LeachMod, based on water and salt balances, is a model for the leaching of saline soils and reclamation (improvement, amelioration) of salty areas in irrigated lands by a subsurface drainage system including the simulation of the depth of the water table

R.J. Oosterbaan, January 2022, https://www.waterlog.info

Abstract
The LeachMod model has been used in the Aral Sea basin (Uzbekistan) an in a coastal saline soil near Chiclayo (Peru) as well as in the Salt Farm Texel (The Netherlands). It is able to calibrate the salt leaching efficiency of the soil, given certain hydrologic data and soil salinity values, and it can predict (simulate) soil salinity given the leaching efficiency. The model employs up to three layers in the root zone, a transition zone in which the subsurface drainage system is situated, and the aquifer. In addition, the transient state of the water table can be calculated.

Contents

1. Introduction

In the 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. [**Ref. 1**].

Data are available for the years 1970 to 1974 on the reclamation of a heavy, motmorillonitic, clay soil (vertisol) by means of irrigated, submerged, rice crops during three seasons in the experimental area of Chacupe in the arid coastal area of Peru near the city of Chiclayo [**Ref. 2**]. The area is under influence of upward seepage of saline groundwater from the uplands, therefore very saline and barren. Despite the difficult soil conditions the experiment has been successful owing to the installation of a subsurface pipe drainage system that intercepted the groundwater flow and drained the leaching water stemming from the irrigation water that percolated slowly downward through the soil to drains. An example of the reclamation results is given in *figure 1.*

In the island of Texel, The Netherlands, an experimental field was made in which various crops were tested for salt tolerance in plots using drip irrigation with water of different salt concentrations [**Ref. 3**]. An example of the results is depicted in figure 2.

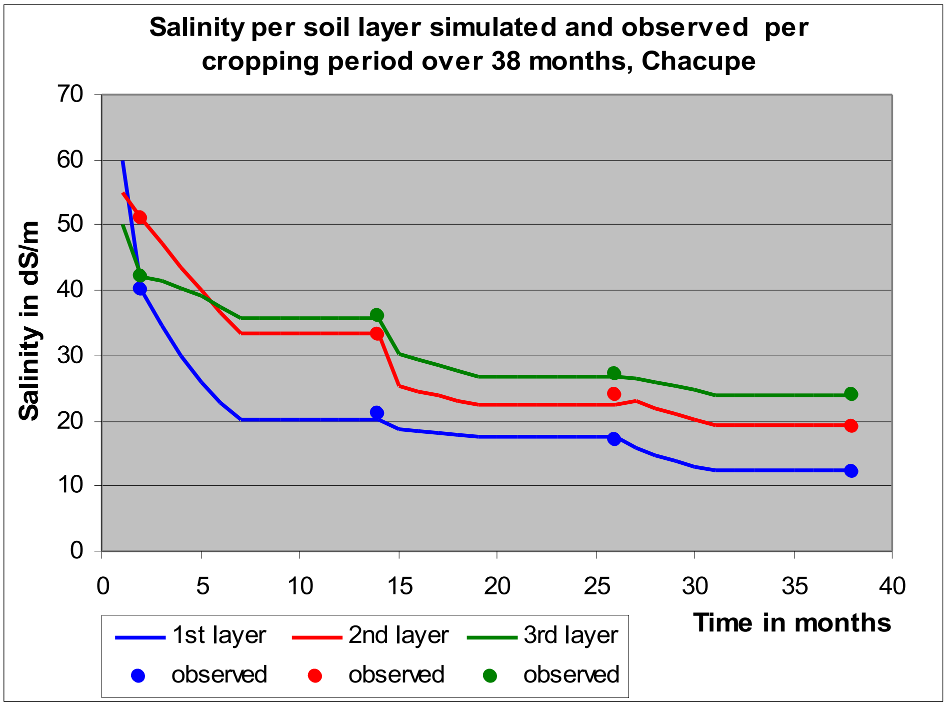


Figure. 1 *The soil salinity analysed with LeachMod per cropping period separately i.e. the initial leaching of 2 months followed by the years 1, 2 and 3* **[Ref. 2]**

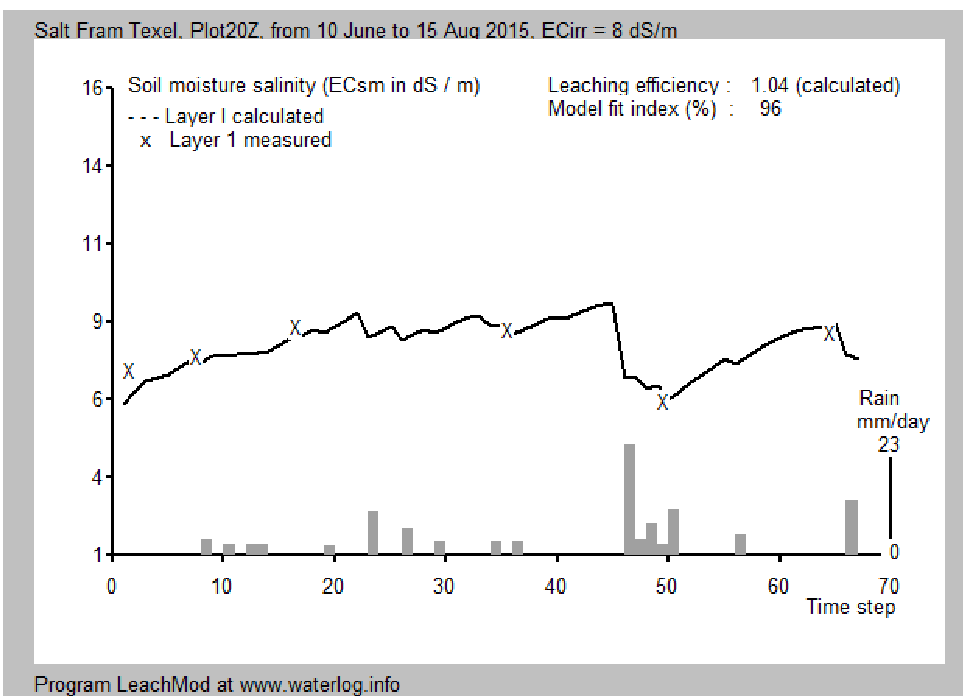


Figure 2. *Example of a LeachMod result for one of the experimental plots in the Salt Farm Texel. Simulated and measured values (X) of soil salinity are shown for a soil layer of 0-20 cm depth during 70 days. The salt concentration of the irrigation water is 8 dS/m, reason why the soil salinity fluctuates around this value. The influence of the high rainfall at day 47 is clearly shown: the rain reduces the soil salinity***[Ref. 3].**

The LeachMod [**Ref. 4**] model is comparable to the SaltMod model [**Ref. 5**] with the difference that the Saltmod model is designed for a long term time span of years with time steps of seasons in agricultural lands with different cropping patterns, while LeachMod is aiming at shorter durations, at most one year, with time steps of days in an agricultural field with one crop.

In practice, there appears to be a considerable variation of the leaching efficiency depending on the type of soil, like swelling clay, stable clay, silty clay, loamy and sandy soils [**Ref. 6**].
A summary of the leaching efficiencies is presented in the following table in which the type of soil is arranged from light (sandy) to heavy (clay).

Type of soil	Country	Leaching efficiency
Sandy	Netherlands	1.0
Loamy	China	1.0
Silty Clay	Tunisia	0.80
Clay, Illitic	India	0.70
Clay, Illitic	Turkey	0.70
Clay, smectitic *)	Thailand	0.20
Clay, smectitic *)	Portugal	0.15
Clay, smectitic *)	Peru	0.11

*) Also called vertisol, montmorillonite, heavy clay, swelling clay, poorly structured **[Ref. 6]**

2. Principles of LeachMod

LeachMod is based on water and salt balances of the soil, transition zone and aquifer (*figure 3*). As an example, only the balance of one-layer the root zone is described below.

The water balance of the root zone reads:

$$I + R + Z = E + P + \Delta w \qquad (1)$$

Here, I is the irrigation, R the rainfall, Z the capillary rise of soil water from the underground, E the actual evapo-transpiration, P the percolation of soil water to the underground, and Δw the change in soil water content. The actual evaporation may be less than the potential evaporation when the soil becomes dry. The units may be mm/day, mm/week, mm/decade, or mm/month.

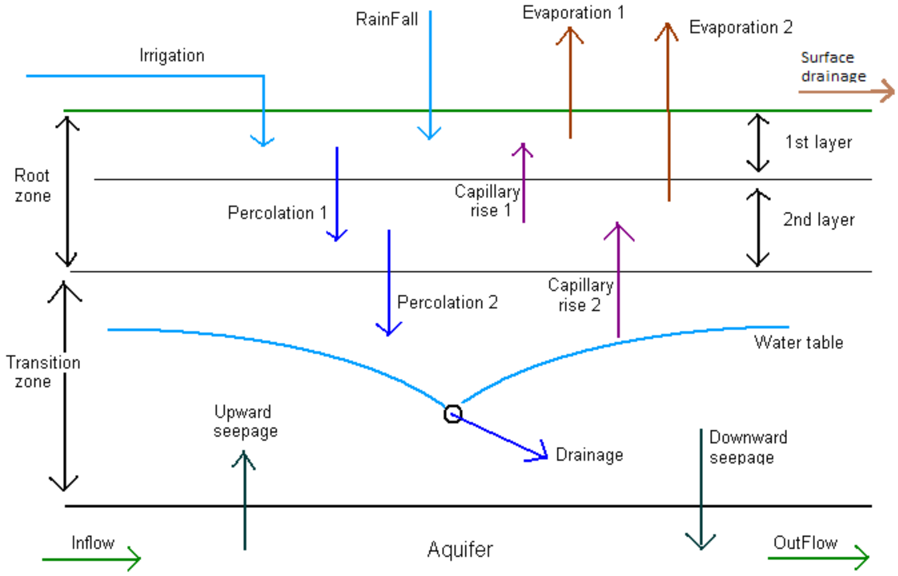


Figure 3. *Water flows in a two layered root zone, the transition zone and aquifer as used in LeachMod.*

Multiplying the water flow with the salt concentration of the water one obtains the salt balance. As the salt concentrations of rainfall and evaporation are negligibly small, the salt balance can be written as:

$$I.Ci + Z.Ct = P.Cp + \Delta s \qquad (2)$$

Here, Ci is the salt concentration of the irrigation water, Cp the salt concentration of the percolation water, Ct that of the transition zone, and Δs the change in salt storage in the soil. The units of salt concentration may expressed in terms of electrical conductivity (EC) in dS/m or mS/cm, which is proportional to the salt content per unit of water.

The salt concentration of the percolation water is a function of the salt concentration of the pore water (Cs):

$$Cp = F.Cs \qquad (3)$$

Here, Cs is the concentration of the pore water (soil moisture), and F the leaching efficiency of the soil pore system. It represents the ratio of the salinity of the percolation water to the average salinity of the soil pore water.
The leaching efficiency accounts for irregular patterns of downward flow through the irregular soil pore system, which may also vary with depth, and for the irregular distribution of salts dissolved in the water inside the pore system.

During a time step the change of the salt concentration of the soil water in the root zone is:

$$Cf - Co = \Delta s/W \qquad (4)$$

where Cf is the final salt concentration of the soil water at the end of the time step, Co is the initial salt concentration of the soil moisture at the beginning of the time step, and W is the amount of water contained in the soil pores of the root zone, equaling:

$$W = D.T \qquad (5)$$

where D is the depth of the root zone and T the total pore space of the soil in the root zone.

During a small time step the average salt concentration of Cs can be taken as:

$$Cs = 0.5*(Co+Cf) \qquad (6)$$

Combining Eq. 4, 5, and 6, one gets:

$$Cf = Co + (I.Ci+A.Ct)/D.T - 0.5*F.P.(Co+Cf)/D.T \qquad (7)$$

or explicitly in Cf:

$$Cf = [Co + (I.Ci+A.Ct)/D.T - 0.5*F.P.Co/D.T] / [1 + 0.5*F.P/D.T] \qquad (8)$$

For more detailed information, including the presence of three layers in the root zone, see the appendix of the publication in the International Journal of Environmental Science **[Ref. 2].**

The LeachMod input menu is shown in figure 4, demonstrating in this case only the selected hydrological data.

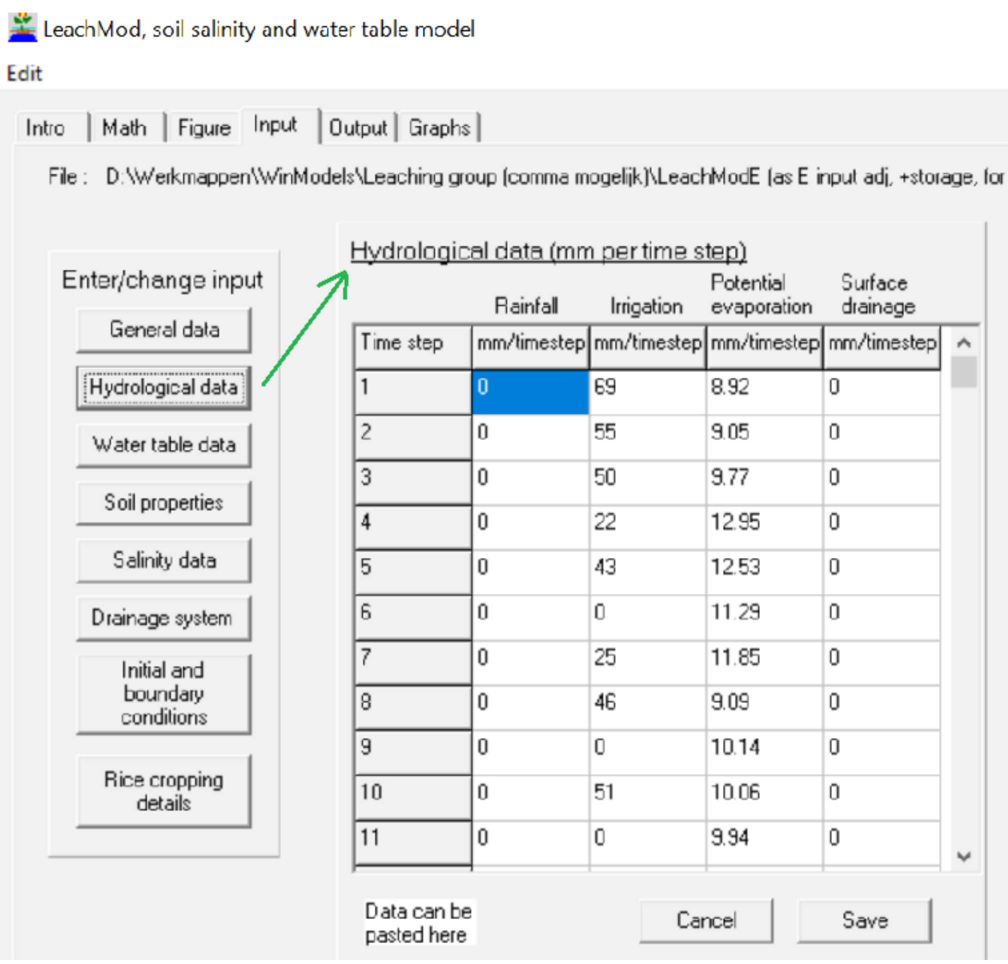


Figure 4. *Input menu of the LeachMod model demonstrating the hydrological data while other types of data, like general data, soil properties, salinity data, drainage data and boundary conditions can be entered by choosing the other selection buttons.*

3. Experiences with LeachMod

Some experience will be described concerning a) the Cotton Research Institute, Urgench, in the Khorezm region, Uzbekistan, b) the Chacupe pilot area near Chiclayo, Peru, and c) the Salt Farm Texel, The Netherlands.

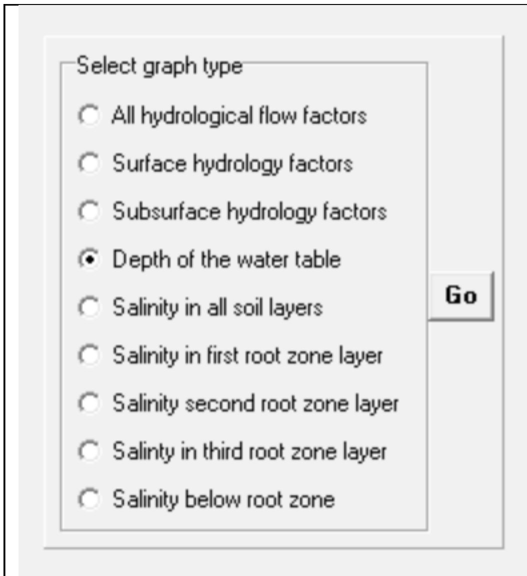
3a. The Cotton Research Institute, Urgench, Khorezm region, in the Aral Sea Basin, Uzbekistan **[Ref. 1]**

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. These crops play 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})

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.

The irrigation of cotton in the research institute, however, started late, which is the reason why the percolation occurred late (blue lines, *figure 5*).

In the case of wheat, due to more than sufficient irrigation, the soil salinity in the second root zone layer remains quite stable at a very low level (*figure 6*).

	*The graph selection options in LeachMod are depicted in the figure to the left.* *Some of the selected graphs are shown in the figures on the next pages.*

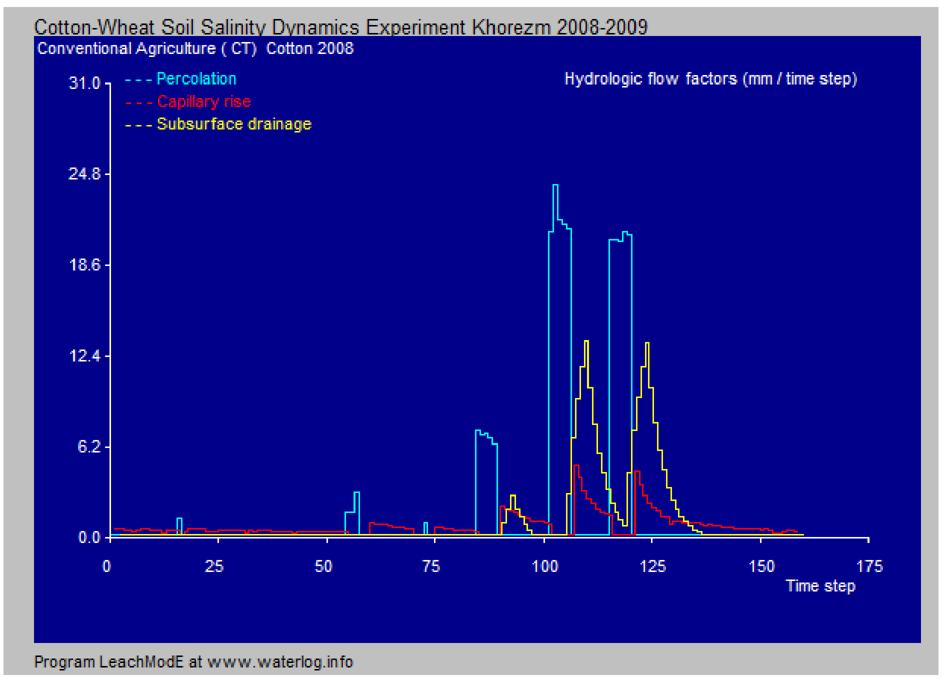


Figure 5. ***Cotton** is grown with little irrigation water. A fair part of the irrigation water is drained off by the subsurface drainage system (yellow curves), which results in periods between irrigation turns with capillary rise as the soil becomes dry and sucks up the ground water (red).*

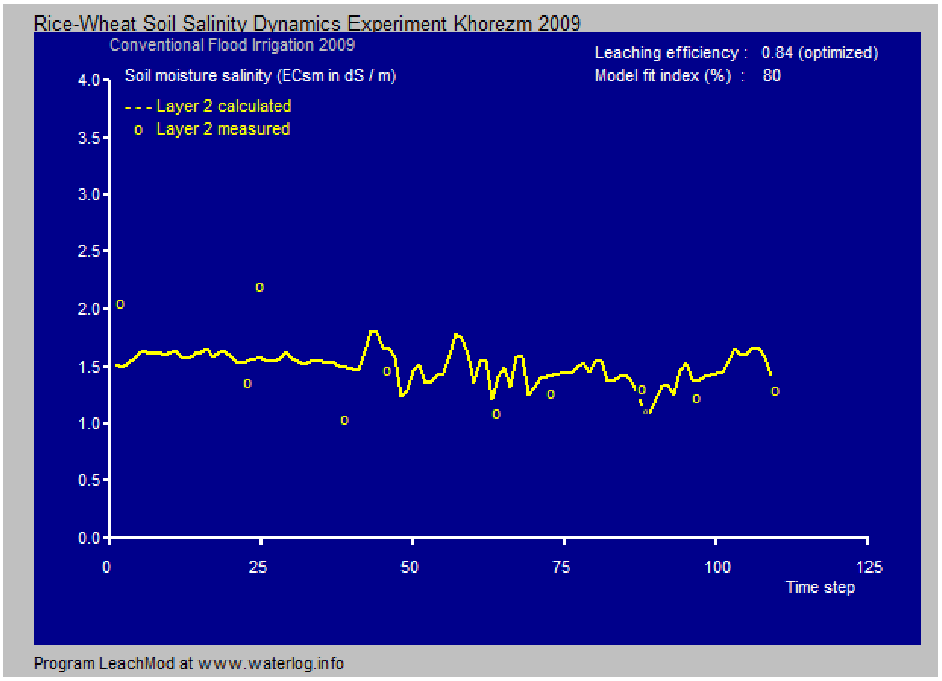


Figure 6. *Simulated (yellow line) and observed soil salinity (circles) in the second soil layer in a* ***wheat*** *cropping case. The optimized leaching efficiency (0.84) is less than 1 owing to the presence of the majority of the salts in the smaller pores and along the surfaces of the soil particles 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.*

3b. The Chacupe pilot area near Chiclayo, Peru **[Ref. 2]**

Data are available for the years 1970 to 1974 on the reclamation of a heavy, motmorillonitic, clay soil (vertisol) by means of irrigated, submerged, rice crops during three seasons in the experimental area of Chacupe in the arid coastal area of Peru near the city of Chiclayo. The area is under influence of upward seepage of saline groundwater from the uplands, therefore very saline and barren. Despite the difficult soil conditions the experiment has been successful owing to the installation of a subsurface pipe drainage system that intercepted the groundwater flow and drained the leaching water stemming from the irrigation water that percolated slowly downward through the soil to the drains. Thus the inflow of salt water was prevented and the soil was desalinized thanks to the removal of the saline percolation water.

Table 2. Cultivation practices and time table of hydrologic factors in Chacupe

Hydrologic Factor in mm/month	Cultivation practices					
	Initial leaching	1st rice crop	fallow	2nd rice crop	fallow	3rd rice crop
Duration (months)	2	5	7	5	7	5
Rain *)	0	10	0	15	0	8
Potential evapotranspiration	94	230	150	236	150	230
Irrigation (Irr)	223	234	0	336	0	359

Surface drainage (Sd)	98	140	0	121	0	94
Net irrigation Irr-Sd	125	194	0	215	0	265

*) In this arid zone the amount of rainfall is negligible.

The rainfall is scarce (white lines, *figure 7*). The irrigation (yellow) is more than the potential evaporation (green), reason why subsurface drainage (brown) occurs, which leads to a reduction of the soil salinity.

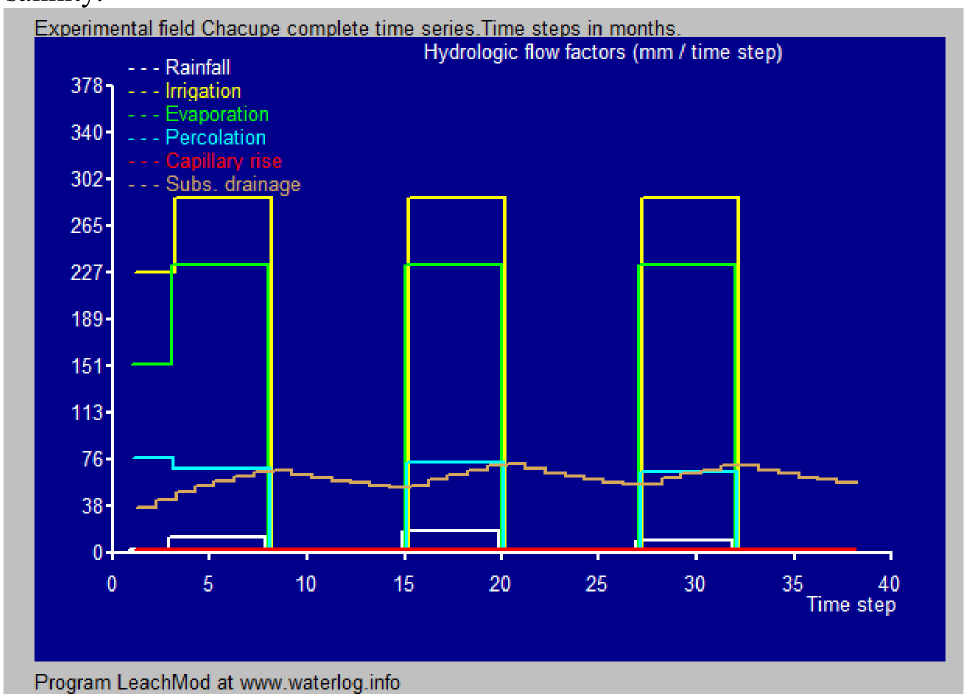


Figure 7**.** *Hydrologic factors (mm per month) in the Chacupe area during the reclamation experiment over 38 months. Rainfall : white, Irrigation: yellow, Actual evaporation: green, Percolation: blue, Subsurface drainage: brown***.**

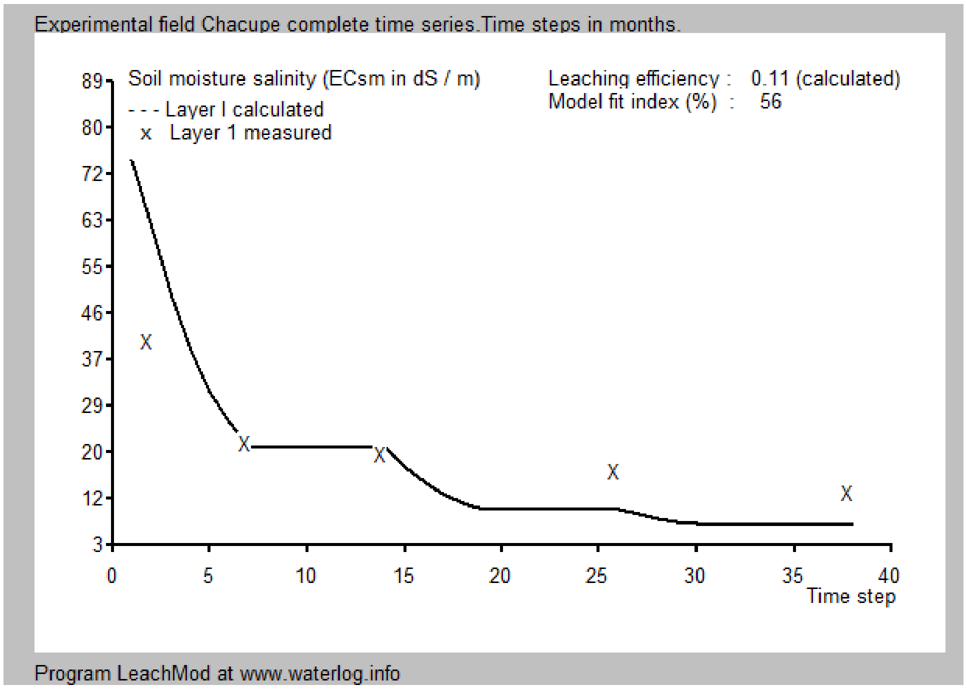


Figure. 8 *LeachMod results for the reclamation experiment in Chacupe. Simulated and measured values (X) of soil salinity are shown for a soil layer of 0-20 cm depth during 38 months. The leaching efficiency is only 0.11 and the model fit index is low (56%).*

The reason for the low fit of simulated to the observed data in figure 8 is that the leaching efficiency decreases during the process. Therefore, the leaching efficiency has been determined separately by cropping period *(figure 9)* and the results are illustrated in *figure 10.*

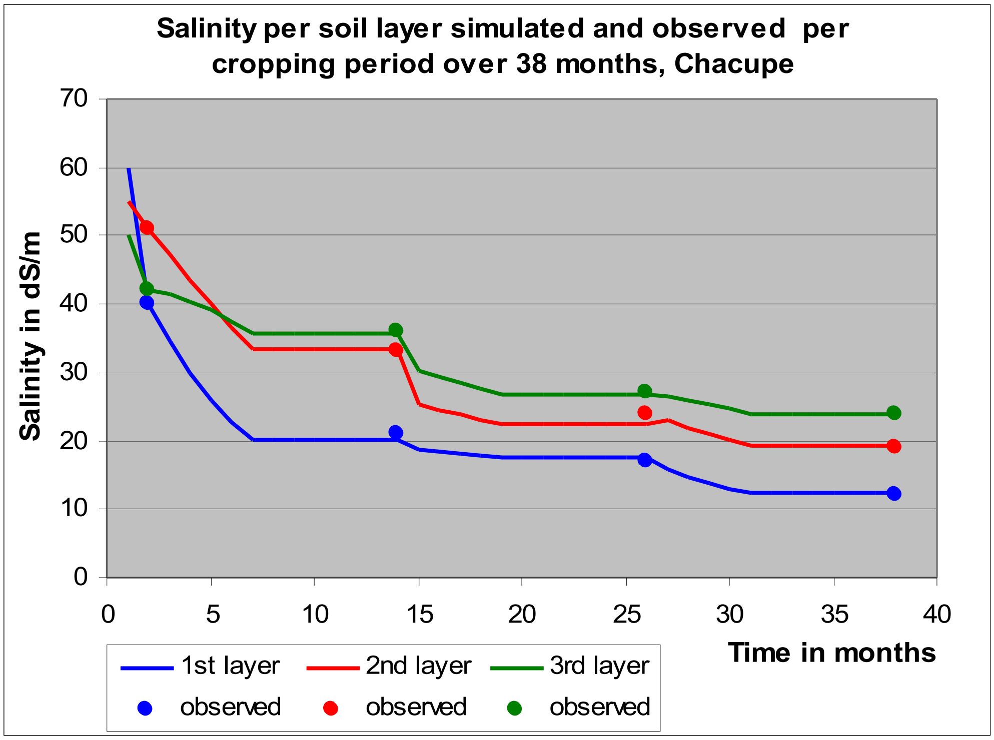


Figure 9. *The soil salinity analysed with LeachMod per cropping period separately i.e. the initial leaching of 2 months followed by the years 1, 2 and 3***.** *The fit of the simulated to the observed data is much better than in figure 8.*

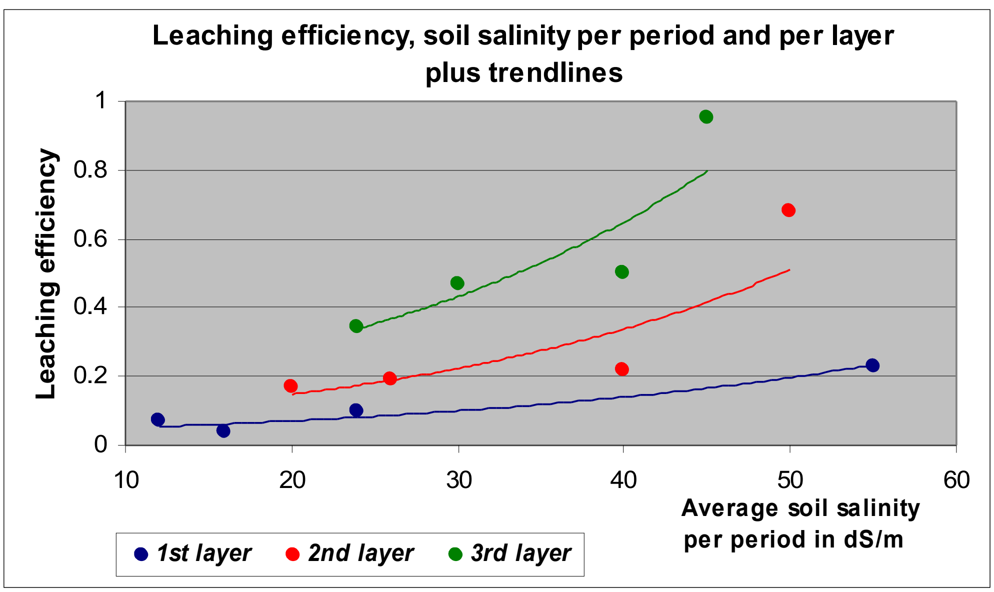


Figure 10. *The trend is that the leaching efficiency reduces as the soil salinity reduces according the principle of the expanding diffuse double layer around the clay particles leading to a loss of soil structure.*

<u>3c. The Salt Farm Texel, The Netherlands</u> **[Ref. 3]**

Between 2012 and 2015 field trials were performed at the open-air laboratory of Salt Farm Texel in The Netherlands. Here, it is possible to conduct field trials under controlled conditions and crops can be irrigated with 7 different salt concentrations. In this way it is possible to evaluate the crop salt tolerance of many different species and many different varieties.

Some of the results of the LeachMod model used to predict the soil salinity in the different field trials are given in the following two figures.

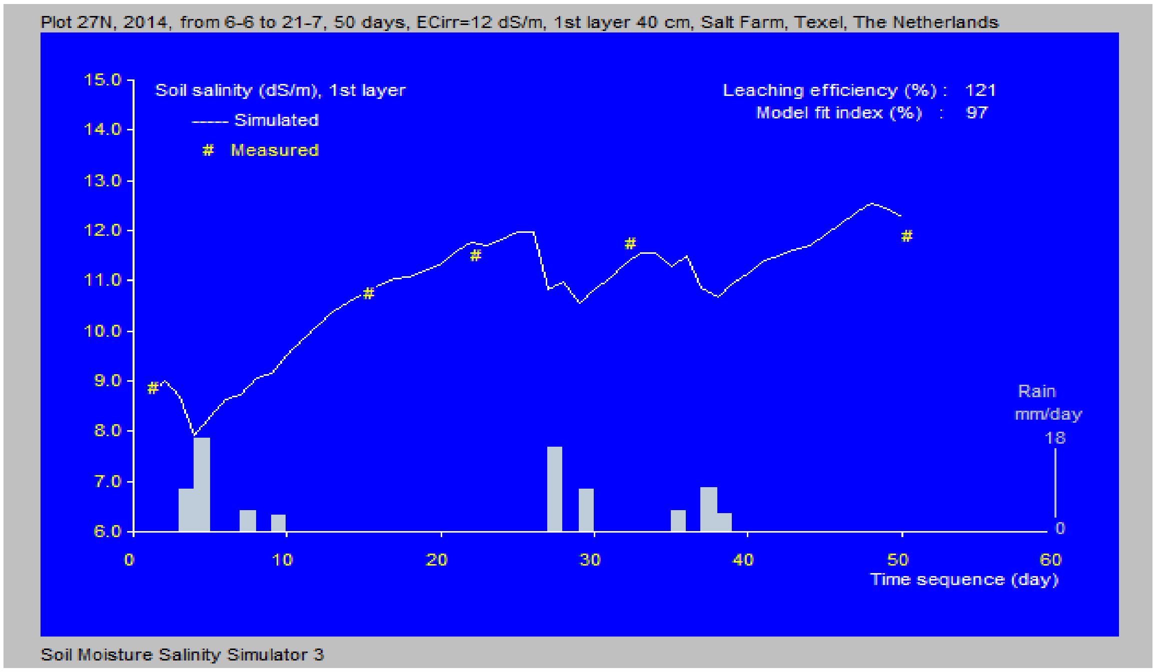


Figure 11. *Overview of the measured and modelled root zone salinity during the season of 2014, data shown of a plot irrigated with water having a salinity of 12 dS/m. In the end the soil salinity in the first layer (40 cm) of the root zone reaches the value of 12 dS/m to equalize that with the salt concentration of the irrigation water. Rain showers (represented by white bars) caused a reduction of the soil salinity. The leaching efficiency is more than 1. Apparently the salinity of the soil moisture in the larger pores through which the percolation water flows more easily is higher than in the smaller ones as it is caused by the incoming salty irrigation water.*

Figure 12. *Overview of the measured and modelled root zone salinity during the season of 2015, data shown of a plot irrigated with water having a salinity of 8 dS/m. After 20 days the soil salinity in the first layer (40 cm) of the root zone reaches the value of 8 dS/m to equalize that with the salt concentration of the irrigation water. Rain showers (represented by white bars) caused a reduction of the soil salinity, especially around day 50.*

4. Conclusions

LeachMod has been able to explain the soil salinity well in all cases discussed. Also the determination of the actual evaporation, which can be less than the potential evaporation when the soil becomes dry, is computed properly (*figure 7*). The same holds for the capillary rise (*figure 5*) that can occur when the water table is above the critical depth for capillary rise and the soil becomes dry to scarcity of irrigation water. The leaching efficiency plays an important role in all the processes.

5. References.

[Ref. 1]
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
Also on line: https://www.waterlog.info/pdf/Khorezm.pdf

[Ref. 2]
Reclamation of a Coastal Saline Vertisol by Irrigated Rice Cropping, Interpretation of the data with a Salt Leaching Model
Also on line: https://www.waterlog.info/pdf/EnvJournal2.pdf
or: https://www.iaras.org/iaras/filedownloads/ijes/2019/008-0006(2019).pdf or:
https://www.researchgate.net/publication/332466176_Reclamation_of_a_Coastal_Saline_Vertisol_by_Irrigated_Rice_Cropping_Interpretation_of_the_data_with_a_Salt_Leaching_Model

[Ref. 3] A. de Vos et al. *Crop salt tolerance under controlled field conditions in The Netherlands based on trials conducted by Salt Farm Texel.* 2016.
On line: http://library.wur.nl/WebQuery/wurpubs/fulltext/409817

[Ref. 4]
LeachMod, free software model for the calculation of water and salt balances in the soil and the determination of leaching efficiency needed for soil salinity control and reclamation (improvement, desalinization, amelioration) of salty soils.
On line: https://www.waterlog.info/leachmod.htm

[Ref. 5]
Saltmod, free software model for the calculation of salt and water balances in irrigated agricultural lands with different crop rotations. On line: https://www.waterlog.info/saltmod.htm

[Ref. 6]
Variations of leaching efficiency determined with soil salinity models calibrated in farm lands and related to soil texture
Also on line: https://www.waterlog.info/pdf/Leaching eff.pdf

6. Appendix A (Subsurface drainage equations)

The subsurface drainage equations used in LeachMod can be seen using the option "See equations" in the selection "Drainage system" in the input menu (see *figure 4,* blue arrows). The result is shown in figure A.

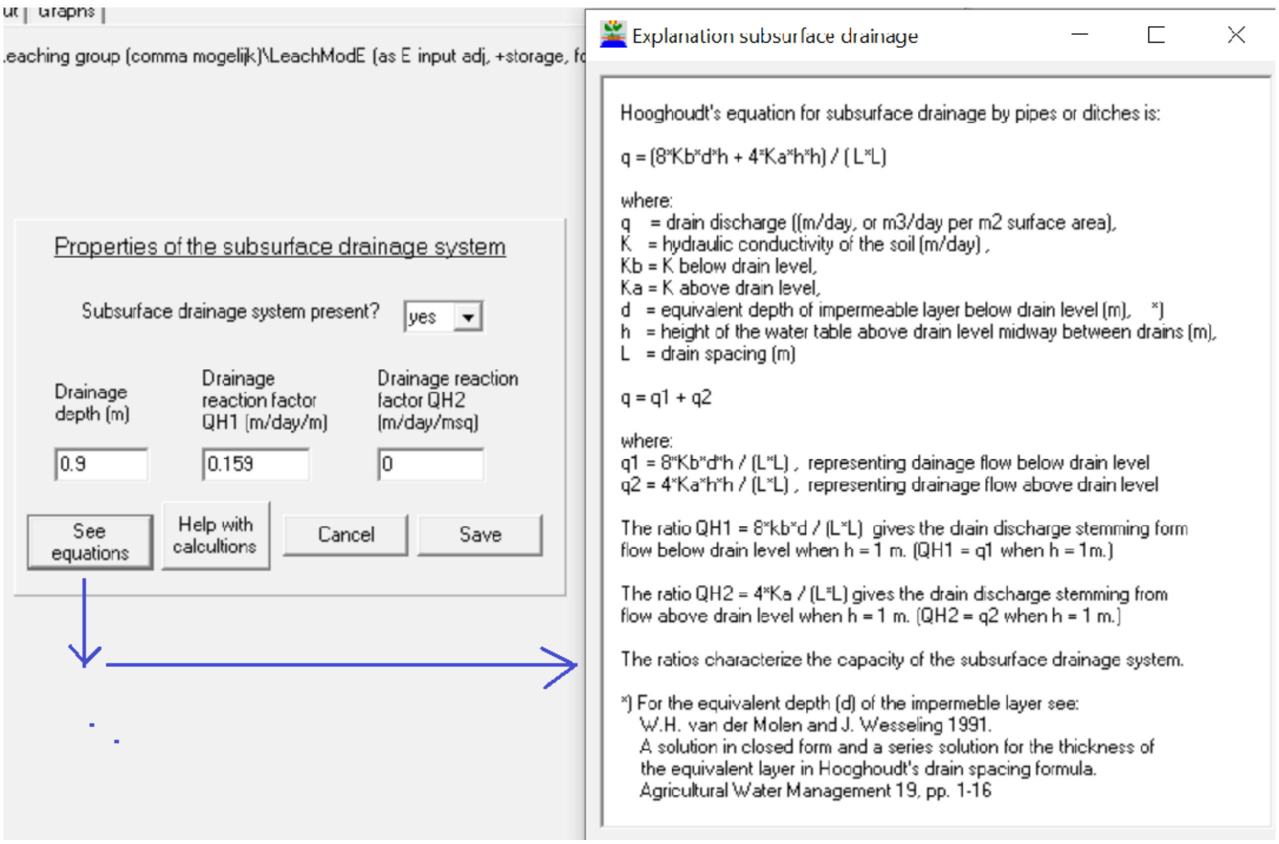


Figure A. *Drainage equations used in LeachMod*

The computation of the equivalent depth (d) is not shown here, but a reference is given to find the principles of it. For all clarity, the computation is specified hereunder

<u>Equivalent depth d</u>

$$d = \frac{\pi L/8}{\ln (L/U) + F(x)}$$

where U = wet circumference of the drain (m) and F(x) is a function of

$x = 2 \pi Da / L$ with Da being the depth of the aquifer below drain level.

When x>1 then:

$$F(x) = \frac{4e^{-2x}}{(1- e^{-2x})} + \frac{4e^{-6x}}{3(1- e^{-6x})} + \frac{4e^{-10x}}{5(1- e^{-10x})} + \ldots$$

For x<=1:

$$F(x) = \pi^2 / 4x + \ln (x/2\pi)$$

Note.

For a half full pipe drain U = π r with r = drain radius. For a ditch drain U equals bottom width + twice the length of the part of the sides that is under water.

7. Appendix B (Help function for subsurface drainage calculations)

The LeachMod program can assist the user in finding the necessary parameters of the drainage system by means of the option "Help with calculations" as illustrated in figure B below.

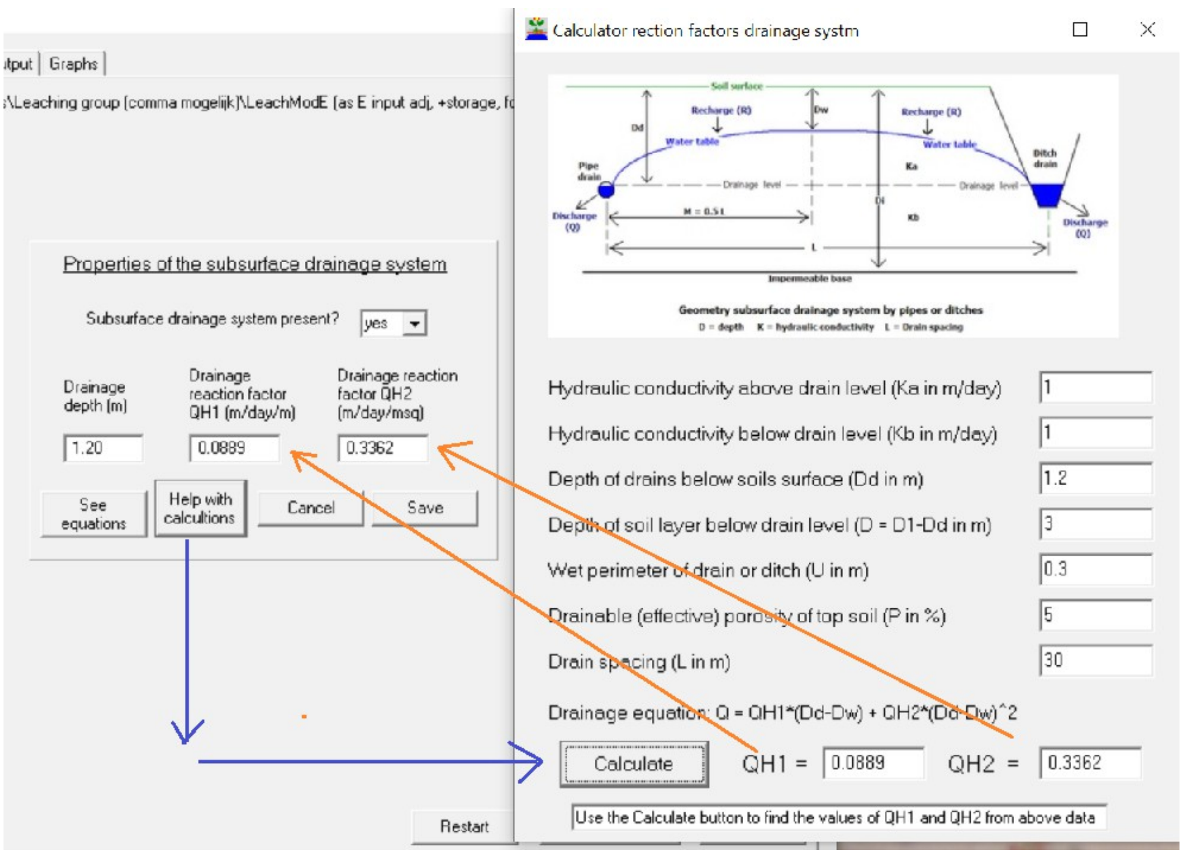


Figure B. The values of the QH1 and QH2 parameters needed by Leachmod can be found with the help function and the corresponding values are automatically transferred to the input menu (orange arrows)