Soil Salinity and Water Table Data in Irrigated Farm Lands in the Arid Aral Sea Basin, Uzbekistan, explained with a Salt Leaching Model including the Determination of Actual Evaporation and Capillary Rise.

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Abstract

Soil salinity, water table depth, irrigation, and other relevant data were collected in on farm irrigated lands in the arid Aral sea basin at the Cotton Research Institute, Urgench, in the Khorezm region of northwest Uzbekistan. The crops grown were Cotton, Maize, Rice and wheat. The data are explained with the free software pertaining to the LeachModE model designed with the purpose to explain the salt leaching processes under such conditions in dependence of the irrigation, crop, water table, and soil conditions. The model finds the leaching efficiency of salts and the capacity of the subsurface drainage system as well as the actual evapotranspiration and the capillary rise. In this paper, the results are presented.

Contents

1. Introduction

In Uzbekistan, cotton (*Gossypium hirsutum* L.), winter wheat (*Triticum aestivum* L.), maize (*Zea mays* L) and rice (*Oryza sativa*) are the predominant crops in the irrigated agriculture system grown in 1.2, 1.4, 0.4 and 0.42 million ha area, respectively [*Ref. 1*]. These crops plays a major role in the country's economic development. Water management is the most important issue constraining and threatening the productivity and sustainability of all these crops as farmers irrigate using a huge amount of irrigation water (rice >30,000 m^3 and for other crops >6,000 m3 ha^{-1}) *[Ref. 2, Ref. 3].* An excessive use of irrigation water raises groundwater tables and this has increased secondary soil salinization and increased soil salinity. About 67% of the fields in Uzbekistan have groundwater levels above the threshold values that induce secondary salinization *[Ref. 4]*.

In irrigated agriculture, salts are brought to the field with irrigation water (primary salinization) and/or when not leached out and removed (naturally to the underground or by a subsurface drainage system), accumulate in the soil profile through evaporative water loss.

LeachModE *[Ref. 5]* is a computer program for the prediction of the salinity of ground water and drainage water, the depth of the water table, and the drainage water discharge and salt content in irrigated agricultural lands under different geo-hydrologic conditions, varying water management practices including the use of groundwater for irrigation. LeachModE is an extension of LeachMod *[Ref. 5, Ref. 6]* allowing optimization of the capacity of the subsurface drainage system. Both models allow optimization of the leaching efficiency of salts from the soil.

Below an analysis is given with data from the Cotton Research Institute, Urgench, in the Khorezm region of northwest Uzbekistan (ZEF/UNESCO project. Economic and Ecological Restructuring of Land- and Water Use in Khorezm Region, Uzbekistan : A Pilot Project in Development Research, [*Ref. 7*].

2. Analysis

2.1 Water balances

In the soil, LeachModE distinguishes a root zone , a transition zone in which subsurface drains can be situated, and an aquifer. The root zone can consist of 1, 2 or 3 layers.
The water balances for these zones used in LeachModE can be found in the Annex *[Ref. 5]*.

The water balance of the transition zone reads:

$$Perc + GwIn - GwOut = Cap + Dra + Drb$$

where Perc is downward percolation from the root zone into the transition zone, GwIn is the groundwater coming in from the aquifer, GwOut is the groundwater leaving through the aquifer, Cap is the capillary rise from the transition into the root zone and Dra + Drb is the drainage through the subsurface drainage system (see below). This balance is calculated for each time step consecutively.

When the irrigation is abundant, Perc is large and Cap small *(figure 1).* When the irrigation is scarce, the root zone in the periods between the irrigation applications may become dry and provide suction forces to originate Cap *(figure 2).*

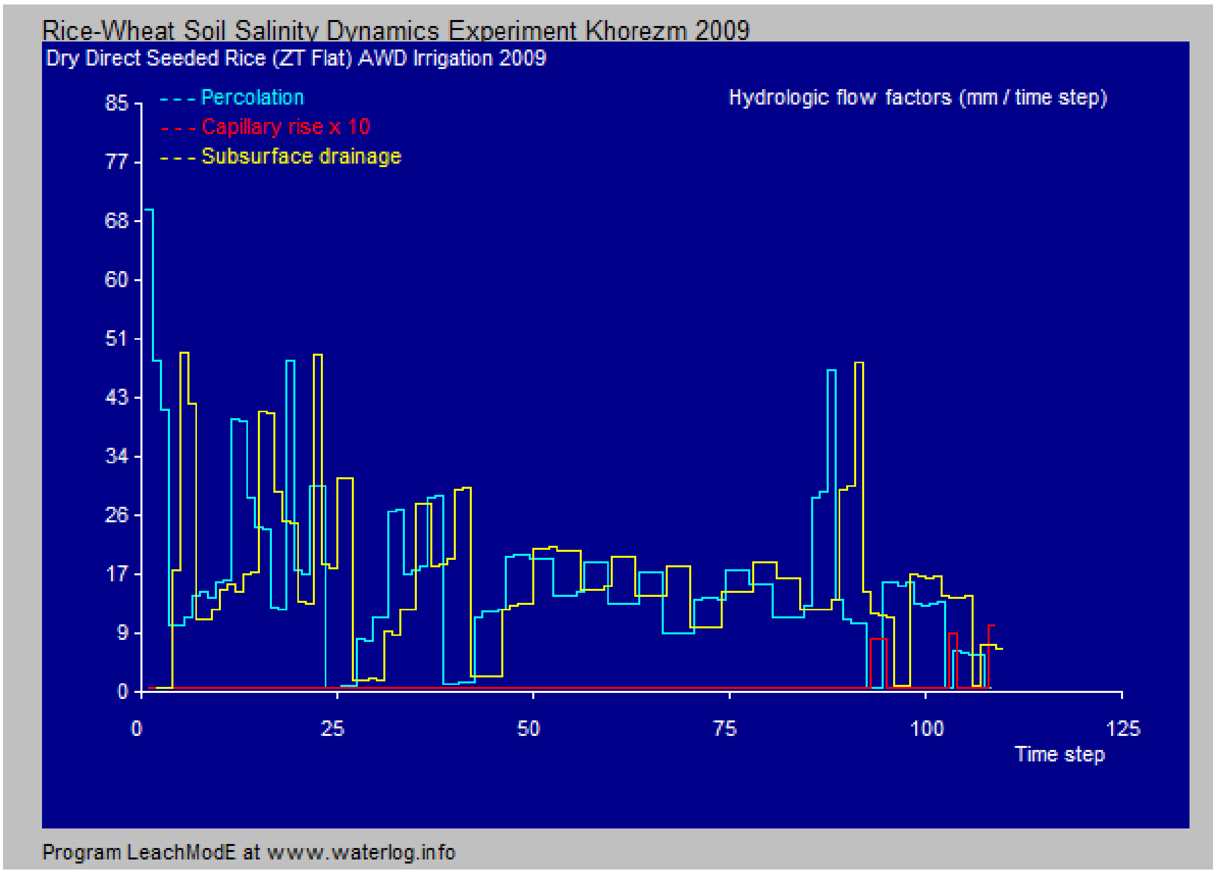

*Figure 1. When **rice** cropping is done with abundant irrigation, the water balance factors in the transition zone shows large amount of percolation (blue) and no capillary rise. Also the subsurface drainage (yellow) is high.*

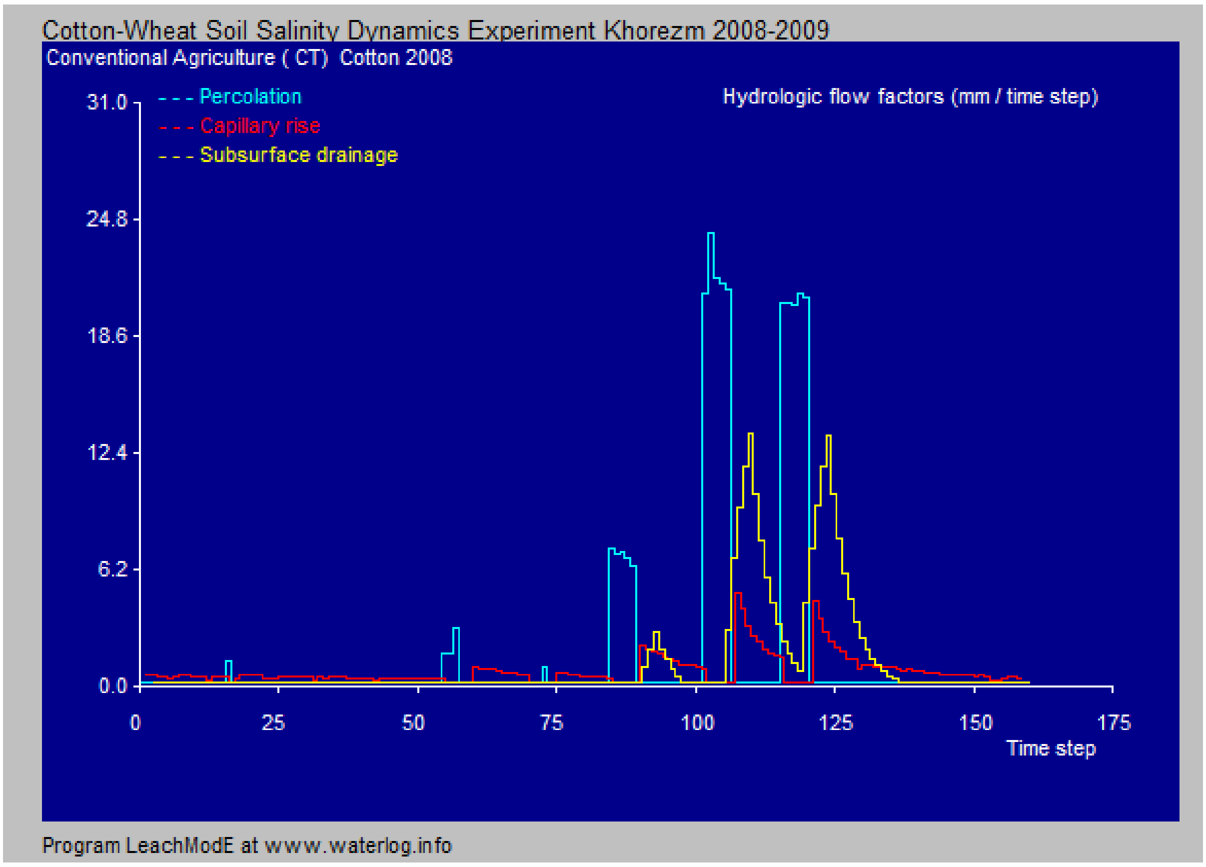

*Figure 2. **Cotton** is grown with less irrigation water than rice (figure 1), which results in periods between irrigation turns with capillary rise (red). The subsurface drainage is smaller (yellow).*

Figure 3 depicts the drain discharge versus the depth of the water table.

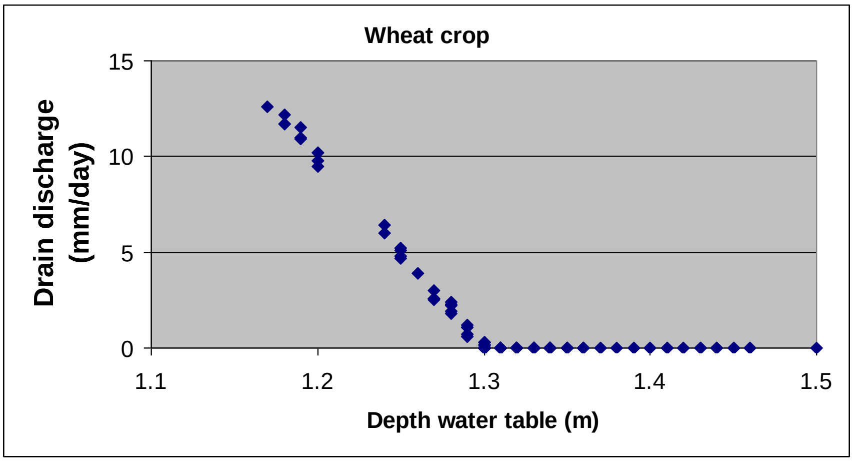

Figure 3. It can be seen that there is no drain discharge when the water table is below drain depth (1.3 m), but when the water table is shallower than that, the discharge increases when the water table rises more. The water table can get below the drain depth when capillary rise occurs provided that the critical depth for capillary rise (1.5 m in this case) is below drain depth.

The correspondence of the simulated and observed water table depths under rice cropping (with abundant irrigation and s drainage system with high capacity is demonstrated in *figure 4* while these depths under wheat cropping are depicted in *figure 5*. In these cases, LeachmodE has been set to optimize the drainage capacity so that simulated and observed depths correspond as closely as possible.

The drainage capacity is used in the subsurface drainage system according to the Hooghoudt equation *[Ref. 8]*:

$$Drt = 8H.Kb.De / L^2 + 4 H^2.Ka / L^2$$

where:

Drt is the drain discharge, H is the height of the water table above drain level midway between the drains, Kb is the hydraulic conductivity of the soil below drain level, De is the equivalent depth of the impermeable layer below drain level depending on drain radius, actual depth of the impermeable below drain level and the drain spacing L, and Ka is the hydraulic conductivity of the soil above drain level.

This equation can also be written as:

- for drainage flow above drain level

$$Dra := QH2 * H^2$$

- for drainage flow below drain level

$$Drb := QH1 * H$$

where:

where Dra is the drainage flow above drain level, Drb is the drainage flow from below drain level, and QH2 and QH1 are the capacities of the drainage system for flow above and below drain level respectively so that:

$$QH2 = 4.Ka / L^2$$
$$QH1 = 8.Kb.De / L^2$$

Finally, the H value need to be expressed as the depth of the water table (Dw) less the drain depth (Dd): H = Dw-Dd. Here, depth of the water table (Dw) is found from:

$$Dw = Dwp - (Perc + GwIn – Cap – Dra – Drb – GwOut) / Pe^*$$

where Dwp is Dw at the previous time step, and Pe* is the drainage or refillable (effective) porosity of the soil in layer * with the symbol * indicating the layer in which the water table is found at the given time step.

Below, *figure 4* shows the simulated depth of the water table (Dw) in the course of the time for the rice growing case, whereas *figure 5* depicts the same for the wheat cropping case. Both come together with the observed values of Dw.

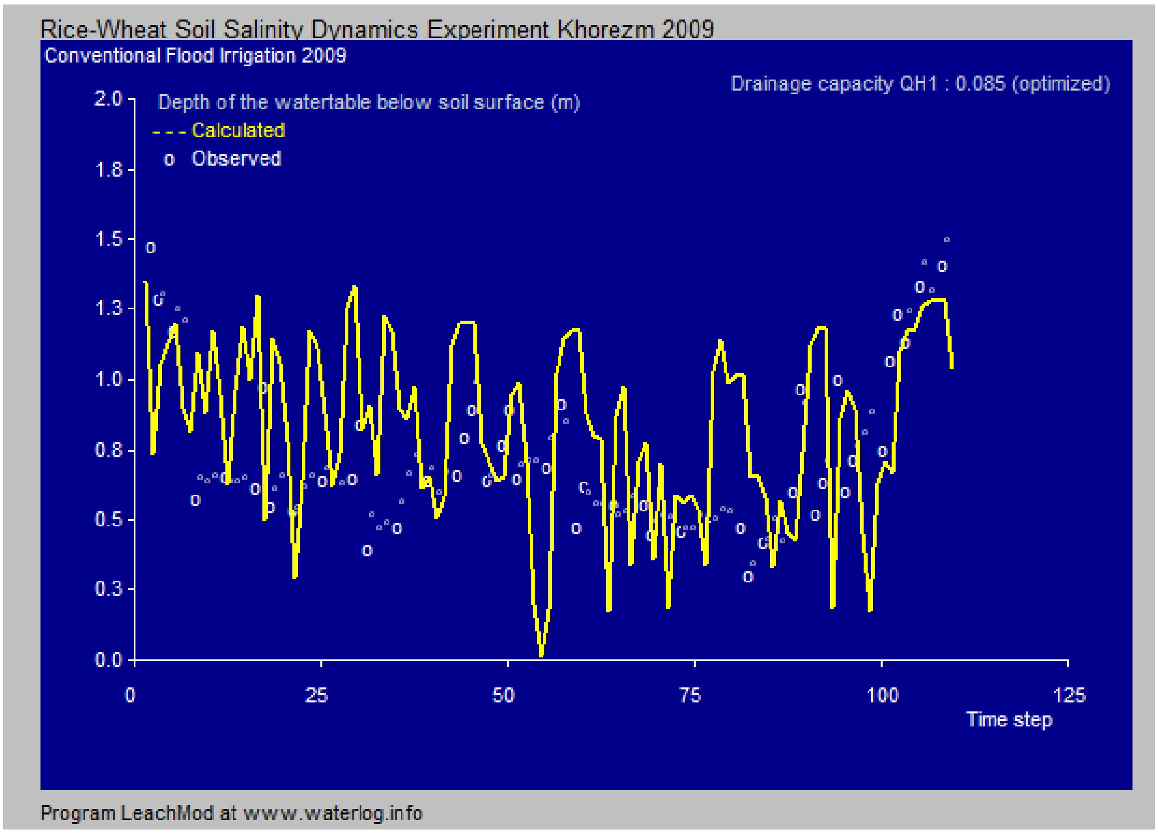

*Figure 4. Simulated (yellow) and observed depths of the water table (circles) under **rice** cropping. The drainage capacity is optimized to QH1 = 0.085. Owing to the very frequent irrigation, the water table fluctuates strongly.*

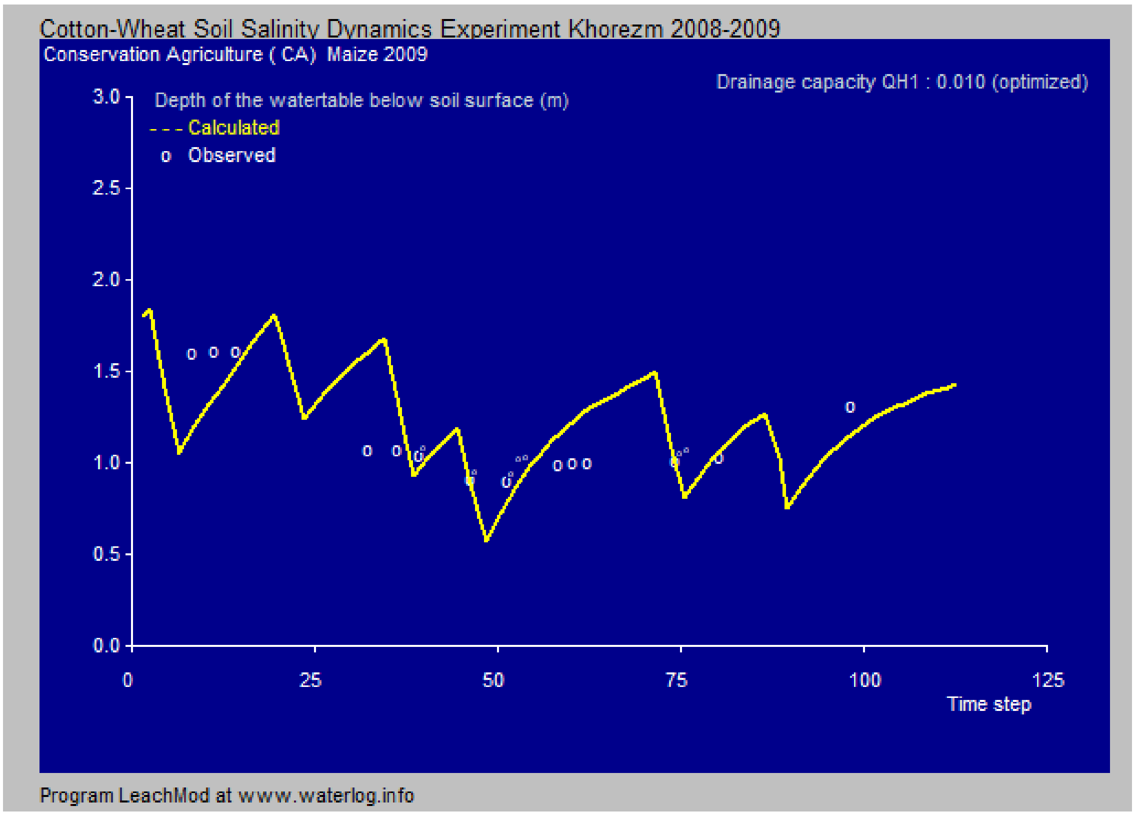

*Figure 5. Simulated (yellow) and observed depths of the water table (circles) under **maize** cropping. The drainage capacity is optimized to QH1 = 0.010.*

The following table gives a summary of the hydrological factors for the Maize cropping case.

Table 1 Seasonal totals of water balance factors in **Maize** cropping, units in mm.

Rain	Irrigation (Irr)	Potential Evaporation (PE)	Percolation (Perc)	Capillary Rise (Cap)	Actual Evaporation (AE)	Subsurface Drainage (Drt)
69.5	814.6	612.7	567	159.3	516.8	369.1

The overall water balance is: Rain+Irr+GI–AE-Drt =69.5+814.6+11.2-616.8-369.1 = 9.4, where GI is the groundwater inflow. The relatively small outcome (9.4 mm) is due to the change in water storage owing to the difference of the water level at the start and at the end of the season.

For the determination of the capillary rise, the percolation and the actual evaporation, see the appendix the article mentioned before [*Ref. 6*]. In table 1, the actual evapotranspiration is less than the potential evaporation as there are intervals between the irrigation applications in which the soil becomes dry and the evaporation reduces. The amount of drainage is small as the percolation is small. The irrigation efficiency, being the ratio between actual evaporation and irrigation, is high (0.80 or 80%). The world average application efficiency for intermittent irrigation systems is about 60% *[Ref. 9].*

2.2 Salt balances

The salt balances are found by multiplying the water balance components with the salinity of the soil moisture in the respective soil layers *[Ref. 5].*

In the present case study, the root zone was divided into 3 soil layers. In the examples below, the soil salinity of the soil moisture in layer 2 is taken as representative for the whole root zone, though there are differences of course.

For the second soil layer the soil salinity (Ss2) is found as:

$$Ss2 = Ss2p + Perc1*Ss1 + Cap3*Ss3 - Perc3*Ss2 - Cap3*Ss3$$

where Ss2p is Ss2 at the previous time step, Perc1 is the percolation from layer 1, Ss1 is the salinity of the soil moisture in layer 1, Perc3 is the percolation from layer 1 into layer 3, Cap3 is the capillary rise entering layer 2 from layer 3, Ss3is the salinity of the soil moisture in layer 3. All values of Perc, Cap and their respective Ss values are taken per time step.

In LeachModE the salinity is represented by the electric conductivity (EC) of the soil moisture (ECsm, dS/m). In practice one often uses ECe, being the EC measured in the laboratory after extraction of the water by centrifuge from a super saturated soil sample. The ECe value is roughly about 1/2 of ECsm and about 2/3 of a fully saturated soil. [*Ref. 10*].

LeachModE provides the option to optimize the leaching efficiency being the ratio between salinity in a soil layer and the salinity of the water moving through the soil pores to the underlying layer. Owing to different soil and pore structures this efficiency can vary from 0.2 to 1 or above. In heavy montmorrilonitc clay soils (vertisols) the leaching efficiency is often very low *[Ref. 6].*

Figure 6 gives a picture of simulated and observed soil salinity in a rice cropping case, while *figure 7* presents similar data for a wheat cropping case in Khorezm.

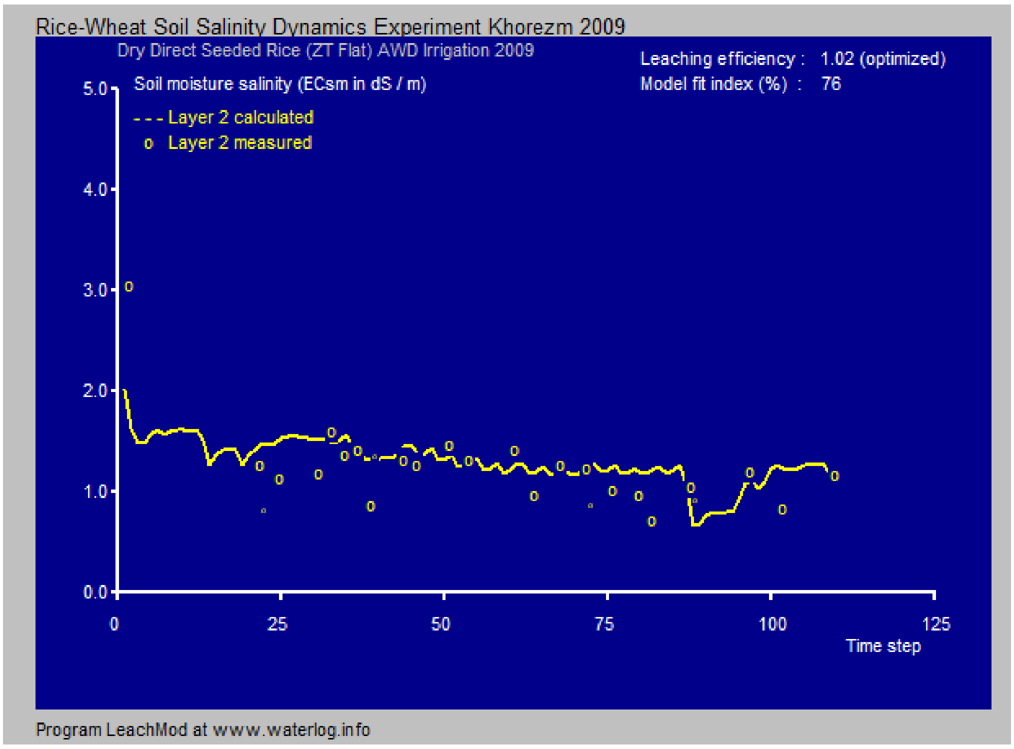

Figure 6. Simulated (yellow line) and observed soil salinity (circles) in the second soil layer in a ***rice*** *cropping case.*

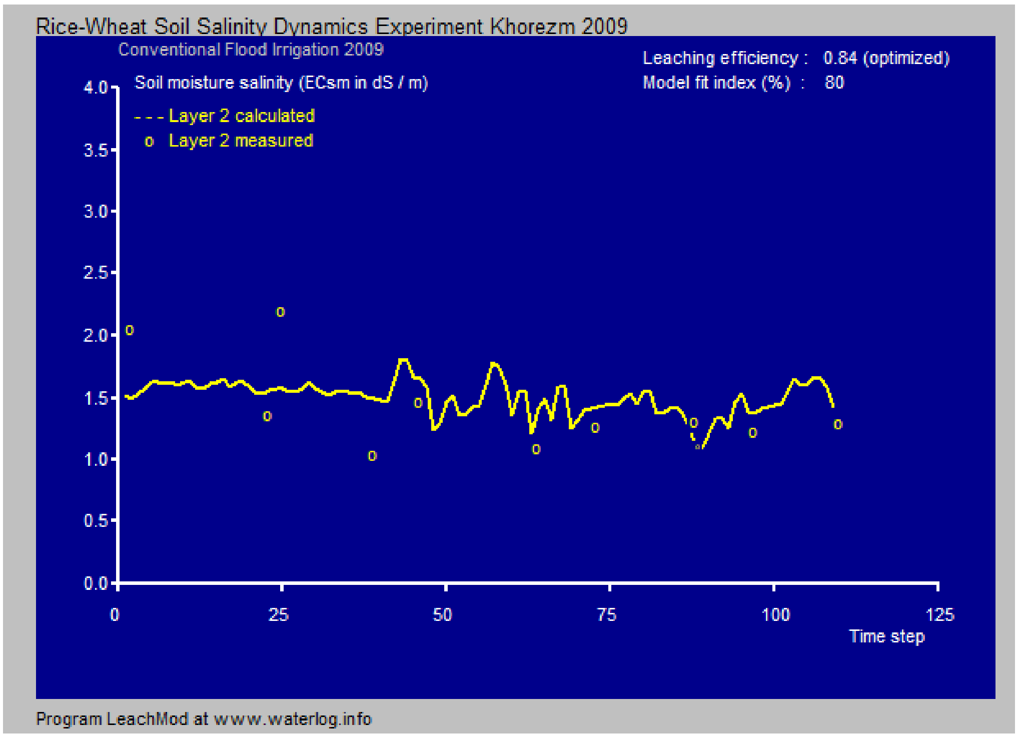

Figure 7. Simulated (yellow line) and observed soil salinity (circles) in the second soil layer in a ***wheat*** *cropping case. The optimized leaching efficiency (0.84) is less than 1 owing to the presence of the majority of the salts in the smaller pores and along the surfaces of the soil particles while in the larger water transmitting soil pores less salts are present. Hence the salinity of the percolating water is lower than the average soil salinity.*

3. Conclusions

By means of water and salt balance equations, LeachModE provides a mathematical explanation of measured values like depth of the water table and soil salinity. On top of that, it defines values that have not been measured, for example actual evaporation and capillary rise.

The soil salinity in the case studies presented here is low and not a hazard to crop production at all. For example, in wheat cropping, the ECsm value is around 1.5 dS/m, so the ECe value is around 1 only. The salt tolerance of wheat measured in farm lands ranges from ECe = 5 to 8 *[Ref. 11]*. Hence the soil salinity in the Khorezm experiments indicate very safe conditions.

When the correspondence between simulated and observed values is satisfactory, the model can be considered calibrated and used for predictions when the need is felt to change irrigation and drainage practices. When, after execution of such changes, the measurements are continued and the correspondence remains satisfactory, the model can also be considered as validated.

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