Reclamation of a coastal saline vertisol by irrigated rice cropping, interpretation of the data with a salt leaching model.

R.J. OOSTERBAAN
Retired from the International Institute for Land Reclamation and Improvement, Wageningen, THE NETHERLANDS.

sitemaster@waterlog.info www.waterlog.info

Abstract: 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. An earlier experiment in the Tagus delta, Portugal, revealed that the reclamation of vertisols was a slow process partly owing to the low leaching efficiency and the slow hydraulic conductivity of the soil. To verify this, the reclamation process in Chacupe is described and a salt leaching model, named LeachMod, is applied to explain the phenomena observed. It introduces the concept of leaching efficiency. In the period of the experiment computer software was not yet available, reason why it is used now. The model uses water and salt balances of the root zone of which sufficient data are available to make the model workable. It is found that the desalinization is faster at the start of the experiments than later on. One reason is that at higher salinity the salt concentration of the percolating water is higher in the beginning so that the removal of salts is faster. A second reason is that the leaching efficiency decreases with decreasing soil salinity, a phenomenon that is related to the expansion of the diffuse double layer of clay particles at lower soil salinity levels whereby the soil loses structure and the soil permeability for water reduces. Without the model, this conclusion could not be found. The consequence of the structure loss is that it will take many years before the soil salinity has gone down sufficiently to allow growing “dry foot” crops. However, the “wet foot” rice crops produced satisfactory yields already after one year owing to the good quality of the irrigation water in which the roots were submerged. The presence of the drainage system was important to remove the salty downward percolating water and to maintain a deep water table during fallow periods thus preventing capillary rise of the groundwater and re-salinization of the soil. An example is given of a situation with an inadequate drainage system using LeachMod with a reduced drainage capacity to demonstrate the danger of such re-salinization.

Key words: Saline soil reclamation, vertisol, leaching model, salinity simulation, water and salt balance, leaching efficiency, capillary rise.

1. Introduction, the project area

In the experimental area of Chacupe in the coastal area of Peru near the city of Chiclayo, the ground water table was found at a depth of 0.8 to 1.1 m. The soil was salinized and the area was barren.

The climate is arid and the presence of a shallow water table under such conditions indicates the presence of upward seeping groundwater [figure 1, Ref. 1 (in Spanish)].

A careful reclamation experiment was carried out on a 4.9 ha plot which formed a part of a larger pilot area in which a drainage system was installed. The reclamation plot is underlain by 6 field drains at a depth of 2.0 m and a spacing of 36 m, discharging into an open collector drain.

The soil from the surface down to a depth of approx. 1.0 m is fine textured (clay fraction 40 to 50%). Of the clay fraction 30 to 40% consists of montmorillonitic (smectitic) clay.

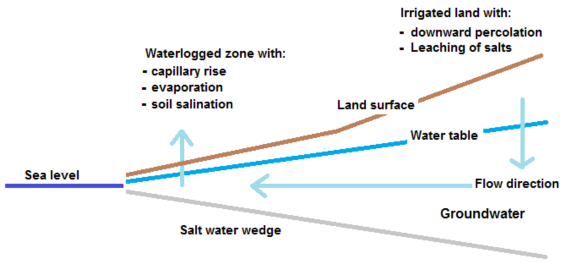

Fig. 1 Sketch showing groundwater flow in a coastal delta and the lower lying area being under influence of upward seepage owing to the blockage of the flow by the sea which results in a waterlogged area where salts accumulate after the water has evaporated.

Montmorillonite clay is of the swelling type and is very slowly permeable when wet, reason why its desalinization with irrigation water is difficult [Ref. 2]. The deeper layers are sandier, although clay lenses occur. The soil is very saline (see table 1, the data are from Ref. 1).

Reclamation of vertisols can best be done with rice cultivation as this crop withstands waterlogged conditions. Further it will be required to install a subsurface drainage system to intercept the incoming ground water and to remove the downward percolating irrigation water in which the salts are dissolved.

After the installation of the drainage system the soil was levelled as well as possible and ploughed to a depth of 15 cm. The depth of ploughing could not be more because of the hardness of the soil.

Irrigation water used for leaching and rice cultivation is of good quality: EC (Electric Conductivity) = 0.6 dS/m at 25°C and the SAR (Sodium Adsorption Ratio) value = 2. Predominant anions are Cl^- and $SO_4^=$.

After an initial leaching period, rice was planted. The initial leaching was done to remove the large amount of salts on the soil surface and in the top layer. The rice season in the region lasts about 150-180 days depending on climatic conditions and the rice variety. The rice crop is followed by a fallow season.

During the fallow season no water is available for a second crop or for leaching. In the following years, again a rice crop was grown. The hydrological factors for the successive cultivation and fallow periods are shown in table 2 (data from Ref. 1).

The reclamation results in terms of reduction of the soil salinity are summarized in Table 3.

Table 1. Some initial soil characteristics of the Chacupe area [Ref.1]

Depth in cm	ECe (dS/m) *)	pH #)	Sodium (%) $)
0 - 10	169	7.4	44
10 - 20	130	7.5	48
20 - 40	75	7.8	55
40 -60	42	8.0	57
60 - 80	34	8.1	55
80 -100	30	8.1	55
100 - 120	27	8.0	54
120 - 160	23	7.9	52
160 - 200	19	7.9	45

*) Electric conductivity of the extract of a saturated paste of a soil sample.
The ECe is proportional to the total salt content. The ECe is very high.
For "dry foot" crop growth the ECe of the soil should be < 10.

#) The pH is a measure of the acidity (pH<7) or alkalinity (pH>7).
The soil is only slightly alkaline and has no alkalinity problem [Ref. 3].

$) The high sodium percentage and the modest alkalinity points to abundance of NaCl.

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 evapo-transpiration	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

Table 3. Development of the soil salinity in different soil layers during the reclamation period. demonstrating the reduction of the soil salinity in the course of time.

Depth (cm)	ECe (mmhos/cm = dS/m at 25 degree C)				
	Initial	After 1st leaching	After 1st rice crop	After 2nd rice crop	After 3rd rice crop
0-10	169	34	20	17	12
10-20	130	45	22	16	12
20-40	75	54	32	21	16
40-60	42	47	33	26	21
60-80	34	42	36	29	23
80-100	30	41	35	30	24
100-120	27	35	35	28	23
120-160	23	31	29	24	22
160-200	19	30	22	20	18
200-240	19	?	21	17	17

The first rice crop yielded only 600 kg/ha, but the second and third rice crop produced some 5000 kg/ha, just above the regional average. The rice plants, standing in ponded water supplied by irrigation with good quality water, apparently grow well when the salinity of the topsoil is not higher than ECe = 20 dS/m. For "dry foot" crops, however, the reclamation process has not advanced enough (figure 2).

The slow progress is due to the limited hydraulic conductivity and leaching efficiency of the heavy clay soil.

In continuation the Chacupe data will be further interpreted using a leaching model.

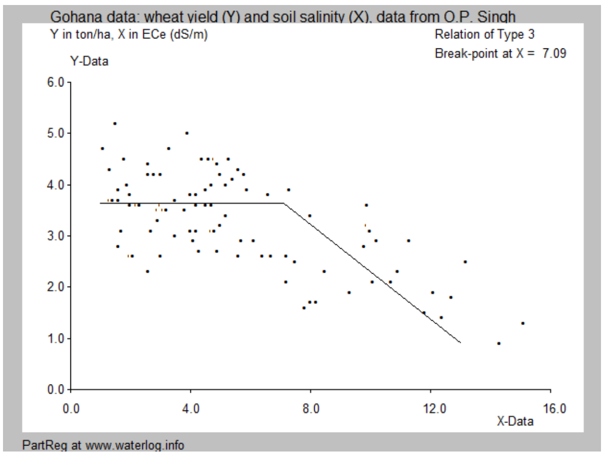

Fig. 2 Relation between wheat yield and soil salinity demonstrating that yields decline when ECe>7 dS/m [Ref. 4].

2. Introduction to the interpretation of Chacupe data with a leaching model

The leaching model LeachMod [Ref. 5] uses water and salt balances to simulate the soil salinity over time. It has been used for the outdoor experimental plots of the Salt Farm Texel, The Netherlands. In this Farm the plots were irrigated with an excessive amount of water of different salinities to create soils with an almost constant salinity of different degrees to test the salt tolerance of crops [Ref. 6].

An example of the LeachMod outcome for the Salt Farm Texel is shown in figure 3.

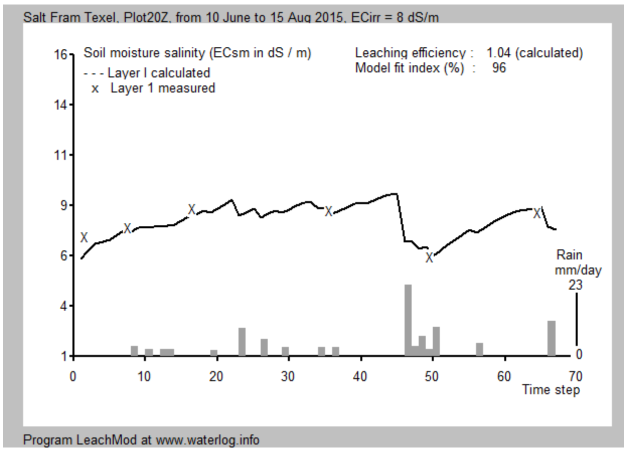

Fig. 3 Example of a LeachMod result for one of the experimental plots in the Salt Farm Texel. Simulated and measured values (X) of soil salinity are shown for a soil layer of 0-20 cm depth during 70 days. The salt concentration of the irrigation water is 8 dS/m, reason why the soil salinity fluctuates around this value. The influence of the high rainfall at day 47 is clearly shown: the rain reduces the soil salinity [Ref. 5].

The conditions in the Salt Farm were relatively simple. Owing to the excessive irrigation and the intensive drainage, a steady downward percolation occurred and capillary rise was absent.

When only one root zone layer is considered, the following water and salt balances can be used [Ref 7].

The water balance of the root zone (Fig. 1) reads:

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

Here, I is the irrigation, R the rainfall, Cr the capillary rise of soil water from the underground, E the evapo-transpiration, P the percolation of soil water to the underground, and Δw the change in soil water content. The units may be mm/day or mm/month.

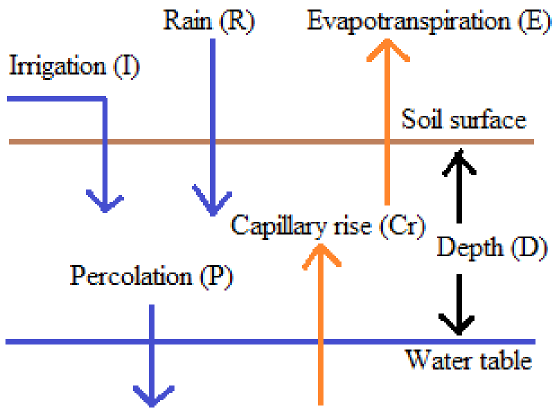

Fig. 4 Water balance factors of the root zone used for the simple conditions of the Salt Farm Texel.

Under the Salt Farm conditions Cr and Δw are negligible and Eq. 1 can be reduced to:

$$I + R = E + P \qquad (2)$$

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:

$$I.Ci = P.Cp + \Delta s \qquad (3)$$

Here, Ci is the salt concentration of the irrigation water, Cp the salt concentration of the percolation water, 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:

$$Cp = F.Cs \qquad (4)$$

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 irregular the 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:

$$Cf - Co = \Delta s/W \quad (5)$$

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:

$$W = D.T \quad (6)$$

where D is the depth of the root zone and T the total pore space of the soil in the root zone (cm^3 of pores per cm^3 of undisturbed soil).

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

$$Cs = 0.5*(Co+Cf) \quad (7)$$

Combining Eq. 3, 4, 5, 6 and 7, one gets:

$$Cf = \frac{Co + I.Ci/D - 0.5*F.P.(Co+Cf)}{D.T} \quad (8)$$

or explicitly in Cf:

$$Cf = \frac{Co + I.Ci/D.T - 0.5*F.P.Co/D.T}{1 + 0.5*F.P/D.T} \quad (9)$$

When the assumptions made for equation 2 are not valid and when more than 1 root zone layer is distinguished, equation 9 becomes more complicated. The LeachMod model provides the possibility of using more complex situations with more than one root zone layer, a transition zone in which the drains are placed, and an aquifer with incoming and outgoing groundwater flow to determine the upward seepage or natural underground drainage. The irrigation can be discontinuous and capillary rise may occur, which is the opposite of leaching and may lead to salinization instead of leaching and desalinization. Also, in the presence of limited rainfall and irrigation, the actual evapo-transpiration can become less than the potential one. In addition, the capacity of the subsurface drainage system can be determined. Finally, the leaching efficiency can either be fixed or the model can look for its optimal value whereby the differences between simulated and measured soil salinity values are minimized.

The complete set of equations for these more complex situations is given in the appendix and can also be seen in the in mathematic tab sheet of the LeachMod model which is freely available [Ref. 4].

3. Evaluation of Chacupe data with LeachMod.

The Chacupe conditions are similar to those of the Salt Farm Texel in the sense that there is excessive irrigation to keep the rice fields ponded, so that the actual evapo-transpiration equals the potential evapo-transpiration and capillary rise is absent. The main difference is that the Texel soils are sandy with a high leaching efficiency while the Chacupe soils are heavy clay with a low leaching efficiency.

Applying LeachMod over the entire three years to the first soil layer results in the following picture (figure 5) and the hydrological conditions are shown in figure 6.

The results indicate a low leaching efficiency (0.11) and modest model fit index (56%). The reason is that vertisols have intrinsically a low leaching efficiency.

Likewise, for the Leziria Grande Polder, Portugal, which is also built up of vertisols it was found that the leaching efficiency was no more than 0.15 [Vanegas, Ref. 8, using Saltmod, Ref. 9]. In addition, the leaching efficiency reduces further during the reclamation process. Saline vertisols soils have usually a good soil structure while the structure may decline at lower salinity values. This phenomenon is related to the thickness of the diffuse double layer around the clay particles that influences the soil structure [Ref. 10].

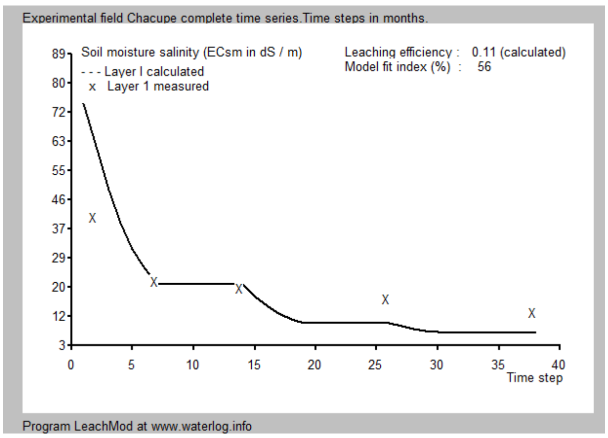

Fig. 5 LeachMod results for the reclamation experiment in Chacupe. Simulated and measured values (X) of soil salinity are shown for a soil layer of 0-20 cm depth during 38 months. The leaching efficiency is only 0.11 and the model fit index is low (56%). The reasons are explained in the text.

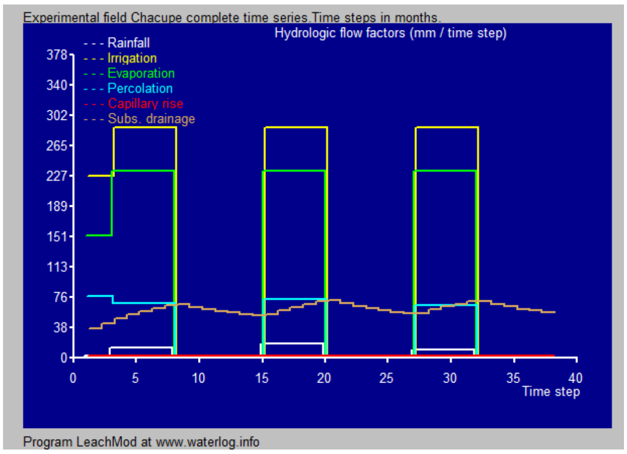

Fig. 6 Hydrologic factors (mm per month) in the Chacupe area during the reclamation experiment over 38 months. Rainfall: white, Irrigation: yellow, Actual evaporation: green, Percolation: blue, Subsurface drainage: brown.

In figure 6 it can be seen that the actual evaporation in the fallow periods (around months 12, 23 and 35) reduces to zero as there is no water supply and capillary rise is absent. Although there is permanent upward seepage of groundwater, this seepage is intercepted efficiently by the subsurface drainage system so that it can not rise into the root zone and evaporate, causing salinization.

As the LeachMod model optimizes the value of the leaching efficiency over the whole period one obtains an average value. In figure 7 it is seen that the simulated reclamation process, compared to the observed desalinization, is slower in the beginning and faster at the end of the experimental period of 38 months. This feature is in agreement with the theory of the diffuse double layer that predicts a lower leaching efficiency at lower soil salinity levels. Therefore, initially the actual leaching efficiency is higher than the average, which is proved by the fact that the observed salinity in the second month is below the simulated value, while in the months 26 and 38 the actual efficiency is lower than the average, proved by the fact that the observed salinity is above it.

To obtain more precise results, the LeachMod analysis can be done for three separate periods of shorter duration: 1st period encompassing the initial leaching operation, the first rice crop and the first fallow periods (months 1 to 14), second period covering the second rice crop and second fallow period (months 15 to 26), and the third period for the third rice crop and third fallow period (months 27 to 38). The results are shown in figure 6 for 3 soil layers.

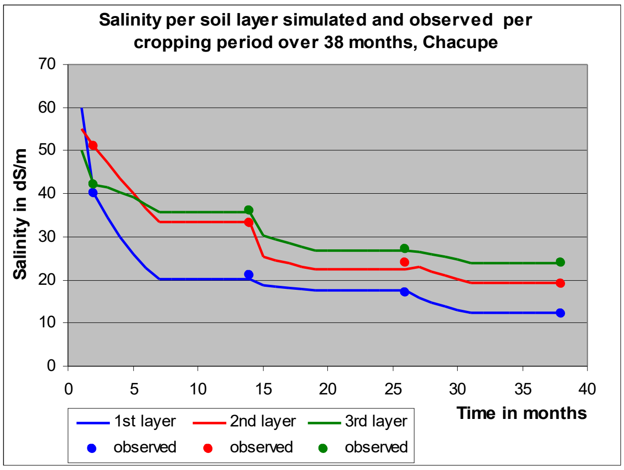

Fig. 7 The soil salinity analysed with LeachMod per cropping period separately i.e. the initial leaching of 2 months followed by the years 1, 2 and 3.

The goodness of fit of the simulated salinity to the measured salinity is very high owing to the fact that the optimization of the leaching efficiency in this case is allowed to be done per period of time and per layer (figure 8). From the trends displayed in figure 8 it can be seen that the leaching efficiencies tend to become constant in the lower range of soil salinity with values between 0.1.and 0.2. Form these low values it can be concluded that a long period of reclamation is required before the Chacupe area can be planted to “dry foot” crops because the reclamation speed will be very low.

Without the leaching model such a conclusion could not be drawn.

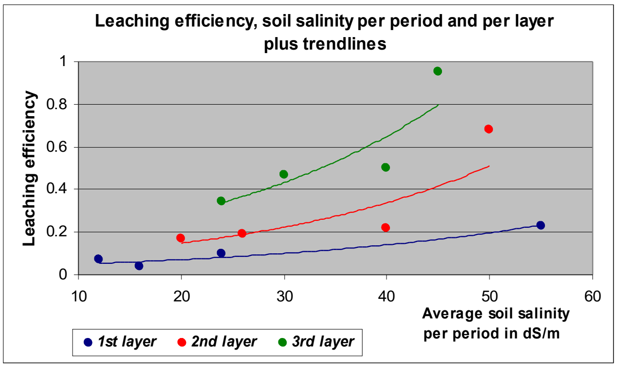

Fig. 8 The trend is that the leaching efficiency reduces as the soil salinity reduces according the principle of the expanding diffuse double layer around the clay particles leading to a loss of soil structure.

The lowest leaching efficiency is found in the top layer (the first layer in figure 8). This feature is explained by the annual puddling of the topsoil before the beginning of the submerged rice cultivation, which activity spoils the soil structure and the release of the salts to the percolating water is hindered.

4. Importance of the subsurface drainage system

When the drainage system has insufficient capacity and it does not maintain the water table out of reach of the depth from where capillary rise may occur, then the desalinization process is different from what has been sketched before.

Assuming that the drainage capacity is half of what it actually is in the Chacupe area and predicting the consequences, LeachMod shows the results as shown in the following three figures.

Figure 9 present the fluctuation of the water table. As the depth is always less than 1.4 m it comes in the zone where capillary rise can occur in the fallow periods when the soil dries out. This leads to re-salinization.

The capillary rise in the fallow period is seen in figure 10. Just after the end of the irrigation period, the rate of rise (more than 60 mm/month) is quite high as the soil is still moist and the water table at its shallowest (compare with figure 6). Thereafter, the rate of capillary rise reduces as the soil dries out and the water table descends.

The re-salinization in the fallow periods is depicted in figure 11. During the fallow periods the soil salinity increases strongly and although it reduces again during the irrigation periods this reduction is not enough to prevent a gradual increase in the long run.

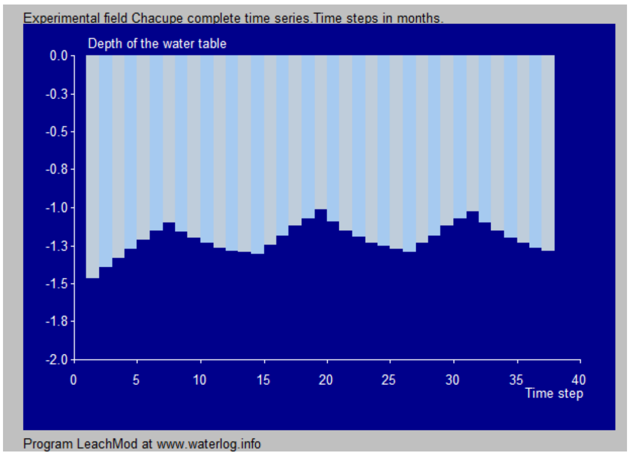

Fig. 9 Fluctuations of the water table in the Chacupe area simulated by LeachMod under the assumption that the drainage capacity is only half of the actual capacity. The depth is given in m below the soil surface.

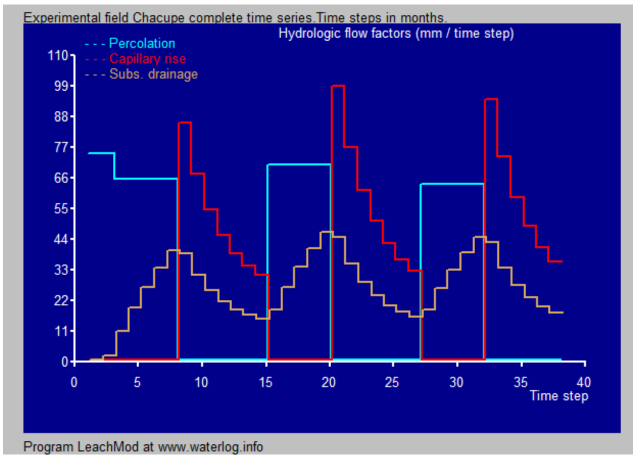

Fig. 10 Hydrologic factors in the entire root zone of the Chacupe area simulated by LeachMod under the assumption that the drainage capacity is only half of the actual capacity. The percolation is in blue, the capillary rise in red, and the drain discharge in brown colour. The units are mm/month.

The outcomes prove that an adequate capacity of the drainage system is of the utmost importance.

An overview of drainage design criteria under all kinds of different conditions has been published by the International Institute for Land Reclamation and Improvement [Ref. 11].

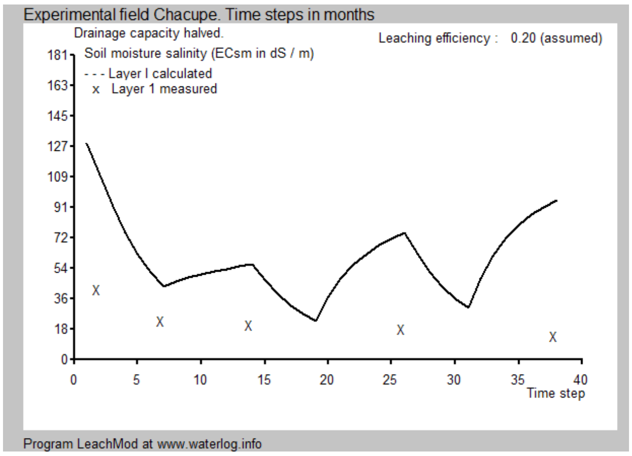

Fig. 11 Soil salinity in the first root zone layer of the Chacupe area simulated by LeachMod under the assumption that the drainage capacity is only half of the actual capacity. The salinity is expressed in ECe with units dS/m. There is no correspondence any more between simulated and measured values, the simulated values are higher.

5. Conclusions

The Chacupe experimental area was well designed and monitored. The report of the experiments (1976) could not go accompanied by an analysis with leaching software as in that time computer science and availability was not as developed as it is nowadays. With the LeachMod model, making use of the recorded data, the performance of the experiment can be evaluated in more depth.

It can be concluded that the subsurface drainage system was adequate and it fulfilled its purpose. The salty percolation water was effectively removed, the water table was well maintained below the zone where capillary rise and re-salinization can take place, and it intercepted the incoming groundwater flow from the aquifer properly. These facts could be proved by a simulation with LeachMod employing an imaginary drainage capacity that was half the actual capacity. The simulation showed unfavourable outcomes.

By optimization of the leaching efficiency, LeachMod produced monthly soil salinities of three root zone layers that corresponded well with the measured values. Overall, the leaching efficiency proved to be low (less than 0.2) as may be expected for the heavy montmorillonitic clay soil (vertisol) prevailing in and around the experimental area. This is in contrast with the high leaching efficiency in the Salt Farm Texel (greater than 1.0, figure 3) where the soils are of a more sandy type.

Due to the low leaching efficiency in Chacupe, the reclamation of the saline area appeared to be a slow process and even after three years the soil salinity was not lowered enough to permit the cultivation of "dry foot" crops.

Thanks to the assessment with LeachMod it could be detected that the leaching efficiency diminished during the reclamation process when the soil salinity was coming down. The cause of this phenomenon can be explained by the fact that the soil structure loses firmness owing to the expansion of the diffuse double layer around the clay particles when the salinity decreases. Moreover, the soil surface is puddled before the submerged rice cultivation is started, which originates a further regression of the structural stability. With the model it could also be detected (figure 8) that the leaching efficiency in the top layer (0 – 20 cm) is the least of all layers, which hampers the reclamation process.

Summary

Vertisols have a low hydraulic conductivity.

Vertisols have a low leaching efficiency.

These two factors hamper the effective reclamation of saline vertisols.

The appropriate reclamation method is by rice cropping with water standing on the soil surface.

For the reclamation, a subsurface drainage system is absolutely required.

Under the hydrologic conditions of groundwater seeping up into the root zone owing to the saline groundwater front extending from the ocean into the land it becomes difficult to ever grow "dry foot" crops in vertisols as it is doubtful that the salinity level of the soil can be lowered sufficiently, i.e. below the maximum salt tolerance level of the crops.

During the reclamation process it is useful to interpret the results with a salt leaching simulation model like LeachMod and to predict the conceivable long-term outcome.

References:

[1] C.A. Alva, J.G. van Alphen, A. de la Torre, and L. Manrique, 1976. *Problemas de Drenaje y Salinidad en la Costa Peruana. Bulletin 16, part II: Experimentos de Recuperacion de Suelos Salino-Sodicos, Area Piloto de Drenaje Chacupe*, p.43 – 113. (Spanish). https://library.wur.nl/isric/fulltext/isricu_t4c178ecc_001.pdf

[2] H. Eswaran and T. Cook. *Classification and management-related properties of vertisols*. http://www.fao.org/wairdocs/ILRI/x5493E/x5493e05.htm

[3] W. P. Kelley and S. M. Brown, 1934. *Principles governing the reclamation of alkali soil.* Hilgardia 8(5):149-177. http://hilgardia.ucanr.edu/fileaccess.cfm?article=152080&p=VEPAFL

[4] *LeachMod*, free leaching model to simulate soil salinity under different soil and hydrologic conditions. https://www.waterlog.info/leachmod.htm

[5] R.J. Oosterbaan, 2018. *Crop tolerance to soil salinity, statistic analysis of data measured in farm lands*. International Journal of Agricultural Science, 3, 57-66. https://www.iaras.org/iaras/filedownloads/ijas/2018/014-0008(2018).pdf

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

[7] J.W. van Hoorn and J.G. van Alphen, *Salinity Control*. Chapter 15 in: H.P. Ritzema (Ed.), Drainage Principles and Applications, p. 533-600. ILRI publication 16, International Institute for Land Reclamation and Improvement. Wageningen, The Netherlands. 1994. ISBN 90 70754 3 39. https://edepot.wur.nl/75186

[8] Vanegas Chacon, 2000*, Using SaltMod to predict desalinization in the Leziria Grande polder, Portugal*. Thesis, MSc program soil and water Wageningen Agricultural University, The Netherlands. https://www.waterlog.info/pdf/Vanegas2.pdf

[9] *SaltMod*, free software for lin term water and salt balances of different cropping patterns https://www.waterlog.info/saltmod.htm

[10] James Patrick Quirk et al. (1986). *Soil permeability in relation to sodicity and salinity.* Philosophical Transactions of the Royal Society of London, Series A, Mathematical and Physical Sciences. https://doi.org/10.1098/rsta.1986.0010

[11] *Agricultural Drainage Criteria*, Chapter 17 in: H.P.Ritzema (2006), Drainage Principles and Applications, Publication 16, International Institute for Land Reclamation and Improvement (ILRI), Wageningen, The Netherlands. https://www.waterlog.info/pdf/chap17.pdf

APPENDIX (Water and Salt Balance Equations Used in LeachMod)

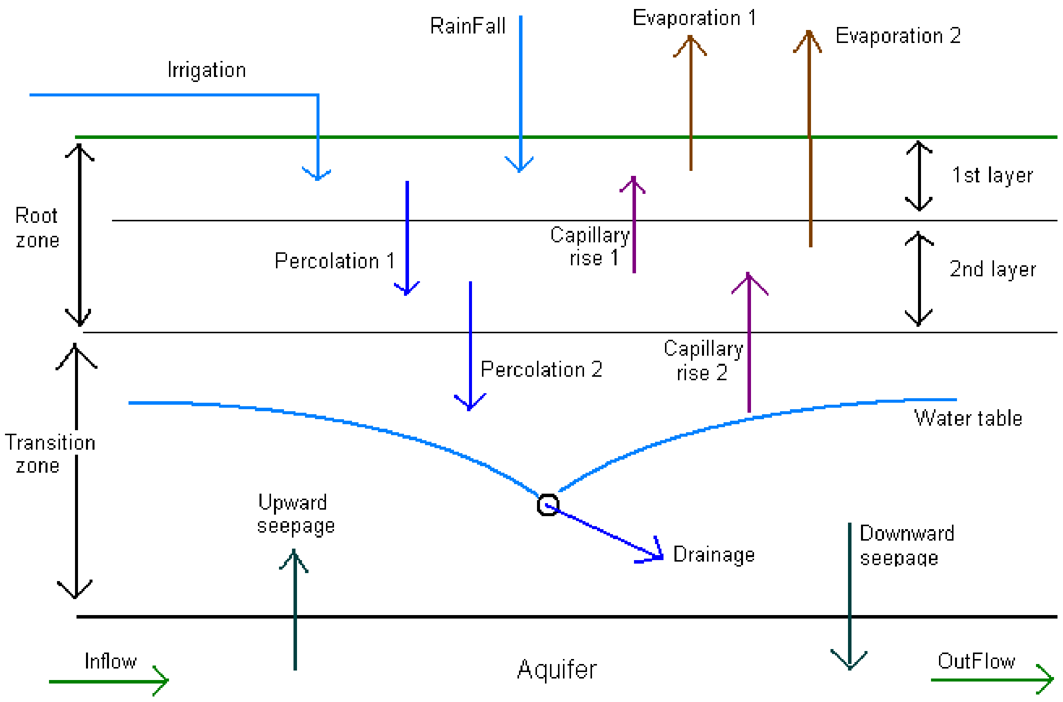

*Figure **A**. Water balances of the soil in the presence of two rootzone layers. For a third layer the symbols used are similar*

I. - **Water Balances** (flows in mm / time step, depths in m, see figure **A**):

First layer: Rain + Irrig + Cap1 = Perc1 + Evap1

Second layer: Perc1 + Cap2 = Perc2 + Evap2

Third layer: Perc2 + Cap3 = Perc3 + Evap3

Transition zone: Perc3+Upw = Drain+ Cap3 + Down

Aquifer: Info + Down = Up + Out
[*Down >= 0, Up >= 0*]

where Rain = rainfall, Irrig = Irrigation, Perc1 = Percolation from the 1st layer, Perc2 = Percolation from the 2nd layer, Perc3 = Percolation from the 3rd layer, Evap1 = Evapo-transpiration (actual) from the 1st layer, Evap2 = Evapo-transpiration (actual) from the 2nd layer, Evap3 = Evapo-transpiration (actual) from the 3rd layer, Cap1 = Capillary rise into the 1st layer, Cap2 = Capillary rise into the 2nd layer, Cap3 = Capillary rise into the 3rd layer, Drain = discharge of the subsurface drainage system, Upw = Upward flow from the aquifer, Down = Downward flow into theaquifer, Inf = Horizontal inflow into the aquifer, Out = Horizontal flow out from the aquifer.

Specification of percolation and capillary rise per layer (when Perc>0 then Cap=0 and vice versa) :

a - only one root zone layer present

Perc1 = (Rain+Irrig) / IrrEff - Evap1
Cap1 = CapT
where IrrEff is the irrigation or storage efficiency and CapT is the total capillary rise from the water table (see below).

b - two root zone layers are present

Perc1 = (Rain+Irrig) / IrrEff - Evap1
Perc2 = Perc1 - Evap2
Cap1 = CapT - Evap2
Cap2 = CapT

c - three root zone layers are present

Perc1 = (Rain + Irri) / IrrEff - Evap1
Perc2 = Perc1 - Evap2
Perc3 = Perc2 - Evap3
Cap1 = Cap2 - Evap2
Cap2 = Cap3 - Evap3
Cap3 = CapT

Specification of actual evapo-transpiration per layer:

a - only one root zone layer is present:
Evap1 = total actual evapo-transpitation (ETa)

b - two root zone layers of equal thickness:
Evap1=2*ETa/3, Evap2=ETa/3

c - three root zone layers of equal thickness:
Evap1=ETa/2, Evap2=ETa/3, Evap3=ETa/6

When the root zone layers are of unequal thickness, then adjustments are made on the basis of their relative thickness.

The total capillary rise and actual evapo-transpiration are calculated as:

$$ETa = IrrEff*WR+CF*(EvapT-IrrEff*WR)$$

$$CapT = EvapA-WR \qquad [CapT>=0]$$

where EvapT is the potential evapo-transpiration, WR is the surface water resources and CF is a capillary rise factor, determined as:

$$WR = Irrig + Rain$$

$$CF = (CDc - Dwt)/CDw \qquad [0 < CF < 1]$$

where Dwt (m) is the depth of the water table and CDc (m) is the critical depth of the water table for capillary rise.

The drain discharge is determined as:

$$DRa = QH1*(Dd-Dwt)^2$$

$$DRb = QH2*(Dd-Dwt)$$

$$Drain = DRa + DRb$$

where DRa is amount of drainage water originating from the soil above drain level, Drb is amount of drainage water originating from the soil below drain level, Dd is the drain depth (m), Dwt is the depth of the water table (m), QH1 is the reaction factor of the drainage system for flow above drain level (mm/m^2 per day), and QH2 is the reaction factor of the drainage system for flow below drain level (mm/m per day).

The depth of the water is calculated as:

$$Dwt = \frac{Dwp - Ts*(Perc3-CapT-Drain+Up-Down)}{10*EffPor}$$

where Dwp is Dwt of the previous time step, Ts is the duration of the time step (day), and EffPor is the effective or drainable porosity (%) of the soil layer in which the water table is situated.

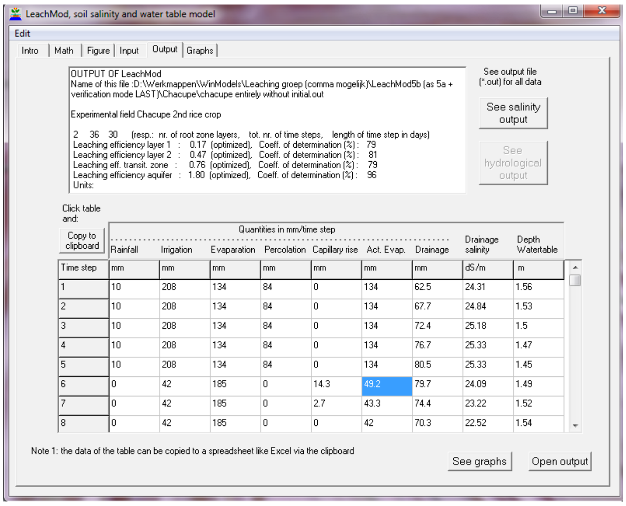

*Fig. **B**. LeachMod output screen with hydrological results*

II. - **Salt Balances** (salinity in dS/m at field saturation)

1. Root zone with only one layer

1a - Root zone salt balance:

$$Sin = Irri*Si + Cap1*STr$$

$$Sout = LEr*Perc1*SRa/100$$

$$SRo = SRp + (Sin-Sout)/Wr$$

where, additionally, Sin is incoming salt, Sout is outgoing salt, Si is the salinity of the irrigation water, STr is the salinity of the transition zone, LEr is the leaching efficiency (%) of the root zone, SRo is the salinity of the root zone, SRp is SRo of the previous time step, SRa is the average of Sro and SRp, and Wr is the amount of water stored in the root zone, equal to:

$$Wr = Dr*TPr/100$$

where Dr is the depth of the root zone and TPr is the total porosity (%) of the root zone.

1b - Transition zone salt balance:

Sin = LEr*Perc1*SRa/100 + Up*SAq/100

Sout = LEt*(Drain+Down+Cap1)*STa/100

STr = STp + (Sin−Sout) /Wt

where, additionally, SAq is the salinity of the aquifer, LEt is the leaching efficiency (%) of the transition zone, STp is STr of the previous time step, STa is the average of STr and STp, and Wt is the amount of water stored in the transition zone, equal to:

Wt = Dt*TPt/100

where Dt is the depth of the transition zone and TPt is the total porosity (%) of the transition zone.

1c - Aquifer salt balance:

Sin = LEt*Down*STa/100 + Inf*Sinf/100

Sout = LEa*(Up+Out) *SAa/100

SAq = SAp + (Sin−Sout) /Wa

where, additionally, LEa is the leaching efficiency (%) of the aquifer, Sinf is the salt concentration of Inf, SAp is SAq of the previous time step, SAa is the average of SAq and SAp, and Wa is the amount of water stored in the aquifer, equal to:

Wa = Da*TPa/100

where Da is the depth of the aquifer and TPa is the total porosity (%) of the aquifer.

2. Root zone with two layers

2a - First layer salt balance:

Sin = Irri*Si + Cap1*S2

Sout = LE1*Perc1*S1a/100

S1 = S1p + (Sin−Sout) /W1

where S1 is the salinity of the first layer, S2 is the salinity of the second layer, S1p is S1 of the previous time step, S1a is the average of S1 and S1p, and W1 is the amount of water stored in the first layer, equal to:

W1 = D1*TP1/100

where D1 is the depth of the first layer and TP1 is the total porosity (%) of the first layer.

2b - Second layer salt balance:

Sin = LE1*Perc1*S1a/100 + Cap2*STr/100

Sout = LE2*(Perc2+Cap1)*S2a/100

S2 = S2p + (Sin−Sout) /W2

where, additionally, LE2 is the leaching efficiency (%) of the second layer, STp is STr of the previous time step, S2a is the average of S2 and S2p, and W2 is the amount of water stored in the second layer, equal to:

W2 = D2*TP2/100

where D2 is the depth of the second layer and TP2 is the total porosity (%) of the second layer.

2c - Transition zone salt balance:

Sin = LE2*Perc2*S2a/100 + Up*SAq/100

Sout = LEt*(Drain+Down+CapT)*STa/100

STr = STp + (Sin−Sout)/Wt

2d - The salt balance of the aquifer remains unchanged.

3. Root zone with three layers

3a- The salt balance of the first layer is the same as that of the first layer in the two layer case.

3b - Second layer salt balance

Sin = LE1*Perc1*S1a/100 + Cap2*S3/100

Sout = LE2*(Perc2+Cap1)*S2a//00

S2 = S2p + (Sin−Sout)/W2

3c - Third layer salt balance:

Sin = LE2*Perc2*S2a/100 + Cap3*STr/100

Sout = LE3*(Perc3+Cap2)*S3a/100

S3 = S3p + (Sin−Sout) /W3

where, additionally, LE3 is the leaching efficiency (%) of the third layer, S3 is the salinity of the third layer, S3p is S3 of the previous time step, S3a is the average of S3 and S3p, and W3 is the amount of water stored in the third layer, equal to:

W3 = D3*TP3/100

where D3 is the depth of the third layer and TP3 is the total porosity (%) of the third layer.

3d - Transition zone salt balance:

Sin = LE3*Perc3*S3a/100 + Up*SAq/100

Sout = LEt*(Drain+Down+CapT)*STa/100

STr = STp + (Sin−Sout) /Wt

3e - The salt balance of the aquifer remains unchanged.

4. Salinity of the drainage water

Sdr = (LEt*DRa*Str + LEa*DRb*Saq)/Drain

where the symbols used are as defined before.

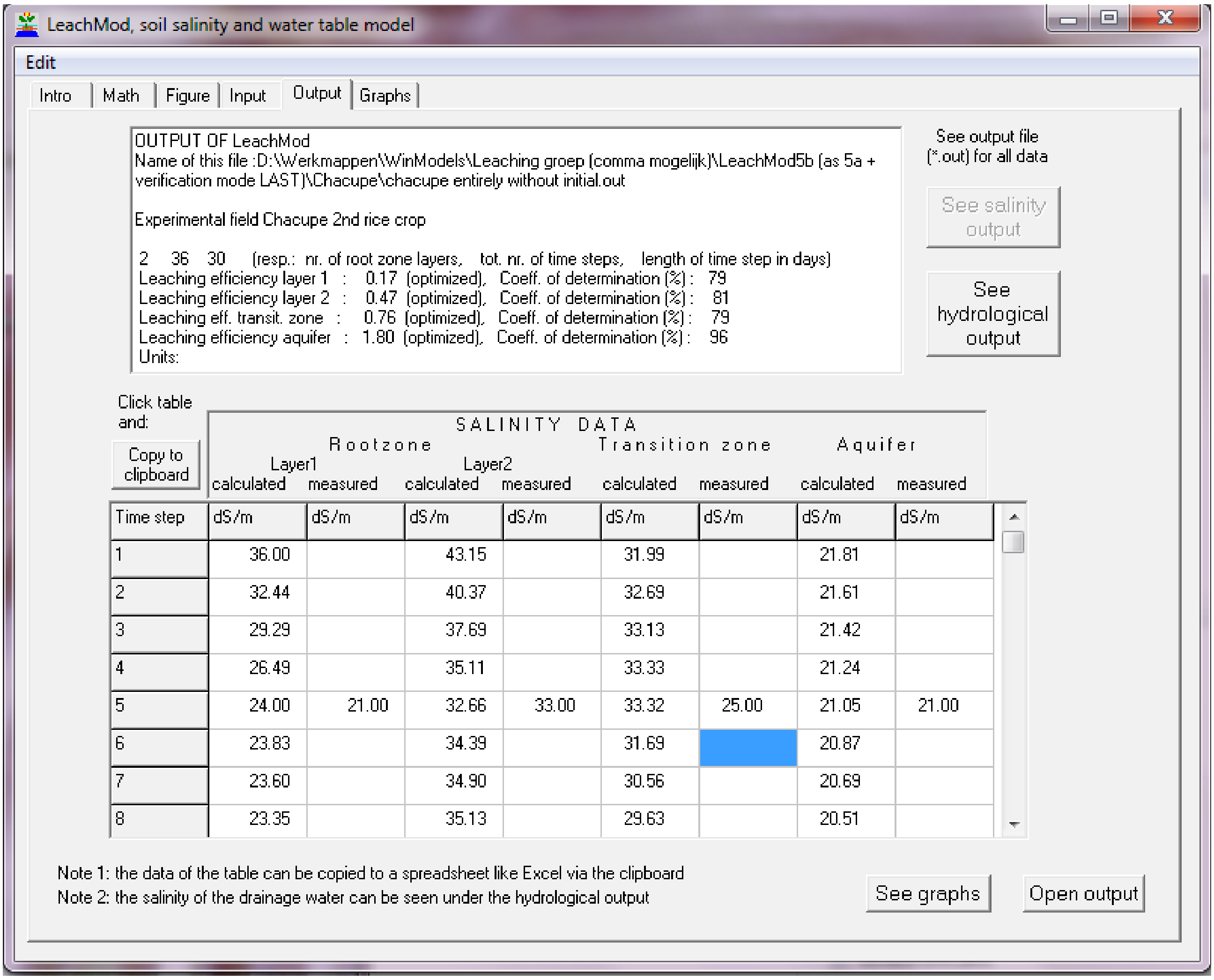

*Figure **C**. Output screen of LeachMod with salinity results*