A Microsoft Excel Application to Simulate Water Harvesting in a Catchment

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Abstract
Due to the climate change the efficient use of fresh water has become a hot issue. One of the ways to collect water that could otherwise be wasted, is the water harvesting technique. These techniques have been known for centuries and widely applied in the Middle East. This paper presents a simple and easy-to-use water-balance based rainwater harvesting model called WHCatch. It has been designed to investigate the effects of water harvesting on the catchment scale. The catchment is divided into several sub-catchments which can store water for the purpose of water harvesting. The model has been created as a simple Excel workbook with some VBA-code for the computations. Results are presented in the same workbook as separate worksheets. Graphical presentations are created automatically. The capabilities of the workbook are presented and examples of in- and output are shown. Due to its flexibility, the model is suitable to show the effects of climate change as well. It is especially suitable to visualize the effects of measures.

Keywords: Rain water harvesting, Excel, climate change.

1. Introduction

As can be read in Machiwal and Jha (2012), about 10% of the worldwide freshwater supplies are used for health and sanitation purposes, compared to 70% and 20% for agriculture and industries, respectively. Problems with fresh water mainly occur in the arid and semi-arid climate zones. The arid and semi-arid regions (ASARs) cover approximately 50 million km^2, representing 35% of the earth's land surface (Ziadat et al., 2012). ASARs are areas where the rainfall is a problem regarding amount, distribution, and/or unpredictability (Hudson, 1987). Arid regions receive an amount of rainfall of about 150-350 mm/year (Ouessar, 2007) and semi-arid regions are receiving little rainfall as well, varying from 350 to 700 mm/year (Oweis et al., 1998). Rainwater harvesting (RWH) is an important way to use surface runoff caused by the limited available rainfall. Different definitions of RWH can be found in literature (Critchley and Siegert, 1991; Fentaw et al., 2002; Gould, 1999; Stott et al., 2001), but in general one considers RWH as the collection and concentration of runoff for productive purposes, livestock and domestic water supply in ASARs.

Modelling the hydrological characteristics of rainwater harvesting facilities can be applied to evaluate the effects of rainwater harvesting (Ghisi et al., 2007), in addition to field measurements. Fewkes (2000) already mentioned the need for a hydrological model to analyze rainwater harvesting facilities. Analyzing water harvesting facilities and long-term rainfall-runoff analyses in a watershed are quite similar. Various hydrological circulation components are considered, e.g. precipitation, evapotranspiration, infiltration, percolation,

groundwater and surface runoff (Kim and Yoo, 2009). A lot of detailed numerical models that are able to simulate the design and/or performance of RWH systems, have been developed and published during the past decade (Ward et al., 2010). Dixon (2000) developed DRHM, a mass balance model with stochastic elements for demand profiling to simulate the quantity, quality and costs of RWH systems. Vaes and Berlamont (2001) developed the Rewaput model, which is a reservoir model based upon rainfall intensity-duration-frequency relationships and triangular distribution. Fewkes (2004) developed the RCSM model which is continuously simulates RWH system with detailed analysis of time interval variation and yield-before/after-spill. Kim and Han (2006) developed the RSR model and applied it in Korea. It optimizes the tank size of a RWH system for storm water relations to reduce flooding. A yield-after-spill algorithm and a whole life costing approach were implemented in an Excel-based balance model (RainCycle) by Roebuck and Ashley (2007). Grum et al. (2017) show that an event-based model like LISEM can be applied to simulate the effects of different existing or new water harvesting techniques on catchment hydrology and sediment yield. A widely-used model is SWMM, described by Rossman (2015).

Water-balance models provide the most fundamental information about the hydrology processes of a catchment and may assess the performance of RWH techniques under current and future climate conditions (Chauvin et al., 2011). The water balance model can be used to improve the understanding of the critical processes that influence the hydrological cycle and to allow the transfer of field or laboratory experiments results to other sites and climates (Zhang et al., 2005). The water-balance equation presents values for inflow, outflow and the change in water storage for an area or water body (Tadesse et al., 2010). The water balance is based upon the principle of conservation of mass, also known as the continuity equation (Tadesse et al., 2010). Representing the rainfall and runoff characteristics of a watershed (e.g. topography, geology, soil, and climate)

adequately is essential to apply such models. Another demand is the proper estimation of the model parameters from the data available (Kim and Yoo, 2009). Verbist et al. (2011) applied a three-dimensional soil hydrological model in combination with a field experiment to find the soil parameters by inverse modelling. They applied the model on a water harvesting trench and concluded that the water harvesting potential of these techniques for reforestation purposes was promising. As all modelers know, the quality of the input data in any hydrological model strongly influences the accuracy of the results. The more input parameters are required, the more knowledge is required about the accuracy and availability of these parameters and their influence on the modeled results. In this study, it was advantageous to develop a simple RWH model that is based on the water balance equation. Using only a few parameters that must be estimated, the model can perform a hydrological analysis regarding rainwater harvesting. All examples in this paper are based upon a study on rainwater harvesting in the Oum Zessar watershed in southeastern Tunisia (Adham et al., 2016). Due to the limited amount of input data available, it wasn't possible to compare the output of our model with the output of a more sophisticated model.

2. Theory
Catchments and sub-catchments

This paper deals with the (surface) water flow in a catchment. According to Gregersen et al. (2007), a drainage basin or catchment basin is a large unit of land that drains into a large body of water such as a river, lake, reservoir, estuary, wetland, sea, or ocean. The term watershed or sub-catchment refers to smaller units that contain all lands and waterways that drain to a given common point. In case of rainwater harvesting, each sub-catchment has its own water barrier, reservoir and outlet in the form of a spillway. An example of a catchment and its 25 sub-catchments is presented in fig. (1A). Initially, it was assumed that the water in a sub-catchment only flows into one other sub-catchment (fig. 1B). During the development and testing of the software it appeared to be necessary to have the option of distributing

the outflow over two neighboring sub-catchments.

Suppose a sub-catchment has an area A_c (m^2). Within this area there is an area A_s where the water will be stored. Assuming a rainfall P, then the volume of water flowing into the storage area from the non-storage area can be written as

$$V_{in} = P\, C\, (A_c - A_s) \qquad (1)$$

C is the (dimensionless) runoff coefficient. It relates the amount of runoff to the amount of precipitation received. Areas with low infiltration and high runoff (pavement, steep gradient) will have large C-values and permeable, well vegetated areas (forest, flat land) will have lower C-values. According to the California Water Board (http://www.waterboards.ca.gov/water_issues/ programs/swamp/docs/cwt/guidance/513.pdf), C- values vary between 0.1 and 0.95.

The water volume that falls on the storage area is computed from its area and the precipitation rate:

$$V_s = P A_s \qquad (2)$$

In the storage area infiltration will take place. The infiltrated water volume V_I (m^3) is computed from the infiltration rate and the area size:

$$V_I = I_r A_s \Delta t \qquad (3)$$

where I_r is the infiltration rate which is usually measured in the field and Δt (d) is the average time during which infiltration occurs. Often the infiltration is estimated as a fraction of the total volume of water flowing into the storage area or

$$V_I = \alpha_I V_{tot}$$
$$(4)$$

where α_I is the fraction (-) and V_{tot} is the total volume of water entering the storage area (m^3).

If there is a cultivated area A_p as part of the sub-catchment, losses will occur due to evapotranspiration E_p. The lost volume can be computed from:

$$V_p = A_p E_p \qquad (5)$$

If a volume of water (V_x) is entering from another sub-catchment as well, then the change of the volume of water in the storage area can be computed from:

$$\Delta V = V_{in} + V_s - V_I + V_x - V_p \qquad (6)$$

Adding this volume to the present volume (S_i) in the storage area yields the new stored volume:

$$S_i = S_i + \Delta V \qquad (7)$$

Assuming the maximum height of water storage is h_S (m), then the maximum volume of storage is:

$$S_{max} = f_S h_S A_S \qquad (8)$$

Where f_S is a correction factor for the unequal height of the terrain (usually 0.9). This implies that, if $S_i > S_{max}$, there will be an outflow to the next sub-catchment of V_x, where

$$V_x = S_i - S_{max} \qquad (9)$$

With the procedure described above, a global estimate of the possible water harvesting volume can be found as S_i when $S_i > 0$. If, on the other hand, $S_i < 0$, all water from the catchment will disappear and there may be an insufficient volume of water available for crop growth. (In some cases, one is interested in the 'uncorrected' value of dV. In the program WHCatch this value is called 'bal'.).

Generating rainfall events from distributions

When considering the water balance of an entire year, the distribution and size of the precipitation events is very important. Of course, it is possible to enter data for a lot of years and generate ranges for the obtained values that way, but this is a cumbersome and laborious option. In this case it is easier to generate a lot of events from a known distribution and evaluate the water balance terms from these generated events. In this case knowledge of the precipitation distribution is a prerequisite. Nowadays weather stations are recording precipitation data all over the world, yielding long-year

datasets. To get an impression of the type of distribution of the maximum daily precipitation in a year, we first investigated the daily precipitation data from the meteorological station in De Bilt (The Netherlands). Daily values were available for the period 1930-2015. We took the maximum value for each year and fitted three distributions with these data. Though the log-normal distribution showed the best fit (see Fig. 2a), differences were small. That's why we decided to use the normal distribution only, despite the fact that there are more sophisticated methods available (see e.g. Ye et al., 2018). The graphical presentation of a normal distribution with mean µ and standard deviation σ is a bell-shaped curve which is symmetric towards the mean. In a normal distribution, 68% of the values are in the range [µ-σ; µ+σ], and 95% of the values are in the range [µ-2σ; µ+2σ] (see Fig. 2b). If another distribution should be used, this can easily be incorporated in the VBA code of WHCatch.

As another example, we assumed the 25 years of precipitation data we had available from our experimental site in Tunisia to be normally distributed with average µ and standard deviation σ as well. We analyzed these data, yielding 3 distributions: the yearly amount of precipitation (N=25), the maximum value of precipitation within a year (N=25) and the distribution of all rainfall events (N=320). The averages and standard deviations are presented in Table (1).
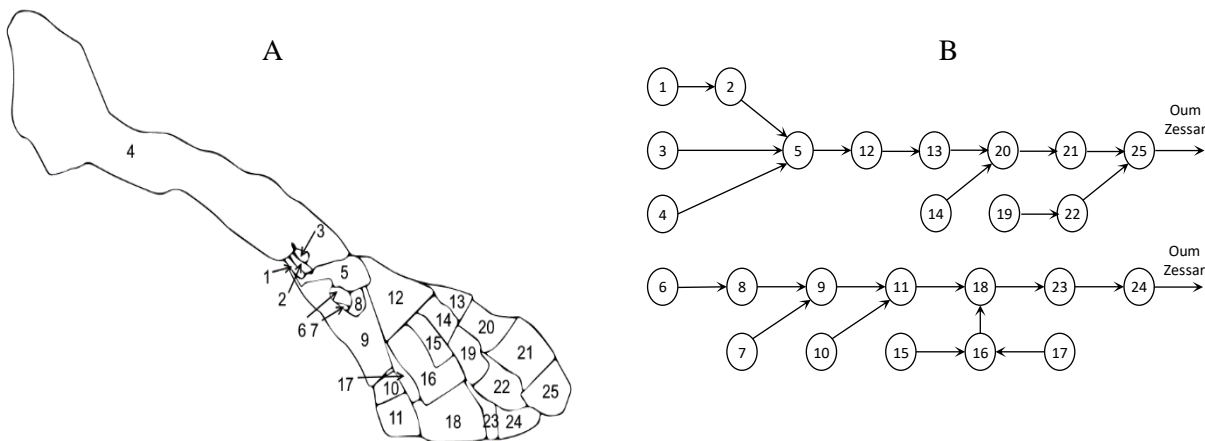

Fig. 1. The sub-catchments of the Oum Zessar Watershed in Southeastern Tunisia and their numbering (A) and the flowpath of water through the sub-catchments (B).
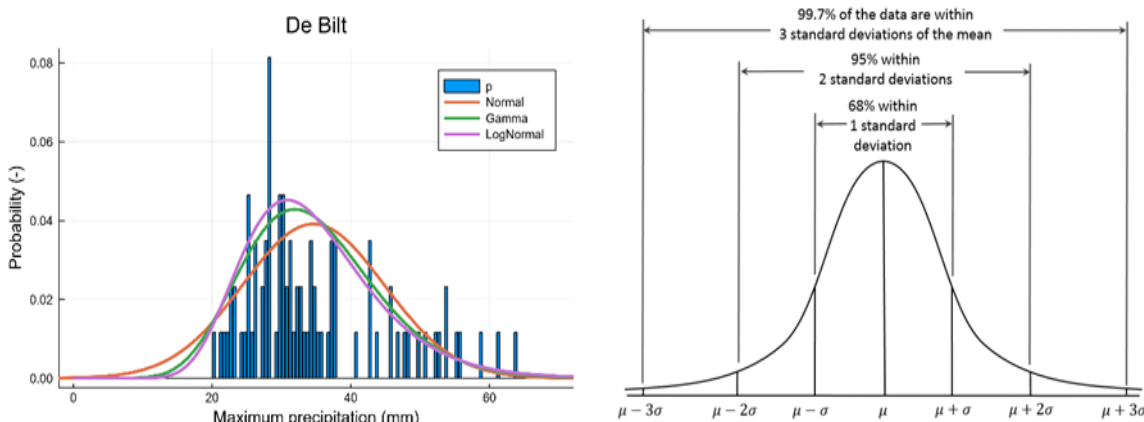

Fig. 2. (a) Distribution of the maximum daily precipitation in a year during 1930-2015; (b) The normal distribution function.

Table 1. An example of the distribution of the precipitation events. Total is the total amount of precipitation, Max is the maximum daily amount.

	Average (mm)	Standard deviation (mm)
Total	145.676	83.390
Max	39.328	23.988
All	11.381	13.389

The calculation procedure
The water balance

Normally the considered catchment consists of a known number (N_s) of sub-catchments and the relationship between these sub-catchments is evident (see e.g. Figure 1), allowing the development of a simple computation scheme:

1. Compute S_{max} for each sub-catchment
2. Compute the water volumes V_i, V_{in} and V_s for each sub-catchment from the equations presented above
3. Compute V_o for the sub-catchments without inflow (1, 3, 4, 14, 19, 6, 7, 10, 15, 17 in the example)
4. Assign V_o as input V_x to the corresponding sub-catchments
5. Compute V_o for those sub-catchments where the upstream sub-catchment(s) is(are) processed
6. Repeat steps 4 and 5 until all sub-catchments are processed

We assume there is no interaction between the precipitation events, which implies that all values are initially zero for each event. If all precipitation events in a year should be considered, the term V_p can be added at the end of the computations.

Generating precipitation events

In one of the previous sections of this paper the (normal) distribution of the precipitation data was described. Using these averages and standard deviations, new precipitation data can be generated in the following way(Assuming there is no correlation between the events.):

1. Draw a number from the distribution of the yearly amount of precipitation (say P_{tot})
2. Draw a number from the distribution of maximum values (say P_{max})
3. If $P_{max} > P_{tot}$ (which may happen if there is an overlap between distributions), redo step 2

4. Draw a number from the distribution of all events (say P_i)
5. If $P_i > P_{max}$, redo step 4
6. $P = P_{max} + \Sigma P_j$, j=1..i
7. If $P > P_{tot}$, then $P_i = P_{tot} - P_i - P$
8. If $P < P_{tot}$ then repeat step 4

Programmatically the drawing of a number from a normal distribution was accomplished with the GASDEV procedure described by Press et al. (1986). The generated year of precipitation was applied as input for the water balance model and the balance term of interest has been read. Repeating this procedure a number of times yields a collection of N_x values of the water balance term (x). This collection of values is then analyzed in the following way:

1. Sort the values of x
2. The range R of the values can be computed as $R = x_{Nx} - x_1$
3. Divide R into N_c equal classes
4. Distribute x over the appropriate classes
5. Count the number of entries in each class
6. Divide each number by N_x to assess the probability of each class

As an example, we computed the runoff in sub-catchment 19 with different values of N_x and N_c. The graphs Fig (3) show that both the values of N_x and N_c have a large impact on the results. It is advised to choose $N_x \geq 50 N_c$. The left figure shows that most runoff values (approx. 5.7%) are in the class around 8150 m^3. From these values a cumulative probability chart can be created fig (4). The dotted line indicates the probability that the runoff exceeds a certain value, the solid line shows the probability that the runoff is smaller than the corresponding value. In our case there is a 10% chance that the value of runoff will be less than 4500 m^3. On the other hand, there is a 1% change on a runoff value of 17500 m^3 or higher, which implies it will occur only once every 100 years.
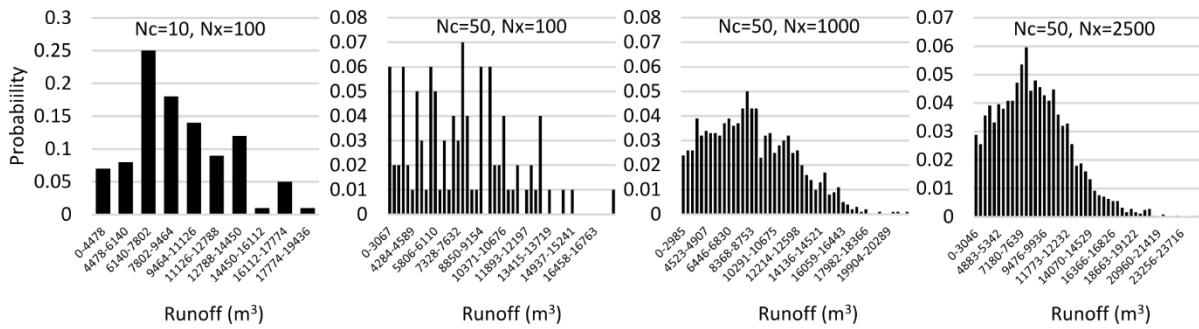
Fig. 3. Distribution of runoff from sub-catchment 4 computed with a generated set of precipitation using four combinations of N_c and N_x.
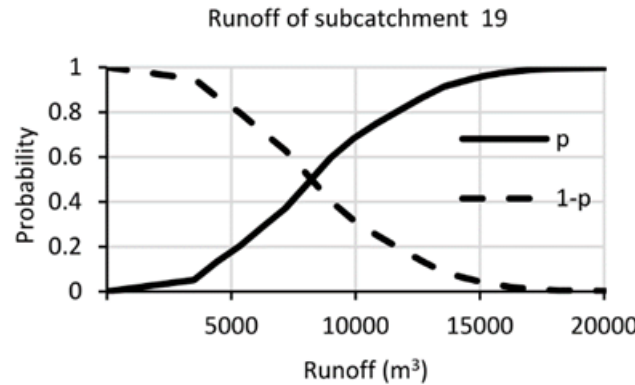

Fig. 4. The cumulative distribution of the runoff values for sub-catchment 19, obtained from 1000 years of generated precipitation events.

The program WHCatch

Originally all input data was available in Excel and only simple computations were required. Therefor the software has been developed as a simple Visual Basic for Applications (VBA) macro in an Excel workbook. As a result all output could be stored and visualized in the same Excel workbook. The Excel workbook consists of several worksheets Table (2) and an application in VBA.

The worksheets
Worksheet Control
The worksheet Control contains the most important control parameters for the computations. It also has the buttons calling the VBA part that performs all calculations Fig (5).

　　Five sections can be distinguished which are surrounded by a colored line. Each section has its own input data, button and functionality:

- Green: compute all terms of the water balance and store the output on the appropriate sheet.

- Blue: find the requested output data and convert it to a format that is readable by a GIS-application.

- Red: Investigate the effects of changing the spillway height of an upstream sub-catchment on a specified term of the water balance of the considered sub-catchment.

- Black: generate a number of precipitation events and analyze the distribution of one of the terms of the water balance.

- Gold: show the distribution of precipitation events in the specified periods.

　　The program can perform computations for an indefinite number of years. For the sake of presentation, 4 periods are distinguished. The first and last year of each period can be specified in the 'Control'-sheet. For each period a representative year may be specified, allowing a short description or name in cells H7:H10.

Table 2. The worksheets in the Excel application WHCatch.

Name	In/Out	Description
Control	In	Settings and options
Catchment	In	Sub-catchments and their properties
ETp	In	Potential yearly evapotranspiration values
Rainfall	In	Rainfall events
Help	In	Data used to temporarily assign to in charts*
Smax	Out	Maximum volume that can be stored in the reservoir
Vin	Out	Volume of water caught in sub-catchment
Vs	Out	Volume of water caught in reservoir
Vinf	Out	Infiltrated volume
Vx	Out	Volume entered from upstream sub-catchments
dV	Out	Volume stored in reservoir
Runoff	Out	Volume leaving the sub-catchment as runoff
Bal	Out	Change in water balance
Chart1	Out	Requested term of water balance shown as hi-lo-chart
Chart2	Out	Chart showing influence of storage height on balance term
HiLo	Out	Chart showing the requested water balance term for specified years
Events	Out	Chart showing the number of runoff events for each catchment during the entire simulation period
GIS	Out	Data for GIS-processing
GenPrecip	In/Out	Sheet where precipitation events are stored that are generated by the precipitation generator**
Distribution	Out	Shows the distribution of the water balance term of interest as generated with the precipitation generator
CumDist	Out	Cumulative probabilities for the water balance term of interest generated with the precipitation generator
Year	Out	Average precipitation for each day of the year during the distinguished periods
Month	Out	Average monthly values of selected water balance term for sub-catchment under consideration
Analyze	Out	Distribution of precipitation

* This sheet is hidden because it is used by the application only.

** Though it is interesting to watch the generation of precipitation events, it was decided to hide this sheet because it is only used by the application.
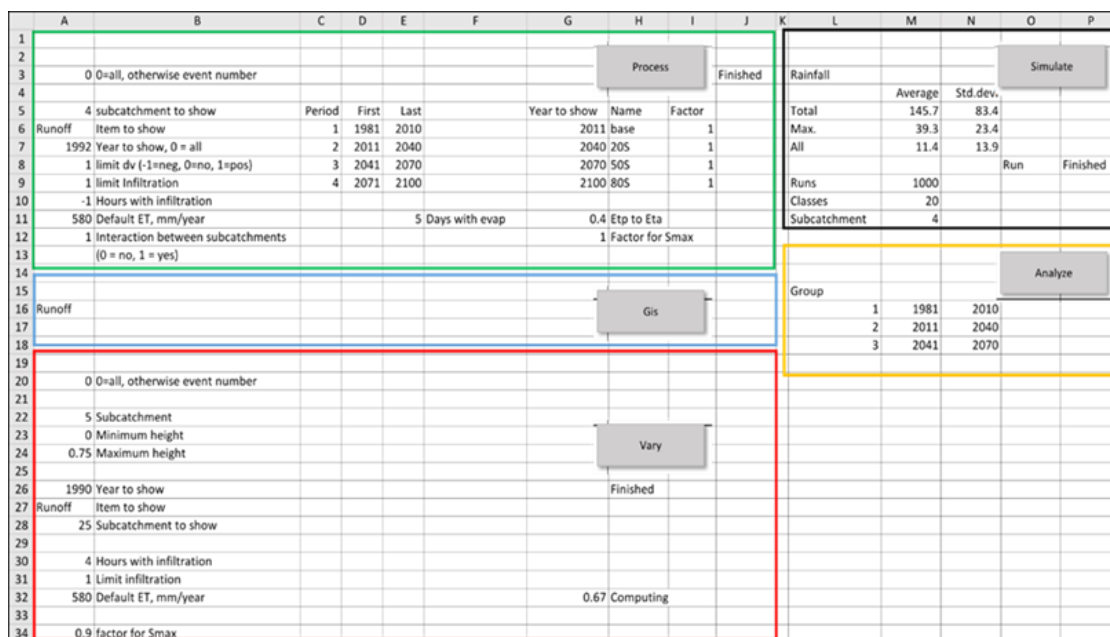

Fig. 5. The Control sheet with five different sections.

The green part is used to compute all terms of the water balance. See the manual of the program for more details. After entering all data, computations can be started by clicking the button in the green area (Be sure to click on an empty cell first when you changed a value before clicking the button, otherwise Excel may not have stored the changed cell content). The message 'Computing' will be shown in cell J4 (Depending on the speed of the processor, the number of sub-catchments and the number of events, computations may take time varying from a few seconds to several minutes). The results of the computations will be stored in the appropriate worksheets and shown in the graphs. When all computations are performed correctly, the word 'Finished' will be written to cell J4 and the sheet 'HiLo' will become the active sheet.

When calculations for all sub-catchments are performed as described in the previous section, one often wants to show one of the terms of the water balance using a GIS-application (e.g. ArcGIS). In most cases the shape-file with the layout of the area and the numbers (id's) of the sub-catchment is available. In this case it is possible to make a join between the sub-catchment id in the shape file and the id in the Excel workbook. The joining is simpler when the data in the Excel sheet is organized with one sub-catchment per row and one year per column. This reorganizing of the output data can be performed in the blue section of the 'Control'-sheet. In cell A19 the water balance term to be considered is specified. Clicking on the button in the blue section will start the conversion and the worksheet 'GIS' will appear.

One of the interesting options of WHCatch is its possibility to show the influence of changing the maximum height of water in a storage area (changing the spillway height) on one of the water balance terms of a downstream sub-catchment. The red part of the 'Control'-sheet contains the required parameters for this option. All input fields are described in the manual. After entering all necessary data, computations will start when the button in the red area has been clicked. When finished, sheet 'Chart2' will be shown.

To generate precipitation data from three specified (normal) distributions and find the distribution of one of the terms of the water balance, the black section of the Control sheet has been created. After clicking the 'Simulate' button, the program will generate one year with precipitation from the specified distributions. The value of the water balance term of interest will then be read for the specified sub-catchment and stored in memory. This procedure is repeated 'numberOfSimulations' times. After finishing the simulations, the obtained data will be analyzed and the worksheet 'Distribution' will be shown with the distribution of the requested water balance term.

Analyzing the data on worksheet 'Rainfall' can be performed in the golden section of worksheet 'Control'. The precipitation data can be divided into 4 series of years. Pressing the button 'Analyze' will then start the analysis. Worksheet 'Analyze' will then appear, showing three charts: the distribution of amounts of rainfall, the probabilities and the number of events per year and class. All data is averaged over the specified period.

Worksheet Catchment

The worksheet 'Catchment' contains all properties of every sub-catchment. The first two lines (green) function as a header (see Fig. 6). From the third line down, the property values Table (3) should be entered for each sub-catchment to be considered. If the water from a sub-catchment flows into just one other sub-catchment, column J should contain the value 100, indicating 100% goes into the sub-catchment specified in column I. In that case column K should contain -99 and column L should contain 0. If a second sub-catchment is receiving water, then the identification number of this sub-catchment should be entered in column K and its percentage in column L (The sum of the values in column J and L of each row should always add up to 100). If a positive number is entered in column H, this value will be considered as the percentage of the total volume of water that infiltrates into the soil. If a negative number is entered, then the volume of infiltrated water will be computed from the infiltration rate (column G) and the specified number of hours with infiltration (Cell A36 on tabsheet

'Control'). One line of data should be present   for each considered sub-catchment.

	A	B	C	D	E	F	G	H	I	J	K	L
1	Catchment	Area	Cultivated	Storage	Max. storage	Runoff coeff.	Infiltration rate	Infiltration	Outflows	Perc	Outflows	Perc
2	number	m2	m2	m2	height m.		mm/hr	%	to1	%	to2	%
3	1	1240.23	20.3	15	0.6	0.21	96.00	41	2	100	-99	0
4	2	1411.66	16.99	17.11	0.1	0.199	101.00	43	5	100	-99	0
5	3	1148.03	119	119.3	0.5	0.181	108.00	46	4	100	-99	0
6	4	193248.68	17	0	0	0.2668	18.00	49	5	100	-99	0
7	5	11287.67	4110.82	2135.84	0.55	0.299	24.00	46	12	100	-99	0
8	6	2447.12	244.3	79.55	0.5	0.297	112.00	44	8	100	-99	0
9	7	390.24	154.2	35.09	0.45	0.291	84.00	43	9	100	-99	0
10	8	2755.67	1002.21	119.88	0.35	0.263	72.00	46	9	100	-99	0
11	9	29160.45	19616.9	2079.38	0.8	0.356	103.00	48	11	100	-99	0
12	10	5290.04	4107.44	520.77	0.4	0.356	103.00	42	11	100	-99	0
13	11	10645.76	9484.25	1600.21	0.5	0.215	108.00	43	18	100	-99	0
14	12	22906.3	16855.07	1323.62	0.4	0.18	111.00	45	13	100	-99	0
15	13	5952.82	6646.88	562.06	0.2	0.12	104.00	49	20	100	-99	0
16	14	7389.23	4993.37	0	0	0.166	102.00	46	20	100	-99	0
17	15	8243.31	2657.66	478.06	0.3	0.335	106.00	47	16	100	-99	0
18	16	21633.79	9707.59	1561.36	0.45	0.241	60.00	49	18	100	-99	0
19	17	4431.85	1646.06	518.04	0.4	0.18	48.00	42	16	100	-99	0
20	18	23413.22	14812.52	2392.02	0.7	0.118	90.00	45	23	100	-99	0
21	19	10307.13	8553.06	0	0	0.298	48.00	41	22	100	-99	0
22	20	11650.54	12093.84	1547.96	0.6	0.146	101.00	48	21	100	-99	0
23	21	19392.32	20814.62	0	0	0.103	108.00	43	25	100	-99	0
24	22	12663.6	8060.47	415.01	0.2	0.281	107.00	44	25	100	-99	0
25	23	4842.04	4150.92	929.45	0.6	0.204	108.00	43	24	100	-99	0
26	24	7989.35	4223.52	316.73	0.5	0.188	100.00	43	-1	100	-99	0
27	25	13182.81	8940.88	1272.58	0.3	0.299	110.00	46	-1	100	-99	0

Fig. 6. The worksheet Catchment contains the properties of each sub-catchment.

Table 3. Meaning of the columns on worksheet 'Catchment'.

Column	Name	Units	Remarks
A	Catchment number	-	identification number
B	Area	m^2	Total area
C	Cultivated	m^2	Cultivated area
D	Storage	m^2	Area of storage reservoir
E	Max. storage height	m	Max. height of water in storage reservoir
F	Runoff coefficient	-	
G	Infiltration rate	mm/hr	Measured infiltration rate
H	Infiltration	%	Percentage of water that infltrates in the storage area. If this value is not available, put a negative number here.
I	Outflows to 1	-	Id of first sub-catchment receiving water
J	Percentage1	%	Percentage of water flowing to sub-catchment 1
K	Outflows to 2	-	Id of second sub-catchment receiving water
L	Percentage2	%	Percentage of water flowing to sub-catchment 2

Worksheet ETp

In worksheet 'ETp' the yearly potential evapotranspiration can be specified. If the value for the considered year is not available, then the value specified in cell A11 and A38 of the 'Control' worksheet will be used.

Worksheet Rainfall

As the program does not consider the interaction between rainfall events, it is sufficient to present a list of precipitation (mm) values (Fig. 7). The first column contains the year, the others contain the precipitation values for each event. Data start in row 3. As the number of events may differ per year, the length of the rows is varying as well between the years. We applied the model for two datasets: one with 25 years (1981-

2005) and one with 120 years (1981-2100). The first dataset was obtained from meteorological stations in Tunisia. The first 30 years of the large dataset were measured in Tunisia again. The data for future years were generated from the output of Global Circulation Models (GCMs) and a downscaling procedure as described by Adham et al. (2019).

Worksheets Smax, Vin, Vs, Vinf, Vx, dV, bal, Runoff

These sheets are used to store data calculated by the program. The values in worksheet 'Smax' represent the maximum volume of water (m^3) that can be stored in each sub-catchment. Worksheet 'Vin' shows the volume of water (m^3) that flows from the

non-storage area into the storage area, 'Vs' shows the volume of water (m^3) that has been fallen in the storage area of each sub-catchment. Worksheet 'Vinf' presents the volume of water (m^3) that has been infiltrated into the soil under the storage area of each sub-catchment and worksheet 'Vx' presents the volume of water (m^3) that has flown into the sub-catchment from other sub-catchment(s) located upstream. Worksheet 'dV' presents the potential change in volume of water (m^3) in the storage area of each sub-catchment. Positive values mean that water is stored in the storage area, negative values mean there will be no storage. If you are interested in the potential storage (i.e. the storage when the reservoir walls would be infinitely high) in m^3, then you can have a look at the worksheet called 'bal'. Worksheet

'Runoff' presents the runoff volume of water (m^3) from the storage area of each sub-catchment. All of these worksheets look the same. Data starts in row 3 again. The first column of these worksheets contains the considered year, the second column shows the amount of precipitation used in the computation. The following columns show the value for each sub-catchment, the rows represent the subsequent years.

Worksheet Chart1

Worksheet 'Chart1' has been developed to present the computed data graphically. The water balance term to be shown is specified in the 'Control' worksheet. At the left hand side of the worksheet, 5 data columns can be seen (see Fig. 8).

	A	B	C	D	E	F	G	H	I	J	K
1	Year	Event									
2			1	2	3	4	5	6	7	8	9
3	1980	4.7	13.5	5.3	2	7	61.5	1.6	7	12	
4	1981	2.7	10	1	70	5.5					
5	1982	3	5	8	20	3	25	19	5	1	
6	1983	5	12	5	18	26	8	40	36	1	
7	1984	15	29.5	22.5	17	5	10	10	5		
8	1985	6	42	7	33	6	15	18	6	5	
9	1986	10	4	0.7	3.9	41	6	1.7	5.8	0.8	
10	1987	5	8	20	15	23	5	2	0.8	10	
11	1988	7.2	1.2	27	15.5	22.5	5				
12	1989	1	0.7	21	4.5	13.5	11	3	15	3	
13	1990	7	6	15	3	10	9				
14	1991	15	6.5	5.5	5.5	13					
15	1992	23	24.5	117							
16	1993	5.5	12.5	11	8	14	12	3	3		
17	1994	2	3	1	3	2	19	2	12.5	10	8
18	1995	26	6	3	2.5	1	17.5	9.5	8.5	31.5	
19	1996	17	26	10	6	58	21	39	24	9	
20	1997	24	4	7.6	7.5	20	8.8	6	7	1.8	

Fig. 7. The measured or generated rainfall events should be stored in worksheet Rainfall, one row with event sizes per year.

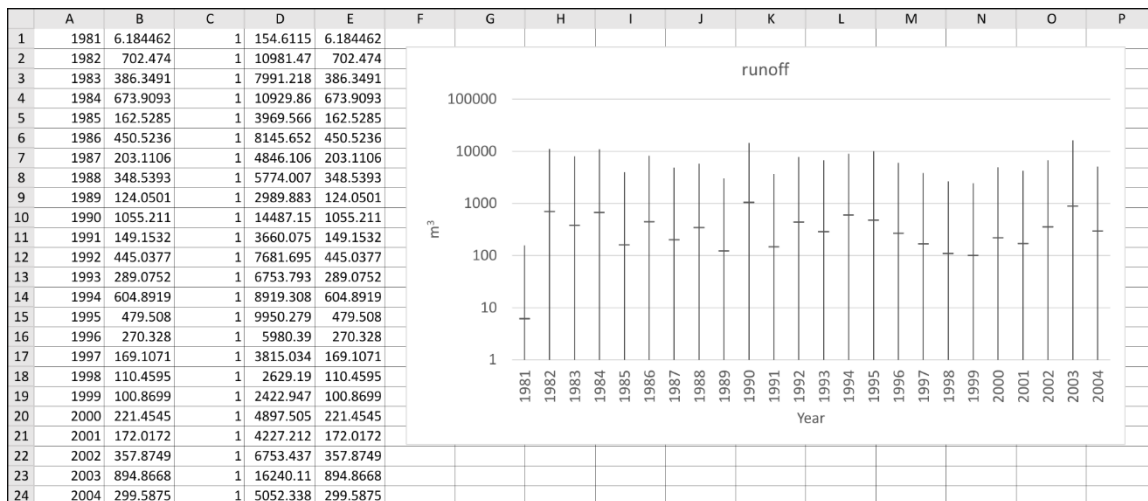|	A	B	C	D	E
1	1981	6.184462	1	154.6115	6.184462
2	1982	702.474	1	10981.47	702.474
3	1983	386.3491	1	7991.218	386.3491
4	1984	673.9093	1	10929.86	673.9093
5	1985	162.5285	1	3969.566	162.5285
6	1986	450.5236	1	8145.652	450.5236
7	1987	203.1106	1	4846.106	203.1106
8	1988	348.5393	1	5774.007	348.5393
9	1989	124.0501	1	2989.883	124.0501
10	1990	1055.211	1	14487.15	1055.211
11	1991	149.1532	1	3660.075	149.1532
12	1992	445.0377	1	7681.695	445.0377
13	1993	289.0752	1	6753.793	289.0752
14	1994	604.8919	1	8919.308	604.8919
15	1995	479.508	1	9950.279	479.508
16	1996	270.328	1	5980.39	270.328
17	1997	169.1071	1	3815.034	169.1071
18	1998	110.4595	1	2629.19	110.4595
19	1999	100.8699	1	2422.947	100.8699
20	2000	221.4545	1	4897.505	221.4545
21	2001	172.0172	1	4227.212	172.0172
22	2002	357.8749	1	6753.437	357.8749
23	2003	894.8668	1	16240.11	894.8668
24	2004	299.5875	1	5052.338	299.5875

Fig. 8. Worksheet Chart1, showing the minimum, maximum and averaged runoff from all catchments for all considered years
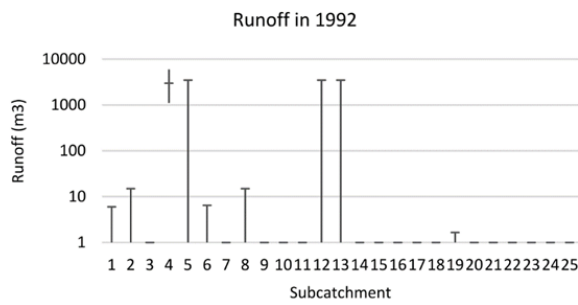
Fig. 9. The runoff of the sub-catchments for the rainfall events of 1992.

In column A the values are stored that should be shown along the x-axis. Column C contains the minimum value, columns B and E contain the average value and column D contains the maximum value to be shown. In this figure the minimum, maximum and averaged runoff from all catchments is shown for all considered years. The minimum value is 0 for all years, indicating there is at least one catchment where no runoff will take place. Because data are shown on a logarithmic scale, a value of 1 is written instead of 0. If the option is chosen to perform computations for all years, then the chart will show the minimum, average and maximum values of all sub-catchments for each year. If calculations had to be performed for a specified year only, then data will be presented as the minimum, average and maximum value of the balance terms of each event for every sub-catchment (see Fig. 9).

Runoff is presented for all events in 1992 and for all sub-catchments. Although there are

4 sub-catchments with a broken spillway (4,14,19 and 21), only sub-catchment 4 always produces runoff. This is caused by the low infiltration capacity of the soil in the sub-catchment (see worksheet 'Catchment').

Worksheet Chart2
In worksheet 'Chart2' the results of varying the maximum storage height of a sub-catchment (red part in worksheet 'Control') are visualized (Fig. 10). If, for example, one wants to know how the storage height of sub-catchment 4 influences the runoff from sub-catchment 25, the corresponding chart is created. Columns A and B of the worksheet 'Chart2' contain the x- and y-values to be shown. The titles of the y- and x-axis are stored in cells D1 and D2 respectively and cell D3 contains the title of the chart.

Worksheet HiLo
In the description of worksheet 'Control' it was mentioned that four years can be specified as years that are representative for the considered period. The results for these years are presented in the chart of worksheet 'HiLo'. The legend shows the name or description of the years as specified in cells H7:H10 of worksheet 'Control'. The identification number of the sub-catchment is stored in column A. Columns B-E contain the data for the specified years. These values are plotted in a chart. See e.g. Fig. (11) where the values of dV are plotted for the four considered years and for every sub-catchment.
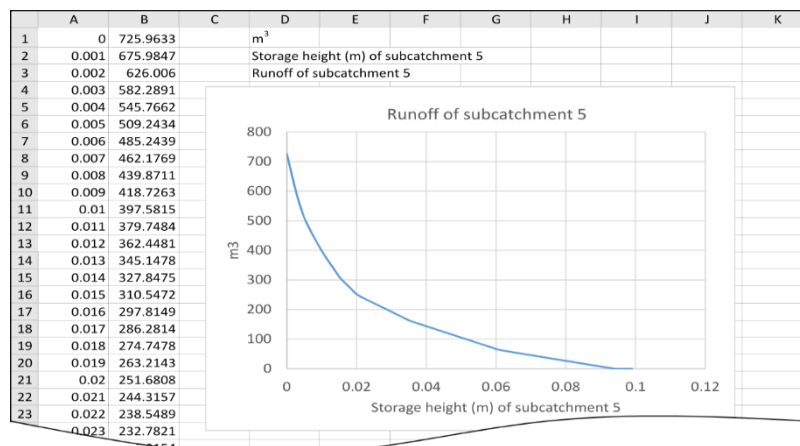

Fig. 10. An example of worksheet Chart2, showing the relation between the storage height of sub-catchment 4 and the runoff of sub-catchment 25.
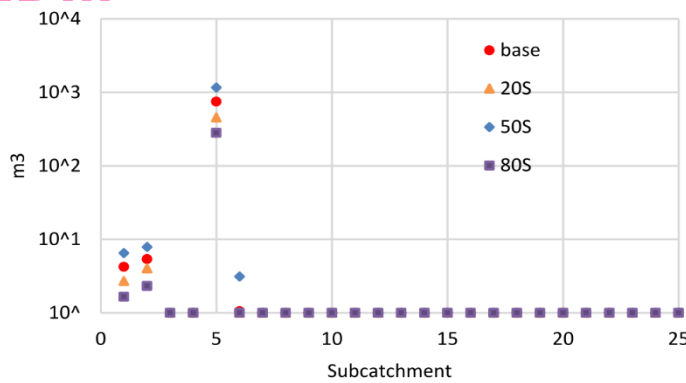
Fig. 11. The chart on worksheet HiLo, showing the values of dV for the four considered years and for every sub-catchment.
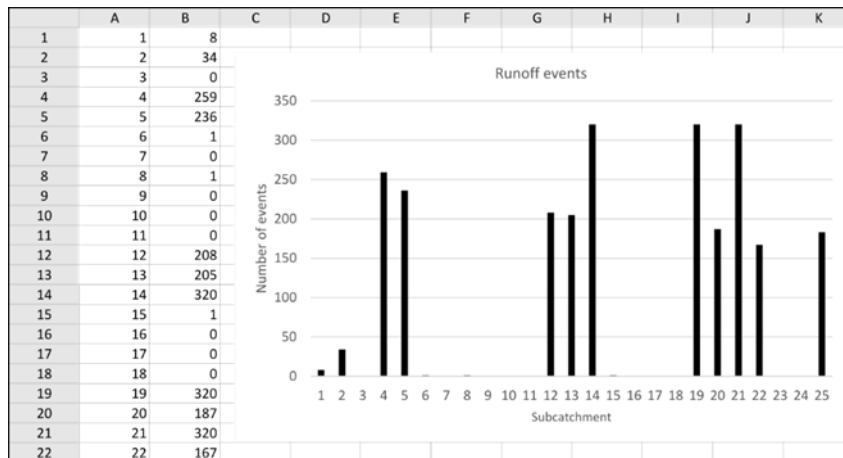

Fig. 12. The number of runoff events for each sub-catchment as shown on worksheet Events.

Worksheet Events

One of the most interesting options of the program is presented on worksheet 'Events' (Fig. 12), showing the number of runoff events for each sub-catchment. This chart indicates which sub-catchment should have a larger storage capacity and where it will take no effect to change the storage capacity. From our example it can be concluded that a lot of runoff can be prevented by changing the storage capacity of the sub-catchments 14, 19 and 21, as they have the largest runoff. From the input data it can be seen these sub-catchments do not have any storage capacity.

Worksheet GIS

The computed data can be read into a GIS application. The item to be shown can be specified in the blue part of the 'Control'-worksheet. Pressing the button in that area will tell the program to write the data to the worksheet 'GIS' (Fig. 13A). This worksheet can easily be imported into a GIS-application and combined with a shape-file to create maps

or movies. An example is presented in Fig. 13B showing the runoff values for 2003.

Worksheet Distribution

When the simulations with the generated rainfall events are analyzed, the worksheet 'Distribution' will be shown. On this sheet (Figure 14), column A contains the lower limit of the classes and column B contains the upper limit. In column C the number of entries in the class can be found and column D shows the probability that a value will be in the class. Finally, column E contains the labels to be shown at the horizontal axis of the chart. As additional information, the average value (cell H2), standard deviation (cell H3) and median value (cell H5) are presented.

Worksheet CumDist

When the probability of the distributions are computed (see the previous paragraph), these data are applied to compute the cumulative distribution is derived and presented on worksheet 'CumDist' (Fig. 15).
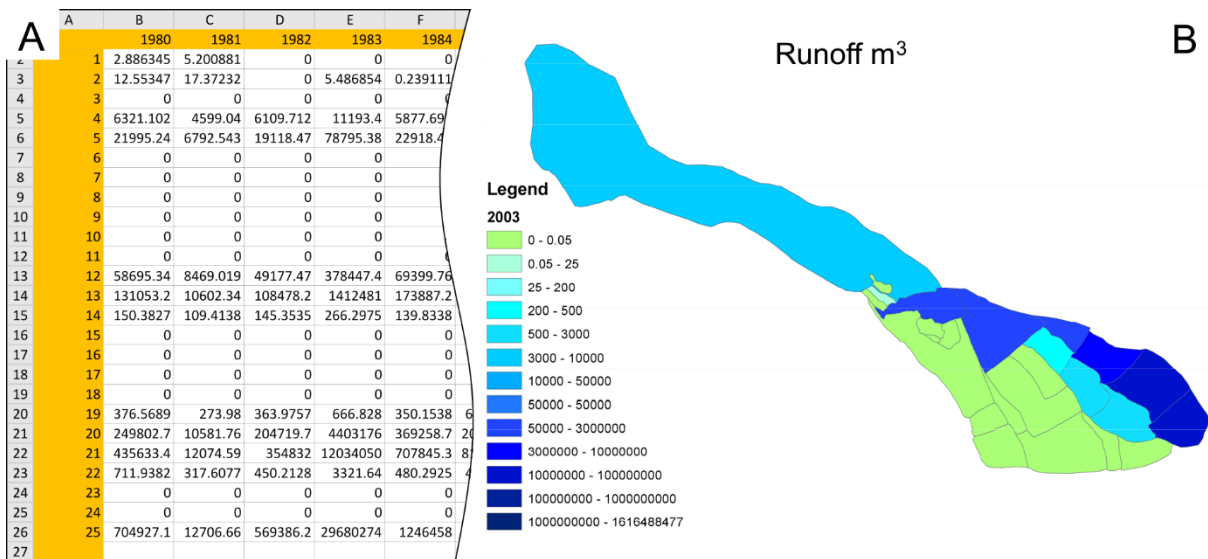
Fig. 13. Runoff data on worksheet GIS (A) and the map obtained from these data with ArcGIS (B).
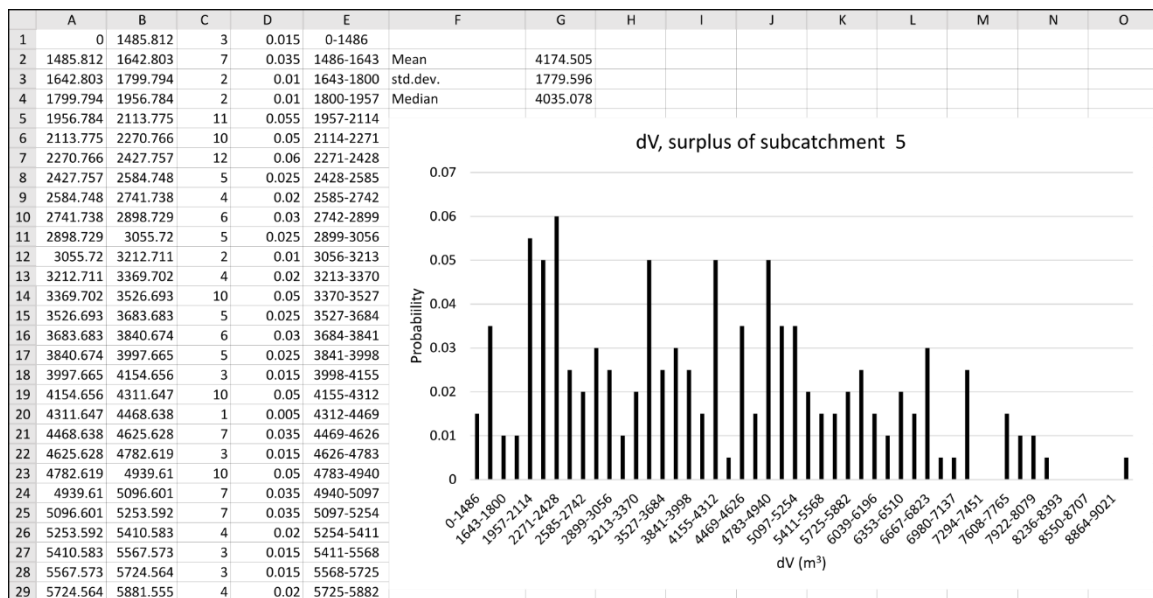

Fig. 14. The distribution of the values of a water balance term obtained from computations with generated precipitation events is shown on the worksheet Distribution.
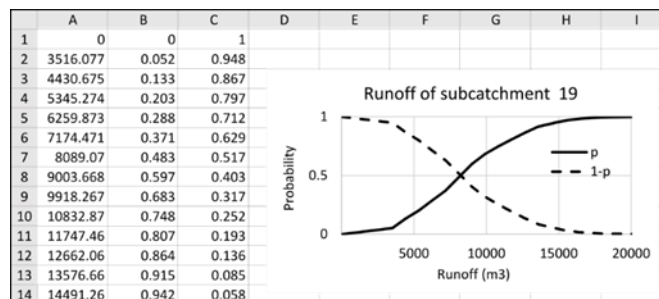

Fig. 15. An example of the worksheet CumDist, showing the cumulative probabilities of the runoff of sub-catchment 19

Column A contains the value of interest (computed as the middle of the corresponding class), column B contains the probability that a value is smaller than the value in column A and column C presents the probability that a value exceeds the one in column A. The solid and dotted line represent these probabilities. As an example, it can be seen that the p-value for 3516 is 0.052, indicating that the runoff of sub-catchment 19 will be smaller than 3516 during 52 out of 1000 years. On the other

hand, the runoff value will exceed 14491 only during 6 years every century.

Worksheet Year

It is always interesting to see the precipitation in a graph. Therefore, WHCatch will automatically show the daily precipitation of the 4 years of interest in a chart on worksheet 'Year' (see Fig. 16, top) (Take care that in this case the program expects precipitation data for each day of the year in worksheet 'Rainfall'. If you only provide the rainfall events (no zeroes), the charts will not show the real course of rainfall in the considered year).

In this worksheet the second row contains the names to be shown in the legend of the chart (equal to the name of the special years presented in cells H7:10 of worksheet 'Control'). The first column presents the day of the year, starting with 1 in row 3. Columns B-E contain the precipitation values, columns F-I have the cumulative precipitation values which are shown in the lower figure (Figure 16, bottom).

Worksheet Month

If the data on worksheet 'Rainfall' is presented daily, it is possible to generate monthly values of output. The water balance

term to show is specified in the black part of the worksheet 'Control'. The values are average daily values during the months and will be presented for the years specified in the 'Control' worksheet (see Fig. 17).

Worksheet Analyze

If the button Analyze in the golden part of the 'Control'-sheet is pressed, the rainfall data on worksheet 'Rainfall' will be analyzed and the results will be stored in the worksheet 'Analyze'. Just like in the other options, 4 different periods may be distinguished that will be analyzed separately. Computations start by creating a number of precipitation classes of 1 mm each and simply counting the number of events in each class. The class-values (middle of the class) and number of events are then stored in columns A-H. From these values the cumulative probabilities $(P(p>x))$ are computed and stored in columns U-AB. Finally, classes of 10 mm are created and it is counted how many times per year an event correspondents to the class. These values are averaged over the number of years in each period and stored in columns J-Q. Starting from column AC three charts are presented to show the results of these computations (see fig. 18).
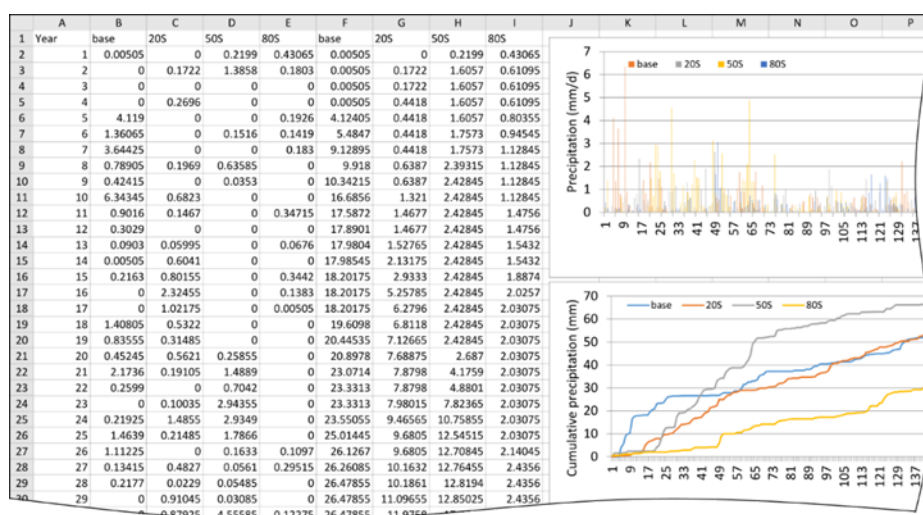

Fig. 16. The worksheet Year showing daily precipitation values (top) and cumulated values (bottom) for the years under consideration
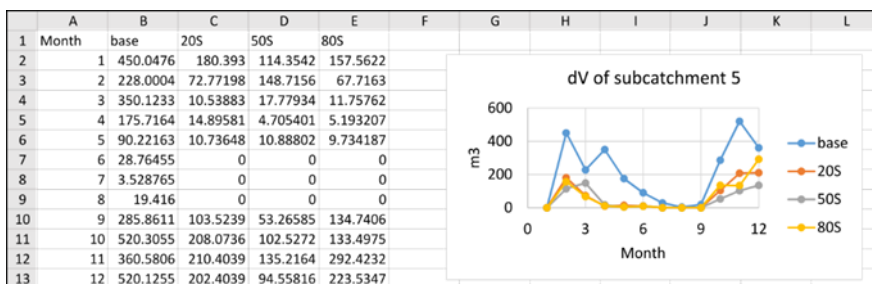
Fig. 17. The values of an output term (in this case dV) as averaged over the months for the specified years as shown on tabsheet Month
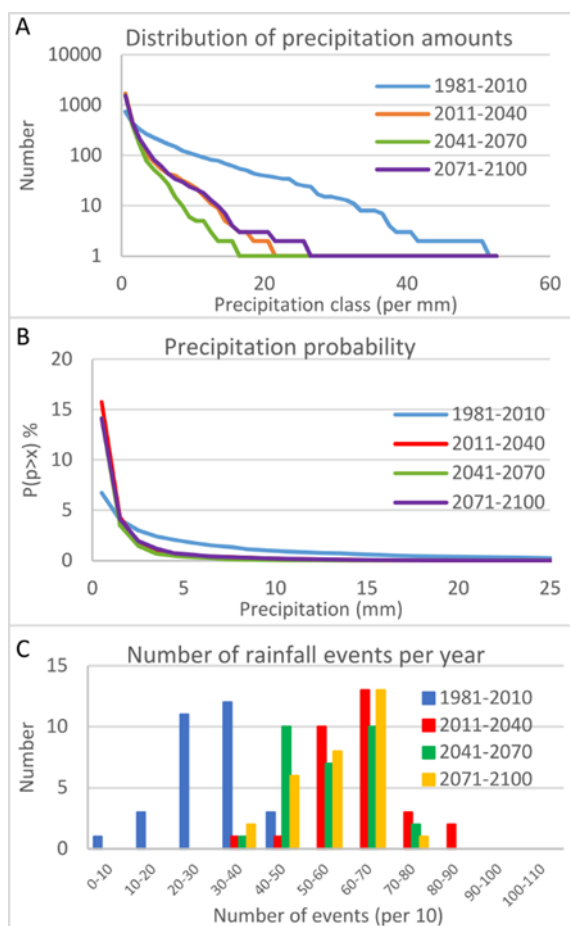

Fig. 18. The results of the analysis of the rainfall data: (A) Distribution of precipitation amounts, (B) Probability of precipitation and (C) Yearly averaged number of occurrences of a rainfall event with specified size.

The VBA part

To perform the calculations described above and put the results in the correct places, some VBA (Visual Basic for Applications) code was developed: a module WHCatch and a class module SubcatchmentClass. The latter contains all the properties of a sub-catchment and software to perform some basic computations. The module WHCatch consists of a number of private subroutines and only 5 public ones, which correspond to the 5 buttons on the 'Control' worksheet.

As the VBA part is well-documented and the names of the variables explain their function, the VBA part will not be discussed in detail here. Common users of the Excel workbook will not see the VBA part. Only when new functionality is required, it is necessary to enter the code part.

Applications

The program has been tested with 25 sub-catchments and with 258 sub-catchments, both with 120 years of rainfall. See Adham et al. (2019) for an application of the program.

Limitations of the program

Because we wanted to create a fast and simple program that requires as little data as possible, there are some known limitations:

- There is no interaction between the events, so computations start at the same initial situation, independent of the time between events, the model can be considered as quasi-steady state. If some "memory" is required, it is advised to use a transient model like SWMM.
- Infiltration of the soil is considered in a simple way: it is represented as a volume of water that is lost from the surface.
- Plant transpiration and soil evaporation are not considered separately because the effect of these kinds of transpiration are identical. It is possible to separate these by adding another column in the input data. Doing so requires knowledge of the crop type and its properties.
- Circumstances do not change in time. It only requires minor efforts to change the program in such a way it can use properties that change in time.
- No human actions are incorporated. This can be implemented by specifying a date and a new value and changing the VBA code.

System requirements

The program has been created as a macro-enabled Excel workbook. The only software requirement is the presence of Microsoft Office on the computer. It was tested with both Office 2013 and Office 2016.

A CPU with a clockspeed higher than 2GHz is recommended and a memory size of 2 GB will be sufficient. Required diskspace varies between 500 kB and 10 MB, depending on the number of years and the number of sub-catchments that have to be processed.

Software availability

The software described in this paper consists of one macro-enabled Excel workbook and a manual (pdf-file). The software can be obtained (free of charge) from the first author. It is distributed under conditions of the GNU-GPLv3 license.

3- Conclusion

This paper shows that, despite the availability of complicated numerical models, a simple Excel workbook can be used to show the effects of water harvesting structures. It may contribute to a better insight in the way water can be used more efficiently. In our opinion this program is a tool that can be used for both educational and research purposes. It is easily extendable, even for people with only little programming experience. Both input and output are in the same Excel Workbook. Changes can be made directly in the sheets without having to keep clicking on the menu's of some fancy user interface. Effects of changes or different scenario's can be shown immediately. No special compilers are required, just Microsoft Office, which is available on nearly every computer nowadays. Due to its simplicity and modular setup everyone can change the VBA code to their own needs.

4- Conflicts of Interest

No potential conflict of interest was reported by the authors.

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