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HYDRUS-1D modelling of soil water regime in a rational irrigation pilot application (Nigrita, Greece)

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ABSTRACT

Accurate estimation of the hydrological features in the unsaturated zone is mandatory for the effective planning of irrigation strategies. Irrigation scheduling depends on crop and soil type as well as climatic characteristics and is usually empirically conducted. This paper simulates the water flow in order to model the soil water balance in three agricultural fields (maize, cotton, alfalfa) located in the River Strymonas basin using the HYDRUS-1D model. The model is fed with meteorological data, soil data and soil moisture measurements. After the calibration, through HYDRUS-1D's inverse solution, model results were used to evaluate the irrigation activities applied in the pilot application fields in terms of irrigation dose, irrigation interval and soil moisture variation for the cultivation period. In addition, in order to measure the efficiency of the irrigation method evaluated in this work, water productivities for all three fields were compared with productivities yielded from similar applications and experiments as well as precision irrigation experiments found around the world at similar climates with the one at Nigrita.

Keywords: Water productivity; HYDRUS-1D model; Maize; Alfalfa; Cotton; Irrigation; Pilot application; Soil water regime; Nigrita

1. Introduction

In agricultural areas, where rain is insufficient during the cultivation period, irrigation takes a significant amount of water resources prompting advances in water saving methods. A significant part of irrigation water is lost mainly by evaporation, deep percolation and surface runoff resulting in low irrigation efficiency. Introducing advanced irrigation methods and strategies can increase irrigation efficiency and therefore secure agricultural production and protect water resources in tandem [1,2].

Optimal irrigation management may vary greatly under different climates and crops. When comes to agriculture in general, irrigation scheduling, is a common part of any cultivation procedure. Optimal planning of irrigation can be achieved by rational and precision means. Precision irrigation involves applying water based on the spatial needs of a given part of the field. This greatly improves irrigation efficiency by applying the proper amount of water at the right time to meet the crop water requirements. However, precision irrigation requires accurate knowledge of field physicochemical processes for all parts within a field, which translates in the installation of expensive monitoring and control equipment that is vital for such practices. Thus, making it unfavourable under current crop yield values and production costs for a typical farmer [3–6]. In contrast,

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rational irrigation can be applied using only meteorological and crop cultivation data, which are considerably less than those used in precision irrigation.

Rational irrigation water management via consulting services and mathematical models is already widely applied with involvement of many universities and research institutions around the world, which contribute knowledge to irrigation scheduling. For example, in the area of Manitoba, Canada, irrigation is carried out using soil moisture measuring devices [7]. In the region of Castilla-La Mancha Spain, the State Institute ITAP (Instituto Técnico Agronómico Provincial de Albacete) provides data on irrigation water requirements for the regional crops, based on lysimeters and meteorological data [8]. In U.S.A., the CIMIS organization (California Irrigation Management Information System) provides data for the estimation of irrigation water requirements and scheduling of local cultivations based on daily evapotranspiration via meteorological stations and a Geographical Information System. In Greece, a pilot system of tele-information was introduced in 2005 for farmers at Crete. A Geographical Information System (GIS) database was created that contains information on soil properties. Based on these data, irrigation dose information is provided to farmers through a simple call during which they supply the system with the necessary information: location of cultivation, kind of cultivation, soil type and date of last irrigation [9]. In addition, LRI [10] presented a methodology towards rationalization of water resources management through irrigation of crops using meteorological data. This methodology was developed for a pilot area of 6,300 ha at Nigrita of the Central Macedonia Region in Northern Greece. Using data provided from meteorological stations, daily evapotranspiration was calculated for common crops of the area (maize, cotton, alfalfa). Farmers are informed of the crop water requirements of each field about the next irrigation via a dedicated web site.

Numerical modelling of the vadose zone can simulate the water balance within the soil-vegetation-atmosphere system to improve water use efficiency in agriculture, especially in case of water scarcity [11]. The HYDRUS-1D model can simulate one-dimensional variably unsaturated water flow, heat movement and transport of solutes involved in sequential first-order decay reactions by handling flexibly various boundary conditions [12]. It has been applied in several case studies and at various climatological conditions to simulate, optimize and predict the water movement and solute transport in the soil vadose zone in field and lab experiments, for example [13–18].

This paper assesses the rational irrigation practices, in order to show their importance in comparison to precision irrigation practices, in three fields located in the River Strymonas basin by simulating the water balance in the vadose soil zone for the growing season of 2008. Model results were compared and evaluated against measured values of applied irrigation, evaporation and soil moisture, that have been conducted by the Institute of Soil and Water Resources in department of LRI [10], in order to improve the understanding of the main characteristics of soil water regime, the dynamics of the rational irrigation practices and their overall viability in improving water use efficiency. The water productivity, water balance and deep percolation are discussed and compared. Furthermore, the soil-water balances and water efficiencies of this study are compared with precision irrigation and sprinkler approaches used in other experiments found around the world.

2. Materials and methods

2.1. Field experimental data

2.1.1. Study area description

River Strymonas basin has a semi-arid climate with cold winters. It receives 445 mm of average annual rainfall, 76% of which occurs from September through May. The annual pan evaporation from the water surface is approximately 1,190 mm, and the average annual air temperature is about 15°C.

Nigrita-Flampouro Agricultural Area (Fig. 1) is located at the southern part of River Strymonas basin at an altitude of around 15 m a.m.s.l and a distance of 22 km from the sea. An irrigation network operates under pressure using five pumping stations which supplies irrigation water to 6,300 hectares. The main crops in the area are maize, cotton, alfalfa and industrial processing tomato. The prevailing soil type in this region is classified as sandy loam. The physical properties of the soil at the study fields are listed in Table 1.

2.1.2. Experimental design

The three fields studied in the pilot application are located in the area which is irrigated by the respective pumping station of the pressurized irrigation network. The crop at each corresponding field is maize, cotton and alfalfa, with an area of 0.54, 3.47 and 2.37 ha, respectively. The simulation started on 01-04-2008 for all fields and ended on 18-08-2008, 30-09-2008 and 07-09-2008 for the maize, cotton and alfalfa field, respectively. Total simulation time was were 140, 183 and 160 d, respectively.

Sowing and harvest were conducted mechanically on 15-04-2008, 10-05-2008 and 18-0-2008, 30-09-2008 for the maize and cotton respectively. The alfalfa cultivation lasted four growth period starting on 10-05-2008 by the first cutting and then was cut another four times on 14-06-2008, 14-07-2008, 14-08-2008 and 07-09-2008.

Water-saving irrigation implemented in this study involved multiple irrigations based on the farmers experience and decision and also by taking into account the calculated ET_c, precipitation events and precipitation forecasting. When rainfall supplied significant amount of water, irrigation was reduced in quantity by subtracting the effective rainfall [20]. For example, when rain was predicted in the following days from an irrigation, irrigation was applied at a lower quantity or not at all, depending on the farmers experience and decision.

2.1.3. Measurements and analysis

Telemetric agro-meteorological stations and Type A evaporation pans were placed at the three pumping stations. The recorded meteorological parameters were precipitation, temperature, relative humidity, wind speed and direction

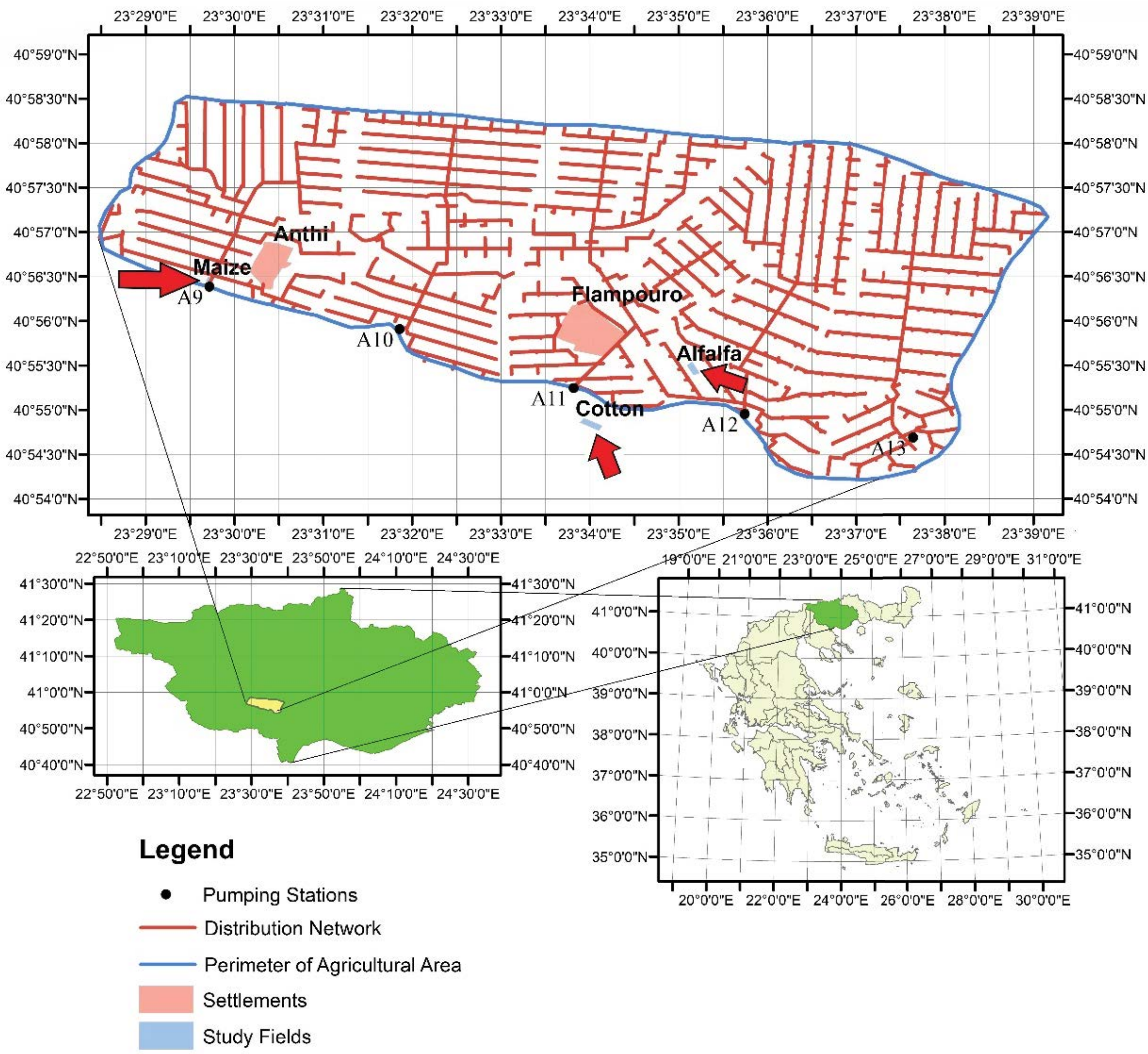

Fig. 1. Nigrita-Flampouro Agricultural Area (outlined by the blue line) and the study fields (pointed with the red arrow); the red lines depict the underground pressurized distribution network.

Table 1
Calibrated hydraulic conductivity and van Genuchten parameters used in the three HYDRUS-1D models

Crop	Saturated water content, θ_s	Residual water content, θ_r	a	n	m	Saturated hydraulic conductivity, K_s
	cm^3/cm^3	cm^3/cm^3		1/m		cm/d
Maize	0.45	0.11	2.38	1.67	0.4	0.404
Cotton	0.45	0.07	1.86	1.67		0.286
Alfalfa	0.45	0.05	3.43	1.67		0.327

and sunshine duration, recorded daily while evaporation was recorded every 10 d. Soil samples were collected from every 10 cm of depth and then analysed in the lab using the Bouyoucos method to determine the percentages of sand, silt and clay while the saturated hydraulic conductivity, K_s, was measured in situ with a Guelph permeameter 200800 K1 device of Soil Moisture Equipment S.A. The hydraulics parameters in the soil column were determined by regression analysis based on the soil moisture characteristic curve and the van Genuchten equation. Soil moisture measurements were taken by field experiments that conducted from early April to late August. A 10 cm diameter hole was dug to 1 m depth and a pipe was installed to take measurements of soil moisture every 10 cm of depth at regular intervals by DIVINER-2000 of SENTEK AUSTRALIA LTD. Also, two wells of 2 m total depth were placed near the edge of the field to monitor the water table level.

Three measures of water productivity (WP, kg of crop yield per m^3 of water) were calculated and compared to further evaluate the productivity of the pilot application, in terms of water use efficiency: the irrigation water productivity (WP_I), which is the ration of crop yield to the amount of irrigation; the input water productivity (WP_{IR}), which is the ration of crop yield to the amount of irrigation water plus rainfall; and the ET water productivity (WP_{ET}), which is the ration of crop yield to ET_c.

2.2. HYDRUS-1D model setup

2.2.1. Flow modelling

The HYDRUS model [21] applies the Galerkin finite element method to discretise the soil profile in vertical one-dimension domain and simulate the unsaturated and transient water movement under the presence of a crop.

The water movement in the vadose soil zone is described with the mixed form of Richard's equation [Eq. (1)]:

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z}+1\right)\right]-S(z,t) \tag{1}$$

where θ is the volumetric water content (cm^3/cm^3); h is the water pressure head (cm); t is time (d); z is the vertical coordinate (cm); K is the hydraulic conductivity (cm/d); and S is root water uptake ($cm^3/cm^3/d$). The calibrated hydraulic conductivity and van Genuchten parameters are presented at Table 1.

In this HYDRUS application, the soil-hydraulic functions introduced by van Genuchten [22], who used the statistical pore-size distribution model presented by Mualem [23], are used to obtain a predictive equation for the unsaturated hydraulic conductivity function in terms of soil water retention parameters. The van Genuchten expressions are formulated as:

$$\theta(h)=\begin{cases}\theta_r+\dfrac{\theta_s-\theta_r}{\left(1+|ah|^n\right)^m} & h<0\\ \theta_s & h\geq 0\end{cases} \tag{2}$$

$$K(h)=K_sS_e^l\left[1-\left(1-S_e^{\frac{1}{m}}\right)^m\right]^2 \tag{3}$$

$$S_e=\frac{\theta-\theta_r}{\theta_s-\theta_r} \tag{4}$$

where θ_s is the saturated water content (cm^3/cm^3); θ_r is the residual water content (cm^3/cm^3); K_s is the saturated hydraulic conductivity (cm d^{-1}); S_e is the effective water content; and α, n, m are relative empirical parameters, where $m = 1–1/n$ and l is the pore-connectivity parameter and is assumed to be about 0.5 as an average for many soils.

The boundary conditions in the soil column were set up in the HYDRUS environment. Uniform soil moisture of 0.35 cm^3/cm^3 was used as the initial condition of the simulation considering adequate precipitation events prior to the simulation period as well as the soil moisture measurements.

The upper boundary condition was subjected to the atmosphere boundary condition with surface runoff boundary condition and includes the inflow from total water inputs (TWIs), surface runoff and the outflow from evaporation with specified daily values of precipitation, irrigation, max and min temperature and other measured meteorological parameters and is given by:

$$-K\left(\frac{\partial h}{\partial z}+1\right)=q_0(t) \quad z=0 \tag{5}$$

where q_0 is the net inflow or outflow.

The lower boundary condition was simulated as a free drainage condition, as the water table was never observed at any of the two wells placed in each field.

$$\frac{\partial h}{\partial z}=0 \tag{6}$$

2.2.2. Evapotranspiration and irrigation

The potential evapotranspiration was calculated using the Penman–Monteith equation as recommended by Allen et al. [24]. Actual evaporation (E_a) is calculated by HYDRUS based on potential evaporation (E_p) and soil water content using Beer's Law [25,26]. Potential evaporation is calculated using Eq. (7).

$$E_p=ET_0e^{-k\text{LAI}} \tag{7}$$

where ET_0 is the reference evapotranspiration (cm), k is the constant for the radiation extinction by canopy and LAI is the leaf area index adapted from data obtained by the study of Antonopoulos [27] for maize, [28] for cotton and [29] for alfalfa.

Root growth was modelled using the Verhulst–Pearl logistic growth function [Eq. (8)] supposing that 50% of the growth is reached at the middle of the growing season. The root growth coefficient is expressed as:

$$f_r(t)=\frac{L_0}{L_0+\left(L_m-L_0\right)e^{-rt}} \tag{8}$$

where L_0 is the initial value of the rooting depth at the beginning of the growing season, r is the growth rate, L_m is the maximum rooting depth and t is the time.

HYDRUS couples the aforementioned growth function with the root distribution model introduced by Hoffman and van Genuchten [30]. The potential water uptake distribution function in the soil root zone, $b(x)$, is given by:

$$b(x)=\begin{cases}\frac{1.66667}{L_R} & x>L-0.2L_R\\ \frac{2.0833}{L_R}\left(1-\frac{L-x}{L_R}\right) & x\in\left(L-L_R,L-0.2L_R\right)\\ 0 & x<L-L_R\end{cases} \tag{9}$$

where x is the soil coordinate measuring from the bottom of the soil column, L is the maximum length of soil column and L_R is the root depth. Therefore, the root depth, L_R, is the product of the maximum rooting depth, L_m, and the root growth coefficient, f_r [31].

Actual transpiration (T_a) is considered equal to the root water uptake assuming that plants use a minor water quantity for tissue building. Actual transpiration was calculated using the Feddes water uptake reduction model [32].

$$T_a=S(z,t)=a(h,z)\beta(z)T_p \tag{10}$$

where S is the water volume removed from the soil volume per time by plant water uptake, α is the root water uptake stress response function (–), $\beta(z)$ is the function of root water uptake distribution (cm^{-1}) and T_p is the potential transpiration (cm).

2.3. Model evaluation

HYDRUS-1D's inverse solution was used to obtain the presented results. This solution uses an objective function F which is minimized during the parameter estimation process [33]. This method uses measured and calculated space-time variables, in this case soil water content at different depths and/or time in the flow domain, to minimize the objective function F using the Levenberg–Marquardt nonlinear minimization method, which is a weighted least-squares approach based on Marquardt's maximum neighbourhood method [34]. The method was found to be very effective and has become a standard in nonlinear least-squares fitting among soil scientists and hydrologists [35,36].

Simulated values of water content at representative soil columns depths and cumulative evaporation fluxes were compared with the observed data for the all three fields during the 2008 season. The model assessment was made between observed and simulated data using the weighted coefficient of determination, R^2_w, and the weighted root mean square error, RMSE$_w$:

$$R^2_w=1-\frac{\sum_{i=1}^{n}\left(w_i\left(\text{obs}_i-\text{sim}_i\right)^2\right)}{\sum_{i=1}^{n}\left(w_i\left(\text{obs}_i-\overline{w.\text{sim}}\right)^2\right)} \tag{11}$$

$$\text{RMSE}_w=\sqrt{\sum_{i=1}^{n}w_i\left(\text{obs}_i-\text{sim}_i\right)^2} \tag{12}$$

where obs$_i$ is the observed value at a specific depth, sim$_i$ is a simulated value at a specific depth and w_i is the weight factor at a specific depth.

A higher weight of 10 was assigned at a 20 cm deep node and the low weight of 1 was assigned at the node of the bottom of the soil. This was done in order to closely capture the irrigation event made by the growers.

3. Results

3.1. Model assessment

Simulated water contents at 20 cm depth for all fields, where the influence of the precipitation and irrigation events can be easily noticed, and at the bottom of the soil column (60 cm for the maize and cotton fields and 100 cm alfalfa field, respectively) matched well with the observed data during the 2008 growing season (n = 46, R^2_w = 0.9242, RMSE$_w$ = 0.066 for the maize field; n = 56, R^2_w = 0.9476, RMSE$_w$ = 0.0191 for the cotton field; n = 58, R^2_w = 0.9608, RMSE$_w$ = 0.0167 for the alfalfa field) and responded well to the precipitation and irrigation events (Fig. 2). This proves a strong correlation between observed and simulated water content. The water input events produced water content variations at the 20 cm depth from large (cotton field) to minimal (maize and alfalfa fields) in contrast to the water content at the bottom of each soil column, where the early precipitation events increased the soil water content almost to 0.45 at all three fields. Water content at 20 cm reached the minimum values of 0.12, 0.18, and 0.26 during crop growth and the maximum values of 0.45, 0.45, and 0.43 due to the occurrence of precipitation events at the time before the crop growth, for the maize, cotton and alfalfa fields, respectively. Water content at bottom of the soil column did not present any variation attributed to irrigation events (Fig. 2) and reached the minimum values of 0.2, 0.22, and 0.31 during crop growth decreasing steadily from the maximum values for the maize, cotton and alfalfa fields, respectively. All the results of the calibration were statistically significant at the 0.01 confidence level.

In addition, simulated evaporation agreed well with the cumulative observed values of 14.13, 19.46 and 11.51 cm, respectively for each field. The correspondence between observed and simulated evaporation fluxes was very good during all simulations.

3.2. Surface runoff

Surface runoff is a direct result of the difference between irrigation and infiltration rates, excluding the one caused by excessive rain, in this case, at April and May. Surface runoff was presented at significant precipitation events and during irrigation. Not all irrigation events resulted in surface runoff as shown in the alfalfa runoff plot in Fig. 3 since they were planned in timely manner. The total surface runoff was simulated, from highest to lowest values, for the cotton, maize and alfalfa fields with values of 8.18, 4.4 and 2.12 cm, respectively. In regard to the surface runoff caused by precipitation events at the beginning of the simulation period, only that at the maize field was substantial and accounted in 4.35 cm, about half of the total simulated surface runoff depth. At the rest of the fields, cotton and alfalfa, that particular runoff was minimal due to different infiltration rates at each field. Observed surface runoff could not be measured due to the type of the fields but it

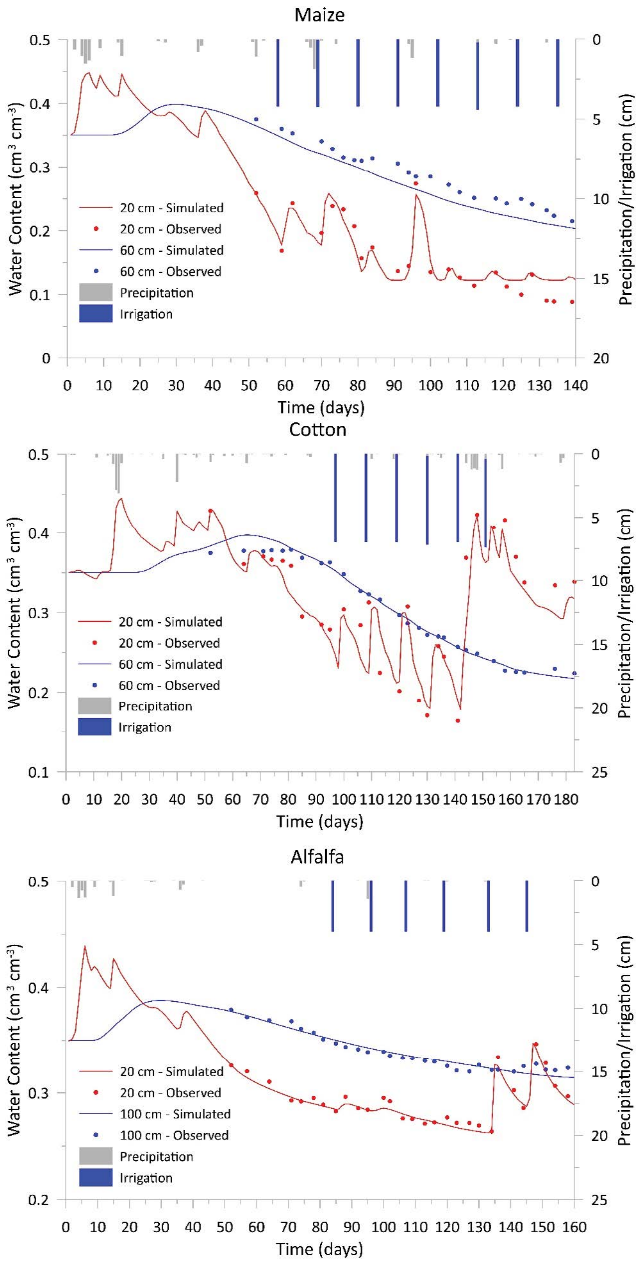

Fig. 2. Simulated and observed water content at 20 cm and bottom of each respective soil column.

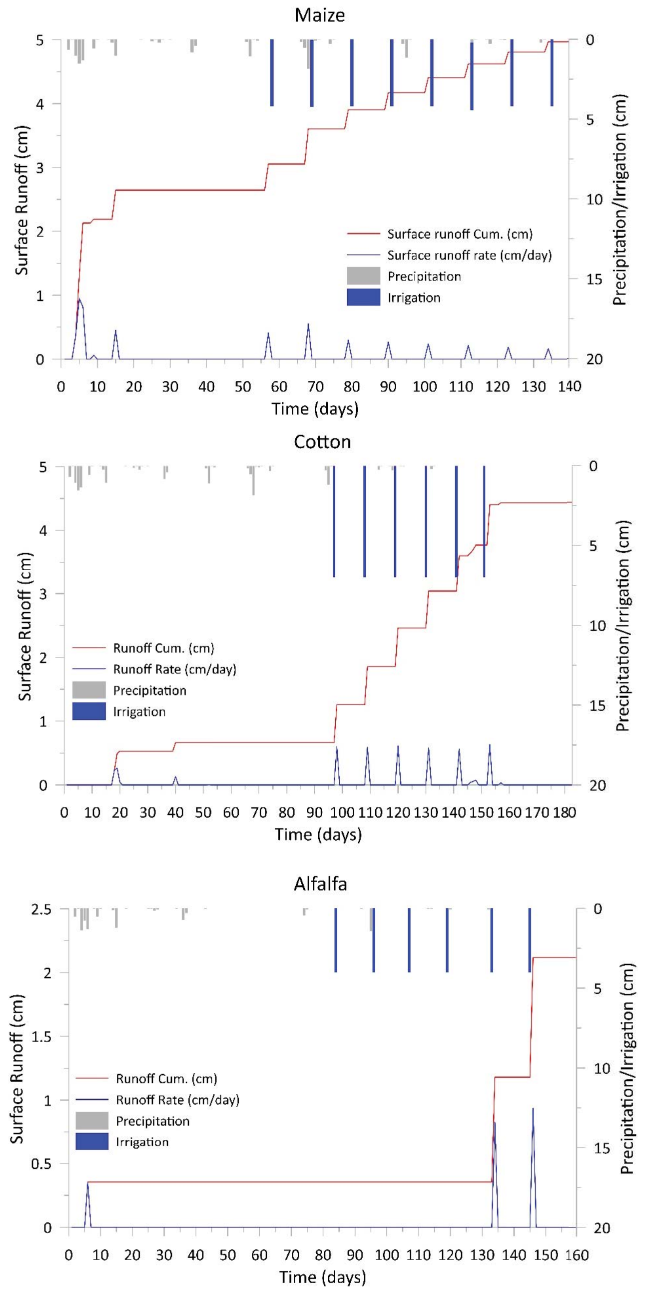

Fig. 3. Simulated runoff rate and cumulative values for each field.

was witnessed by the farmers who owned the fields during irrigation, in terms of occurrence. The observed runoff occurrences matched well with those simulated at which farmers slightly over-irrigated mainly for the maize and cotton fields and for the last two irrigations events at the alfalfa field where over-irrigation was relatively significant.

3.3. Evapotranspiration

Simulated transpiration started after introducing crop growth increasing gradually. Each modelled field had a different behaviour root water uptake since a different crop is cultivated in each field. The maximum transpiration values of 0.59 and 0.64 cm/d were reached at 63 and 129 simulation days for the maize and cotton fields, respectively. At the alfalfa field the maximum transpiration of 0.48 cm/d were reached in 149th day of simulation, during the four and final growth cycle. It is notable that at the cotton field in 161st day the transpiration gradually decreases, this is due to a technique with which the farmers do not apply irrigation to stress the plant so it can reach maturity earlier to help in collection. Also, cultivation at the maize and alfalfa fields starts from 0 simulation day when the maize was sowed and due to alfalfa being a multi-year cultivation, respectively. In respect to the alfalfa field, the first cutting is start of the first growth cycle as stated earlier. The growth cycles themselves are not clearly evident. This is also stated in the bibliography regarding alfalfa cultivation [19]. Cumulative simulated transpiration rises rapidly at all fields, when crop growth is introduced. Alfalfa produced a step-like cumulative transpiration curve, attributed to the growth cycles. Cumulative transpiration amounted in 28.69, 42.35 and 15.07 cm for the maize, cotton and alfalfa fields, respectively. Simulated evaporation values rose gradually for the maize field. For the cotton field a reduction was presented during the bulk growth. For the alfalfa field evaporation followed the fluctuations of the transpiration. The average values of simulated evaporation for the three fields are 0.1, 0.11 and 0.07 cm/d while the maximum values are 0.33, 0.3 and 0.17 cm/d, which were reached 125, 165 and 50 d, respectively. Cumulative values reached approximately 14.05, 19.46 and 11.4 cm at the end of each simulation. The total ET amounts for each field are 42.8, 62 and 26.41 cm with an average rate of 0.31, 0.34 and 0.17 cm/d for the maize, cotton and alfalfa field, respectively.

3.4. Soil water content change

Simulated soil water content changes in the root zone responded well to rainfall and irrigation events. It varied relatively quickly with abrupt increments during any water input. At all fields the precipitation events increased the soil water content in the root zone considerably, afterwards the root water uptake was introduced started to drop pretty quickly. During that time, major water input caused an abrupt but small change in the soil water storage in the root zone. Small water inputs, for example, <1 cm, had no effect in the root zone. As shown in Fig. 2, the soil water content presented a decreased affinity to respond to water inputs at the bottom of the soil column compared with the one at 20 cm depth. From Fig. 5, the soil water content in root zone for the maize and cotton fields rose up from 0.21 to 0.24 at the most during the early precipitation events while at the alfalfa field the soil water content rose up by 0.05 reaching 0.4. In addition, the total soil water change of each field was 10.63, 9.16 and 5.5 cm reduction, respectively.

3.5. Water percolation

Water percolation from the bottom of the soil column (Fig. 6) closely corresponded with precipitation and irrigation events. Precipitation events did not result in any significant cumulative percolation rate during each respective cultivation season, for example, above 10 cm. This was also presented by the irrigation events for the cotton and alfalfa fields in contrast to the maize field, where noticeable percolation rates were induced by irrigation. The average rates of downward percolation are about 0.03, 0.023 and 0.045 cm/d for three fields, respectively. The largest maximum rate value is 1.2 cm/d presented at the maize field, the cotton and alfalfa fields follow with values of 0.07 and 0.09 cm/d, respectively. The cumulative amount of percolated water at the bottom of each respective soil column is 4.5, 4.18 and 7.25 cm for each field respectively.

4. Discussion

Maize and cotton are typical water consuming crops, among others, followed by alfalfa in this case. Sufficient soil water contents in the root zone are critical for the growth and yield of any cultivated crop. The average grain yield of maize, cotton and alfalfa in Greece is 10,407; 2,630 and 13,660 kg/ha, respectively [37]. The grain yields of the three pilot application fields are 13,480; 3,400, and 13,650 kg/ha, respectively. The yield of the maize and cotton are beyond the average while the yield of alfalfa approximately matches the average.

The TWIs for each field were 48.3, 65.1 and 33.5 cm while irrigation water was 33.6, 42 and 24 cm for each field respectively. The amount irrigated by crop growers was relatively higher than the optimal amount suggested by LRI [10] for the maize field and alfalfa fields while slightly higher for the cotton field. However, the TWIs in this case was substantially lower than the amounts the farmers used to irrigate at the study area during previous years without the method suggested by LRI [10], thus reducing the total irrigation amount by 50%, 17% and 34%, respectively even despite the slight over-irrigation.

Simulated runoff was relatively higher than suggested by LRI [10] for the maize field but were substantially lower than that observed by farmers before LRI's pilot application at the selected fields. This indicates that different water management techniques resulted in different total surface runoff patterns and depths. Total surface runoff during the cultivation period of each field accounted for 10.4%, 6.8% and 6.3% of the TWIs for each field respectively. However, most of the surface runoff is attributed to the early precipitation events. In similar pilot applications [38–40], and the FIGARO project, for maize using deficit irrigation, almost no surface runoff during the cultivation while applying full irrigation doses. Tsakmakis et al. [41] in a precision irrigation experiment for cotton, compared different simulated full and deficit irrigation scenarios via AQUACROP and CROPWAT for both sprinkler and drip irrigation methods, also reported almost no surface runoff in the sprinkler applied irrigation in addition to Lamm et al. [42] for alfalfa.

Water inputs of an excessive manner are directly linked with high percolation rates. In this study, the total percolation accounted for about 9.3%, 6.5% and 21.8% of TWIs for each field respectively. Experiments for maize [39,43], cotton [41] and alfalfa [42,44] with similar setups reported almost no percolation rates during two successive growing seasons outside heavy precipitation events. The current differences in deep percolation and surface runoff in comparison with previous unsupervised irrigation practices showed that irrigation management significantly decreased runoff losses in all three fields, despite the farmer's deviation from the suggested irrigation doses at the end of the growing season for the alfalfa field.

Simulated evapotranspiration (Fig. 4 and Table 2) in this pilot application has been similar with the one suggested by LRI [10]. Studies have shown that over-irrigation results in water ponds with significant standing water depths which leads to high water losses by evaporation. Planning many irrigation events with shorter doses reduces runoff, evaporation

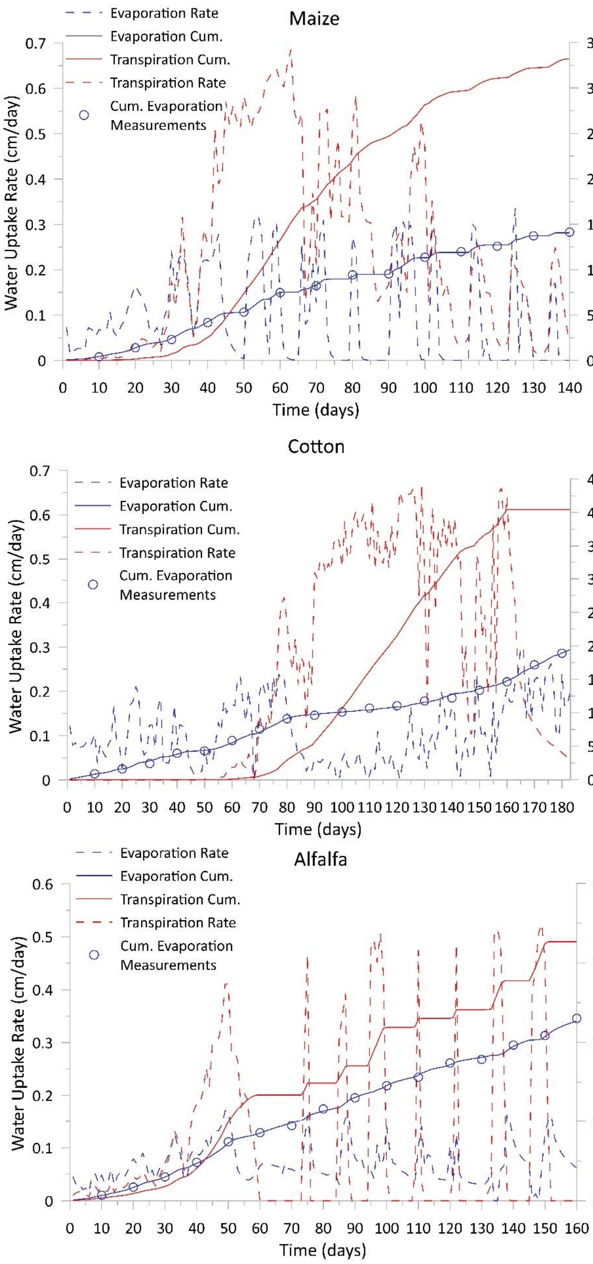

Fig. 4. Simulated evaporation, transpiration and cumulative values for each field.

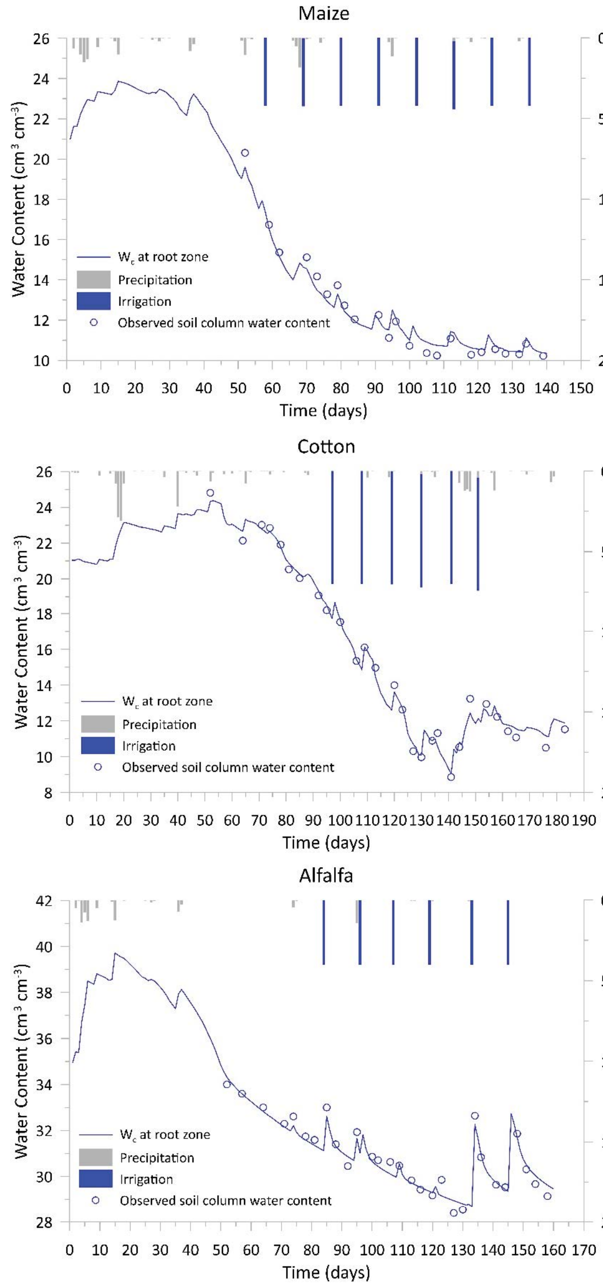

Fig. 5. Simulated and observed water content in the root zone of each respective soil column.

and percolation losses. In this study, simulated ET_c accounted for 98%, 97.5% and 82.5% of TWIs for each field respectively. These values are quite comparable to experiments with similar setups to this pilot application. Greaves and Wang [39] measured ET_c to be 100%, 40.5% (due to heavy rain) and 99% of TWIs during three maize irrigation experiments while applying full doses. Tsakmakis et al. [41] and Lamm et al. [42], Kazumba et al. [44] reported ET_c almost equal to TWIs for their base experiments for cotton and alfalfa respectively.

Water productivity can be used to evaluate the water use efficiency in a field and to compare the produced efficiency under other cultivation conditions. The WP_I, WP_{IR} and WP_{ET} were 4.01, 2.79, 3.15 for the maize field, 0.81, 0.52, 0.55 for the cotton field and 5.69, 4.07, 5.17 for the alfalfa field, respectively (Table 2). These values are similar or higher to those of similar studies which indicates a similar or more rational use of water respectively, despite using a less sophisticated irrigation approach and less controllable environment. The WP_I, WP_{IR} and WP_{ET} for maize [39] derived as mean values for the three experiments they conducted are 3.13, 1.63 and 2.17 while at Paredes et al. [40] are 2.15, 1.5 and 2.55, respectively. For cotton, derived as mean values of 0.81, 0.65 and 0.87 respectively, between the 2013 and 2015 base experiments and the AQUACROP and CROPWAT estimations. For alfalfa, derived as mean

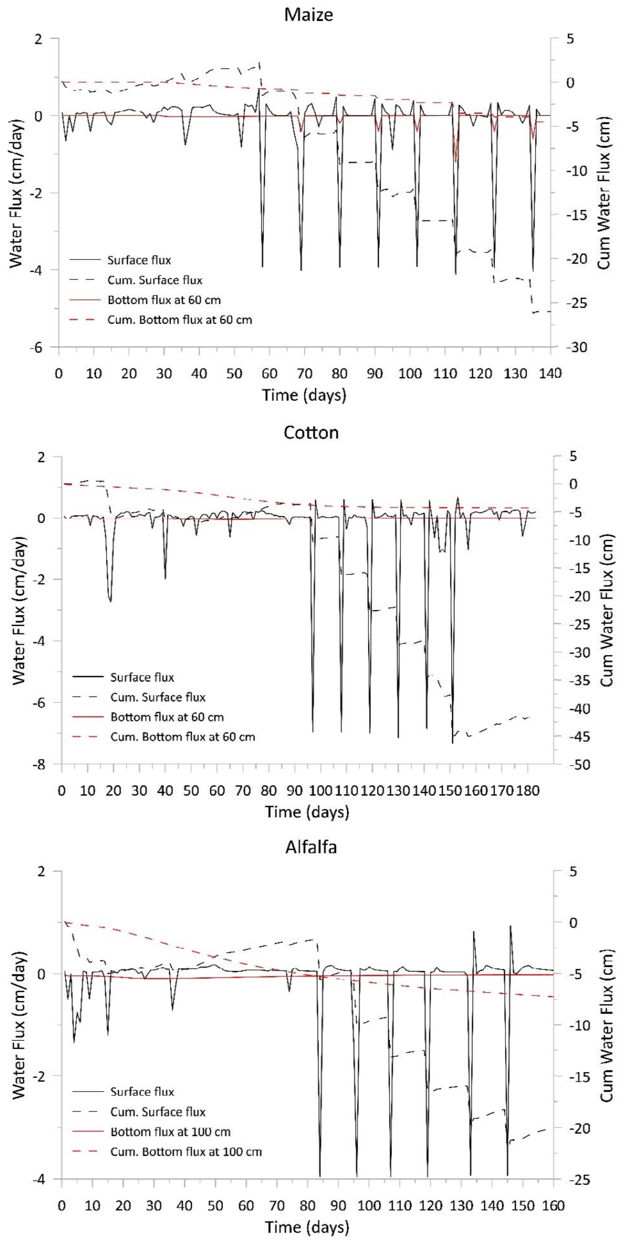

Fig. 6. Surface, bottom flux and cumulative values for each respective soil column.

values 3.43, 2.06 and 2.04 from the study of Lamm et al. [42] for three successive years 2005–2007 while applying full irrigation doses with subsurface drip irrigation.

Maximizing WP may be more profitable for crop growers in dry or semi-dry areas, where water availability is the most important crop growing factor, in areas such as Nigrita, Northern Greece. During the last decades, non-rational irrigation significantly reduced water resources since crop fields located at Nigrita. Increasing the WP by adopting rational irrigation methods can assist in slowing the reduction of water resources but also in minimizing soil nutrient losses and the degradation of the water resources quality due to nitrogen and phosphorus surface runoff and percolation, at a much lower cost than precise irrigation in terms of equipment acquisition and ease of appliance.

5. Conclusions

The HYDRUS-1D simulation model was used to evaluate water flow and water losses during one growing season of maize, cotton and alfalfa in Nigrita, Northern Greece under the semi-arid conditions in the presence of a deep groundwater table. HYDRUS-1D has been proven to be a reliable tool to evaluate water movement in agricultural fields under various irrigation schemes and different crops around the world, despite considerable demand for input data. In addition, HYDRUS-1D was found useful in evaluating water balance components of the pilot irrigation application of maize, cotton and alfalfa fields in the area of Nigrita, Northern Greece.

Excess irrigation triggers the runoff and leaching losses that result in fertilizer loss. As rainfall events generally do not happen during the growing season irrigation is need to fulfill the crop water requirements. The soil water content was lowered but not significantly except for the cotton field where the growers deliberately apply water at lower depths than estimated in order to aid the plant collection. The results suggest that the proposed by LRI irrigation scheduling with doses estimated with data received from automatic meteorological stations set near the fields succeeded in lowering the actual watering amount to plant requirement needs pushing the irrigation practices at the selected fields towards rationality.

This study applies three measures of crop productivity namely WP_I, WP_{IR} and WP_{ET} which act as environmental indicators for the rational use of water and were compared

Table 2
Simulated (using HYDRUS-1D) components of water balance (in cm) in the soil column and water productivities (WP) (kg/m^3) for three pilot irrigation application fields in Nigrita-Flabouro Agricultural Area, Northern Greece

Field	Input (cm)		Output (cm)				δ (error)		Water productivities (kg/m^3)		
	R	I	SR	ET	SSC	P	cm	%	WP_I	WP_{IR}	WP_{ET}
Maize	14.7	33.6	5.0	47.3	–10.63	4.5	2.1	4.4	4.01	2.79	2.85
Cotton	23.1	42.0	4.4	63.5	–9.16	4.2	2.2	3.3	0.81	0.52	0.54
Alfalfa	9.5	24.0	2.1	28.4	–5.49	7.3	1.2	3.6	5.69	4.07	4.80

Notes: R – rainfall, I – irrigation, SR – surface runoff, ET – evapotranspiration, SS – soil storage, P – percolation, δ – total water balance error, WP_I – the ratio of grain yield to the amount of irrigation water, WP_{IR} – the ratio of grain yield to the amount of irrigation water plus rainfall, WP_{ET} – the ratio of grain yield to crop ET.

with the same type of those derived for drip and/or deficit irrigation on maize, cotton maize, cotton and alfalfa. Other factors, such as the availability of the water resources during the cultivation period, the irrigation cost per m^3 as well as agricultural infrastructure costs, are not integrated. These factors vary significantly among regions, countries and continents. Consequently, future research on the field should be heading towards a more sustainable framework by incorporating in the water footprint calculation process the economic dimension and introducing local level socio-economic constraints, with an ultimate goal to obtain an optimal, environmentally and economically viable water footprint for each region.

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