NATURAL RESOURCES SYSTEMS PROGRAMME
PROJECT REPORT[1]

DFID Project Number

> **R8088A**

Report Title

> Agro-meteorology and hydrology.
>
> Annex B23 of the Final Technical Report of project R8088A.

Report Authors

> Mahoo, H.F. and Tumbo, S.D

Organisation

> SWMRG, Sokoine University of Agriculture, Tanzania

Date

> 2005

NRSP Production System

> Semi Arid

TABLE OF CONTENTS

LIST OF FIGURES

5. Agro-meteorology and Hydrology

Objectives of the module

> **Having completed this exercise you will be able to:**
> - Generate missing rainfall data given historical data of a station
> - Establish the rainfall – runoff relationships for selected sites

Requirements for the module

> - Computer with Microsoft Windows Operating Systems (Windows 98, 2000, XP)
> - Spreadsheet and word processing packages (Microsoft Excel and Microsoft Word)
> - PARCHED – THIRST Model (Version 2.3)
> - 35 years weather data for a Met Station eg. Morogoro

5.1   Formation of Precipitation

Moisture is always present in the atmosphere, even on cloudless days. For precipitation to occur, some mechanism is required to cool the air sufficiently to bring it to or near saturation. The large scale cooling needed for significant amounts of precipitation is achieved by lifting the air. This is accomplished by convective systems resulting from unequal radiative heating or cooling of the earth's surface and atmosphere or by convergence caused by orographic barriers. Saturation, however, does not necessarily lead to precipitation.

5.1.1   Measurement of Rainfall

All forms of precipitation are measured on the basis of the vertical depth of water that would accumulate on a level surface if the precipitation remained where it fell. In the metric system, precipitation is measured in millimeters. The instrument commonly used is the rain gage.

5.1.2   Precipitation - gage network

The spatial variability of precipitation and intended uses of the data should determine network density. Relatively sparse network of stations would suffice for studies of 1arge general storms or for determining annual averages over large areas of level terrain. A very dense network is required to determine the rainfall pattern in thunderstorms. The probability that a storm center will be recorded by a gage varies with network density. A network should be planned to yield a representative picture of the area distribution of precipitation. On the other hand, the cost of installing and maintaining a network and accessibility of the gage site to an observer are always important considerations.

5.1.3   The analysis and presentation of rainfall data

Hydrologists' interest in precipitation data relates to engineering design; water supply and river forecasting, watershed management and research. The data are usually subjected to analysis of frequency characteristics, extremes, regression and physical relationships. Some of the methods and problems relating to data interpretation and processing are discussed in this section.

5.1.4   Climatological records

The quality and completeness of records should be considered in analysis. Homogeneous, complete series are required for many studies, but are not always available. The observer, the location and exposure of instrument, the type and shielding of instruments may change from time to time, thereby necessitating checks on homogeneity. Observational errors are probably less common in current publications, because of present quality control methods. However, historic data may require close scrutiny and adjustment.

5.1.5   Estimating missing data

Missing rainfall data may be estimated from values measured at about three other locations or index stations, near and evenly spaced around the station with the missing record. If the normal annual rainfall at each of the index stations is within 10 percent of that for the station with the missing record, a simple arithmetic average provides an estimate.

If the normal annual rainfall at any of the index stations differs from that at the station in question by more than 10 percent, the Normal Ratio Method is used. In this method, the amounts at the index stations are weighted by the ratios of the normal annual precipitation values. That is, rainfall P_x at station X is

$$P_X = \frac{1}{3}\left[\frac{N_X}{N_A}P_A + \frac{N_X}{N_B}P_B + \frac{N_X}{N_C}P_C\right] \hspace{3cm} (2)$$

Where

Px = Rainfall of the station with missing data

PA, PB, PC = Rainfall at the index stations

NA, NB, NC = Normal annual precipitation at the index stations

Multiple linear regressions will yield an equation of the form

$$P_X = a + b_A P_A + b_B P_B + b_C P_C \hspace{3cm} (3)$$

Where a should be near zero and the bs' will approximate the three coefficients of Equation (1) divided by 3. The advantage of the regression approach is that it allows for some weighting of the stations and adjusts, to some extent, for departures from the normal ratio assumption of Equation (1).

If a large amount of data must be estimated, random error term should be added to the equation. In this term, t is normal random number with mean of zero and standard deviation. of 1, and Sy is the standard error of estimate of Px. Inclusion of the term recognises the departures from the regression and maintains the standard deviation of the estimated values of Px near the observed standard deviation.

5.2 PARCHED-THIRST Climate Generator

If sufficient historical data are not available, the PARCHED-THIRST Climate Generator can be used to generate weather variables at a site when only rainfall data are available, and if there are periods of missing data in weather records, it can be used to 'fill in' the gaps.

The PARCHED-THIRST Climate Generator works by extracting the statistical properties of historical weather data and using these, in combination with random number generators to produce novel series of weather data with the same statistical properties as that which was input. It is important to realise that it is in no way a weather forecasting tool and that the weather it generates takes no account of long-term climate change.

5.2.1 Input

The model obtains the necessary statistical parameters from one of the following three ways:

- Historical data - as with any statistical method, the larger the sample (i.e. the number of years of weather data at a site), the better will it represent the population from which it is taken (i.e. the long-term weather at that site).
- Default weather parameter files - the PARCHED-THIRST Climate Generator is supplied with weather parameter files for a number of sites in Tanzania.
- User-defined weather parameter files - these can be created from historical data. In future, it will be possible to use the monthly averages of rainfall, temperature, etc. to generate daily weather (albeit with limited reliability) but this capability is still being developed.

5.2.2   Output

It can generate two different types of weather data depending upon the data available:
- Full agro meteorological weather files - this is the generation of the full range of variables required by PT software.
- Rainfall dependent weather files - in many areas, rainfall data have been collected for long periods of time while other agro-meteorological data have only been recorded in recent years. To allow the full potential of these long-term rainfall records to be realised, the Climate Generator can use the statistical properties of the recent agro-meteorological data to realistically generate the rest of the weather variables in the years for which only rainfall data are available.

5.3   Rainfall – Runoff Relationship

5.3.1   Surface runoff phenomena

Depending, upon the rate at which rain falls, water may either infiltrate into the soil or accumulate and flow from an area as surface runoff. If the intensity of rainfall is less than the rate of infiltration, all water will enter the soil profile. Conversely, when the intensity of rainfall is greater than the rate of infiltration, a sequence of events occur which ultimately will produce surface runoff.

Excess water produced by a high intensity of rainfall must first satisfy soil and vegetal storage, detention and interception requirements. When the surface depressions are filled, surface water then begins to move down the slopes in thin films and tiny streams. When the rain is particularly intense and prolonged, or both, the surplus runoff becomes large and the stream and river channels cannot accept all the water suddenly arriving. They become filled and overflow causing flooding and damage to property. The disposition of storm rainfall is shown in Figure 5.1.
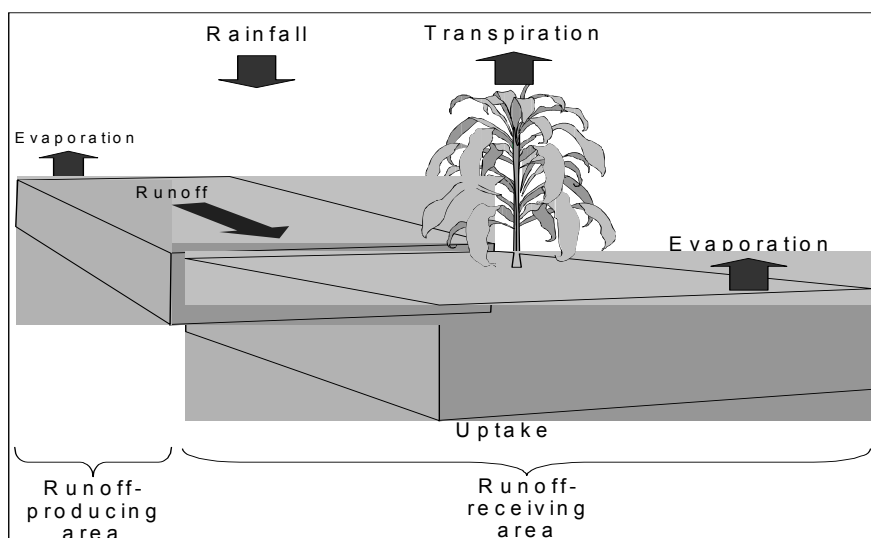

Figure 5.1. The hydrological components of a conceptual rainwater harvesting system

5.3.2   Catchment characteristics and their effect on runoff

Catchment area
The topographic water divide usually, but not necessarily bound the catchment area. Because of the underlying geology, it is perfectly possible for areas beyond the divide to contribute to a catchment.

Main stream length
This is measured in kilometres from the gauging station or catchment outfall. When measuring from maps it is normal to use a standard routine to remove subjectivity (e.g. set dividers at 0.1 km on a 1:25000 scale map)

a)   Slope of Catchment
The more the steepness of the ground surface the more rapidly will surface runoff travel. Also both the time of concentration and time to peak will be short. Infiltration capacities tend to be lower as slopes get steeper; since vegetation is less dense and soil more easily eroded, thus accentuating runoff.

b)   Catchment orientation
Orientation is important with respect to meteorology of the area in which the catchment lies. If the prevailing wind and lines of storm movements have a particular seasonal pattern, as they usually have, the runoff hydrograph will depend to some degree on the catchment orientation within the pattern.

Climatic factors
The main effect of climate is in rainfall intensity and duration. Rainfall intensity has a direct bearing on runoff since once the infiltration capacity of the soil is exceeded; all the excess rain is available and flows to the surface water courses.

5.3.3   Rainfall – Runoff correlation

While there is a general cause – and -effect relationship between rainfall and the resulting runoff, it is not a direct one. By the time evaporation, interception, depression storage, infiltration and soil moisture deficiency are taken into account and the resulting residual rainfall at various intensity applied to catchments that vary in size, slope, shape, altitude, subsurface geology and climate, the relationship must include extreme values that defy rational correlation, at least in the short time.

Notwithstanding the foregoing, it may be possible to establish an empirical relationship for particular catchment based on annual precipitation and runoff. To do this it is a 12 - month period starting and finishing at the time of seasonal minimum flow. If precipitation and runoff are plotted against each other as catchment depths, a correlation like the one shown in Figure 5.2 is obtained.
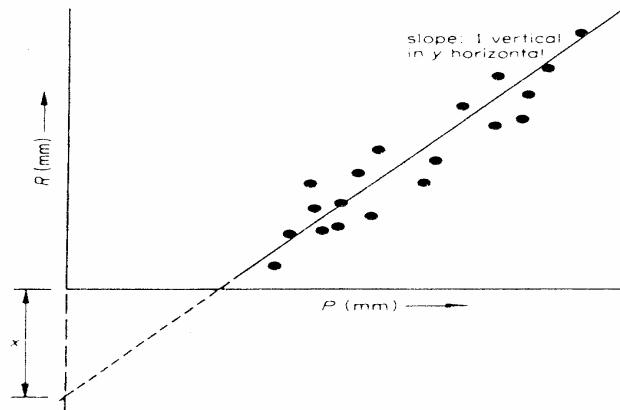
Figure 5.2. Rainfall – Runoff Correlation

In many tropic and humid climates, a straight-line relationship is generally found i.e.

$$R = \frac{P}{y} - x \qquad (4)$$

        Where P = annual precipitation
              R = annual runoff
              x and y are as shown in Figure 5.2

5.4 PT Model Software

PARCHED THIRST is an acronym for Predicting Arable Resource Capture in Hostile Environment During The Harvesting of Incident Rainfall in Semi Arid Tropics. The model was developed to simulate the rainwater harvesting system in semi arid tropics. It simulates the runoff process, soil-water movement and the crop growth and yield in response to daily climatic data. It is a process-based model with a user-friendly interface. PARCHED-THIRST (PT) is a lumped parameter model where the landscape is divided into units of land assumed to be homogeneous landscape; this is referred to as profile in the model. The collection of these profiles forms a system, which can either, be rainfed or rainwater harvesting depending on the number of profiles. Rainwater harvesting system is represented by more than one profiles where one or more profiles represent the runoff generation areas and the other represent the runoff receiving area and the only transferable mass between these profiles is the surface runoff.

At the system level the inputs to the model are weather variables (Rainfall, Evaporation, Maximum and Minimum temperature, Relative humidity, Wind speed and Radiation). Other inputs at the system level include location and latitude. Criteria for sowing (timing) are entered at the system level, these can be user defined or predicted by model. In case of user defined, the input is the date of sowing for a particular season. The number of years of simulation is entered at the system level together with start date of the season and number of seasons to be simulated.

The inputs at the profile level are crops, weeds, soil properties and soil surface characteristics. Soil properties inputs to the model include soil layer depth and initial soil moisture content for each layer, soil type (texture), soil fertility equilibrium rate, soil strength which determines the resistance of soil to root growth, soil drainage parameter which determines rate at which water drains out of the soil profile and macro pores distribution and flow rate. Soil surface parameters inputs are bund height if storage is allowed, percentage of soil evaporation

reduction if there is any surface treatment like crop cover, and mulching, area represented by the profile and slope of the profile.

Given all these input, the PT model is capable of simulating crop yield. Other parameters that can be found in the simulation output summary file include Surface Runoff, Evapotranspiration, dry matter accumulation and grain weight gain.

The PT Model will be used in the following two (2) exercises. The first exercise involves the generation of missing climatic data given historical data of the same station. The second exercise seeks to establish the rainfall/runoff relationship from simulation output file.

5.4.1 Exercise 1: Generating Missing Rainfall Data

Step One: Starting the PT Model and accessing the climatic generator
- Double-click on the PTv2.3 model icon or from the Start task bar go to Programs and from the program list click PTv2.3. The PTv2.3 main window and Welcome screen will appear as shown in Figure 5.3.
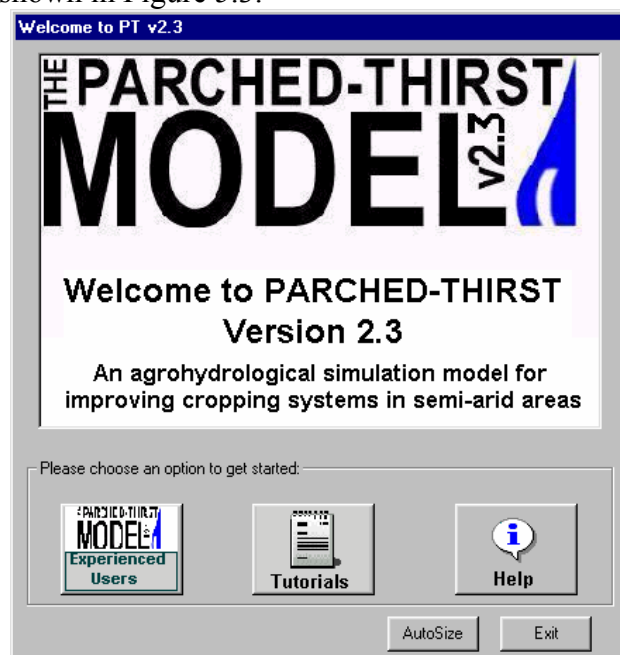
Figure 5.3. Welcome screen of the PT Model

- On the Welcome screen click on the icon Experienced User to be taken straight to the main system window of PTv2.3 as shown on Figure 5.4.
- On the menu bar click on Tools and from the Tools submenu select and click Climate Generator. The Climate Generator main window will appear as in Figure 5.5.
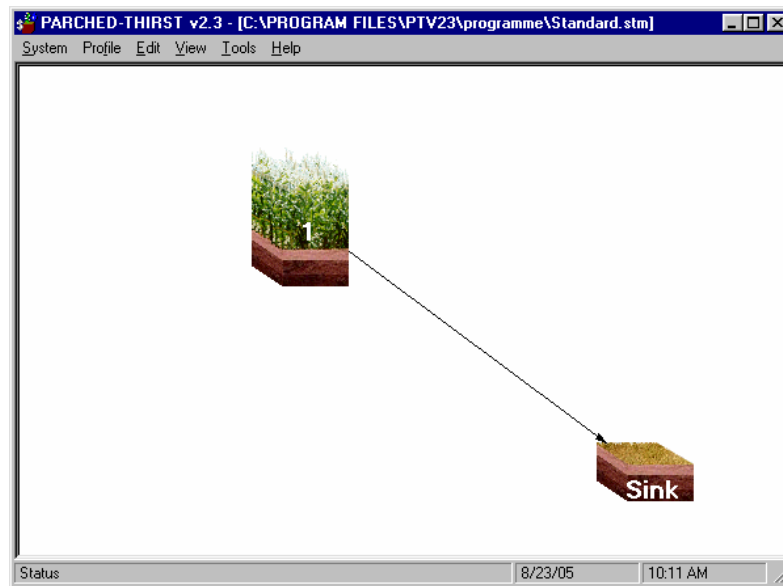
Figure 5.4. PT Model Main window
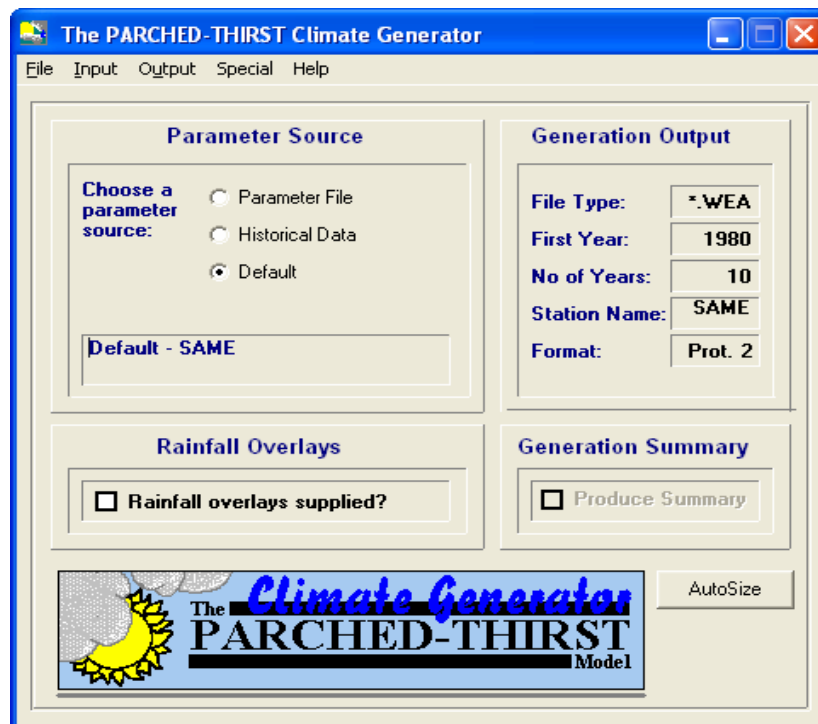
Figure 5.5. Climate Generate Main Window

Step two: Specify the input data file
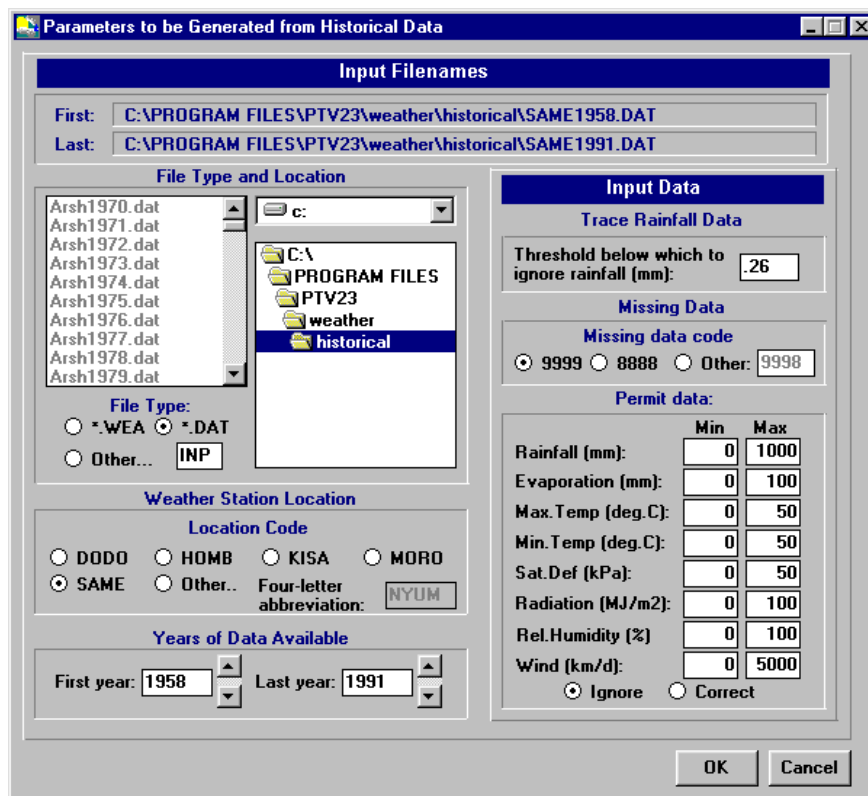- On the Climate Generator menu, click on the word Input and a drop-down menu will appear.

Figure 5.6. Climate Generator input window

- Click the Historical item on the drop down menu to indicate that the parameter source will be our historical data file. The Parameter File Window will then appear as shown in Figure 5.6.
- Under File Type, choose the option button labelled *.DAT to indicate that our file names end in. DAT. A list of files of this type will appear in the left hand box.
- Under Location Code (within Weather Station Location), choose the option button labelled Other… The text box after the Four-letter abbreviation will be active. Type CGEN in this textbox..
- Under Years of Data Available, click on the arrows to change the First year to 1971 and the Last year to 1980. The names of the first and last files should now be shown in blue in the two textboxes (Labelled First and Last) at the top of the window.
- Under Permit data choose the Correct option.
- Click OK to return to the Climate Generator window.

We have indicated the source of the data. Now we need to tell the programme how much data to generate and where to store these data.

Step Three: Specify Output File Settings
- On the Climate Generator window menu click on Output.
- On the output sub menu click on Evaporation. The Evaporation data window similar to Figure 5.7 will appear.
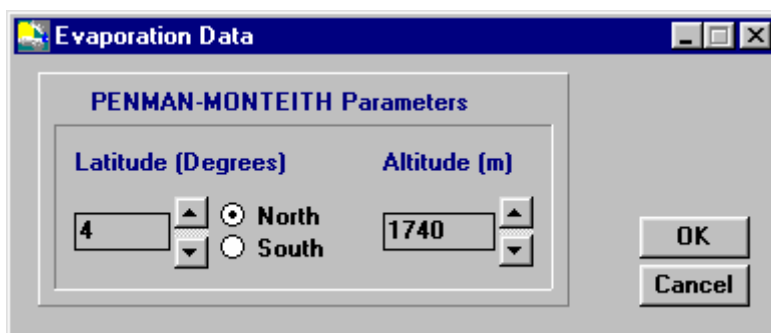
Figure 5.7. Evaporation data window

- Set Latitude to –6 and Altitude to 520m (Morogoro). Click OK to go back to the Climate Generator main window.
- Select Output from the window menu and on the output sub menu click on Create parameter file… to open the Create a weather parameter file… window as shown in Figure 5.8.
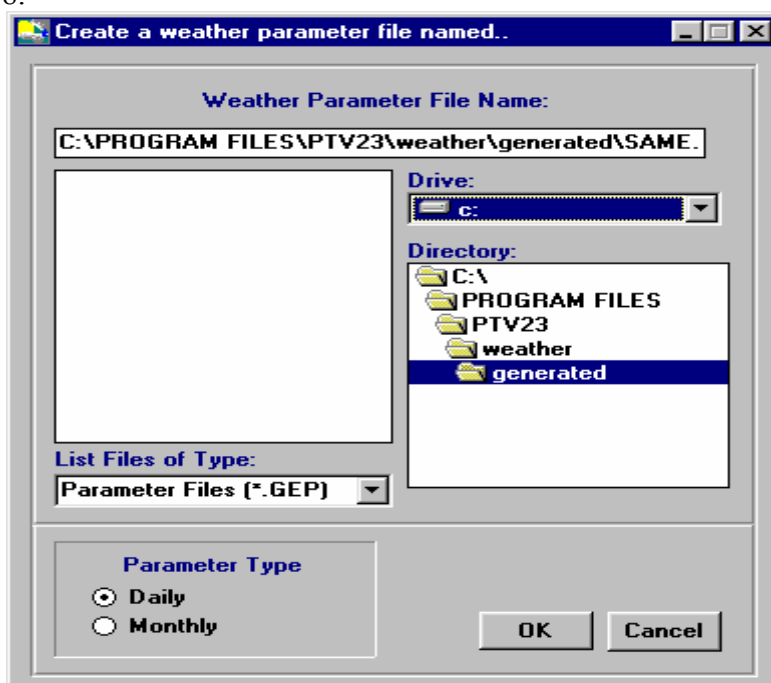

Figure 5.8. Weather parameter file

- Under Weather Parameter File Name, change whatever in the textbox to C:\PROGRAM FILES\PTV23\weather\generated\CGEN.GEP.
- Under Parameter type check Daily option button and click OK. You will be taken back to the Climate Generator input window you completed in Step two.
- Verify the Climate Generator input window to check if the parameters you specified in step two were not altered.
- Rectify any changes if any and click OK.
- A Data input error message box will appear as shown in Figure 5.9 below.
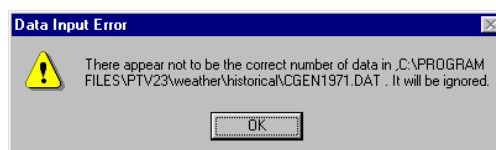
Figure 5.9. Data Input Error

- Click OK to continue. You will see a series of progress bars similar to that of figure 5.10.
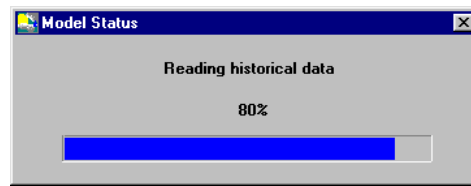
Figure 5.10. Progress Bar

- Wait until another message appears (Figure 5.11), indicating the location where the .GEP file is saved. Click OK to return to the Climate generator main window.
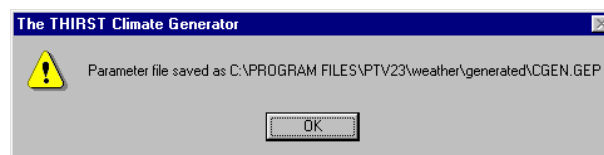
Figure 5.11. Location of the parameter file

Step Four: Specify the Output File Location
- From the Climate generator menu, select output and click files.. the simulation Option window similar to that of Figure 5.12 will appear.
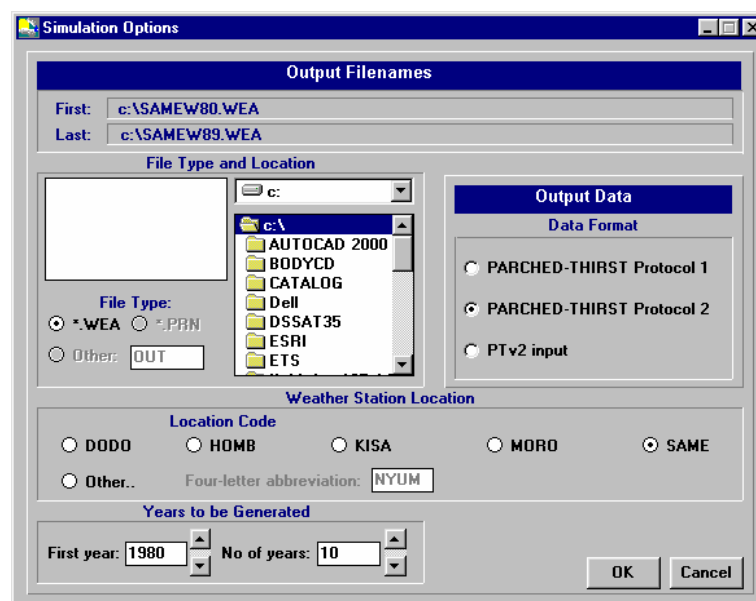
Figure 5.12. Climate Generator output window using Historical *.DAT Files

- Under file type and location choose *.WEA
- Browse to the folder C:\Program files\PT v2.3\Weather\Generated\ as shown in Figure 5.13. That is where the generated data files will be stored.
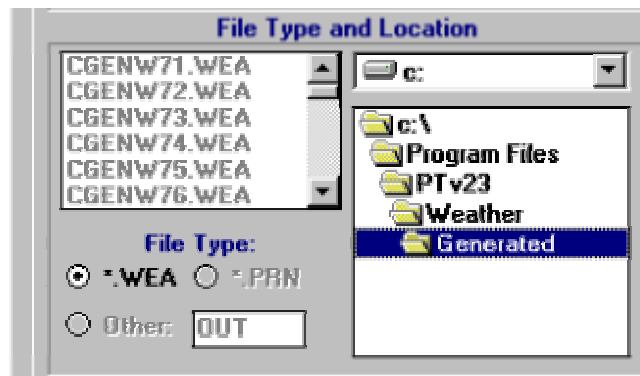
Figure 5.13. Location of the output data files

- Under Output Data, choose PTv2 input option.
- Under Location Code check the other button and type CGEN in the Four-letter abbreviation text box.
- Under Years to be Generated, change First Year to 1971 and No of years to 10. The output file window should then appear as shown in Figure 5.14 below.
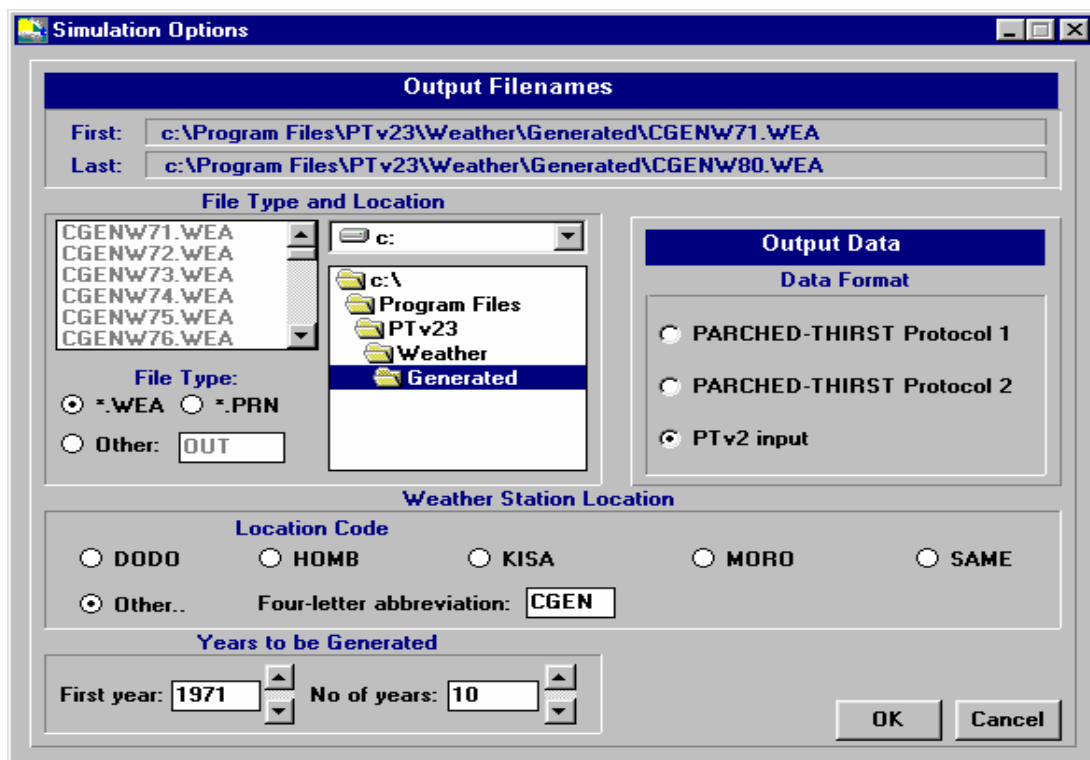
Figure 5.14. Climate Generator output window (with all settings)

- Click OK to return to the Climate Generator window. Now we can run the Climate Generator to produce the data.

Step Five: Running the Climate Generator
- Click on the word File on the Menu bar and select save from the drop-down menu. In the File name textbox, type Moro 1971_1980.GEN as shown in Figure 5.15.
- Click on Save to continue.
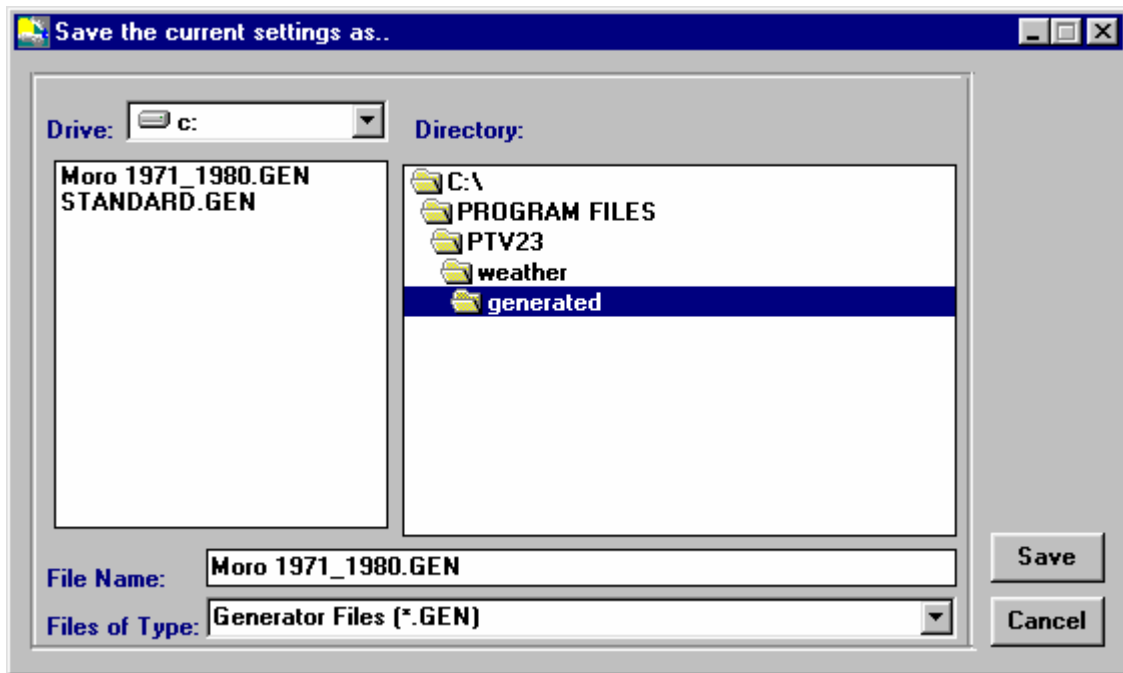
Figure 5.15. Saving the Climate generator file

Now we can run the Climate Generator to produce the data. However, it would be nice to see a comparison between the data we have input and the data the model is going to generate. To achieve it check Produce Summary check box on the Climate Generator window (under GENERATION SUMMARY).

- Finally, go to the File drop-down menu and select RUN. You will see the data input error of Figure 5.16. Click OK to continue.
- A status box (Figure 5.17) indicates the progress. At the end of the simulation, you will be asked whether you wish to see a comparison of observed and generated data.
- Answer Yes and the Generation Summary Window of Figure 5.18 will appear.
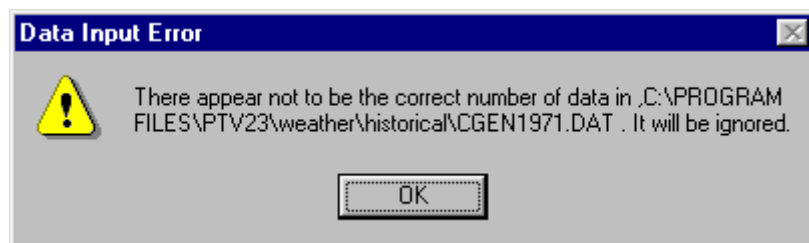
Figure 5.16. Data Input error
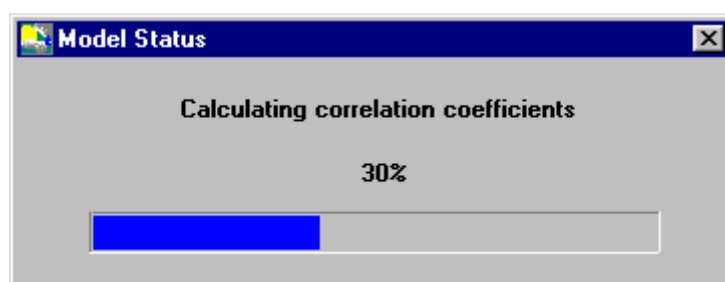
Figure 5.17. Progress bar

By clicking on the buttons to the right (Say Rainfall), and the option buttons at the bottom of the window (Mean monthly daily rainfall (mm), you can see a comparison of various aspects of the historical and simulated data as shown in Figure 5.18.
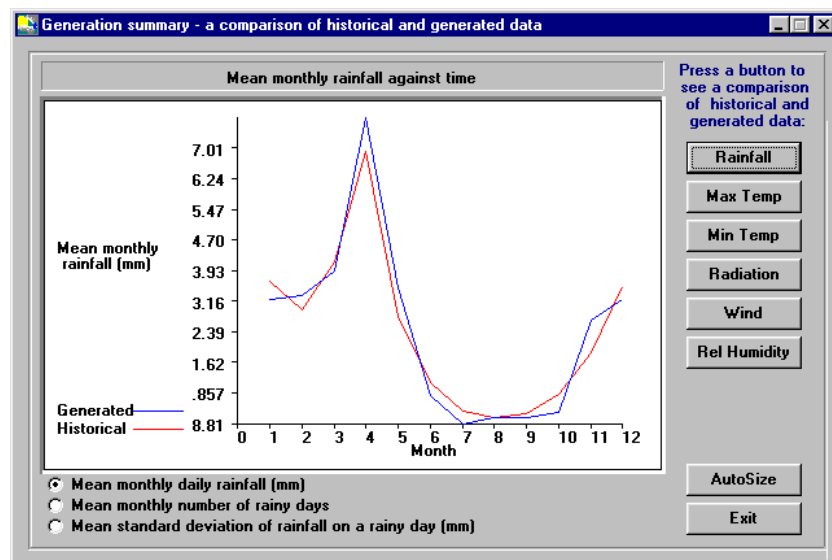
Figure 5.18. Generation summaries

▪ When you have finished press Exit. You will then be asked whether you wish to generate more data. Answer No and you will be returned to the Main Window.

You have now generated 10 years of data for Morogoro Station including 1977 data, which was missing.

Step Six: Accessing the generated rainfall data
The synthetic data generated were saved in C:\Program files\PT v2.3\Weather\Generated\ with names CGENW71.WEA, CGENW72.WEA, … and CGENW80.WEA. They are then in .WEA format and they can be opened with Microsoft Excel.
▪ Open Microsoft Excel
▪ From the File menu click Open or click on the Open toolbar. Go to the folder C:\Program files\PT v2.3\Weather\Generated\ and in the Files of type list box, select All files (*.*) as shown in Figure 5.19.
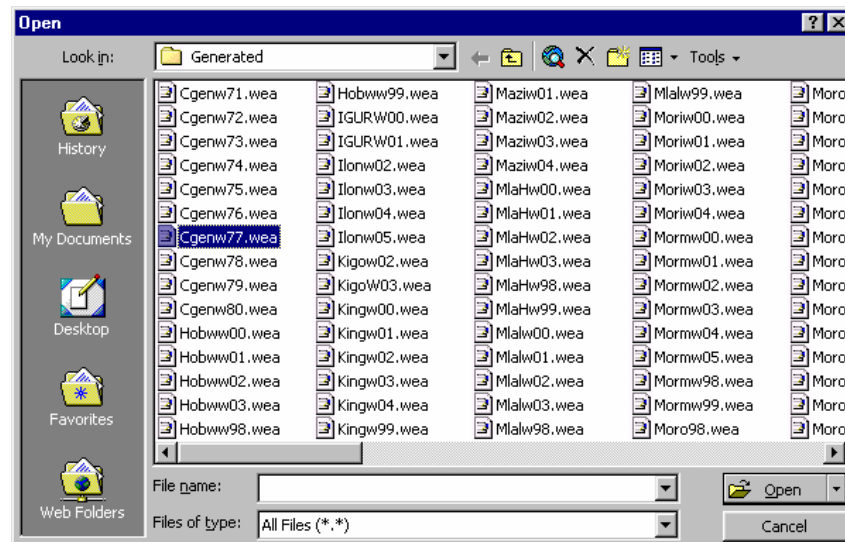
Figure 5.19. Open file window

- Select the file CGENW77.WEA and click the on Open. You will see a Text Import Wizard window similar to that of figure 5.20.
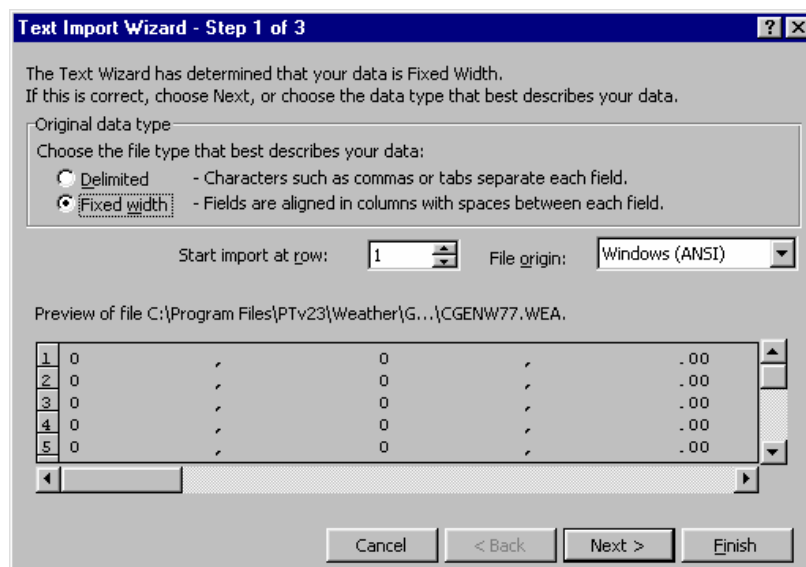

Figure 5.20. Text Import Wizard - Step 1 of 3

- Select the Delimited option and click next.
- On the next Text import Wizard - step 2 of 3, check the Comma Check Box and click Finish to view the generated data.

The data are arranged in columns (365 or 366 rows for leap years) in the following order: Null, Null, Rain(mm), Evap(mm), MaxT(C), MinT(C), Null, Null, Null, SatDef(kPa), Radn(MJ/m2), RelHum(%), Wind(km/d); i.e. the rainfall data is displayed in column C which is highlighted in Figure 5.21 below.

- To open other generated files, follow the same procedure. Also, to open the .DAT files used to generate data the same procedure applies except that On the Text import Wizard - Step 2 of 3window you should check the Space Check Box instead of the Comma Check box.

Figure 5.21. Generated data file (CGENW77.WEA) opened with MS Excel.

5.4.2 Assignment

- Open the synthetic generated data files and copy the rainfall columns for every year into a new Excel workbook. Calculate the mean daily and the mean monthly rainfall.
- Open the original data files (.DAT) files used to generate data and copy the rainfall columns (without column headings) into another sheet on the same workbook. Calculate the mean daily rainfall and the mean monthly rainfall.
- Plot generated mean daily rainfall and actual mean daily rainfall (January to April) and February in one chart and comment on your results. You graph should be similar to that shown in Figure 5.22.
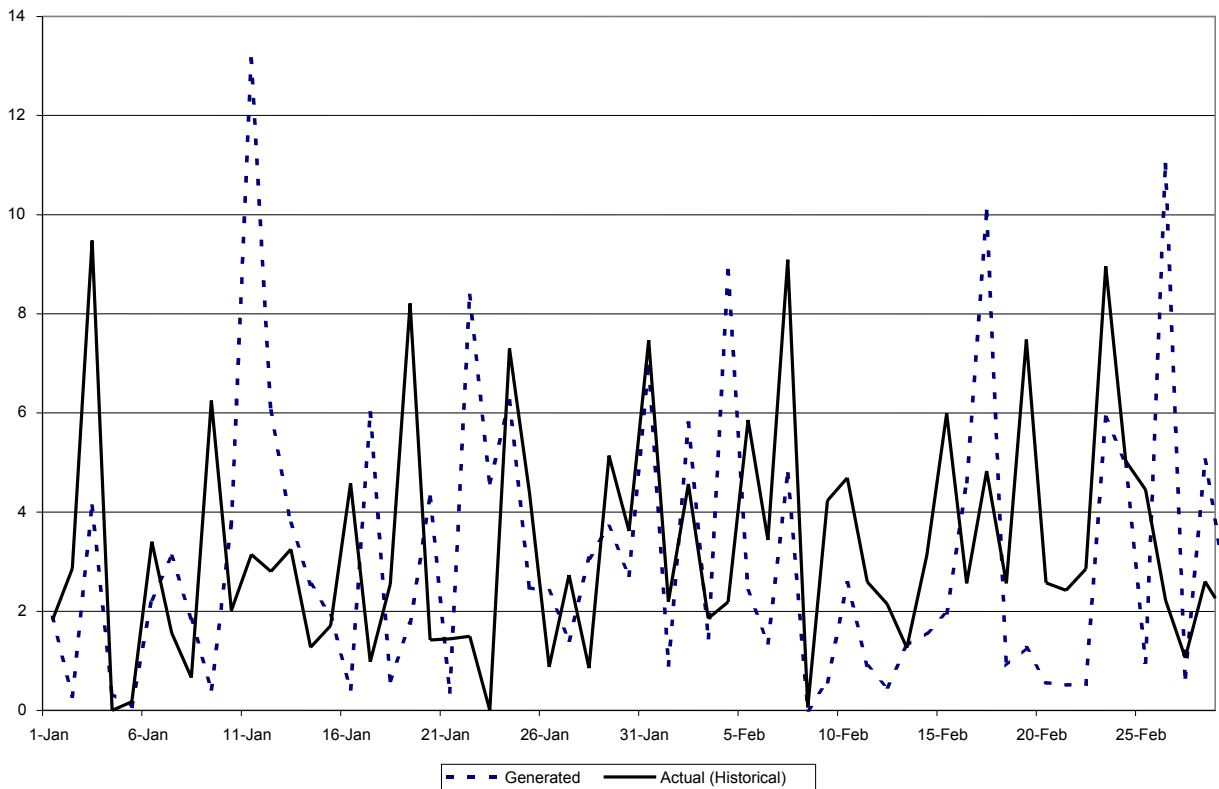- Plot also means monthly rainfall.

Figure 5.22. Actual Vs Generated Daily Rainfall

5.4.3 Exercise 2: Investigating Runoff Generation

Step One: Starting the PT Model
- Double-click on the PTv2.3 model icon or from the Start task bar go to Programs and from the program list click PTv2.3. The PTv2.3 main window and Welcome screen will appear.
- On the Welcome screen click on the icon experienced user to be taken straight to the main system window of PTv2.3.
- Go to the Systems menu and select Open. Select the file "Rainfall Runoff VLAB" and click open.

Step two: Specify System
- On the main windowpane select System and click on Properties to open the System Properties window of Figure 5.23.

Figure 5.23. System properties window

Set the following properties as follows:
  Timing (Click on the Timing button)
  – Number of years: 35
  – Number of seasons: 1 per annum
  – Season start date: 1st January 1971
  Sowing (Click on the Sowing button)
  – Sowing decision: Defined
  – Sowing date: 1st March
  Site (Click on the Site button)
  – Location: Morogoro
  – Latitude: -6
  Weather (Click on the Weather button)
  – File stem: morx
  – File type: Standard
Click OK to continue

Step three: Specify profile settings
Double click on the profile 1 icon or, right click on profile 1 and select Properties of profile
(See Figure 5.24). You will be taken to the profile properties window of Figure 5.25.
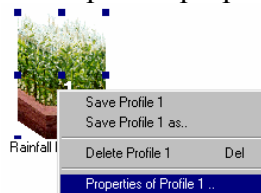

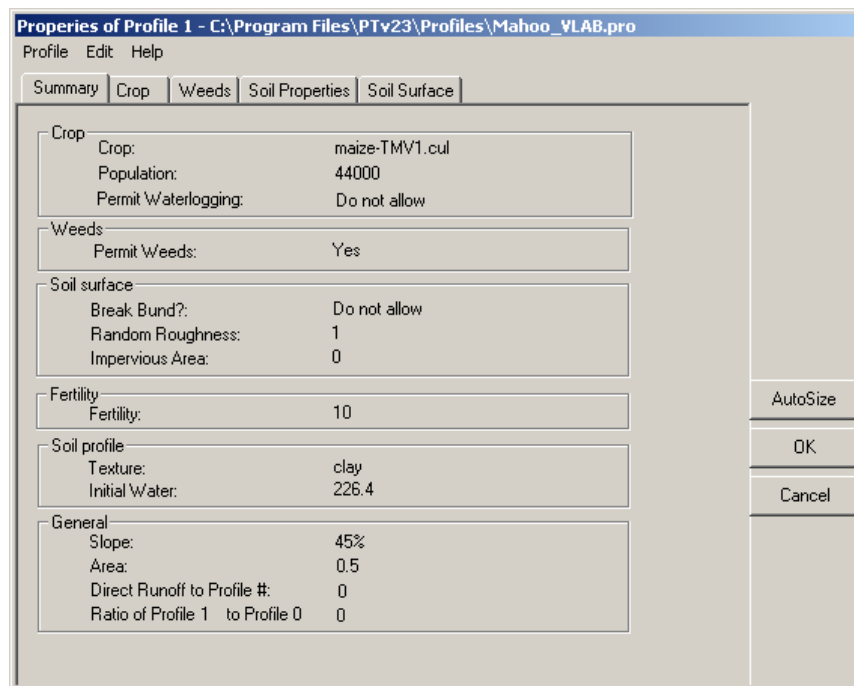Figure 5.24. Opening the profile properties window

Figure 5.25. Profile 1 Properties window

- Click on Soil surface option to verify the following settings:
  Surface storage: The Area is bunded and the Release ponded water checkboxes should remain unchecked.
  Surface characteristics: Impervious area: 0%
                                       Reduce Soil Evaporation by: 0%
  Topography: Area represented by profile: 0.5 ha
                              Slope of area: 45%
- Click on OK to continue

Step Four: Running Simulation
- Go to the system menu and click on Save.
- Go again to the system menu and click on RUN. You will be prompted to specify simulation summary and daily output file name as shown in Figure 5.26.
- Name the simulation summary file as RainfallRunoffSumary and the simulation daily output file as RainfallRunoffDaily.
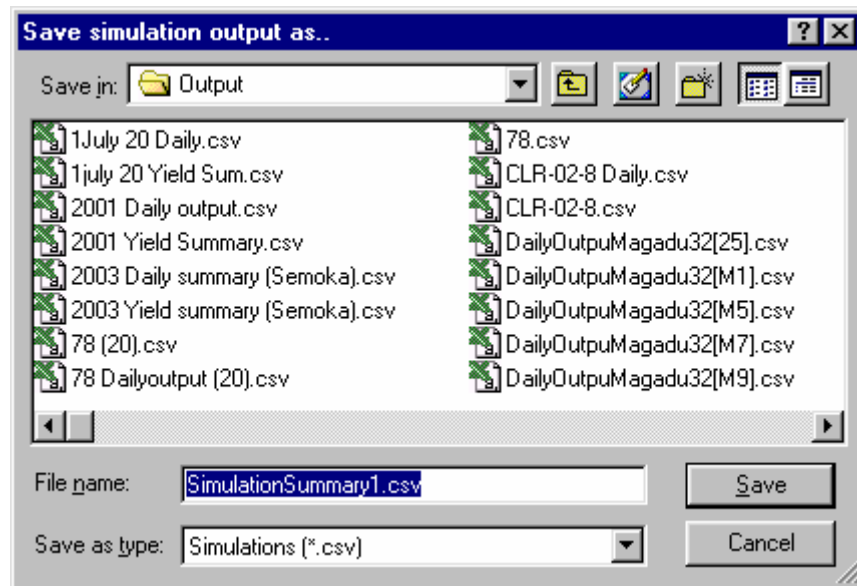
Figure 5.26. Saving Simulation summary

- On the see simulation graphics? Dialogue box click on Yes (Figure 5.27) to view simulation graphics.
- Under Speed of simulation (Figure 5.28) select Fast
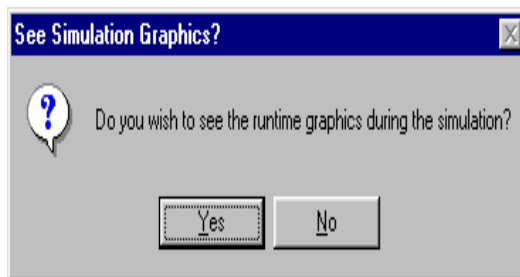- Click OK to continue. You will see simulation graphics of Figure 5.29 below.

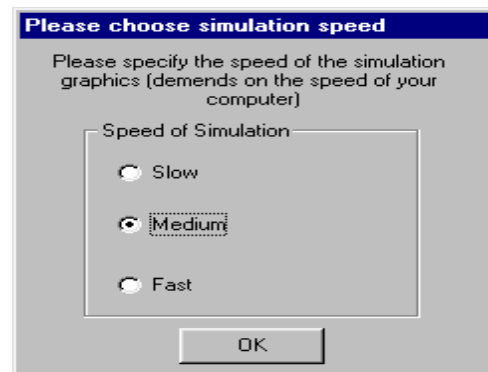Figure 5.27 . Simulation graphics dialogue

Figure 5.28 . Simulation Speed dialogue

- Wait until you see the message "End of Simulation." Click OK to view the simulation output summary graphs of Figure 5.30 below.
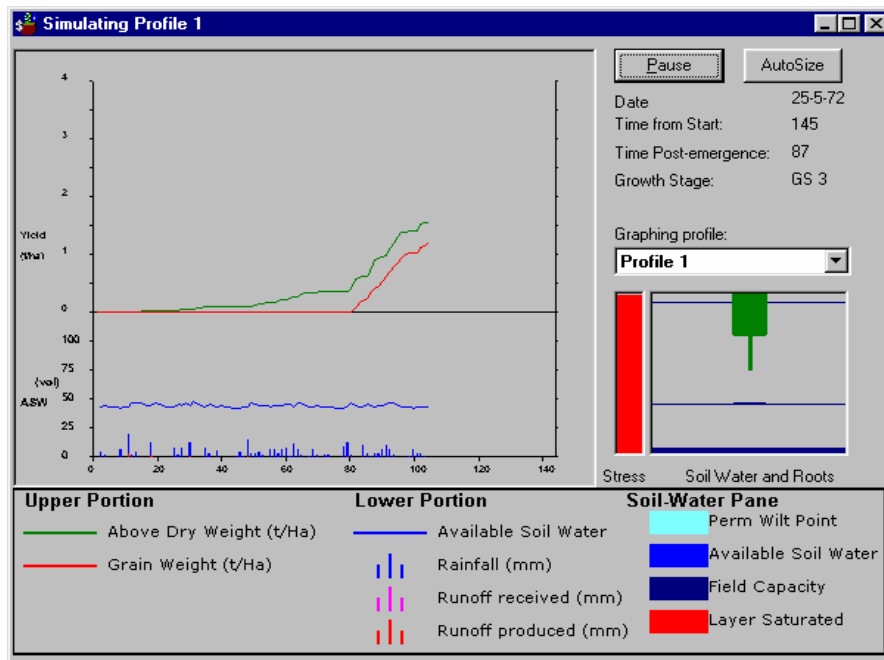
Figure 5.29. Simulation graphics window

The window shows the total seasonal rainfall for all 35 years simulated. To view other parameters (Runoff, Yield, ET, Evaporation, Drainage), click on the corresponding option buttons on the left of the summary graphs.
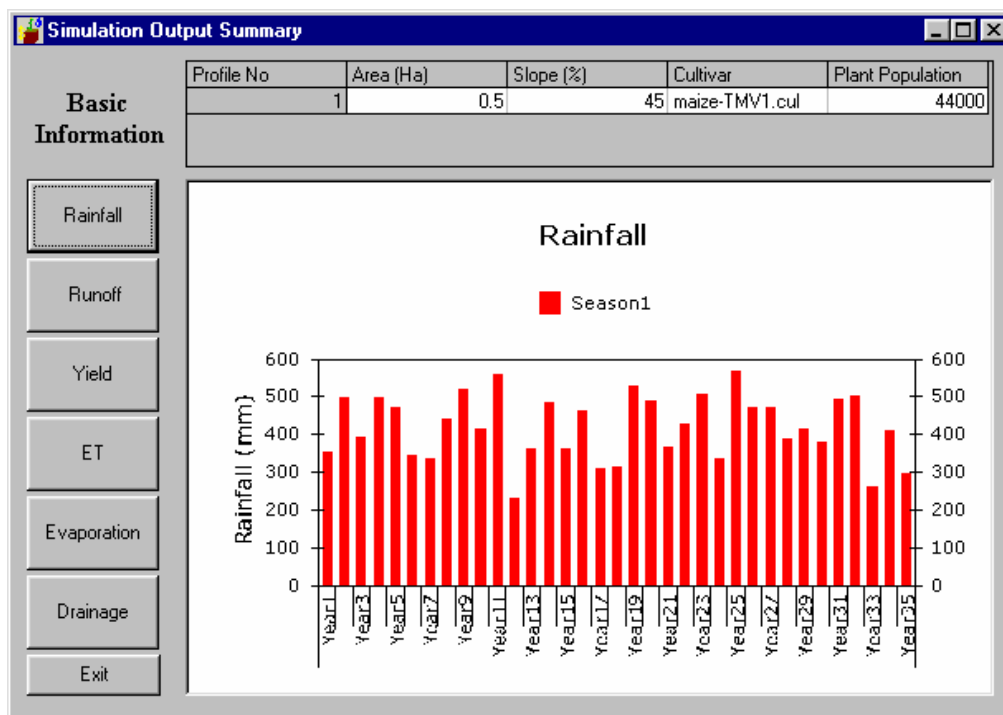

Figure 5.30. Simulation output summary window

You have now run 35 years simulation. Let's go to the output file to view the results of our simulations.

Step Five: Accessing the Output File
- Minimize or Close the PT Model window and start Microsoft Excel. Go to the File menu and click on open (or click on the open toolbar).
- Look for the folder c:\Program files\PTv23\output\. In the files of type text box select All files (as you did in step 6 - Exercise 1). Choose the file "RainfallRunoffSummary" and click on Open.. You will see the simulation output summary as shown in Figure 5.31.
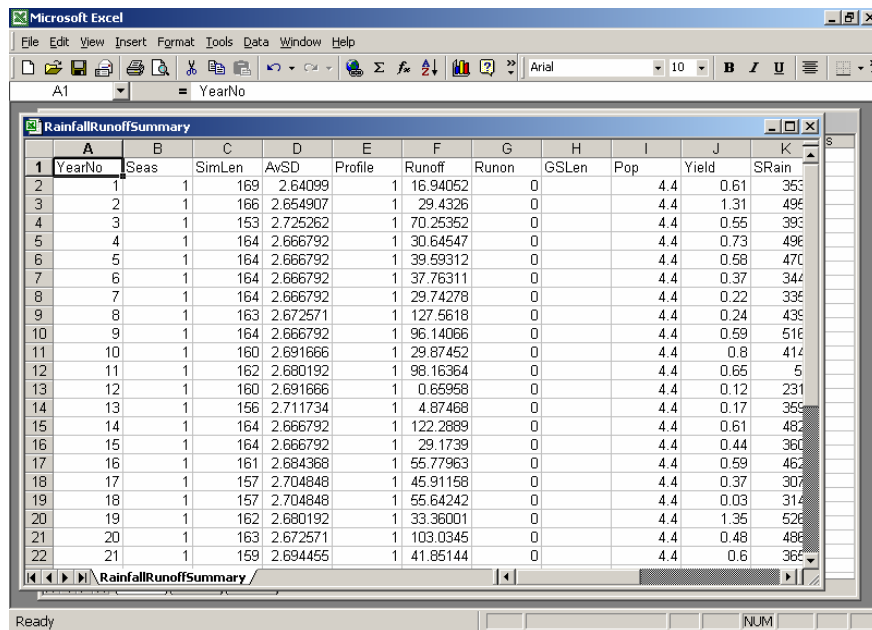

Figure 5.31. Output summary file

5.4.4 Assignment

- Open a new blank Excel workbook and save it as RainfallRunoffCorrelation on the desktop.
- Copy columns A (YearsNo), K(Srain) and F(Runoff), from RainfallRunoffSummary file and paste them into sheet 1 of the RainfallRunoffCorrelation file you created.
- Draw The Rainfall Runoff Correlation graph (Use the XY scatter option and add a trend line to the plot) as shown in Figure 5.32.
- Deduce an equation of the form

$$R = \frac{P}{y} - x \qquad (5)$$

Where   P = annual precipitation
                          R = annual runoff
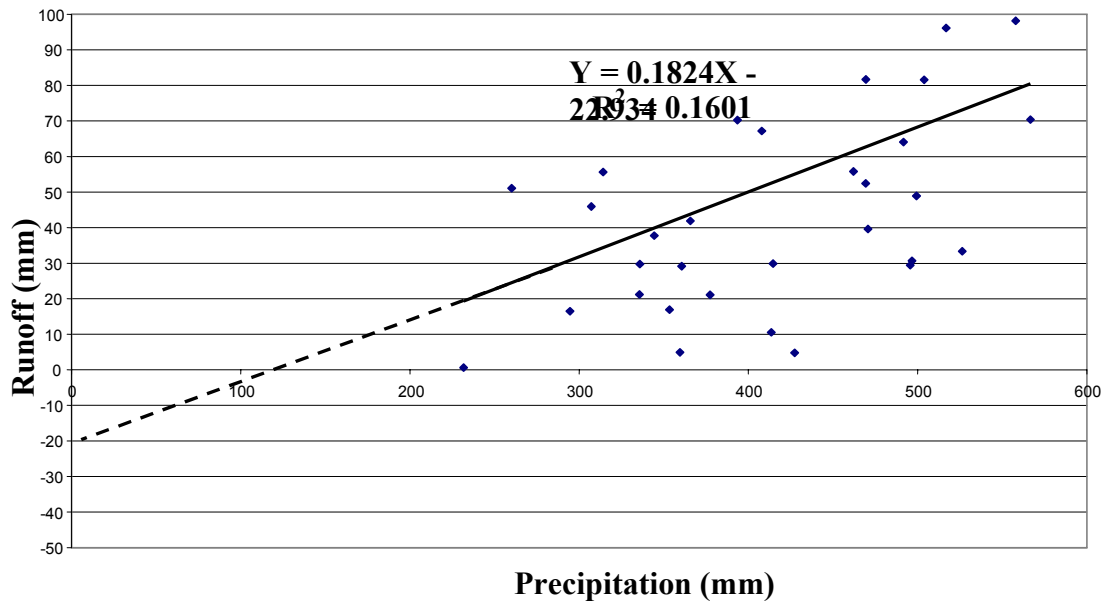   x and y are The intercepts

Comment on your results.

Figure 5.32. Rainfall-runoff correlation

5.5   References

Mahoo, H.F.(2000), Agrometeorology and Hydrology - A TEACHING MANUAL, SUA Press Unit, Morogoro

Mzirai, O.B.,T. Bwana, S.D. Tumbo, F.B. Rwehumbiza and H.F. Mahoo (2004), PARCHED THIRST HANDBOOK, SWMRG – PT Help Office