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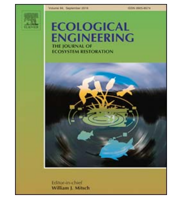

Energy and water balance of a treatment wetland under mediterranean climatic conditions

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ABSTRACT

During 2013–2014 period, the surface renewal (SR) – energy balance (EB) method combined with the water balance approach was adopted to define the energy and water budget of a treatment wetland (TW) in Eastern Sicily (Italy). The main objective was to evaluate the differences between energy and water balances and understand the underlining mechanisms of environmental control. Results shown that the seasonal variation in evapotranspiration (ET) had similar trend as the seasonal variation of leaf area index (LAI) and net radiation (R_n). During the study period, the daily rate of ET by EB ranged from -0.1 mm d^{-1} to 9.3 mm d^{-1}, with a total ET of about 1837 mm in 17 months. The crop coefficient K_c (e.g. obtained using the FAO-56 mean K_c approach) for the TW ranged from 0.5 to 2.4, with a mean annual value of 1.24. On a 10-day mean basis, ET fluxes from the TW water balance were 15% higher than ET by EB.

1. Introduction

Treatment wetlands (TW_s) are designed plants where the natural mechanisms and interactions of vegetation, soils and the microbial populations contribute to reduce surface water or wastewater contaminants (Headley et al., 2012). Their use, as decentralized systems for the treatment of domestic water, is increasingly mainly due of their low operation and maintenance requirements (Cirelli et al., 2007, Barbagallo et al., 2003, 2011) and low risk associated to human contact.

In TW_s, water cycle and the associated energy exchange process have a fundamental role in the operation of these systems (Rejšková et al., 2012). The wetland plants, both in natural wetlands and in those constructed, are adapted to grow in a not limited water availability conditions, with associated high evapotranspiration (ET) rate (Borin et al., 2011).

A detailed knowledge of ET can be crucial for the functioning of TW_s. In fact, especially when the treated water are indispensable resources to be reused for irrigation (Barbagallo et al., 2012, Toscano et al., 2013, Castorina et al., 2016), excessive ET losses may increase salt concentrations in the effluent (Headley et al., 2012).

The hydrological processes occurring in TW_s, such as horizontal flow wetlands, are different from those in the natural wetland systems, due to the infiltration and surface runoff exclusion and the identification of stream flow with wastewater influent and effluent (Headley et al., 2012), which can be measured with flow metering devices. In these systems, the direct measurement of ET fluxes generally present difficulties (Price, 1994, South et al., 1998, Moro et al., 2004, Noormets et al., 2006).

Several studies have explored how to directly measure or estimate ET fluxes from natural or TW systems (e.g. Idso, 1981, Idso and Anderson, 1988, Abtew and Obeysekera, 1995, Soucha et al., 1996, Wilson and Baldocchi, 2000, Drexler et al., 2004 Toscano et al., 2015), and ET term has become a subject of debate. However, few studies have dealt with the analysis of the relationship between ET, the surface energy fluxes and the related physical processes especially in TW systems (Goulden et al., 2007, Clulow et al., 2012). Different procedures of direct measurement or estimation of ET fluxes were adopted, and, as consequence, significantly different results were obtained, thus contributing to increase the uncertainty about the most appropriate methods for treatment wetland ET determination.

Relevant studies were conducted by Abtew and Melesse (2013) on ET direct measurement by lysimeters, other by Burba et al. (1999) and Peacock and Hess (2004) on the adoption of micrometeorological methods, based on the energy fluxes budget, to measure ET from wetland systems.

Among the micrometeorological methods, the eddy covariance (EC) technique is recognized as one of the most accurate for estimating

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wetland ET (Acreman et al., 2003, Goulden et al., 2007, Siedlecki et al., 2016), even if it involves relevant instrumental costs (Clulow et al., 2012) and specialized personnel for data processing. An important advantage of the EC method is that the obtained water vapour flux comes from a source area within a distance of 200–300 m from the sensor.

In the recent past, the applied research has recognized the Surface Renewal (SR) technique as valid alternative to EC sonic anemometer for sensible heat flux (H) direct measurements (Drexler et al., 2004). The SR is reasonable accurate, cheaper than EC and easily maintained for heterogeneous systems measurements like wetlands. When SR is integrated with direct measurements of net radiation and soil heat flux, it allows to estimate ET as residual of the energy balance equation.

Other studies conducted within treatment wetlands have calculated ET fluxes by the resolution of the water balance using off-site data (Kadlec and Wallace, 2008) or by simple meteorological equations such as the Penman-Monteith model, and other hydrological and crop-growth models (Annandale et al., 2003, van Heerden et al., 2009). The use of these models requires vegetation specific parameters for calibration (Mao et al., 2002).

In this study, the eddy covariance (EC) method was adopted over a period from July 2013 to December 2014, to determine energy fluxes and ET from a treatment wetland system in Eastern Sicily (Italy). The results on ET fluxes were compared to ET estimates from both a hydrologic water balance of the wetland and the FAO-56 Penman-Monteith model. The valuable alternative technique surface renewal (SR) was also adopted at the site to estimate sensible heat fluxes (H_{SR}) from TW areas. The results on ET fluxes were compared to ET estimates from both a hydrologic water balance of the wetland and the FAO-56 Penman-Monteith model.

The results of this study are crucial from the point of view of the works aimed at assessing the role of ET in the functioning of the TW systems. Moreover, despite the extensive research on the topic of TW, there are still few studies on the complex characteristics of evapotranspiration in Italy's full-scale wetland systems.

2. Materials and methods

2.1. The study site

The study site is the largest TW of Sicily (South Italy), used as tertiary wastewater treatment of 5000 Persons Equivalent (PE) (Fig. 1).

It is located in the small village of S. Michele di Ganzaria in Eastern Sicily (37°17′0″N, 14°26′0″E). The TW areas (12,700 m^2) is part of the wastewater reuse project of the village, consisting of four horizontal sub-surface (H-SSF) reed beds (H-SSF1, H-SSF2, H-SSF3 and H-SSF4), followed by three batch wastewater storage reservoirs (S1, S2 and S3) working in parallel (Fig. 2) (Castorina et al., 2016).

The sewerage system collects wastewater from almost every household in a conventional wastewater treatment plant (WWTP), north-west of San Michele di Ganzaria, where urban wastewater receive a pre-treatment step followed by two parallel water lines (Imhoff tank, trickling filter and a secondary sedimentation tank). For tertiary treatment, the effluent is sent in four H-SSF beds (about 2 $L\,s^{-1}$ per bed), of which H-SSF1 and H-SSF2 are in operation respectively since 2001 and 2006, while H-SSF3 and H-SSF4 since summer 2013.

The research focused on the study of the H-SSF3 TW bed, that has a surface area of about 2300 m^2 (36 × 64 m) and a theoretical flow rate of about 173 $m^3\,d^{-1}$. The TW depth (e.g. 0.6 m) is filled with 8–10 mm of volcanic gravel. The TW bottom has a slope of 1% and the average water depth is 0.5 m. Both the excavated beds and banks were lined with a 4 mm thick bentonite sheet to prevent groundwater contamination. Earth banks, with a slope of 3:1, were covered with jute netting to facilitate vegetation and prevent soil erosion. In September 2012, the H-SSF3 was planted with *Phragmites australis* (Cav.) Trin. ex Steud at a density of one rhizome m^{-2}; the complete plant cover was reached a year later. The vegetation had average maximum height of 2.0 m, with homogeneous canopy cover and no areas of fully exposed substrate and plant roots were in water saturation conditions. The leaf area index (LAI) ranged between 0.4 $m^2\,m^{-2}$ in winter and 5.0 $m^2\,m^{-2}$ in summer.

In the TW, the influent is distributed at the bed-head through a perforated 200 mm PVC pipe above the substrate and oriented normal to the flow direction to allow homogenous wastewater distribution. Wastewater is intercepted downstream by a cross perforated pipe located in the final section at the bottom of the bed. Electromagnetic flow meters (ISOIL mod. MS2500), installed at the inlet and at the outlet pipes, measure the flow rate ($L\,s^{-1}$) in continuous. In the bed, nine piezometers (i.e. 0.2 m of diameter) were arranged in 3 rows; they consist of open perforated plastic tubes inserted into the substrate to the bottom of the bed, used to measure the water height and to collect wastewater samples.

The wetland area has been instrumented with an automatic weather station (Campbell Scientific, Logan, UT) to measure air temperature, wind speed and direction, rainfall, global radiation and relative humidity. These data were used to calculate the Penman-Monteith equation (Allen et al., 1998) for reference ET (ET_0) estimation. The FAO-56 Penman-Monteith model provides estimates of hourly ET from a hypothetical grass reference surface (ET_0) (Eq. (1)). It is well-known to estimate the crop coefficient (K_c) as ratio between crop evapotranspiration during no water-stress conditions (ET_c, in turn ET from EC or ET from TW water balance) and ET_0.

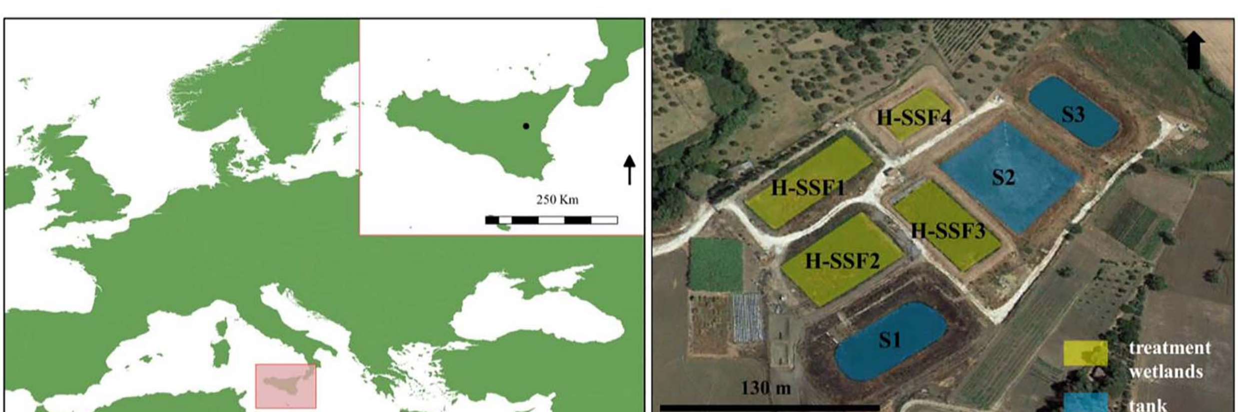

Fig. 1. Geographical location of the treatment wetland areas in Eastern Sicily.