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Evapotranspiration affecting redox conditions in horizontal constructed wetlands under Mediterranean climate: Influence of plant species

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ABSTRACT

The aim of this study was to conduct a comparative evaluation of evapotranspiration (*ET*) rates for eight different mesocosm constructed wetlands (CWs), and the relationship with redox potential (E_H). Inflow, outflow and E_H were measured over 4 years in winter and summer campaigns as well as over 24 h on selected days in summer. Vegetation was the main design parameter which affected water loss in the wetlands (on average, *ET* in planted wetlands was 4 times higher than in unplanted ones), and *Typha angustifolia* was more active than *Phragmites australis* (mean daily *ET* – expressed as the average of *ET* rate measured every 2 h in selected days in summer – was 36.8 ± 2.3 mm d^{-1} and 23.0 ± 1.9 mm d^{-1} for hydroponic wetlands planted with cattail and common reed, respectively), although *P. australis* water use efficiency was lower. Positive relationships were found between *ET* and E_H for planted wetlands. Cattail presented a stronger linear regression than common reed, demonstrating that *ET* and consequently redox conditions are plant species-dependent.

1. Introduction

Wastewater disposal constraints largely determine the type of treatment used. Thus, a wetland can be designed to achieve zero discharge if rigorous quality standards for effluent must be adhered to, if soil infiltration is not possible (Gregersen and Brix, 2001), or when water reuse is priority, i.e. for restoring sensitive areas (Greenway, 2005; Guardo, 1999; Paulo et al., 2012). One of the most important factors in designing and dimensioning constructed wetlands (CWs) for wastewater treatment is the water balance, which depends on the hydraulic loading rate (HLR), rainfall and plant-mediated evapotranspiration (*ET*). At constant inlet flow rates, evapotranspiration will induce changes in the water table (Mann and Wetzel, 1999), which has been related to enhanced removal efficiencies (Tanner et al., 1999). Therefore, *ET* is a decisive factor in achieving water discharge targets.

Evapotranspiration in a CW is the only means by which wetlands lose water, given that the water basin is insulated to avoid water infiltration of the soil. Evapotranspiration is intimately related to meteorological conditions (Kumar et al., 2012), but is also related to plant growth stage (Borin et al., 2011; Headley et al., 2012). In temperate climates with pronounced seasonality, *ET* differs greatly from winter to summer, with a maximum *ET* rate at mid summer, when the vegetation attains its effective full ground cover. Moreover, *ET* is subjected to a diurnal cycle, with maximum values in early afternoon and minimum values at night (Kadlec and Wallace, 2009), which can lead to a lack of outflow in periods of high *ET*. Therefore, variations in *ET* rates should be considered when dimensioning and modelling a constructed wetland (Galvão et al., 2010).

Additionally, *ET* has an effect on treatment performance, mainly because water loss increases hydraulic retention time (Kadlec and Wallace, 2009). Furthermore, contaminant removal is closely related to the redox state of the system (Ávila et al., 2013; Faulwetter et al., 2009; Pedescoll et al., 2011). Therefore, *ET* should contribute to the redox conditions within the systems, at least during periods of high *ET*. Several studies have reported the effect of redox soil conditions on macrophyte growth and activity (Gorai et al., 2011; Pezeshki et al., 1996), indicating that wetland plants (such as cattail, common reed or common rush) present tolerance

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to hypoxia. However, no information is available on the influence of *ET* on the redox conditions of the system.

Understanding the main factors that affect evapotranspiration would help to clarify decision-making during the system design process. Vegetation is the most important factor, in as much as plants are primarily responsible for wetland water loss. Vegetation height and leafiness plays an important role in *ET* rates within a system, as those wetlands with a high leaf area index (LAI) and tall vegetation present higher *ET* values. Pauliukonis and Schneider (2001) found that *ET* rates were three times higher for *Salix babylonica* than for *Typha latifolia*, and that the LAI for willow was triple that of cattail. Similarly, *Eichhornia crassipes* presented *ET* rates two times higher than those of *Lemna minor* in mesocosm tanks (DeBusk et al., 1983). In fact, species with a high LAI can intercept more dry wind, thus enhancing evapotranspiration. Nevertheless, other design parameters are also involved in water loss, such as flow type. Free water surface (FWS) and horizontal subsurface flow (HSSF) systems perform differently in terms of hydraulics (Pedescoll et al., 2013) and as regards sensitivity to environmental conditions (Kadlec, 2009).

The main aim of this study was to conduct a comparative evaluation of evapotranspiration rates for different constructed wetland designs and to determine the relationship with redox conditions within the systems. To this end, an experimental plant with 8 mesocosm wetlands was constructed and operated over almost 4 years. The plant included the most common wetland designs, such as FWS, SSF and floating macrophytes. This wide variety of configurations enabled us to evaluate different design parameters, e.g. presence/absence of vegetation, plant species, flow type and presence/absence of gravel matrix. As far as we are aware, this is the first time that evapotranspiration and redox conditions have been tested for different configurations under the same climatic conditions.

2. Methods

2.1. Experimental plant description

Eight mesocosm-scale CWs were built inside the facilities of the León wastewater treatment plant (WWTP), in the northwest of Spain (Latitude: 42° 33′ 30″ N; Longitude: 5° 34′ 50″ W). Each CW consisted of a fibreglass container measuring 80 cm wide, 130 cm long and 55 cm high which differed from each other in the design configuration. CW1 and CW5 were constructed as soilless wetlands (30 cm water depth) with floating macrophytes, supported by garden net cylinders. CW2, CW3 and CW4 were designed as free water surface (FWS) systems, with 25 cm of siliceous gravel (d_{60} = 7.3 mm) and 50 cm water depth (this is 25 cm of water ponding above the gravel surface). CW2 was a strict FWS with inlet and outlet pipes located on the surface of the wetland. In CW3 and CW4, the outlet pipe was placed at the bottom of the container, thus forcing the water to flow through the subsurface. CW2 and CW3 were planted with *Typha angustifolia* while CW4 was an unplanted system. CW6, CW6′ and CW7 were typical SSF wetlands, with a 50 cm layer of siliceous gravel (d_{60} = 7.3 mm) and 45 cm water depth. In these wetlands, inlet pipe was located at the surface while the outlet pipe was placed at the bottom. CW6′ received a 2-fold higher organic load than CW6. CW6 and CW6′ were planted with *Phragmites australis* whereas CW7 was an unplanted system. The configuration of the experimental plant enabled us to evaluate the effects of different design parameters by conducting comparisons between those pairs of wetlands differing in only one design parameter (Fig. 1). Further details on the wastewater characteristics and efficiencies are presented elsewhere (Hijosa-Valsero et al., 2011; Hijosa-Valsero et al., 2012).

The experimental plant was operated for almost 4 years (from May 2007 to December 2010). The wetlands were fed with homogenised wastewater from the primary settler of the León WWTP at a hydraulic loading rate of 50 mm d^{-1} (CW6′ received 100 mm d^{-1}) with a continuous flow rate. However, in order to ensure outflow (for purposes other than those of this study), for the last four months (from September to December 2010) the wetlands were fed with twice the previous hydraulic loading rate. All the wetlands (except unplanted ones) were planted with 50 seedlings m^{-2} of the species chosen in May 2007. Starting from 2008, plants were harvested every year in early autumn. Tanks were protected with expanded polystyrene sheets in order to avoid the direct effect of the sun on the CW walls.

2.2. Data collection

Daily meteorological data for the entire study period were obtained from an automatic weather station located 8 Km from the León WWTP (Latitude: 42° 35′ 18″ N; Longitude: 5° 39′ 4″ W) (AEMET, 2012). Throughout the experiment, inlet and outlet flows were periodically measured in order to monitor the water balance. Measurements were taken in winter and summer campaigns in early morning. Flow rate was measured volumetrically, using a 250 mL graduated cylinder and stopwatch. Each measurement was taken in triplicate. Additionally, measurements of redox potential were taken within each CW at 15 cm and 32 cm from the surface by means of a probe submerged in a piezometer situated at 2/3 of the length from the inlet in each wetland.

In order to characterise nocturnal and diurnal differences in evapotranspiration, inlet and outlet flow rates were also measured every 2 h one day per month in summer from 2008 to 2010. Redox potential at 15 cm and 32 cm from the surface of the wetlands was also measured.

Furthermore, from the second year of operational period vegetation was yearly harvested, dried and weighed (in summer end). Thus, above-ground plant production was measured year by year.

2.3. Evapotranspiration and plant coefficient calculations

Reference evapotranspiration (ET_o) was calculated from microclimatic data, obtained from the weather station, using the FAO Penman–Monteith equation (Allen et al., 1998):

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma(900/(T + 273))u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

where ET_o is reference evapotranspiration (mm d^{-1}); R_n is net radiation at the crop surface (MJ m^{-2} d^{-1}); G is soil heat flux density (MJ m^{-2} d^{-1}); T is mean daily air temperature at 2 m height (°C); u_2 is wind speed at 2 m height, in ms^{-1}; e_s is saturation vapour pressure (kPa); e_a is actual vapour pressure (kPa); $e_s - e_a$ is saturation vapour pressure deficit (kPa); Δ is the slope vapour pressure curve (kPa C^{-1}); and γ is the psychrometric constant (kPa C^{-1}).

ET rate for each CW was calculated according to a daily water balance by means of Eq. (2):

$$ET_{cw} = Q_{in} + P - Q_{out} \quad (2)$$

where ET_{cw} is evapotranspiration (mm d^{-1}); Q_{in} is the inlet flow rate (mm d^{-1}); P is precipitation (mm d^{-1}); and Q_{out} is the outlet flow rate (mm d^{-1}).

The plant coefficient for each treatment condition was obtained by dividing the ET_{cw} by the ET_o (Allen et al., 1998), as follows:

$$K_{cw} = \frac{ET_{cw}}{ET_o} \quad (3)$$