RainOff, a rainfall-runoff model applied to a subsurface drainage system by calibration and validation

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Abstract
The RainOff model has been used for rainfall-runoff relations in hydrological catchment and watershed areas to determine their runoff parameters and to simulate the discharge (runoff).
The model can also be used for subsurface drainage systems. The system parameters can be determined from drain spacing, hydraulic conductivity of the soil and other data of the drainage system. Alternatively, the parameters can be found by calibration given the rainfall, evaporation and drain discharge. In this article both methods are used. The calibration is done with data during one month and verified/validated for the next month.

Contents

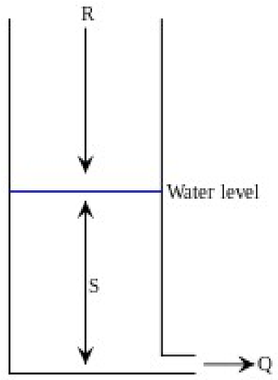
1. Introduction

The RainOff model has been used for a small valley in Sierra Leone [Ref. 1] and for the Herbornseelbach and Martinsthal catchment (watershed) areas in Hesse, Germany [*Ref. 2 and 3 respectively*]. For subsurface drainage calculations a comparison was made between steady and non-steady state [*Ref. 4*].

2. The RainOff model principles

The RainOff model (of which the latest version is called RainOffT) is based on the principles of a non-linear reservoir. It is an improvement over the linear reservoir of which the principles are described in continuation [*Ref. 5*].

The linear reservoir is described by D.A.Kraijenhof van de Leur [Ref. 4] and its principles are given in figure 1.



R = recharge {dimension L/T}

S = storage {dimension L}

Q = discharge, runoff {dimension L/T}

Figure. 1.

The concept of a linear reservoir.

The reservoir (response) function is:

$Q = \alpha . S$ (Eq. 1)

where α = reaction factor {1/T}

Differentiating S to time T gives

$dS/dT = d(Q/\alpha)/dT = R - Q$ (Eq. 2)

Integrating Eq. 2 with limits Q_1, Q_2, T_1 and T_2 yields:

$$Q_2 = Q_1 \exp \{- \alpha (T_2 - T_1) \} + R [1 - \exp \{ - \alpha (T_2 - T_1) \}] \qquad \text{(Eq. 3)}$$

where Q_2 and Q_1 are Q at time T_2 and T_1 respectively.

With Equation 3 the discharge Q_2 can be calculated from R, Q_1, α, and the time difference.

This concept is often to simple to characterize the watershed as its reaction factor is usually more complicated. Therefore Nash [*Ref. 6*] employed a cascade of linear reservoirs, one reservoir emptying into the next, while Kraijenhoff [*Ref. 4*] used a number of parallel reservoirs over which the rainfall is distributed in some proportion, while the reservoirs joined their discharge.

In hydrology, the concept of non-linear reservoirs has seldom been applied. Instead of a reservoir with a constant reaction factor, one could employ a non-linear reservoir with a reaction factor that changes linearly with storage (figure 3) instead of being a constant, thus avoiding the difficulty of dealing with a series of reservoirs.

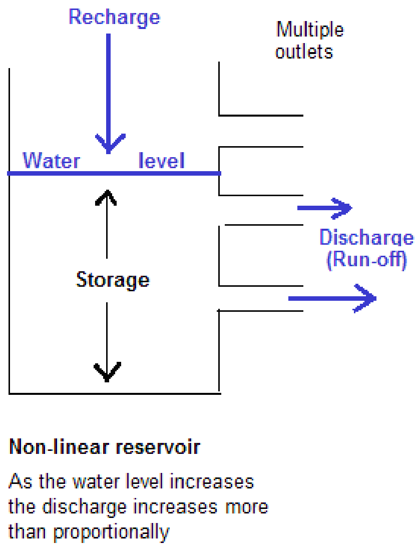


Figure 2.

A non-linear reservoir with multiple outlets whereby the discharge increases more than proportionally with the storage.

The equivalents of equation 1, 2 and 3 for the non-linear reservoir are equations 4, 5 and 6 as follows [*Ref. 3*]:

$$Q = (A.Q + C).S \qquad \text{(Eq. 4)}$$

$$\begin{aligned} dS/dt &= R-(A.Q+C).S \\ &= R - A.Q.S + C.S \qquad \text{(Eq. 5)} \end{aligned}$$

$$\begin{aligned} Q_2 = Q_1 \exp \{ -(A.Q_1+C).(T_2-T_1) \} + \\ R[1-\exp\{-(A.Q_1+C).(T_2-T_1)\} \qquad \text{(Eq. 6)} \end{aligned}$$

The reaction factor can now be written as

$$\alpha = A.Q + C \qquad \text{(Eq. 7)}$$

It is no longer a constant, but it depends on the discharge. The factor A and the term C are found by RainOffT with a numerical method, varying the A and C values and selecting the combination that maximizes the fit of the simulated discharge/runoff in time to the observed one.

The values B and C represent the properties (characteristics) of the catchment (watershed), which needs only two parameters.

It is also possible to use a quadratic α function: $\alpha = A.Q^2 + B.Q + C$ [*Ref. 3*]. The software for this case is called RainOffQ. In some cases it gives a still better result [*Ref. 3*].

The recharge depends on the rainfall and the escape factors like evaporation and percolation to an aquifer with natural drainage. When the percolation is taken negative it will represent upward seepage from the aquifer. The rainfall enters a pre-reservoir with a storage function as shown in figure 3.

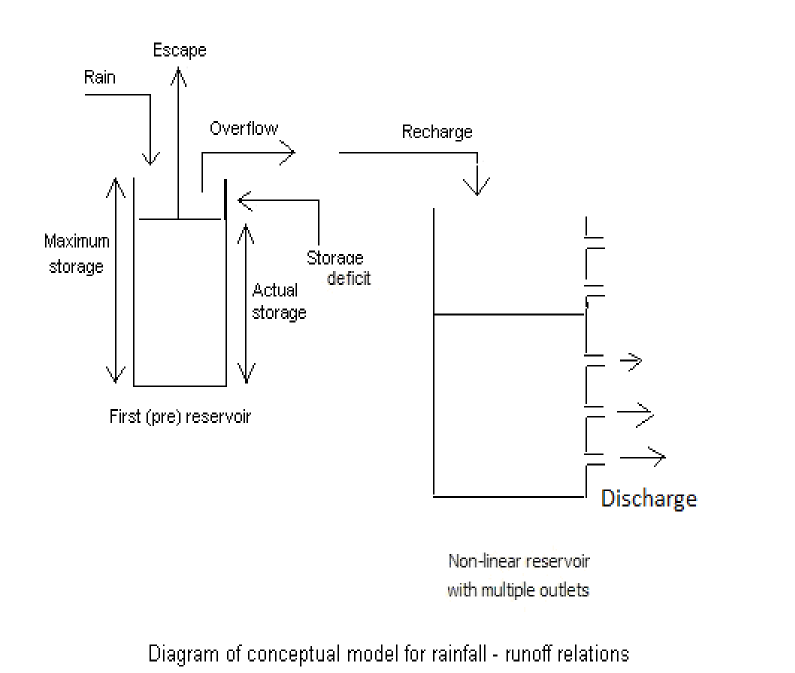


Figure 3.

The second (main) reservoir is preceded by a pre-reservoir that provides the net recharge after deducting evaporation (escape) and replenishment of the soil moisture

The Escape usually consists of evaporation, but it may include percolation to the aquifer and natural drainage, while upward seepage from the aquifer can be considered as a negative Escape. The Recharge is thus found from:

Recharge = Overflow = Rain – Escape – Storage Deficit. (**Eq. 8**)

During rainy periods the Storage Deficit can become zero and the Recharge will equal the Rainfall less Evaporation. In dry periods the Escape may exceed the Rainfall and the Storage Deficit will then increase.

3. Parameter determination from drainage system properties for the second month

Figure 4 shows the input menu for the “Predict” option (green ellipse). Further it exhibits an “AlfaCalc” button (blue ellipse) that gives the possibility to calculate the Alpha function with factor A and constant C (orange block).

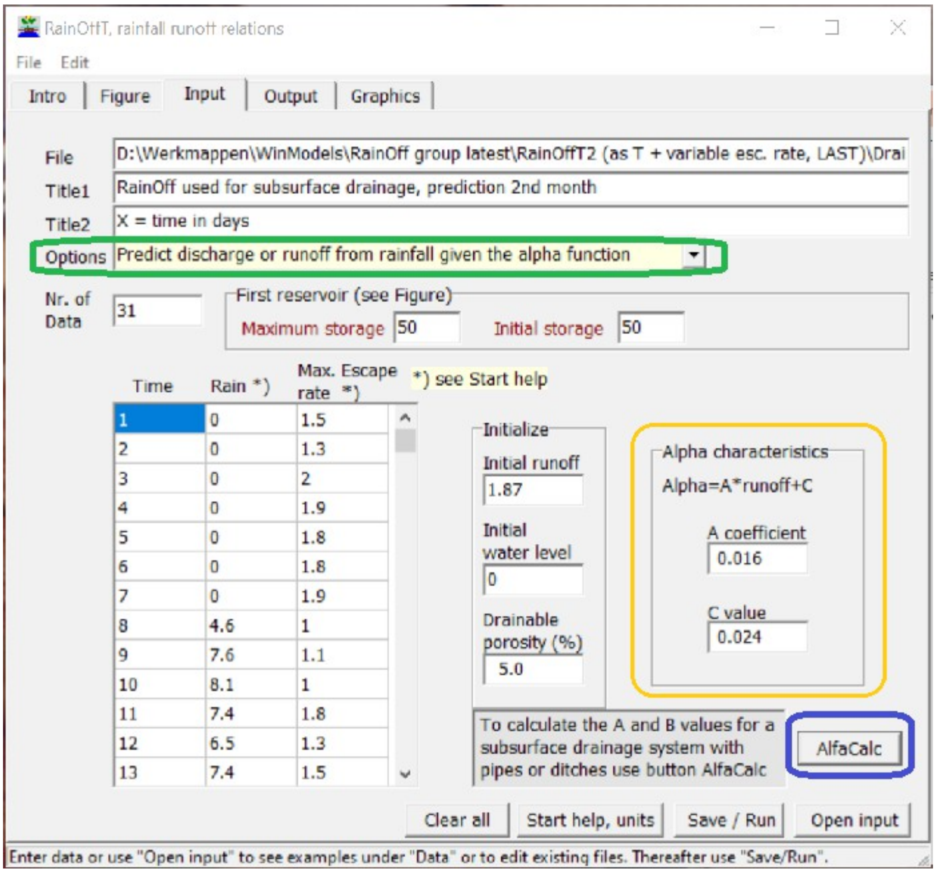


Figure 4. *Input menu for the "Predict" option (green ellipse) with an "AlfaCalc" Button (blue ellipse) that gives the possibility to calculate the Alpha function (equation 6) having a coefficient factor A and constant value C (orange block).*

Upon clicking the "AlphaCalc" button, a new screen is opened as depicted in figure 5. The screen shows an illustration of subsurface drainage parameters, a table where these parameters can be filled in (blue block) plus a "Calculate" button that produces the Alfa parameters (yellow arrows).

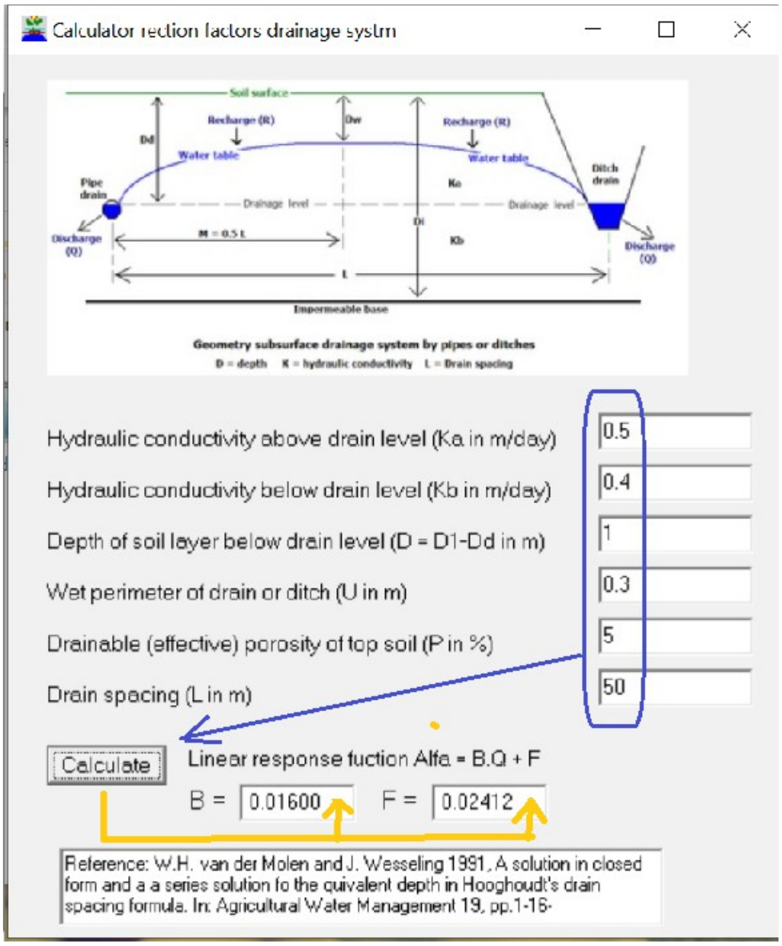


Figure 5. *The figure shows an illustration of subsurface drainage properties, a table where these properties can be filled in (blue block) plus a "Calculate" button that produces the Alfa parameters (yellow arrows).*

The calculated Alfa parameters in figure 5 are automatically transposed to the input screen, see figure 6.

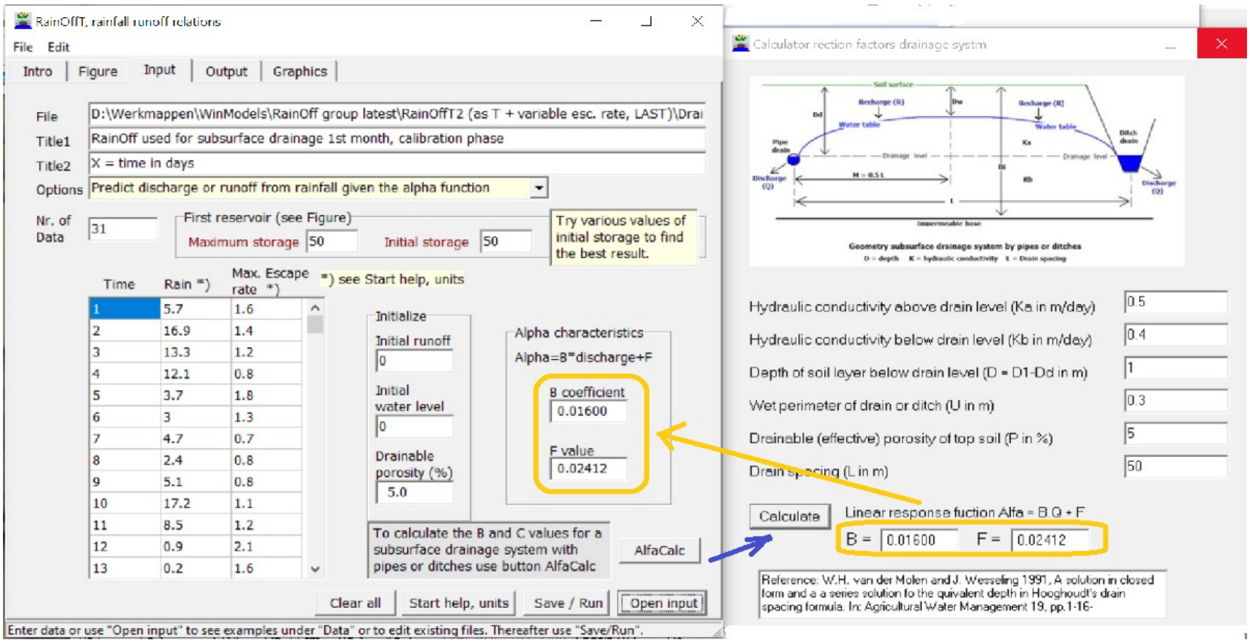


Figure 6. *The transposition of the calculated Alfa parameters to the input menu (yellow blocks and yellow arrow). For the reference cited see list of references.*

During the calibration phase (next section) we will see that the calibrated Alpha parameters are practically the same as those revealed in figure 6.

Figure 7 depicts the results of the prediction based on drainage system properties, while figure 8 compares the predicted and measured drain discharge. These results are for the second month, as the data for the first month are used for calibration.

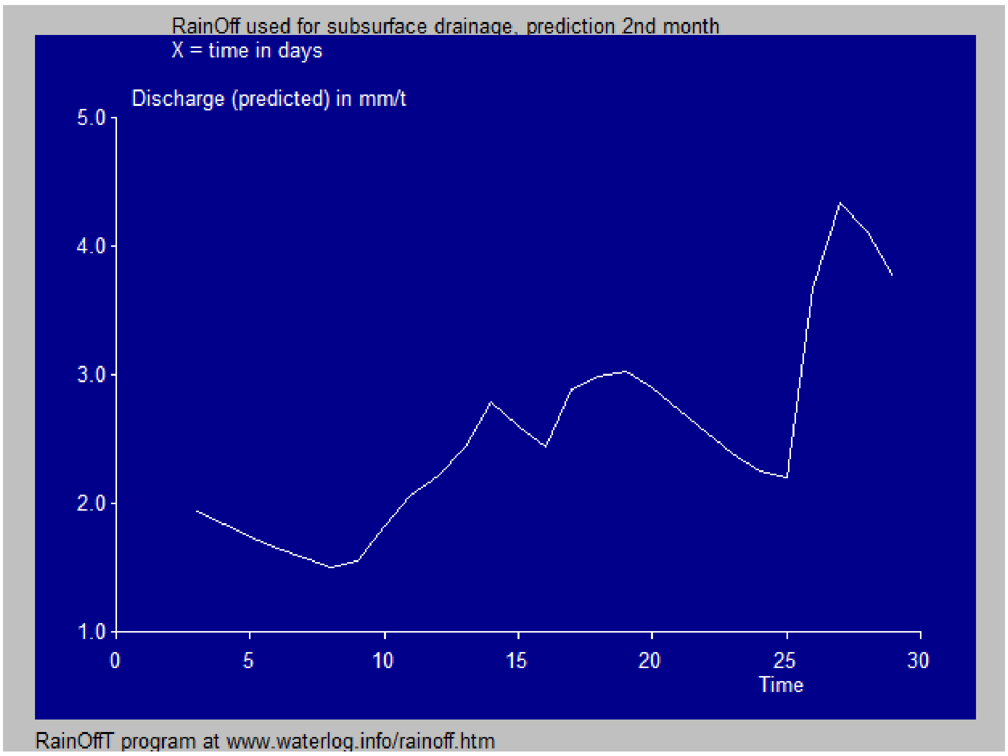


Figure 7. *Predicted discharge on the basis of the properties of the subsurface drainage system (figure 5).*

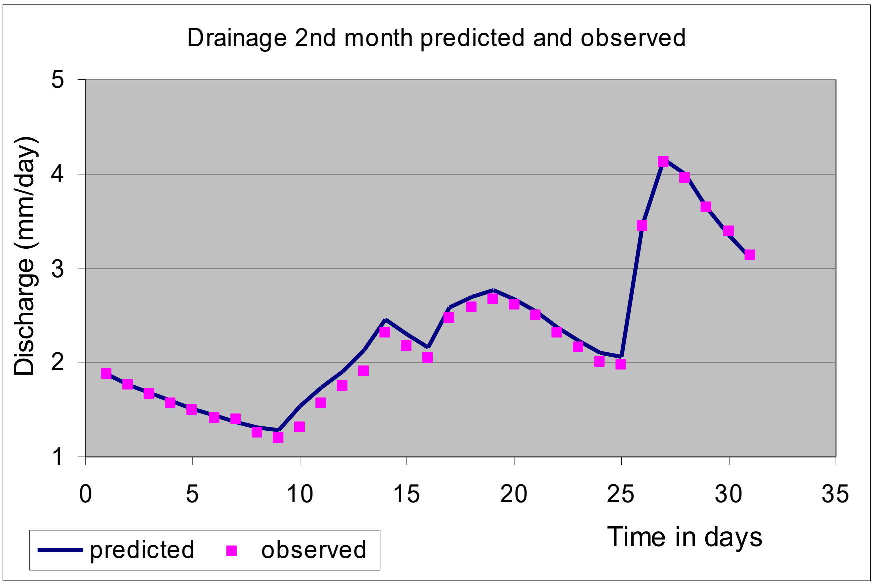
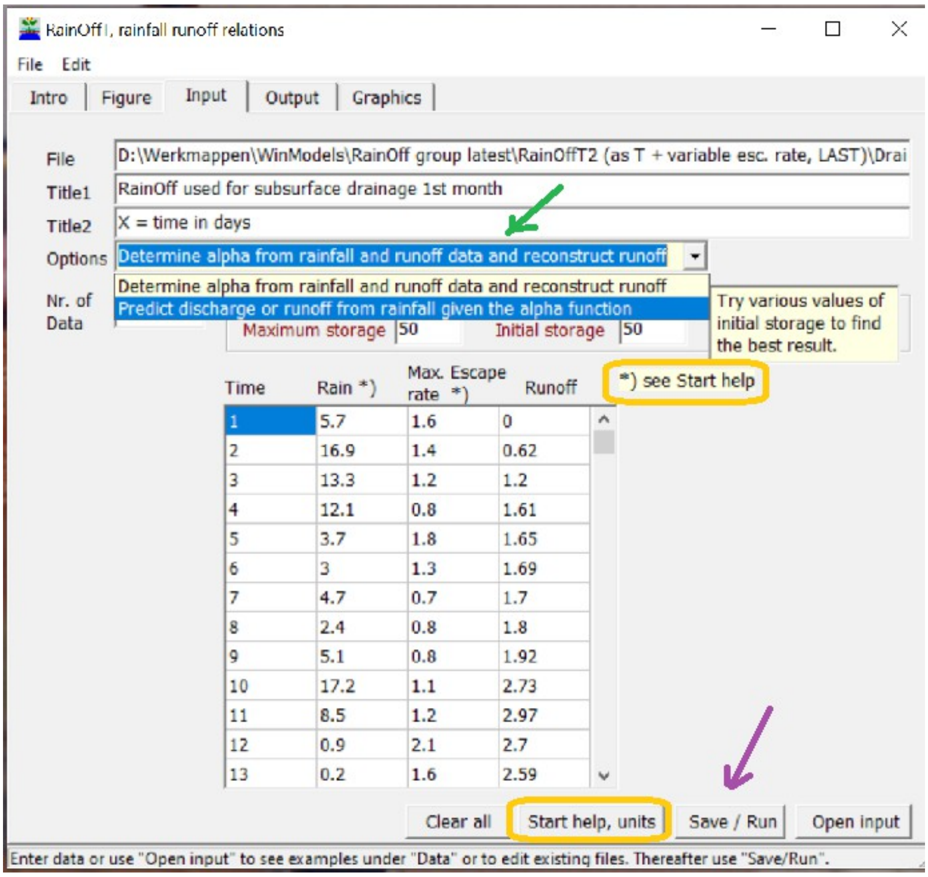


Figure 8. Comparison of the predicted discharge on the basis of the properties of the subsurface drainage system (figure 7) with the measured discharge. The agreement is quite high.

4. Parameter determination by calibration using rainfall, evaporation and discharge data for the first month.

Using the calibration option (determine alpha, figure 9, green arrow), instead of the prediction option as in figure 4, and clicking "Save / run" (purple arrow), the RainOff model will produce an output (figure 10) with various graphic options (figure 11) .



Time	Rain *)	Max. Escape rate *)	Runoff
1	5.7	1.6	0
2	16.9	1.4	0.62
3	13.3	1.2	1.2
4	12.1	0.8	1.61
5	3.7	1.8	1.65
6	3	1.3	1.69
7	4.7	0.7	1.7
8	2.4	0.8	1.8
9	5.1	0.8	1.92
10	17.2	1.1	2.73
11	8.5	1.2	2.97
12	0.9	2.1	2.7
13	0.2	1.6	2.59

Figure 9. *The input menu in the case of "Determine alpha" (green arrow, the calibration phase). The determination of the "Rain" and "Maximum escape rate" is clarified using the "Start help" button (yellow boxes). After completing this input menu (the data can be copied from a worksheet and pasted in the table), the "Save / run" button (purple arrow) can be used to perform the calculations.*

A version (DrainCalc) with the additional option to determine alpha from rainfall and measured depths of the water table (hence not only from the measured runoff/discharge data) and reconstruct the depth is also available [*Ref. 7*].

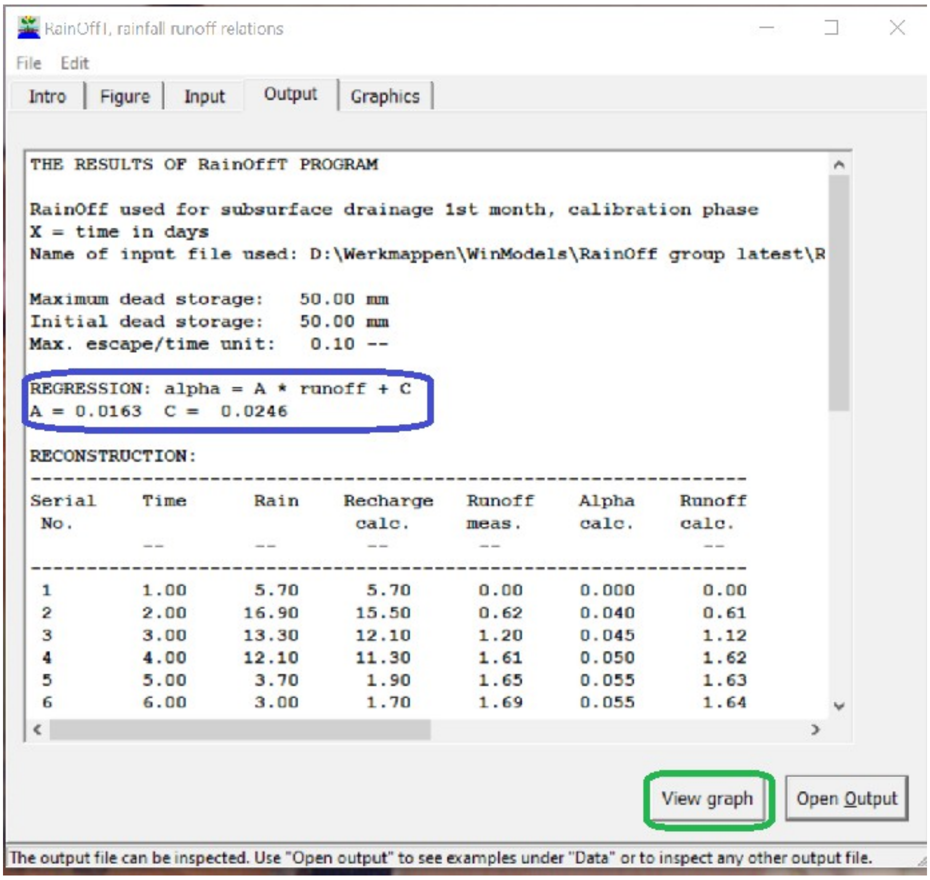


Figure 10. *Output menu, showing the calibrated parameters of the alpha function (blue box) and the option to view graphics (green box).*
Note that the A and C parameters (blue box) are practically equal to those obtained in the prediction phase on the basis of the properties of the subsurface drainage system (figure5 and 6).

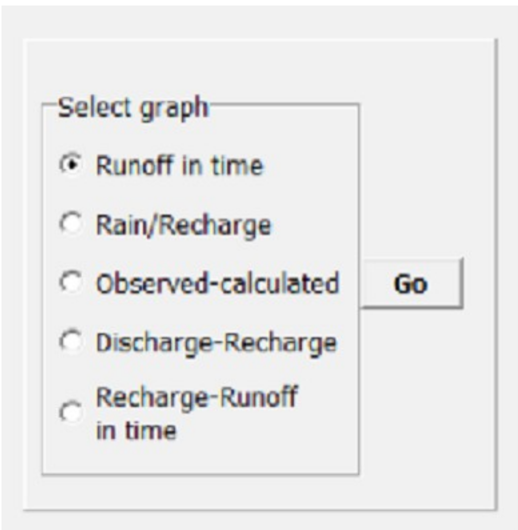


Figure 11. *Graphics menu, showing the options for graph types. Using the "Rain/Recharge" option, one will see figure 12, while using the "Runoff in time" option (the first one), figure 13 appears*

In the subscript of figure 12 the role of the storage deficit (figure 3) is explained.

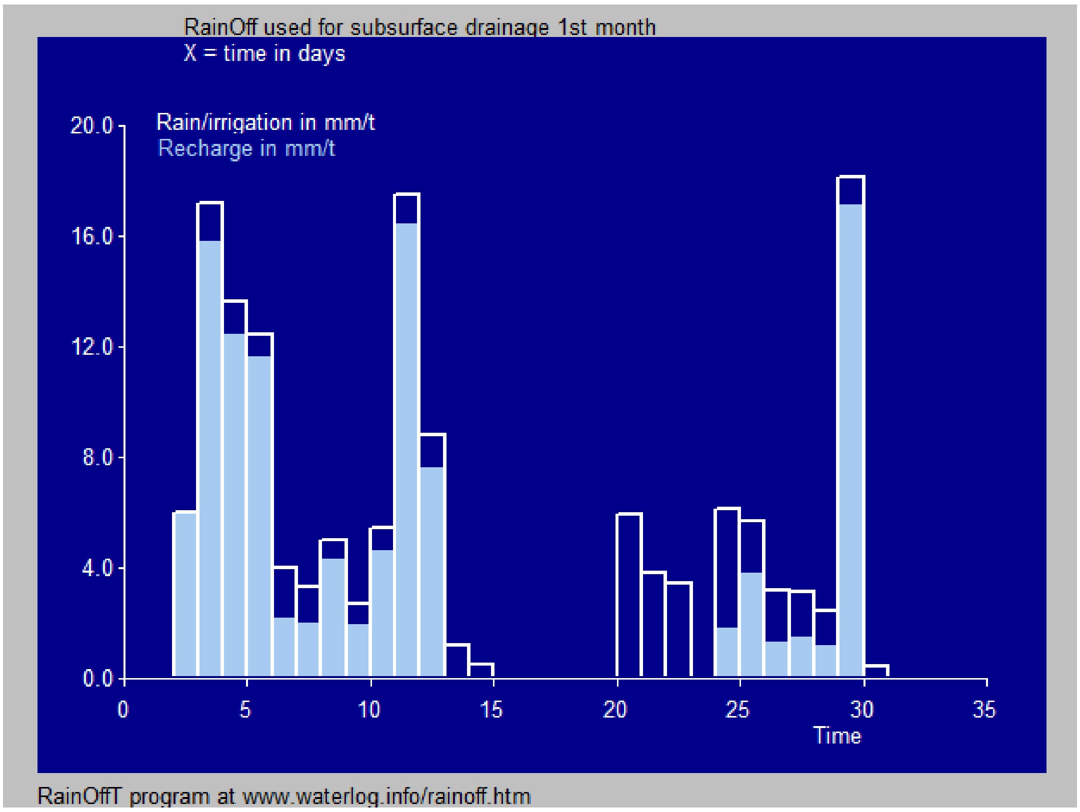


Figure 12. *After the dry spell from day 13 to day 20, the soil has dried out and a deficit was created, reason why the first rains after day 20 did not come to runoff as there was no overflow (recharge, figure 3) until the storage deficit was filled up.*

Figure 13 gives the results (in terms of drain discharge) of the calibration of the the parameters of the Alpha function, and compares those with the discharge observed.

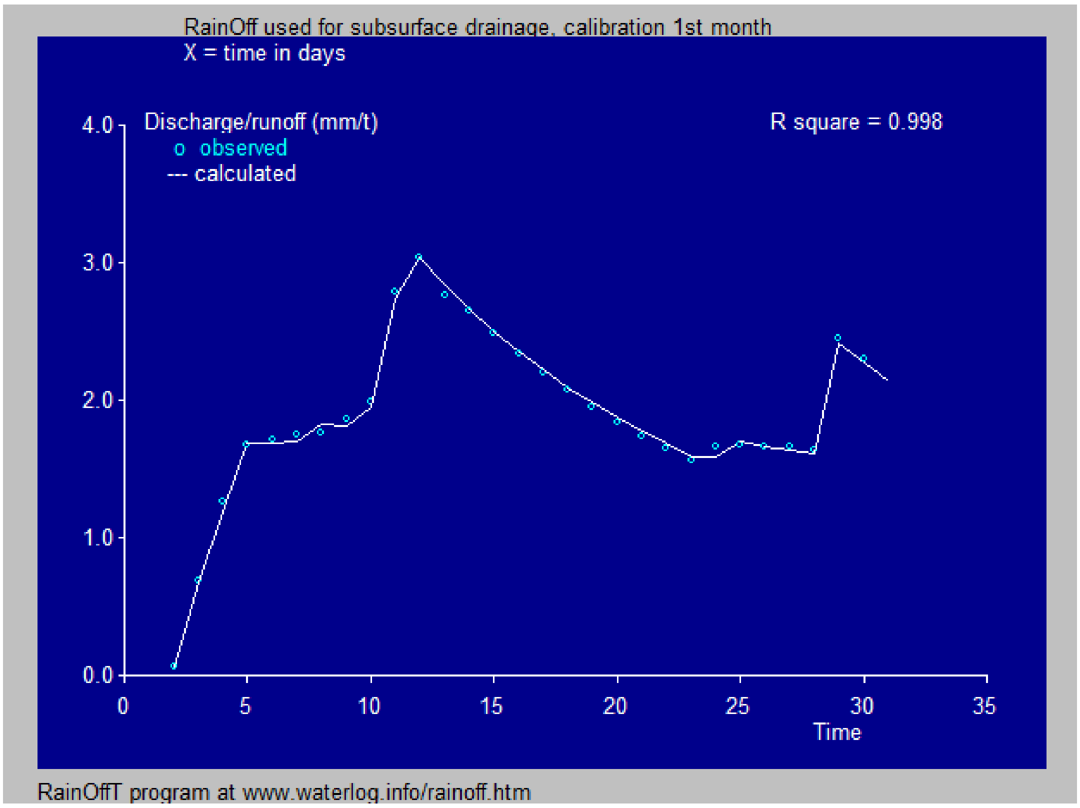


Figure 13. *The calculated and observed discharges for the calibration phase, with data of the first month, coincide nicely.*

Figure 14, finally, shows recharge, discharge and height of the water table versus time in days during the first month. The level of the water table is found from Recharge-Discharge divided by the drainable porosity.

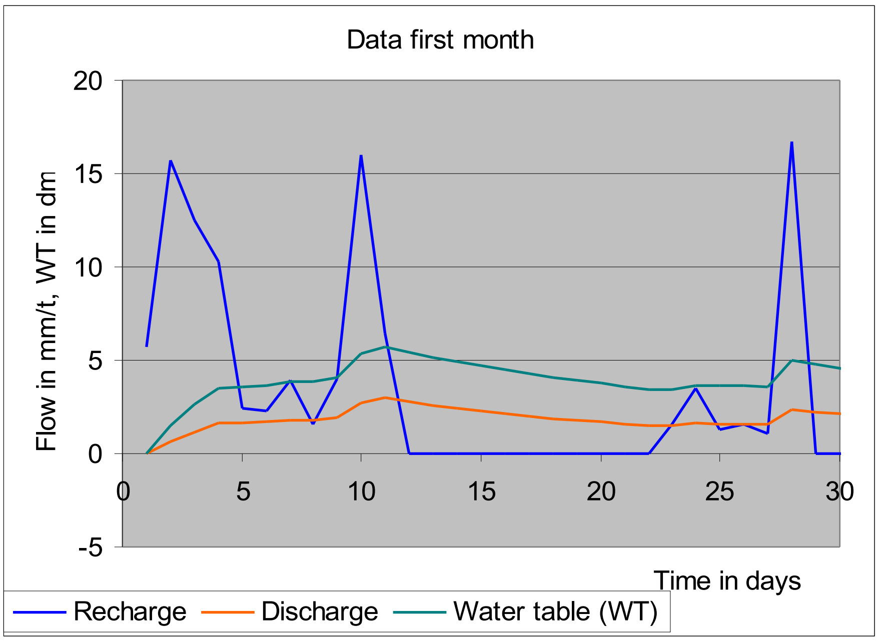


Figure 14. *Recharge flow, Discharge flow and Water table (WT, height midway between drains above drain level) during the first month. There were no WT data to check the simulation.*

5. Verification and validation

The verification and validation has been done using the parameters found by the calibration procedure for the first month (section 4, figure 10) to compute the discharge in the prediction procedure (section 3, figure 4, figure 8) and it is found that the predicted and observed discharges correspond well.

For extra certainty, the data of Ritzema [Ref. 8] regarding non-steady state subsurface drainage systems, are used to test the RainOff model. Figure 15 shows his data entered in the input menu of RainOff.

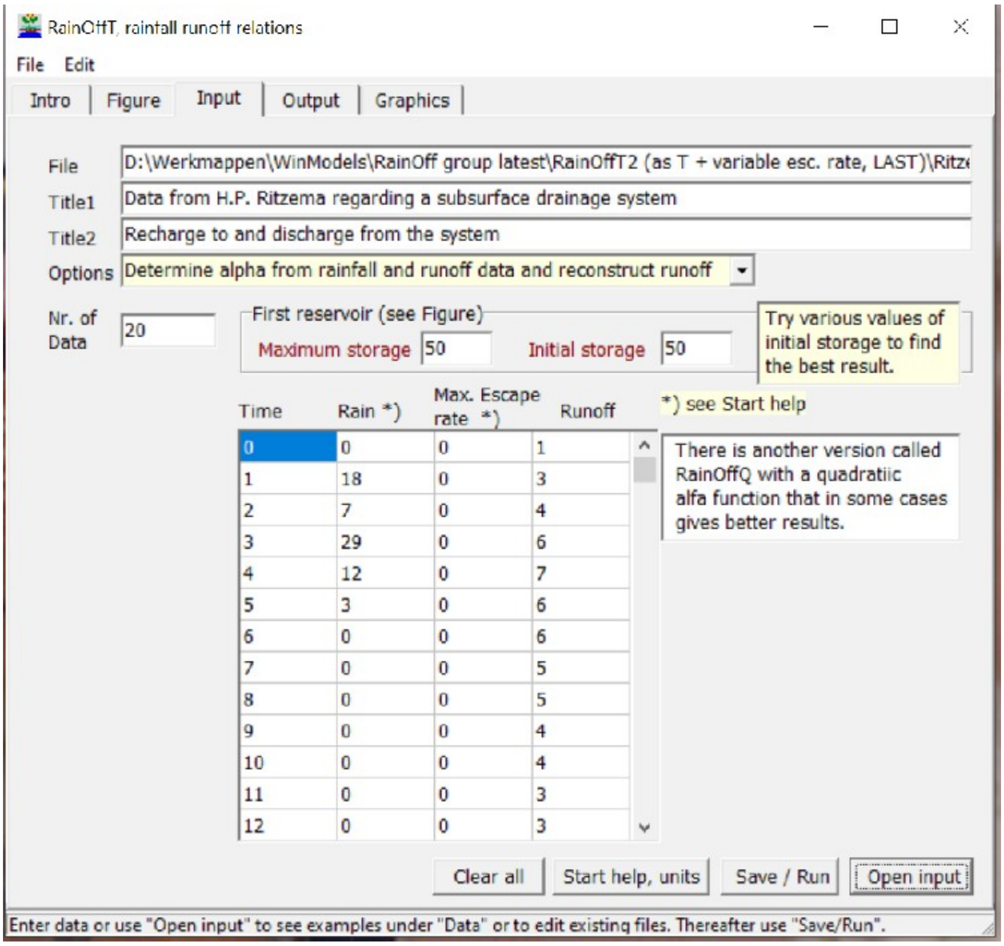


Figure 15. *Input data for the case reported by Ritzema.*

After doing the calculations using the “Save / Run” button, the output graphics are found as depicted in figure 16.

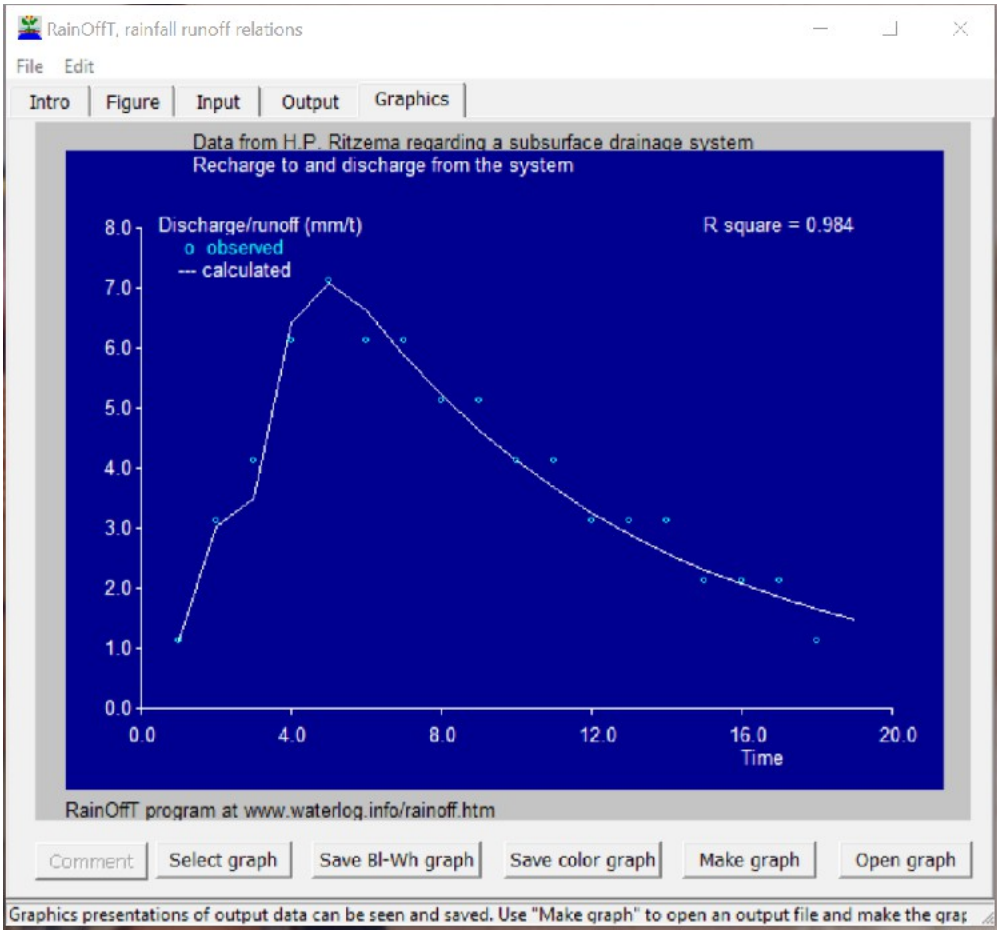


Figure 16. *Demonstrating an acceptably good fit of the calculated discharges to the ones given by Ritzema. The reservoir (response) function is optimized to:*
*Alpha = 0.0047 * Discharge + 0.0986.*

The Ritzema case confirms the validation.

6. Conclusions.

The application of the principles of the non-linear reservoir are applicable both to rainfall-runoff relations in a watershed and to recharge-discharge relations in a subsurface drainage system.

7. References

[Ref. 1] R.J. Oosterbaan, 2019. *Rainfall-runoff relations of a small valley in Sierra Leone with a non-linear reservoir model*. International Journal of Environmental Science, *4, 1-9, 2019. On line: https://www.waterlog.info/pdf/SLeone.pdf*
or:
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[Ref. 2] Rainfall and runoff data of the "Herbornseelbach" catchment (watershed), Hesse, Germany, evaluated with the RainOff model by calibration and validation of catchment parameters. On line: https://www.waterlog.info/pdf/Hesse Herborn.pdf
or:
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[Ref. 3] Rainfall and runoff data of the "Martinsthal" catchment, Hesse, Germany, evaluated with the RainOff model by calibration and validation of catchment parameters .
On line:
https://www.researchgate.net/publication/349551261_Rainfall_and_runoff_data_of_the_Martinsthal_catchment_Hesse_Germany_evaluated_with_the_RainOff_model_by_calibration_and_validation_of_catchment_parameters

[Ref. 4] Comparing steady and non-steady state subsurface drainage using calculations with relevant models. On line: https://www.waterlog.info/steady and non-steady.pdf
or:
https://www.researchgate.net/publication/349038802_Comparing_steady_and_non-steady_state_subsurface_drainage_using_calculations_with_relevant_models

[Ref. 5] RainOff, free software for the runoff in watersheds or the discharge in subsurface drainage systems. Download from https://www.waterlog.info/rainoff.htm

[Ref. 6] Simulating subsurface drain discharge and depth of the water table in transient (non-steady) state using the RainOff model. On line:
https://www.researchgate.net/publication/343943124_Simulating_subsurface_drain_discharge_and_depth_of_the_water_table_in_transient_non-steady_state_using_the_RainOff_model

[Ref. 7] DrainCalc, free software for the runoff in watersheds or the discharge in subsurface drainage systems. Extension to the RainOff model (see Ref. 5) incorporating the analysis of the depth of the water table in addition to the runoff/discharge analysis. Download from
https://www.waterlog.info/draincalc.htm

[Ref. 8] H.P. Ritzema, 1994. *Subsurface Flow to drains*. Chapter 8 in: H.P. Ritzema (editor), Drainage Principles and Applications, ILRI Publication 16. International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands. On line:
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or:
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[Reference cited in figure 6] W.H. van der Molen and J. Wesseling, 1991. A solution in closed form and a series solution to replace the tables for the thickness of the equivalent layer in Hooghoudt's drain spacing formula. Agricultural Water Management 19, pp. 1-16.