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Effect of temperature, HRT, vegetation and porous media on removal efficiency of pilot-scale horizontal subsurface flow constructed wetlands

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ABSTRACT

In order to investigate the effect of temperature, hydraulic residence time (HRT), vegetation type and porous media material and grain size on the performance of horizontal subsurface flow (HSF) constructed wetlands treating wastewater, five pilot-scale units of dimensions 3 m in length and 0.75 m in width were operated continuously from January 2004 until January 2006 in parallel experiments. Three units contained medium gravel obtained from a quarry. The other two contained one fine gravel and one cobbles, both obtained from a river bed. The three units with medium gravel were planted one with common reeds and one with cattails, and one was kept unplanted. The other two units were planted with common reeds. Planting and porous media combinations were appropriate for comparison of the effect of vegetation and media type on the function of the system. Synthetic wastewater was introduced in the units. During the operation period, four HRTs (i.e., 6, 8, 14 and 20 days) were used, while wastewater temperatures varied from about 2.0 to 26.0 °C. The removal performance of the constructed wetland units was very good, since it reached on an average 89, 65 and 60% for BOD, TKN and *ortho*-phosphate (P-PO_4^{3-}), respectively. All pollutant removal efficiencies showed dependence on temperature. It seems that the 8-day HRT was adequate for acceptable removal of organic matter, TKN and P-PO_4^{3-} for temperatures above 15 °C. Furthermore, based on statistical testing, cattails, finer media and media obtained from a river showed higher removal efficiencies of TKN and P-PO_4^{3-}.

1. Introduction and background

The need for treatment of municipal wastewater, even for small towns, is now imperative, based on EU directive 1991/271/EEC. A good alternative for small settlements is the use of constructed wetlands (CW). The use of these systems is becoming very popular in many countries. It is necessary then to find the optimal CW design characteristics in order to maximize their removal efficiency and keep the area to a minimum. The main characteristics, affect the removal efficiency of CWs are the hydraulic residence time and temperature (Kuschk et al., 2003), while the effect of vegetation type and porous media have not been studied adequately.

Several studies have shown the overall effectiveness of constructed wetlands in treating municipal wastewater (e.g., Hammer, 1989; Reed et al., 1995; Kadlec and Knight, 1996; He and Mankin, 2002). Organic matter is removed in a subsurface flow (SF) constructed wetland by the aerobic bacteria attached to the porous media and plant roots (Al-Omari and Fayyad,

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2003; Greenway and Woolley, 1999; Steer et al., 2002; Vymazal, 2002). Plant roots, except providing the necessary surfaces for bacteria to grow, also provide oxygen to them (Brix, 1994; Reed et al., 1995). Nitrogen removal is achieved not only by bacteria, but also by plant uptake, adsorption, where ionized ammonia reacts with the media in SF constructed wetlands (Kadlec and Knight, 1996; Yang et al., 2001; Al-Omari and Fayyad, 2003), and volatilization, where ammonia is transformed to free nitrogen (Kadlec and Knight, 1996; Yang et al., 2001; Vymazal, 2002; Tanner et al., 2002; Al-Omari and Fayyad, 2003; Mayo and Mutamba, 2004). Phosphorus removal in SF constructed wetlands is a result of bacteria removal, plant uptake, adsorption by the porous media and precipitation, where phosphorus reacts with the porous media and with minerals such as ferric oxyhydroxide and carbonate (Kadlec and Knight, 1996; Yang et al., 2001). Bacteria removal and plant uptake are responsible for $P\text{-}PO_4^{3-}$ removal, while precipitation and adsorption are responsible for the removal of all phosphorus forms (Kadlec and Knight, 1996).

Although the main mechanisms for organic matter, nitrogen and phosphorus removals have been identified, the precise contribution of vegetation type and porous media has not been examined in detail. One of the reasons for this fact is the small number of studies in pilot or laboratory-scale systems, where these factors could be understood better through controlled parallel experiments. Such studies present quite interesting results. He and Mankin (2002) carried out experiments in six pilot-scale HSF wetland models, 2.4 m long, 0.3 m wide and 45 cm deep each. The purpose of the study was to evaluate vegetation, media and seasonal effects on system performance. Planted cells exhibited higher treatment efficiency in COD and ammonia. Huang et al. (2000) conducted a study on SF constructed wetlands installed at two locations. Twelve small (52 cm in length, 36 cm wide and 42 cm deep), gravel-based SF wetlands were constructed at Virginia Tech's Kentland Research Farm (KRF). Twelve larger (11.8 m long, 1.1 m wide and 0.45 m deep) SF wetlands were constructed at the Powell River Project (PRP) site. Ammonium and TKN effluent decreased exponentially with increased wastewater residence time. Temperature dependent rate constants for ammonium and TKN were developed, and the results showed that the data from the small HSF CW could be used to predict the N concentrations at the larger HSF CW. Brooks et al. (2000) conducted a study on phosphorus removal by wallostonite as an alternative constructed wetland substrate. Phosphorus removal was greater than 80% and the concentrations of phosphorus in the effluent ranged from 0.14 to 0.50 mg/L. The results were for residence time up to 40 h. For lower residence times, phosphorus removal was 39%. A direct relationship between residence time and soluble phosphorus removal was established. Drizo et al. (2000) investigated phosphate and ammonium distributions in a pilot-scale HSF flow constructed wetland (1 m long, 0.5 m wide and 0.5 m deep). Shale was selected as a substrate, on the basis of its P adsorption capacity, as well as its suitability for plant growth. The results, which came from the use of a theoretical removal model, predict an exponential decrease in pollutant concentrations. Gray et al. (2000) evaluated the performance of maerl (calcified seaweed) as a substrate in artificial wetland treatment systems. Nitrogen removal did not show differences with figures in the literature; on the contrary phosphorus removal by maerl was much higher than the ones in gravel bed wetlands. In fact, the removal of phosphorus in these experiments was one of the highest found in the literature. This study proved that maerl has great potential as a constructed wetland substrate, due to its high phosphorus-adsorbing capacity. Although not examined in the present study, CWs also achieve high removal of pathogens (total and fecal coliforms). For example, Neralla et al. (2000) and Steer et al. (2002) reported 99% removal of fecal coliforms, and Mashauri et al. (2000) reported 90% removal of total coliforms. However, one should be careful with these high efficiencies, because the effluent pathogen population may still be above limits (typically, 1000N/100 mL).

The aim of the present study is to examine the effect of temperature, HRT, vegetation and porous media size and type on the removal of organic matter, nitrogen and phosphorus by pilot-scale HSF constructed wetlands, in an effort to describe the function of these systems in controlled experiments under Mediterranean climate conditions. With this in mind, we have designed, constructed and operated for 2 years in our open-air laboratory five small-scale HSF constructed wetlands receiving synthetic wastewater.

2. Materials and methods

2.1. Pilot-scale unit description

Various wetland models have been constructed in our open-air laboratory, a facility with a total surface area of approximately 400 m^2. A portion of the area is assigned to the experiments described here. Five similar pilot-scale horizontal subsurface flow constructed wetlands have been constructed and are in operation in this facility (Fig. 1). A schematic of the experimental layout is shown in Fig. 2. They are rectangular tanks made of steel, with dimensions 3 m long, 0.75 m wide and 1 m deep. Each tank has four openings on each side, approximately 47 cm wide and 66 cm high, which are covered with plexiglas screwed, glued and properly sealed in place. After the placement of the Plexiglas, the water tightness of each tank was checked. Then the porous media were placed in each tank at a thickness of 45 cm, and the plants were planted. During the experiments, the plexiglas sides were covered with dark plastic material to obstruct sunlight. To exclude the parameter length-to-width ratio from the study and have common conditions for comparison, the five CW tanks were constructed of the same shape and dimensions, even though in real operating CW systems the length-to-width ratio is determined from the hydraulics of the system and depends on the substrate material size. The relatively small width of the CW was chosen in order to ensure plug flow conditions in the units and the relatively large length was chosen in order to examine the pollutant removal along the units.

Three different porous media were used (Fig. 3), i.e., medium gravel (MG, D_{50} = 15.0 mm, range 4–25 mm), fine gravel (FG, D_{50} = 6 mm, range 0.25–16.0 mm) and cobbles (CO, D_{50} = 90 mm, range 30–180 mm). The porous media were of different origin. Medium gravel, which was obtained from a quarry, is a carbonate rock (main elements: Si 3.39%; Al 0.90%; Fe 0.82%; Ca 27.20%; Mg 4.53%; P 0.03%). Fine gravel and