Tools and models [Part 1. Components of drought planning. 1.3. Methodological component]

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Chapter 11. Tools and models

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Medbasin - A Mediterranean rainfall-runoff model and software

Introduction

Medbasin is a daily-monthly rainfall-runoff model and software with a Windows interface and additional tools.

Numerous rainfall-runoff models have been proposed over the last four decades. To a great extent the complexity of these models seem to follow the advancement in computing and computer technology rather than the advancement in understanding of the physical processes. Therefore, new complicated models do not offer substantially to the improvement of representation of hydrological processes in a watershed.

Very important is also the fact that most rainfall-runoff models have been produced based on observations related to the study area, therefore being region related. It can be easily deduced that most conceptual models developed for the northern part of Europe cannot be used successfully in Mediterranean countries. Further physical models are not usually recommended for practical and operational studies.

In an attempt to model rainfall-runoff, FAO produced a comprehensive conceptual model for the Mediterranean Island environment called MERO. However, MERO was not used extensively during the sixties when it was proposed, due to computing difficulties. Based on this "old" model a modern computer package, *Medbasin*, was recently produced at the Laboratory of Reclamation Works and Water Resources Management of the National Technical University of Athens, in the framework of Medroplan project.

Model structure of the daily rainfall-runoff model

Medbasin's rainfall-runoff simulation procedure is based on the basic principles of MERO model, which had been used in several projects of F.A.O. in Mediterranean basins (e.g. Underhill *et al.*, 1970, Schenkeveld, 1971). MERO is a comprehensive conceptual rainfall-runoff model, based on the hydrologic cycle processes. These processes and the interactions between them are described by empirical relationships such as the overland flow function, the interflow function and the soil water storage-recharge relationship (Giakoumakis *et al.*, 1991). Daily values of average basin's rainfall and potential evapotranspiration are used as input data, while daily and monthly runoff is the output of the model.

The model is essentially an accounting procedure, in which the input (precipitation) passes through storage zones, from each of which some outflow is removed, until the whole input has been accounted for (Underhill *et al.*, 1970). The river flow is finally made up of outflow from four different reservoirs: the overland flow reservoir, the interflow reservoir, the temporary spring reservoir and the permanent spring reservoir (Fig. 1).

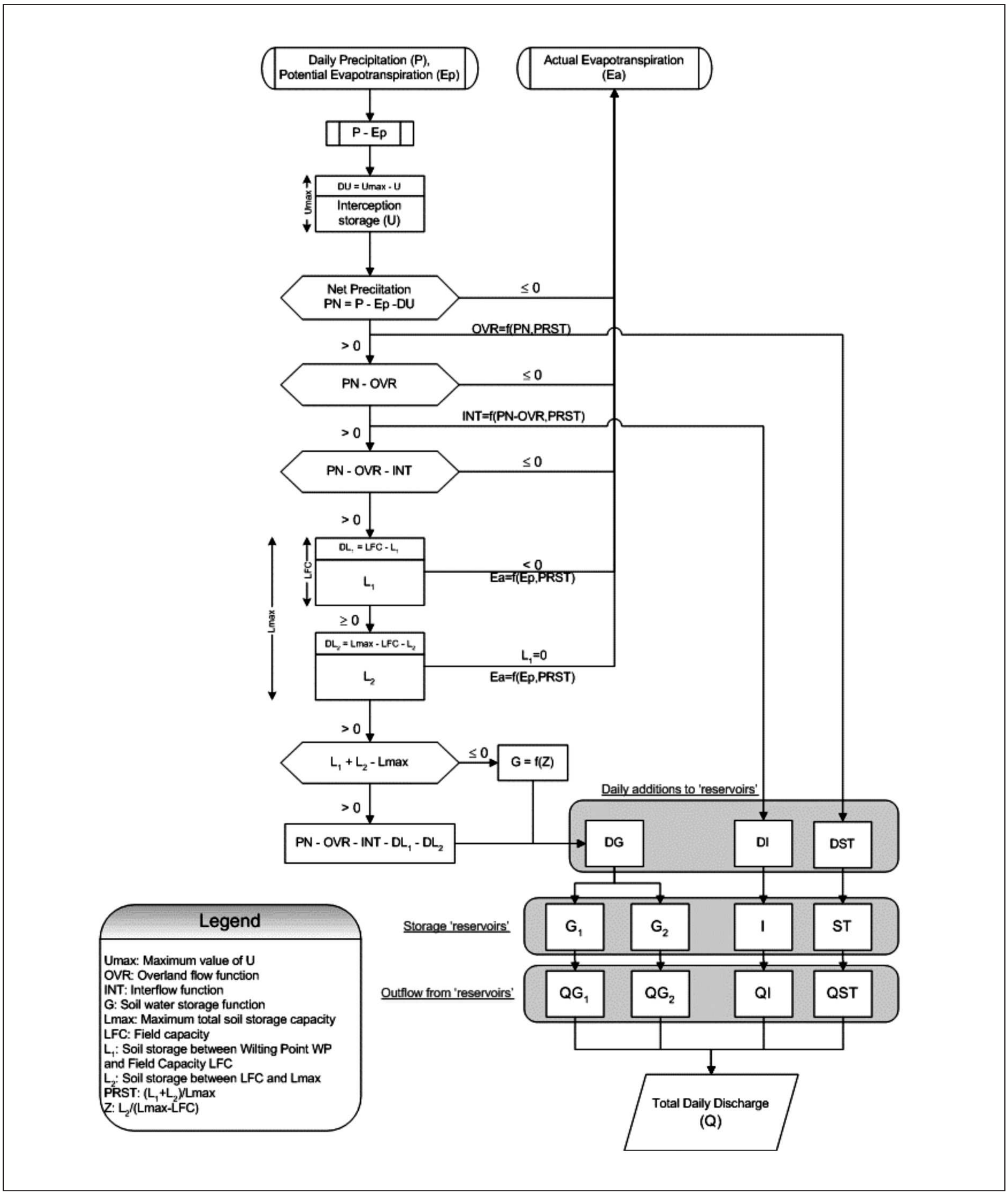


Fig. 1. Structure of the Medbasin model (Tigkas and Tsakiris, 2004).

According to the principles of the model, the soil has been divided into two different interconnected storage reservoirs: the interception storage U and the total groundwater storage L. In turn, the latter has been divided into two soil-water storage zones: the upper soil zone L_1 that may be considered as the root zone and in which soil moisture can reach a maximum value, up to field capacity LFC, and the lower zone L_2 that receives moisture from above when field capacity is exceeded (Giakoumakis *et al.*, 1991).

The river flow is made up of outflow from four reservoirs: the overland flow reservoir ST, the interflow reservoir I, the temporary spring reservoir G_1 and the permanent spring reservoir G_2. The distribution of moisture over the various storage zones occurs according to the following rules: Evaporation takes place from the interception storage U and the precipitation P is added to U. If U is less than the potential evapotranspiration EVPD, evaporation takes place from the soil moisture L. If the interception storage has a value greater than its maximum Umax the addition STPR to the storm runoff reservoir STmm and the addition GPR to the interflow reservoir INmm are calculated. If I is less than Imax, there is an addition to the interflow reservoir only if the soil moisture L is greater than its maximum Lmax. The addition GWPR to the shallow and deep spring reservoirs occurs when the soil moisture L is greater than the field capacity LFC.

The maximum value of interception storage Umax as well as the maximum total soil moisture capacity of both zones Lmax and the field capacity LFC, are not usually based on actual field measurements, but they are determined during the model calibration stage to give the best possible fit with the measured runoff volumes.

The reservoirs release water to the river according to a delay function:

$$F = (1\text{-}\exp(1\text{-}/T_0)) \tag{1}$$

where T_0 is a characteristic value for each of the reservoirs.

In the model each of the reservoirs has a certain intake area. The total area of the basin is allocated to storm runoff reservoir. To the remaining reservoirs parts of the basin are allocated which normally make up the total area. When there are losses from the basin through underground flow, the whole area should not be allocated to the remaining reservoirs. On the other hand, if there is underground inflow, the sum of the allocated areas should be greater than the area of the basin. The volume of this flow (deep percolation) is equal to the total moisture flow to the spring reservoir multiplied by the area, which is not allocated.

For a more extensive theoretical description of the model the reader can refer to Tigkas and Tsakiris (2004).

Model calibration

The model has fourteen calibration parameters which represent the physical characteristics of the basin:

(i) Umax, Lmax and LFC limit the size of the basin.

(ii) A1, A2, A3 and A4 represent the intake areas for the reservoirs determining their respective outflow.

(iii) T01, T02, T03 and T04 are the delay constants for the outflow of the reservoirs.

(iv) Constants that used for the size of the storm runoff: CT as a multiplier and Q0 as the amount that should be added or subtracted initially.

(v) CL2 controls the flow to the spring reservoirs.

Calibration process is usually applied to a portion of the available dataset and may follow a manual (trial-and-error) or automatic (based on objective functions) procedure by comparing the model estimated runoff values with the measured ones. Medbasin uses the Route Mean Square Error (RMSE) objective function:

$$\min_{\theta} RMSE(\theta) = \sqrt{\frac{1}{n}\sum_{t=1}^{n}[q_t^{sim}(\theta) - q_t^{obs}]^2} \tag{2}$$

where q_t^{sim} is the simulated discharge q_t^{obs} is the observed discharge and *n* is the total number of observations. This function is the unbiased, minimum variance estimator, and it is the Maximum Likelihood Estimator under the assumption that measurement errors ($et = q_t^{sim} - q_t^{obs}$), are normally distributed with zero mean and constant variance σ^2 (Yapo *et al.*, 1998).

Model validation

For the verification of the results five criteria are used (WMO, 1975, 1986, 1992; Cavadias and Morin, 1986):

The coefficient of variation of the residual of errors for the discharge variables

$$Y = \frac{\left[\frac{\sum (q_{sim} - q_{obs})^2}{n}\right]^{1/2}}{\bar{q}_{obs}} \tag{3}$$

The ratio of relative error to the mean of the discharge variables

$$R = \frac{\sum (q_{sim} - q_{obs})}{n\bar{q}_{obs}} \tag{4}$$

The ratio of absolute error to the mean of the discharge variables

$$A = \frac{\sum | q_{sim} - q_{obs} |}{n\bar{q}_{obs}} \tag{5}$$

The arithmetic mean of the discharge variables

$$D = \frac{\sum q_{sim,obs}}{n} \tag{6}$$

One minus the ratio of the sum of squares of the daily residuals to the sum of squares of the deviations of the observed flows from their mean

$$NTD = 1 - \frac{\sum (q_{sim} - q_{obs})^2}{\sum (q_{obs} - \bar{q}_{obs})^2} \tag{7}$$

where $q_{obs,sim}$ is the observed and the simulated discharge and

$$\bar{q}_{obs} = \frac{\sum q_{obs}}{n}$$

Monthly rainfall-runoff model

Apart from the daily rainfall-runoff component, another simple conceptual rainfall-runoff model, namely the Simple Water Balance Model (SWBM), is included in Medbasin. SWBM operates on monthly basis, therefore it can be useful when daily data are not available. The SWBM is based on the assumption that the water storage in the basin takes place only into the upper soil zone (e.g. root zone). Monthly precipitation P and potential evapotranspiration E_p data are used as inputs, while monthly values of runoff R are calculated.

SWBM uses two calibration parameters: the maximum total soil storage capacity, Smax and C which is taking into account the deep percolation losses.

According to the model, the soil may be taken to be a container with maximum total storage capacity Smax. The monthly precipitation P_i is added to this container, while the monthly value of potential evapotranspiration Ep_i is subtracted, as well as the losses because of the deep percolation D_i. The amount of water that exceeds Smax is splitting in two parts, based upon the value of C parameter: the first part is added directly to runoff R_i, while the second is considered as deep percolation loss D_i (Fig. 2).

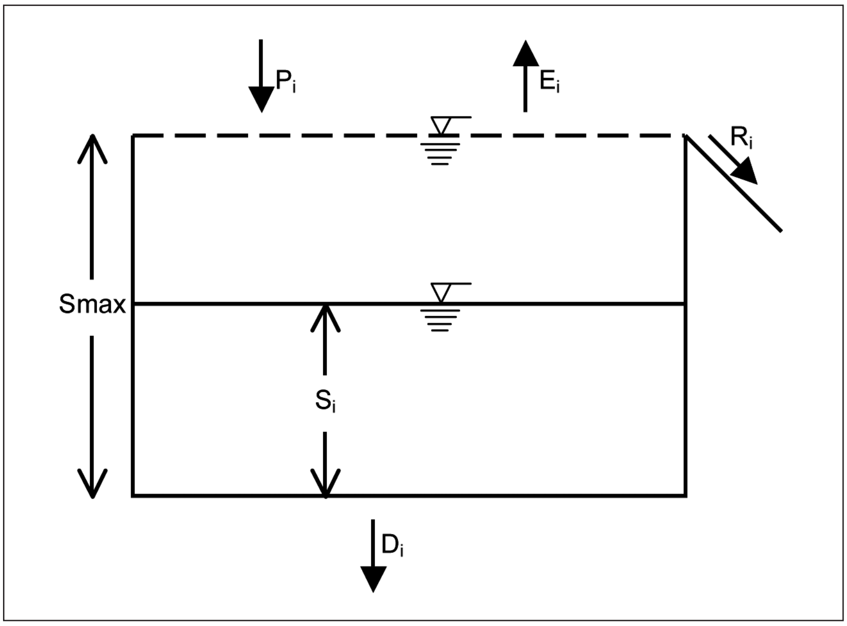


Fig. 2. Simplified Medbasin monthly water balance model.

The first step is to compute a trial value of depth S'_i of the water in the container, by the following equation:

$$S'_i = S'_{i-1} + P_i - Ep_i$$

where: i = 1,2,…,n subscript denoting number of months.

According to the magnitude of this trial depth, the values of the output R_i and D_i are determined as follows:

If $S'_i < 0$, then:
$S_i = 0$
$R_i = 0$
$D_i = 0$

If $0 \leq S'_i \leq Smax$, then:
$S_i = S'_i$
$R_i = 0$
$D_i = 0$

If $S'_i > Smax$, then:
$S_i = Smax$
$R_i = (1 – C) (S'_i – Smax)$
$D_i = C (S'_i – Smax)$

Medbasin software interface

General description

The software interface of Medbasin has been programmed in Visual Basic 6. The recommended system requirements are a Pentium 4 processor computer with 256MB of RAM, running on a Windows operating system.

In the Main window of the program (Fig. 3) the model's parameters, the values of the initial conditions for the deep and shallow spring flow ($S1_{in}$, $S2_{in}$) and the upper soil moisture (L_1), as well as the EVPC evaporation constant, can be assigned. The number and the actual period of water years are also defined in this window. This information must be accurate in order to calculate the leap years.

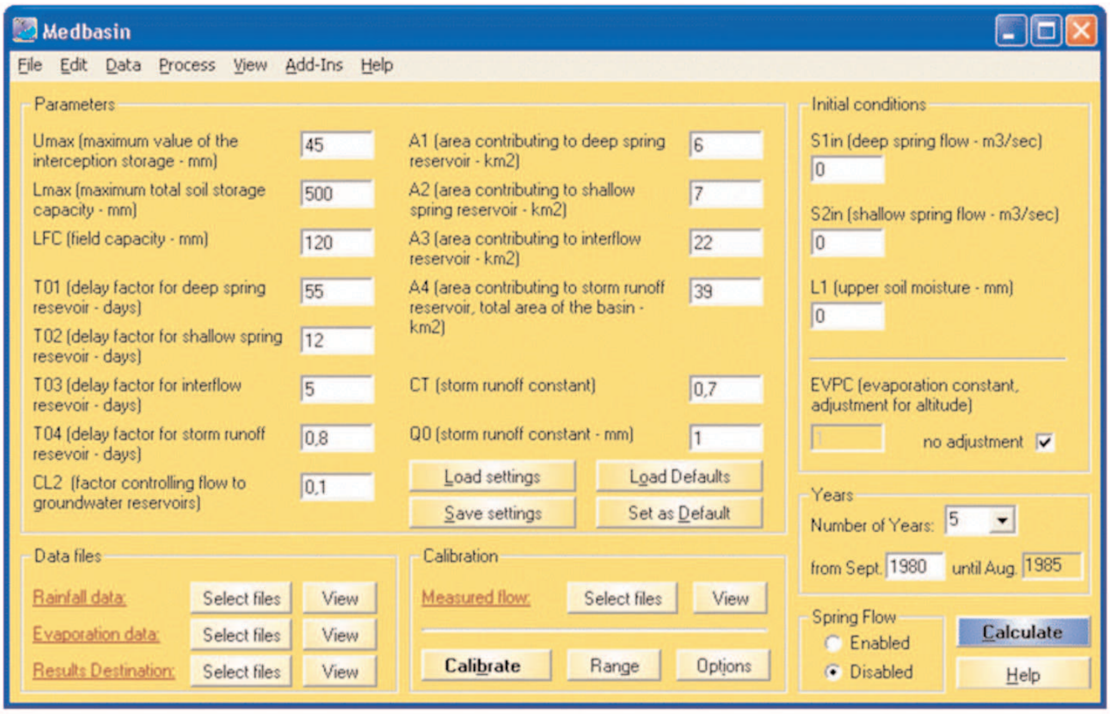


Fig. 3. Medbasin's Main Window.

All the basic commands, user's preferences and other settings can be accessed or executed directly from the menu list of the program (Fig. 4). There are also web links to Medbasin website (*www.ewra.net/medbasin*) for technical support and other information.

Data input

The main data requirements of the program are surface average rainfall and potential evapotranspiration. If there is a spring which contributes to the river runoff and its water supply is located in an area outside the basin, average monthly spring flow data is accounted as input to the model. For the calibration process, measured river flow data is also required.

Datasets can be imported in the program from Excel worksheet archives. To select and load the data files there are 4 data-selection windows, for rainfall, evaporation, river flow and spring flow data, respectively. Regarding the evaporation data, there is the ability to use directly potential evapotranspiration (PET) values (calculated outside the program e.g. with the Penman method) or to use pan evaporation data (E) and calculate PET by multiplying either with a standard annual constant or with monthly constants (if the correlation between E and PET is known for the specific region).

In case of existing gaps in the datasets (empty cells in source file), they will be automatically replaced by a zero value. Especially for evaporation data an interpolation algorithm is used to fill gaps not greater than 40 days.

Calibration procedure

The optimization algorithm used in the calibration procedure is based on an iterative routine. Initially, the limits of each parameter as well as the loop step are defined in the "Calibration Range" window (Fig. 5). The selection of the limits depends on basin's characteristics.

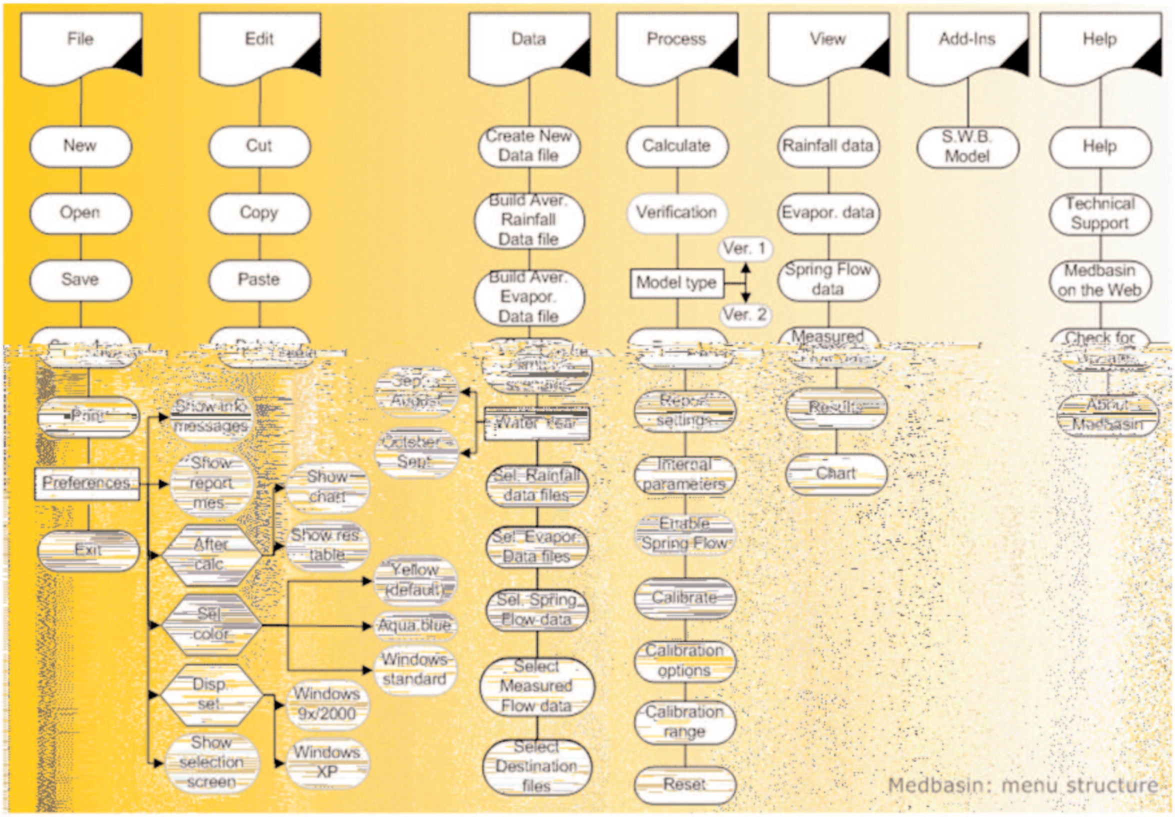


Fig. 4. The structure of the program's menu.

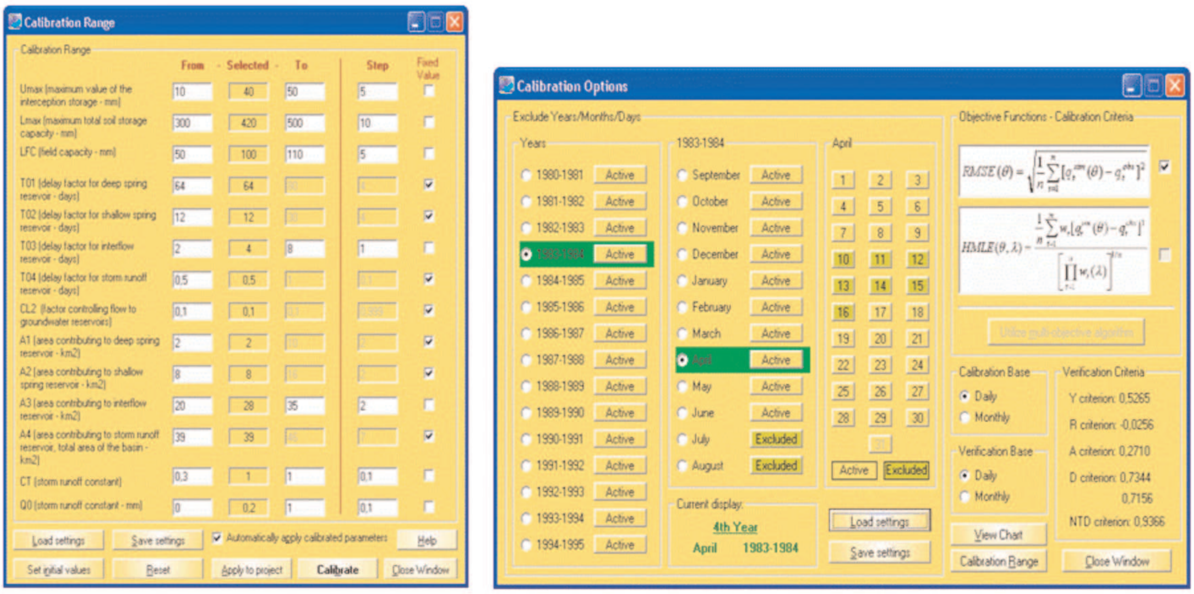


Fig. 5. The "Calibration Range" and the "Calibration Options" windows.

The optimization process intents to specify the set of parameters which minimizes the selected objective function. The procedure may be repeated several times, by changing the range and the "fixed value" option of the parameters, until a satisfying value of the objective function is being achieved.

In the "Calibration Options" window it is possible to exclude data from the calibration procedure. Data exclusion is a way to avoid problems caused by incorrect or incomplete data. However, it can also be used as a technique to focus the optimization on specific parts of the hydrograph (e.g. peaks).

Results and Reports

Loaded data and the runoff simulation results are displayed in data grids and they can also be projected graphically in the Chart window (Fig. 6), as single series or combination charts. There are several 2D and 3D projection options, on daily or monthly basis for the specified period of years. The charts can be printed, saved as bitmaps or exported to compatible grid-based programs.

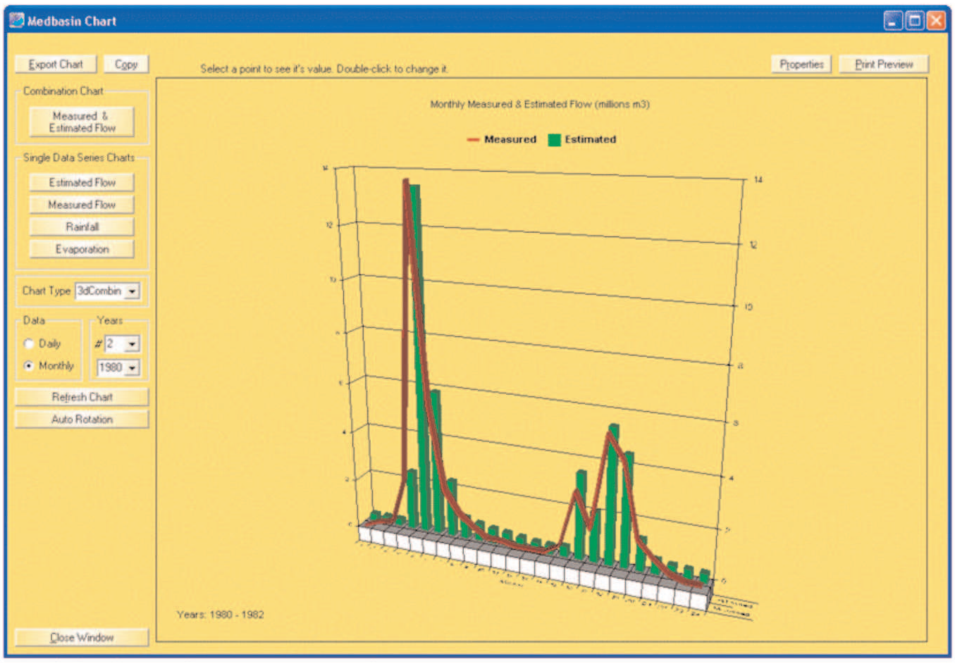


Fig. 6. The "Chart" window.

A list of the values of the internal parameters of the model and a report of the calibration and verification criteria is been created, after the end of the calibration or the runoff simulation.

A detailed calibration report file may also be created, containing the optimum parameters' sets (depending on the objective function's value) with their calibration and verification criteria, respectively.

Climatic scenarios

An important task for water resources management is to assess the changes of runoff in various climatic conditions. Medbasin includes a tool which uses an algorithm to alterate the original datasets of precipitation, potential evapotranspiration and inflow by defined percentages. If several years are selected, which represent the normal conditions of the watershed then the produced climatic scenarios can indicate the variation of runoff from the normal conditions for each scenario (Tsakiris *et al.*, 2004).

There is also the ability to use climatic scenarios together with drought indices (Tigkas *et al.*, 2005). The climatic scenarios can be formulated either by using the daily or the monthly rainfall-runoff component of Medbasin (Fig. 7).

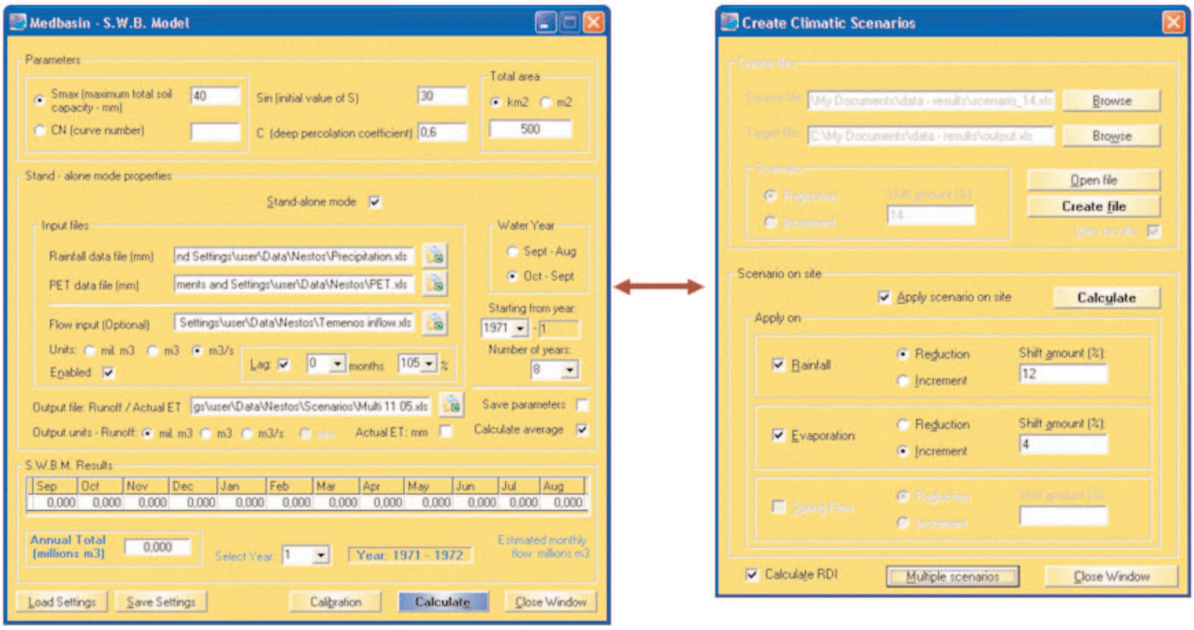


Fig. 7. Climatic scenarios.

Data requirements

Table 1 shows the optimum and minimum data requirements for the simulation of runoff with Medbasin and the calculation of drought indices.

Table 1. Data requirements

	Daily	Monthly	
Precipitation	■ (Medbasin – Optimum)	■ (Medbasin – Minimum) ■ (RDI – Optimum)	
PET	■ (Medbasin – Optimum)	■ (Medbasin – Minimum) ■ (RDI – Optimum)	
Penman - Monteith		Temperature, Humidity, Wind Speed, Sunlight h/day	■ (RDI – Optimum)
Thornthwaite		Temperature	■ (RDI – Minimum)
Pan evap. method		Pan evaporation	■ (RDI – Minimum)
Runoff	■ (Medbasin – Optimum)	■ (Medbasin – Minimum)	

Medbasin – *Optimum* ■ *Minimum* ■
RDI – *Optimum* ■ *Minimum* ■

Redim[1]

The package REDIM (Rossi and Cancelliere, 2003) is an user friendly software which allows to perform drought analysis on hydrological series both at a site and over a region. It, also, allows to test statistically for the existence of nonstationarity in a time series, whose presence would lead to misleading drought analyses (Fig. 8). REDIM is freeware and it can be downloaded from the following web site: http://www.risorseidriche.dica.unict.it.

1. The REDIM software has been developed by A. Cancelliere, G. Rossi, B. Bonaccorso (Department of Civil and Environmental Engineering, University of Catania) and L. Cavallaro (Department of Civil and Environmental Engineering, University of Messina).

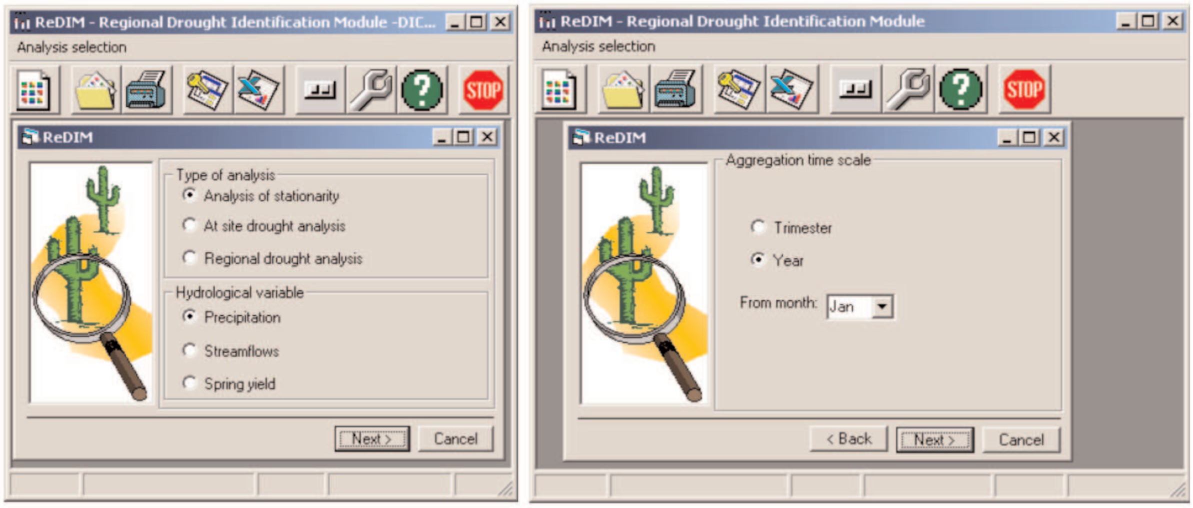


Fig. 8. Main dialog box and aggregation time scale dialog box of REDIM.

The software is written in Visual Basic, runs under Windows platforms, and is structured as a succession of dialog boxes which guide the user throughout the analysis of stationarity and drought identification and characterization steps.

The main features of REDIM can be listed as follows:

(i) Different aggregation time scales can be used (monthly, three months and yearly), with the possibility to select the initial month of aggregation in order to take into account water years instead of calendar years.

(ii) Testing for stationarity in hydrological series is carried out by means of six different statistical test namely: Student's t-test for linear trend, Kendall's t or rank correlation test and turning points, Mann-Withney rank-sum test for detecting the homogeneity of the series, F test for detecting change in variance, and t test for detecting change in mean.

(iii) Identification and characterization of drought is performed by means of run method or the Standardized Precipitation Index.

(iv) Return periods of at site drought characteristics are computed.

(v) Graphical output of results to easily identify droughts and related characteristics are provided.

(vi) Results can be saved in a report file in rtf format.

Drought analysis at site through the run method can be customized by specifying the threshold level, as well as the options to compute return period (Fig. 9).

With reference to the evaluation of drought return period, the user can select either the non-parametric approach or the parametric approach to compute the parameters of the probability distribution (gamma) adopted for accumulated deficit. In the former case (non parametric), such parameters will be computed from the sample moments of the single deficit identified on the series. In the latter case (parametric), the parameters will be estimated by assuming a normal, log normal or gamma distribution for the underlying hydrological series.

Once that the drought analysis is performed by clicking "Next", a table containing the number of identified droughts and, for each drought, the related characteristics (duration, accumulated deficit, intensity), as well as the return periods, corresponding to different combinations of such characteristics, is shown (Fig. 10).

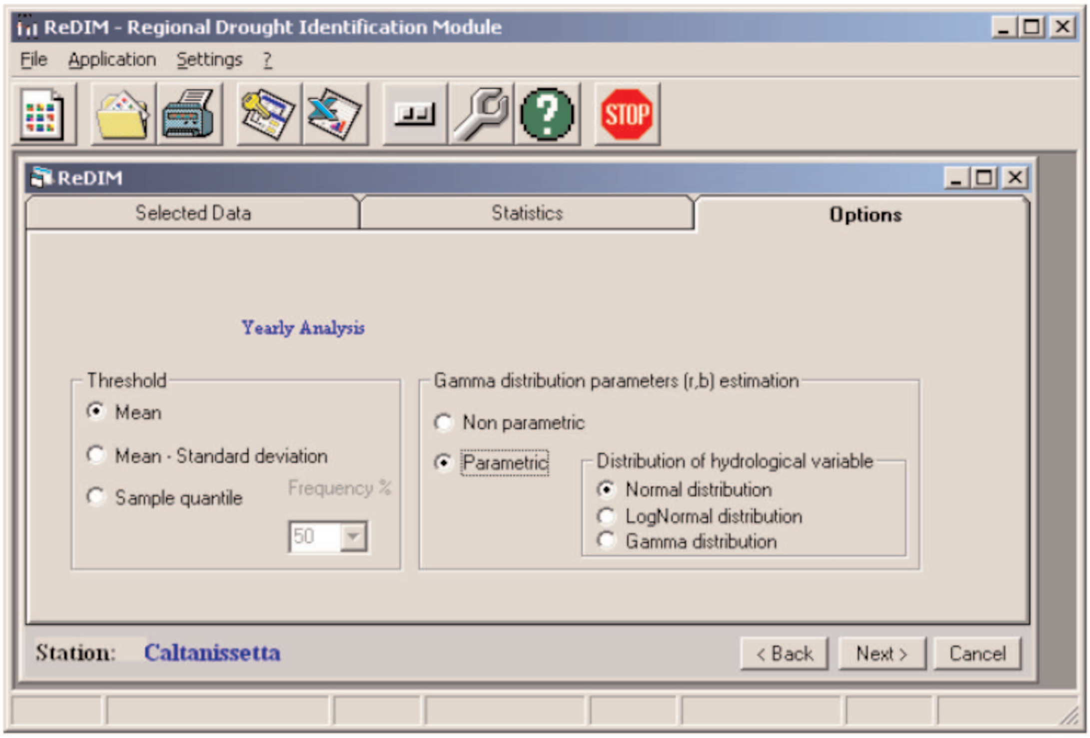
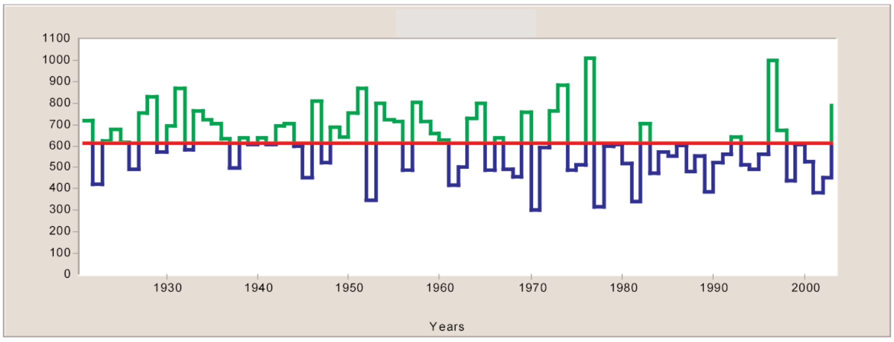


Fig. 9. Drought analysis at site through the run method.

Drought identification - Site analysis (trough REDIM)



Station name: Simeto
Hydrological variable: Precipitation
Aggregation time scale: year
Initial month: January
From year: 1921 To: 2003
Threshold (Average 50%):613.91 mm

Number of drought periods: 20

N	Begin.	End	Durat.	Cum. Def.	Drought Int.	Tr(L=l)	Tr(L=>l)	Tr(D>d)	Tr(L=l,D>d)	Tr(L=>l,D>d)
			[years]	[mm]	[mm/year]	[years]	[years]	[years]	[years]	[years]
1	1922	1922	1	189.84	189.84	8.58	7.55	8.39	61.67	8.57
2	1926	1926	1	123.43	123.43	8.58	7.55	6.23	24.70	6.20
3	1929	1929	1	39.29	39.29	8.58	7.55	4.46	10.09	4.32
4	1932	1932	1	29.47	29.47	8.58	7.55	4.32	9.45	4.20
5	1937	1937	1	116.38	116.38	8.58	7.55	6.04	22.59	6.00
6	1939	1939	1	6.79	6.79	8.58	7.55	4.06	8.63	4.03
7	1941	1941	1	6.49	6.49	8.58	7.55	4.06	8.63	4.03
8	1944	1945	2	181.81	90.91	16.13	14.19	8.09	27.39	9.70
9	1947	1947	1	90.55	90.55	8.58	7.55	5.42	16.55	5.32
10	1952	1952	1	267.25	267.25	8.58	7.55	12.10	199.17	12.55
11	1956	1956	1	126.17	126.17	8.58	7.55	6.30	25.59	6.29
12	1961	1962	2	312.21	156.11	16.13	14.19	15.05	88.97	16.29
13	1965	1965	1	127.16	127.16	8.58	7.55	6.33	25.92	6.32
14	1967	1968	2	275.60	137.80	16.13	14.19	12.60	61.00	13.88
15	1970	1971	2	329.82	164.91	16.13	14.19	16.42	107.77	17.64
16	1974	1975	2	230.16	115.08	16.13	14.19	10.13	40.00	11.52
17	1977	1981	5	689.83	137.97	107.07	94.14	103.30	539.97	121.36
18	1983	1991	9	823.28	91.48	1335.45	1174.21	208.38	1744.18	730.45
19	1993	1995	3	268.62	89.54	30.32	26.66	12.18	46.82	17.64
20	1998	2002	5	662.11	132.42	107.07	94.14	89.38	445.58	109.45

Fig. 10. Example of drought analysis carried out on the areal precipitation series over the Simeto river basin by using REDIM software.

If the SPI method is selected for drought analysis at site, the results of the analysis are shown for five aggregation time scales defined by default, i.e. k=1, 3, 6, 12 and 24 months (Fig. 11). The dialog box contains a table with the identification of drought periods, corresponding to SPI < -1.00, and a table with mean and minimum value of the SPI index and the duration for different classes. The analysis can be repeated for aggregation time scales selected by the user.

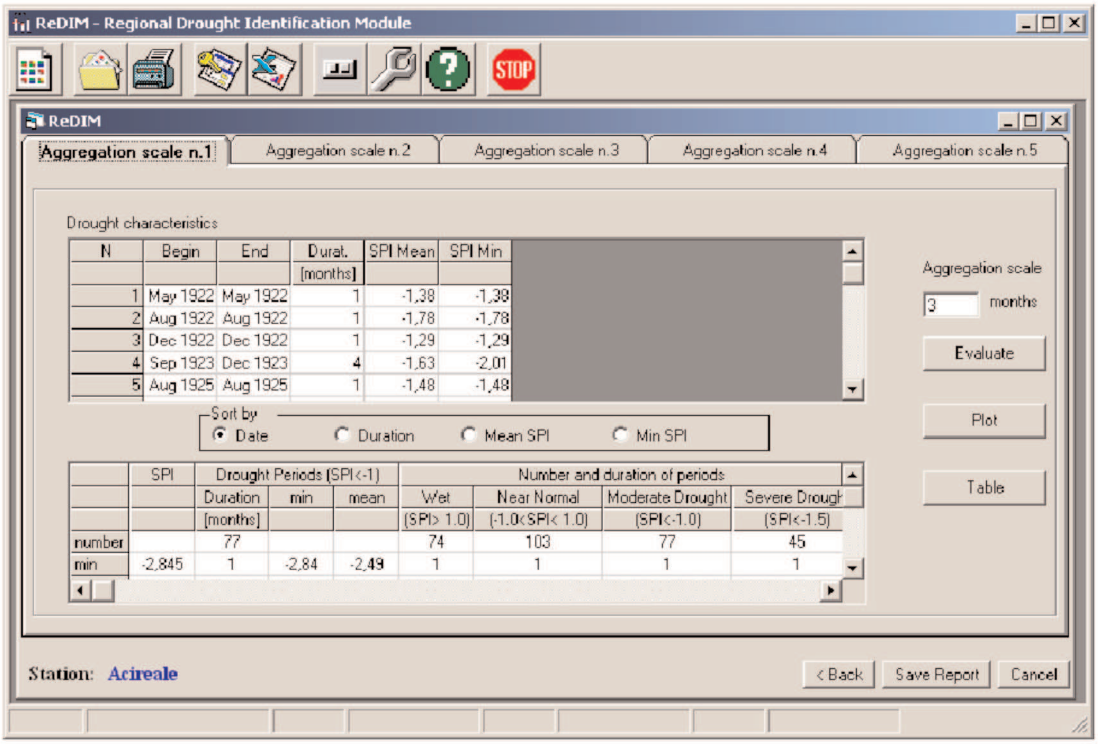


Fig. 11. SPI analysis at site results.

The regional drought analysis can be carried out based on either the run method and the SPI follows a similar approach.

Regional drought identification through the extended run method

Run method can be extended to the case of regional droughts by considering several series of the variable of interest and selecting, besides the truncation level at each site, an additional threshold, which represents the value of the area affected by deficit above which a regional drought is considered to occur. In particular, once the threshold levels $h_0(k)$ for each site k=1,..,K are defined, it is possible to identify for each time interval i, sites which present deficit:

$$h_0(k) - h(i,k) > 0 \quad (1)$$

with h the generic variable under investigation (e.g. precipitation).

Then, it is assumed that the deficit at each site is extended to an influence area around the observation station, which for example can be estimated by Thiessen polygons method (Fig. 12). Such area S(k) is usually expressed in terms of the total area under investigation as:

$$A(k) = S(k)/S_{tot} \quad (2)$$

where the total area S_{tot} is obviously:

$$S_{tot} = \sum_{k=1}^{K} S(k) \quad (3)$$

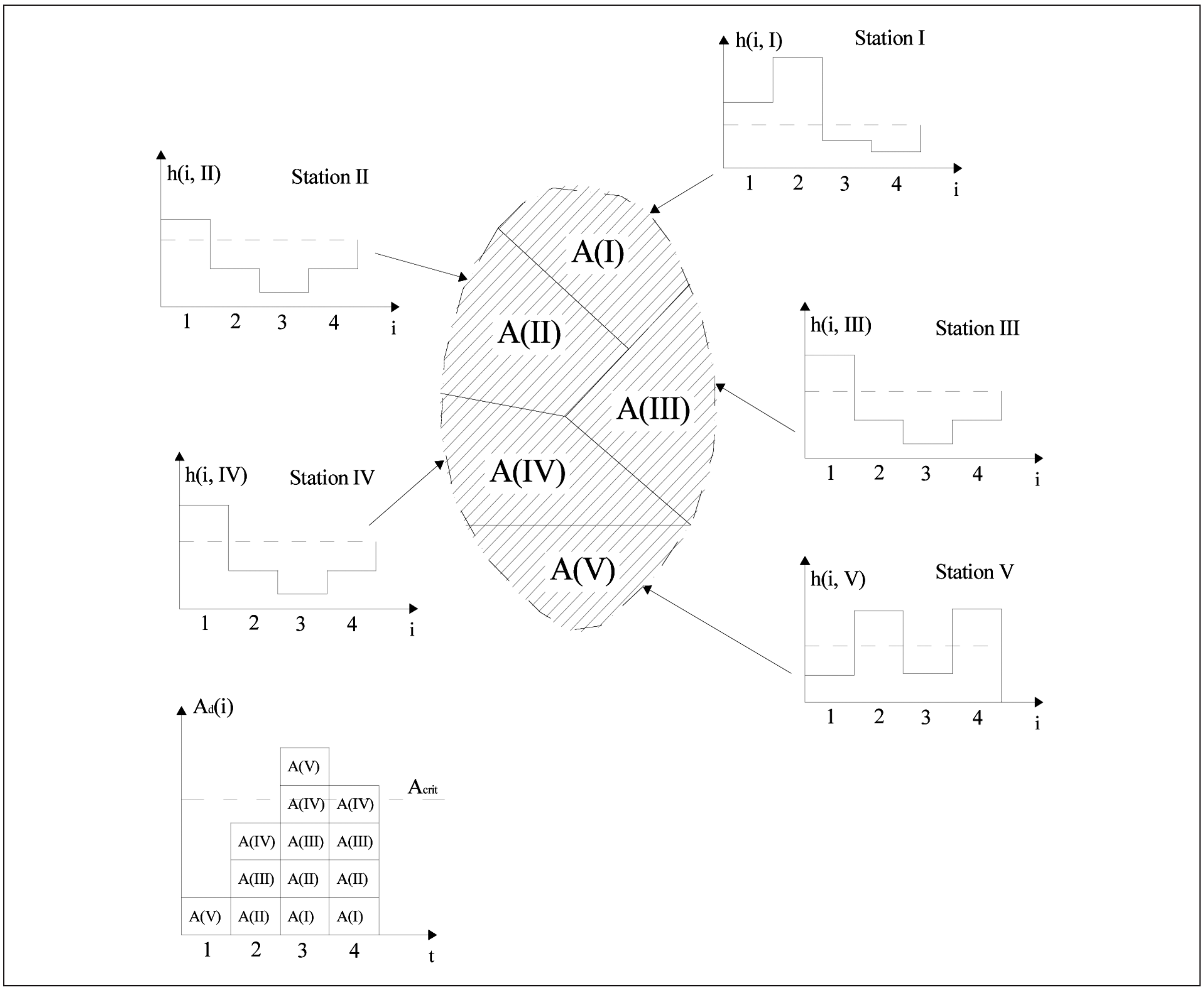


Fig. 12. Regional drought identification.

By fixing the areal threshold A_{crit}, two indices can be computed, namely the areal coverage of deficit $A_d(i)$:

$$A_d(i) = \sum_{k=1}^{K} I[h(i,k)]A(k) \tag{4}$$

where:

$$I[h(i,k)] = 1 \quad if \quad h(i,k) < h_0\,(k)$$
$$I[h(i,k)] = 0 \quad if \quad h(i,k) \geq h_0\,(k)$$

and the areal deficit $d(i)$ in the interval i:

$$\begin{aligned} d(i) &= \sum_{k=1}^{K} [h_0(k) - h(i,k)] \cdot I[h(i,k)]A(k) \quad & if \quad A_d(i) \geq A_{crit} \\ d(i) &= 0 & if \quad A_d(i) < A_{crit} \end{aligned} \tag{5}$$

The $A_d(i)$ index is a measure of the area affected by deficit, expressed as a fraction of the total area, ranging between 0 and 1. The second index provides some insight on the total amount of the deficit in the area.

For each drought r, regional drought duration is defined as:

$$L(r) = i_f(r) - i_i(r) + 1 \tag{6}$$

where i_f and i_i are such that $d(i) > 0$ for $i_i(r) \leq i \leq i_f(r)$ and $d(i_i(r) - 1) = 0$, $d(i_f(r) + 1) = 0$.

The accumulated areal deficit is computed as:

$$D(r) = \sum_{i=i_i}^{i_f} d(i) \qquad (7)$$

while the regional drought intensity is given by:

$$\text{ID}(r) = \text{D}(r)/\text{L}(r) \qquad (8)$$

Finally, the mean areal coverage of drought can be computed as:

$$AD(r) = \sum_{i=i_i}^{i_f} Ad(i)/L(r) \qquad (9)$$

To perform this type of analysis, first stations to be considered for regional drought identification have to be selected (Fig. 13).

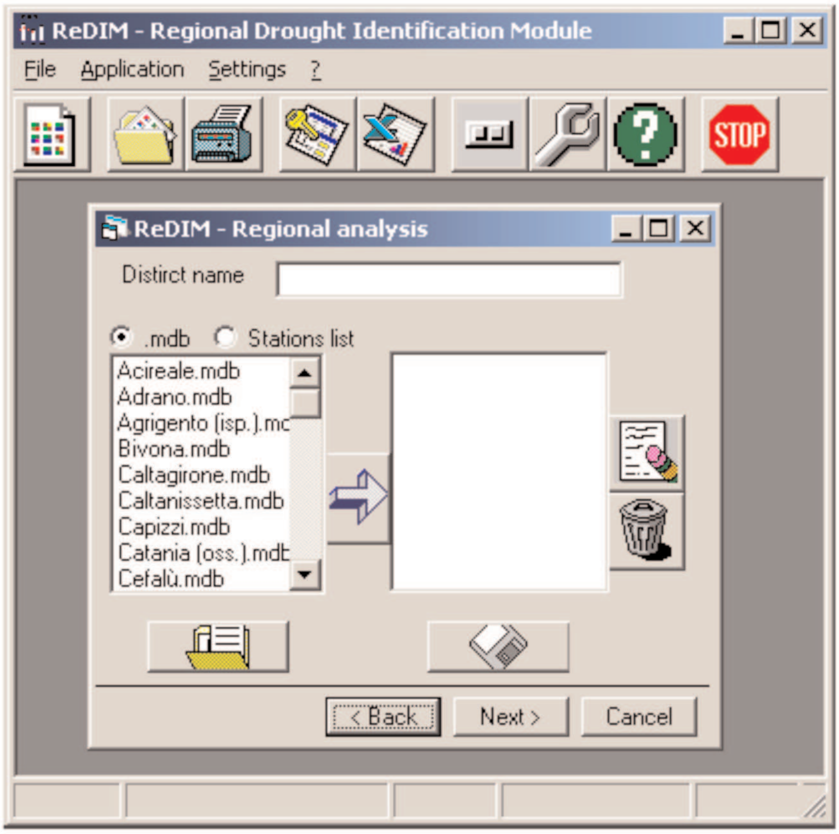


Fig. 13. Selection of stations for regional drought analysis.

By clicking Next, a dialog box appears prompting for the total area of the region of interest and for the influence areas of each station, expressed as a percentage of the total area. By clicking Next, the areas expressed in km^2 appear, as well as the common period of observation. The time span to be analyzed can be changed at this stage if needed. By clicking Next again, the dialog box in Fig. 14 appears.

Note that the user must provide the areal threshold expressed as a percentage of the total area. The option tab allows to select the threshold, the Statistics show the threshold values and the Selected Data allows to check that the analyzed data is correct. By clicking Next, the drought analysis results appear (Fig. 15).

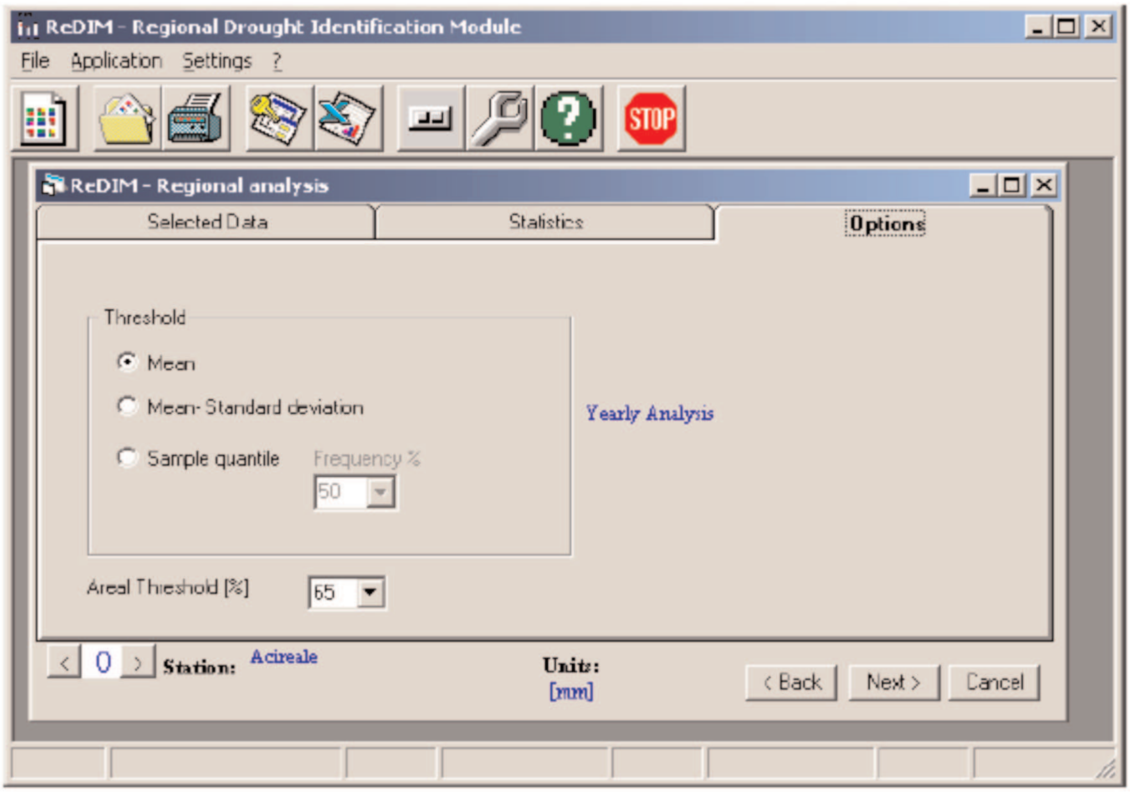


Fig. 14. Regional drought analysis options dialog box.

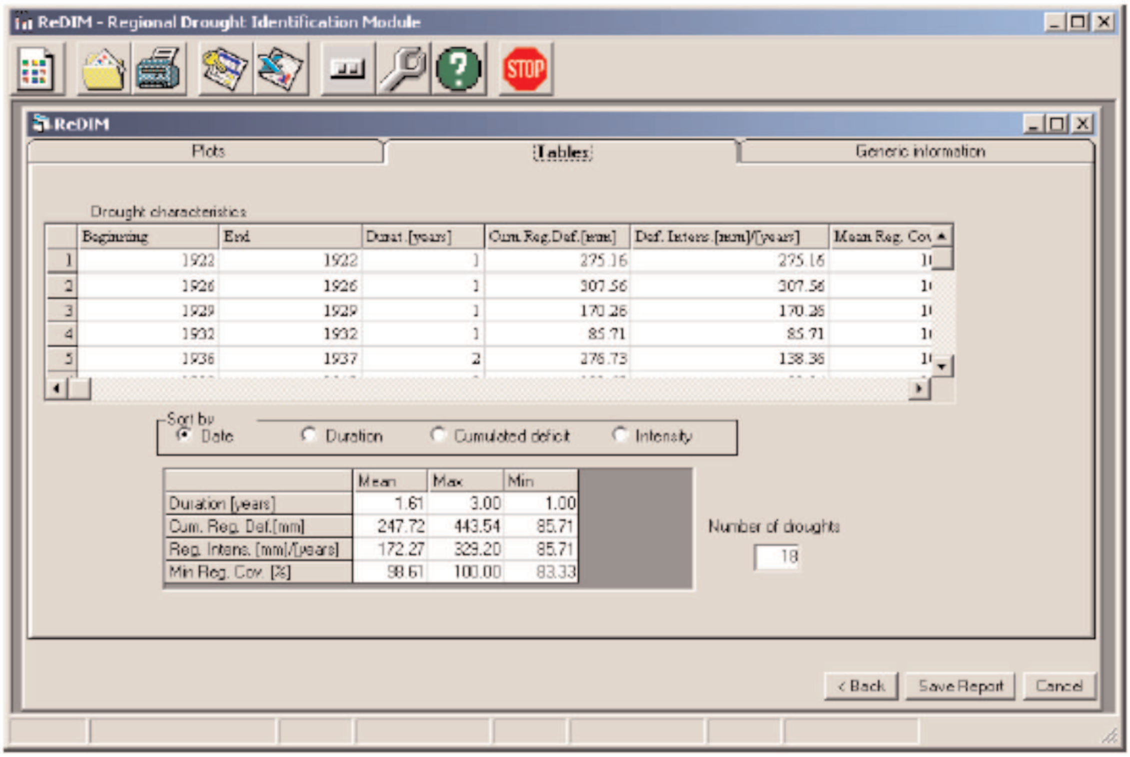


Fig. 15. Regional drought analysis results.

The windows has three tabs. The tables tab (shown below) contains the number of identified droughts, a detailed list of their characteristics, as well as their mean, max and min values. The Plots tab shows the areal coverage and areal deficit plots. An example of such plots is reported in Fig. 16. The Generic Information tab contains plots of the thresholds and other information, such as the total number of periods and the extensions of the critical area.

Fig. 16. Example of regional drought identification.

Regional drought identification through the SPI

A regional drought analysis can be carried out based on the SPI values computed for a given month *i* and a given aggregation time scale *k* at different sites. In particular, a similar approach adopted for the regional run method can be considered.

More specifically, once that the SPI series for a fixed aggregation time scale are computed at several sites, local drought conditions at each site *p* and at each month *i* can be identified if SPI (*i*, *k*) < SPI_{th}, where SPI_{th} is a fixed value of SPI considered as a threshold level for drought identification.

Drought conditions detected at each site *k* can be extended to influence areas S(*k*) (or polygons) around the stations, so that a drought areal coverage Ad(*i*) for each month *i* can be determined by summing polygons corresponding to the stations affected by drought according to the SPI values.

$$A_d(i) = \sum_{k=1}^{K} I[\mathrm{SPI}(i,k)]\, A(k) \qquad (10)$$

where:

$$I[\mathrm{SPI}(i,k)] = 1 \quad \text{if} \quad \mathrm{SPI}(i,k) < \mathrm{SPI}_{th}$$
$$I[SPI(i,k)] = 0 \quad \text{if} \quad \mathrm{SPI}(i,k) \geq \mathrm{SPI}_{th}$$

Finally, the drought areal coverage $A_d(i)$ is compared to a fixed areal threshold A_{crit}, representing the value of the area above which a regional drought is considered to occur. If $A_d(i)$ is greater than or equal to A_{crit}, then a regional SPI series for the considered aggregation time scale, is computed based on the areal rainfall h_{areal}, obtained as the weighted rainfall mean with respect to the polygons of the stations under drought conditions. Further for each regional drought, the regional drought characteristics can be computed as in the case of the regional run method.

In REDIM, after selecting the stations and the corresponding influence area, the dialog box showed in Fig. 17 appears. This dialog box contains two tabs: the former contains the selected data, the latter the statistics of the selected data on a monthly scale. The last one contains also two combo-box for the selection of the areal and SPI thresholds for the identification of regional drought.

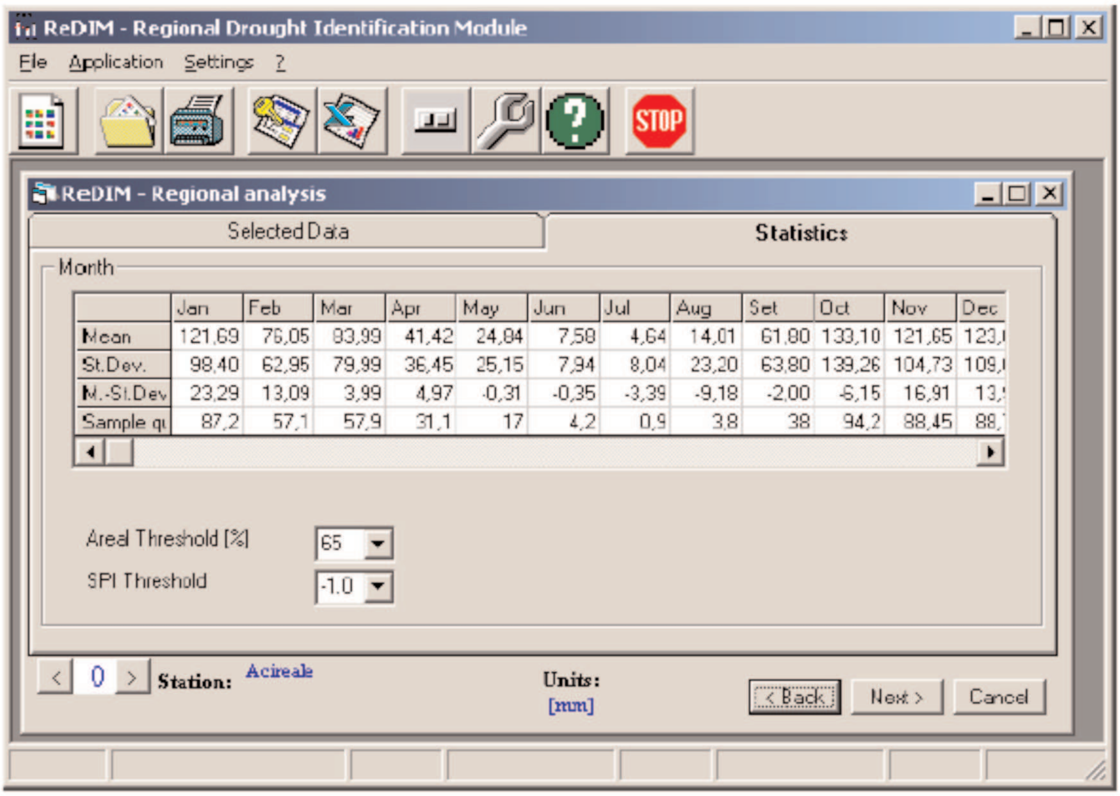


Fig. 17. Selected data, statistics and selection of threshold dialog box.

By clicking on the "Next" button the dialog box showed in Fig. 18 appears. Such dialog box contains five sub-dialog box which show the results of the analysis for five different aggregation scale. Each tab shows two tables. The former contains a detailed list of the drought period characteristics, the latter contains the mean, maximum and minimum values of duration, SPI index and the drought areal coverage. By changing the aggregation scale and clicking on the "Evaluate" button the analysis is repeated for the new aggregation scale.

By clicking on the "Plot" button the graphical representation of the SPI time series appears showing the areal coverage and SPI index evaluates obtained by taking into account the areal hydrological variable, computed on the basis of the sites for which the SPI values are below the fixed threshold. An example of such plots is reported in Fig. 19.

By clicking on the "Table" button the graphical representation of the SPI time series disappears and the table results appears again. By clicking on Save Report button, it is possible to save a report file for the selected aggregation time scales.

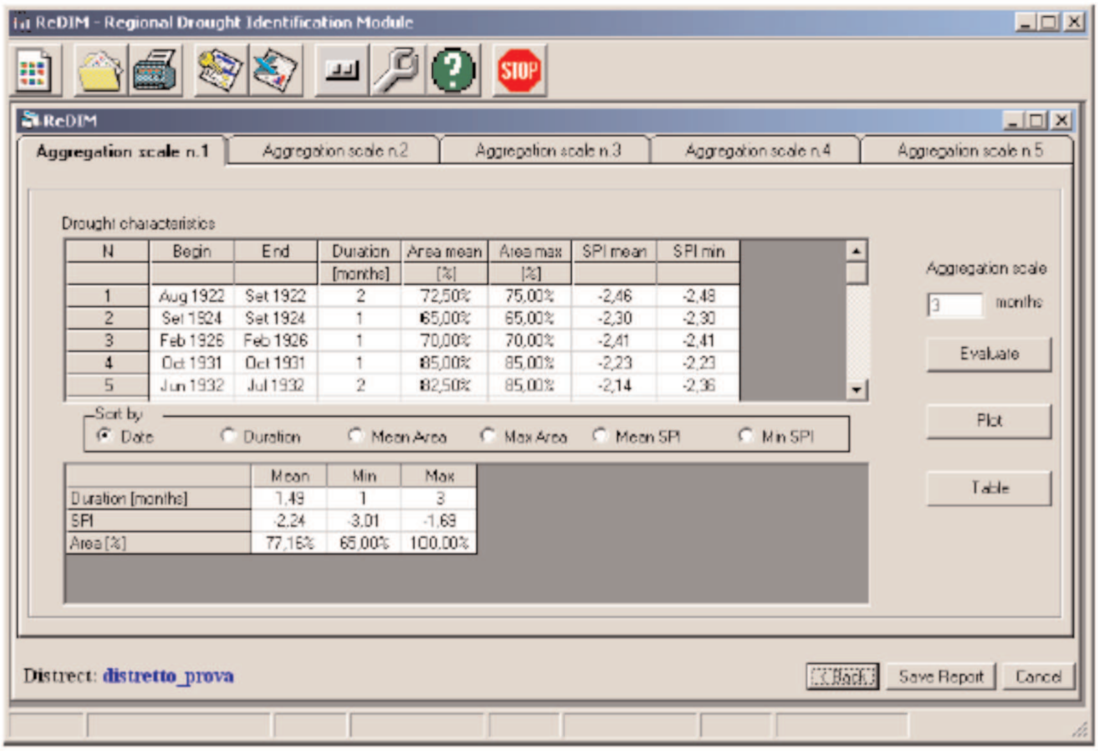


Fig. 18. Regional drought identification through SPI index.

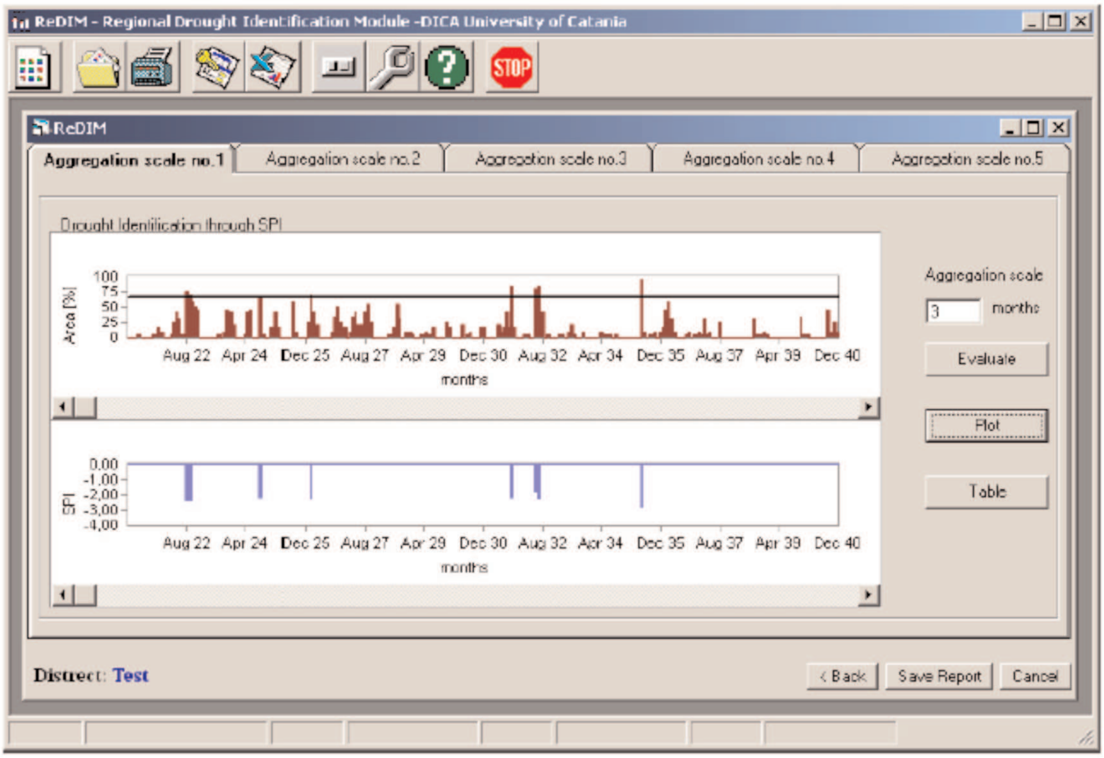


Fig. 19. Regional drought identification through SPI index – graphical results.

Simdro[2]

SIMDRO (SIMulation of water supply systems under DROught conditions) is a software package specifically oriented at simulating complex water supply system with particular reference to the the implementation of mitigation measures against drought impacts (Nicolosi, *et al.*, 2007a,b). Coupled with an appropriate data generation model it can be used to perform Montecarlo simulation of water supply systems providing statistically-based information about the system behaviour corresponding to different management policy in order to draft plans to cope with drought.

The SIMDRO 1.0.0 Italian release (the English version is in progress) has been developed by the Department of Civil and Environmental Engineering of the University of Catania (Fig. 20). The software package is written in Visual Basic and runs under Windows platforms. Use of the software is simplified through a succession of dialog boxes which guide the user throughout the description of the water supply system network, the representation of activation process of planned mitigation measures against drought effects and the analysis of the results of the simulations.

Fig. 20. SIMDRO 1.0.0 Introductory window.

SIMDRO simulates a water supply system through a node-link network, where sources (reservoirs, diversions) and demands (municipal, irrigation, industrial,…) are represented by nodes whereas system connections (rivers, channels, pipes,…) are represented by links characterized by origin node (source) and final node (source or demand).

The system configuration is defined specifying in appropriate windows (varying on the specific features of the type of node/link represented) all the peculiar characteristics both of nodes and links.

Simulation of the system is carried out at a monthly timescale respecting for each reservoir the following mass-balance equation:

$$V_{t+1} = V_t + I_t - E_t - R_t - Sf_t \pm Tr_t$$

Where

- t is the current step defined as $[t = \tau + 12^* (\nu - 1)]$ with $1 \leq \tau \leq 12$ month of the *n* year;
- V_t is the stored volume at the beginning of the month t;

2. The SIMDRO software has been developed by A. Cancelliere, G. Rossi, N. Nicolosi and G. Cristaudo (Department of Civil and Environmental Engineering, University of Catania).

– I_t is the net streamflow to the reservoir at month t;

– E_t is the evaporation at month t;

– R_t is the release at month t;

– Sf_t is the spill at month t occurring when volume V_{t+1} is greater than the maximum capacity of reservoir;

– Tr_t is the transfer between two sources at month t.

In addition the constraints, such as minimum and maximum storages, are implemented.

Net streamflow to reservoirs is computed as the difference between regulated inflows and a priori defined in-stream ecological releases.

Monthly evaporation losses are computed considering monthly evaporation heights times an average area function of the areas obtained by the storage-area relationship for the beginning and the end of the current timestep. Due to the fact that stored volume at the end of the timestep is unknown an iterative procedure till convergence is carried out.

As an example in Fig. 21 the window to define the characteristic of a node representing a reservoir is depicted. Reservoir characteristics are defined in terms of maximum storage capacity, dead storage and initial stored volume. Coefficients of storage-area relationships (assuming a relationship of the type $A = a + bV + cV^2$ with A = area and V = storage) and monthly evaporations have to be defined as well.

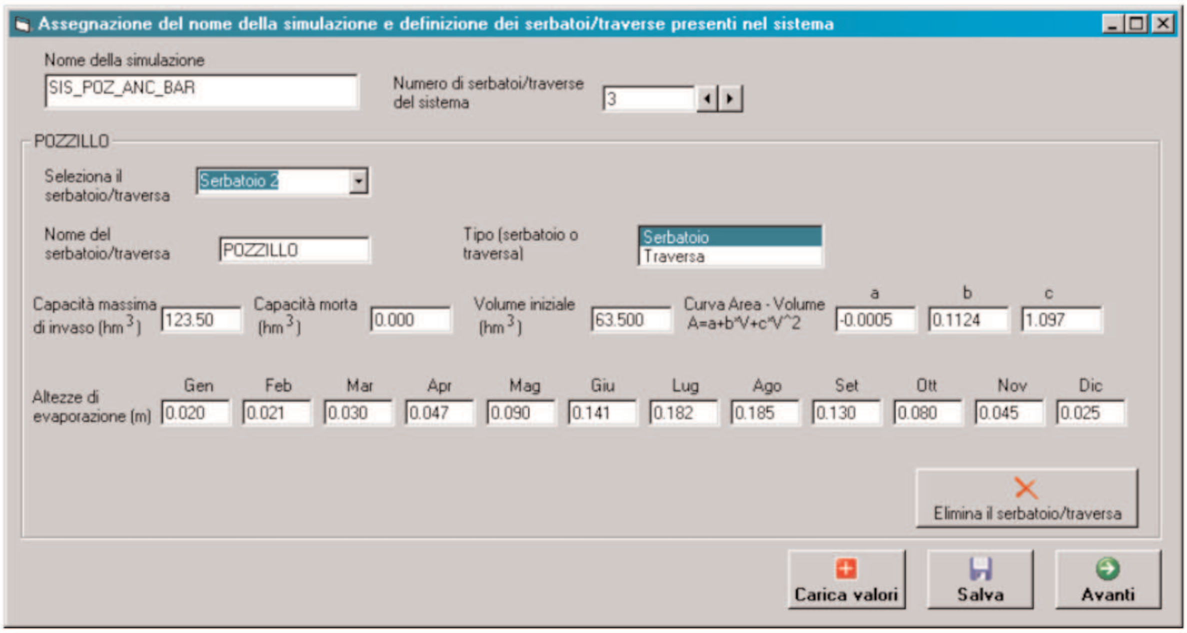


Fig. 21. Definition of the characteristics of a node representing a reservoir (source).

For nodes representing diversions it is possible to define a minimum volume that can be diverted and monthly utilization coefficients in order to take into account the effective water availability at the diversion in relation to its technical features (Fig. 22). Once demand node have been defined it is possible to implement the water supply system network linking the several nodes defining the link typology through the window shown in Fig. 23.

One of the most important features of SIMDRO is that it is able to simulate different management configurations of the system to which correspond different possible drought mitigation measures defined by the user, according to different hydrological conditions or states.

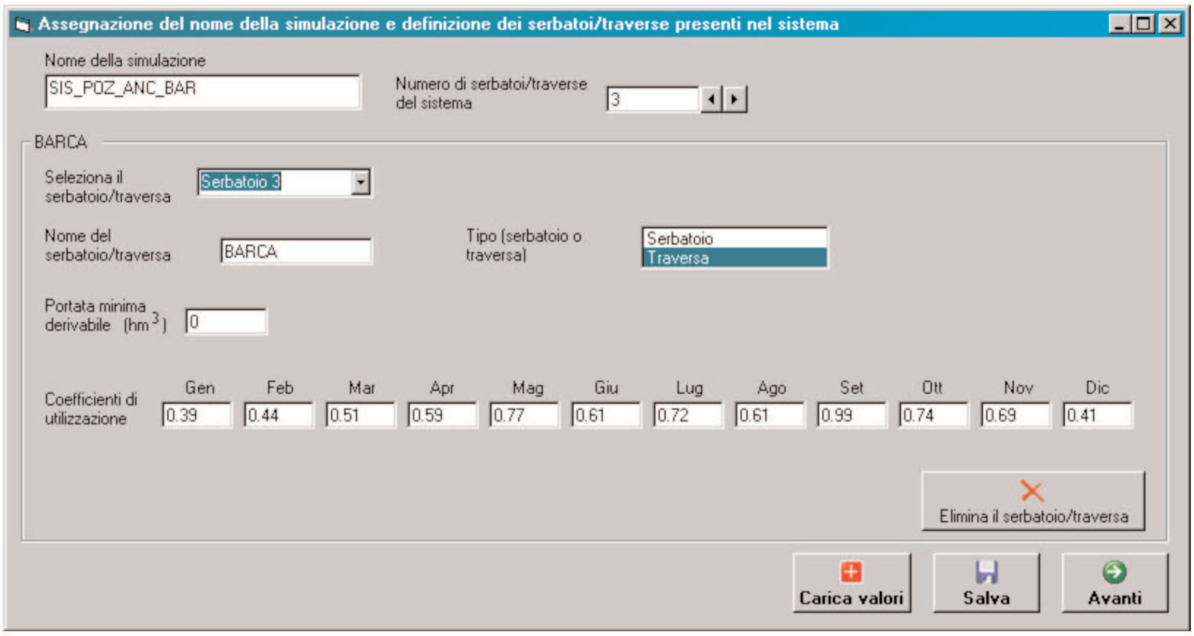


Fig. 22. Definition of the characteristics of a node representing a diversion (source).

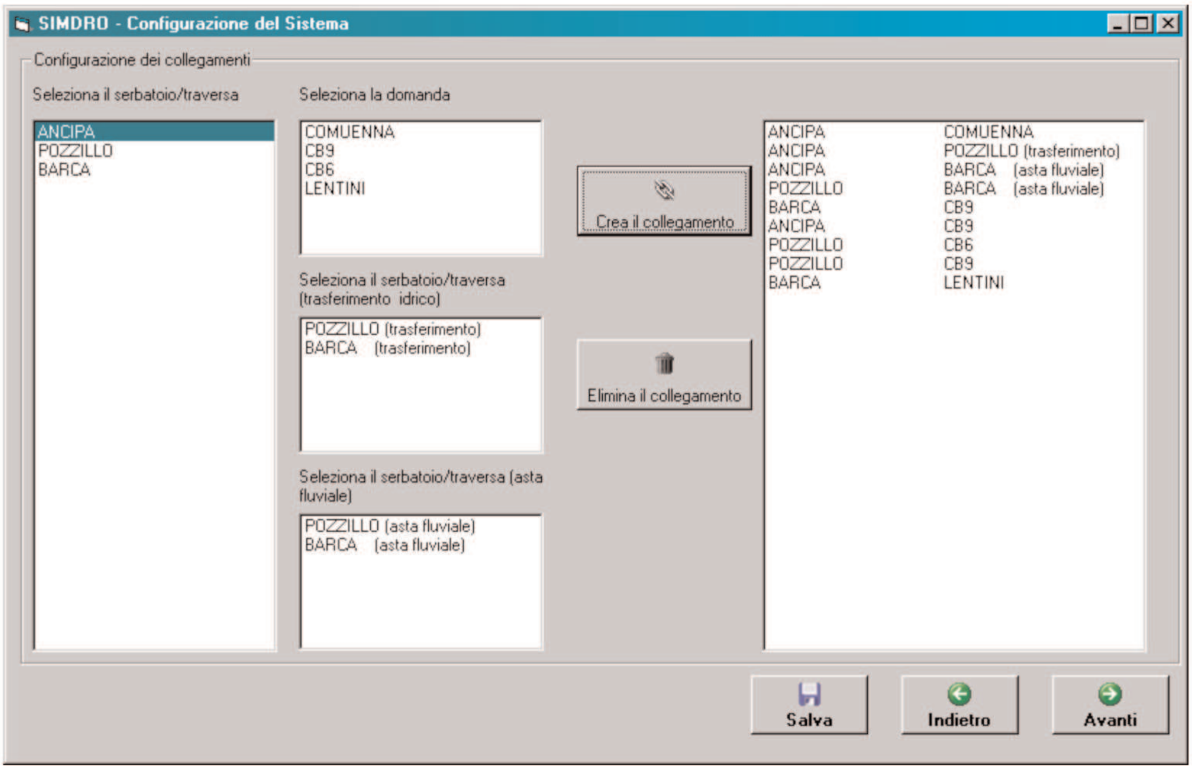


Fig. 23. Building the water supply system network.

The hydrological state of the system is defined at each time step by comparing water availability at selected reservoirs and/or diversions, with predefined levels. Current release of SIMDRO considers three different hydrological states namely *normal*, *alert* and *alarm*. Accordingly, different drought mitigation measures are triggered corresponding to each hydrological state (Fig. 24).

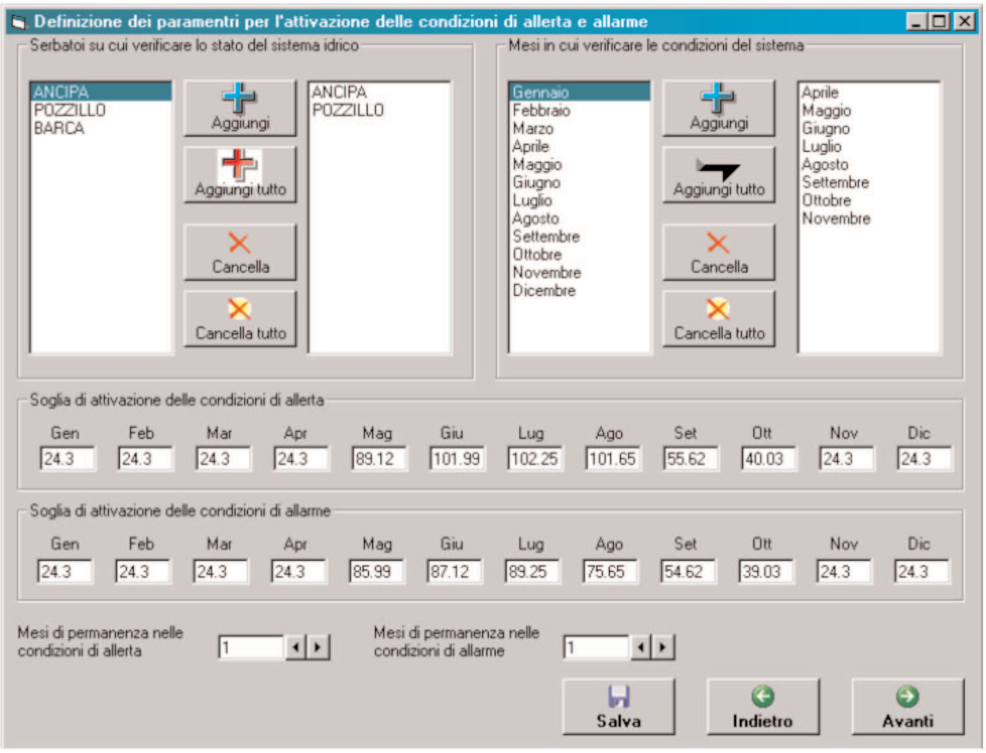


Fig. 24. Definition of the monthly thresholds to trigger alert and alarm condition to which correspond different mitigation measures.

Thus, for instance, if in a given month water availability is less than the trigger defined for the hydrological state characterized by normal conditions the system will switch from normal condition to alert conditions, implementing the corresponding drought mitigation measures. The measures can consist in release hedging, release reduction to the water demand reduction levels for each type of demand, fulfilment of municipal demand before other uses, etc.

The system will remain in alert or alarm conditions for a period of time defined by the user; at the end of this pre-defined period SIMDRO will re-check the hydrological state of the system switching to different states if it is the case.

The different management configurations, to which correspond the different drought mitigation measures in alert or alarm conditions are listed below:

(i) priority of demands;

(ii) priority of sources to meet a specified demand;

(iii) maximum release in a given month;

(iv) maximum in stream ecological release for a given month;

(v) minimum stored volume on reservoirs under which not consider low priority demands;

(vi) demands and their monthly distribution.

As an example Fig. 25 shows the definition of the management configuration of the system for normal conditions; similar windows have to be filled by the user in order to represent the mitigation measures to be implemented in alert or alarm conditions.

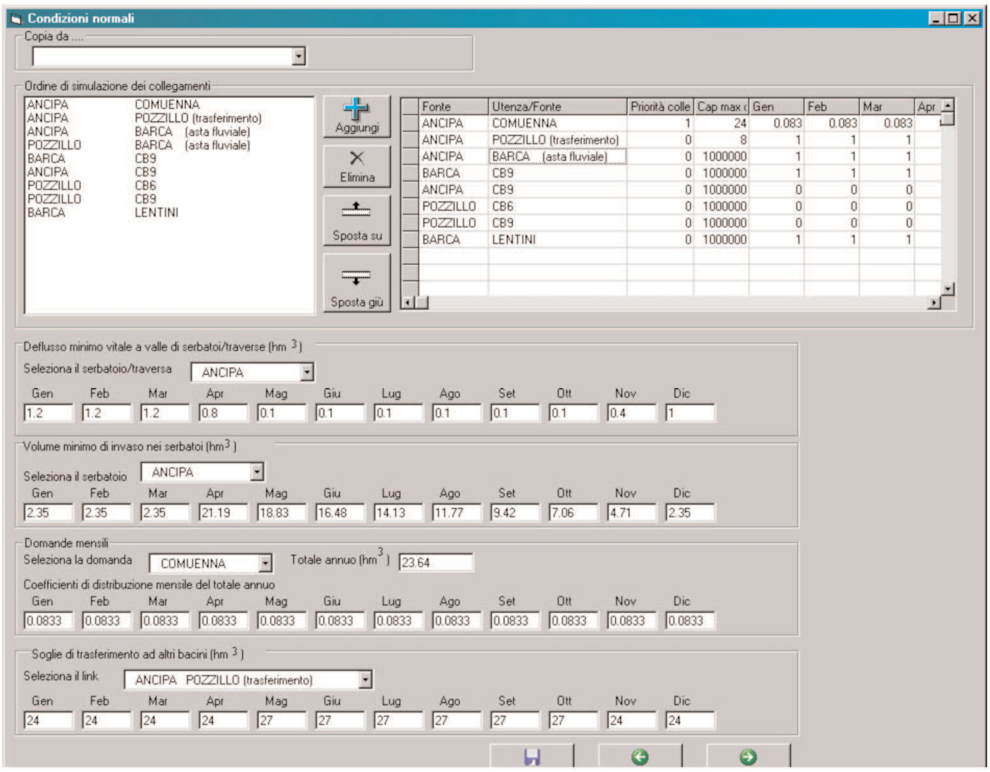


Fig. 25. Definition of the simulation of the system for normal conditions.

Results of the simulations can be represented in tabular or graphic form and some elaborations such as the probability of shortages belonging to different classes (0-25%, >25%-<50%, >50%-<75%, >75%-100%) expressed as percentage of the total demand for the different uses (Fig. 26) or the non-exceedence probability of monthly shortages (Fig. 27) are available. An examples of application of SIMDRO for the analysis of a complex water supply system is reported in the Chapter "Methods for risk assessment in water supply systems" of this document.

Calculation of Drought Indices - DrinC Software

For the calculation of three drought indices, the SPI, the Deciles and the RDI, the new software *DrinC – Drought Indices Calculator*, was developed at the Laboratory of Reclamation Works and Water Resources Management of the National Technical University of Athens. *DrinC* is a stand-alone PC software and operates on Windows platforms (Fig. 28).

The input data are the annual or monthly precipitation for the calculation of Deciles and SPI, while potential evapotranspiration (PET) data are also required for the calculation of RDI.

In order to improve the interface of the software the input and output files are in MS Excel worksheet format. The data files are selected in the File Management window (Fig. 29). For the calculation of the indices in annual basis, data may be either annual or monthly, while for calculations in seasonal basis (monthly, 3-months, 6-months), monthly data are required. The software includes an algorithm in order to recognize automatically the position of the data and to ignore other information included in the file.

The calculation of the indices is performed from the Indices window (Fig. 30). Each index (or all indices at once) will be calculated by ticking in the relevant boxes. The outputs may be saved either in separate files, or in the same file for all the indices. For each index there are different output options. For the Deciles each decile threshold may be displayed in the output file, whereas for the RDI, each one of the different forms of the index can be selected for output. Four time steps are available for calculation: monthly, 3-months, 6-months and annual.

For more information about DrinC the reader can refer to the website *www.ewra.net/medbasin/DrinC.html.*

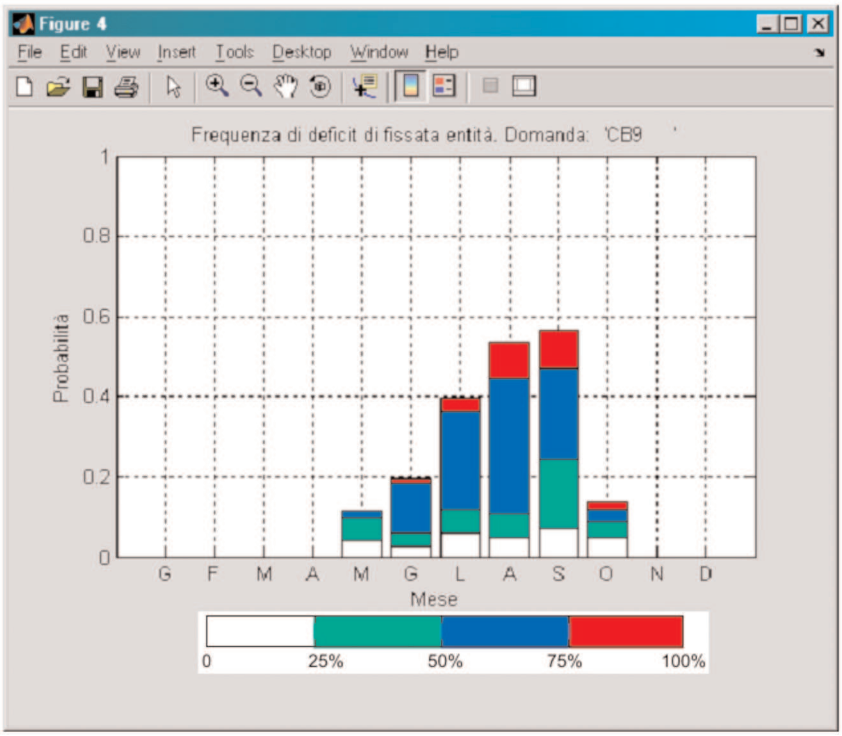


Fig. 26. Probability of shortages belonging to different classes expressed as percentage of the total demand.

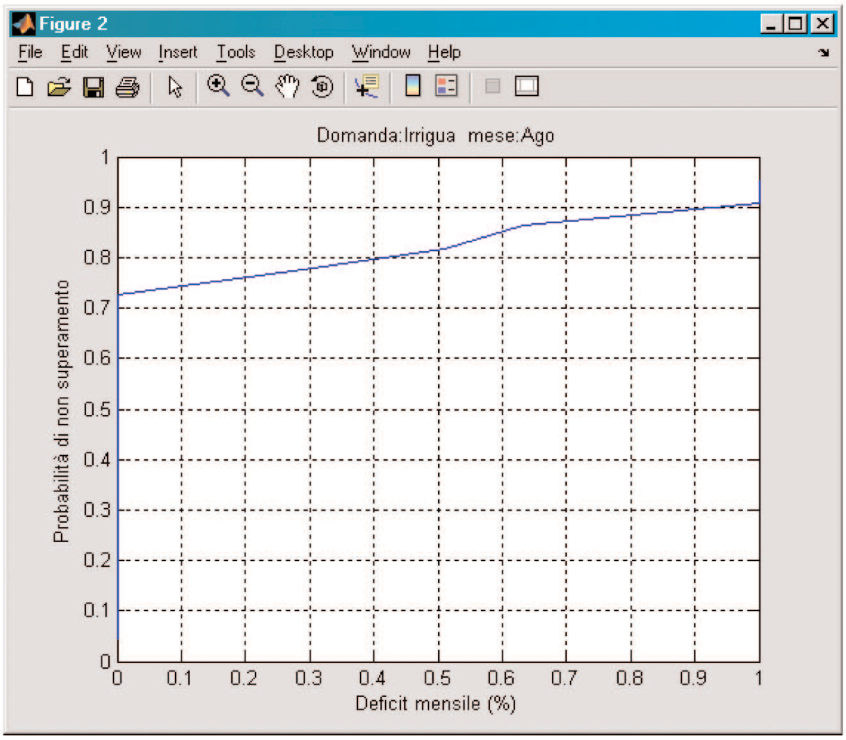


Fig. 27. Non-exceedence probability of monthly shortages.

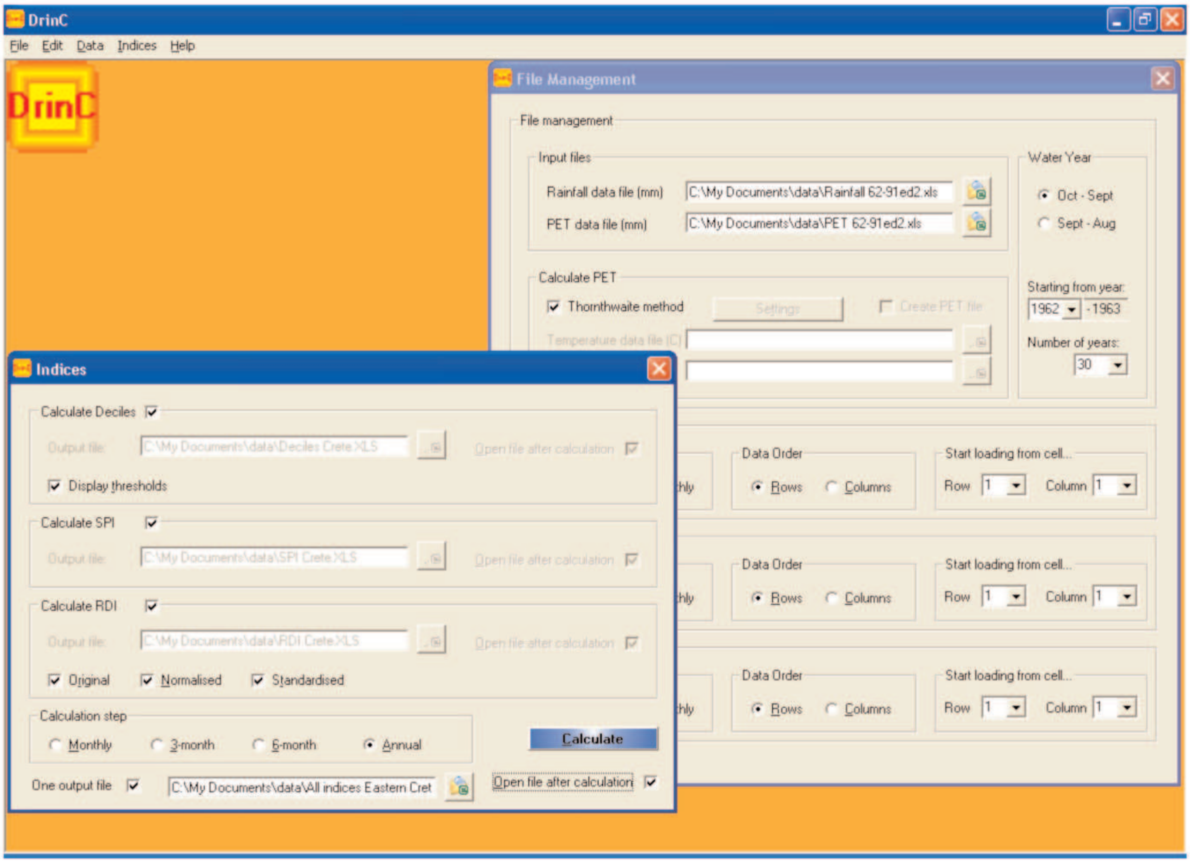


Fig. 28. Main window of DrinC software.

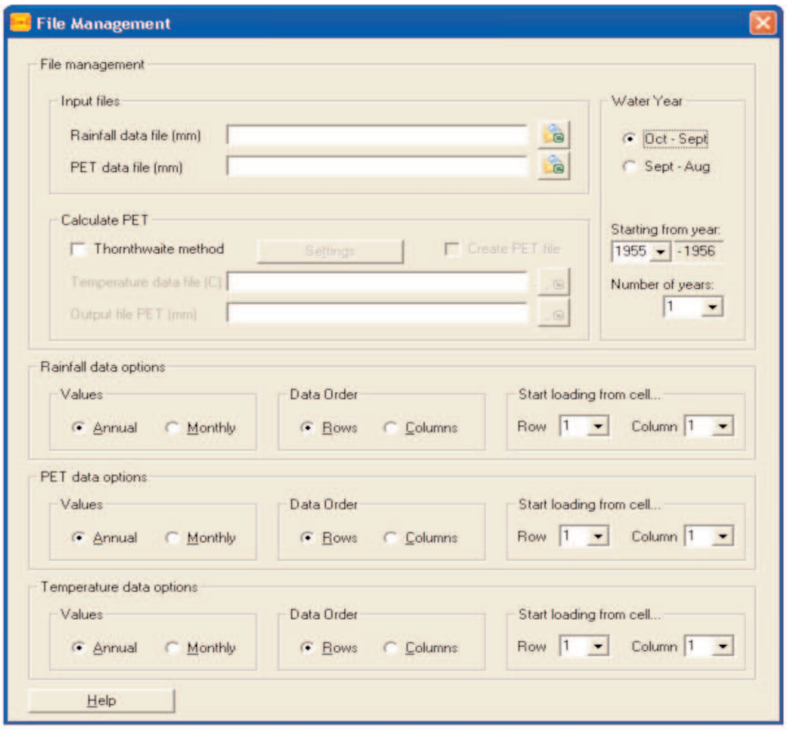


Fig. 29. File management window.

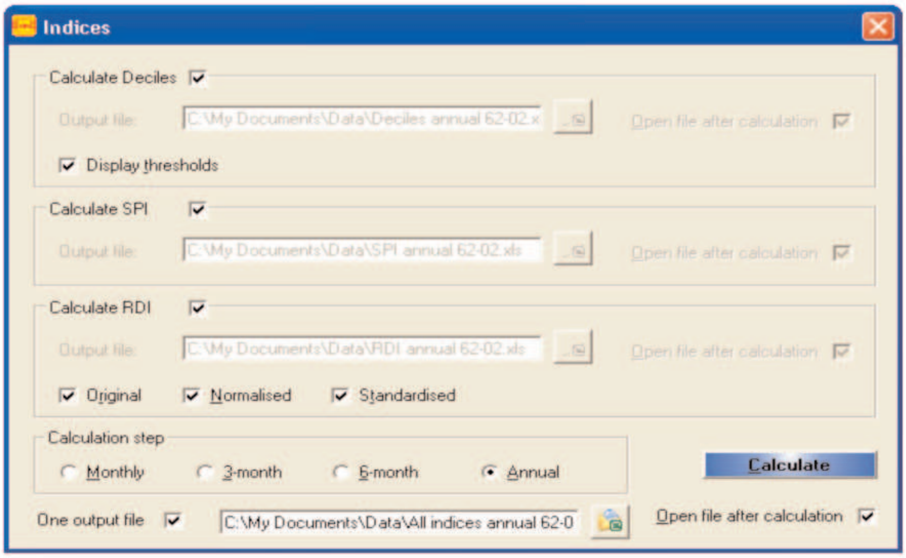


Fig. 30. Indices calculation window.

WEAP

The Water Evaluation and Planning model Version 21 (WEAP21) attempts to address the gap between water management and watershed hydrology and the requirements of an effective integrated water resources management that can be useful, easy to use, affordable, and readily available to the broad water resource community.

WEAP 21 presents a user-friendly, geographically based interface helping the user to understand the hydrological system of the basin. A conceptual model of the hydrologic cycle is defined for each sub-catchment using a semi-distributed water balance approach that yields streamflow and groundwater recharge throughout the watershed (Yates, 1996; Yates and Strzepek, 1998). It operates at a monthly step on the basic principle of water balance accounting. The user represents the system in terms of its various sources of supply (e.g. rivers, groundwater, and reservoirs), withdrawals, water demands, and ecosystem requirements (Fig. 31).

WEAP applications generally involve the following steps (SEI, 2001):

(i) Problem definition including time frame, spatial boundary, system components and configuration.

(ii) Establishing the current accounts', description of the average situation that provides a snapshot of actual water demand, resources and supplies for the system.

(iii) Building scenarios based on different sets of future trends for policies, technological development, and other factors that affect demand, supply and hydrology.

(iv) Evaluating the scenarios with regard to criteria such as adequacy of water resources, demand satisfaction, costs, benefits and environmental impacts.

This model has a long history of development and use in the water planning arena and presents several advantages that make it a very useful tool in water management:

(i) It uses a Water balance database: provides a system for maintaining water demand and supply information.

(ii) It has scenario generation tools: simulates water demand, supply, runoff, streamflows, storage, pollution generation, treatment and discharge.

(iii) It can apply Policy analysis tools: evaluates a full range of water development and management options, and takes account of multiple and competing uses of water systems.

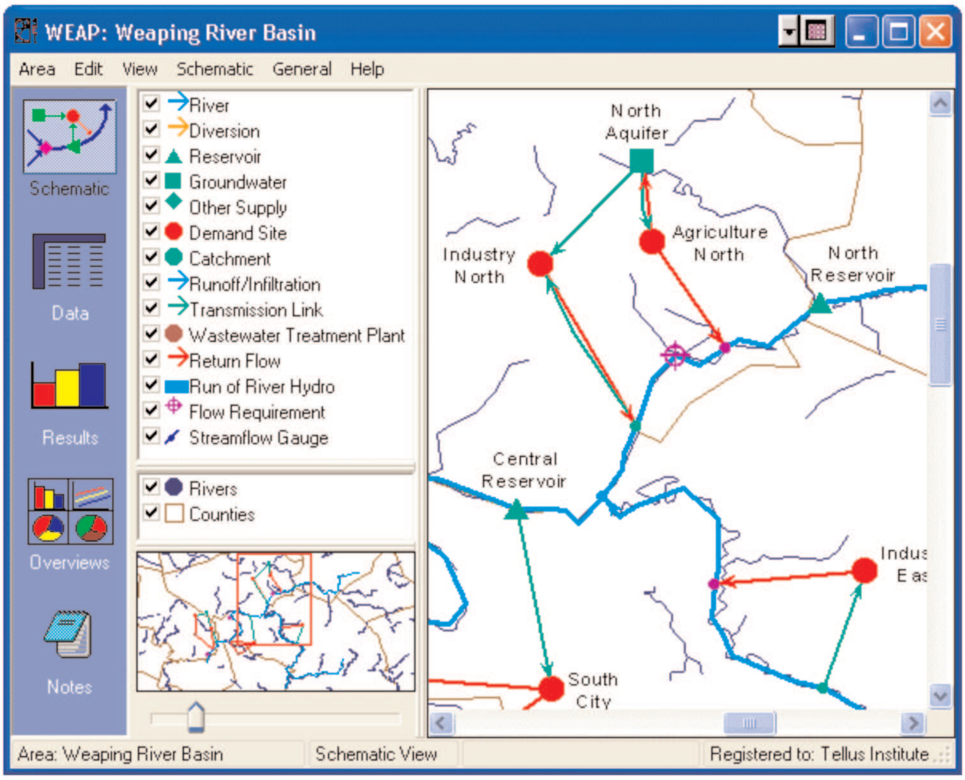


Fig. 31. Schematic view of WEAP.

The scenarios can address a broad range of "what if" questions, such as: What if population growth and economic development patterns change? What if ecosystem requirements are tightened? What if irrigation techniques and crop patterns are altered? What if various demand management strategies are implemented? What if water availability changes? What if drought frequency increases?

An intuitive graphical interface provides a simple yet powerful means for constructing, viewing and modifying the system and its data. The main functions –loading data, calculating and reviewing results– are handled through an interactive screen structure. WEAP also has the flexibility to accommodate the evolving needs of the user: e.g. availability of better information, changes in policy, changes in demand priorities, planning requirements or local constraints and conditions (Levité *et al.*, 2003).

WEAP21 model simulations are constructed as a set of scenarios, where simulation time steps can be as short as one day, to weekly, to monthly, or even seasonally with a time horizon from as short as a single year to more than 100 years. The use of this kind of model is especially relevant for evaluating the consequences of drought management on the hydrological system and the changes in demand satisfaction. The different drought management actions can be applied in order to evaluate the results over the hydrological system and propose an optimal combination through simulations.

Agricultural models

In the context of drought risk analysis in agricultural systems, the use of agricultural models can be useful for several reasons:

(i) Evaluate changes in water demand for the different crops, regions and meteorological conditions.

(ii) Evaluate changes in leached water quality due to the variations in water availability.

(iii) Evaluate the adaptation of different crop varieties to drought.

(iv) Evaluate the consequences of changes in irrigation periods as a measure for drought adaptation.

The methods for assessing crop production in different meteorological conditions and adaptation strategies are extensively developed and used widely by scientists, extension services, commercial farmers, and resource managers.

There is a number of different approaches to assess the impacts of climate on agriculture and many studies have been developed to date. Approaches used to assess biophysical impacts include:

(i) Agroclimatic indices and geographic information systems (GIS).

(ii) Statistical models and yield functions.

(iii) Process-based models.

Process-based models use simplified functions to express the interactions between crop growth and the major environmental factors that affect crops (i.e., climate, soils, and management), and many have been used in climate impact assessments. Most were developed as tools in agricultural management, particularly for providing information on the optimal amounts of input (such as fertilizers, pesticides, and irrigation) and their optimal timing. Dynamic crop models are now available for most of the major crops. In each case, the aim is to predict the response of a given crop to specific climate, soil, and management factors governing production. Crop models have been used extensively to represent stakeholders management options (Rosenzweig and Iglesias, 1998).

The ICASA/IBSNAT dynamic crop growth models (International Consortium for Application of Systems Approaches to Agriculture – International Benchmark Sites Network for Agrotechnology Transfer) are structured as a decision support system to facilitate simulations of crop responses to management (DSSAT – Decision Support Tool for Agrotechnology Transfer). The ICASA/IBSNAT models have been used widely for evaluating climate impacts in agriculture at different levels ranging from individual sites to wide geographic areas (see Rosenzweig and Iglesias, 1994, 1998, for a full description of the method). This type of model structure is particularly useful in evaluating the adaptation of agricultural management to climate change or extreme weather events.

The DSSAT models use simplified functions to predict the growth of crops as influenced by the major factors that affect yields, i.e., genetics, climate (daily solar radiation, maximum and minimum temperatures, and precipitation), soils, and management. Models are available for many crops; these have been validated over a wide range of environments and are not specific to any particular location or soil type. Modeled processes include phenological development, growth of vegetative and reproductive plant parts, extension growth of leaves and stems, senescence of leaves, biomass production and partitioning among plant parts, and root system dynamics. The models include subroutines to simulate the soil and crop water balance and the nitrogen balance.

The primary variable influencing each phase of plant development is temperature. Potential dry matter production is a function of intercepted radiation; the interception by the canopy is determined by leaf area. The dry matter allocation to different parts of the plant (grain, leaves, stem, roots, etc.) is determined by phenological stage and degree of water stress. Final grain yield is the product of plant population, kernels per plant, and kernel weight. To account for the effect of elevated carbon dioxide on stomatal closure and increased leaf area index, a ratio of transpiration under elevated CO_2 conditions to that under ambient conditions is added.

The DSSAT software includes all ICASA/IBSNAT models with an interface that allows output analysis (Fig. 32).

Crop models are assisting tools for assessing the vulnerability and adaptation to climate variability: the stakeholder participation is essential. A mandatory first step is that technical stakeholders need assemble field agricultural data for calibration and validation of the crop models. Subsequently, regional stakeholders evaluate the representativeness of the agricultural model results for spatial upscalling of the model results. Table 2 summarizes some of the essential data needed as input for the model and the potential sources for these data.

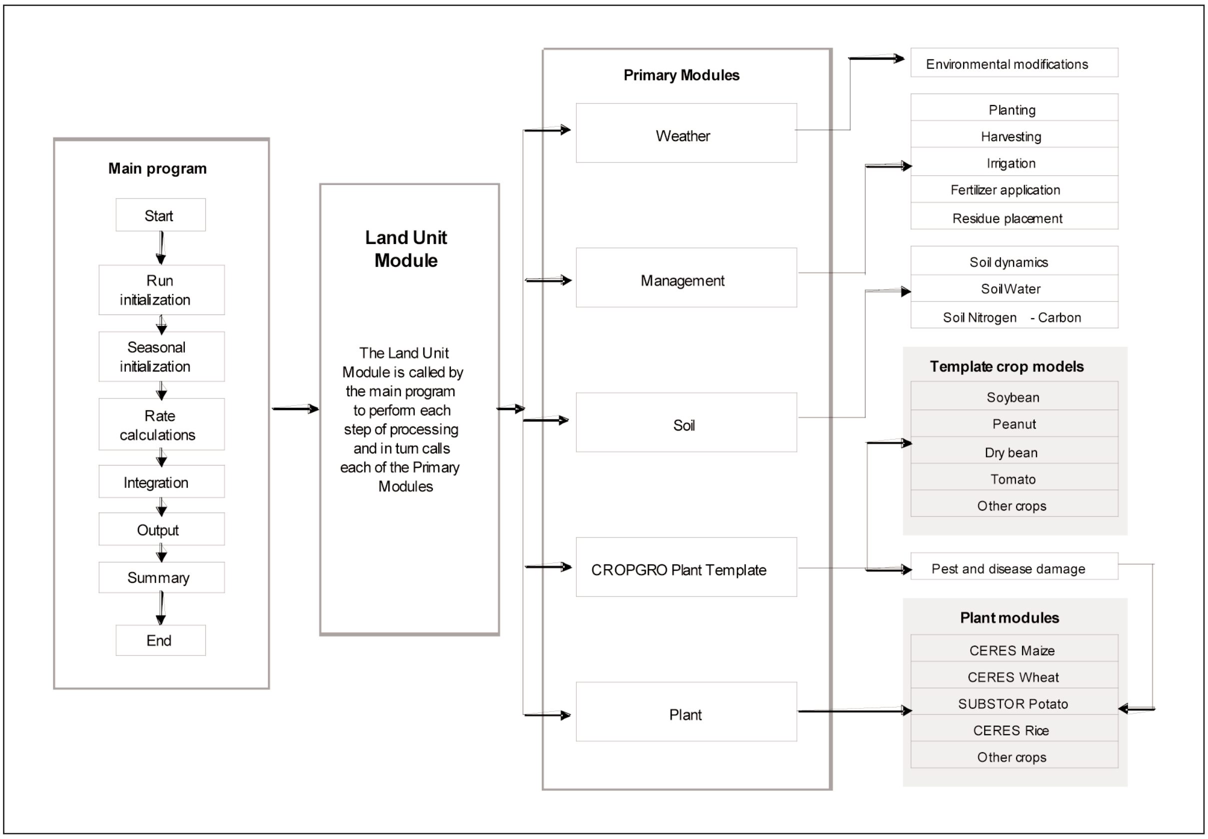


Fig. 32. Structure of models included in DSSAT.

Table 2. Input data for DSSAT and potential sources

Type of data	Requirements	Source of data
Average climatic conditions	Daily maximum and minimum temperatures and solar radiation for at least a 20-year period	National meteorological or research institutions. Daily data simulated from monthly averages.
Modified conditions (drought event conditions)	Modified daily maximum and minimum temperatures, precipitation, and solar radiation for a period of drought	National meteorological or research institutions
Crop management	Crop variety, sowing date and density, fertilizer and irrigation inputs (dates and amounts)	Agricultural research institutions
Soils	Soil albedo and drainage, and a description of the different layers of the soil profile (texture, water holding capacity, organic matter, and nitrogen)	Agricultural or hydrological research institutions
Economics (optional)	Cost of labor and price of unit production	Agricultural statistics
Outputs: Variables included in the summary output file are the main phenological events, yield and yield components		

References

Cavadias, G. and Morin, G. (1986). The combination of simulated discharges of hydrological models. Application to the WMO intercomparison of conceptual models of snowmelt runoff. *Nordic Hydrology*, 17: 21-32.

Giakoumakis, S., Tsakiris, G. and Efremides, D. (1991). On the rainfall-runoff modelling in a Mediterranean region environment. In: *Advances in water resources technology*. Tsakiris G. (ed). A. A. Balkema Publishers, Rotterdam.

Levité, H., Sally, H. and Cour, J. (2003). Testing water demand management scenarios in a water-stressed basin in South Africa: application of the WEAP model. *Physics and Chemistry of the Earth*, 28: 779-786.

Nicolosi, V., Cancelliere, A. and Rossi G. (2007a). Drought risk analysis in water supply systems using genetic algorithms and Montecarlo simulation. In: *Proceedings of the EWRA Conference: Water Resources Management: New Approaches and Technologies*, Chania, Crete - Greece, 14-16 June 2007.

Nicolosi V., Cancelliere A. and Rossi G. (2007b). Risk analysis for mitigating drought impacts on an irrigation water supply system. In: *Proceedings of the ICID 22nd European Regional Conference*, Pavia, Italy, 2-7 September 2007.

Rosenzweig, C. and Iglesias, A. (eds) (1994). *Implications of Climate Change for International Agriculture: Crop Modeling Study. EPA 230-B-94-003*. U.S. Environmental Protection Agency, Washington, DC.

Rosenzweig, C. and Iglesias, A. (1998). The use of crop models for international climate change impact assessment. In: *Understanding Options for Agricultural Production*, G.Y. Tsuji, G. Hoogenboom and P.K. Thornton (eds). Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 267-292.

Rossi, G. and Cancelliere, A. (2003). At-site and regional drought identification by REDIM model. In: *Tools for drought mitigation in Mediterranean regions*, G. Rossi, *et al.* (eds). Kluwer Academic Publishing, Dordrecht, pp. 37-57.

Schenkeveld, M.M. (1971). *Study of water resources and their exploitation for irrigation in eastern Crete. Watershed of Messara basins*. Food and Agriculture Organization of the U.N. - Working document No. 24. Iraklio, Greece.

SEI (2001). *WEAP (Water Evaluation and Planning): User Guide for WEAP21*. Stockholm Environment Institute, Boston USA. Available from <www.seib.org/weap/>.

Tigkas, D. and Tsakiris, G. (2004). Medbasin: A Mediterranean rainfall – runoff software package. *European Water*, 5-6: 3-11

Tigkas, D., Pangalou, D., Vangelis, H. and Tsakiris, G. (2005). On the assessment of drought scenarios in the river basin of Nestos using the new drought index RDI. In: *Proceedings of the 5th Conference of GCWRM 'Integrated Water Resources Management on River Basin Scale*'. D.U.TH., Xanthi; 487-492 (in Greek).

Tsakiris G., Tigkas D. and Pangalou D. (2004). On the assessment of climatic and drought scenarios on runoff in Mediterranean island river basins. In: Proceedings of EWRA International Symposium, Water Resourses Management: Risks and Challenges for the 21st century, Harmancioglu N. *et al.* (ed.), Izmir, Turkey, 2-4 September 2004. Vol. 2, pp. 627-647.

Underhill, H.W., Schenkeveld, M.M. and Goodwill, I.M. (1970). *Study of water resources and their exploitation for irrigation in eastern Crete. Trials of mathematical watershed model for runoff simulation*. Food and Agriculture Organization of the U.N. - Provisional document, Iraklio, Greece.

World Meteorological Organization (WMO) (1975). *Intercomparison of conceptual models used in operational hydrological forecasting*. *Operational Hydrology Report No. 7*. WMO – No 429. Secretariat of the WMO, Geneva, Switzerland.

World Meteorological Organization (WMO) (1986). *Intercomparison of models of snowmelt runoff. Operational Hydrology Report No. 23*. WMO – No 646. Secretariat of the WMO, Geneva, Switzerland.

World Meteorological Organization (WMO) (1992). *Simulated real-time intercomparison of hydrological models. Operational Hydrology Report No. 38*. WMO – No. 779. Secretariat of the WMO, Geneva, Switzerland.

Yapo, P.O., Gupta, H.V. and Sorooshian, S. (1998). Multi – objective global optimisation for hydrologic models. *J. Hydrol.*, 204: 83-97.

Yates, D. (1996). WatBal: An integrated water balance model for climate impact assessment of river basin runoff. *Water Resources Development,* 12, No. 2: 121-39.

Yates, D. and Strzepek, K. (1998). Modeling the Nile Basin under Climatic Change. *Journal of Hydrologic Engineering,* 3, No. 2: 98-108.