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A SIMULATOR FOR RAINFALL-RUNOFF-YIELD PROCESSES WITH IN-FIELD WATER HARVESTING

by

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Executive Summary

In order to quantify long-term crop production risks with different production techniques (a water harvesting production technique and a conventional total soil tillage production technique), it is probably necessary to carry out crop simulation studies. If long-term runoff data is not available, these studies require reliable simulation of rainfall-runoff processes, and therefore, need long-term rainfall intensity data. In the Water Research Commission project entitled "Estimation of rainfall intensity for potential crop production on clay soil with in-field water harvesting practices in a semi-arid area," a model has been developed to simulate a rainfall intensity-runoff-yield process. However, the rainfall intensity, runoff and crop yield models have not been linked, by means of computer programming, to form one comprehensive simulator. In this project, a complete simulator for crop yield by linking the combination of rainfall-runoff processes to the crop model has been developed. The simulator is user-friendly, and therefore, available to agronomists / crop scientists / soil scientists / agrometeorologists who are not computer-literate. This report includes the model description and the user manual (installation and simulation run).

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Contents

1. Introduction

Peak rainfall intensity values are vital to model runoff from a variety of catchments. However, measured runoff and rainfall intensity data are not readily available. Rural development and city planning require the control of water quality, so an estimate of peak runoff (or flood) is necessary for these development and planning. Concerning agricultural development, in semi-arid and sub-humid areas, the availability of water for crop production is unreliable due to erratic and low rainfall. Efficient use of water is, therefore, essential for crop farming. In order to quantify long-term crop production risks with different production techniques (WHBM – a water harvesting technique using a combination of a no-till type of micro-catchment, as shown in Figure 1, and basin tillage covered by mulch; CT – a conventional total soil tillage production technique) (Hensley *et al.*, 2000), it is necessary to carry out crop simulation studies. These studies require reliable simulation of the rainfall-runoff processes, and therefore, need long-term rainfall intensity data.

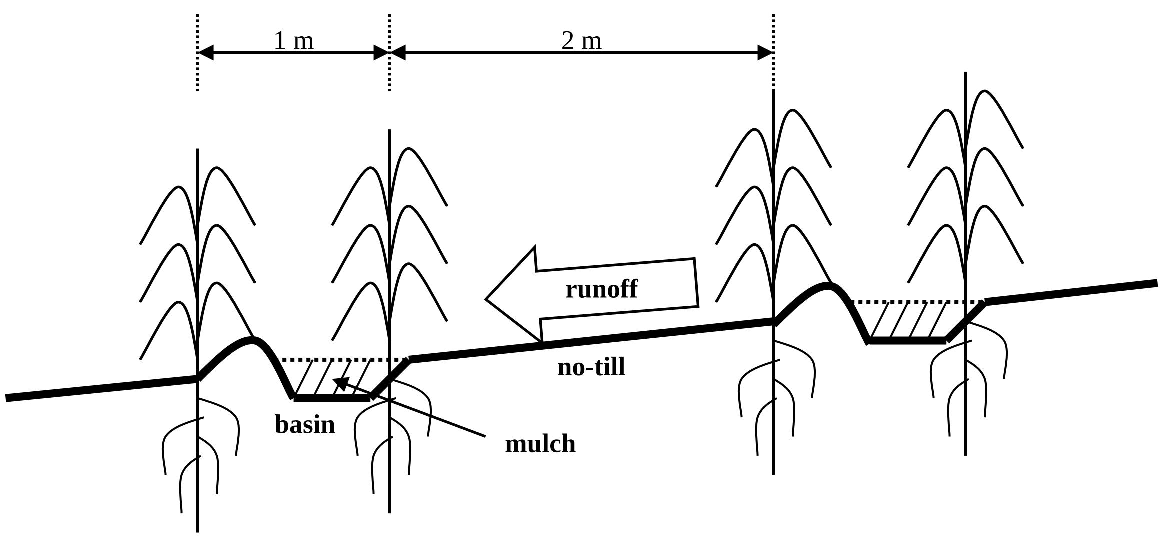


Figure 1. A diagrammatic representation of the water harvesting / basin tillage / no-till / mulching production technique.

The Huff curve procedure has been developed to simulate the rainfall intensities in the Water Research Commission project entitled “Estimation of rainfall intensity for potential crop production on clay soil with in-field water harvesting practices in a semi-arid area” (Walker and Tsubo, 2003). This stochastic rainfall intensity model has been developed from Bloemfontein and Pretoria data to provide long-term rainfall intensity values as applied in agricultural water harvesting projects. Furthermore, a comprehensive model has now also been developed to simulate rainfall intensity – runoff – yield processes. These results would then be available to the agriculturists / soil and crop scientists, hydrologists / agrohydrologists and meteorologists / agrometeorologists in South Africa to be used in peak rainfall intensity estimation (for food production) and soil erosion and water quality studies. This would greatly enhance the existing hydrological models and predictions.

With respect to model users, an important task which should be carried out is to link by means of computer programming the rainfall intensity, runoff and crop yield models to form one comprehensive simulator. In this follow-up project, therefore, a complete simulator for crop yield by linking the combination of rainfall-runoff processes to the crop model has been developed. The program is written in C++ language and Quick Basic.

2. Model description

The model flow for rainfall-runoff-yield processes includes:

(1) Rainfall intensity data is stochastically generated using the Woolhiser and Osborn (1985) type model (Walker and Tsubo. 2003).
(2) Runoff is deterministically estimated using the Morin and Cluff (1980) model.
(3) Crop yield is predicted using the Putu crop growth model (de Jager *et al.*, 2001).

An alternative modelling flow is the estimation of runoff from daily rainfall using rainfall-runoff linear relationships (i.e., empirical rainfall-runoff models), and then the prediction of crop yield using the Putu crop growth model.

<u>Woolhiser and Osborn (1985) type model (Waker and Tsubo, 2003)</u>

Within a rainfall event, the amount of rainfall received in a period between x_{i-1} minute and x_i minute, P_i (namely, rainfall intensity), is given by:

$$P_i = \frac{Y(y_i - y_{i-1})}{X(x_i - x_{i-1})} \qquad i = 1, 2, \cdots, n \qquad (1)$$

where X is the total duration of event rainfall (min), Y is the total amount of event rainfall (mm), y_i is the fraction of the cumulative event amount at a given time from the starting time of rain to the total event amount (the dimensionless amount of rainfall events), x_i is the fraction of the cumulative event duration from the starting time of rain to the total event duration (the dimensionless duration of rainfall events), and n is the number of steps in which rainfall intensity is divided (the nth increment). The start point (x_0, y_0) and the end point (x_n, y_n) of the dimensionless hyetograph are equal to the point (0, 0) and the point (1, 1). The other points fulfill $x_i > x_{i-1}$ in a range between x_0 and x_n ($0< x_1 <x_2 < \cdots < x_{n-1} <1$) and $y_i > y_{i-1}$ in a range between y_0 and y_n ($0< y_1 <y_2 < \cdots < y_{n-1} <1$).

The increment process of the dimensionless amount at a given interval of the dimensionless duration, z_j ($0 < z_j <1$), is defined as:

$$z_j = \frac{y_j - y_{j-1}}{1 - y_{j-1}} \qquad j = 1,2\cdots,n-1 \tag{2}$$

For depicting a complete dimensionless hyetograph from y_0 to y_n, the probability density function of the beta distribution may describe the distribution of the increment process of dimensionless amount for any j, $f(z_j)$, as follows:

$$f(z_j) = \frac{\Gamma(\alpha_j + \beta_j)}{\Gamma(\alpha_j)\Gamma(\beta_j)} z_j^{\alpha_j - 1}(1 - z_j)^{\beta_j - 1} \tag{3}$$

where α_j and β_j are the shape parameters ($\alpha_j > 0$ and $\beta_j >0$). For any j, z_j is stochastically chosen using the cumulative distribution function. The parameters α_j and β_j are estimated from the mean $E(z_j)$ and the variance $V(z_j)$:

$$E(z_j) = \frac{\alpha_j}{\alpha_j + \beta_j} \tag{4}$$

$$V(z_j) = \frac{\alpha_j \beta_j}{(\alpha_j + \beta_j)^2 (\alpha_j + \beta_j + 1)} \tag{5}$$

Because it has been fount that α_j and β_j are dependent on the dimensionless duration, α_j and β_j are calculated using a reciprocal quadratic equation and a quadratic equation, as follows:

$$\alpha_j = \frac{1}{A_1 x_i^2 + A_2 x_i + A_3} \tag{6}$$

$$\beta_j = B_1 x_i^{\,2} + B_2 x_i + B_3 \tag{7}$$

where A_1, A_2, A_3, B_1, B_2 and B_3 are coefficients. The coefficients B_1, B_2 and B_3 have a linear relationship with the number of steps (N), as follows:

$$\left.\begin{array}{l} B_1 \\ B_2 \\ B_3 \end{array}\right\} = C_1 N + C_2 \tag{8}$$

where C_1 and C_2 are coefficients.

Concerning X, the probability density function of the gamma distribution, $f(X)$, is used to describe the distribution of the total duration of event rainfall, and X is also stochastically chosen using the cumulative distribution function. The gamma probability density function on X is given by:

$$f(X) = \frac{1}{\beta'^{\alpha'}\Gamma(\alpha')} X^{\alpha'-1} \exp\left(-\frac{X}{\beta'}\right) \tag{9}$$

where α' (> 0) is the shape parameter and β' (> 0) is the scale parameter. The two parameters can be estimated from the mean, $E(X)$, and variance, $V(X)$:

$$E(X) = \alpha'\beta' \tag{10}$$

$$V(X) = \alpha'\beta'^2 \tag{11}$$

Published algorithms have been used to calculate inverse beta and gamma cumulative distribution functions. Some of the source codes in C language are obtainable from DCDFLIB (Double precision Cumulative Distribution Function LIBrary) (Brown *et al.*, 1997).

With respect to time interval resolution, setting the minimum and maximum event duration to 30 min and 1440 min (one day), respectively, rainfall amount per a half hour (which could change the number of steps of the increment process from 1 to 48) can be simulated. Parameters and coefficients of the rainfall intensity model have been calibrated with 30 year's data at Bloemfontein (semi-arid climate) (29º06´S, 26º18´E, 1354 m) from 1962 to 1992 and at Pretoria (warm-temperate climate) (25º44´S, 28º11´E, 1330 m) from 1966 to 1996. The parameters and coefficients are summarised in the following table. Also, the parameters and coefficients for Bloemfontein can be used for generating rainfall intensities at Glen (semi-arid climate) (28º57´S, 26º20´E, 1304 m) because they have similar rainfall distributions.

Parameter/Coefficient	Bloemfontein	Pretoria
A_1	2.0863	2.0873
A_2	0.4858	1.1073
A_3	–2.4667	–2.9493
C_1 *for* B_1	–0.1576	–0.2040
C_2 *for* B_1	–4.4563	–4.0253
C_1 *for* B_2	0.1584	0.2013
C_2 *for* B_2	2.9603	2.7225
C_1 *for* B_3	0.1394	0.1160
C_2 *for* B_3	1.3346	1.1394
α'	1.65	1.02
β'	212	282

Morin and Cluff (1980) model

There is an exponential relationship between the infiltration and rainfall intensity, as follows:

$$I_t = I_F + (I_I - I_F)\exp(-\gamma P t) \tag{12}$$

where I_t is the infiltration rate, I_F and I_I are the final and initial infiltration rates of the soil, γ is the soil factor (determined by the stability of the soil surface aggregate to the reorientation of soil particles, by the impact of the raindrops to form a crust), P is rainfall intensity, and t is the time elapsed from the beginning of the rainfall event. From Equation 12 it is possible to obtain, by substitution and integration, Equation 13 which makes it possible to compute the runoff of any storms, segment by segment, by means of Equation 15.

$$IF_k = I_F \Delta t_k + \frac{(I_I - I_F)}{-\gamma P_k} \left[\exp\left(-\gamma D_k\right) - \exp\left(-\gamma D_{k-1}\right) \right] \tag{13}$$

where IF_k is the total amount of infiltration of rain water into the soil over period k with rainfall intensity P_k, and D_k, is the amount of rainfall over period k (k = 1, 2,…, m: the number of the given periods per rainfall event) which is given by:

$$D_k = \sum_{k=1}^{m} P_k \Delta t_k \tag{14}$$

The runoff model computes the amount of runoff (RO_k,) in a time period from t_{k-1} to t_k (Δt_k) of any rainfall events, as follows:

$$RO_k = RF_k - IF_k - \left(SD_{\max} - SD_{k-1}\right) \qquad k = 1, 2, \ldots, m \tag{15}$$

where RF_k is the amount of rainfall (=D_k), SD_{k-1} is storage and detention of soil surface water in the previous period Δt_{k-1}, and SD_{max} is maximum storage and detention of soil surface water. So, the total amount of runoff per rainfall event is the sum of runoff amounts in all m periods, as follows:

$$RO = \sum_{k=1}^{m} RO_k \tag{16}$$

When the Morin and Cluff (1980) model parameters are not calibrated, they may be assumed; for instance, the parameters for the Glen/Bonheim ecotope areas are: I_I = 25 mm/hr, I_F = 6 mm/hr, γ = 0.2/mm, and SD_{max} = 5 mm for the CT production technique and 0.025 mm for the WHBM production technique.

Putu crop growth model (de Jager et al., 2001)

The crop growth model "Putu", which means maize porridge in Zulu, was developed by Prof. J. M. de Jager of the Department of Agrometeorology, University of the Orange Free State, South Africa (currently, Department of Soil, Crop and Climate Sciences, University of the Free State). The model was developed under South African semi-arid conditions and demonstrated an acceptable degree of reliability in simulating crop yields. The model describes the proportionate limitation on growth due to each of the climatic variables for each day of the growing season. The details have been reported by de Jager *et al*. (2001): "Research on a computerised weather-based irrigation water management system" (the WRC report number 581/1/01). The simulator developed has included the maize version (PutuMaize).

Empirical rainfall-runoff models

The threshold linear models of daily rainfall (*RF*) and runoff (*RO*) processes have also been incorporated into the simulator. For a conventional soil tillage production technique (de Jager *et al.*, 2001), the runoff sub-model of the Putu crop growth model is used.

$$RO = \begin{cases} 0 & RF \le 15 \\ 0.05RF & 15 < RF \le 25 \\ 0.1RF & 25 < RF \le 50 \\ 0.2RF & RF > 50 \end{cases} \qquad \text{mm/day} \qquad (17)$$

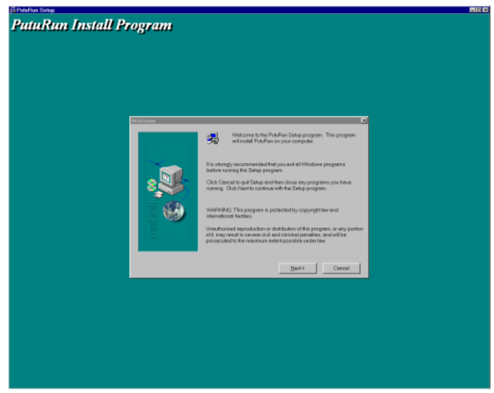
For a no-till production technique (Walker and Tsubo, 2003), the area under the rainfall intensity curve model (AUC) is used:

$$RO = \begin{cases} 0 & RF \le 8 \\ 0.61RF - 3.11 & RF > 8 \end{cases} \qquad \text{mm/day} \qquad (20)$$

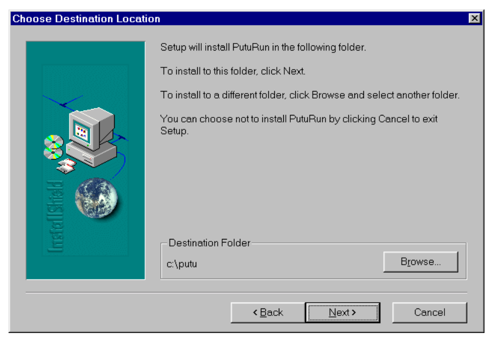
3. Installation

The program is basically written for Windows 98.

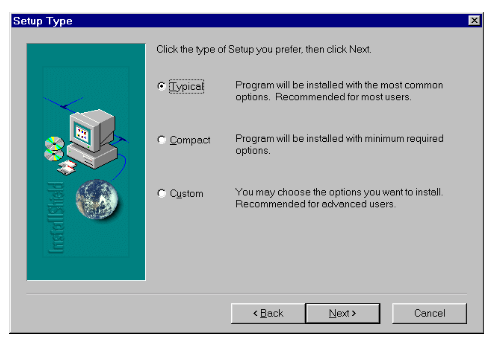
Turn on the computer and insert the CD-ROM disc. Open the CD-ROM drive and double-click the Set up.exe icon.



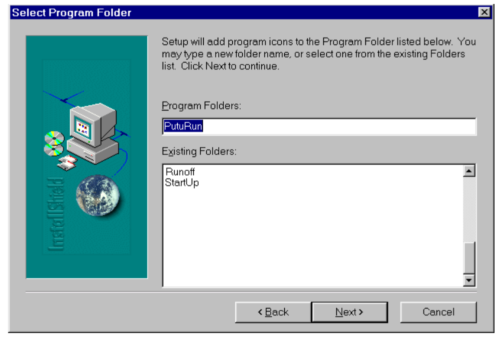
Click **Next**.



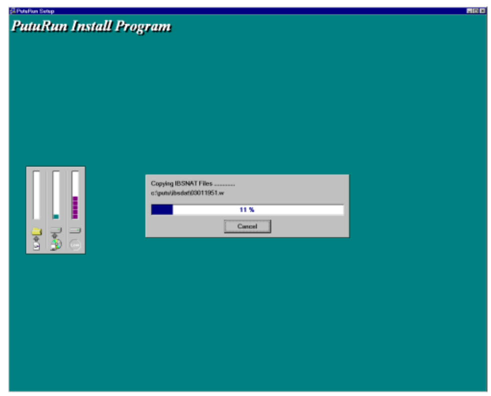
Click **Next** (if you choose the default folder c:\putu)**.**



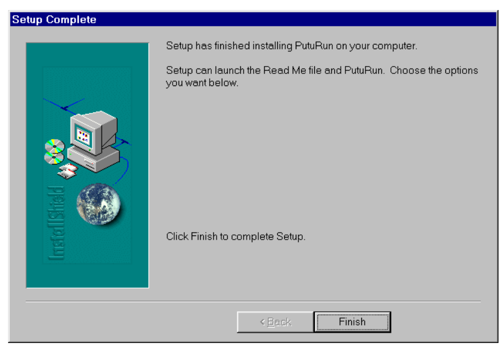
Choose **Typical** and click **Next**.



Click **Next** (if you choose the default folder PutuRun).



Wait for a while (installing the program).



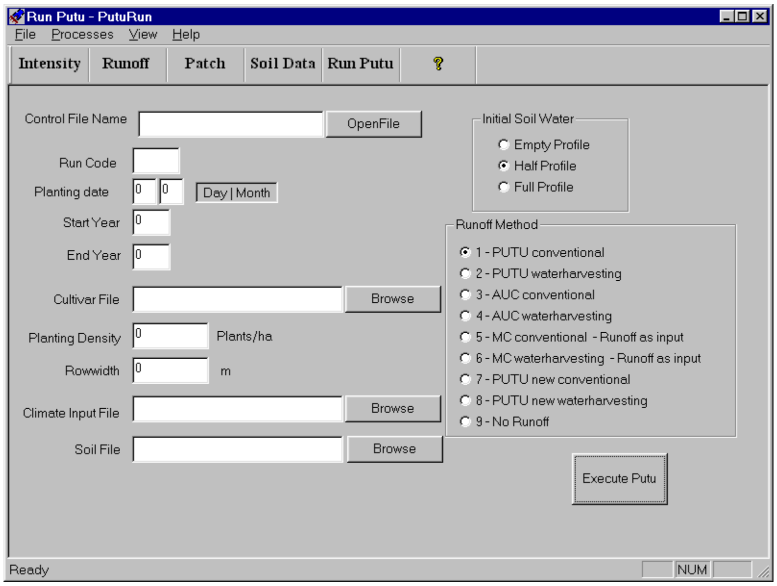
Click **Finish**.

Note: The following setting is needed to run the PutuRun program.

By clicking secondary (right) mouse button, display a menu of **MS-DOS putumgis** in the program folder and then choose **properties** from the menu. On the **program** tub, set **Run** to **Minimized** and select the **Close on exit** check box.

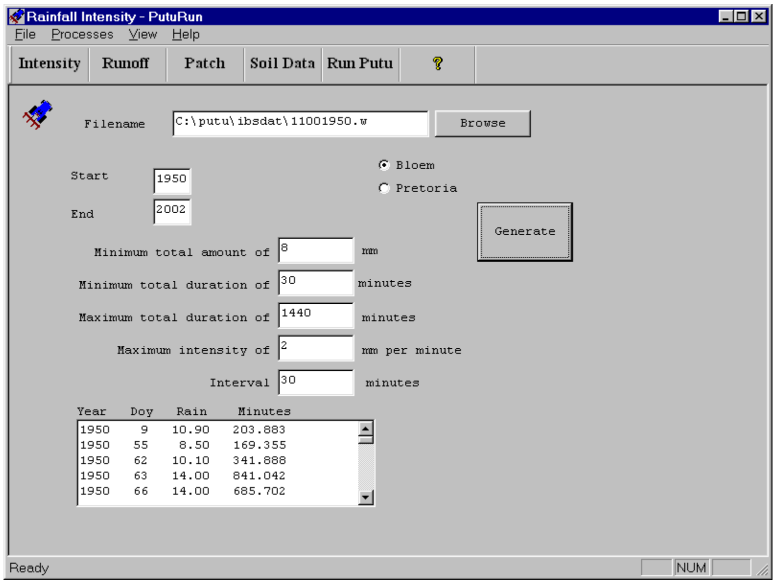
4. Simulation Run

Click **PutuRun** in the program folder. This is the main screen (also the Run Putu screen).



Calculating rainfall intensity

Choose **Intensity** from the menu.



Click **Browse** to open climate files (in IBSNAT format) in the folder c:\putu\ibsdat. Choose only one file (the program automatically uses all the files for a specific location.). Click **Open**. Return to the Intensity screen.

IBSNAT format: An example of an IBSNAT file is shown in Table 1 (e.g., c:\putu\ibsdat\11001950.w). The first row gives weather station number, latitude, longitude, and two numbers, while nine numbers on the second row and thereafter are the weather station number, year (the last two digits of year), day of year (DOY), radiation, maximum temperature, minimum temperature, rainfall, PAR, and runoff. The file name consists of three parts: the first part (the first 4 digits) for the weather station number (e.g., 1100 for Bloemfontein, 0301 for Pretoria, 0863 for Glen), the second part (the second 4 digits) for the year (e.g., 1950), and the third part for the file extension of .w.

Table 1. IBSNAT format.

```
1100 -29.12  26.37 12.07  0.00
1100 50   1 31.22  33.3  16.1   0.0 15.61  0.00
1100 50   2 31.52  33.9  15.6   0.0 15.76  0.00
1100 50   3 25.77  36.1  20.6   5.4 12.88  0.00
1100 50   4 17.23  28.3  18.3   0.8  8.61  0.00
1100 50   5 15.20  27.2  15.6   6.1  7.60  0.00
1100 50   6 23.72  26.7  15.6   5.5 11.86  0.00
1100 50   7 30.83  28.9  13.9   0.0 15.41  0.00
1100 50   8 21.83  28.9  17.2   1.1 10.92  0.00
1100 50   9 22.90  24.4  14.4  10.9 11.45  0.00
1100 50  10 30.78  27.2  11.1   0.0 15.39  0.00
```

Chose a location, i.e., Bloemfontein or Pretoria, and type start and end years. Specify the following values (or use the defaults): Minimum total amount of daily rainfall (or 8 mm), Minimum total duration of rainfall events (or 30 min), Maximum total duration of rainfall events (or 1440 min), Maximum rainfall intensity (or 2 mm/min), and Interval time (or 30 min).

Click **Generate** to calculate rainfall intensity. **Finished calculating intensity** will confirm that the rainfall intensity calculation has been completed. Click **OK**.

There are three output files for this process.

(1) The minute-by-minute rainfall file (this file is also the input file for the next process: calculating runoff.) (e.g., 1950_009.txt in Table 2) is based on each day. The each row of data describes year, DOY, hour, minute, rainfall amount (mm), and code for rainfall intensity (ignore!).

(2) The dimensionless rainfall intensity file (e.g., 19500009.txt in Table 3) is based on each day. The row describes year, DOY, cumulative dimensionless amount, and cumulative dimensionless duration.

(3) The day-by-day rainfall file (e.g., Out1950.txt in Table 4) is based on each year. The each row of data describes year, DOY, rainfall amount (mm), and rainfall duration (min.).

Table 2. An example of the minute-by-minute rainfall file (1950_009.txt)

1950	9	0	1	0.350	25
1950	9	0	2	0.350	25
1950	9	0	3	0.350	25
1950	9	0	4	0.350	25
1950	9	0	5	0.350	25
1950	9	0	6	0.350	25
1950	9	0	7	0.350	25
1950	9	0	8	0.350	25
1950	9	0	9	0.350	25
1950	9	0	10	0.350	25

Table 3. An example of The dimensionless rainfall intensity file (19500009.txt)

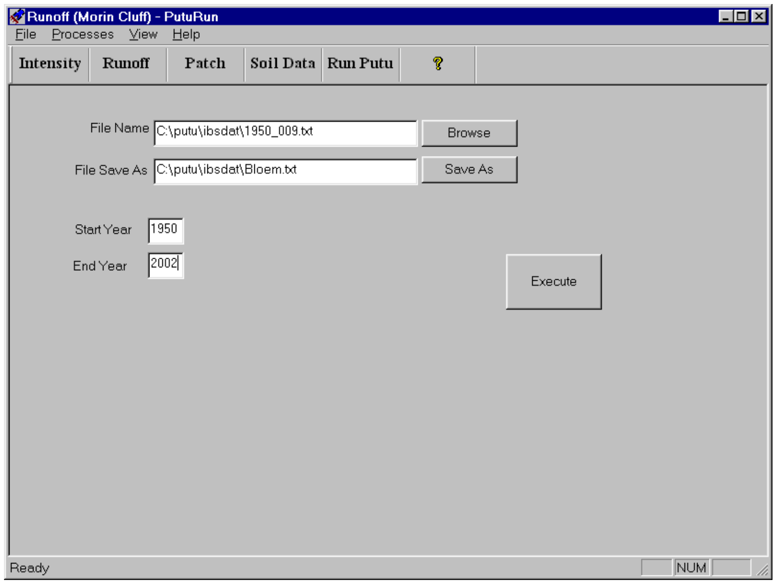
1950	9	0.000000	0.000000
1950	9	0.147143	0.963874
1950	9	0.294286	0.969207
1950	9	0.441429	0.982724
1950	9	0.588573	0.982901
1950	9	0.735716	0.983082
1950	9	0.882859	0.997202
1950	9	1.000000	1.000000

Table 4. An example of the day-by-day rainfall file (Out1950.txt)

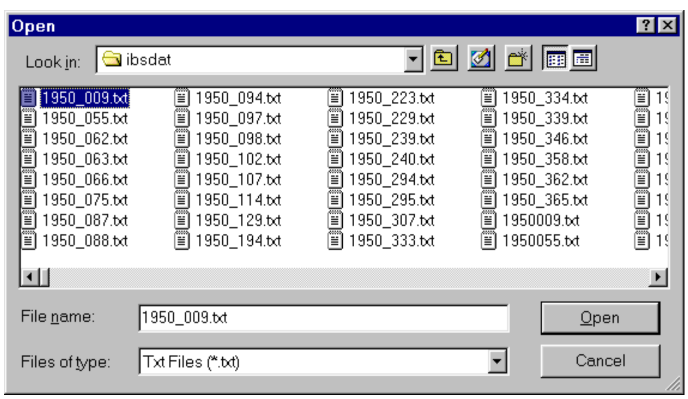
1950	9	10.90	204
1950	55	8.50	169
1950	62	10.10	342
1950	63	14.00	841
1950	66	14.00	686
1950	75	20.40	603
1950	87	20.30	270
1950	88	20.00	503
1950	94	11.10	263
1950	97	48.10	67
1950	98	9.30	335
1950	102	10.90	303
1950	107	20.50	473
1950	114	18.20	568
1950	129	9.50	197
1950	194	9.60	152
1950	223	8.00	226
1950	229	8.20	233
1950	239	20.90	102
1950	240	17.60	1042
1950	294	8.90	100
1950	295	40.90	809
1950	307	14.30	142
1950	333	23.40	463
1950	334	10.40	113
1950	339	23.60	135
1950	346	19.40	372
1950	358	11.10	393
1950	362	18.20	50
1950	365	42.90	645

Calculating runoff

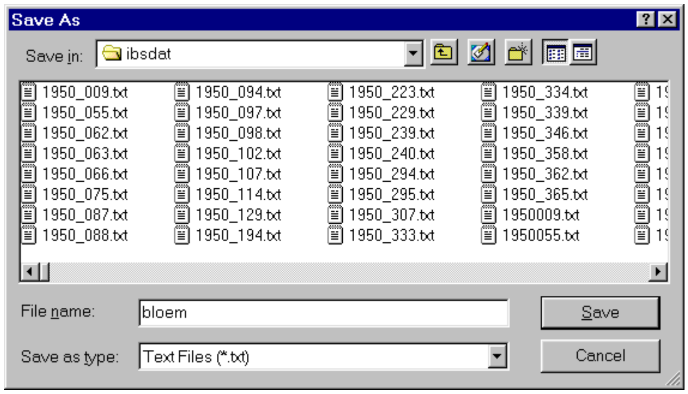
Choose **Runoff** from the menu.



Click **Browse** to open rainfall intensity files (the same file as the minute-by-minute rainfall file in the previous process: calculating rainfall intensity) in the folder c:\putu\ibsdat. Choose only one file (the program automatically uses all the files for a specific location.). Click **Open**. Return to the Runoff screen.

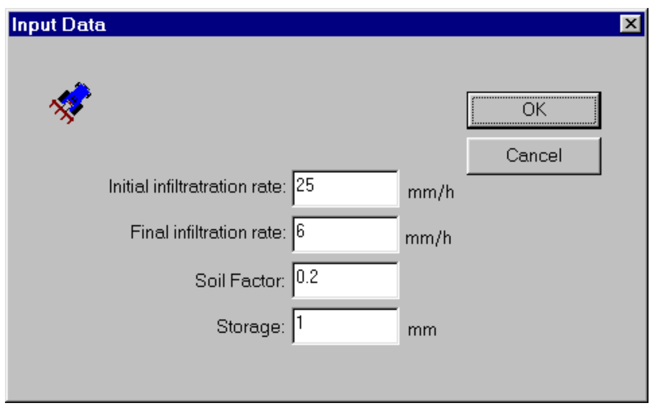


Click **Save As** and type a file name to which you want to save the outputs, which is situated in the folder c:\putu\ibsdat (e.g., bloem.txt). Click **Save**. Return to the Runoff screen.

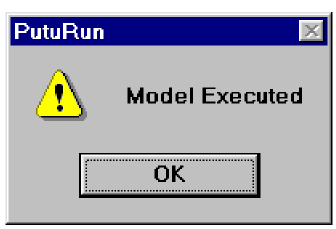


Click **Execute** to calculate runoff.

Specify the following values: Initial infiltration rate, Final infiltration rate, Soil factor, and Storage. Click **OK**.



Model Executed will confirm that the runoff calculation has been completed. Click **OK**.



There is one output file for this process.

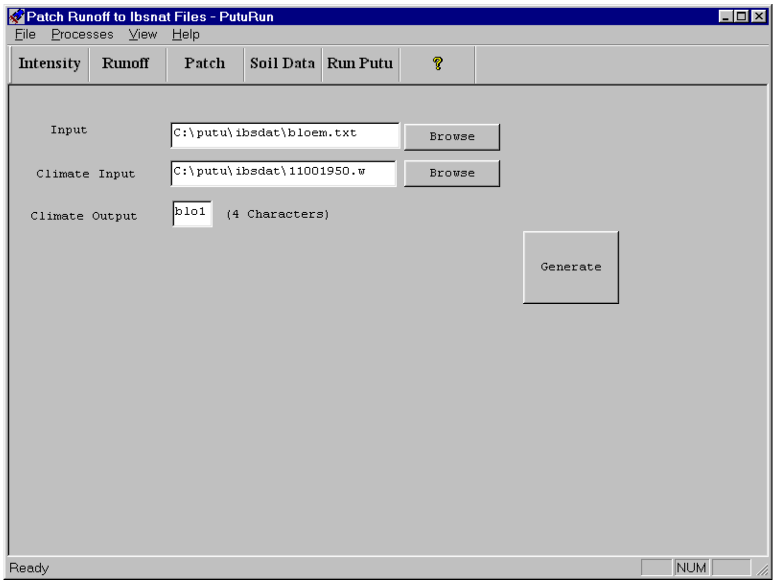
The day-by-day runoff file (e.g., bloem.txt in Table 5). The row describes input file name, year, DOY, runoff estimated, rainfall, and runoff measured (ignore!).

Table 5. An example of the day-by-day runoff file (bloem.txt)

1950_009.txt	1950	9	3.635	10.860	0.000
1950_055.txt	1950	55	0.000	7.890	0.000
1950_062.txt	1950	62	0.000	10.080	0.000
1950_063.txt	1950	63	0.000	13.860	0.000
1950_066.txt	1950	66	1.651	13.980	0.000
1950_075.txt	1950	75	4.592	20.370	0.000
1950_087.txt	1950	87	4.248	20.310	0.000
1950_088.txt	1950	88	2.664	19.980	0.000

Patching the runoff file to the climate file

Choose **Patch** from the menu.



Click **Browse** of the input. Choose the runoff file (the same file as the output file in calculating runoff: e.g., bloem.txt). Click **Open**. Return to the Patch screen.

Click **Browse** of the climate input. Choose the climate file (the IBSNAT file: e.g., 11001950.w). Click **Open**. Return to the Patch screen.

Type a climate output file name (4 characters) to which you want to save the outputs (e.g., blo1).

Click **Generate** to patch the runoff file to the climate file.

Finished Patching will confirm that the patching has been completed. Click **OK**.

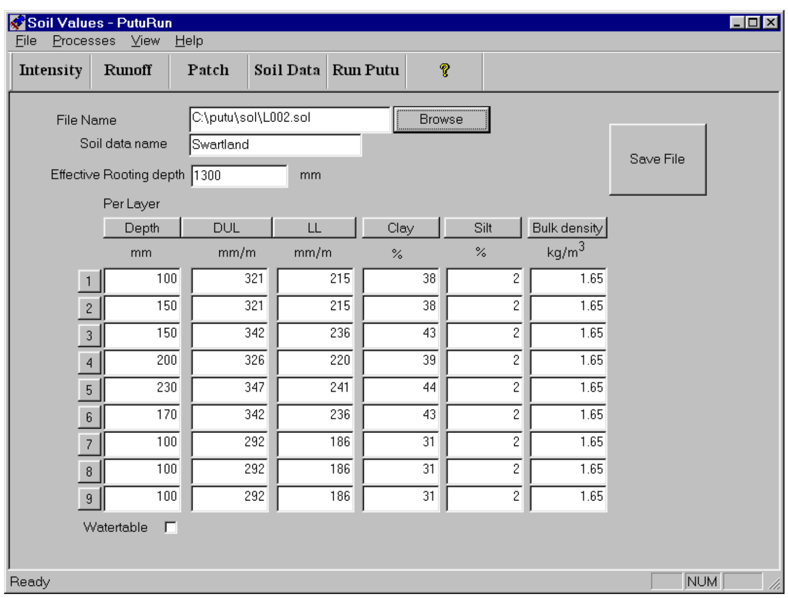
The climate file is IBSNAT format, but the weather station number (4 digits) is replaced by the 4 characters typed (e.g., blo11950.w in Table 6).

Table 6. An example of the new climate file (blo11950.w)

Blo1	-29.12	26.37	12.07	0.00			
Blo1	50	1	31.22	33.3	16.1	0.0 15.61	0.00
Blo1	50	2	31.52	33.9	15.6	0.0 15.76	0.00
Blo1	50	3	25.77	36.1	20.6	5.4 12.89	0.00
Blo1	50	4	17.23	28.3	18.3	0.8 8.62	0.00
Blo1	50	5	15.20	27.2	15.6	6.1 7.60	0.00
Blo1	50	6	23.72	26.7	15.6	5.5 11.86	0.00
Blo1	50	7	30.83	28.9	13.9	0.0 15.41	0.00
Blo1	50	8	21.83	28.9	17.2	1.1 10.91	0.00
Blo1	50	9	22.90	24.4	14.4	10.9 11.45	3.63
Blo1	50	10	30.78	27.2	11.1	0.0 15.39	0.00

Inputting soil data

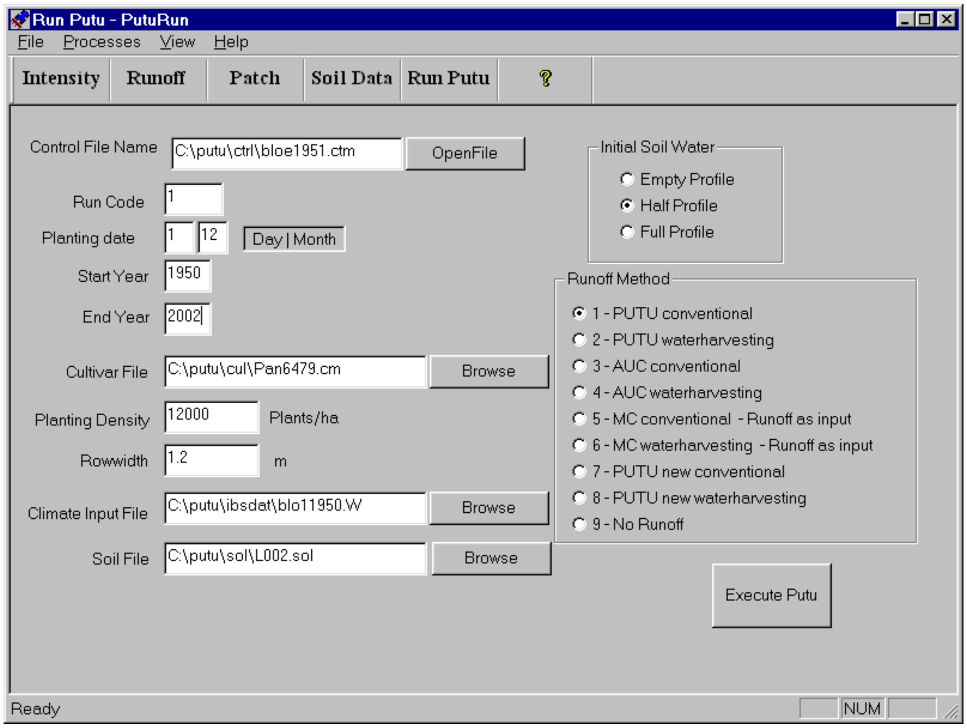
Choose **Soil Data** from the menu.



Specify file name, soil data name and effective plough depth. Input soil data of depth, DUL, LL, Clay, Silt and Bulk density (9 layers). Click **Save File** to save the soil data to the file in the folder c:\putu\sol.

<u>Running PutuMaize</u>

Choose **Run Putu** from the menu.



Click **Open File** to choose a control file (e.g., bloe1951.ctm) in the folder c:\putu\ctrl. Or change the first 4 characters of the control file name.

Specify Run code (any numbers; ignore!), Planting date, and start and end years.

Click **Browse** to choose a cultivar file in the folder c:\putu\cul (e.g., Pan6479.cm).

Specify Planting density and Row width.

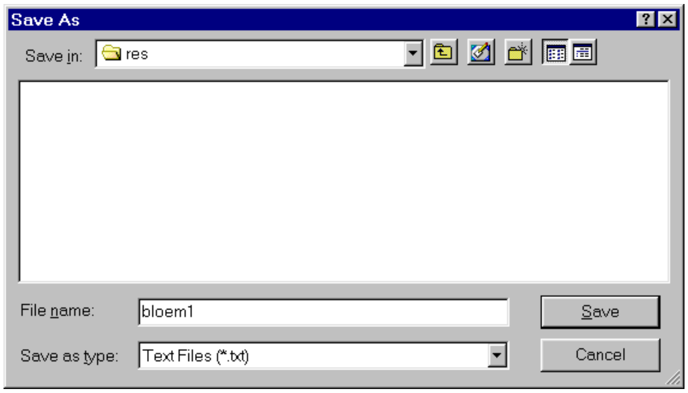
Click **Browse** to choose a climate input file (the program automatically uses all the files for a specific location.) in the folder c:\putu\ibsdat (the same file as the file created in patching the runoff file to the climate file: e.g., blo11950.w).

Click **Browse** to choose a soil file in the folder c:\putu\sol (the same file as the file created in inputting soil data: e.g., L002.sol).

Choose an initial soil water content, i.e., empty profile, half, profile or full profile. Choose a runoff calculation method, i.e., PUTU conventional, PUTU water harvesting, AUC (the area under the rainfall intensity curve model) conventional, AUC water harvesting, MC (the Morin & Cluff model) conventional, MC water harvesting, PUTU new conventional, PUTU new water harvesting, or No runoff.

Click **Execute Putu**.

Type a file name to which you want to save the outputs in the folder c:\putu\res (e.g., bloem1.txt).



Finished will confirm that the Putu run has been completed. Click **OK**.

The output file of the yields (e.g., bloem1.txt in Table 7) can be imported into a spreadsheet.

Table 7. The yield output file (bloem1.txt)

1951	3848
1952	3138
1953	4347
1954	3905
1955	2628
1956	3802
1957	4380
1958	975
1959	3482
1960	4104
1961	2319
1962	2533
1963	3469
1964	2231
1965	3974
1966	4387
1967	4380
1968	184
1969	3411
1970	448
1971	3326
1972	4381
1973	3234
1974	4385
1975	2451
1976	3282
1977	4382
1978	2207
1979	1120
1980	2263
1981	4386
1982	4153
1983	855
1984	267
1985	2976
1986	670
1987	1459
1988	2702
1989	3363
1990	3402
1991	4386
1992	0
1993	2286
1994	4387
1995	1694
1996	4374
1997	2465
1998	4384
1999	217
2000	4383
2001	148
2002	2222

5. References

Brown, B.W., Lovato, J. and Russell, K., 1997. DCDFLIB (Double precision Cumulative Distribution Function LIBrary), Library of C routines for cumulative distribution functions, inverses, and other parameters, Version 1.1. Department of Biomathmatics, M.D. Anderson Cancer Center, The University of Texas, Huston, TX. Source code: ftp://odin.mdacc.tmc.edu/pub/source/dcdflib.c-1.1.tar.gz

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