Assessing Hydrus-2D to Simulate Soil Water Content (SWC) and Salt Accumulation Under an SDI System: Application to a Potato Crop in a Semi-Arid Area of Central Tunisia — Source link

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Irrigation and Drainage

Decision Letter (IRD-13-0152.R4)

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Assessing Hydrus-2D model to simulate soil water content (SWC) and salt accumulation under a SDI system. Application to a potatoes crop in a semiarid area of central Tunisia

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ASSESSING HYDRUS-2D TO SIMULATE SOIL WATER CONTENT (SWC) AND SALT ACCUMULATION UNDER A SDI SYSTEM: APPLICATION TO A POTATOES CROP IN A SEMIARID AREA OF CENTRAL TUNISIA[†]

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ABSTRACT

In this paper the suitability of HYDRUS-2D model to simulate volumetric soil water content in the root zone of a potatoes crop under subsurface drip irrigation (SDI) is initially assessed on the basis of a field study. Then, considering that the crop is moderately sensitive to soil salinity, the model is tested to predict the salt distribution around a buried emitter, when two different water qualities (i.e. electrical conductivity of 1.0 dS m^{-1} and 4.0 dS m^{-1}), are used during the growing season (treatments T1 and T2). Finally, the soil volume in which salts accumulates is distinguished by the model for the two treatments, for which the respective yield are not significantly different.

The results evidenced that in the root zone, simulated and measured soil water content (SWC) are fairly close. HYDRUS-2D well enough predicts the average salt concentration in the soil and evaluates the dynamic of mass-conservative solutes around buried emitters. In both the treatments, the salt concentration resulted increasing in the wetting bulb, with a maximum located towards the edge of the wetting bulb and near the soil surface.

KEY WORDS: HYDRUS-2D; subsurface drip irrigation; salt accumulation; potato crop.

[†] Évaluation HYDRUS-2D pour simuler teneur du sol en eau (CFC) et l'accumulation de sel dans un système SDI: Application à une culture de pommes de terre dans une zone semi-aride du centre de la Tunisie

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RESUME

Dans cet article, HYDRUS-2D a été utilisé pour l'estimation de la teneur en eau moyenne dans la zone racinaire de la culture de pomme de terre irriguée avec la goutte à goutte enterré sous le climat Tunisien. Ainsi, le modèle a été utilisé pour l'estimation de la distribution de sel autour de goutteur enterré, lorsque l'irrigation se produit avec deux qualités différentes d'eau caractérisées par des conductivités électriques égale à 1.0 dS m^{-1} et 4.0 dS m^{-1}, respectivement (traitements T1 et T2). Aussi, ce modèle permet de prédire le volume du sol dans lequel les sels s'accumulent. Selon le test Student (*t*), les valeurs de la teneur moyenne en eau du sol dans la zone racinaire qui sont prévu par HYDRUS-2D sont significativement corrélées aux valeurs réelles mesurées en T1 et T2. Les résultats ont également mis en évidence que le modèle est capable d'estimer la concentration moyenne de sel dans le sol et d'évaluer la dynamique des solutés de masse conservatrices autour d'un goutteur enterré. En outre, dans les deux traitements, la concentration de sel augment à l'extérieur de la bulbe, avec un maximum de concentration de sel située dans le front d'humectation et à proximité de la surface du sol. La concentration de sel dans T2 est légèrement plus élevée que dans T1. Cependant, la salinité de l'eau légèrement élevée utilisée pour l'irrigation n'a pas affectée significativement la transpiration réelle de la culture de pomme de terre et par conséquent son rendement.

MOTS CLÉS: HYDRUS-2D; irrigation goutte à goutte enterrée; accumulation de sel; culture de la pomme de terre.

INTRODUCTION

In the recent decades, countries located in arid, semiarid, and even sub-humid regions have developed irrigated areas to satisfy the increasing demands for food at world scale. Moreover, in regions with scarce water resources, it is not always possible to irrigate with waters of good quality, and therefore even saline waters are seen as an important resource. The National water strategy of Tunisia focuses on water as a major natural resource, a basic human need and a previous natural asset. Developing the potential of Tunisian agricultural sector, could allow to achieve food self-sufficiency and security. The demand of water is increasing both in agriculture and municipal sector at significant rates. It is therefore unavoidable and necessary to pay attention to the unsustainable consumption of water resources.

Soil and water salinity in arid regions are continuously increasing and globally, more than 770.000 km² of lands, representing 20% of irrigated area and about 2% of the agricultural lands (Food and Agriculture Organisation of the United Nations (FAO), 2000), are affected by secondary salinization. In Tunisia soil affected by salts at a different degree, cover about 1.5 million hectares, around 10% of the local country area, corresponding to about 30% of irrigated area (Kahlaoui *et al.*, 2011).

Several studies have been addressed toward methodologies aimed to increase water use efficiency. Optimization of irrigation management, especially in arid and semiarid regions has to face to many challenges, mainly related to the limited amount of available water resources, that frequently imposes the use of low quality waters, i.e. saline-sodic or treated waste water (Provenzano *et al.*, 2013; Selim *et al.*, 2013).

Drip irrigation systems are considered the most efficient form of irrigation, when compared with other irrigation methods. As an alternative to traditional drip irrigation is subsurface drip irrigation (SDI), defined by the American Society of Agricultural Engineers (American Society of Agricultural Engineers (ASAE), 1996) as 'the application of water below the soil surface through emitters, with discharge rates generally in the same range of the drip irrigation'. Although SDI has been experimented many time ago (House, 1920), relatively recent advance in plastic technology and SDI equipment's have made it more affordable and long lasting (Camp, 1998). SDI allows reducing health hazards when it is necessary to irrigate with waste waters and also the contamination of groundwater when the plants are correctly managed. Placing emitters below the ground surface also allows controlling weeds, to reduce soil evaporation and finally, to save water.

When traditional DI plants are used, salt accumulates on the soil surface before migrating and reaching the root zone. Saline irrigation water can be used with SDI while maintaining yields and improving water use efficiency compared with surface irrigation (Siefert *et al.*, 1975; Tingwu *et al.*, 2003). According to Phene *et al.* (1991) and Oron *et al.* (1998), SDI decreases accumulation of salts in the root zone, maintaining the yield and the fruit quality. Moreover, this irrigation system allows precise application of water and nutrients in the root zone, even if, according to Roberts *et al.* (2009), application of water below the surface can lead to upward flow of water and solutes, which accumulate at the soil surface.

Salt accumulation from SDI is of particular concern in arid and semi-arid regions where annual reference evapotranspiration is much higher than precipitation, and special management techniques are needed, especially for crops sensitive or moderately sensitive to soil salinity, to prevent mortality of germinating or emerging seeds (Hanson and Bendixen, 1995). The problem assumes a particular relevance in countries like Tunisia, between many others, where potatoes represents one of the most important food crops (Chehaibi *et al.*, 2013).

Potatoes crop is characterized by a threshold of salt tolerance, in terms of electrical conductivity of the saturated extract, EC_e, equal to 1.7 dS/m and a reduction of relative crop yield of 12% per 1.0 dS/m of increment in soil electrical conductivity (Tanji and Kielen, 2002).

Conceptual knowledge of water flow, solute transport, and root water uptake in irrigated systems has been integrated into various software package, already available to the public (Cote *et al.*, 2003). Agro-hydrological models can be considered an economic and simple tool for optimizing water use in areas where water represents a limiting factor for crop yield (Rallo *et al.*, 2010; Rallo *et al.*, 2012a), even when a certain level of crop water stress is desired in order to reduce water consumes (Cammalleri *et al.*, 2013; Rallo *et al.*, 2012b).

HYDRUS-2D/3D numerical model (Simunek *et al.*, 2006) allows to simulate water and solute movement in two or three-dimensional variably saturated porous media. Several Authors have been assessing the suitability of HYDRUS-2D to simulate the infiltration processes of water and solutes around an emitter installed below the soil surface (Provenzano, 2007; Roberts *et al.*, 2009). Anyway, a site-specific validation of the model under SDI in Tunisia, in which the use of such irrigation system has been increasing during the last years, is necessary to achieve a better knowledge of soil water and solute distribution, even to overpass the restrictions associated to the lack of devices, that quite often limits the access to field measurements.

After a site-specific validation, in fact, the model can be used to define design parameters, like the optimal pipe installation depth as well as the best combination of emitter spacing and flow rates aimed to wet, as closely as possible, the root systems. Moreover, for irrigation scheduling, model simulations permit to identify the evolution of the wetting bulb under unsaturated soil conditions, to define irrigation timing and consequently to maximize water use efficiency.

The main objective of the paper is to assess the suitability of HYDRUS-2D model to predict the average soil water content in the root zone of a potato crop irrigated with a subsurface drip irrigation plant, under semi-arid climatic conditions typical of Central Tunisia. Moreover, the ability of the model to predict the salt distribution around a buried emitter, when water of different qualities are applied from the crop development to the late stage, is tested. Finally, the soil volume in which salts accumulates around the emitter is identified as well as the effects of salt accumulation on crop yield are presented and discussed.

MATERIALS AND METHODS

Site description and field measurements

Experiments were carried out at the higher Institute of Agronomy of Chott-Mériem, Tunisia (Long. 10.5632° E, Lat. 35.9191° N, Altitude 19 m a.s.l.). The climate is semi-arid, characterized by an average annual precipitation of 230 mm and reference evapotranspiration of about 2100 mm yr^{-1}. Soil is sandy loam (clay = 8%, silt = 31% and sand = 61%) with a bulk density equal to about 1.60 g cm^{-3} for the layer 0-80 cm. Potato crop '*Solanum tuberosum L.',* cultivar Safran*,* was seeded on March 14; plants were spaced 40 cm along the rows, with distance between the rows equal to 80 cm.

Experiments were carried out in 2012 on two plots with similar management, except that for the quality of irrigation water. In particular, water for the first plot (treatment T1), characterized by an electrical conductivity EC_w = 1.0 dS m^{-1}, was provided by the Nebhana Dam, whereas the second plot (treatment T2) was irrigated with the water pumped from a well located near the experiment area, having an EC_w value of 4.0 dS m^{-1}.

The crop is irrigated by a SDI system, with a single pipe per plant row. Each pipe, having a nominal diameter of 16 mm and emitters spaced 40 cm apart, was installed at 25 cm depth; co-extruded emitters were characterized by a flow rate equal to 4.0 l h^{-1} at a nominal pressure of 100 kPa.

Standard meteorological data are recorded from a weather station placed about 300 m far from the experimental area. Irrigation was supplied once a week at the beginning of crop cycle (from March 14 to April 30) and twice a week during the crop full development stage, for a total of 14 watering. This irrigation scheduling allowed, on average, to replace the crop potential transpiration during the growing period. Soil matric potentials were measured several times during the investigation period by means of 'Watermark' probes. Measurements were taken near the emitter, at depths of 30, 45 and 60 cm. Time Domain Reflectometry (TDR) was used to determine the volumetric soil water content using a portable soil moisture monitoring system 'TRIME FM' probe, with a precision of about ±0.03 cm^3 cm^{-3}, as obtained by a site specific calibration previously carried out by Douh (2012). In each treatment, a total of six measurement tubes were installed around one emitter, as showed in Figure 1; in particular, the access tubes were located near the emitter, as well as at 20 cm and 40 cm along two directions, distant 20 cm and perpendicular to the plant row. The vertical profile of soil water content was monitored during the investigation period, by measuring every 10 cm, in the layer 0-70 cm.

Potato development cycle is between 90 and 120 days. At the end of the cycle, the maximum root density was observed between 30 and 40 cm depth for both treatments T1 and T2.

Soil electrical conductivity in T1 and T2 was determined on saturated extract (EC_e) every 15 days, using soil samples collected at three different depths, (from 0 to 20 cm, 20-40 cm and 40-60 cm) along a vertical profile near the emitter. Considering that the method is destructive, each measurement was carried out in correspondence of a different emitter. At harvesting the crop yield was determined by weighting, for both the treatments, the total production obtained in ten plants.

Model simulation description and assumptions

HYDRUS-2D, which incorporates a numerical solution of Richard's equation (Simunek *et al.*, 2006) was applied in order to simulate the distribution of water and solute around a buried emitter, so to reproduce the axis-symmetrical physical process occurring during the experiments. The simulation domain was assumed 80 cm depth and 40 cm width. A single emitter, characterized by a radius of 1.0 cm and placed at 25 cm below the soil surface, was considered as a punctual source of water and solutes. The domain was discretized with 799 nodes, corresponding to 1507 triangular elements, as illustrated in Figure 2. A constant flux density of 318 cm h^{-1}, obtained by dividing the emitter flow discharge of 4.0 l h^{-1} by the surface of a sphere having a diameter of 20 mm (slightly higher than the pipe diameter), was assumed at the emitter boundary surface during irrigation, whereas the absence of flux was considered during the redistribution processes. Even if according to Shani *et al.* (1996) depending on the emitter's flow rate, on the soil texture and on the dimension of the cavity around the emitter a rising positive back pressure could occur, the assumption to suppose a constant flux density is consistent with the quite high sand content, the very limited irrigation timing, as well as the rather low soil water content before starting irrigation, allowing to consider emitter's discharge always lower than the soil infiltration capacity (Provenzano, 2008).

Atmospheric boundary condition was considered on the soil surface, and the absence of flux along the lateral boundaries and at the bottom of the soil profile. This latter assumption is consistent with the measured values of soil water contents at 70 cm depths, that resulted almost constant ($\theta \approx 0.15$) during all the investigated period as well as by the very low value of the corresponding soil hydraulic conductivity. Moreover, because of the limited volumes supplied by irrigation or precipitation during the entire season, water has never reached the bottom of the simulation domain. Similar boundary conditions, except for the emitter flux assumed equal to zero, were considered in the interval between consecutive watering.

The van Genuchten - Mualem model (Mualem 1976; van Genuchten, 1980) was used to describe the soil water retention, $\theta(h)$, and the hydraulic conductivity, $K(\theta)$, curves:

$$\theta = \theta_r + (\theta_s - \theta_r)\frac{1}{\left[1+|\alpha h|^n\right]^m} \quad (1)$$

$$K = K_{sat} S_e^{\lambda}\left[1-\left(1-S_e^{\frac{1}{m}}\right)^m\right]^2 \quad (2)$$

With:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad (3)$$

where θ is volumetric soil water content [m^3 m^{-3}], h is pressure head [m], θ_r and θ_s are residual and saturated water content [m^3 m^{-3}] respectively, K_{sat} [m s^{-1}] is saturated hydraulic conductivity and finally *m* [-], *n* [-] and α [m^{-1}] are fitting parameters, with m = 1-1/n. Such parameters were estimated by using the RETC code (van Geunchten *et al.*, 1991), on the basis of the values of θ and h contemporarily measured in the field and assuming $\theta_r = 0$ and $\theta_s = 0.36$.

Saturated hydraulic conductivity at the soil surface, determined with a single ring infiltration experiment (data not showed), resulted equal to 16.2 cm h^{-1}.

Daily values of reference evapotranspiration ET_0 were determined on the basis of the available climatic data, according to Hargreaves-Samani formula (Hargreaves and Samani, 1982), representing a simple procedure to evaluate ET_0, that has been previously verified under Tunisian climatic conditions (Jabloun and Sahli, 2008). The dual approach coefficient suggested by FAO (Allen *et al*., 1998), was used for partitioning potential evapotranspiration, ET_p, in maximum daily values of soil evaporation, E_p, and crop transpiration, T_p. Values of the basal crop coefficient, K_{cb}, were assumed increasing between 0.1 and 1.1 during the development stage (from March 31 to April 20) and decreasing to 0.86 during the late stage (from May 20 to June 1).

For both the treatments, simulations were run from April 7 to June 1 and therefore from the begin of the development stage to the harvesting.

According to the measurements, initial soil water contents were assumed linearly variable from the soil surface to the bottom of the profile, with values ranging between 0.22 cm^3 cm^{-3} and 0.28 cm^3 cm^{-3} for treatment T1 and between 0.18 cm^3 cm^{-3} and 0.19 cm^3 cm^{-3} for treatment T2.

A sink term was used to account for water uptake by plant roots, according to a dimensionless water response function α(h), as proposed by Feddes *et al.* (1978), that includes the five variables describing the water extraction from the soil profile, whose values are indicated in Table I.

Table I. HERE

In particular, P_0 is the pressure head below which roots extract water from the soil, P_{opt} is the pressure head below which roots extract water at the maximum rate, P_{2H} is the limiting pressure head below which roots no longer extract water at the maximum rate (a potential transpiration rate of r_{2H}), P_{2L} is the limiting pressure head below which roots no longer extract water at the maximum rate (a potential transpiration rate of r_{2L}), P_3 is the pressure head below which root water uptake ceases and finally r_{2H} and r_{2L}, are the potential transpiration rates [L T^{-1}].

The root distribution is defined in HYDRUS-2D according to the model proposed by Vrugt *et al.* (2001), for which it is necessary to define the maximum radius [L], r_m, and the depth of the root zone [L], z_m, the locations of the maximum root water uptake in vertical and horizontal directions [L], respectively z* and r*, as well as two additional empirical parameters, p_r and p_z, whose values were assumed to be equal to one except for $r > r^*$ and $z > z^*$, when they become zero (Vrugt *et al.*, 2001). Table II shows the root parameters used at the different simulation steps, obtained by assuming a linear root system growth and being the final values obtained by measuring the maximum vertical and horizontal root depths at the end of the season.

Table II. HERE

Soil salinity was modelled by considering the convection-dispersion equation for non-reactive solute, neglecting any solubilization or dissolution process during the investigated period. Salinity of irrigation water was inputted into the time-dependent boundary condition, so that solutes entered into the system only during irrigation. For both the treatments, the initial salt concentration in the simulation domain was assumed slightly linearly variable from the soil surface to the bottom, with values in the range between 0.62 g dm^{-3} and 0.68 g dm^{-3}, according to EC_e values measured on April 7. In the simulations it was assumed negligible, for the examined soil-crop system, the reduction of root water uptake due to saline stress. This last assumption is consistent with EC_e values measured in both the treatments during all the simulation period, that exceptionally and only in treatment T2 resulted locally higher than the threshold values of 1.7 dS m^{-1}.

Simulated values of salt concentration [g dm^{-3}] were converted into electrical conductivity [dS m^{-1}] by dividing by a factor of 640 (U.S. Salinity Laboratory Staff, 1954). A third type mass conservative boundary condition was considered, with solute flux along the emitter boundary equal to 0.64 and 2.56 g dm^{-3} for treatment T1 and T2 respectively.

Simulations carried out with HYDRUS-2D allowed to evaluate, on hourly basis, the distribution of soil water content and salinity for each node of the considered domain. The resultant distributions of water and salinity were generated every 24 h. The average soil water contents and EC_e in the root zone, simulated by the model, were finally compared with the corresponding measured values.

Model input parameters

Figure 3 shows the soil water retention curve obtained with the values of h and θ contemporarily measured during the investigated period, in both T1 and T2 treatments. According to the regression analysis on h(θ) data pairs, the values of the fitting α and n parameters resulted equal to 0.007±0.002 and 1.613±0.140, respectively (m = 0.380). Despite the water contents punctually measured in T2 were in general lower than the corresponding measured in T1, a single θ(h) function was considered for both the treatments, as represented in Figure 3. In the figure, for each fixed soil water content, the range of variability of the soil matric potential, obtained considering the standard deviations of the fitted α and n parameters, is also indicated. As can be observed, a certain dispersion of the experimental points is evident as a consequence of measurement errors and soil spatial variability.

Figure 4a shows, for the entire growing period, the daily values of reference evapotranspiration, ET_0, whose values increased according to the climatic conditions from about 2.0 mm d^{-1} at the begin of March to a maximum of about 6.0 mm d^{-1}, at the end of May. Daily values of precipitation and irrigation are also showed in the secondary axes. Figure 4b illustrates the daily values of potential evaporation, E_p, and transpiration, T_p, the latter obtained on the basis of ET_0, assuming the basal crop coefficient, K_{cb}, variable during the investigated period, as indicated in the figure. As can be observed, T_p is practically constant for about three weeks after plantation (from March 14 to April 7) and tends to increase during the growing season (from April 7 to April 26) from 0.4 mm d^{-1} to about 4.0 mm d^{-1}, according to the values of ET_0 and K_{cb}. During the full development stage, daily values of T_p resulted variable between 3.0 and 6.6 mm d^{-1}, with an average of about 4.6 mm d^{-1}, according to the variability of ET_0. On the other hand, on the basis of the assumption and climatic data, potential soil evaporation resulted approximately constant during the entire period and equal, on average, to 0.18 mm d^{-1}.

Figure 5 shows, for the considered period, the cumulative values of precipitation, P, potential soil evaporation, E_p, and crop transpiration, T_p. As can be detected, during the growing season, cumulative transpiration was 212 mm, about three times higher than the cumulative precipitation, equal to 65.4 mm. The low value of cumulative soil evaporation at the end of the growing period, equal to only 14.3 mm, is a consequence of the small amounts of rainfall during the investigated period, as well as of the system used for irrigation.

Statistical analysis

The performance of the model was evaluated by using various quantitative measures of uncertainty, such as, the mean bias error (MBE), the root mean square error (RMSE), and the value of a parameter *t*, defined as:

$$MBE = \frac{1}{N}\sum_{i=1}^{N} d_i \tag{4}$$

$$RMSE = \sqrt{\left(\frac{1}{N}\sum_{i=1}^{N} d_i^{\,2}\right)} \tag{5}$$

$$t = \sqrt{\frac{(N-1)\,MBE^2}{RMSE^2 - MBE^2}} \tag{6}$$

where N is the number of measured data and d_i is the generic difference between predicted and measured value (Kennedy and Neville 1986).

RMSE has been used by different authors to compare predicted and measured parameters (Skaggs *et al.*, 2004; Arbat *et al.*, 2008), because of the advantage to express the error with the same units of the variable, thus providing more information about the efficiency of the model (Legates and McCabe, 1999). The lower is RMSE, the more accurate is the simulation.

To determine whether the differences between measured and simulated soil water contents and soil salinity were statistically significant, the absolute value of *t*, evaluated with eq. 6, must be lower than the critical *t* value (t_{crit}) obtained for the fixed significance level and for *N*-1 degrees of freedom. A significance level $\alpha = 0.05$ was assumed.

RESULTS AND DISCUSSION

Simulated punctual values of soil water contents versus the corresponding measured at different distances and depths from the emitter are illustrated in Figure 6, for T1 and T2 treatments. The high dispersion observed in the figure could be consequent to the circumstance that the model simulates soil water contents in each single node of the simulation domain, whereas the measurements involved a certain soil volume in which, due to the irrigation system, the gradient of soil water content around the emission point is high. Moreover, the presence of the growing tubercles inside the sensing volume, could have influenced in a different way the soil dielectric permittivity during the investigated season and consequently the measured SWCs. A general overestimation of the simulated punctual soil water contents, in fact, can be observed for both the treatments, with differences statistically significant according to a paired t-test ($\alpha = 0.05$).

On the other hand, if considering only the soil volume where the roots are concentrated, Figure 7a,b shows the temporal variability of measured and simulated soil water contents (average in the root volume) for treatment T1 and T2 respectively. As it can be observed in both the treatments, during the considered period, the mean soil water content in the root zone generally tends to decrease, with local peaks occurring after each watering or rainfall event. Considering that the cumulative seasonal irrigation depth and rainfall height (240 mm) resulted slightly higher than the total potential crop transpiration (212 mm), the water stored in the root zone during the growing period allowed to guarantee values of actual crop transpiration slightly lower than the potentials in both the treatments. As consequence of the frequent watering, especially during the full development stage, insignificant crop water deficit could have occurred in the root zone during the growing period. Moreover, the mean soil water contents simulated in the root zone resulted quite similar to those measured in the field. Table III shows the results of the statistics analysis, confirming that for both the treatments, the differences between simulated and measured soil water contents are not significant at a significance level $\alpha = 0.05$.

Table III. HERE

This result evidences that despite the poor estimation of the punctual soil water contents, the model simulates fairly well the mean values corresponding to the root zone as well as their seasonal trend. A similar result was found from Pang *et al.* (2000), who concluded that HYDRUS-2D is capable of simulating the general trend of soil water contents, even for soils characterized by lesser homogeneity than those examined.

Figure 8 shows, for treatment T1 and T2, simulated and measured values of soil electrical conductivity determined on saturated paste extract. As for the soil water content, for each simulated EC_e, a certain variability of the measured values can be observed, with higher values observed for treatment T2 (RMSE = 0.522, MBE = 0.069) compared to T1 (RMSE = 0.225, MBE = 0.051), even if in both the cases, according to a paired t-test, differences between measured and simulated values are not significant, at $\alpha = 0.05$ (for treatment T1: $t = 1.343$ and $t_{crit} = 2.034$ and for T2: $t = 0.794$ and $t_{crit} = 2.030$). As for the soil water content, the reason of a so high variability observed in both the treatments could be due to the spatial variability of EC_e measured in correspondence of different emitters, as well as to the gradient of salt concentration in the soil surrounding any buried emitter. In fact, similarly to what discussed for soil water content, EC_e values were obtained on soil samples collected along a certain segment of the soil profile and therefore should be referred to a definite soil volume rather than to a single point. Despite the differences between simulated and measured values of EC_e resulted statistically not significant, the dispersion of the points around the 1:1 line suggests that the model could be considered acceptable to predict the mean EC_e values and to evaluate the seasonal dynamic of salt concentration around the buried emitter. A similar variability was found by Roberts and *al*. (2009), even if in their results a certain underestimation of the predicted EC_e, compared to the measured values, has been observed. According to these AA., the root growth and their distribution within the soil profile, as well as the conservative or non-conservative nature of the solutes, may play an important role in simulating the seasonal dynamics of water and solute in the soil and therefore, a better knowledge of these variables, could concur to improve the simulation results.

Distributions of salt concentration in the simulation domain, obtained for both the treatments at different dates of the growing period and immediately after irrigation supply, are illustrated in Figure 9. As can be noticed, for both the examined treatments and in each considered date, the salt concentration inside the wetting bulb tends to increase with the distance from the emitter (decreasing soil water contents), with the highest salt concentration located towards the wetting front and near the soil surface.

Similar soil salinity patterns were recently obtained by Selim *et al*. (2013) on the basis of the simulations carried out with HYDRUS-2D on tomato crop. Even other AA. assessed that the highest salinity occurs midway between the emitters and towards the edge of wetted band (Laosheng, 2000; Nagaz *et al*., 2007).

Figure 9 also shows that after the last irrigation, on May 26, a certain salt accumulation occurred in both the treatments at the same depth of the emitter and at a distance of about 25 cm, with maximum values equal to 4.0 g dm^{-3} and 5.4 g dm^{-3} for treatment T1 and T2 respectively. On the contrary, no salt accumulation is observed at the bottom of soil profile, because of the very limited amount of water provided during each watering.

Figure 10a,b illustrates the profiles of salt concentration for treatment T1 obtained in two vertical sections (A and B) of the simulation domain, 5.0 cm and 25.0 cm far from the emitter, whereas in Figure 10c,d, the salt concentration profiles are referred to treatment T2 (sections A and B). As can be seen, for both the considered sections, salt concentration tends to increase progressively during irrigation season, with a substantial increment during the last period of simulation in which root water uptake is maximum. On the other hand, in both the treatments, salt profiles resulted quite different between the two examined sections, as consequence of the root distribution in the simulation domain. The simulation results evidenced that during the initial period of simulation, the punctual EC_e values in the root volume, for both the treatments, resulted in general lower than the threshold value of 1.7 dS m^{-1} after which a reduction of yield takes place, and only during the last two weeks of simulation occurred an adverse salt buildup at the edge of the root zone. For this reason and due to the limited length of the crop development stage, despite in both the treatments the salt concentration at the end of the season resulted locally slightly higher than the threshold value, the crop yield was on average equal to 27.4±2.3 t ha^{-1} and 25.9±3.1 t ha^{-1}, for treatment T1 and T2 respectively, with differences statistically not significant according to a Student t-test ($\alpha = 0.05$).

The minor and statistically not significant yield reduction observed in T2, confirms the absence or the limited saline stress during the growing phase of the crop, as well as corroborate the hypotheses to assume negligible, for the examined soil-crop system, the reduction of root water uptake due to the saline stress. Even Nagaz *et al.* (2007), comparing the productive results of potato crop irrigated with different quality waters (EC = 1.0 and EC = 3.2 dS m^{-1}) on a sandy soil, concluded that when the crop is fully irrigated (irrigation depth equal to the potential transpiration), no significant differences in yield occurred, whereas deficit irrigation treatments determined lower yields and resulted in higher salinity in the rooting zone than the full irrigation. According to this result, even using irrigation water characterized by electrical conductivity around 4.0 dS m^{-1}, despite the minor accumulation of salt at the end of the growing season, on a sandy loam soil, not significant reduction of the crop yield are observed. Of course it remains to verify, in the long period, the possible effects in terms of salinity build-up consequent to the repeated use of irrigation water characterized by identical quality, supplied with the same management, as well as to assess the effectiveness of rainfall regime to leach the salt accumulating in the soil profile.

Moreover, further investigation are necessary in order to consider, more in detail, the role of the root system variations (in space and time), when simulating water and solute dynamic around a buried emitter.

CONCLUSIONS

Results of this study indicate that HYDRUS-2D model is able to simulate, with a good accuracy, the mean soil water content in the root zone of potato crop and its seasonal trend. Moreover, the model can be considered acceptable to predict the mean salt concentration in the soil and its distribution, as well as to evaluate the seasonal dynamic of mass conservative solutes around a buried emitter. According to the results experimentally obtained by other Authors, the salt concentration tends to increase with the decreasing soil water content in the wetting bulb, with a maximum of concentration located towards the wetting front and near the soil surface.

In the investigated sandy loam soil, using irrigation water with an electrical conductivity of 4.0 dS m^{-1}, with frequent applications and volumes replacing approximately the potential crop transpiration did not affect the final crop yield compared to the treatment using better quality water, despite the slightly higher salt concentration in the simulation domain. The quite low and statistically not significant differences in crop yield are consequent to the absence or limited saline stress in the root volume during the phenological sensitive phases of the growing period.

An improvement of the simulation results, in terms of water and solute distribution, could be obtained with a more accurate schematization of the spatial and temporal dynamic of the crop root system, as well as by taking into account the conservative or non-conservative nature of the solutes. Further analysis are also necessary in order to quantify the possible long term effects of the application of saline water and the role of rainfall temporal distribution in leaching the soil profile.

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REFERENCES

Allen RG, Pereira LS, Raes D, Smith M. 1998. Crop Evapotranspiration – Guidelines for Computing Crop Water Requirements. Irrig. Drain. Pap. 56. FAO, Rome, Italy.

American Society of Agricultural Engineers (ASAE). 1996. I. Soil and water terminology. 43rd Ed., S 526., St. Joseph, Mich.

Arbat G, Puig-Bargues J, Barragan J, Bonany J, Ramirez de Cartagena F. 2008. Monitoring soil water status for micro-irrigation management versus modelling approach. Biosyst. Eng. 100(2), 286–296.

Cammalleri C, Ciraolo G, Minacapilli M, Rallo G. 2013. Evapotranspiration from an olive orchard using remote sensing-based dual crop coefficient approach. Water Resour. Manage. DOI: 10.1007/s11269-013-0444-7.

Camp CR. 1998. Subsurface drip irrigation: A review. Trans. ASAE, 41(5), 1353-1367.

Chehaibi S, Hamdi W, Abroug K.. 2013. Effects of planting depth on agronomic performance of two potato varieties grown in the Sahel region of Tunisia. J. of Devel. and Agric. Econ., 5(7), 272-276.

Cote CM, Bristow KL, Charlesworth PB, Freeman J, Cook FJ, Thorburn PJ. 2003. Analysis of soil wetting and solute transport in subsurface trickle irrigation. Irrig. Sci. 22, 65-71.

Douh B. 2012. Etude théorique et expérimentale de l'irrigation goutte a goutte souterraine sur une culture de maïs (Zea Mays L.). Ph.D. thesis. Higher Agronomic Institute of Chott Meriem, (Sousse), Tunisia, 210 pp.

Food and Agriculture Organisation of the United Nations (FAO). 2000. Global network on integrated soil management for sustainable use of salt-affected soils. Available in: http://www.fao.org/ag/AGL/agll/spush/intro.htm

Feddes RA, Kowalik PJ, Zaradny H. 1978. Simulation of field water use and crop yield. Simulation Monographs Pudoc., Wageningen, The Netherlands.

Hanson BR, Bendixen WE. 1995. Drip irrigation controls soil salinity under row crops.

California Agric. 19-23.

Hargreaves GH, Samani ZA. 1982. Estimating potential evapotranspiration. J. Irr. Drain. Eng. 108(3), 225-230.

House EB. 1920. Irrigation by means of underground porous pipes. Colorado Experiment Station Bulletin, Fort Collins, Colorado.

Jabloun M, Sahli A. 2008. Evaluation of FAO-56 methodology for estimating reference evapotranspiration using limited climatic data. Application to Tunisia. Agric. Water

Manage. 95, 707-715.

Kahlaoui B, Hachicha M, Rejeb S, Rejeb MN, Misle E. 2011. Effects of saline water on tomato under subsurface drip irrigation: Nutritional and foliar aspect. J. Soil Sci. Plant Nutr. 11, 69-86.

Kennedy JB, Neville AM. 1986. Basic statistical methods for engineers and scientists. 3rd Ed., Harper & Row, New York.

Laosheng W. 2000. Drip irrigation using low quality water. Irrig. J., 7, 18-20.

Legates DR, McCabe J. 1999. Evaluating the use of 'goodness-of fit' measures in hydrologic and hydroclimatic model validation. Water Resour. Res. 35 (1), 233–241.

Mualem Y. 1976. A new model for predicting the hydraulic conductivity of unsaturated porous media. Water Resour. Res. 12, 513-522.

Nagaz K, Masmoudi M, Ben Mechlia N. 2007. Soil salinity and yield of drip irrigated potato under different irrigation regimes with saline water in arid conditions of Southern Tunisia. J. Agron., 6(2), 324-330.

Oron G, De Malach Y, Gillerman L, David I, Rao VP. 1998. Improved saline water use under subsurface drip irrigation. Agric. Water Manage. 39, 19-33.

Pang L. Close ME, Watt JPC, Vincent KW. 2000. Simulation of picloram, atrazine and simazine leaching through two New Zealand soils and into groundwater using HYDRUS-2D. J. Contam. Hydrol. 44, 19-46.

Phene CJ, Davis KR, Hutmacher RB, Bar Yosef B, Meek DW. 1991. Effect of high frequency surface and subsurface drip irrigation on root distribution of sweet corn. Irr. Sci. 12, 135-140.

Provenzano G. 2007. Using HYDRUS-2D simulation model to evaluate wetted soil volume in subsurface drip irrigation systems. J. Irr. Drain. Eng. 133(4), 342-349.

Provenzano G. 2008. Closure of 'Using HYDRUS-2D simulation model to evaluate wetted soil volume in subsurface drip irrigation systems'. J. Irrig. Drain. Eng., 134(6), 878-879.

Provenzano G, Rodriguez-Sinobas L, Tarquis AM. 2013. Soil and irrigation sustainability practices. Agric. Water Manage. 120, 1-4.

Rallo G, Agnese C, Blanda F, Minacapilli M, Provenzano G. 2010. Agro-hydrological models to schedule irrigation of Mediterranean tree crops. Italian J. of Agrometeorology. 15(1), 11-21.

Rallo G, Agnese C. Minacapilli M, Provenzano G. 2012a. Comparison of SWAP and FAO agro-hydrological models to schedule irrigation of wine grapes. J. Irr. Drain. Eng. 138(7), 581-591.

Rallo G, Agnese C. Minacapilli M, Provenzano G. 2012b. Assessing Aquacrop water stress function to evaluate the transpiration reductions of olive mature tree. Italian J. of Agrometeorology. 17(1), 21-28.

Roberts T, Larazovich N, Warrick AW, Thompson TL. 2009. Modeling salts accumulation with subsurface drip irrigation using HYDRUS-2D. Soil Sci. Soc. Am. J., 73, 233-240.

Selim T, Berndtsson R, Persson M. 2013. Simulation of soil water and salinity distribution under subsurface drip irrigation. Irrig. and Drain., 62, 352-362.

Shani U, Xue S, Gording Kats R, Warrick AW. 1996. Soil limiting flow from subsurface emitters. I: Pressure measurements. J. Irrig. Drain. Eng., 122(5), 291-295.

Siefert WJJr, Hiler EA, Howell TA. 1975. Trickle irrigation with water of different salinity levels. Trans. ASAE, 18, 89-94.

Simunek J, van Genuchten MT, Sejna M. 2006. The HYDRUS software package for simulating two-and three-dimensional movement of water, heat and multiple solutes in variably saturated media. Technical Manual. Version 1.0. PC Progress, Prague, Czech Republic, 241pp.

Skaggs TH, Trout TJ, Simunek J, Shouse PJ. 2004. Comparison of HYDRUS-2D simulations of drip irrigation with experimental observations. J. Irrig. Drain. Eng. 130(4), 304–310.

Tanji KK, Kielen NC. 2002. Agricultural Drainage Water Management in Arid and Semi-Arid Areas. Irrig. Drain. Pap. 61. FAO, Rome, Italy.

Tingwu L, Juan X, Guangyong L, Jianhua M, Jianping W, Zhizong L. Jianguo Z. 2003. Effect of drip irrigation with saline water on water use efficiency and quality of water melons. Water Resour. Manage. 17, 395-408.

U.S. Salinity Laboratory Staff, 1954. Diagnosis and improvement of saline and alkali soils. Handbook, vol.60. U.S. Dept. Agriculture, U.S. Government Printing Office, Washington, DC, 160pp.

van Genuchten MT. 1980. A closed form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Am. J.44, 892-898.

van Genuchten MT, Leij FJ, Yates SR. 1991. The RETC Code for Quantifying the Hydraulic Functions of Unsaturated Soils. Report No. EPA/600/2-91/065. R.S. Kerr Environmental Research Laboratory, US Environmental Protection Agency, Ada, OK, 85pp.

Vrugt JA, van Wijk MT, Hopmans JW, Simunek J. 2001. One-, two-, and three dimensional root water uptake functions for transient modeling. Water Resour. Res., 37(10), 2457-2470.

Table I. Root water uptake parameters used in the simulations (Feddes *et al.*, 1978)

P_0	P_{opt}	P_{2H}	P_{2L}	P_3	r_{2H}	r_{2L}
[cm]	[cm]	[cm]	[cm]	[cm]	[cm d^{-1}]	[cm d^{-1}]
-10	-25	-320	-600	-16000	0.021	0.004

Table II. Parameters of the Vrugt *et al.* (2001) model, used for the simulations

Period	r_m [cm]	z_m [cm]	r* [cm]	z* [cm]
April 1 – April 25	20	40	10	20
April 26 - May 6	26	44	15	23
May 7 - June 1	33	48	20	27

Table III. Results of the statistical comparisons between simulated and measured SWCs

	T1	T2
RMSE	0.012	0.012
MBE	0.004	-0.004
t_{value}	1.259	0.849
t_{crit}	2.201	2.306

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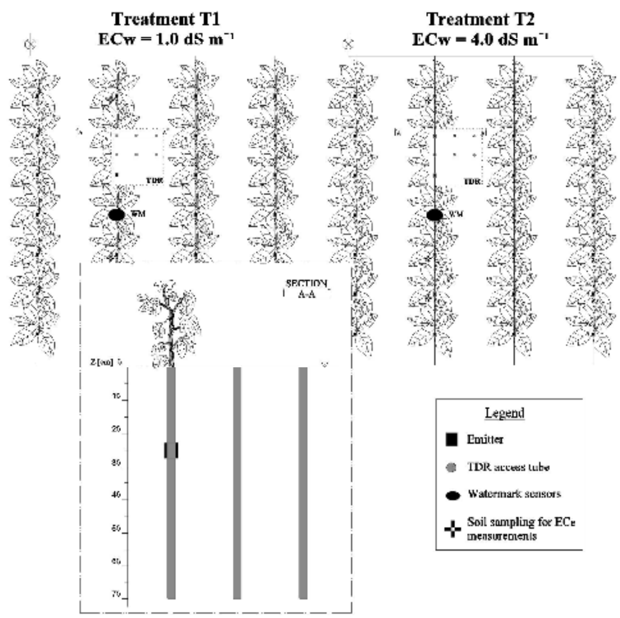

Fig. 1 – Experimental setup with indication of the measurement tools
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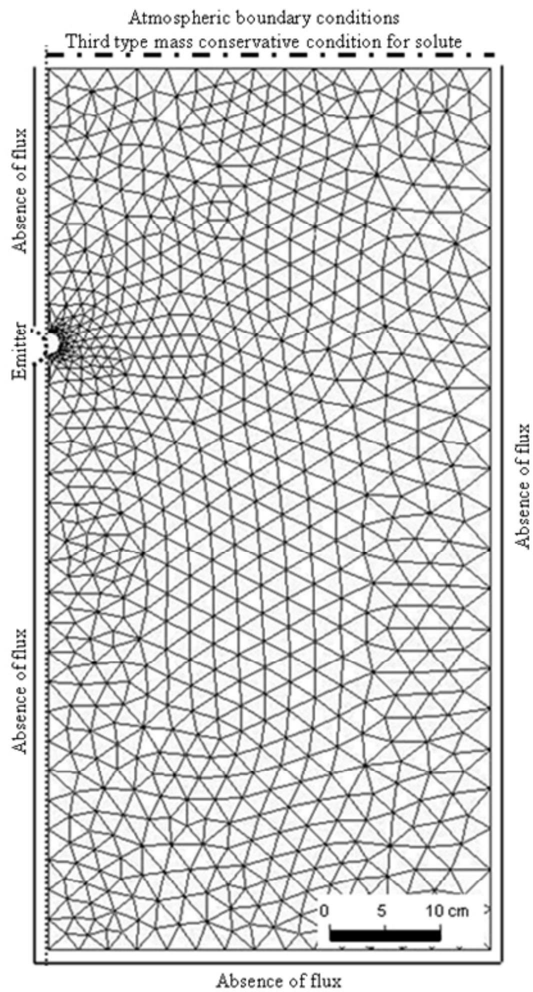

Fig. 2 – Grid used for simulations and boundary conditions
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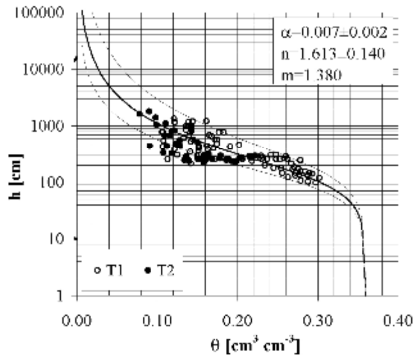

209x297mm (300 x 300 DPI)

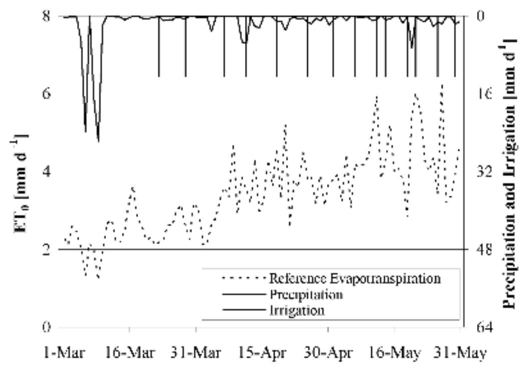

Fig. 4a - Daily values of reference evapotranspiration, ET0, precipitation, P, and irrigation heights, I, (secondary axes) during the growing season
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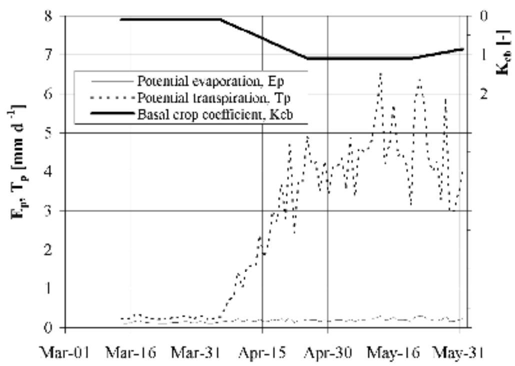

Fig. 4b - Daily values of potential evaporation, Ep, and transpiration, Tp, during the growing period. Basal crop coefficient, Kcb, is also showed in the secondary axes
209x297mm (300 x 300 DPI)

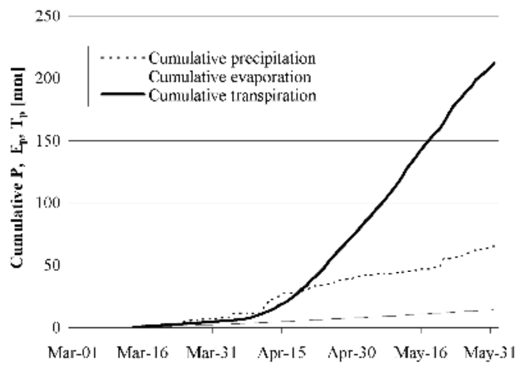

Fig. 5 - Cumulative precipitation, P, potential soil evaporation, Ep, and plant transpiration, Tp, during the growing period (from March 14 to June 1)
209x297mm (300 x 300 DPI)

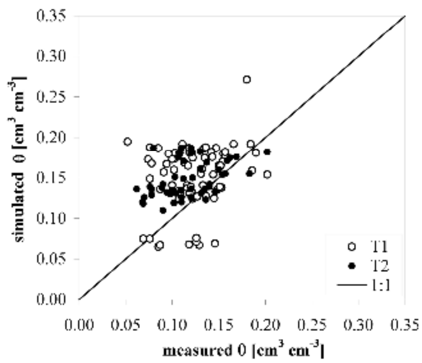

Fig. 6 - Simulated and measured soil water contents obtained at different depths and distances from the emitter for T1 and T2 treatments
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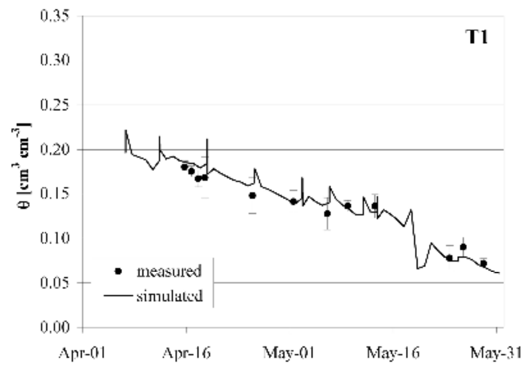

Fig. 7a - Temporal variability of the average simulated and measured soil water contents in the root zone for treatment T1
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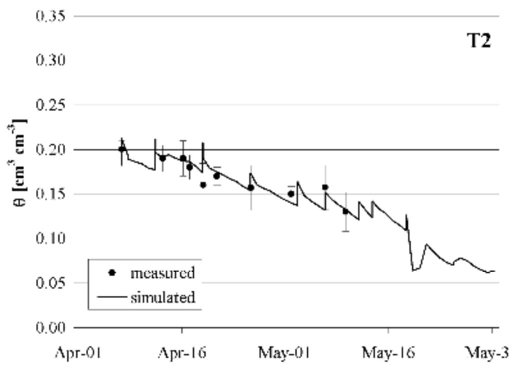

Fig 7b - Temporal variability of the average simulated and measured soil water contents in the root zone for treatment T2
209x297mm (300 x 300 DPI)

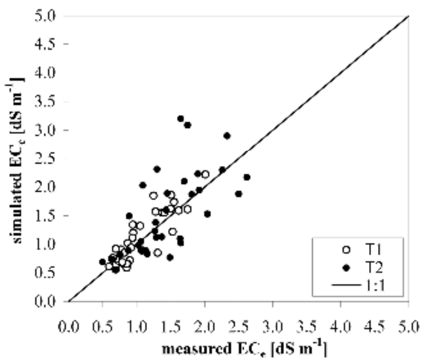

Fig. 8 - Simulated and measured average soil electrical conductivity for T1 and T2
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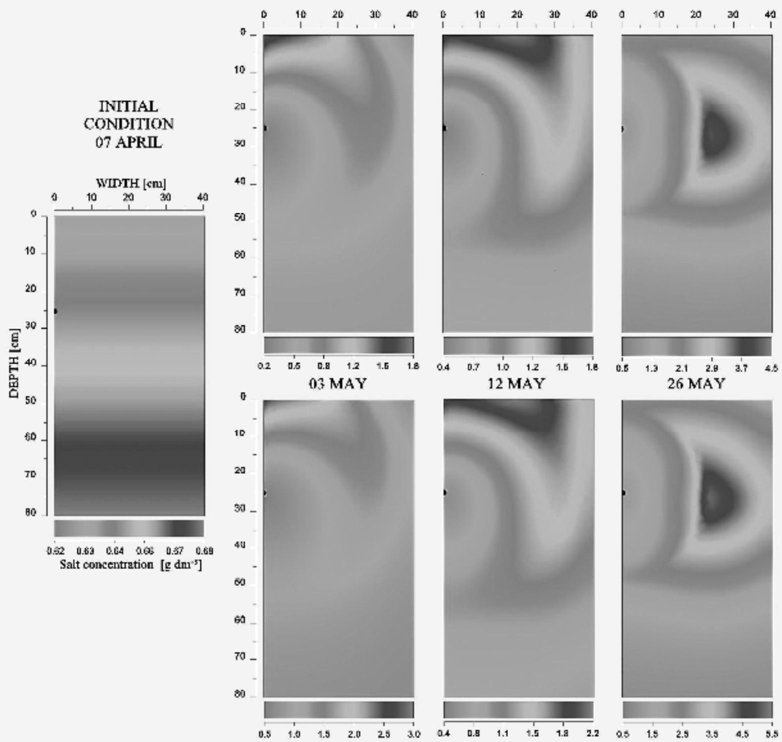

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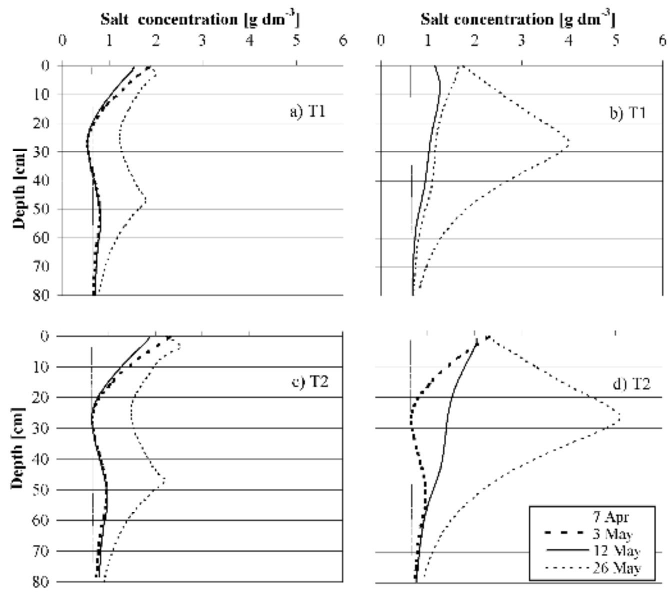

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