MONITORING AND MODELING OF SOIL WATER COMPONENTS IN A COASTAL DUNE ENVIRONMENT OF THE DOÑANA NATIONAL PARK USING A PRECISION METEO-LYSIMETER

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RESUMEN. Se instaló un meteo-lisímetro de alta precisión 2015 en una duna costera de la Reserva Natural de Doñana para cuantificar los flujos de agua y energía en sistemas dunares y para estimar su dependencia de las tendencias climáticas regionales. El lisímetro de pesaje contiene una muestra de suelo no alterada de 1 metro cuadrado de superficie, 1,50 m de altura con una resolución de pesaje de 10 g y control de las condiciones de contorno inferior. Los flujos individuales se cuantificaron utilizando observaciones lisimétricas. Se calibró un modelo 1D que en función de la recarga y los datos de las series de tiempo TDR. El modelo calibrado reproduce bien los datos monitoreados y, por lo tanto, constituye una herramienta poderosa para investigar el impacto de los escenarios climáticos en el presupuesto de agua del suelo y la recarga de agua subterránea en las zonas costeras de dunas.
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ABSTRACT. A high-precision meteo-lysimeter was installed 2015 on a coastal dune in the Doñana Natural Reserve to quantify the water and energy flux in dune systems and to estimate its dependence on regional climatic trends. The weighing lysimeter contains an undisturbed soil sample of 1 square meter in area, 1.50 m in height with a weighing resolution of 10 g and control of the lower boundary conditions. The individual flows were quantified using lysimetric observations. A 1-D model was calibrated based on the recharge and data of the TDR time series. The calibrated model reproduces well the monitored data and, therefore, constitutes a powerful tool to investigate the impact of climate scenarios on the soil water budget and the recharge of groundwater in coastal areas of dunes.

1.- Introducción

Dune belts are fundamental for groundwater recharge in coastal aquifers and consequently for the maintenance of ecological habitats. The site is located in a coastal dune of the Doñana National Park, a highly groundwater dependent wetland area (Fig. 1). Due to their elevated recharge rates, dune belts are important for the recovery of groundwater levels and for the prevention of saline intrusion. Therefore they play a critical role for the conservation of coastal wetlands, especially in the Doñana National Park, which are threatened by intensive agricultural irrigation and intensive tourism. The main objective of this study is to quantify the recharge in dune belts under a semiarid climate, and its dependence on regional climate trends.

Beyond the large number of methods for recharge estimation, weighing lysimeters yield the most precise measures of recharge, evapotranspiration and precipitation (Peters et al. 2014). Nonetheless, precise weighing lysimeters have been mostly installed for agricultural purpose in crop areas and therefore only limited knowledge exists about recharge dynamics and its dependence on meteorological parameters in dune belts.

The Geological and Mining Institute of Spain (IGME), in collaboration with the Biological Station of Doñana (EBD-CSIC), started recently a research project to monitor the natural recharge in the dune belts of the Doñana National Park. A high precision weighing meteo-lysimeter with lower boundary control was installed in September 2015 for continuous monitoring of recharge and other soil and meteorological parameters.

The climate of the area is sub-humid Mediterranean with Atlantic influence, dry summers and humid winters. The average rainfall, which occurs between October and March, is between 500 and 600 mm, with a great interannual variability, between 250 and 1100 mm (Custodio et al., 2009). The average annual air temperature is about 17 °C near the coast and 18 °C in the center of the Park. There are around 3000 hours of sunshine every year (Manzano, 2009).

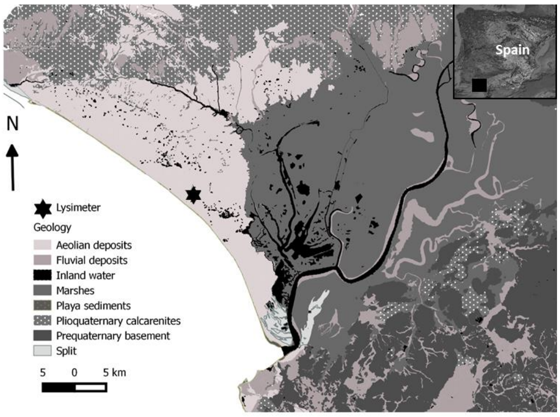

Fig. 1. Meteo-Lysimeter placement, located in Doñana National Park, province of Huelva, Southwest of Spain (source: Kohfahl et al. 2011 and wikipedia.com)

2.- Lysimeter experiment

Sediment analysis from previous projects have shown that the Doñana dune belt material is made up of medium coarse sands of a well-sorted grain size distribution. The aeolian dune sands are composed of quartz and feldspars. Some secondary minerals, such as carbonates, clay, sulphides or Fe-oxides, might have formed afterwards in situ due to subsequent weathering processes.

In September 2015, the site was equipped with a UMS (UMS AG, Munich, Germany) cylindrical lysimeter of 1 m^2 surface, 1.50 m height and a weighing resolution of 10 g (Fig. 2).

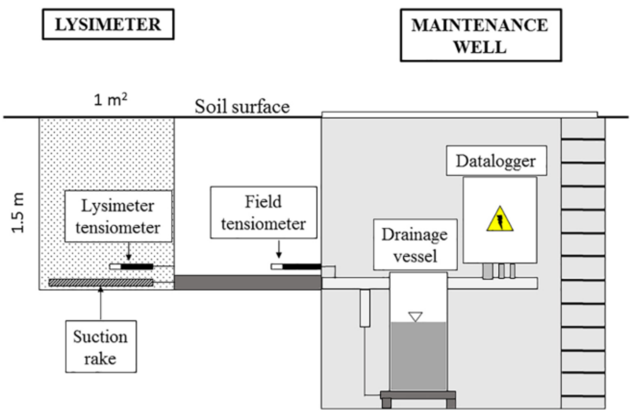

Fig. 2. Sketch of the Lysimeter.

Additionally 2 automatic meteorological stations (Vantage PRO2 Davis, California, USA; UMS AG, Munich, Germany) and six CS650 soil moisture sensors (Campbell Scientific, Logan, UT) were installed at 0.30, 0.60, 1.20, 1.60, 2.20, and 3 m depth. The lower boundary condition at the bottom of the lysimeter is controlled at 1.4 m depth using a peristaltic pump. A peristaltic pump maintains the bottom of the lysimeter at the same potential as measured by the field tensiometer installed outside the lysimeter. Table 1 shows the measurements that are continuously performed. Physico-chemical soil properties such as density, grain size, mineralogy and metals were also analysed at different depths.

Table 1. Measured parameters and intervals. Air and soil temperature was measured at 2, 0.5, 0.05,-0.05-0.1,-0.2,-1.4 m depth. Soil depth indicated by negative value.

Measured parameter	Time interval (minutes)
Soil mass lysimeter	1
Water mass drained from lysimeter	1
Soil water tension	10
Soil moisture	10
Wind direction	10
Wind velocity	10
Net radiation	10
Precipitation	10
Air humidity	10
Air and soil thermal profile	10
Soil bulk density	Once
Grain size distribution	Once
Mineralogy	Once
Metals content	Once

To eliminate measurement noise, the raw data are corrected to accurately calculate precipitation (P) and recharge (R) from lysimeter data. Intrinsic noise in lysimeter data was reduced by smoothing through the AWAT filter (Peters et al. 2014). This method has been recently applied in other studies (Hoffmann et al. 2016). For the application of the AWAT algorithm, the parameters maximum window width and maximum threshold were defined according to optimized values in former lysimeter studies (Peters et al. 2014) with values of 31 min and 0.24 mm, respectively. Occasional short gaps in the lysimeter data time series occurred due to power failures leading to a data loss of around 1%.

According to the soil water balance the infiltrating rain water, P, increases soil water storage, Δw_{lys}, and recharge, R, assuming that no evapotranspiration, ET, occurs during rainfall. The hydrological balance equation states that:

$$P = R + ET + \Delta w_{lys} \quad (1)$$

P can then be calculated according to Schrader et al. (2013) as:

$$\Delta W = \Delta w_{lys} + \Delta w_{drain}$$

$$P = \begin{cases} \Delta W, & \Delta W > 0 \\ 0, & \Delta W \leq 0 \end{cases} \quad , \quad (2)$$

where Δw_{lys} [kg] is the mass change of the lysimeter during each time interval which corresponds to the water storage change, Δw_{drain} [kg] is the mass change in the drainage sampling vessel, P [kg] is the sum of

precipitation recorded by the lysimeter.
Registration of reliable lysimeter data started in December 2015.

3.- Numerical model

The lysimeter experiment was simulated with CODEBRIGHT, a finite element code for modelling multiphase flow and heat transport (Olivella et al., 1996). The lysimeter is represented by a vertical one-dimensional finite element grid of 1.4 m length, divided into 140 elements of 0.01 m. The domain is homogeneous representing the homogeneous dune sand. The model used all available data, including almost 2 hydrological years from November 25, 2015 to October 4, 2017. Balance equations were solved for water, air and energy in an unsaturated medium. Both water and air can exist in the liquid and gas phase and be transported in these two phases though advection, diffusion and dispersion. To account for dry conditions which are not well represented by the Van Genuchten retention curve, two additional retention curves were considered by the simulations (Rossi & Nimmo and a double porosity retention curve). Table 1 gives the most important parameter values. Moreover, densities, viscosities of gas and liquid and surface tension of the gas-liquid interface all depend on temperature through standard functions. For more details, we refer to Olivella et al. (1994 and 1996).

Retention curve					
	Van Genuchten	p_0	34 hPa	m	0.76
		$S_{l,s}$	1.0	$S_{l,r}$	0.15
	Rossi & Nimmo	p_0	34 hPa	p_{dry}	$1{\cdot}10^7$ hPa
		m	0.76	α	0.1
		$S_{l,s}$	1.0	S_0	0.15
	Double porosity retention curve	$p_{0,1}$	34 hPa	$p_{0,2}$	$5{\cdot}10^5$ hPa
		m_1	0.76	m_2	0.5
		f_1	0.85	f_2	0.15
Porosity		ϕ	0.37		
Solid density		ρ_s	2670 kg m^{-3}		
Permeability		$\mathbf{K}_{int}$	$1.0{\cdot}10^{-11}$ m^2		
		m	0.76		
Vapor diffusion		D_0	$5.6{\cdot}10^{-6}$ m^2 s^{-1} K$^{-2.3}$ Pa		
		n	2.3		
		τ	6.0		
Thermal conductivity		λ_g	0.025 J ^{0}C^{-1} m^{-1} s^{-1}		
		λ_l	0.60 J ^{0}C^{-1} m^{-1} s^{-1}		
		λ_s	2.0 J ^{0}C^{-1} m^{-1} s^{-1}		
Atmospheric parameters		z_a	2.0 m		
		z_0	0.01 m		

Table 1. Main parameters used for the models. $\mathbf{K}_{int}$, τ, λ and z_0 are obtained from calibration.

Fluxes at the top boundary of water, air and energy are calculated as a function of meteorological measured data (rainfall, temperature, net radiation, relative humidity and wind velocity) and the state variables temperature, gas and liquid pressure calculated by the model. The gas pressure is fixed to the atmospheric pressure of 0.1 MPa at the top boundary. At the bottom of the model the liquid pressure and temperature is prescribed to values calculated from daily averaged measurements of suction in the undisturbed soil next to the lysimeter at the same depth as the bottom of the lysimeter. A zero air flux boundary condition was used at the bottom. Initial liquid pressure is 945 hPa (which corresponds to a suction of 55 hPa). This gives a volumetric water content of 0.03 which corresponds to measured values ranging between 0.02 and 0.04 at various depths. Initial gas pressure is 1000 hPa. Initial temperatures are calculated by linear interpolation of measured temperatures.

Solid density, porosity and retention curves were determined from laboratory experiments. We used three retention curves, the classical retention curve of van Genuchten (1980), the Rossi and Nimmo (1994) retention curve and a two porosities curve according to Durner (1994).

4.- Results

4.1 Results of the lysimeter experiment

Results of the lysimeter experiment are shown for one hydrological year to allow comparisons of annual hydrological balances measured in other studies. For the hydrological year 01.09.2016–31.08.2017 the resulting annual recharge was 413 mm corresponding to 64% of precipitation measured by the lysimeter (Figure 3).

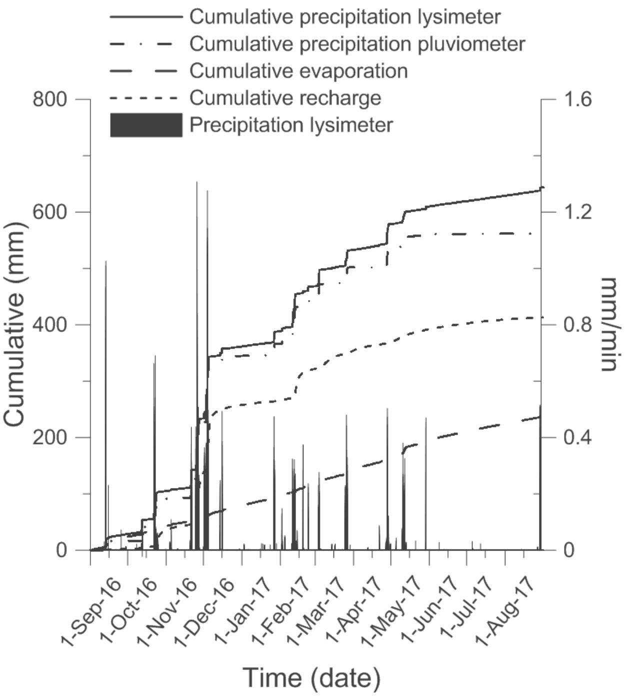

Fig. 3. Measured soil water components for the hydrological year 2016/2017.

A further important result is that the annual precipitation registered by the lysimeter exceeds the pluviometer (tipping bucket) data by 13%. As illustrated in Figure 4 this difference is attributed to measured cumulative weight increase by vapor adsorption in days without rainfall summing up to an annual amount of 77 mm.

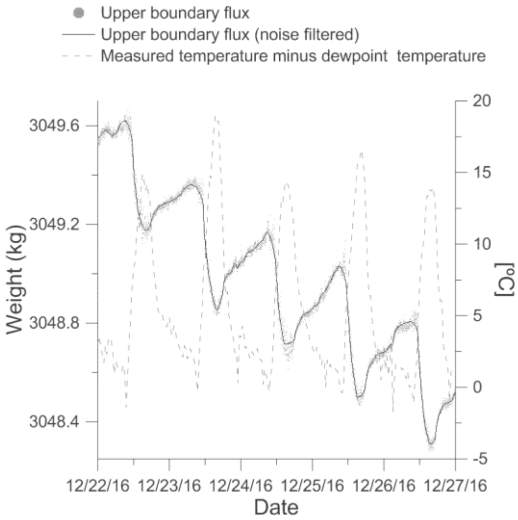

Fig. 4. Measured soil water components for the hydrological year 2016/2017.

4.2.- Results of the numerical experiment

The model with the double porosity retention curve gave the best fit with the measurements. The model fits well the accumulative flux measured at the bottom and the mass of water at a yearly timescale (Figure 5). Therefore, the model also reproduces well the average net diffusion related to condensation-evaporation at the boundary at this time scale.

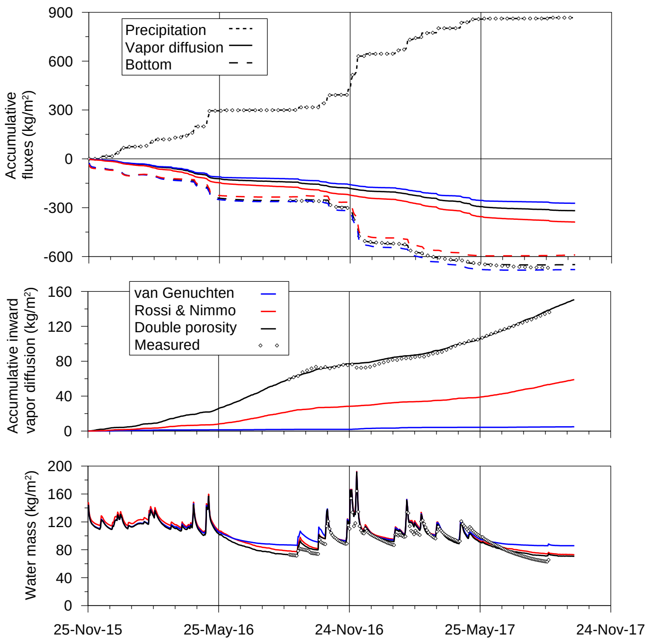

Fig. 5. Accumulative boundary fluxes (above and middle graph) and mass of water in the lysimeter (lower graph). Inflow is positive, outflow negative. Measured rainwater was used as input.

To compare the effect of retention curves on the simulated results, Figure 6 shows the respective vapor fluxes at the boundary during a week in summer and in winter. The model results of the model with the double porosity retention curve show similar oscillations as the measurements. During the day there is clearly a negative (or outward) diffusion, related to evaporation which is reversed at night. Nevertheless, during summer the modelled oscillations are somewhat delayed with respect to the measurements. The large measured inward diffusion during the afternoon is not reproduced by the model. Also the model underestimates the size of the oscillations in vapor diffusion during the winter.

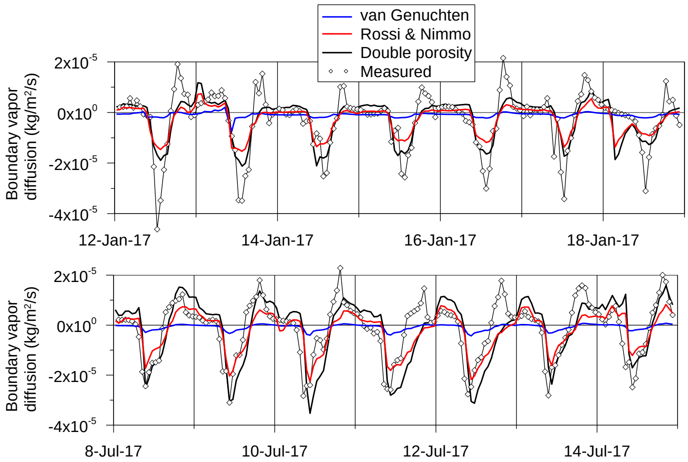

Fig. 6. Evolution of vapor diffusion at the boundary during a week in winter (above) and in summer (below). Positive refers to inward and negative to outward diffusion.

To gain insight in the dynamics of the processes taking place considering the role of different retention curves, we have plotted simulated profiles of various variables for a point of time at night and at day in summer (Figure 7). We can observe an evaporation front at about 0.8 m and deep below this front water flows downwards, enabling the drainage at the lower boundary. Up to 0.1 m below the front liquid water flows upwards, evaporates at the front and continues its upward transport as vapor diffusion. Moreover, (Figure 7) shows within the top few decimeters of the soil a pattern of alternating bands of condensation and evaporation, which follows the daily temperature oscillations that fade out deeper in the soil.

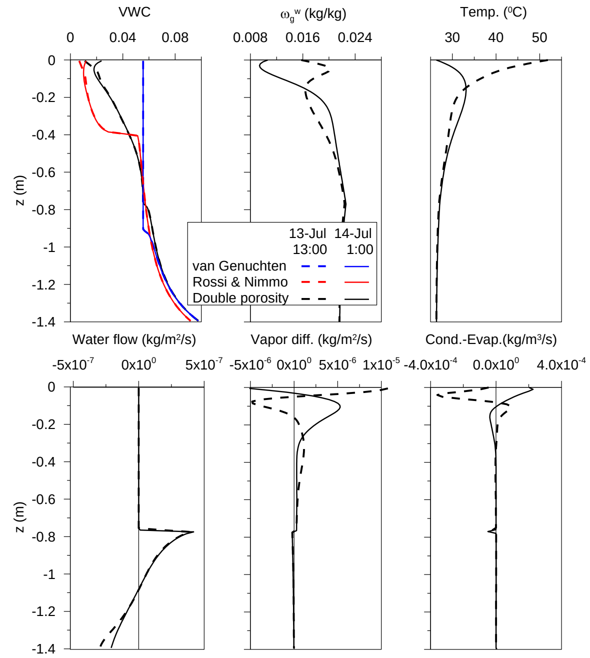

Figure 7. Simulated profiles during summer of VWC (volumetric water content), ω_g^w (vapor mass fraction), temperature, fluxes of liquid water flow, vapor diffusion and condensation-evaporation of water. Positive fluxes are upward, negative downward. Condensation is positive and evaporation negative.

5.- Conclusions

The presented study shows measurements of soilwater components and vapor flow during a hydrological year by a high precision meteolysimeter with lower boundary control installed within a coastal dune belt subjected to a dry subhumid climate. Results are in agreement with studies in similar environments and show a recharge rate corresponding to 64% of precipitation measured by the lysimeter. Diurnal oscillations of the measured upper boundary during minutes without rainfall represent vapor adsorption and real evaporation rates ranging from 0.3 to 0.4 mm/day and 0.4 and 0.6 mm/day, respectively throughout the whole year. The registered precipitation of the lysimeter exceeded the pluviometer data by 13% due to vapor adsorption which was only measured by the lysimeter summing up an annual cumulative vapor adsorption of 77 mm.

A numerical model taking into account water, vapor and heat transport in unsaturated soil could simulate the water adsorption deduced from the daily oscillations of the mass of water, measured in the lysimeter. Simulated and measured water vapor adsorption is 81 and 77 kg m^2 $year^{-1}$, respectively, which is comparable to other studies.

The model shows that water vapor adsorption is driven by daily temperature oscillations at the soil surface, which can be much higher than oscillations in air temperature. On the other hand, specific (or absolute) humidity remains more constant. This means that relative humidity and suction will oscillate according to Kelvin's law and the temperature dependency of saturated humidity. In turn, according to the retention curve this leads to oscillation in retained water. The required water is taken from or released to the atmosphere through evaporation or, more precisely, vapor diffusion at the soil surface. Both experimental and model results demonstrate that this evaporation can oscillate significantly during a day. Water vapor adsorption can be understood best as an inward or negative evaporation.

The retention curve, particularly its driest part, plays an important role in this mechanism. It determines the amplitude of the evaporation oscillations. When for high suctions in the retention curve the VWC changes more with suction, evaporation also oscillates more. Therefore, a retention curve of van Genuchten with a constant residual saturation hardly gives any oscillation. A double porosity retention curve gives the highest oscillations similar to the measurements.

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