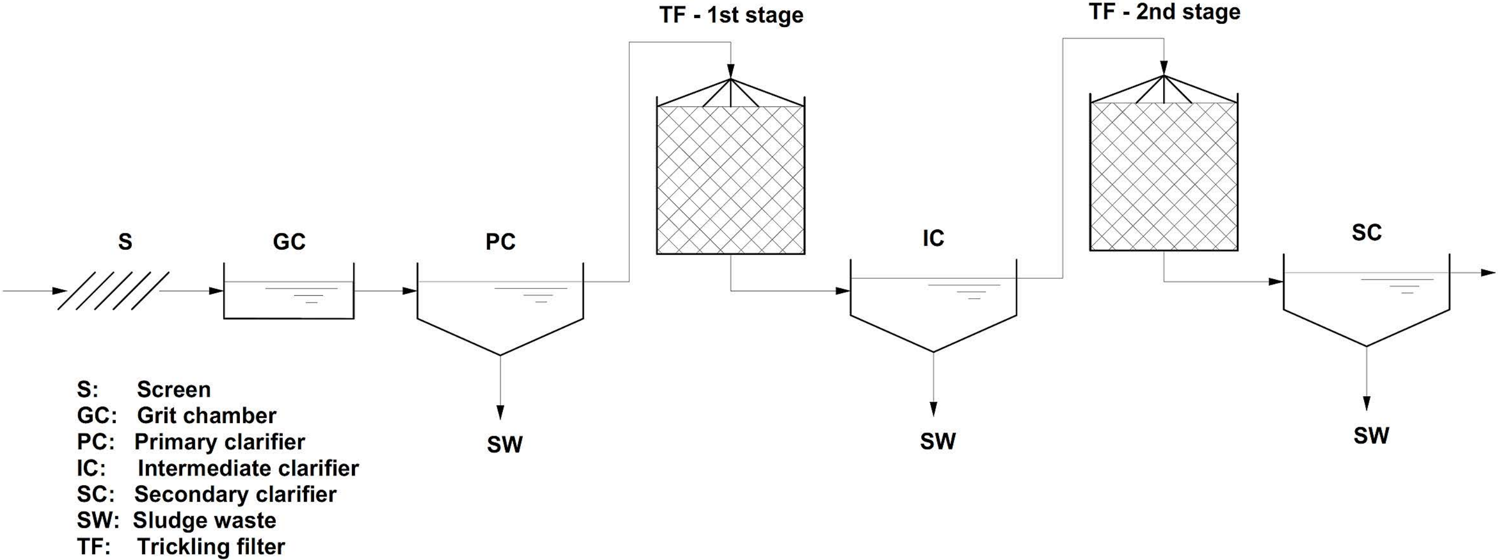
Model Parameter	Default value	Adjusted
OHO anoxic yield	0.54	0.90
P in biomass AOB, NOB, OHO (mgP mgCOD^{-1})	0.022	0.012
P in endogenous residue (mgP mgCOD^{-1})	0.022	0.012
AOB maximum specific growth rate μ (d^{-1})	0.9	0.5
AOB half-saturation coefficient K_N (mgN L^{-1})	0.7	1.0

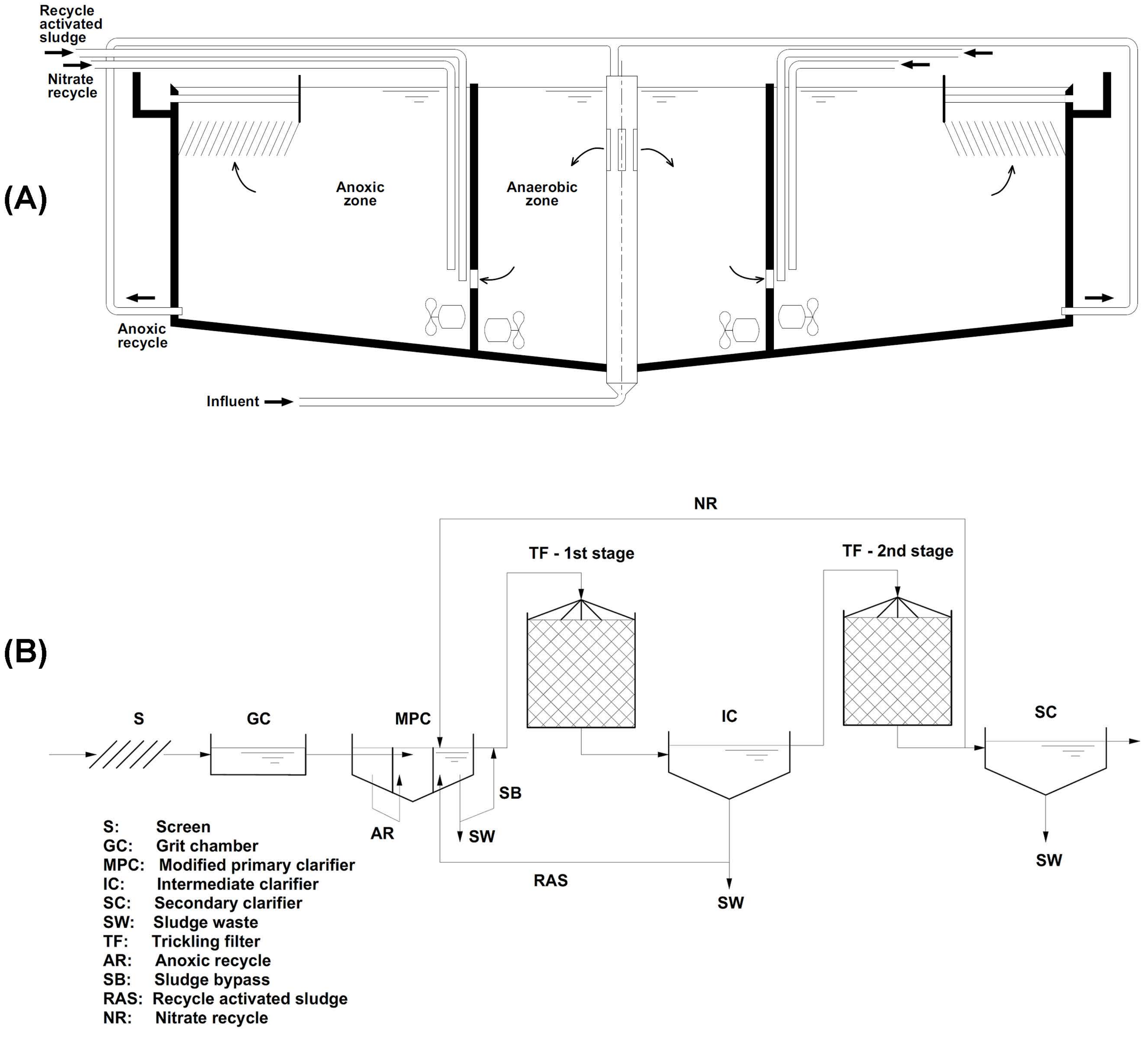
OHO = Ordinary Heterotrophic Organisms; AOB = Ammonia Oxidizer Bacteria; NOB = Nitrite Oxidizer Bacteria

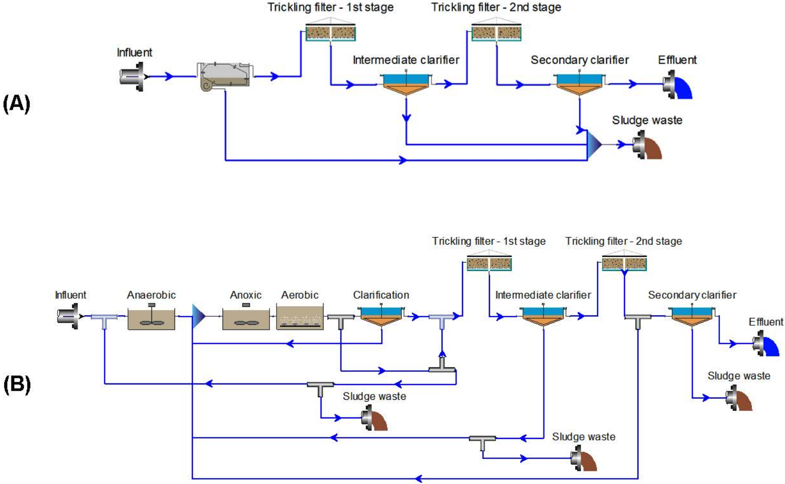
Table 4 - Simulated overall effluent quality, MPC effluent concentration of nitrate, and TSS concentration in the modified treatment train

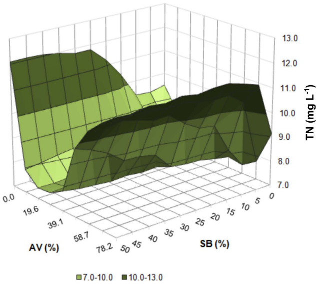
		Total suspended solids (mg L^{-1})			Overall effluent (mg L^{-1})						MPC effluent (mg L^{-1})
	SB (%)	Anaerobic zone	Anoxic zone	Hybrid trickling filter	Total COD	Soluble COD	TN	NH_4-N	NO_3-N	TP	NO_3-N
Run001	0	1959	2798	90	34.8	30.3	9.5	2.9	4.5	3.2	0.07
Run002	5	1838	2615	195	35.3	30.8	9.4	2.9	4.4	3.2	0.05
Run003	10	1917	2734	234	35.3	30.6	9.4	3.0	4.3	3.2	0.04
Run004	15	1950	2784	270	36.2	30.2	10.6	4.5	3.9	3.2	0.04
Run005	20	2001	2861	307	36.7	30.0	11.2	5.4	3.6	3.2	0.03
Run006	25	2007	2869	338	37.3	30.0	11.6	6.0	3.5	3.2	0.03
Run007	30	1987	2839	364	37.8	30.1	11.7	6.2	3.4	3.2	0.03
Run008	35	1952	2786	385	38.4	30.3	11.9	6.4	3.3	3.2	0.03
Run009	40	1908	2721	403	39.0	30.6	11.9	6.5	3.2	3.1	0.02
Run010	45	1860	2649	417	39.6	30.9	12.0	6.6	3.2	3.1	0.02
Run011	50	1810	2572	430	40.2	31.2	12.0	6.6	3.1	3.1	0.02

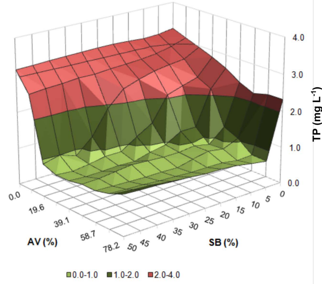
SB: sludge bypass from the anoxic zone to the first stage TF, expressed as percentage of the influent flowrate
MPC: modified primary clarifier

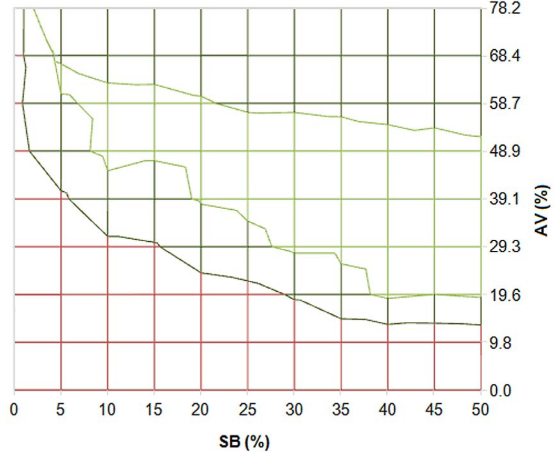

TF - 1st stage
TF - 2nd stage
S
GC
PC
IC
SC
SW
SW
SW
S: Screen
GC: Grit chamber
PC: Primary clarifier
IC: Intermediate clarifier
SC: Secondary clarifier
SW: Sludge waste
TF: Trickling filter

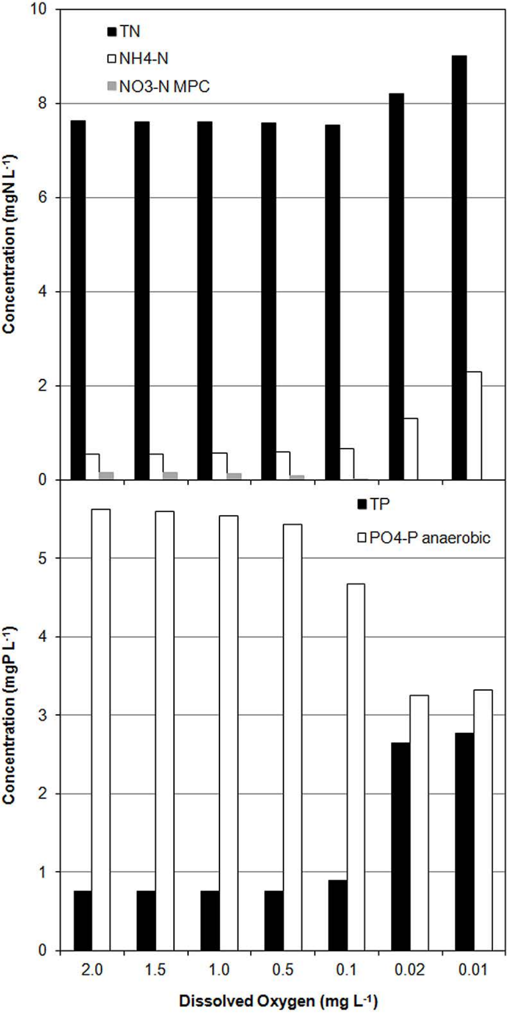

(A)
Recycle activated sludge
Nitrate recycle
Anoxic zone
Anaerobic zone
Anoxic recycle
Influent
(B)
NR
TF - 1st stage
TF - 2nd stage
S
GC
MPC
IC
SC
SB
AR
SW
RAS
SW
SW
S: Screen
GC: Grit chamber
MPC: Modified primary clarifier
IC: Intermediate clarifier
SC: Secondary clarifier
SW: Sludge waste
TF: Trickling filter
AR: Anoxic recycle
SB: Sludge bypass
RAS: Recycle activated sludge
NR: Nitrate recycle


(A)
Influent
Trickling filter - 1st stage
Trickling filter - 2nd stage
Intermediate clarifier
Secondary clarifier
Effluent
Sludge waste
(B)
Influent
Anaerobic
Anoxic
Aerobic
Clarification
Trickling filter - 1st stage
Trickling filter - 2nd stage
Intermediate clarifier
Secondary clarifier
Effluent
Sludge waste
Sludge waste
Sludge waste


13.0
12.0
11.0
10.0
9.0
8.0
7.0
TN (mg L^{-1})
0.0
19.6
39.1
58.7
78.2
AV (%)
50
45
40
35
30
25
20
15
10
5
0
SB (%)
🟩 7.0-10.0
🟩 10.0-13.0


4.0
3.0
2.0
1.0
0.0
TP (mg L^{-1})
0.0
19.6
39.1
58.7
78.2
AV (%)
50
45
40
35
30
25
20
15
10
5
0
SB (%)
🟩 0.0-1.0
🟩 1.0-2.0
🟥 2.0-4.0


78.2
68.4
58.7
48.9
39.1
29.3
19.6
9.8
0.0
AV (%)
0
5
10
15
20
25
30
35
40
45
50
SB (%)


10
8
6
4
2
0
TN
NH4-N
NO3-N MPC
Concentration (mgN L-1)
5
4
3
2
1
0
TP
PO4-P anaerobic
Concentration (mgP L-1)
2.0
1.5
1.0
0.5
0.1
0.02
0.01
Dissolved Oxygen (mg L-1)