Rainfall and runoff data of the “Herbornseelbach” catchment, Hesse, Germany, evaluated with the RainOff model by calibration and validation of catchment parameters.

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Abstract

There exists a database of 88 catchments located in the state of Hesse, Germany with daily discharge and climatic data over 26 years (1992–2018). For analysis, due to the vast database, a selection of cases is unavoidable. The initial choice fell on the Herbornseelbach catchment of 13455 ha (a relative large one) consisting mainly of forest. The years selected were 2001 and 2002, with emphasis on winter time (January) when the runoff is higher. Catchment properties are found for the year 2001. This is the construction or calibration phase. Validation is done in the prediction phase using the same month a year later, employing the calibrated properties of the year before. Both the calibrations and predictions are made with the RainOff model. The results will be extensively discussed and data incorrectness will be identified. This article will be followed by articles with an analysis of other cases.

Contents

1. Introduction

F.U. Jehn et al. 9 [Ref 1.] published an article on the storage-discharge relationship in hydrological catchment areas, Hesse, Germany. The database consists of 88 catchments located in the state of Hesse, Germany with daily discharge and climatic measurements over 26 years (1992–2018).

The literature on rainfall-runoff relations in hydrological catchment areas is wealthy. However, the database used is generally not publicly available. The public data base of the Hess catchments provides an ample opportunity to apply rainfall-runoff models and to increase the experience.

Previously, the rainfall-runoff model RainOff has been applied to a small valley in Sierra Leone [Ref. 2] based on data that were made publicly available [Ref. 3]. In this article the model will be applied to the Hernbornseelbach catchments in Hess. Owing to the many daily data in over 26 years, also a time selection is made using the months of January (winter) and July (summer) in the years 2001 and 2002.

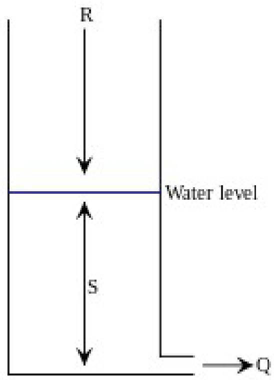
The catchment choice fell on the Herbornseelbach catchment of 13455 ha consisting mainly of forest. Analysis will be made for winter (January) when the higher discharges.The RainOff model will firstly be used to calibrate the model parameters in the selected catchment with the January 2001 data while in continuation, these parameters will be verified with the January data of 2002.

Before presenting the simulation results, the RainOff principles, based on the concept of a non-linear reservoir, will be briefly described, followed by illustrations of the RainOff operational techniques.

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.

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 function is:

$$Q = \alpha . S \qquad \text{(Eq. 1)}$$

where α = reaction factor {1/T}

Differentiating S to time T gives

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

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. 5*] 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.

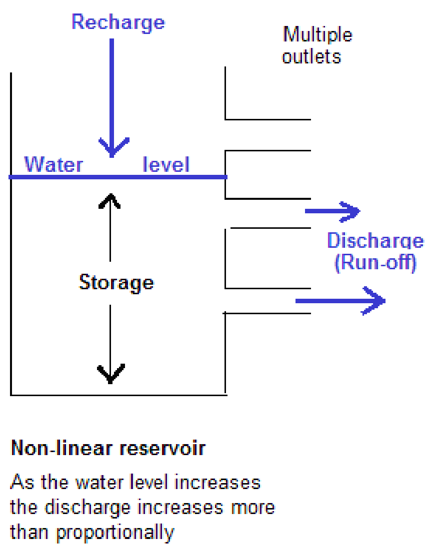


Figure 2.

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*]:

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

$$dS/dt = R-(B.Q+C).S$$
$$= R - B.Q.S + C.S \qquad \text{(Eq. 5)}$$

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

The reaction factor can now be written as

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

It it is no longer a constant, but it depends on the discharge. The factor B and the term C are found by RainOffT with a numerical method, varying the B 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, 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.

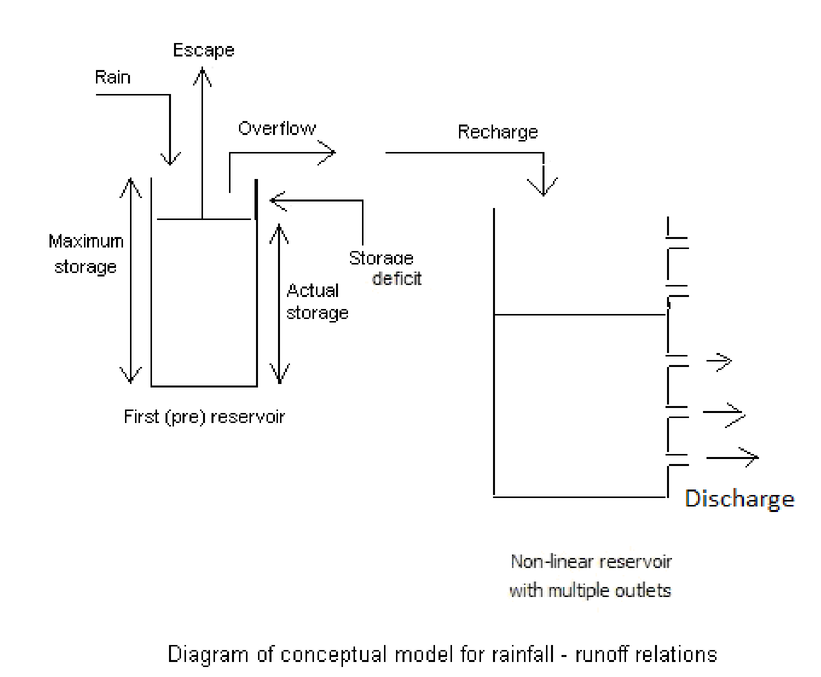


Figure 3.

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.

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

3. The RainOff model operation

Figure 4 shows the input menu for the option “Determine alpha from rainfall and runoff data and reconstruct runoff”, see the blue arrow [*Ref. 6*]. In the data table the time steps (in this case the days), the rainfall, evaporation (escape rate) and runoff data, all in mm/day, have been entered by copying them from an Excel worksheet an pasting them in the table. The escape rate consists only of evaporation because the is no natural drainage to the aquifer nor any upward seepage from the aquifer. It concerns the Herbornseelbach catchment for January 2001 (green arrow). Use the button "Save / Run" to save the data and perform the calculations.

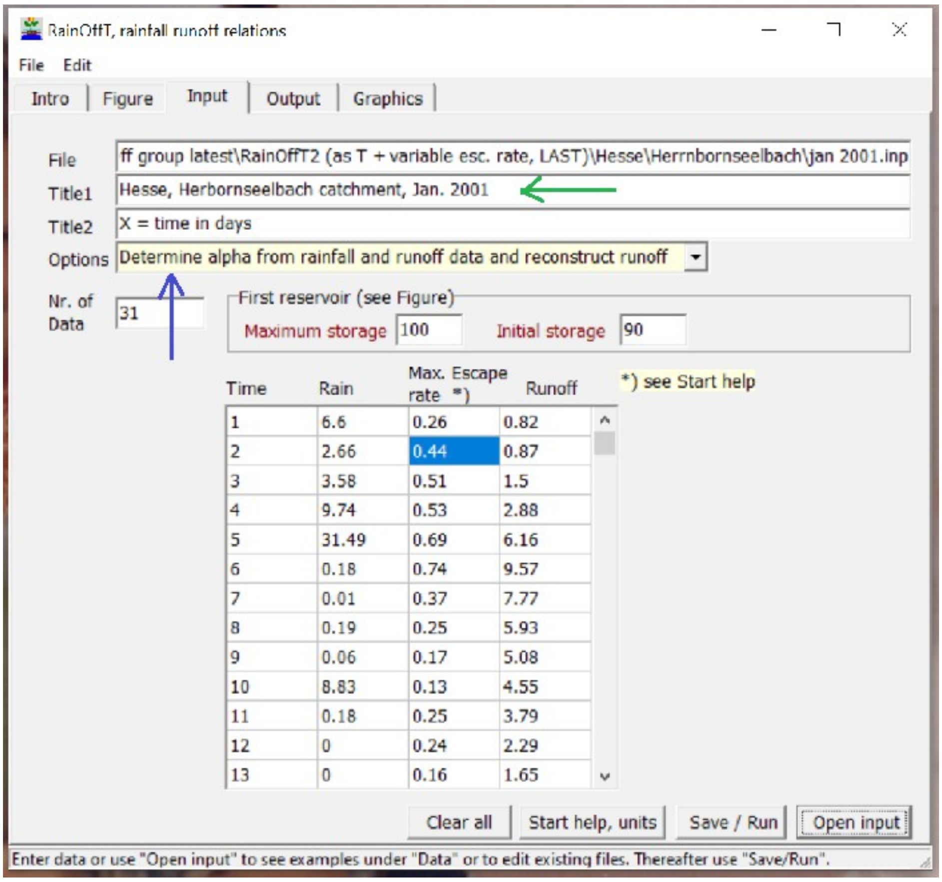


Figure 4.

Input menu of the RainOffT program for the option "Determine alpha from rainfall and runoff data and reconstruct runoff" (blue arrow).

It concerns the Herbornseelbach catchment for January 2001 (green arrow).

The output menu is depicted in figure 5 below [*Ref. 6*]. It shows the Alpha function and the graphics button. The Alpha function is obtained by optimization and, the parameters are calibrated.

Figure 6 illustrates the graphic choices after clicking on the graphics button.

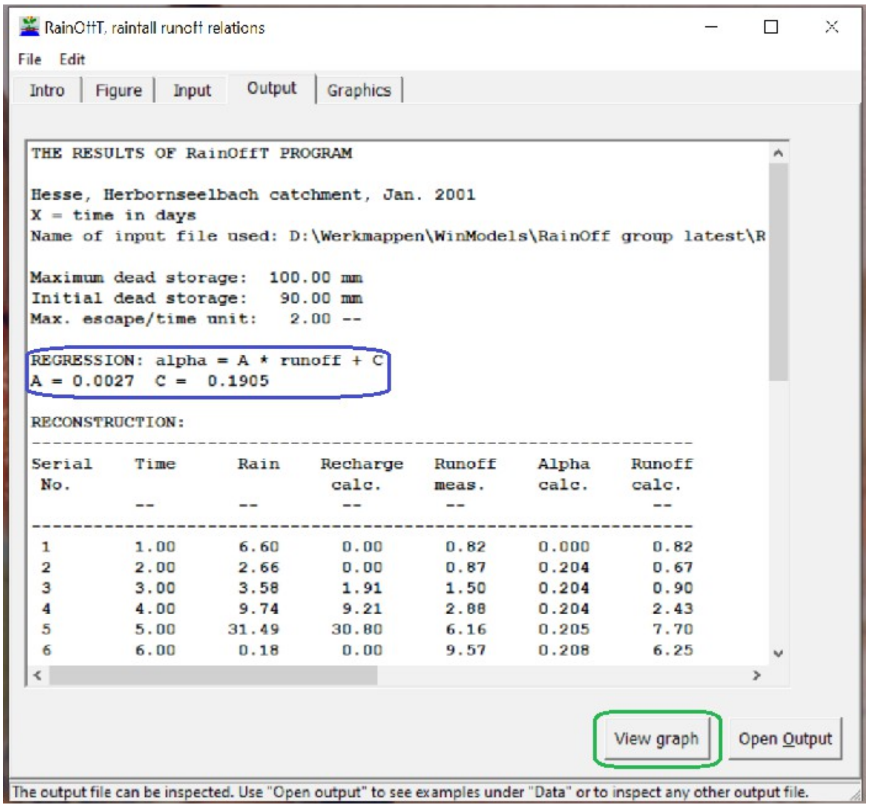
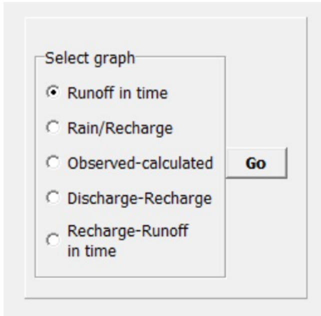
	

Figure 5. *Output menu of RainOffT. It shows the Alpha function (blue square) and the graphics button (green square).*	***Figure 6**.* *After clicking on the graphics button in figure 5, the choices for the type of graph are shown.*

Figure 7 shows the input menu for the option “Predict discharge or runoff from rainfall given the Alpha function”, see the blue arrow [*Ref. 6*]. It concerns the Herbornseelbach catchment for January 2002 (green arrow), with the intention to apply the Alpha function found for the year 2001 to the data in 2002. The initial runoff (brown ellipse) is very important, because with each different value one obtains different results, although at the end of the time the differences will come closer. The parameters of the Alpha function (orange square) are the same as those calculated with the data of 2001 (figure 5). This serves for verification.

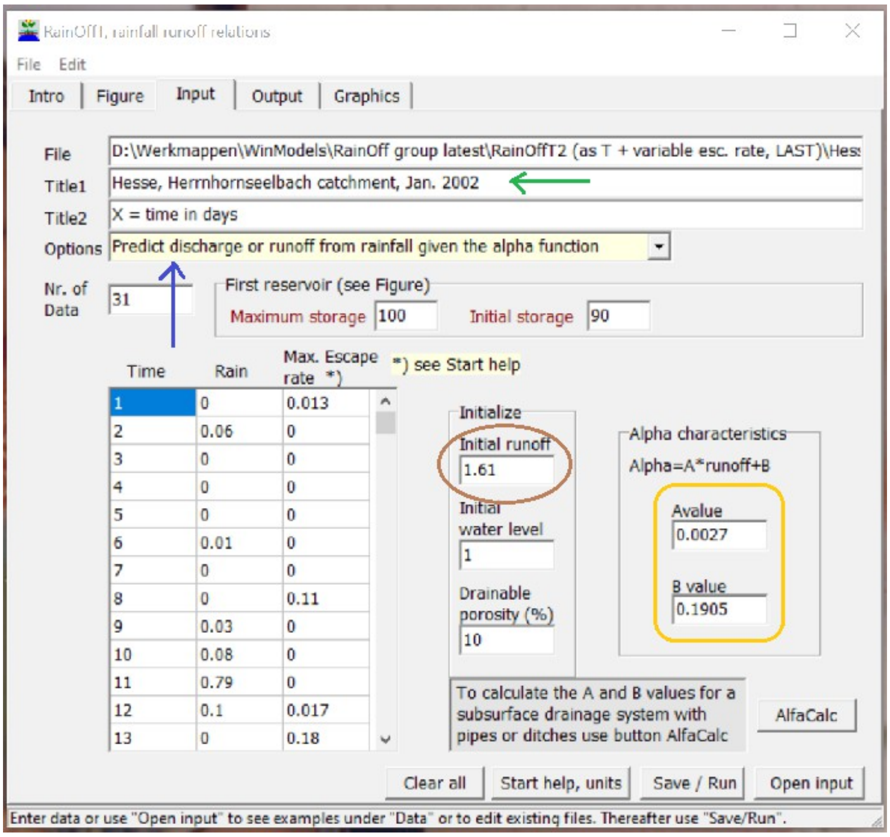


***Figure** 7.*

Input data for the prediction option of the runoff (blue arrow) given the initial runoff (brown ellipse) and the parameters of the Alpha function (orange square).

This option may serve the verification phase.

4. The Herbornseelbach catchment in winter

The Herbornseelbach catchment has a surface area of 13455 ha in is mainly under forest.

The first analysis is to determine Alfa from the rainfall, evaporation, and runoff data using the input menu of figure 4. The month of January 2001 is used. There was no snow then.

The result is shown in figure 8. Although the general trend of the relation between calculated and observed runoff is acceptable, the are deviations as can be seen in the figure. An explanation of the deviations is demonstrated in figure 9 and discussed in its subscript, concluding that the original data show imperfections and it is demonstrated that the RainOffT model proves to be helpful to evaluate the consistency of the data.

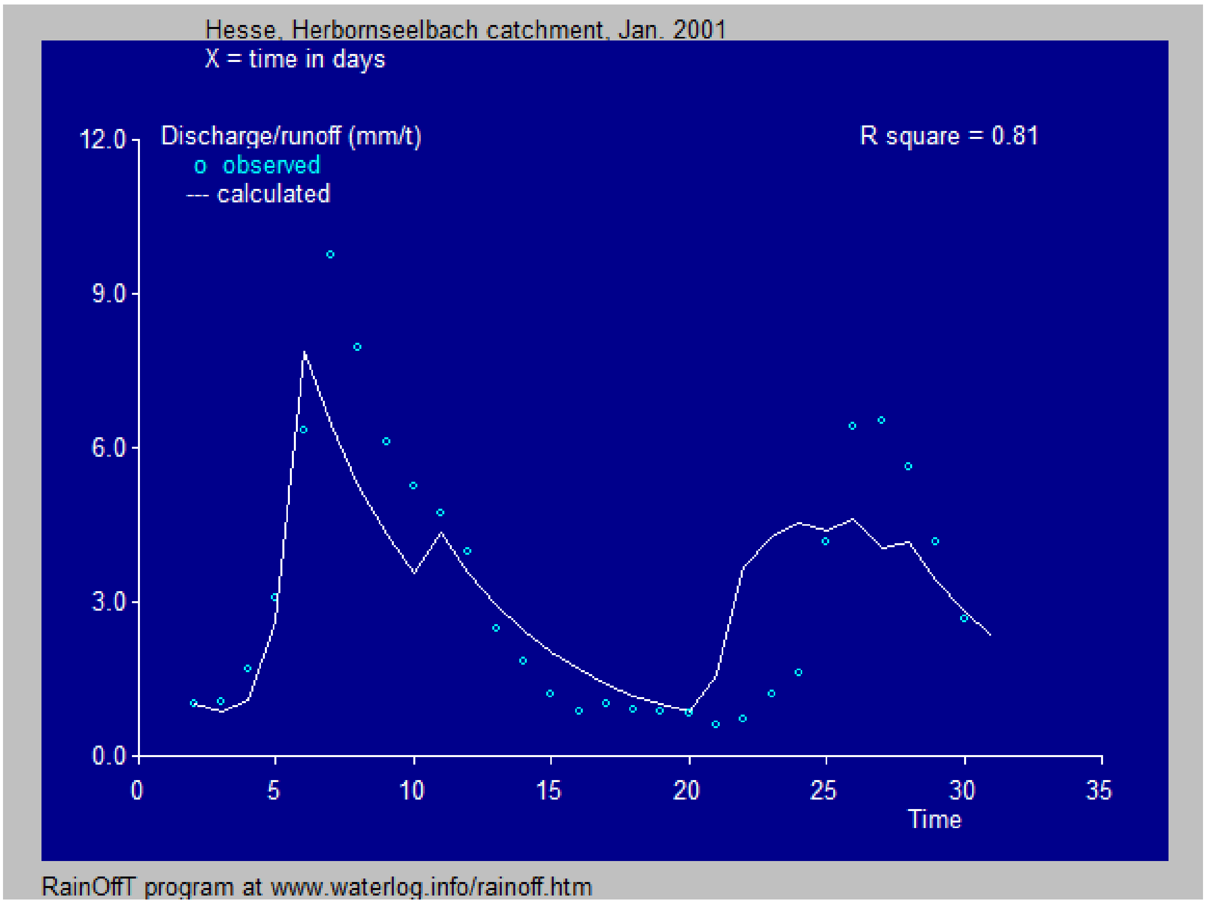


***Figure 8**. Caculated and observed runoff, month of January. The fit between days 8 to 12 is not perfect and the same holds for the fit between days 21 and 24. The reason is the imperfect relation between recharge and runoff (figure 9).*

The peak discharge of 9 mm/day corresponds to 90 m^3/ha.day and with 13455 ha this leads to a total discharge of 1210050 m^3/day or 14 m^3/sec

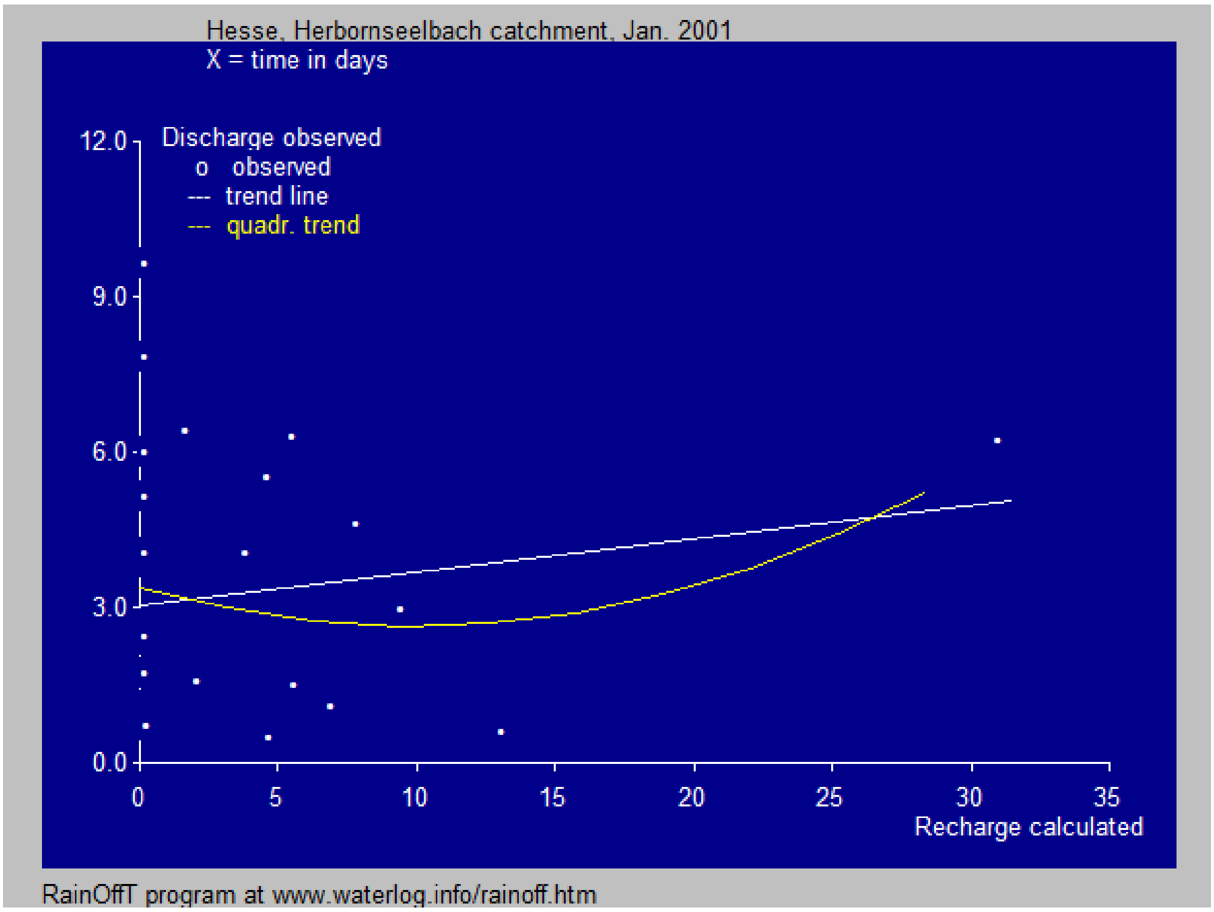


Figure 9*. Relations between observed discharge and calculated recharge. The variation in the observed discharge is quite large. The quadratic trend shows descent of the relation in the first 10 days. This is problematic as the discharge is supposed to increase with increasing recharge. Here, the highest discharges occur at Hence it can be concluded that the given rainfall and runoff data are probably not perfect and that measuring errors have occurred. The RainOffT model proves to be helpful to evaluate the consistency of the data.*

When considering the recharge on the X-axis in figure 9, it would be good to realize that recharge can be different from the rainfall owing to the influence of the pre-reservoir in figure 3.

For this reason a relation between rainfall and recharge is revealed in figure 10.

Note. The sum of the daily recharges over the month equals 95.15 mm while that of the recharge is 93.97. The difference, mainly due to rounding off, is negligible.

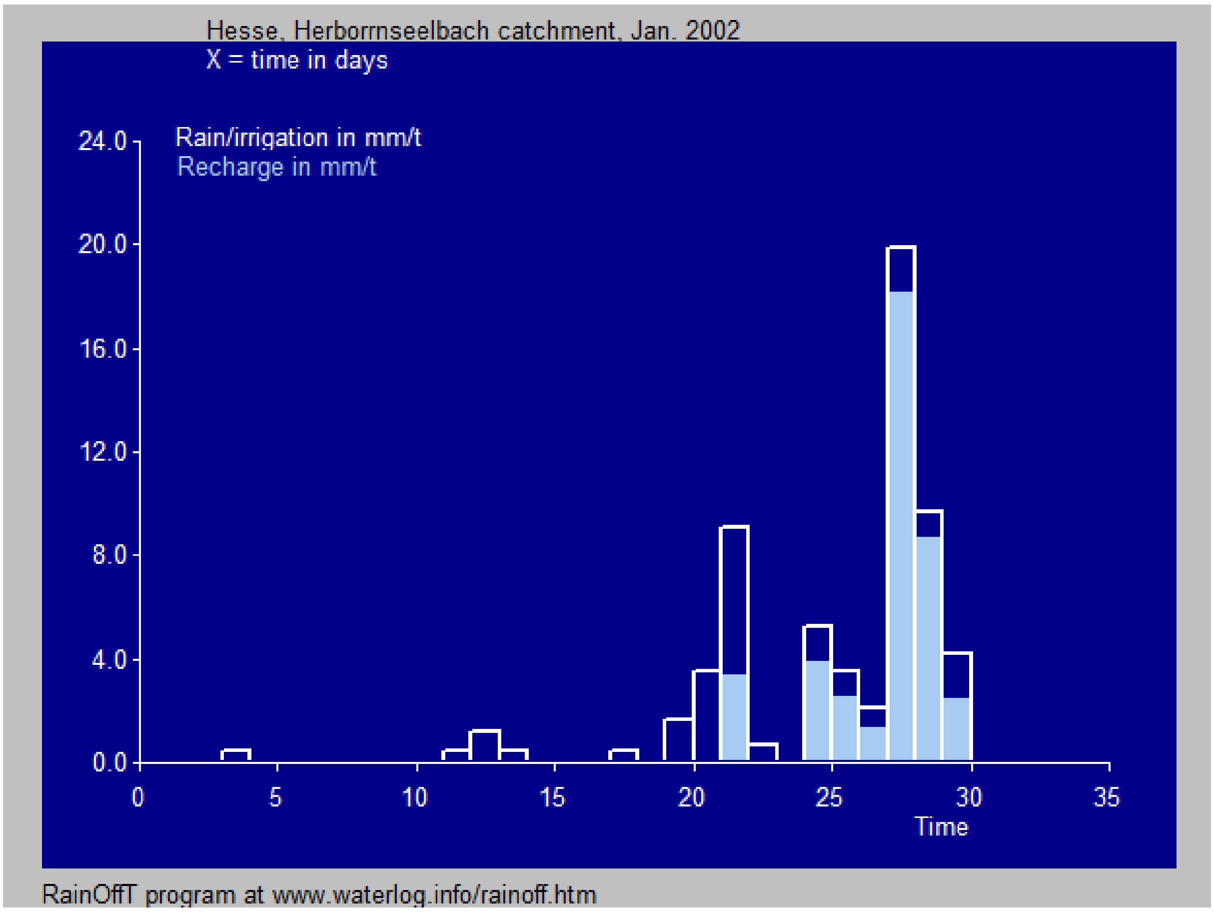


Figure 10. *Presenting the rainfall in white rectangles and the recharge in light blue columns for the month January 2002, it may become apparent that during a dry period with little rainfall (from day 1 to 24) the recharge is negligible owing to the drying out of the soil in which the scarce rainfall is stored and it will not come into runoff. During the wet spell (from 25 to 30 January) the ratio between recharge an rainfall is almost equal to 1, and the major part of the rainfall will go into runoff.*

Having found the parameters B and C of the discharge function Alpha for January 2001 (figure 5, equation 7) :

$$\alpha = B.Q + C = 0.001 * \text{Discharge} + 0.1905$$

one can use these values for the validation exercise on the data of January 2002, using the input menu depicted in figure 7 to predict the runoff on the basis of the calibration of parameters in the previous year.

The result of the prediction is presented in figure 11.

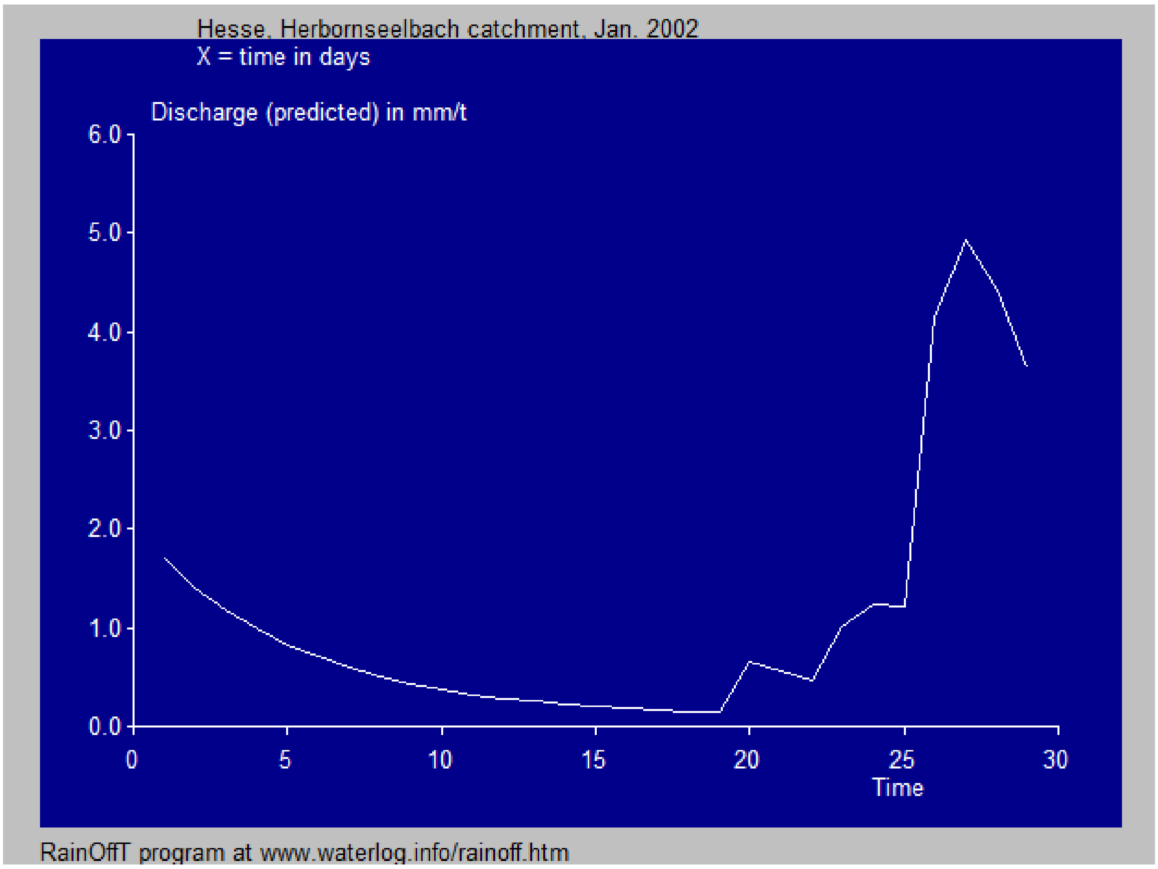


***Figure 11**. Prediction of the runoff in January 2002 using the catchment parameters determined in January 2001. A comparison with the observed runoff is needed to judge the success of the prediction. This is done in figure 12.*

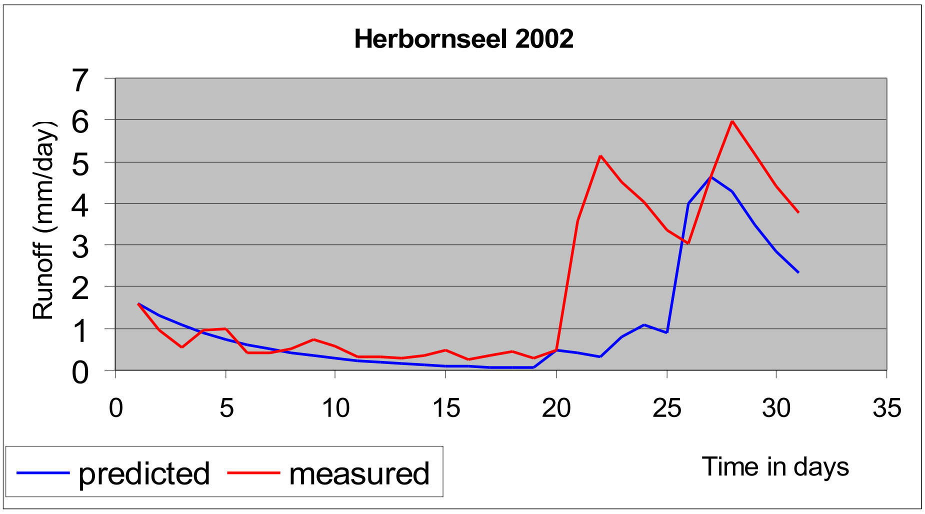


***Figure 12**. Comparison of the predicted runoff in figure 11 with the observed runoff. In the period of 20 to 25 January 2002 the measured discharge is much higher than the predicted one. Hence a further check is needed on the correctness of the measured data. This is done in the next table.*

***Table 1**. Rainfall, recharge and observed runoff in mm per day, January 2002.*
It can be seen that in the period 20 to 25 January there is hardly any rainfall and recharge after a long dry spell of 19 days during which the storage in the pre-reservoir has diminished.. So one would not expect runoff of any significance after day 20. Yet, the runoff increases sharply, especially on the 22nd day. This phenomenon is not very likely and makes one suppose that either the rainfall or the discharge data, or both, are incorrect.

Time (day)	Rain (mm/day)	Recharge (mm/day)	Runoff measured (mm/day)		Time (day)	Rain (mm/day	Recharge (mm/day)	Runoff measured (mm/day)
1	0	0	1.61		17	0	0	0.36
2	0.06	0	0.95		18	1.25	0	0.46
3	0	0	0.55		19	3.16	0	0.28
4	0	0	0.97		20	8.67	2.98	0.48
5	0	0	1		21	0.32	0	3.59
6	0.01	0	0.43		22	0	0	5.16
7	0	0	0.43		23	4.88	3.5	4.51
8	0	0	0.52		24	3.18	2.2	4.04
9	0.03	0	0.72		25	1.75	0.99	3.36
10	0.08	0	0.59		26	19.49	17.78	3.03
11	0.79	0	0.32		27	9.31	8.32	4.65
12	0.1	0	0.31		28	3.81	2.13	5.98
13	0	0	0.3		29	0	0	5.17
14	0	0	0.36		30	0.23	0	4.41
15	0	0	0.49		31	0.05	0	3.78
16	0.04	0	0.27					

A similar problem as identified in the title of table 1, was signalled before (figure 7 for year 2001), be it in a different way.

5. Conclusions

For the year 2001, the calibration resulted in a reasonable relation between calculated and measured runoff (figure 8), despite a signaled inconsistency in the data (figure 9). This leads to the conclusion that RainOffT is able to simulate runoff from rainfall and, moreover, it can help to detect illogical data values.

For the year 2002, RainOffT came up with a reasonable prediction of the runoff on the basis of the optimized catchment characteristics (the parameters B and C) determined for the year 2001. The runoff increased sharply towards the end of the month when the rainfall started to increase. The first part of the month was dry and the runoff rate (calculated and observed) remained low. However, a comparison of predicted and observed runoff (figure 12) also lead to the detection of inconsistent data values, especially from 20 to 25 January.

6. References:

[Ref.1] F.U. Jehn et al 2021. *Simple Catchments and Where to Find Them: The Storage-Discharge Relationship as a Proxy for Catchment Complexity*. DOI: 10.3389/frwa.2021.631651 The data used can be found in: https://github.com/zutn/Simple-Catchments-Hesse

[Ref. 2*] Rainfall-runoff relations of a small valley in Sierre Leone using RainOff with a non-linear reservoir.* In: International Journal of Environmental Science, 4, 20-27. On line: https://www.iaras.org/iaras/filedownloads/ijes/2019/008-0002(2019).pdf
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https://www.waterlog.info/pdf/EnvJournal.pdf
or:
https://www.researchgate.net/publication/332466264_RAINFALL-RUNOFF_RELATIONS_OF_A_SMALL_VALLEY_ASSESSED_WITH_A_NON-LINEAR_RESERVOIR_MODEL

[Ref. 3] A. Huizing, 1988. *Rainfall-runoff relations in a small cultivated cultivated valley in Sierra Leone*. On line: *https://www.waterlog.info/pdf/SLeone.pdf*

[Ref. 4] D.A.Kraijenhoff van de Leur,1958. *A study of non-steady state groundwater flow with special reference to a reservoir coefficient.* De Ingenieur 70: p. 387 – 394 . On line: https://library.wur.nl/WebQuery/hydrotheek/604860

[Ref. 5] J.E.Nash, 1958. *Determining runoff from rainfall*. Proc. Inst. Civ. Engs. 10 : p. 163 – 184. On line: https://www.icevirtuallibrary.com/doi/10.1680/iicep.1958.2025
Software:
https://www.waterlog.info/nashmod.htm

[Ref. 6] RainOff, RainOffT and RainOffQ, free software for rainfall-runoff analysis. On line: https://www.waterlog.info/rainoff.htm