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Decrease in the trophic status of a second-order oligotrophic stream (Zbytinský Potok) by a new wastewater treatment plant with two low-loaded stabilisation ponds

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Abstract
In recent years, the importance of wastewater treatment in small municipalities has risen as the pollution from agriculture has decreased. A typical example is the municipality of Zbytiny, which requires higher wastewater treatment efficiency than usual for a village of its size. This is because of the occurrence of freshwater pearl mussels in the Blanice River. The wastewater treatment plants (WWTP) designed for municipalities up to 500 inhabitants are efficient for treating organic pollution, but their treatment efficiency for total nitrogen and phosphorus is relatively low. Therefore, a unique solution was chosen in Zbytiny; two low-loaded stabilisation ponds, connected in a series, were built in addition to a new mechanical biological WWTP. These stabilisation ponds are used to post-treat wastewater discharged from the WWTP. The results from two years of regular monitoring clearly show a positive influence of these stabilisation ponds on total treatment efficiency. The best results from post-treatment in the stabilisation ponds were observed for total nitrogen and phosphorus, which showed treatment efficiencies of 38% and 88%, respectively. The water quality in the Zbytinský Potok stream is now closer to the biotope required by freshwater pearl mussels. Furthermore, the nutrient loading of the lower part of the Blanice River has decreased. Today, only nitrate concentrations and conductivity are higher in the stream below the village than above; however, the values are much lower than before the construction of the WWTP.

Key words: freshwater pearl mussel, WWTP, wastewater, stabilisation ponds, treatment efficiency, Blanice

Introduction

The Blanice National Natural Monument (NNM) is the most important location in the Czech Republic for the protection of freshwater pearl mussels (*Margaritifera margaritifera* L.). Here, in the Blanice River, the mussel population is the most numerous and genetically varied in the Czech Republic (Absolon & Hruška 2000) and Central Europe (Machordom et al. 2003). This location is part of a rescue program for freshwater pearl mussels in the Czech Republic (Švanyga et al. 2012), and detailed information on this species' biotope requirements has been described. Almost all populations of freshwater pearl mussels in the Czech Republic (Simon et al. 2006) and Central Europe (Geist 2010) are threatened by the excessive trophic status of the waters they inhabit. The Blanice River, together with the Teplá Vltava River, represents locations with the lowest disturbance of the species' biotope (Simon et al. 2006, Simon 2007). In recent years, a significant decrease in nitrogen and phosphorus loading was measured in the Blanice River (Bílý & Simon 2007, Douda et al. 2007), though some inflows and lower parts of the stream are still not suitable biotopes for *M. margaritifera* (Švanyga et al. 2012, Simon, unpubl. results). The lower part of the Blanice NNM, where the species was originally found, now has unsuitable water quality. This area includes the Zbytinský Potok stream and the main flow of the Blanice River from this inflow to the end of the NNM. The improvement of water quality is one of the most important tasks of the Management Plan of the Blanice NNM for the years 2000–2010 (Majer 2000). This task is made difficult by the high requirement of this species for water quality. The ideal biotope for the freshwater pearl mussel is characterised by several parameters: conductivity of 50 μs.cm^{-1}, concentrations of NO_3-N below 0.6 mg.l^{-1} and concentrations of total phosphorus below 15–30 μg.l^{-1} (Bauer 1988, Absolon & Hruška 1999). For example the conductivity increases precipitation of very fine particular organic matter (VFPOM <40 μm), which is used by the freshwater pearl mussel as a nourishment. WTTPs for small municipalities (population of 500 or less) are not designed to remove nitrogen and phosphorus, because Czech laws do not require their removal.

The concentrations of dissolved nutrients in major upper parts of catchments in South Bohemia have been decreasing over the long-term period. This is caused by the reduction in arable land and less intensive agricultural management (Kvítek et al. 2009). A positive trend of decreasing loads of non-point sources has also been observed in the Blanice River (Simon, unpubl. results); however, this trend must be combined with the elimination of pollution from local municipalities. The largest municipality in the observed locations is the village of Zbytiny. The water chemistry of the lower part of the Blanice River is not in line with the typical biotope required by freshwater pearl mussels and includes increased concentrations of nitrogen (especially nitrates) and total phosphorus. Additionally, the conductivity and other salt concentrations are high.

In 2002, a proposal for treating wastewater from the village of Zbytiny was prepared. At the time, there were no sewerage systems, and most of the wastewater was disposed of by distributing septic tank contents to the local fields. The Zbytinský Potok stream was polluted by only a small amount of these wastewaters, which occurred predominantly by infiltration and illegal discharges into the stream. When a sewerage system with a classic WWTP, with a common treatment efficiency removal of approximately 60%, was constructed, there was a huge risk of increasing the total nutrient loads, in mineral form, in the Zbytinský Potok stream. The system was designed with the participation of the Water Research Institute and consisted of a WWTP with two low-loaded stabilisation ponds. These ponds also serve to receive rainfall overflow from the sewerage system as a buffer zone for potential sludge leaks and, as a result of the low water levels, they are also able to accumulate approximately three months of wastewater in case of a WWTP failure.

In contrast to constructed wetlands, stabilisation ponds are able to reduce the concentrations of nitrogen and phosphorus, given a sufficient retention period (Toe et al. 2005, Mlejnská et al. 2009). Many processes are involved in decreasing these concentrations, such as sedimentation (Valero et al. 2010) and diffusion over the water level (Rockne & Brezonik 2006). Nitrogen and phosphorus concentration decreases are also often caused by infiltration to the bottom of the stabilisation pond (Lund 1999).

Today, the use of low-loaded stabilisation ponds is uncommon. Stabilisation ponds are used in direct wastewater treatment in fully developed countries (Porges 1963) and in developing countries (Gloyna 1971). In the fully developed countries with higher water quality requirements, stabilisation ponds are commonly used as a tertiary treatment (Maynar 1999). But in most cases, stabilisation ponds have eutrophic and hypertrophic characteristics (Bode et al. 1998). Despite their high treatment efficiency, the use of low-loaded stabilisation ponds to improve total treatment efficiency to reach higher-than-average quality is almost never mentioned in the literature (Gloyna 1971, Mara et al. 1987, Maynar et al. 1999, Walmsley & Shilton 2005). Furthermore, in a detailed project researching constructed wetlands and stabilisation ponds in the Czech Republic, only ponds with high water trophic status were found (Mlejnská et al. 2009). Low temperatures during the winter are often mentioned as a key condition for the use of stabilisation ponds (Schneiter et al. 1983, Rockne & Brezonik 2006).

Four years of observation were necessary to determine the influence of the village on the water quality: 2 years before the WWTP installation and 2 years after the WWTP was operational. This period included data variations resulting from regular fluctuations in nitrogen concentrations in small-flow streams (Webb & Walling 1985) as well as phosphorus variations (Heckrath et al. 2008). The data from the period before the WWTP was built were available from long-term monitoring of the water quality, which has been in progress in the Blanice NNM since 2000 (Bílý & Simon 2007).

The aim of this article is to present the treatment efficiency of the new WWTP with low--loaded stabilisation ponds in connection with the improving water quality in the Blanice River. We also discuss the possibility of using this system in the Bohemian Forest and other colder upper part of catchments with high requirements for wastewater treatment efficiency.

Materials and methods

Location description

The village of Zbytiny is situated in the southern part of Bohemia, between the cities of Prachatice and Volary. The Zbytinský Potok stream flows through the village of Zbytiny and then flows into the Blanice River. The locations of the WWTP and sample profiles are shown in Fig. 1.

A solution for treating wastewater in the municipality of Zbytiny was proposed in 2008. The Zbytiny WWTP was projected for 450 population equivalent (PE) with a designed discharge of Q_{24} 67.5 m^3 per day. It was put into operation in November 2008.

The Zbytiny WWTP (Fig. 2) is equipped with mechanical pre-treatments consisting of fine screens and sand catchers. The biological part of the plant consists of two parallel lines. The water divider allows for the operation of just one of the water lines, but both lines are currently in operation. Each line consists of an anoxic and an oxygenated part, divided by the barrier. The anoxic part of the aeration tank is mixed by two coarse-bubble elements.

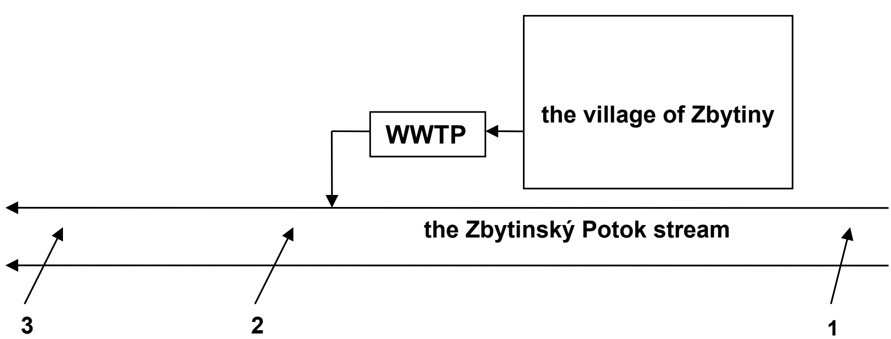

Fig. 1. Scheme of observed locations. Sample profiles of the Zbytinský Potok stream: 1 – above village, 2 – beyond WWTP effluent, 3 – outfall into the Blanice River.

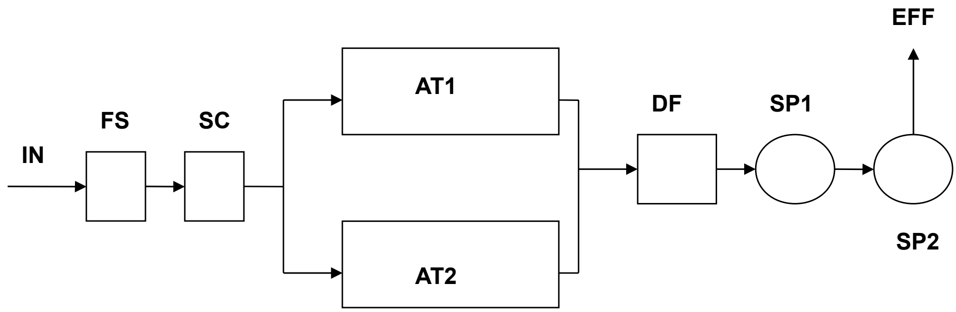

Fig. 2. Scheme of the Zbytiny WWTP. IN – influent (sample profile WWTP influent); FS – fine screen; SC – sand catcher; AT1, AT2 – aeration tanks with secondary clarifiers; DF – micro-screen drum filter (sample profile WWTP effluent); SP1, SP2 – stabilisation ponds; EFF – effluent (sample profile SP2 effluent).

The oxygenated part is separated by the barrier and aerated with 15 fine-bubble elements. The sludge separation is ensured by two built-in clarifiers in the oxygenated zones. Micro-screen drum filters for eliminating sludge leaks are located beyond the outflows from both clarifiers.

Sampling and analyses

The WWTP in the village of Zbytiny was monitored at regular one-month intervals during the two-year period from November 2008 through November 2010. Two-hour mixed samples (consisting of 8 simple samples taken every 15 minutes) were sampled in the profiles: WWTP influent, WWTP effluent, and the effluent from the second stabilisation pond into the Zbytinský Potok stream. Terrain measuring devices (WTW Company) were used for measuring basic technological parameters, including pH, conductivity, and dissolved oxygen in the stabilisation ponds. Samples were analysed in the technological laboratory of the T.G. Masaryk Water Research Institute. The following parameters were analysed according to Pitter (2009): chemical oxygen demand (COD, dichromate method); biochemical oxygen demand (BOD_5); suspended solids (SS); total nitrogen (TN, Kjeldahl method), NH_4-N, NO_2-N, NO_3-N; total phosphorus (TP), and PO_4-P.

Basic chemical parameters were used to determine levels of organic, nitrogen and phosphorus pollution. The water quality of the Zbytinský Potok stream has been regularly monitored since 2003 by a special monitoring program for the Blanice NNM. Simple samples were taken monthly. Terrain measuring devices (Hach-Lange Company) were used to assess basic parameters in the surface waters, including pH, conductivity, and temperature.

The samples were taken in compliance with the appropriate ISO/EN/CSN standards and transported to the laboratory in cooling boxes. The samples were analysed in the laboratory within 24 hours of collection. Monthly water data from the 2-year period before the WWTP became operational were used to evaluate the situation prior to the WWTP installation.

Results

The average values of each parameter measured from the individual profiles are shown in Tables 1 and 2. Since beginning operation, the Zbytiny WWTP maintains stable results without any notable variations in treatment efficiency. The efficiency results correspond with those expected for the size category and designed parameters of the WWTP. The best results were observed for removing organic pollution, represented by COD and BOD_5. For total

Table 1. Average values of chemical parameters in the observed profiles (November 2008–November 2010).

Profile	COD (mg.l^{-1})	BOD_5 (mg.l^{-1})	SS (mg.l^{-1})	NH_4-N (mg.l^{-1})	NO_3-N (mg.l^{-1})	TN (mg.l^{-1})	TP (mg. l^{-1})	PO_4-P (mg.l^{-1})
WWTP inflow	514	258	194	47.6	0.86	71.9	8.2	5.4
WWTP Effl.	46.4	6.4	9.0	2.12	22.4	25.9	2.9	2.8
SP2 Effl.	32.4	5.3	11.9	0.21	14.6	16.2	0.36	0.26

Table 2. Average treatment efficiency in the observed profiles (November 2008–November 2010).

Profile	COD (%)	BOD_5 (%)	SS (%)	NH_4-N (%)	NO_3-N (%)	TN (%)	TP (%)	PO_4-P (%)
WWTP Infl. - WWTP Effl.	91.0	97.5	95.4	95.6	<0	64.0	63.9	50.5
WWTP Effl. – SP2 Effl.	30.2	16.9	–32.8	90.3	34.8	37.3	87.8	90.3
WWTP Infl. – SP2 Effl.	93.7	97.9	93.8	99.6	<0	77.4	95.6	95.2

nitrogen (TN) and total phosphorus (TP), only 60% removal efficiency was reached. The WWTP is able to nitrify inflowing ammonia pollution to nitrate nitrogen; however, it was not designed for complete denitrification of nitrate into nitrogen gas. Additionally, the removal of phosphorus is limited in biological systems. For higher phosphorus removal efficiency, it is necessary to add a solution of iron sulphate for chemical precipitation. It is important to point out that, for this size of WWTP, the complete removal of nitrogen and phosphorus is not required by law.

For advanced treatment, treated wastewater is led through two serially connected stabilisation ponds, located behind the wastewater treatment plant. These stabilisation ponds were built together with the WWTP. They were originally filled with water from the Zbytinský Potok stream, but the only influent now is the discharged wastewater from the WWTP. These ponds function to improve the final efficiency of wastewater treatment. In case of an operation halt in the WWTP, wastewater can be collected in the stabilisation ponds. Thus, the stabilisation ponds serve to prevent the discharge of untreated wastewater directly into the Zbytinský Potok stream.

The two stabilisation ponds greatly improved the total treatment efficiency during the first two years of operation (cf. Tables 1 and 2). The highest treatment efficiency was achieved for total phosphorus, its average concentrations in the WWTP effluent (2.9 mg.l^{-1}) were significantly reduced (0.3 mg.l^{-1}) in the second stabilisation pond effluent (Fig. 3). The stabilisation ponds were also able to remove residual ammonia nitrogen and partly remove nitrate nitrogen. A different situation occurred for organic pollution. Low treatment efficiencies for COD, BOD_5, and suspended solids were observed. Surprisingly, increased concentrations were observed in the second stabilisation pond effluent compared to the WWTP effluent (Fig. 3). However, this was explained by the fact that the concentrations of organic pollution discharged from the WWTP were very low. Moreover, phytoplankton developed in the stabilisation ponds in the vegetation period in response to the high concentrations of nitrogen and phosphorus discharged from the WWTP. The concentrations of chlorophyll *a* reached values higher than 200 µg.l^{-1} during the spring and summer months. However, the phytoplankton was eliminated by the subsequent growth of zooplankton, especially *Daphnia magna*, in the stabilisation ponds, which caused a decrease in chlorophyll *a* below 10 µg.l^{-1}. This cycle of phytoplankton expansion and elimination during the spring

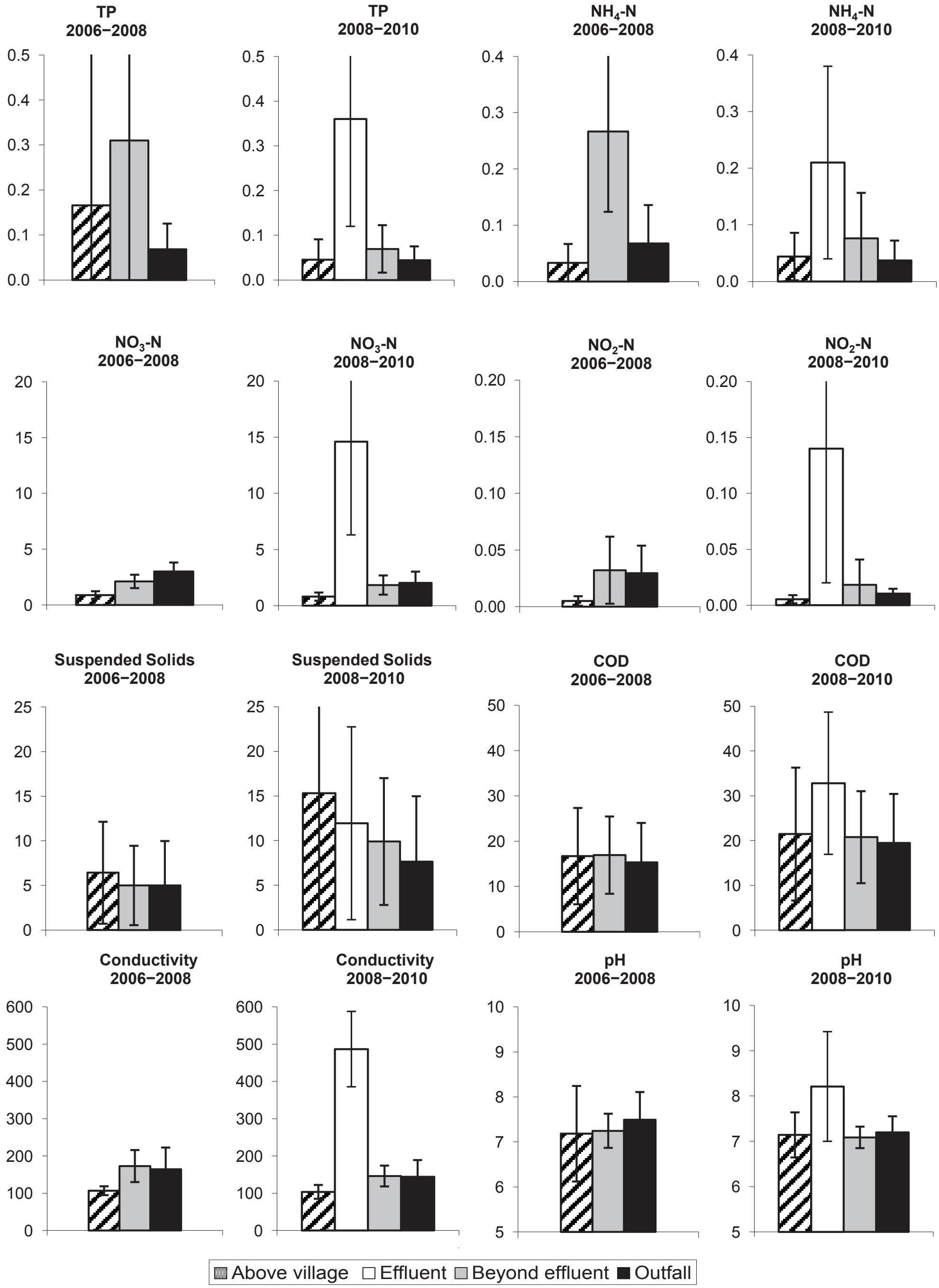

Fig. 3. The changes in the average concentrations of selected parameters in the Zbytinský Potok stream and in the effluent from the second stabilisation pond during the two-year periods before and after beginning WWTP operation. Scales are in $mg.l^{-1}$ for all graphs, except for the pH scale, and $\mu S.cm^{-1}$ for conductivity. bars represent standard deviations

Table 3. Average values and standard deviations (±SD) of pollution in the observed profiles (November 2006–October 2008).

Profile	COD (mg.l⁻¹)	SS (mg.l⁻¹)	NH_4-N (mg.l⁻¹)	NO_3-N (mg.l⁻¹)	TP (mg.l⁻¹)
Zbytinský Potok stream – Above Village	16.7±10.6	6.4±5.7	0.03±0.03	0.9±0,3	0.17±0.6
Zbytinský Potok stream – Below village	16.9±8.5	5.0±4.5	0.27±0.14	2.1±0.6	0.31±1.0
Zbytinský Potok stream – Outfall	15.4±8.7	5.0±5.0	0.07±0.07	3.0±0.8	0.07±0.1

Table 4. Average values and standard deviations (±SD) of pollution in the observed profiles (November 2008–November 2010).

Profile	COD (mg.l⁻¹)	SS (mg.l⁻¹)	NH_4-N (mg.l⁻¹)	NO_3-N (mg.l⁻¹)	TP (mg.l⁻¹)
Zbytinský Potok stream – Above village	21.5±14.8	15.3±35.6	0.04±0.04	0.81±0.36	0.05±0.05
Zbytinský Potok stream – Below village	20.8±10.3	9.89±7.11	0.08±0.08	1.84±0.86	0.07±0.05
Zbytinský Potok stream – Outfall	19.5±10.9	7.65±7.32	0.04±0.04	2.03±1.16	0.04±0.05

and summer months was observed three times in the second year of monitoring. Because of these cycles, the values of BOD_5 measured in the effluent from the stabilisation ponds varied from <3 $mg.l^{-1}$ to 12 $mg.l^{-1}$. This also caused the values of suspended solids in the effluent to vary substantially, from 2.4 $mg.l^{-1}$ up to 21 $mg.l^{-1}$.

Tables 3 and 4 show the change in pollution concentrations before and after the WWTP began operation. From 2006–2008, the concentrations of COD and SS were lower than those measured during the 2008–2010 time period. More importantly, during the 2008–2010 time period (when the WWTP was operational), we observed a significant decrease in nutrient concentrations, particularly in ammonia nitrogen and total phosphorus. In addition, the variability in the ammonia nitrogen and total phosphorus concentrations significantly decreased (Fig. 3).

We did not observe a simultaneous increase in concentrations of NO_3-N and conductivity with the elimination of loads of total phosphorus, NH_4-N, and NO_2-N. The WWTP reached high treatment efficiency (77%) for total nitrogen. The total concentrations of NO_3-N were influenced by loading into the stream between the above-village and below-village profiles (cf. Tables 3 and 4). This was determined because the increase in the NO_3-N concentrations between these profiles is permanent. When the WWTP was put into operation, the values of NO_3-N below the village remained the same; however, large concentration decreases were measured in the outfall profile (Fig. 3). Currently, the effluent from the village results in a doubling of these concentrations. The concentration in the stream does not meet the requirements for maintaining the biotope of the freshwater pearl mussels (0.6 $mg.l^{-1}$) and represents the primary load of the main stream of the Blanice River (Simon, unpubl. results).

Generally, the influence of stabilisation ponds on the biotope of freshwater pearl mussels has been shown to be negative, and the ponds are often eliminated in locations where the species is present (Švanyga et al. 2012). The effluent from the Zbytiny WWTP stabilisation pond has a higher pH than expected (average value of 8.2); however, this has not influenced the pH in the recipient areas. In light of favourable diluting ratios, buffering of high pH values is relatively easy, and the stream is capable of maintaining a neutral pH. Furthermore, the variation in pH values decreased, which is propitious. The values of SS and COD increased after the WWTP began operating. This pollution arose in the stream basin above the village and was not influenced by the WWTP effluent. The conductivity in the WWTP effluent was much greater than in the recipient stream. In addition to wastewater flow into the stabilisation ponds, this may also be caused by spring-water influents to the ponds (see Fig. 1). The concentrations of the conductivity in the outfall profile have not changed compared to the 2-year period before the WWTP was constructed.

The quality of the effluent from the WWTP was more like the slightly eutrophic surface water of the small water flow. We also observed that extreme values were eliminated. Thus, the pollution loads were largely removed. Only the concentrations of NO_3-N and total phosphorus were still increasing in areas below the village; however, these are increasing at significantly lower rates than before the WWTP was put into operation. The Zbytinský Potok stream, which was a significant source of the pollution for the entire Blanice River (Bílý & Simon 2007), now has the potential to regain its status as a biotope of the freshwater pearl mussel.

Discussion

The elimination of nutrients from villages by small WWTPs

With the construction of an innovative small WWTP with two low-loaded stabilisation ponds, the threat of increasing loads of mineral nutrients into the Zbytinský Potok stream and downstream parts of the Blanice River was eliminated. The schematic approach to the protection of water polluted by small villages typically applied in the CR was overcome. The common approach is to build a central sewerage system and a WWTP and to direct discharge into the recipient (Just et al. 1999). Even in optimal conditions, small WWTPs can only achieve nutrient removal efficiencies of approximately 50% (Just et al. 1995). Furthermore, these WWTPs often deal with operational failures caused by unskilled operators and a low--quality sewer system (Just et al. 1999). In recent years, it was demonstrated that villages without central wastewater treatment systems introduce the lowest direct mineral nutrient loads into the recipient waters. When a WWTP with a sewer system is constructed, this influence is significantly increased due to changing the pollution source form non-point to point. The worst influence was documented in villages where the sewer systems discharged untreated waste directly to the recipient (Just & Mattiello 1995). The system constructed in the village of Zbytiny demonstrates that even centrally-treated wastewater in small WWTPs can be post-treated such that the recipient waters are not influenced by nutrient loads. Experiences with long-term operation of stabilisation ponds, described in the literature, illustrate the necessity of regular removal of the sediments (Bode et al. 1998). We next aim to determine what nutrients accumulate in the sediments and which nutrients are then exported to the underground waters (Lund 1999), into the air, or transferred to terrestrial ecosystems (Bode et al. 1998).

The application possibilities for small WWTPs with low-loaded stabilisation ponds

The protection of oligotrophic water basins against nutrient loading is expensive. Therefore, in Central Europe, only a few flow streams have been preserved that are unpolluted by nutrients. Many point or non-point sources of pollution do not have any wastewater treatment, and are fields where this system may be applied.

The prototype WWTP with low-loaded stabilisation ponds in Zbytiny was designed with the cooperation of the municipal authority, T.G. Masaryk Water Research Institute, the Administration of the Šumava National Park and Protected Landscape Area (PLA), and finally Agency for Nature Conservation and Landscape Protection of the Czech Republic**.** The project was elaborated by "Projekční Kancelář – Ing. Jan Beránek & Ing. Vlastimil Jiráň, Těšovice" (Czech Republic). The two-year WWTP operation verified the high treatment efficiency of the system. A similar system has been proposed for Arnoštov and the project of flat buildings on the Soumarský Most (both locations are in the Prachatice district in the Šumava PLA). The combination of verified technologies and specific handling regulations can be applied in other locations. The limiting factors for wide usage of these systems may be higher construction costs, area demands, and climatic conditions. The advantages of this system are the safe barrier effect of the ponds, aesthetic function, and the possibility of extensive fish farming in the second pond.

The influence of low temperatures and ice cover on the stabilisation pond are considered important limits to its function (Mara et al. 1987, Maynard et al. 1999). Many reports indicate that the treatment efficiency is worse under these conditions, but the overall function is not disturbed. Stabilisation ponds covered with ice enter into an anaerobic regime, which can have positive effects on some treatment functions. Sedimentation is not disturbed, and the water is not mixed by wind in shallow ponds (Rockne & Brezonik 2006). However, these findings come from high- or middle-loaded stabilisation ponds, which have eutrophic or hypertrophic characteristics (Schneiter et al. 1983, Bode et al. 1998). The influence of low temperatures and ice cover on Zbytiny low-loaded stabilisation ponds is less important, and no lack of oxygen is observed. According to the results from the first two winter periods, the concentrations of SS in the effluent decreased by approximately 35%. In contrast, concentrations of total nitrogen and phosphorus increased by 55% and 63%, respectively. With respect to the high treatment efficiency, the concentrations in the effluent were tolerable. For example, the concentrations of the possibly toxic ammonia nitrogen were measured at an average of 0.34 $mg.l^{-1}$. These levels are in compliance with the strict limits for short-term maximums in the freshwater pearl mussel biotope. A detailed investigation of the stabilisation pond treatment efficiency differences between summer and winter periods is the next task of this research.

Only a few studies in comparable systems can be found in the literature. Similar results for total inorganic nitrogen treatment efficiency are reported from a special WWTP with middle-loaded stabilisation ponds that was constructed for the protection of the Hidden Halley Wildlife Area in California (Lund 1999).

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