Controlling a combined lagoon/reed bed system using the oxidation-reduction potential (ORP)

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Abstract Lagoon systems achieve good and stable effluent data in regard to organic pollutants, but they charge the receiving waters with relatively high ammonium loads. Therefore an existing lagoon-plant was extended by a vertical flow reed-bed for the special purpose of nitrification. This paper presents the efficiency of the combination plant as well as the possibility to monitor and control the reed-bed operation by the oxidation-reduction potential (ORP). The results show that the combination plant achieved excellent purification results, the average efficiency degrees were 97% for COD, 77% for N\textsubscript{total} and 94% for the TKN elimination. The ORP in the effluent of the reed bed showed a clear dependence in its characteristic course and its absolute values on the current nitrification performance, the oxygen supply and the hydraulic behaviour of the reed bed. Therefore the ORP is a very good indicator for the state of the reed bed, which ultimately results from the accumulation of a large number of different influencing parameters. As the preservation of aerobic conditions in the reed bed is the crucial prerequisite for a high nitrification performance and for the avoidance of clogging, the ORP thus offers the possibility of immediate operation control.

Keywords Vertical-flow reed beds; wastewater lagoons

Introduction

Lagoon plants are a widespread method of wastewater treatment all over the world. They are regarded as robust and inexpensive, and they achieve very stable purification results. The results are particularly good in regard to the carbon degradation. However, nitrification occurs only to a low degree (Kunst and Kayser, 2000). NH\textsubscript{4}-N effluent values considerably exceeding 20 mg/l are not infrequent (Schleypen and Wolf, 1983; Racauld et al., 1995). In the context of increasing demands for completely nitrified effluents even from small wastewater treatment plants (Cooper, 1999), lagoon plants must be improved particularly in regard to the ammonium load discharged into the receiving water. As vertical-flow reed beds are known as very effective regarding nitrification (Laber, 1997; Cooper et al., 1997; Platzer, 1998) an existing old lagoon plant was combined with a vertical-flow reed bed.

The currently valid calculation methods for the design of reed beds in Germany are based on the area demand per person (ATV A262, 1998). Only the carbon degradation is formulated as a purification target in this context. Examination of the dimensioning of vertical-flow reed beds for a complete nitrification show that a limitation of the ammonia surface loading rate alone does not provide for a sufficient dimensioning criterion. For instance, the hydraulic load, the method of operation, and the type of filter sand are additional influencing factors (Platzer, 1998; Laber, 2001). It is generally agreed that the oxygen balance in the reed bed has a key position for the nitrification process. Thus, Platzer (1998) developed a dimensioning approach for vertical-flow reed beds on the basis of oxygen supply and oxygen demand. In case of sufficient oxygen supply, the oxidation of the organic pollutants and of the ammonium can be guaranteed. Furthermore, another decisive
aspect is that the preservation of the aerobic conditions in the filter is the crucial prerequisite to avoid clogging of the filter (Platzer and Mauch, 1997; Müller and Lützner, 1999). However, it is difficult to estimate the oxygen transport in the filter. There are several approaches to the calculation of the oxygen input (Schwager and Boller, 1997; Platzer, 1998). Because of the complex processes influencing the gas flow in a reed bed with intermittent operation, these approaches are based on strongly simplified assumptions or are clearly dependent on the conditions of the examined plants. Generally, one has to state that currently it is not possible to make any definite statements about up to which hydraulic or substantial loads at which temperatures a complete nitrification is reachable.

One central target of the three-year examination of the combined lagoon/ reed bed plant at “Ettenbuettel” was thus the optimisation of the plant in regard to its nitrification performance. The nitrification ability of the reed bed should be fully exploited, but without overcharging the filter. Therefore it should be evaluated whether the conditions in the reed bed can be monitored by a parameter that can easily be measured, in order to create the chance of immediate operation control. The emphasis of the analyses was on the observation of the Oxidation-Reduction Potential (ORP), which is a measure of the activity of the oxidised and reduced substances in a system. As all biological conversions of the elements C and N are ultimately redox reactions, the knowledge of the ORP should allow for the diagnosis of the processes in the system.

Methods

Figure 1 shows the general design of the combined plant at “Ettenbuettel”. The first stage is the settlement pond, the second step is a facultative lagoon. The effluent of this lagoon is conveyed by a pump into the vertical-flow reed bed (VF), which is divided into two parts of the same size (VF1/VF2).

The size of the reed bed was designed at 2.25 m²/PE, which is rather small for the combined sewage from the village (average wastewater amount about 200 l/(PE*d)) and therefore requires a high hydraulic load. The filter is fed intermittently. The treated wastewater is discharged from the VF into the receiving water or can be pumped back into the settlement pond. Apart from intermediate storage, the recirculation serves to achieve a better purification, particularly a better de-nitrification. A third lagoon provides a sufficient buffer volume for the necessary water-volume management. During the first 2 years of operation of the filter (10/99–10/01), a wide range of hydraulic loads up to 290 mm/d were tested. For each test setting, the influent and effluent loads and the specific conversion rates were determined. In the effluent of the VF, the ammonium and oxygen concentration, the ORP, and the pH value are measured continuously and recorded online. The evaluation of the interdependencies of the parameters and of their relation to the operation settings was to
yield insights into the suitability of single parameters as control or regulation parameters for the optimal utilisation of the nitrification ability of the reed bed.

Results and discussion

Influent quality of the reed bed

The influent concentrations to the VF fluctuate considerably due to the fact that at the “Ettenbuettel” plant storm sewage is being treated. The COD concentration in the influent of the VF ranges between 57 and 376 mg O₂/l, which leaves the median at a value of 176 mg O₂/l. The median value of the TKN concentration is 36 mg/l and fluctuates between 17 and 56 mg/l. The TKN consists of two parts of ammonium nitrogen and one part of organic nitrogen. The nitrate nitrogen concentration is almost constantly below 0.23 mg/l. The average amount of suspended solids was 50 mg/l TSS. Peaks of up to 167 mg/l TSS were measured particularly during the summer months in cases of heavy algae growth.

The nitrification performance of the vertical flow reed bed

Figure 2 shows the hydraulic loading and the development of the ammonium concentrations in the influent as well as the ammonium and nitrate concentrations in the effluent of the reed bed (to simplify matters all results and operation modes presented in this chapter are related to one half of the reed bed (VF2)).

After the initiation of the plant in October 1999, both the ammonium effluent and the influent concentrations increased considerably when the temperatures dropped in November. The maximum NH₄-N effluent concentration measured in the winter of 1999/2000 was 18 mg/l. After that, there occurred a slow but constant decrease of the NH₄-N influent and effluent values up to the middle of April 2000, which saw a minimal NH₄-N concentration in the effluent of 2 mg/l. The following slight increase of the effluent concentrations can definitely be traced back to a reduced infiltration capacity. Because of this slight clogging of the filter, the operation of both filter parts was stopped alternately for a few weeks. After this operation break, up to the middle of November 2000 NH₄-N effluent values below 1 mg/l were measured almost constantly. Simultaneously, during this period the nitrate effluent concentrations were about equivalent to the ammonium influent concentrations, which speaks for a very well aerated filter with high nitrification performance and accordingly low de-nitrification potential. From the middle of November 2000, this situation changed. There occurred a strong increase of the ammonium concentration in the VF effluent up to a maximum value of 29 mg/l NH₄-N at the end of January 2001. The

![Figure 2 Temporal development of the NH₄-N and NO₃-N concentrations in the effluent of VF2](https://iwaponline.com/wst/article-pdf/48/5/167/423467/167.pdf)
respective nitrate effluent concentrations were below 2 mg/l. In this operation situation of the filter (which had to be regarded as particularly problematic) once again a clogging of the filter surface could be observed. The following decrease of the ammonium effluent concentration was supported by a low loading and the regeneration of the bed in 2 short operation breaks. Since July 2001, there has been a situation with ammonium effluent concentrations below 1 mg/l NH₄-N comparable to that of the summer of 2000, despite at times extreme hydraulic loads of up to 290 mm/d.

The nitrification capacity of the reed bed is influenced by several parameters. One crucial influence is the temperature. This becomes obvious in Figure 3 which shows the correlation of the nitrification rates to the TKN surface loading rate and the wastewater temperature.

The figure shows that:
1. The nitrified nitrogen load increases linearly with ascending TKN surface loading at wastewater temperatures over 10°C. A permanent nitrification performance of approximately 90% can be achieved.
2. The nitrification performance decreases if the wastewater temperature drops below 10°C. At temperatures between 5 and 10°C, still about 70% of the TKN influent load was nitrified.
3. Below 5°C, the average nitrification performance is still at 50%, although the results fluctuate considerably.

Within the examined loading range between approximately 1 and 8 g TKN/(m²*d), no influence of the TKN surface load on the nitrification performance can be observed. Within the single “temperature classes”, influences of other parameters on the nitrification can be shown. Particularly the C/N ratio and the hydraulic load seemed to have an important impact, which, however, changes with the seasons. For instance, in winter the hydraulic load capacity is reduced compared to summer time. Furthermore, the preliminary load of the filter and its degree of clogging are crucial for the current load capacity. The exact influences and dependencies will not be discussed in detail in this paper. Instead, the following will show to which degree the condition of the filter (which is a result of the accumulation of a large number of single influences) can be monitored and controlled.

Dependencies between ORP and nitrification performance
In the effluent of the VF “Ettenbuettel”, the ammonium and oxygen concentration, the ORP, the pH-value, and the flow-rate are continuously measured and recorded online. The
different parameters are documented in order to understand the dependencies and correlations between them. The main result was that the ORP in the effluent of the reed bed is clearly dependent on the current nitrification performance and the oxygen supply of the reed bed. Figure 4 shows the clear correspondence between the ORP (daily average values) and the current nitrification performance of the reed bed.

Thus, the ORP is on a lower level in phases of low nitrification performance, whereas in periods of decent nitrification performance positive ORP values are measured. Interesting is the examination of the phases with extreme hydraulic loads in the summers of 2000 and 2001. Then, an initial decrease of the nitrification performance went along with a marked decrease of the ORP level. This dropping of the ORP value gives an early warning of the overcharging of the filter.

The daily progression of the data recorded online also confirms the correlation between ORP and ammonia concentration. Figure 5 presents the data for two exemplary days with different loads. The ORP as well as the concentration of oxygen in the effluent of the reed bed decreased instantly after each feeding on the 11/8/00 at the following times: 3 am, 9 am, 3 pm, and 9 pm. A minimum ORP value is always accompanied by a maximum ammonium concentration. Between the feedings, the oxygen concentration and the ORP increase to their initial values. On days with a higher hydraulic loading (as on the 23/7/00), the ORP maxima prior to each new feeding continuously decrease throughout the day; this phenomenon is accompanied by a corresponding continuous increase of the ammonia concentration maxima. This shows that in this situation the intensity of the reducing milieu conditions in the filter increases. In regard to operation monitoring, in such a situation one has to check whether the ORP settles after some days on a constant level or whether it decreases any further and drops below a defined critical value.

**Control and operation concept for the lagoon/reed bed plant using the ORP**

From the above results, it can be derived that the ORP in the effluent of the reed bed shows a distinct dependence on the current nitrification performance and oxygen supply of the reed bed in its characteristic course and in its degree. Thus, the ORP is a suitable control parameter for an efficient operation of the reed bed. For the plant at “Ettenbuettel”, it was defined after the evaluation of the data that the plant can be run without problems at any possible load as long as the respective value does not decrease under the critical ORP value of 0 mV (reference system Ag/AgCl). If it does drop below this value, this indicates an overload situation which can lead to a clogging of the filter. In such a case, the load must be
reduced or there must be an operation break for the respective part of the reed bed. This value of 0 mV must be regarded as specific for the plant at “Ettenbuettel”, as the absolute values of the ORP depend strongly on the respective wastewater quality and the operation conditions. Thus, it is not possible to state any universally valid values which show the good condition of reed beds. If the ORP in the effluent of a reed bed is to be used as a control parameter, it is recommended to go at first for an observation of the occurring potentials in relation to the purification results. Of particular importance, apart from the absolute ORP values, is the daily course of the ORP curve in relation to the feeding. For instance, a strong decrease of the ORP after a feeding followed by a fast increase of the value shows an undis-
turbed oxygen transfer into the reed bed.

One special feature of a combined lagoon/reed bed plant is that the buffer volume in the lagoons allows for water volume management. For the optimal utilisation of the current purification capacity of the entire plant, at “Ettenbuettel” it was possible to develop an overall control concept via the ORP-measurement in the effluent of the reed bed and a water level measurement in the lagoons. The ORP was thus used not only to monitor and control the state of the filter, but also to regulate the hydraulic load. The feeding of the reed bed was started for a duration of 20 minutes whenever the ORP exceeded a value of 100 mV. The recirculation pump was controlled in relation to the water level in the lagoons (that means in relation to the available storage volume). This form of plant management was

Figure 5 Daily progression of ammonia concentration, oxygen concentration and ORP in the effluent of the vertical-flow reed bed (date: 11/8/00 – hydraulic loading 80 mm/d; date: 23/7/00 – hydraulic loading 136 mm/d)
successfully tested in the last months of the research project. Over this time, the reed bed was fed with high hydraulic loads of up to 290 mm/d, without any increase of the NH$_4$-N concentrations in the effluent (cf. Figure 2). At the same time, the N$_{\text{total}}$ elimination of the entire plant could considerably be increased via the increase of the recirculation ratio.

**Purification capacity of the combined treatment plant**

In order to ultimately evaluate the efficiency of the combination of a lagoon plant with a vertical-flow reed bed, Figure 6 shows the average efficiency degrees (related to the loads) for the parameters COD, TKN, and N$_{\text{total}}$. The ratios for the lagoons and the reed bed are shown separately. Thus, the average efficiency degree for the COD is very high, reaching a value of 97%. The N$_{\text{total}}$ elimination amounted to 77% in the entire plant, the nitrification performance TKN elimination 94%. The lagoons alone achieved for the COD an elimination of 80%, for N$_{\text{total}}$ 63% and a nitrification performance (TKN elimination) of 60%. This shows that – as expected – the extension by the reed bed can be regarded as very effective, particularly in regard to the increase of the nitrification performance.

**Conclusions**

The combination of an unaerated lagoon system with a vertical-flow reed bed can be evaluated as very effective in regard to the reduction of the ammonium discharge into the receiving water. The combination plant achieved excellent purification results – in the first 2 years of operation, the average efficiency degrees were 97% for COD, 77% for N$_{\text{total}}$ and 94% for the average nitrification performance (TKN elimination).

Even at high loads (hydraulic load up to 290 mm/d, TKN surface load up to 7.9 g/(m$^2$*d)), the vertical-flow reed bed achieves excellent nitrification results, which are mainly influenced by the wastewater temperature:

- $T > 10^\circ$C: nitrification performance about 90%
- $5^\circ$C $< T < 10^\circ$C: nitrification performance about 70%
- $T < 5^\circ$C: nitrification performance about 50%

Apart from the temperature, operational parameters such as hydraulic load and C/N ratio influence the nitrification performance. Furthermore, the preliminary load and degree of clogging have a crucial impact. However, these influences cannot be formulated as clearly as the temperature impact. For instance, in winter the hydraulic load capacity is reduced compared to summer time.

The ORP in the effluent of the reed bed shows a clear dependence in its characteristic

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**Figure 6** Efficiency degrees of the combination plant (and the respective ratios of the lagoons and the reed bed) for the parameters COD, N$_{\text{total}}$ and TKN

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course and its absolute values on the current nitrification performance, the oxygen supply and the hydraulic behaviour of the reed bed. Therefore the ORP is a very good indicator for the state of the reed bed, which ultimately results from the accumulation of a large number of different influencing parameters. As the preservation of aerobic conditions in the reed bed is the crucial prerequisite for a high nitrification performance and for the avoidance of clogging, the ORP thus offers the possibility of immediate operation control. If – as in the combined lagoon/reed bed plant – water volume management is possible, the reed bed can be fed directly in relation to its capacity via regulating the hydraulic load by the ORP. In this way, the nitrification ability of the reed bed can be fully exploited, but without overcharging the filter.

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