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PERFORMANCE OF PREFABRICATED PACKAGE PLANTS FOR ON-SITE WASTEWATER TREATMENT IN THE VANSJØ- AND HOBØL WATERSHED (MORSA), NORWAY

Funksjonskontroll av minirenseanlegg i Vansjø- og Hobølvassdraget (Morsa), Norge

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 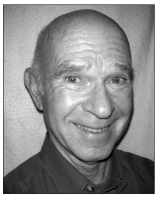   

Abstract

Prefabricated package wastewater treatment plants are increasingly used to treat on-site discharges in Norway. The performance of these plants, and their compliance with national and regional legislation, has been thoroughly evaluated. During 2006–2008 two separate studies investigated 91 on-site wastewater treatment plants, in the Vansjø- and Hobøl Watershed. The removal of organic matter was satisfactory with an average effluent concentration of 17.7 mg BOD_5/L. The removal of phosphorus did not satisfy discharge requirements with an average effluent concentration of 1.9 mg Tot-P/L. Insufficient phosphorus removal was caused by a variety of factors, such as; suboptimal pH for precipitation, suspended solids loss, insufficient sludge collection, low chemical dosage, equipment malfunction and insufficient maintenance. Many plants experienced unintentional nitrification. Chemical precipitation was effective for many plants even at very low pH values (pH 4 to 5).

Key words – On-site, wastewater, phosphorus, nitrogen, sludge, pH, precipitation, Morsa, watershed, eutrophication

Sammendrag

Prefabrikkerte minirenseanlegg blir stadig oftere benyttet for å rense avløpsvann i spredt bebyggelse i Norge. Disse anleggene er grundig vurdert mht. til ytelse sett i forhold til nasjonale og regionale utslippskrav. I perioden 2006–08 ble det gjennomført to separate studier hvor 91 spredte avløpsrenseanlegg i Vansjø- og Hobølvassdraget ble undersøkt. Reduksjon av organisk stoff var tilfredsstillende med en gjennomsnittlig utløps-konsentrasjon på 17,7 mg BOF_5/L. Fosforreduksjonen tilfredsstilte ikke utslippskravene med en gjennomsnittlig utløpskonsentrasjon på 1,9 mg Tot-P/L. Ikke tilstrekkelig fosfor-fjerning var forårsaket av forskjellige faktorer; ikke optimal fellings-pH, tap av suspendert stoff, ikke tilfredsstillende slamtømming, for lav kjemikaliedosering, feil på utstyr, samt ikke tilfredsstillende drift og vedlikehold. Mange anlegg hadde utilsiktet nitrifikasjon. Kjemisk felling var effektiv for en del anlegg, selv med meget lav pH (pH 4–5).

1 Introduction

In many areas throughout the world increased eutrophication in lakes is a common result of human activities. The sources of excess nutrients, such as nitrogen and phosphorus, in rural areas are mainly agricultural run-off and household wastewater. Phosphorus is often the limiting nutrient for algae growth in Norwegian lakes. To reduce phosphorus supply to vulnerable watersheds wastewater treatment is introduced, both by centralized wastewater treatment plant and on-site treatment systems.

There are numerous on-site wastewater treatment plant systems available for treatment of wastewater in rural areas (e.g. Leverenz et al., 2002). Excluding dry toilets and blackwater collection systems, on-site wastewater treatment systems may be divided in two main categories; Natural systems and Conventional systems. Natural systems consist of a variety of solutions that could be divided in two sub-categories; soil infiltration systems and constructed wetland systems (CW). The conventional solutions are downsized systems utilizing process configurations that are used in larger centralized wastewater treatment plants. Soil infiltration systems can be used in areas were soil hydraulic conditions are suitable (Jenssen et al., 2006), whereas both CW and Conventional systems can be used in areas with low to no hydraulic conductivity.

This article involves two separate studies; *i) Pilot study* (Johannessen et al., 2007), and *ii) Main study* (Johannessen et al., 2008). In the Pilot project also management aspects were discussed and effluent control was only a limited part of the study. The results found in the Pilot study justified further research, and this initiated the Main study. Both projects are discussed in this paper, but with major focus on results from the Main study.

2 Objectives

The objectives of the investigations were to examine a wide selection of on-site wastewater treatment plants already in operation, and to identify managerial, operational or process related problems that might affect the performance. It was not the intention of the study to range the different types of plants.

3 Materials and methods

3.1 Description of the study site

The Vansjø- and Hobøl watershed (traditionally and hereinafter referred to as Morsa) is located approximately 50 km south east of Oslo. The watershed has an area of 690 km^2, where 15 % is cultivated land and 85 % is mainly forest. There are about 40 000 inhabitants in the watershed. Lake Vansjø is the main water body with an area of ~36 km^2 and an average depth of 7.4 m. The lake is the water source for more than 60 000 persons. With its vicinity to densely populated areas, it also serves as a popular recreational resource.

Lake Vansjø has experienced increased eutrophication, and recreational use has been disturbed due to frequent algae blooms in summer. As a response to the deteriorating conditions in the lake several measures have been taken to reduce nutrient loads. In addition to actions directed to agricultural run-off, old septic tank systems are replaced with more sophisticated prefabricated package wastewater treatment plants. About 1600 such plants are installed in the watershed. As a supplement to national legislation and standards, local regulations in the Morsa watershed are implemented with effluent requirements of maximum 1.0 mg Tot-P/l and 25 mg BOD_5/l as annual average values (Morsa, 2007).

3.2 Plant types

There are 6 different types of plants that dominate in the Morsa watershed. Schematic drawing of each plant type in Figure 1 illustrate the different processes/systems. For the purpose of organic matter removal two of the plants employ aerated fixed film technology with forced aeration (A and B), another type of plant uses a gravel bed biofilter (C), one type is based on the rotating biological contactor process (E), and finally two types of plants are based upon the sequencing batch reactor (SBR) process (D and F).

Except plant C, all plants are originally developed for the purpose of removing organic matter only. To comply with requirements for P-removal the suppliers have added a chemical step using aluminum based chemicals for phosphorus precipitation. Plant C uses aluminum sulfate (Alum), and the other plants use pre-polymerized aluminum products (PAX21, Kemira). Plant A adds chemicals prior to the bioreactor, and plant B introduces chemicals to the sludge return line. Plant C adds chemical to a tilting bucket prior to the pre-settling tank. Plant E adds chemicals after the second contact chamber, at the inlet to the final clarifier. Plants D and F employ chemicals directly to the reaction chamber at the end of the aeration phase (before sedimentation phase). All plant types have either separate or built-in septic tanks for removal of coarse particles.

3.3 Sampling

The preferred method for sampling of effluent wastewater is in general flow proportional composite samples (e.g. USEPA 1982, Farestveit and Hoel, 1997 and WEF,

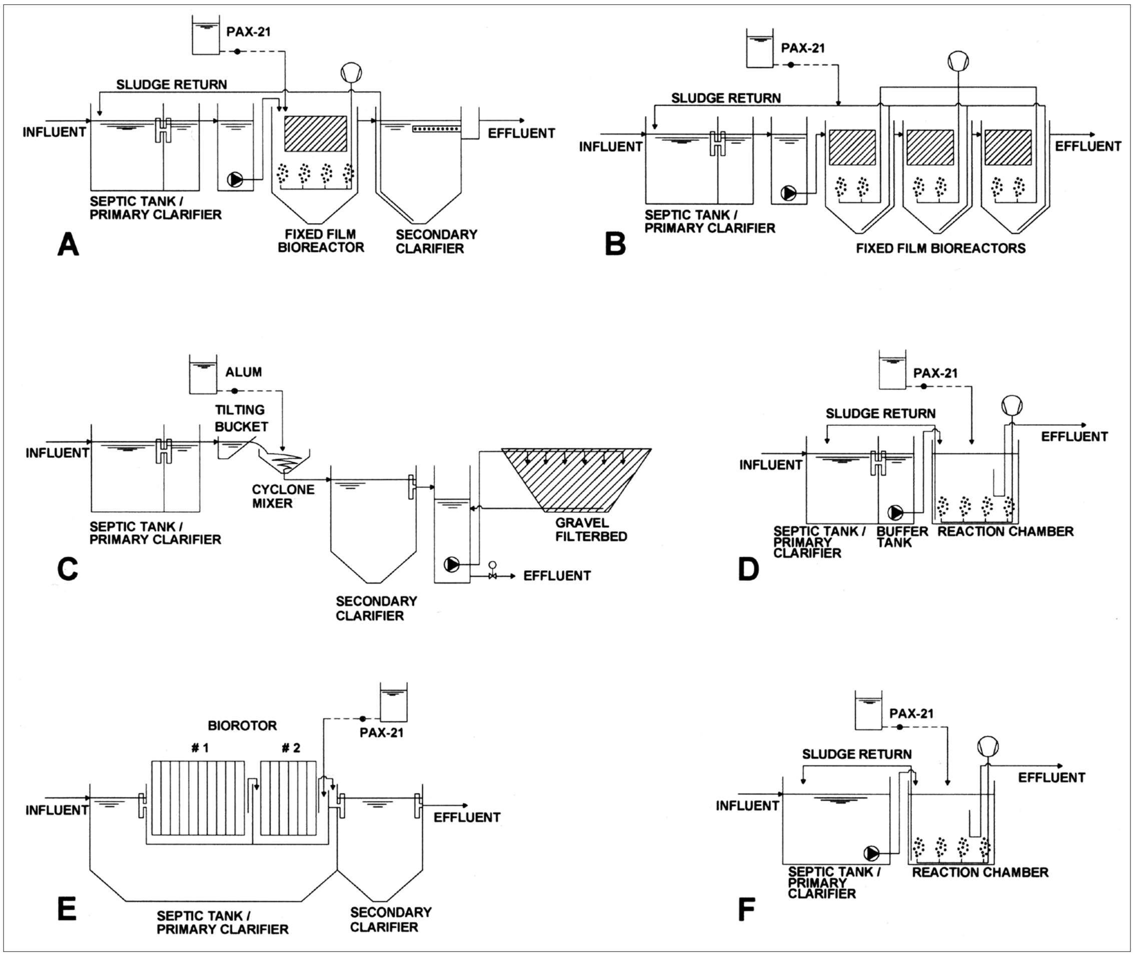

Figure 1. *Schematic drawing of processes for each plant type.*

1996). However, due to constraints in the design of these types of plants it is not feasible to use flow proportional composite sampling method, and thus grab samples were used. The grab sampling method used is later studied and found to sufficiently characterize the effluent of investigated systems (Johannessen et al., 2012). Sampling positions are shown in Figure 1. The samples were stored in cooler directly from sampling, and delivered to an accredited laboratory the same day (Analycen AS, Norway).

3.4 Analysis and measurements

In the Pilot study 24 plants were investigated. All plants were visited once, and pH, dissolved oxygen (DO) and temperature were measured in situ. The samples were analyzed at an accredited laboratory for the following parameters: Suspended Solids (SS), Chemical Oxygen Demand (COD), 5-day Biochemical Oxygen Demand (BOD_5), Total Phosphorus (Tot-P), Reactive phosphate (PO_4-P) and Nitrite/Nitrate Nitrogen (NO_2/NO_3-N).

In the Main study 90 plants were investigated, of which 23 of the plants were the same as in the Pilot study. The data comprises 200 samples with 2–6 samples from each plant. Half of the plants were analyzed for the same parameters as above, and in addition ammonia nitrogen (NH_4-N). For the remaining 50 % of the plants, only Tot-P and BOD_5 were measured. Temperature and pH were measured at 130 and 151 of the plant visits respectively.

Table 1. *Suggested influent on-site wastewater characteristics (mass and concentration) estimated from literature values (Johannessen et al., 2007).*

Parameter	g/pe*d	mg/l
Suspended solids (SS)	50	333
Biochemical oxygen demand (BOD_5)	50	333
Chemical oxygen demand (COD)	125	833
Total nitrogen (Tot-P)	12	80
Total phosphorus (Tot-P)	2,2	15
Water consumption (l/pe*d)		150

4 Results and discussion

4.1 Pilot study

Due to technical and practical constraints it is not possible to obtain representative influent samples of these small on-site systems. Literature values were therefore used to estimate influent loads, and hence influent wastewater characteristics were suggested as in Table 1 (Johannessen et al., 2007). These influent wastewater characteristics were used to evaluate the plants' performance in both studies.

The plants performance in terms of BOD removal was satisfactory. The effluent BOD_5 concentration ranged from 2 to 36 mg BOD_5/L with an average of 11 (+/–10) mg/L. Of the 24 plants investigated only 2 plants exceeded the required maximum of 25 mg BOD_5/L, with 35 and 36 mg BOD_5/L respectively.

In terms of phosphorus removal, the performance was not as satisfactory. The effluent Tot-P concentration ranged between 0.2 and 11.5 mgP/L with an average 3.3 (+/–3.0) mg Tot-P/L. Of the 24 plants included in the study, only 6 plants met the requirement of <1.0 mg Tot-P/L. The phosphate values were relatively high, with an average of 2.7 (+/–3.0) mgPO_4-P/L. This parameter, representing the soluble phosphorus fraction, varied between 0.1 and 11.0 mgPO_4-P/L. The PO_4-P to Tot-P ratio was relatively high, with an average of 82 %. Several causes were identified to be responsible for the inferior performance: *Suboptimal pH, too low chemical dosage, insufficient mixing of coagulant, insufficient flocculation and sedimentation, equipment malfunction* or *lacking coagulant*. These factors were also of interest in the Main study, and are discussed more in detail below.

4.2 Main study

The effluent BOD_5 concentration ranged between 2 to 195 mg BOD_5/L with an average of 17.7 (+/–36.1) mg BOD_5/L. Of the 90 plants investigated 74 plants (82 %) had in average effluent concentrations below 25 mg BOD_5/L, and the corresponding numbers for all individual samples where 163 out of 194 (84 %). The effluent COD concentration ranged from 30 to 260 mg COD/L with an average of 93.5 (+/–56.5) mg COD/L. The results are shown in Figure 2, displaying average effluent BOD_5 and COD concentrations of each plant.

Average effluent Tot-P concentrations for all plants in the Main study are given in Figure 3, and show that many of the plants do not comply with the local regulations. The average and median effluent concentrations were 1.9 (+/–2.7) and 1.0 mg Tot-P/L respectively. The variability of the results was substantial with maximum and minimum at 17.8 and 0.03 mg Tot-P/L respectively (individual samples). In terms of meeting the required effluent concentration (1.0 mg Tot-P/L) 47 of the 90 (52 %) plants were in compliance, when average values are concerned. For all individual samples the corresponding numbers were 105 out of 199 samples (53 %). The PO_4-P concentration was in average 0.4 (+/–0.8), yielding a PO_4-P/Tot-P ratio of 19 %. Effluent PO_4-P concentrations varied between 0.002–6.1 mg PO_4-P/L.

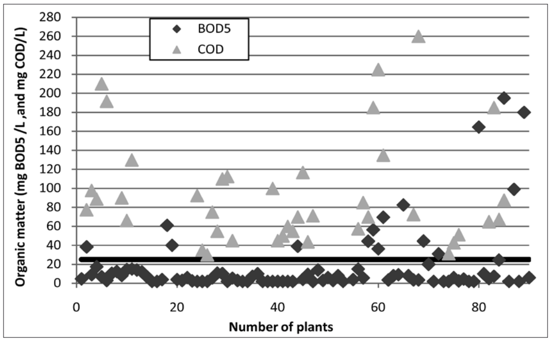

Figure 2. *Effluent average BOD_5 and COD concentrations for all plants in the Main study (black line indicates discharge limit; 25 mg BOD_5/L).*

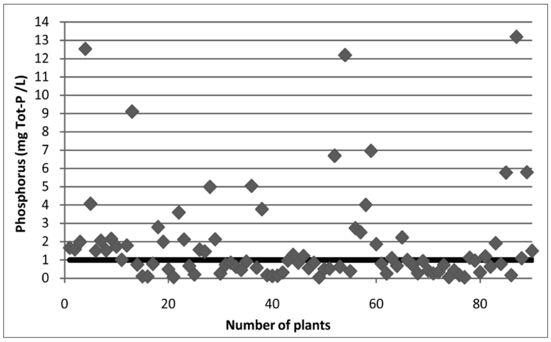

Figure 3. *Effluent average phosphorus concentrations for all plants in the Main study (black line indicates discharge limit; 1 mg Tot-P/L).*

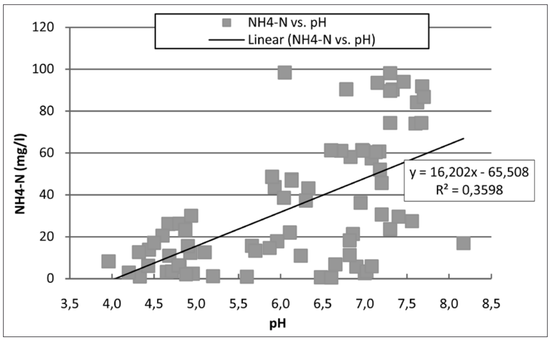

Figure 4. *Effluent NH_4-N concentrations as a function of pH.*

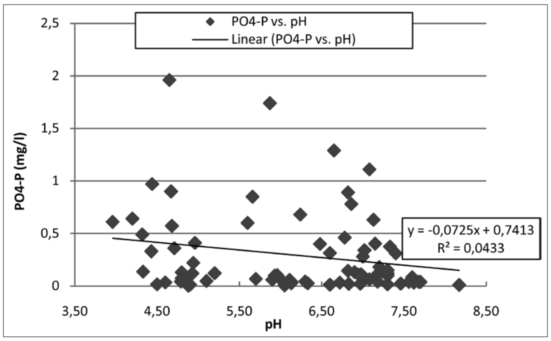

Figure 5. *Effluent PO_4-P concentrations as a function of pH.*

As a consequence of the findings in the Pilot study most suppliers increased their dosages substantially in the Main study. In the Pilot study the molar ratio (Al/P) given by the suppliers ranged from 0.7 to 1.7 for 4 of the six plant types investigated. This is substantially lower than experience in Norway from larger centralized plants show, where a mol ratio in the range ~2:1–3.5:1 is necessary to obtain satisfactory P-removal (Ødegaard et al., 1990; Ødegaard, 1992). The increase in dosage was not quantified in the Main study, but resulted in a substantial decrease in the PO_4-P /Tot-P ratio from 82 % to 19 %. This shows the importance of public attention and suggests that frequent effluent control can contribute to increased performance of the plants.

pH is a vital parameter in controlling chemical precipitation of phosphorus. A total of 151 observations showed that only 1/3 of the observations were in the optimal range, i.e. between pH 5.5 and pH 7 (Verpe, 1998; Hansen, 1997; Ødegaard et al., 1990; Ødegaard and Karlsson, 1994; Gillberg et al., 1996). About 1/3 of the observations had pH > 7, and 1/3 was < 5.5. This can be caused by overdosing of coagulant, nitrification in the biological treatment step and/or naturally low pH in the raw water. Nitrification is a process that consumes alkalinity, and with low buffering capacity in the wastewater this will subsequently result in decreased pH values. In Figure 4, the effluent NH_4-N is plotted as function of pH. There is just a very weak correlation between NH_4-N and pH, with lower values of NH_4-N for lower pH, possibly as a result of unintentional nitrification in the biological treatment step.

It is well known that the nitrification process is inhibited by low pH, and it is interesting to observe the low NH_4-N at pH levels below pH 5.5. It has been reported that the nitrification rate is only 10–20 % at pH 6 compared to pH 7 (Gujer and Boller, 1986; Tchobanoglous et al., 2003). More recent studies indicate however, that acidophilic bacteria of the *Nitrospira* and /or *Nitrosomonas* families also may have high nitrification rates under low pH conditions, even below pH 4 (Tarre et al., 2004; de Boer and Kowalchuck, 2001; Gieseke et al., 2006; Tarre and Green, 2004). In some plants the low pH could be explained by the fact that the coagulant was added directly to the effluent from the biological reactor. With most of the alkalinity used by nitrification, the wastewater has low buffering capacity to withstand the acidifying effect of coagulant dosage. Hence, the low pH might also be a combined effect of nitrification and chemical dosage.

The effluent PO_4-P concentrations as a function of pH is given in Figure 5, and it is interesting to see the relatively many observations with simultaneously low pH and low PO_4-P concentrations. Further, one can see there is no correlation between PO_4-P and pH, suggesting that the PO_4-P concentration is independent of pH. This is not in agreement with an optimum pH between 5.5 and 7. However, the solubility of aluminum phosphate has a minimum around pH 5 and quite stable between pH 4 and pH 6.5 (Leckie and Stumm, 1970). In addition, when investigating the effect of pH when precipitating orthophosphate with aluminum and iron salts, Gillberg et al. (1996) found that maximum PO_4-P precipitation appeared when the pH was between 4.5 and 5.5 with prepolymerized aluminum chloride as the precipitant. The average effluent wastewater concentration of 0.3 mg PO_4-P indicated that neither suboptimal pH, nor too low coagulant dose and poor mixing of coagulant were general causes for insufficient phosphorus removal in the Main study. The results therefore suggest that increased dosages had a positive effect on the treatment efficiency.

As opposed to larger centralized wastewater treatment plants sludge is not separated from the process train in on-site wastewater treatment facilities. In Norway the normal sludge collection frequency is 6–12 months depending of the size and type of plant. Sludge is stored

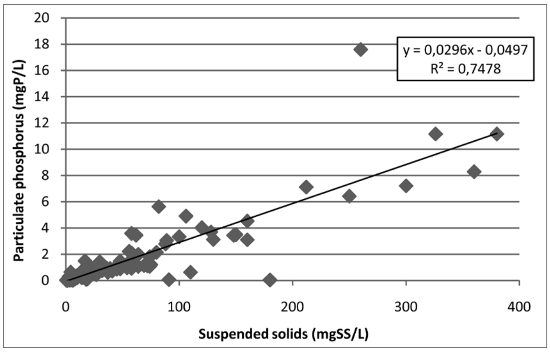

Figure 6. *Relationship between particulate phosphorus (P_{part}) and suspended solids (SS).*

in the primary settling tank and/or in a final clarifier. Increased coagulant dosage has two potential negative effects, if not accounted for in the design and operation of these plants: i) increased sludge production increases the risk of exceeding the sludge storage capacity, and ii) increased suspended solids concentration yielding decreased separation capacity. The first challenge must be met by increased sludge collection frequency (or larger storage capacity). The collection intervals were not changed, i.e. the increased sludge production was never followed up, neither by the suppliers nor the municipalities responsible for sludge collection. The second challenge could result in loss of suspended solids and subsequently loss of associated P, as none of the plants were rebuilt to meet the higher solids overflow rates.

Effluent suspended solids (SS) concentrations were also investigated. Combined with Tot-P and PO_4-P this parameter provides information on the plants solids separation capacity. A high concentration of suspended solids will normally also give high concentration of P in the effluent, regardless of proper coagulation. There was a large variety in the suspended solids concentration, both between the plant types, and within each type. The average effluent SS concentration of the plants varied between 2.5 and 231 mg SS/L, with a mean concentration of all observations 57 (+/–78) mg SS/L. The highest individual effluent suspended solids concentration was 380 mg SS/L.

Particulate phosphorus (P_{part}) can roughly be defined as the difference between Tot-P and PO_4-P. In Figure 6 P_{part} is shown as a function of SS. The scatter plot shows a distinct relationship between particulate phosphorus and suspended solids. Combined with the low PO_4-P/Tot-P ratio, this suggests that most phosphorus in the effluent wastewater is present as particulate fraction. It is therefore much likely that many of the high effluent Tot-P observations were a result of increased sludge production and/or increased bulk water suspended solids concentration, with subsequent sludge loss due to either limitations in the separation capacity or sludge storage.

Many studies have shown that phosphorus leaches from anoxic sediments in lakes and from sewage and manure-amended soils in agriculture (e.g. Gächter et al., 1988; Rydin, 1996; Berkowitz et al., 2005; Ortuno et al., 2000; Lake et al., 2007; Elliot et al., 2002; Hooda, 2000; Fine, 1996). It is therefore a possibility that some of the precipitated phosphorus might be re-solubilized due to biological degradation and/or chemical reactions in long term sludge storage in the plants. More data however, is necessary to fully understand and quantify this potential problem for package treatment plants.

None of the plants investigated were designed for nitrification or nitrogen removal. The nitrogen parameters were measured to evaluate nitrogen transformation and how that affected other processes. In average for each plant type the effluent NH_4-N ranged between 16 (+/–16) and 69 (+/–27) mg NH_4-N/L. Correspondingly; NO_2/NO_3-N ranged between 36 (+/–20) and 110 (+/–77) mg NO_2/NO_3-N/L. A measure of the extent of nitrification can be the nitrate fraction of total nitrogen, where high values indicate nitrification. The average nitrate fraction, as (NO_2/NO_3-N) / (NO_2/NO_3-N + NH_4-N), for each plant type ranged between 0.52 (+/–0.36) to 0.65 (+/–0.30) for 5 of the plants (B–F), indicating significant nitrification in these plants. The last plant (A) had a nitrate fraction of 0.03 (+/–0.06) suggesting no nitrification.

Low nitrate concentrations do not automatically mean that no nitrification is occurring in the plants. It may also indicate that nitrification is accompanied by denitrification. The sum of effluent NO_3-N and NH_4-N ranged from 6.5 mg/L to 198 mg/L for all plants. This variation can be a result of different influent loads. For plant types A, B, D and F where wastewater cycling occurs, mixing organic rich influent wastewater (carbon source) with treated and possibly nitrified water/sludge, can provide favorable conditions for denitrification. In the case of the RBC plant (E) denitrification probably occurred in settled sludge in the post sedimentation tanks. This hypothesis was supported by floating chunks of sludge in the post sedimentation tank that could be a result of rising N_2-gas.

5 Conclusions

Prefabricated package plants demonstrated an overall good removal of organic matter, with effluent BOD_5 concentrations well below discharge requirements.

Phosphorus removal improved when more coagulant was added, and demonstrated that prefabricated package plants for on-site wastewater treatment have the capacity to meet effluent requirements, when operated properly. Based upon assumed influent concentration at 15 mg Tot-P/L the effluent concentrations represent average removal efficiency for all plants of 88 %.

The results of the Main project demonstrated substantial improvement compared to the Pilot study. Chemical precipitation of PO_4-P was significantly improved when comparing the results of the Pilot project with the Main project. This is a direct result from actions undertaken by the suppliers, where they amongst others had increased chemical dosing and changed dosing points. The results from the Pilot study created much attention both within the industry and in the public eye; hence the level of attention is considered an important factor in maintaining good performance of these types of plants.

Increased chemical dosing resulted in increased sludge production and increased suspended solids concentration. This reduces the available storage capacity elevating the risk for solids loss. Increased sludge production should therefore have been followed up by shorter interval between sludge collections or increased storage volume. This was not done, and is therefore assumed to be one of the main causes for high effluent Tot-P concentrations in some plants.

Many plants are operated beyond optimal pH range for chemical precipitation. The results suggest that this is a result of nitrification in combination with increased chemical dosing, and might have had influence on phosphorus removal in some plants.

Substantial nitrification was found in many plants, and also denitrification in plants with some kind of water/sludge recirculation. This indicates that nitrogen removal can be obtained relatively simply in some of the plant types by just increasing the recirculation. This is important in areas where also nitrogen emissions have to be reduced.

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