On Efficiencies and Sufficiencies of Crop Land Irrigation, Drainage and Soil Salinity Control using the DrainApp Model in various Scenario's

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Abstract
In many irrigation projects in the world, installed to enhance crop production under conditions of rainfall shortage, there are problems of low field irrigation efficiency and/or sufficiency. Also, there can be drainage problems owing to high water tables, especially in the low lands, which may reduce the crop yield or hamper the soil tillage operations. The drainage may be inefficient or insufficient. Further, soil salinity is a frequently occurring hazard owing to inefficient or insufficient leaching of the soil. The excessive soil salt content may be related to shallow water tables or lack of sufficient irrigation water. Examples of such cases (scenario's) and their interactions will be given using the DrainApp model. The model can also be instrumental to analyze the proposed measures to improve the situation.

Contents

1. Introduction

In literature there is much information on "irrigation efficiency". Distinction is made between conveyance efficiency, distribution efficiency and field application efficiency [Reference 1]. The field applications are divided into drip, sprinkler and surface irrigation whereby the last is broken up into basin, flood, border strip, and furrow irrigation. The average field application efficiency worldwide ranges between 50 to 60% [Reference 1], meaning that about half of the supply of irrigation water to the field is used for crop consumption, while the remainder is lost somehow. This article concentrates on the surface irrigation as a field application method.

In literature there is little information "irrigation sufficiency", that is related to the question in how far the field irrigation is covering the crop water consumption demand. The SaltMod software has been used to determine the field irrigation sufficiency as a function of size of the irrigated area and depth of the groundwater table [Reference 2].

Like the irrigation sufficiency, the "drainage efficiency" as such has not been discussed often in literature. There is more information on drainage efficiency in relation to soil salinity control [Reference 3]. Here drainage efficiency is meant as an indicator of how much the actual water table depth is deeper then design depth.

Drainage sufficiency in the control of the depth of the groundwater table has hardly been discussed. Some information on water table indices for drainage design is available [References 4 and 5]. However, it is difficult to find the “drainage sufficiency” in literature, in the sense of sufficient control of the water table without hampering the crop production. Water tables that are too shallow may negatively affect crop yield.

The term “leaching efficiency” is used often in literature. However, mostly is explained how it can be calculated: leaching efficiency can be determined from the ratio of the collected drained salt mass to the applied salt mass, without giving a definition [Reference 6]. In the present paper, “leaching efficiency” is defined as the ratio of the salt concentration of the water percolating down from the root zone into the underlying transition zone (in which a subsurface drainage may have been installed) to the salt concentration of the soil moisture in the root zone [Reference 7].

The term “leaching fraction” is defined in literature a measure of the proportion of the water supposedly dedicated to leaching salts from the root zone [Reference 6]. It is not used in this publication.

For “leaching sufficiency” literature provides hardly any references. In this article this term is meant to indicate whether the amount of leaching water (that percolates through the root zone down to the deeper transition zone in the soil) is enough to maintain an acceptable soil salinity in the root zone, such that the crop production is not negatively affected by the salinity [Reference 7].

Finally, the term “leaching effectivity” as used here, is probably not used in literature. It gives the ratio of the salt tolerance of the crop [Reference 8], beyond which he crop yield starts to reduce, to the actual soil salinity.

2. Principles of the DrainApp model

The DrainApp model calculates hydraulic and soil salinity phenomena in agricultural lands with or without irrigation and subsurface drainage systems, but its main purpose is compute these values in (semi)arid irrigated crop land [References 9 and 10]. It has similarity to the LeachMod model [References 11 and 12], but it gives extra facilities with respect to drain discharge, water storage and goodness of fit when observed values are given.

The models are designed for practical use and ask for data that are usually available or that can be estimated confidentially from experience. It does not use complicated equations for unsaturated groundwater flow, like the Richards equation, as unsaturated flows like downward percolation or upward capillary rise can be derived from simple water balances.

The DrainApp model has several user interfaces amongst which there is an input and output menu as shown in the following figures.

As examples the next figures show the groups of hydrological input data.

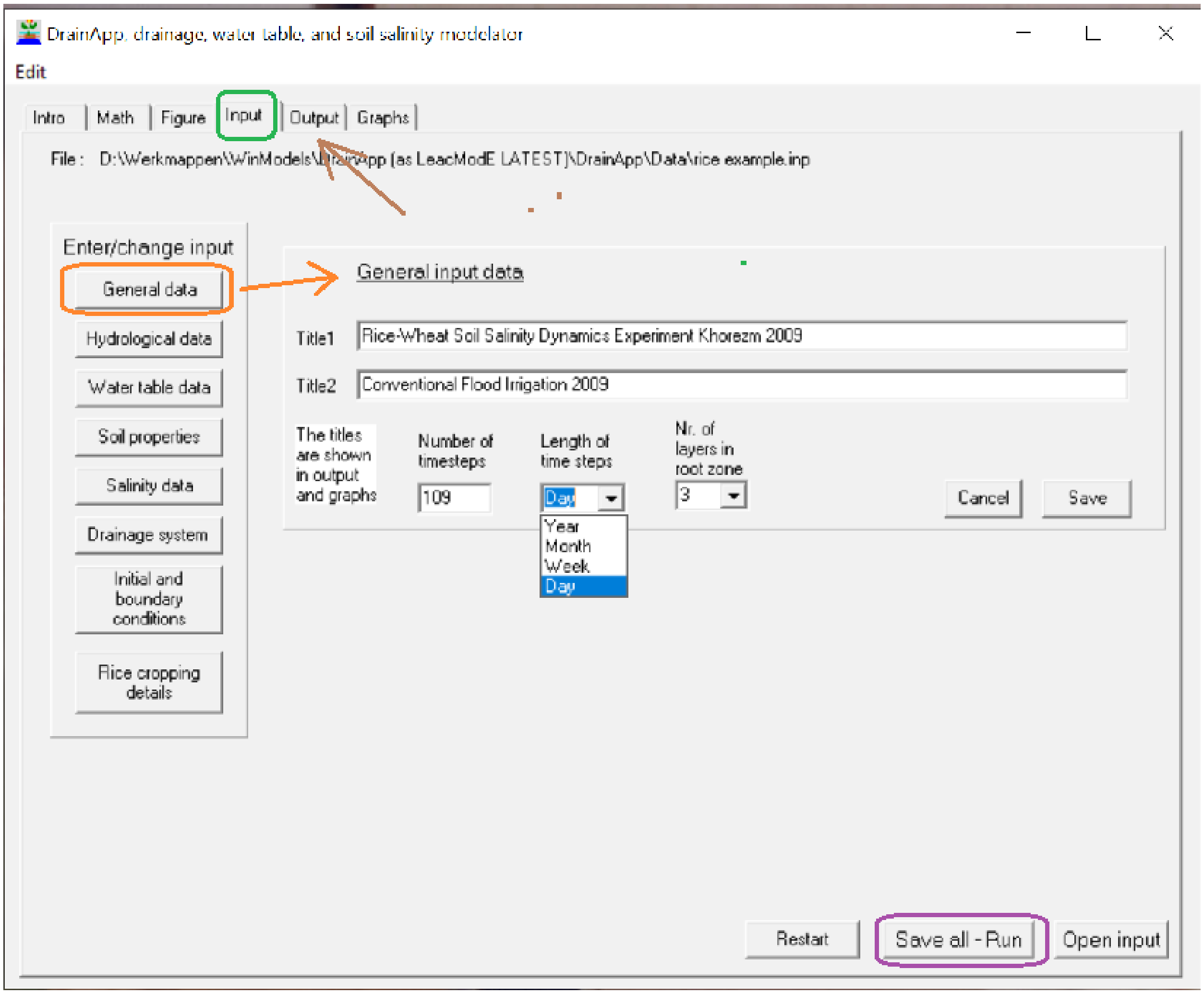


Figure 1. *The input menu of DrainApp (green square) with various input groups (left hand table) of which the group of general data is opened (orange square and arrow), in which the number of time steps, the length of each time step (in blue) and the number of soil layers (from 1 to 3) in the root zone are to be defined. The brown arrow points to the output option and the purple square emphasizes the option to save the input data and run the program (that is to. do the calculations).*

The next figure shows an example of the group of hydrological input data.

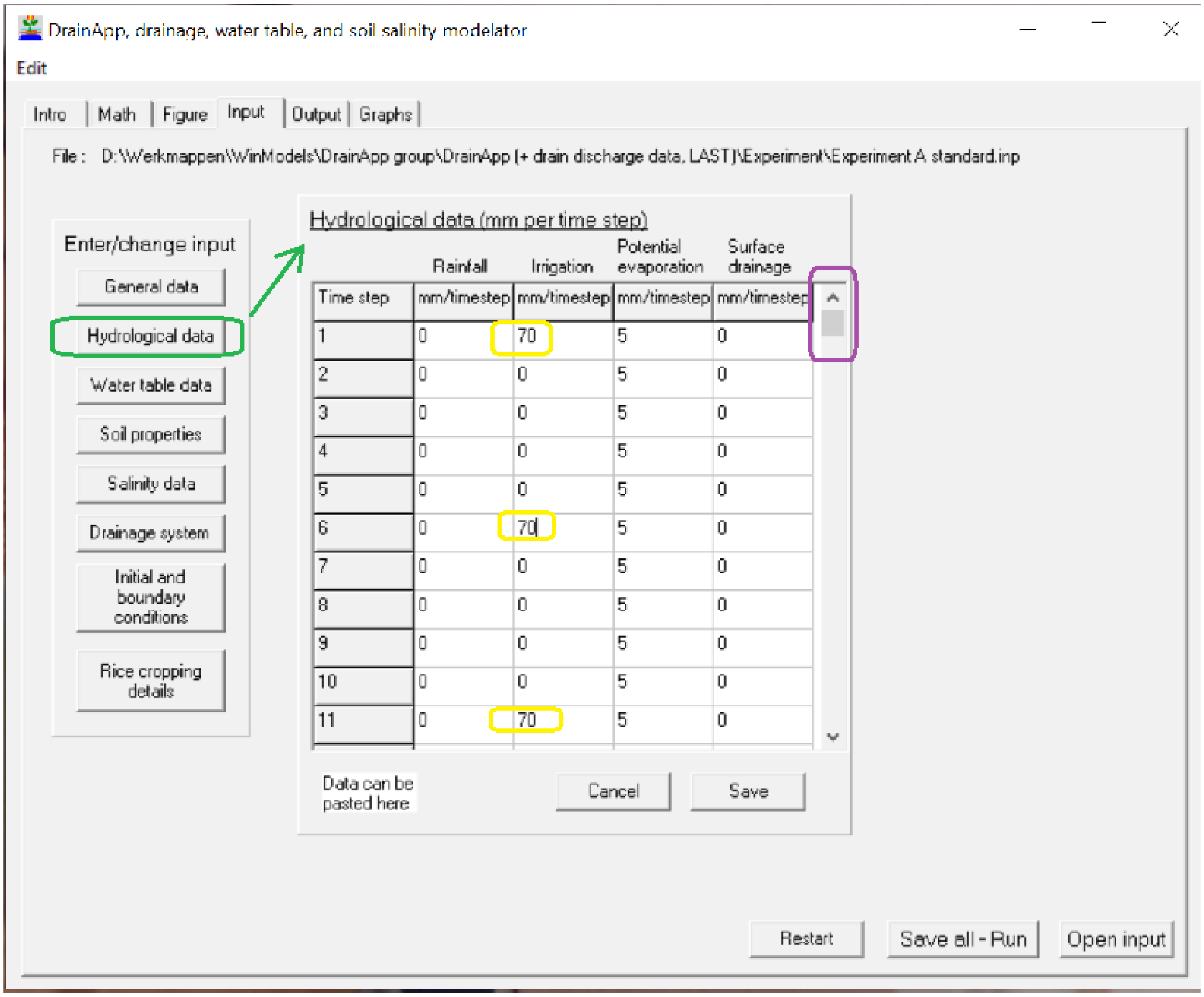


Figure 2. *In the DrainApp input menu the hydrological data group is opened (green square and arrow). The data needed are rainfall, field irrigation, potential (maximum) evapotraspiration, and surface drainage. In this example there is no rainfall and no surface drainage in the first 11 days, while the potential evaporation equal 5 mm per time step in all firs 1 days and there is field irrigation of 70 mm on time step 1, 6 and 11 (yellow squares). The scroll bar (purple square) gives access to the data at later time steps.*

The following figure illustrates the output menu.

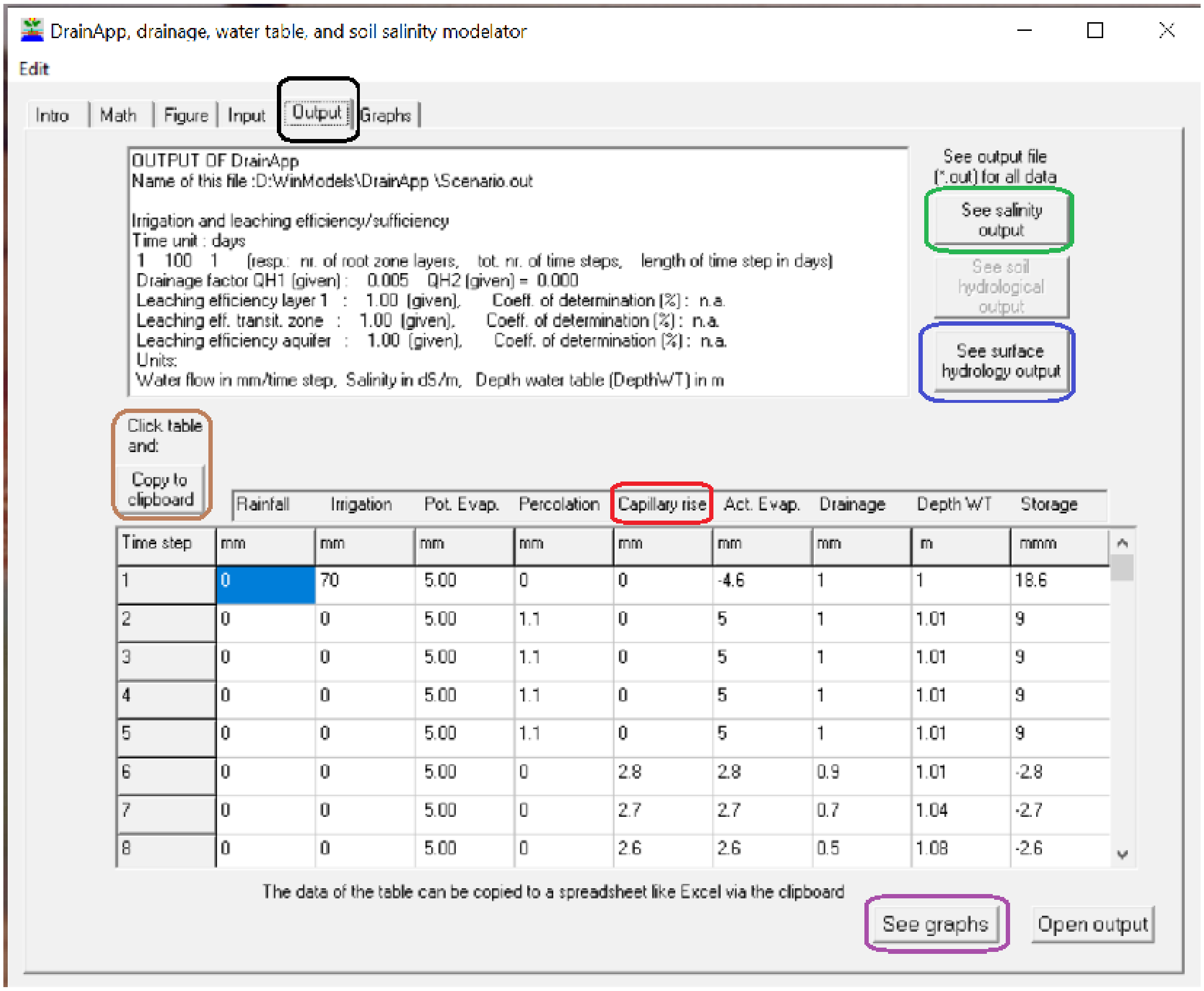


Figure 3. *The output menu of DrainApp. To see the output one can select the salinity group (green square) or the hydraulic group (blue square), as done in this example. The hydrologic output contains amongst other the downward percolation from the root zone into the transition, where the subsurface drains are located), the capillary rise (red square) from the transition zone into the root zone in periods when the soil dries between irrigations as the dry soil will suck up the water), the actual evapotranspiration (which may be less than the potential evapotranspiration given in the input (figure 2) when the soils becomes dry between irrigations), the drain discharge and the depth of the water table (DWT). There is an option to copy the data to the clipboard (brown square) for use in a spreadsheet program like Excel or for reporting in a text file. Further, one can see the graphs (purple square).*

In *figure 3* the capillary rise has been encircled in red color because it will be studied more closely in *figure 4*. The DrainApp model gives the opportunity to produce various types of graph. *Figure 4* reveals the hydraulic/hydrologic factors in the transition zone below the root zone and above the aquifer.

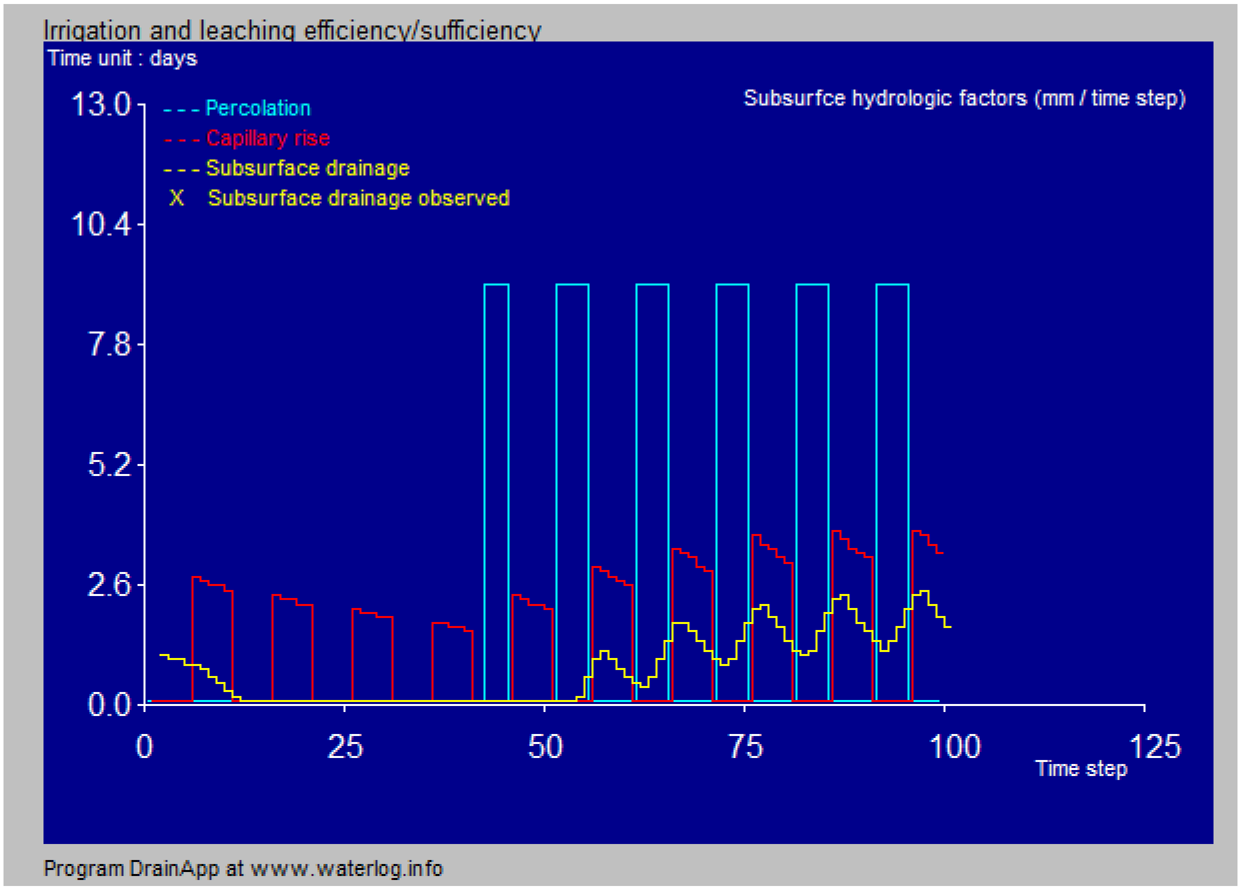


Figure 4. *The DrainApp model gives the opportunity to produce various types of graph. This picture reveals the hydraulic/hydrologic factors in the transition zone below the root zone. In the first 40 days there is no percolation as it takes time to saturate the soil before any percolation can take place. In the first 10 days there is some drainage because the initial depth of the water table was above drain level (1.2 m below soil surface), but thereafter the water table has dropped down to drain level and until day 40 no drain discharge occurs because there is no percolation. The critical level of capillary rise was is given in the input file as 2 m. below the soil surface, so when the water table has dropped down to drain level at 1.2 m depth, there can still occur capillary rise (red lines) causing the water table to drop down to below drain level. However, as the water table drops the capillary rise decreases. After day 40 the percolation starts to take place (blue lines) while between irrigation the capillary rise begins again. After day 55 the water table comes above drain level and the drain discharge sets in.*

In the Appendix (*section 7*) graphs are shown of the depth of the water table with time and the hydrologic factors of the root zone.

3. Definition of efficiency, sufficiency and effectivity indicators.

a. Irrigation efficiency: actual evapotranspiration / amount of rainfall + irrigation
Note : it concerns averages during the cropping season in mm / time step

b. Irrigation sufficiency: actual evapotranspiration / potential evapotranspiration
Note : it concerns averages during the cropping season in mm / time step

c. Drainage efficiency: average depth of the water table / 0.6, maximum 1 or 100% when the average depth is greater then 0.6 m.
Note: the average concerns the duration of the cropping season. The depth is expressed in m.

d. Drainage sufficiency: 1 – (0.6 – average depth of the water table), maximum 1 or 100% when the average depth is greater than 0.6 m.
Note: the average concerns the duration of the cropping season. The depth is expressed in m.

The expressions under c. and d. is based on the experience that at average depths greater than 0.6 m no yield reduction occurs due to water table problems.

e. Leaching efficiency: salt concentration of the percolation water / salt concentration of the soil moisture
Note: it concerns averages during the cropping season. The concentration is expressed in ECe (dS/m).

f. Leaching sufficiency: see the next table.

Soil salinity classes in ECe in the first row and in the second row the corresponding indicators of leaching sufficiency (Lsuff) in %

ECe (dS/m)	<2	2-4	4-5	5-6	6-6.5	6.5-7	7-7.5	7.5-8	8-9	9-10	>10
Lsuff (%)	100	90	80	70	60	50	40	30	20	10	0

This classification is based on the experience that at lower ECe values (<4) the crop yield is normally not negatively affected by the soil salinity while at ECe values >4 many crops undergo a yield reduction, though the more salt resistant crops experience a yield decline when ECe>6 and only the very resistant crops reduce their yield when ECe is greater than 8 [Reference 8].

g. Leaching effectivity: 4 / seasonal average soil salinity in the root zone in dS/m, maximum 1 or 100% when the average salinity is less than 4.
Note the basis of the indicative salinity value 4 is defended in the text below the table above.

3. Scenario's and Discussions of Interactions

In this section various irrigation and leaching efficiency scenario's (from A to F) will be dealt with. The particulars of each scenario are defined under the scenario description.

3.1 Scenario A

The standard case, as the first scenario (case A) concerns an area with a crop irrigated during 100 days. The field irrigation gifts are 70 mm/day every 10 days, in total 700 mm. The potential (maximum) evapotranspiration of the crops is 5 mm/day, in total 500 mm. So there seems to be an excess of irrigation, provided that the irrigation efficiency is at least 5/7 = 0.71 or 71%. There is a subsurface drainage system with capacity factors are Q_{H1} = 0.005 (m*day^{-1}) and Q_{H2} = 0 m*day^{-2} (for explanation see *section 2*). The soil consists of a root zone of 0.5 m. thickness, underlain by a transition zone 2 m. thick, covering an aquifer of 3 m thickness. The salt leaching efficiency of the root zone is L_{Er} = 100% meaning that the salinity of the water percolating through the root zone and entering the transition zone equals the salinity of the soil moisture in the root zone. The initial salinity of the root zone is expressed in ECe (see *section 2*) equaling 6 dS/m.

The outcome of DrainApp is shown in *table 1* under "Scenario A". It can be seen that the field irrigation efficiency is low, only 54% owing to the fact that a large part of the irrigation water is lost to the drainage system, though these losses help to control the soil salinity. Yet, the efficiency is not extremely low, as worldwide they normally range between 0.5 and 0.6 (see section 1 and Reference 1)

The leaching sufficiency is 100% because the processes are able to bring the time-average soil salinity down to below ECe=6 dS/m, assumed to be the critical (maximum permissible) value. The average salinity in this scenario is ECe = 5.9 dS/m.

The field irrigation sufficiency is the ratio between actual and potential evapotranspiration. In an effort to increase the field irrigation sufficiency (here only 76%, which may lead to yield reduction) *scenario B* is developed with a different field irrigation schedule.

Figure A1 in the *appendix* shows a picture of the fluctuations of the depth of water table in time. In addition Figure A2 in the annex gives the surface water balance factors irrigation and actual evapotranspiration. Both figures refer to this *scenario A*. Additionally, figure A3 in the *appendix* shows part of the mathematics tab sheet in which all the water and salt balances and movements used in the DrainApp model are recorded. In figure A4 the water flows used in DrainApp are illustrated.

Table 1. Efficiency and Sufficiency Factors in Scenario's from A to J

<table>
<tr><th rowspan="2">Factors Studied</th><th colspan="8">Irrigation, Drainage, and salt leaching scenario's</th></tr>
<tr><th>A</th><th>B</th><th>C</th><th>D</th><th>E</th><th>F</th><th>G</th><th>H</th></tr>
<tr><td>Irrigation Efficiency (%)</td><td>54</td><td>56</td><td>59</td><td>59</td><td>59</td><td>59</td><td colspan="2" rowspan="6">The scenario's G and H are derivatives of scenario A.

They concern calibrations with observed values.

Results are similar.</td></tr>
<tr><td>Irrigation sufficiency (%)</td><td>76</td><td>78</td><td>83</td><td>83</td><td>83</td><td>83</td></tr>
<tr><td>Drainage efficiency (%)</td><td>90</td><td>82</td><td>92</td><td>92</td><td>92</td><td>92</td></tr>
<tr><td>Drainage Sufficiency (%)</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td></tr>
<tr><td>Leaching #) effectivity (%)</td><td>67</td><td>67</td><td>64</td><td>64</td><td>58</td><td>58</td></tr>
<tr><td>Leaching sufficiency (%)</td><td>67</td><td>80</td><td>60</td><td>60</td><td>50</td><td>50</td></tr>
</table>

*) The letter symbols of the scenario's are all being explained in this *section 3*.
#) Leaching effectivity and leaching efficiency are different concepts, see *section 2*.

3.2 Scenario B

The irrigation sufficiency in *scenario A* is rather low (76%). It may therefore be tried to increase the amount of irrigation water. Instead of 70 mm every 10 days in *scenario A*, this amount is increased to 90 mm every 10 days in the present scenario.

In *table 2* it is seen that there is hardly no improvement of the irrigation sufficiency (78%) compared to that in *scenario A* (76%), being the ratio of total actual evapotranspiration (391 mm in 100 days) divided by the total potential evapotranspiration (500 mm in 100 days).

The strongest affected factor is the time-averaged soil salinity of the root zone that has come down from ECe = 5.9 dS/m in *scenario A* to ECe = 4.8 dS/m. This improvement is, by the way, not so important as the critical (maximum allowable) value is assumed to be ECe = 6 dS/m.

The idea rises that it is not the total amount of irrigation that promotes the irrigation sufficiency, but perhaps the frequency of application. Maintaining the total amount of irrigation at 700 mm, of *scenario A*, the irrigation frequency will be changed from 70 mm every 10 days to 50 mm every 7 days in *scenario C*.

3.3 Scenario C

With the idea that more frequent irrigations with smaller amounts of irrigation water might enhance the irrigation sufficiency, being only around 70% in the previous scenario's, in the present the irrigation frequency is changed from 70 mm every 10 days to 50 mm every 7 days.

As shown in *table 1*, the irrigation sufficiency has increased from about 77% to 83% because the actual evapotranspiration has increased from 380 mm to 414 mm in 100 days.

On the other hand, the leaching effectivity and the leaching sufficiency have gone down compared to those in *scenario's A and B* due to the increased irrigation sufficiency and reduced drain discharge (from 71 mm in to 23 mm in 100 days). Hence, the intent to increase both the irrigation sufficiency and the leching effectivity/sufficiency seems to be unrealizable. At least under the general conditions employed here in the senario's.

Assuming that a reduction of the drainage capacity factor $Q_{H1} = 0.005$ (m*day^{-1}) might reduce the quantity of drainage water and in increase the irrigation sufficiency still more. In *scenario D*, this reduction will be effectuated.

3.4 Scenario D

Assuming that a reduction of the = 0.005 (m*day^{-1}) might reduce the quantity of drainage water and increase the irrigation sufficiency still more. In scenario D, the drainage capacity factor Q_{H1} is taken as 0.002.

The results recorded in *table 1* reveal that there is no difference with *scenario C*. Hence, it can be concluded that a less intensive drainage system, and therefore a cheaper one, is recommendable.

The leaching efficiency of the soil in the root zone in the *scenario's from A to D* was fixed at 100%. Let us see in *scenario E* what happens when this efficiency is lower.

3.5 Scenario E

The leaching efficiency of the soil in the root zone in the scenario's from A to D was fixed at 100%. In scenario E this efficiency is lowered to 50%.

The results recorded in table 1 show that the hydrological efficiency/sufficiency indicators have not changed. The leaching effectivity and sufficiency, however, have decreased to 58% and 50% respectively.

Figure 5 shows the development of the soil salinity in the course of time for the situation in the standard *scenario A*, while figure 6 depicts the same for *scenario E*.

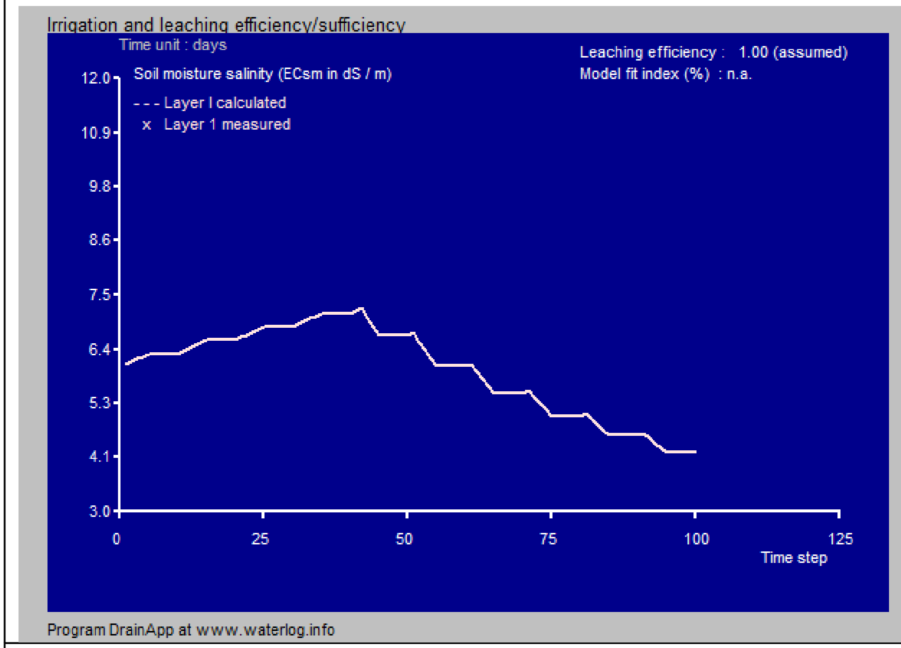


Figure 5

Development of the soil salinity in the course of time for the situation in the standard scenario A

From an initial value of ECe=6 dS/m the salinity rises to a maximum of 7.3 (owing to the lack of percolation in the intial period), then it drops to 4.1 dS/m.

The average value is 5.9 dS/m.

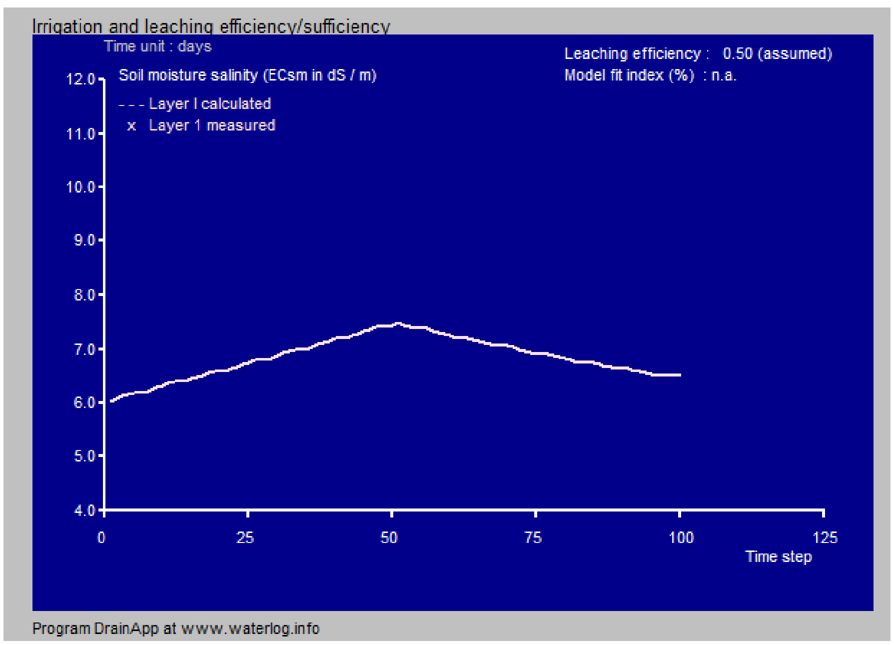


Figure 6

Development of the soil salinity in the course of time for the situation in the standard scenario E

From an initial value of ECe=6 dS/m the salinity rises to a maximum of 7.5 (owing to the lack of percolation in the intial period), then it slowly drops to 6.4 dS/m.

The average value is 6.8 dS/m.

The leaching efficiency gives the relation between the salt concentration of the water percolating from the root zone into the underlying transition zone and the soil moisture salinity in the root zone. When the water percolates down mainly through the larger soil pores in the root zone, the salt concentration of the percolation water may be relatively low.

In *figure 1* a leaching efficiency of 100% is used. With a lower salt leaching efficiency (Leff = 0.5 or 50%), as in figure 2, the soil salinity in the root zone becomes higher. With an average of 6.8 dS/m when Le = 0.5 , the leaching effectivity is 4/6.8 = 0.58 or 58%. (see the definition in *section 2*, where it is assumed that the effectivity is based on a reference value of soil salinity ECe = 4 dS/m). *In scenario A* (figure 1), the leaching efficiency equals 1 or 100%, the average salinity is ECe = 0.59 dS/m, so that the effectivity is found as 0.67 or 67% (see table 1).

The leaching sufficiency in *scenario E* is found to be 50% according to the classification presented in *section 2*, whereas for *scenario A* it is 67%, while in *scenario B* it is still higher (80%). It may be remembered that in *scenario B* the supply of field irrigation water has been increased, so that more percolation and salt leaching occurs.

It can be deduced that more field irrigation leads to lower soil salinity, provided that the subsurface drainage system has sufficient capacity.

When soil salinities of the root zone have been actually measured, the leaching efficiency can be calibrated and optimized as is the case in *scenario F*.

3.6 Scenario F

In scenario F observed soil salinity values of the root have been entered in the input menu (f*igure 7*) and the soil salinity graph as an output is demonstrated in figure 8.

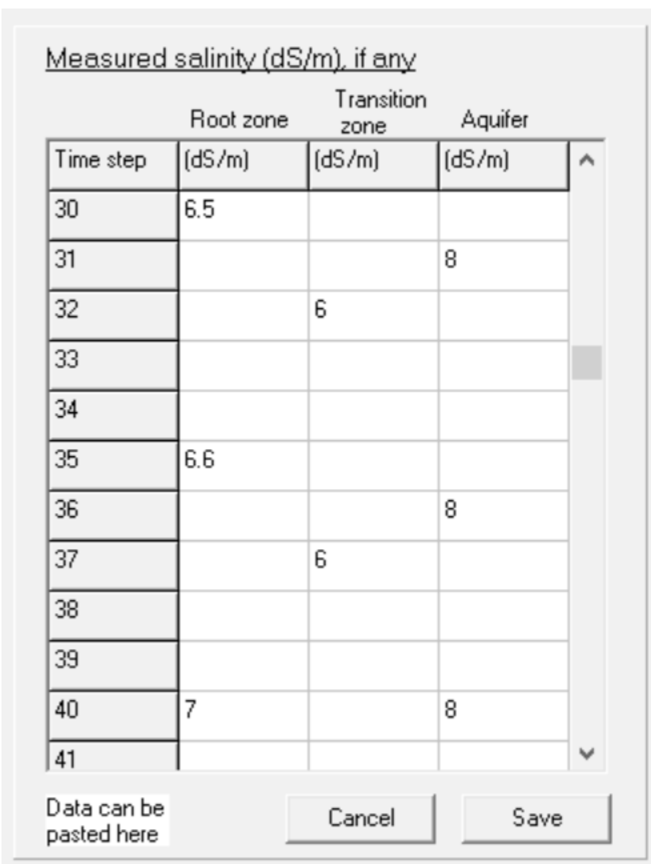


Figure 7. *Observed soil salinities entered in the input menu*.

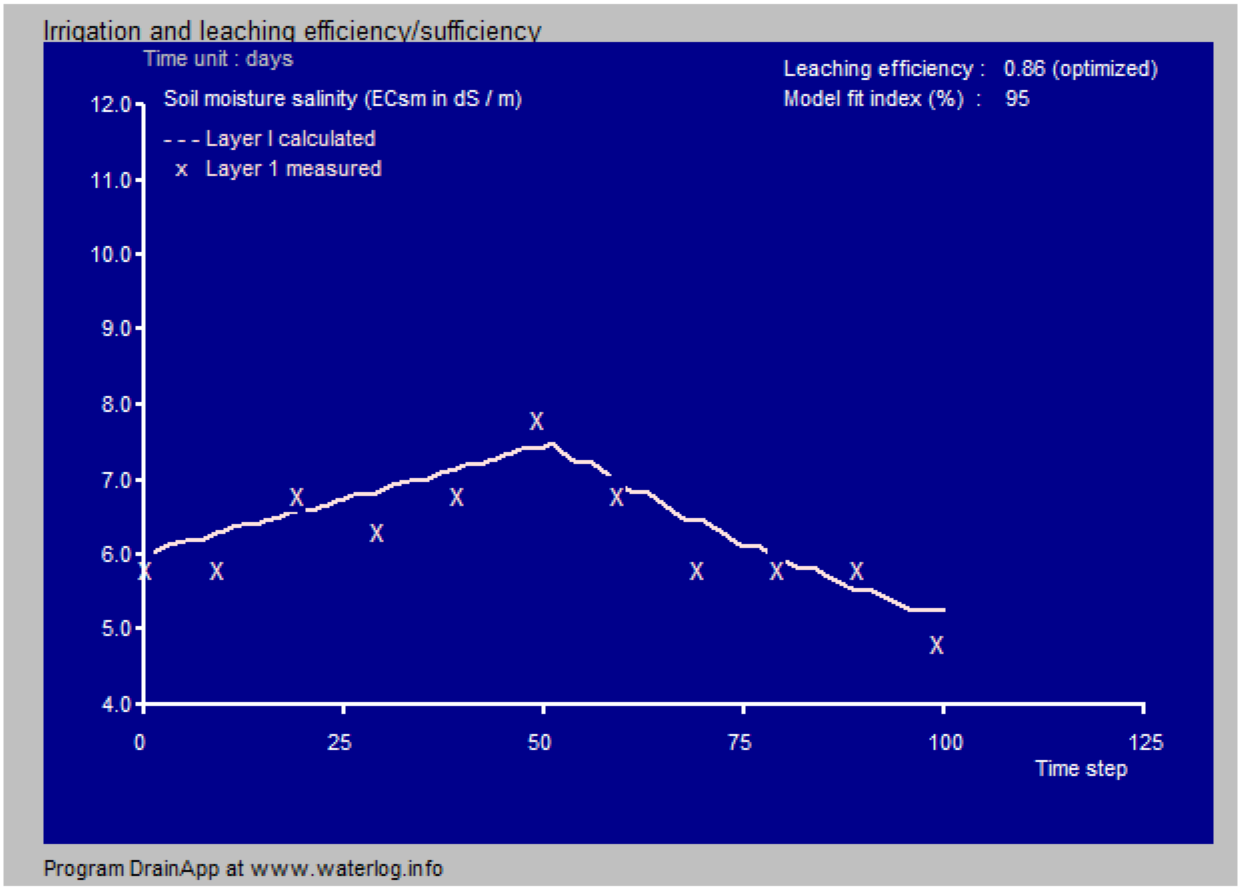


Figure 8. Output graph of soil salinity in the root zone giving calculated (simulated) salinity (white line) and observed (measured) values (white crosses). The optimized leaching efficiency is 0.86. The goodness of fir of the simulated values with leaching efficiency = 0.86 to the observed values is 95%.

In the DrainApp model, also the capacity factors of the subsurface drainage system can be optimized (calibrated) when observed data on the depth of the water table and/or of the drain discharge. In scenario G measured depth values are used.

3.7 Scenario G

The capacity factors in the previous scenario's were given as Q_{H1} = 0.005 (m*day^{-1}) and Q_{H2} = 0. When drain discharge measurements have been made, these values can be optimized (calibrated). The same holds for depth of water table measurement. In *scenario G*, the second possibility will be exploited.

In *scenario G* observed water table depth values have been entered in the input menu (*figure 9*), part of the output menu is shown in *figure 10* and the water table graph as an output is depicted in *figure 11*.

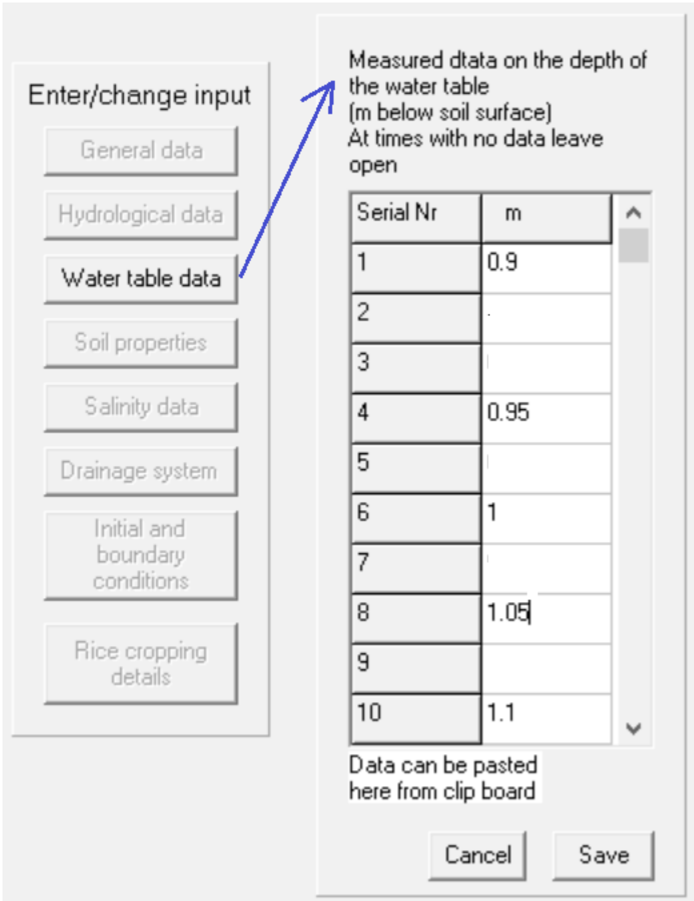


Figure 9. *Part of the input menu of DrainApp where the possibility exists to enter observed values of the depth of the water table. At time steps where no data are available the cell can be left blank.*

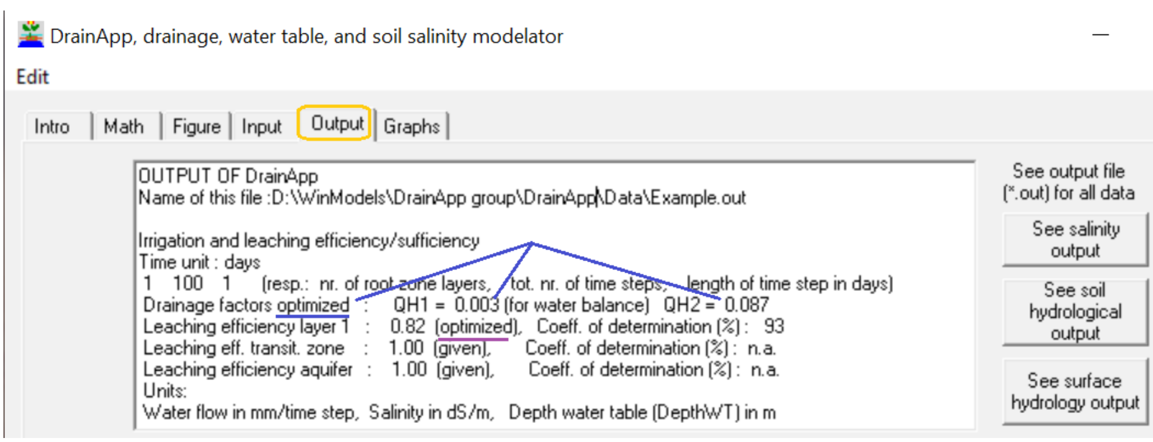


Figure 10. *Part of the output menu (orange square) of DrainApp where the values of the optimized (calibrated) capacity factors Q_{H1} and Q_{H2} of the subsurface drainage system are displayed (blue lines). They differ from the initially assumed values $Q_{H1} = 0.005$ (m*day^{-1}) and $Q_{H2} = 0$ m*day^{-2} (see* scenario A*). At the right hand side the selection options of viewing other output data are mentioned (see for example* figure 3*). Also the leaching efficiency of the root zone (layer 1) is optimized (purple line).*

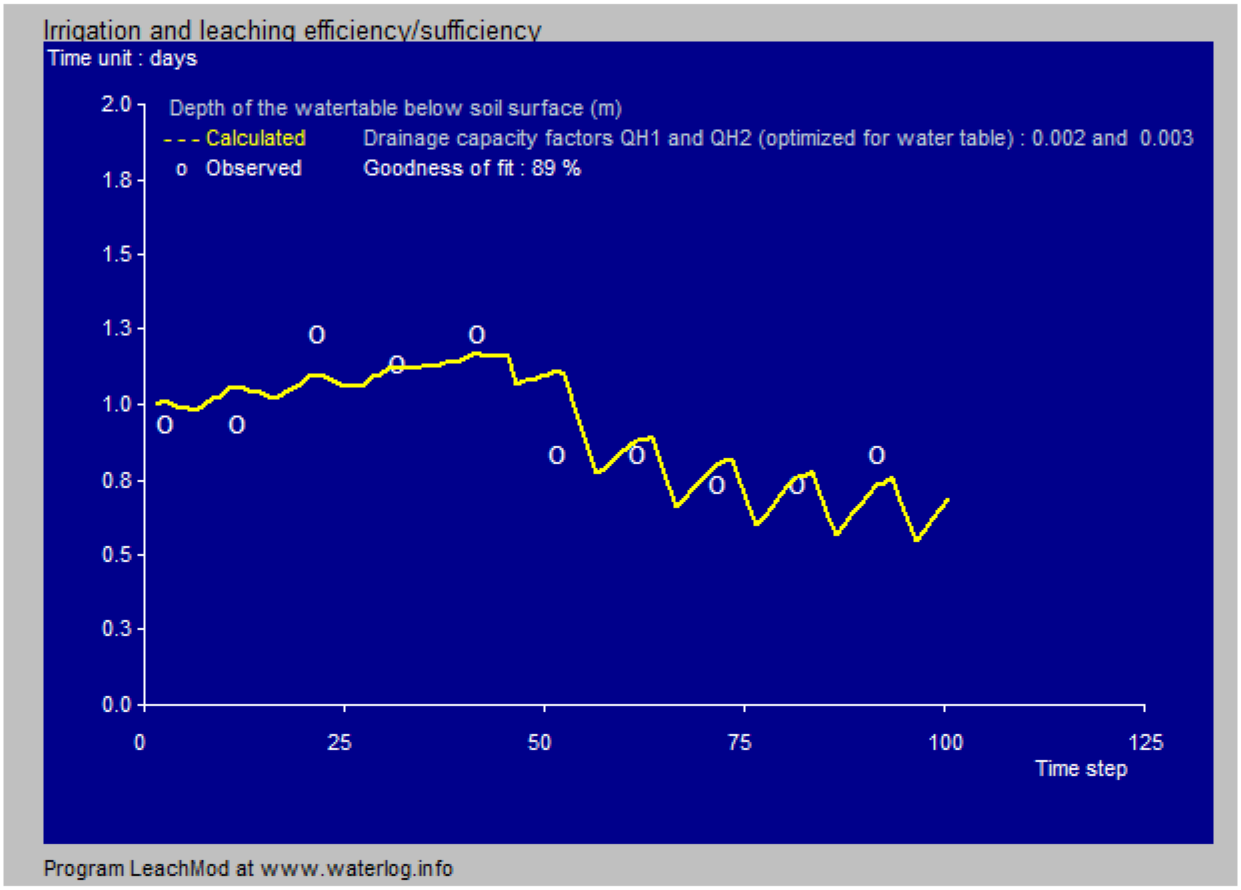


Figure 11. *Graph of the time fluctuations of the depth of the water table calibrated through the drainage capacity factors in* figure 10. *The observed values are given as white circles. The fit of the calculated (simulated) yellow lines to the observed values is 89 %.*

In *scenario G* the drainage capacity factors are calibrated (optimized) with the help of observed depths of the water table. In *scenario H* the optimization is effectuated by means of observed discharges of the subsurface drains.

3.7 Scenario H

The capacity factors in the previous scenario's were given as Q_{H1} = 0.005 (m*day^{-1}) and Q_{H2} = 0 (see the *scenario A*). When drain discharge measurements have been made, these values can be optimized (calibrated). The same holds for depth of water table measurement. In *scenario G*, the second possibility was exploited. In this *scenario H* it is the first option that is employed.

In *scenario H* observed drain discharge values have been entered in the input menu (f*igure 12*), and the drain discharge graph as an output is depicted in *figure 13*.

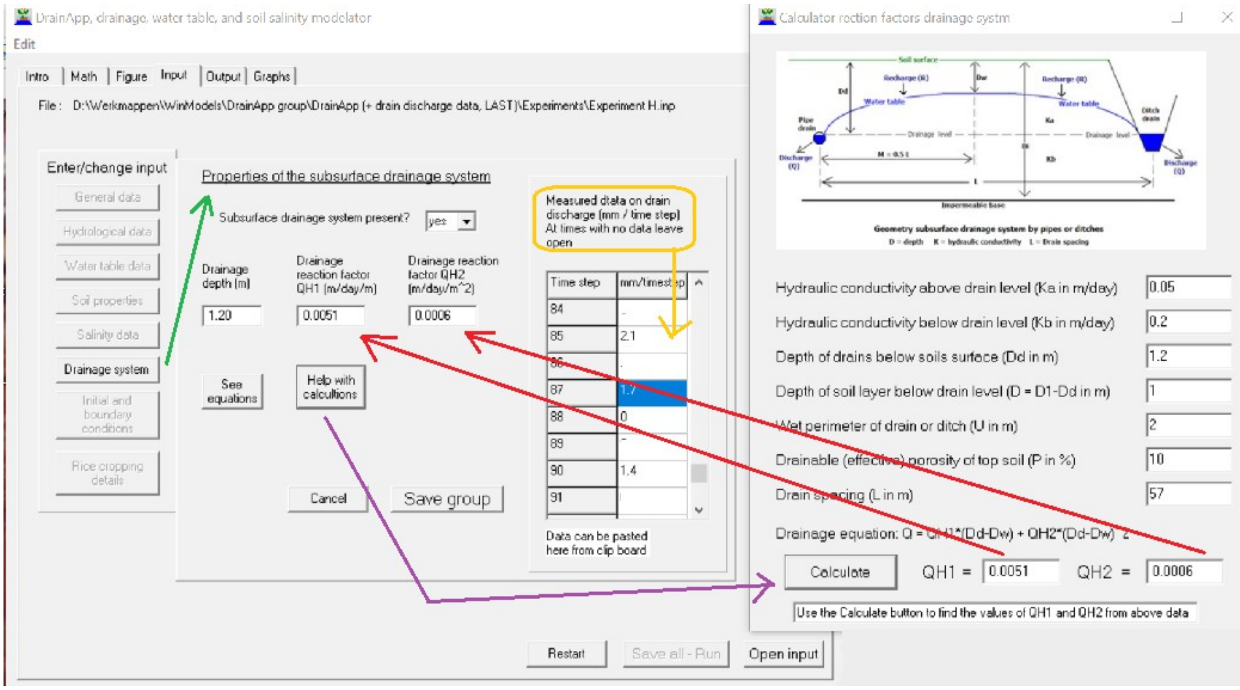


Figure 12. *Part of the DrainApp input menu for the properties of the subsurface drainage system (green arrow). The orange square and arrow point to the possibilities for entering observed drain discharges (mm per time step). When at a certain time step no observation is available the corresponding cell can be neglected. There is a button that can be clicked to a help screen for the calculation of the capacity factors* Q_{H1} *and* Q_{H2} *of the subsurface drainage system (purple arrow). After completion of the drainage conditions at the right, clicking on the "calculate" button will reveal the capacity factors and transpose them to in input menu (red arrows).*

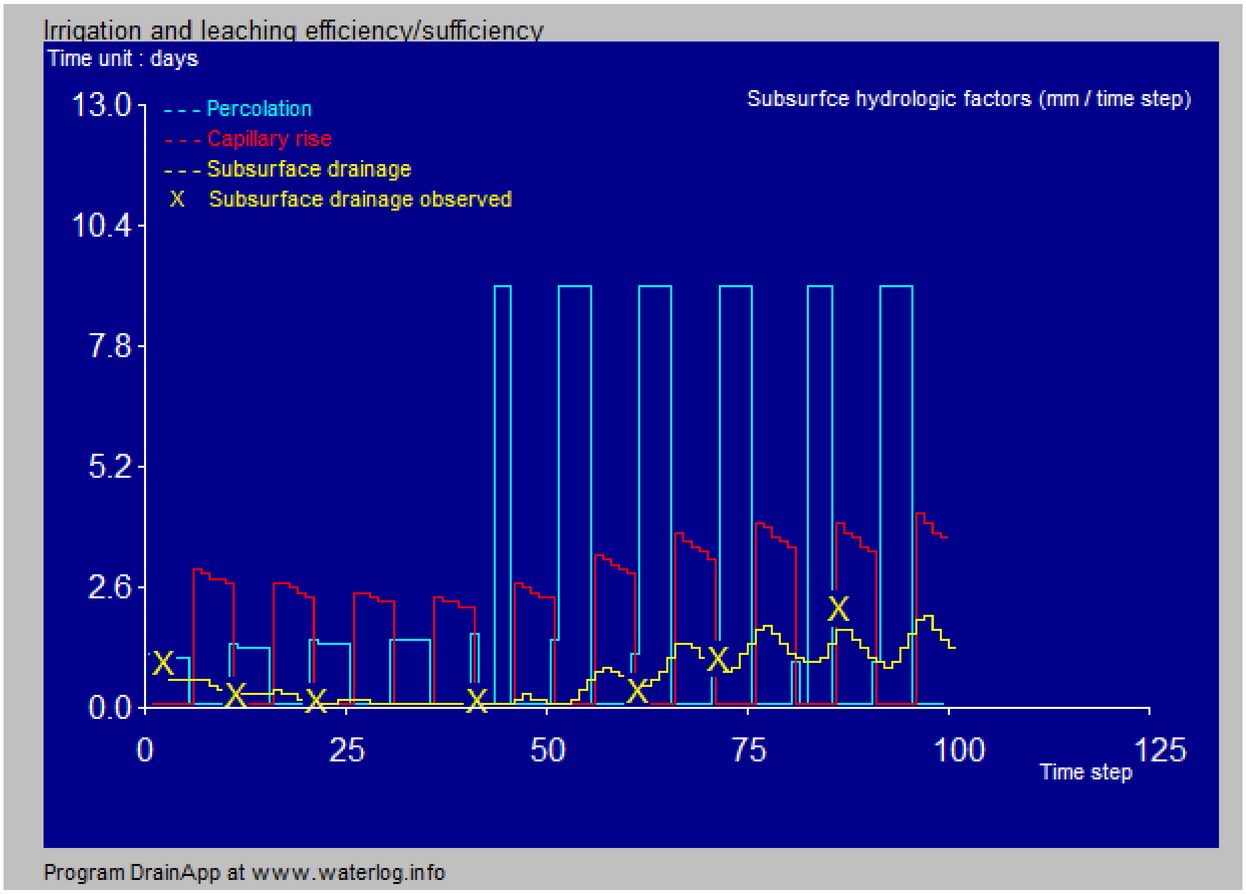
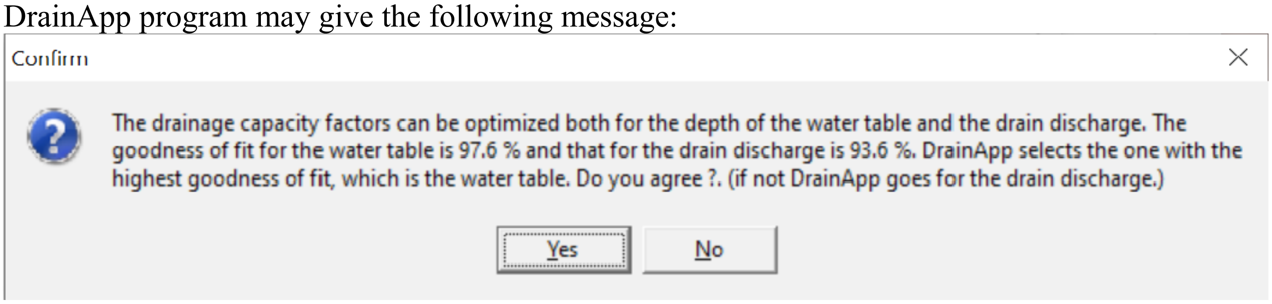


Figure 13. *Graph showing the subsurface hydrologic and hydraulic factors. The drain discharge (mm per time step) optimized (calibrated) by means of the drainage capacity factors in* figure 12 *is characterized by the yellow curves, while the observed values are indicated by yellow crosses. The fit of the calculated and observed values looks reasonable. The red lines represent the capillary rise that occurs when the soil becomes dry after an irrigation so that it sucks up water from the transition zone underlying the root zone. The blue lines give the percolation water moving downward through the root zone to the transition zone is shown by blue lines. The percolation occurs after part of the irrigation water has evaporated from the root zone*.

Note

When an input file contains both measured water table data and drain discharge data, then the DrainApp program may give the following message:



In this case the water table data yield a higher goodness of fit index. In case the discharge comes with a higher index then the message will be the other way around.

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Reference 9.
DrainApp, model for subsurface drainage systems with emphasis on their response functions, behavior of the groundwater table, and simulation of soil salinity in 5 soil layers optimizing their leaching efficiency. Download from: https://www.waterlog.info/zip/DrainApp.zip

Reference 10.
Manual of the free DrainApp model for subsurface drainage systems with emphasis on their response functions, behavior of the groundwater table, and simulation of soil salinity in 5 soil layers optimizing their leaching efficiency. On line:
https://www.waterlog.info/pdf/DrainApp manual.pdf

Reference 11.
LeachMod, a free model for reclamation and desalinization of irrigated agricultural lands in (semi) arid regions. On line: https://www.waterlog.info/leachmod.htm

Reference 12.
Reclamation of a coastal saline vertisol by irrigated rice cropping, interpretation of the data with a salt leaching model. International Journal of Agricultural Science Volume 3, 2018
On line: https://www.waterlog.info/pdf/EnvJournal2.pdf

7. Appendix with illustrations

This appendix shows two figures of which two concern hydrological phenomena playing a role in the *scenario A* and the third relates to the used equations described in the DrainApp software program.

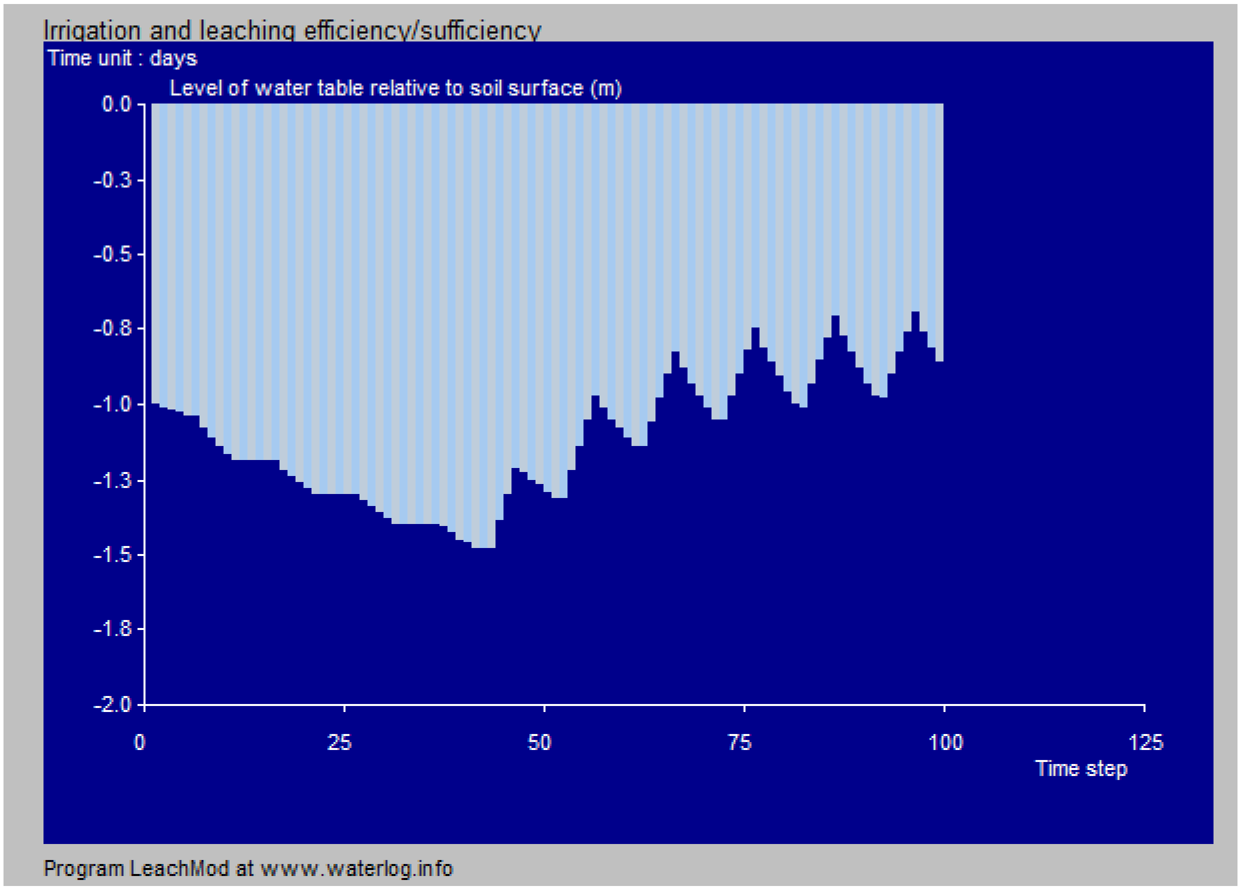

Figure A1. *Fluctuations of the depth of the water table with time in scenario A. Initially the water table descends because the first irrigations refill the dry root zone before recharge to the underground occurs. In this period there is capillary by which water goes up from the water table into the root zone. Thereafter the irrigation water percolates downward, recharging the water table, reason why it gets a rising trend. The fluctuations happen between the times of irrigation* (see next figure A2).

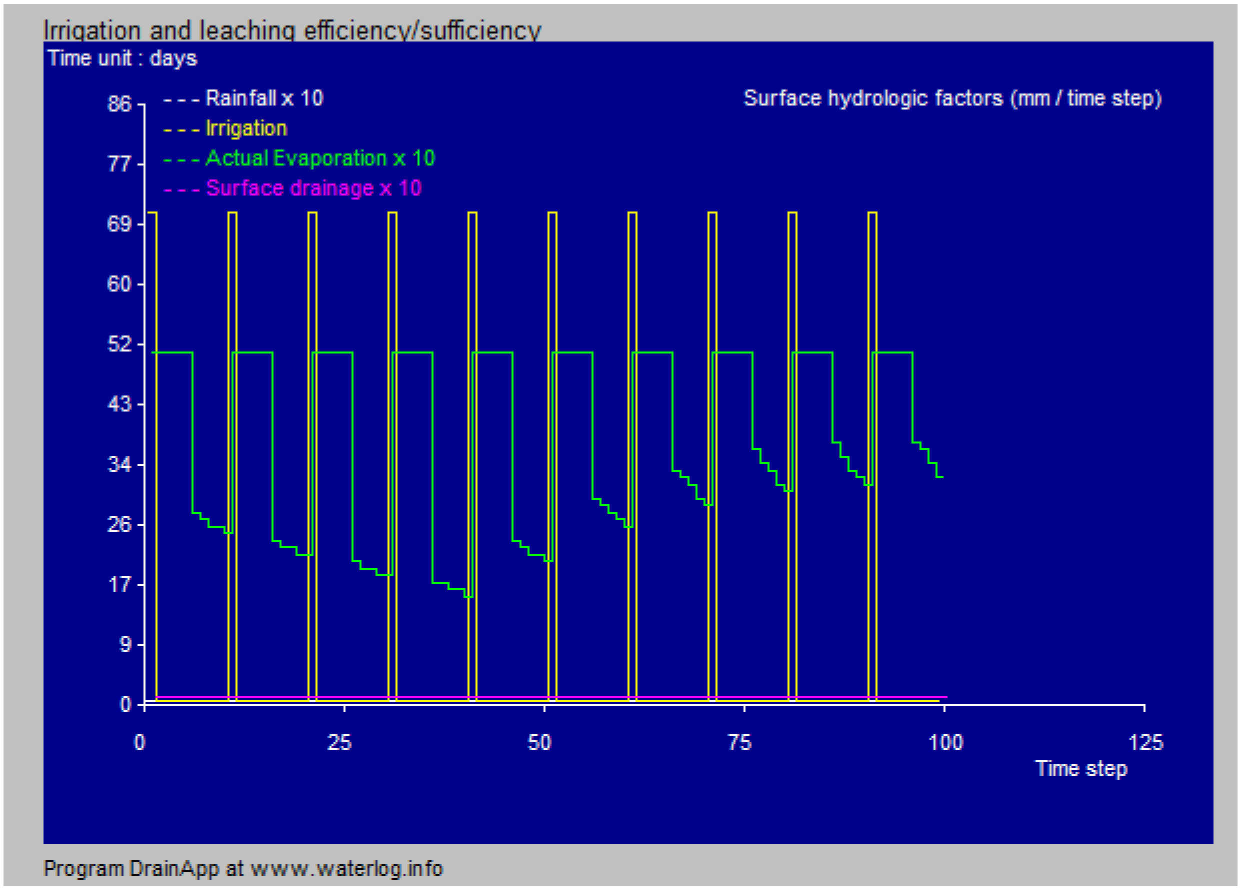

Figure A2. Surface hydrological values consisting mainly of irrigation (yellow lines) and actual evapotranspiration. The rainfall and surface drainage are negligible. The evaporation has been multiplied with a factor 10 to fit the scale of this graph. The major part of the irrigation water first replenishes the dry soil and thereafter it percolates down and is removed by the subsurface drainage system. This process is required to leach the excess salts from the root zone.

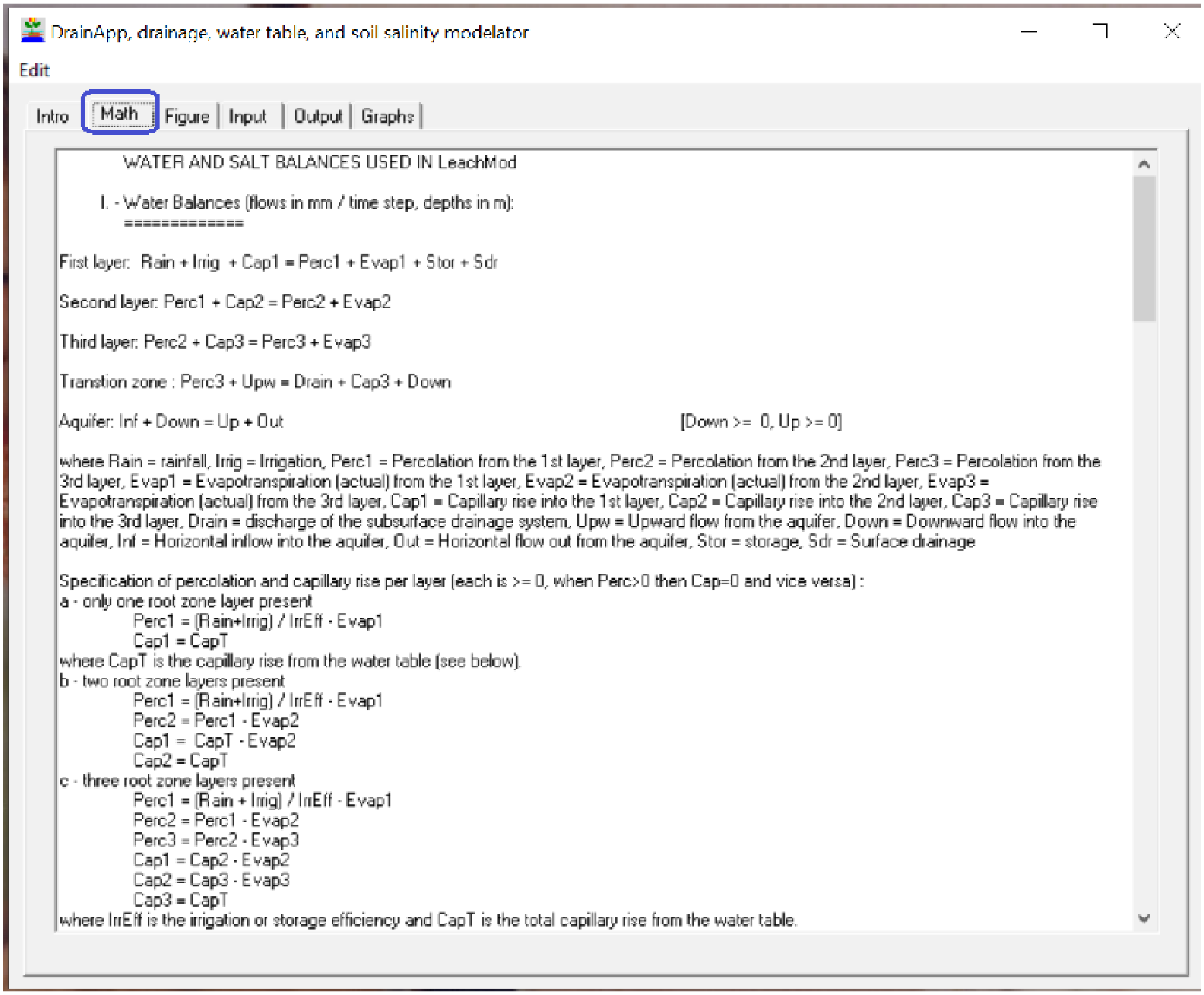

Figure A3. *The mathematics tab sheet (blue square) explains all the equations of water and salt balances and flows used in the DrainApp model. The scroll bar helps in getting a complete overview. The flow factors used are illustrated in the next figure (A4).*

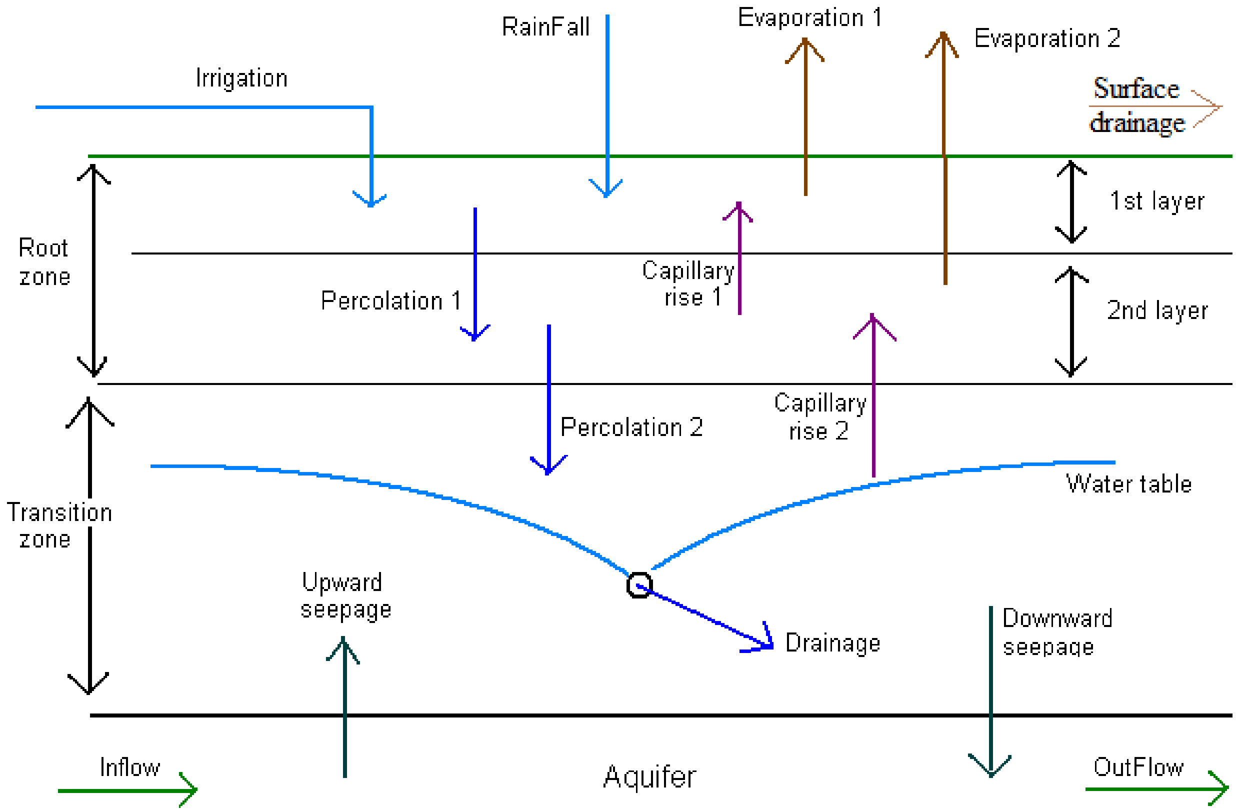

Figure A4. *Sketch of water flow factors used in DrainApp in case of a root zone with two layers. There are also options to have a root zone with one or three layers.*