

Constructing synthetic time series of rainfall events for a hyperarid environment, southern Arava, Israel

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Abstract A method is proposed for simulating a long-term event-related daily precipitation series in a hyperarid environment. The method permits a rapid and relatively easy way to manipulate the time series to simulate not only the present climate, but other assumptions regarding past changes in rainfall properties too. The method is applied to the hyperarid environment (30 mm year^{-1} , 2–10 rain-days year^{-1}) of the southern Arava, Israel. The properties of a synthetic 1000 year daily precipitation record were compared with a dataset from Eilat. The annual rainy-days distribution of the synthetic series and the actual data were found to be similar and the stochastic precipitation procedure accurately simulated both the mean and the variance of annual precipitation amounts. Our approach allows better sensitivity analyses, since the basic parameters (such as seasonality, rainfall amounts, number of rain days, daily rainfall amounts) can be tested separately or combined with other parameters in terms of the impact on model outcome.

Key words Arava Valley; daily precipitation; hyperarid environment; Negev, rainfall modelling; reg soil; soil water balance; stochastic modelling

INTRODUCTION

In recent years computerized models have been constructed to test palaeoclimatic hypotheses and to simulate long-term processes in natural open systems such as the soil environment. In particular, computer models have been developed to simulate the relations between climate, soil water balance and the distribution of pedogenic properties in semiarid and arid environments (McFadden, 1982; McFadden & Tinsley, 1985; Marion *et al.*, 1985; Mayer, 1986; Mayer *et al.*, 1988; Marion & Schlesinger, 1994; McDonald *et al.*, 1996). Each of these soil modelling efforts faces a dichotomy: on one hand, the model is based on short duration measured present-day climatologic hydrological data, and yet on the other hand the model has to simulate soil forming processes over thousands of years. This dichotomy was solved through various analytical approaches and statistical tools to produce synthetic time series, but still remains a basic problem in modelling efforts.

In extremely arid regions such as the Arava Valley in southern Israel and Jordan (Fig. 1), the rainfall pattern consists of isolated rainfall events with long dry spells in between (Sharon, 1972, 1979; Wheater *et al.*, 1991a). The impact of a rain event upon the

soil and the ground surface is closely related to their respective initial conditions as influenced by the previous rain event and the subsequent dry spell (McFadden *et al.*, 1991; O'Connell & Todini, 1996). Thus for modelling purposes, an event-related, long-term precipitation time series should be constructed (Mayer, 1986). The synthetic rain generators should determine not only the annual or monthly precipitation amounts. They should go one step further and determine single precipitation events that are scattered through the year in a way such that their frequency and magnitude resemble the actual data set. Although the time series is composed of a chain of single events, the statistics of the synthetic series as a whole should resemble the actual data set (Marion *et al.*, 1985; Wheeler *et al.*, 1991a,b). A method to produce such a precipitation time series is described below.

Computer models and precipitation time series

Rainfall is the key input variable, which activates flow and mass transport in rainfall–runoff–soil moisture–groundwater systems (O'Connell & Todini, 1996). A significant deficiency in computer models is the difficulty of simulating a time series of the distribution and magnitude of individual precipitation events. In long-term modelling of soil formation, some of the models use statistics of annual or monthly precipitation to produce time series (McFadden, 1982; McFadden & Tinsley, 1985; Mayer *et al.*, 1988). More recent models use daily precipitation records as their input to various approaches (Marion *et al.*, 1985; Marion & Schlesinger, 1994; McDonald *et al.*, 1996; Barzilay *et al.*, 1996, 1997). In the earlier efforts the major consideration in using monthly data was the saving of computing power when using monthly time steps instead of daily time steps over thousand to tens of thousands of years (Marion *et al.*, 1985). Another reason was the lack of modern data to support daily time steps. In hyperarid environments additional fundamental problems arise: individual rainstorms can last only tens of minutes during a single year yet control the series of rains. The conventional modelling approaches use statistics of the interval between rain events to produce time series. However, this method is unsuited for such conditions since the series tend to be unstable and differ from the actual data when the dry spells are long.

A closely related problem, and perhaps more challenging, is how to simulate temporal changes in climate, especially changes in climate associated with the Pleistocene–Holocene transition. In that case, two of the main climatic factors in question are again the distribution and magnitude of precipitation events.

Objectives

In recent studies of soil formation there has been a strong inclination to incorporate physically realistic rainfall features into stochastic models with the hope of providing a sound basis for prediction (McFadden *et al.*, 1991; Marion & Schlesinger, 1994; McDonald *et al.*, 1996; O'Connell & Todini, 1996). In seeking a way to characterize the behaviour of rainfall in time and space, various stochastic modelling approaches have been adopted (Cowperton *et al.*, 1996a). One approach, namely point rainfall models characterizing a time series of rainfall at a single point (Cowperton *et al.*, 1996b), has been used in the above-mentioned soil water balance models for arid soils.

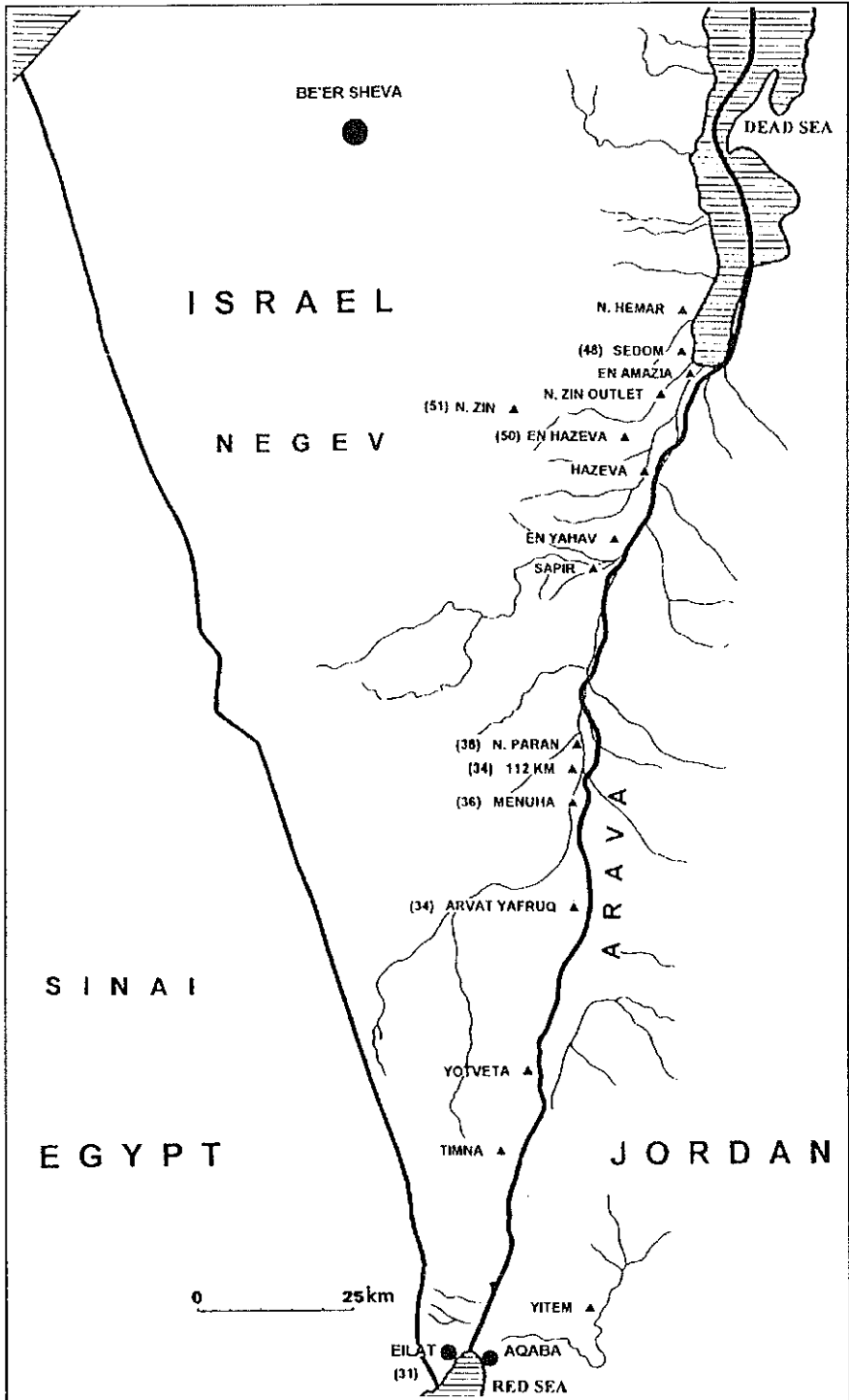


Fig. 1 Study area and rainfall gauging stations (▲) in the Arava region with their average annual precipitation.

Here we propose a method to simulate a long-term event-related daily precipitation series in a hyperarid environment. This method permits a rapid and relatively easy way to manipulate the time series to simulate not only the present climate, but other assumptions regarding changes in the rain properties over time as well. This method has been successfully used as an input for the GYPREG model for reg soil development in the hyperarid environment of the southern Arava, Israel (Fig. 1), (Barzilay *et al.*, 1996, 1997).

Study area

The southern Arava is a narrow valley within the Dead Sea Rift. Its width reaches only 8–10 km and it is approximately 70 km long from the Gulf of Eilat (Fig. 1) to the central Arava. The climate in the southern Arava valley is extremely arid. Mean annual precipitation is 30 mm with a standard deviation of 20 mm and an annual variation of 58% (Katsnelson, 1979). Most of the annual rainfall occurs during the rainy season (October–May) in one or two short-duration storms. Thus a drought or even an extreme rainstorm can alter the mean annual precipitation by 25–32 mm year⁻¹. The mean annual temperature is 25°C, with a mean daily range of 14°C. The highest and lowest temperatures records are 47.4°C and 1.2°C (Bitan & Rubín, 1991). The annual potential evaporation is 2600 mm (Dan, 1981). The mean annual humidity near Eilat on the northern coast of the gulf is 40–45% (Bitan & Rubín, 1991).

PRECIPITATION IN THE SOUTHERN ARAVA

Data sources

Although the area is situated in a hyperarid zone, 18 rainfall gauging stations exist along the Arava Valley of Israel (Meteorological Service of Israel database, 1998), (Fig. 1, Table 1). Nine of these stations provide daily rainfall measurements while the other stations provide only annual precipitation amounts. Only the stations at Sedom, Yotveta and Eilat have operated for a relatively long period (Table 1). The Sedom station has a record of 40 years, including three years (1980–1982) with partial records. The Yotveta station has operated since 1949 except for a gap of eight years (1968–1974). The records of many years at this station are incomplete. The Eilat station provides partial records since 1941, with a complete record since 1949. In addition to the 18 stations mentioned above, a network of rain recorders and rain collectors were operated in the Negev and southern Arava during 1972–1975 and 1983–1988 (Sharon, 1979; Karni, 1992). Two Jordanian meteorological stations, Aqaba and Yitem, are located within 15 km of Eilat (Sharon, 1979).

Rainfall characteristics

The annual precipitation along the Arava valley decreases from 50 mm in Sedom to 25–32 mm in Eilat (Bitan & Rubín, 1991) (Fig. 1). The synoptic conditions contributing to the majority of rain events are related either to the Red Sea trough, or western cold fronts and frontal rain-bearing depressions originating from the Mediterranean, which

Table 1 Location and periods of operation of rainfall gauging stations in the Arava.

Location of station	Period of operation	Measurements	Average annual precipitation (mm)
N. Hemar	1974–1998	Yearly	
Sedom	1959–1988	Daily	48
N. Zin outlet	1961–1998	Yearly	53
N. Zin	1960–1998	Yearly	51
Ein Amaziah	1961–1998	Yearly	50
Ein Hazeva	1940–1950	Daily	
Hazeva	1955–1998	Yearly	
Hazeva	1966–1969, 1972–1976, 1987–1998	Daily	
Ein Yahav	1950–1966, 1984–1987	Daily	
Sapir	1981–1993	Daily	
N. Paran	1949–1998	Yearly	38
112 km	1959–1998	Yearly	34
Menuha	1958–1998	Yearly	36
Arvat Yafruq	1949–1998	Yearly	34
Yotveta	1949–1998	Daily	
Timna	1989–1998	Yearly	
Timna	1955–1975	Daily	
Eilat	1949–1998	Daily	31

pass at an extreme southern trajectory above the southern Negev and Sinai (Sharon, 1972, 1979; Katsnelson, 1979; Karni, 1992). The western systems occur mainly during the mid-winter and result in regional rainstorms of low to moderate intensities and of relatively long duration. The rains associated with the Red Sea troughs occur during fall (autumn) and spring and are characterized by the development of relatively small convective rain cells of short duration and high intensities (Sharon, 1972, 1979; Katsnelson, 1979; Sharon & Kutiel, 1986; Karni, 1992).

The southern Arava receives a relatively high percentage of convective rains (Sharon, 1972). These small convective rain cells that produce local showers are both temporally and spatially isolated from each other (Sharon, 1979; Wheeler *et al.*, 1991a). Hence, the spottiness of the rainfall events in the Arava observed when comparing records of adjacent stations over short periods of time (Sharon, 1972). One would assume that this spottiness of rainfall would rule out a modelling approach since the data obtained at any station cannot be used even within a relatively short distance from it. However, when comparing longer records from the same stations it was found that the number of rain events and the similar annual averages indicate that the storm cells hit at random (Sharon, 1979). Furthermore, Karni (1992) concluded that the records of the Eilat station represent well the other meteorological stations in the southern Arava and that the records of the Sedom station represent well the northern Arava. The boundary between the two groups is approximately 70 km north of Eilat (Karni, 1992).

METHODS AND PROCEDURES

Database

The database from which the synthetic series were produced contained all the daily precipitation records at the Eilat station, recorded during rain years 1950–1994 (Fig. 2).

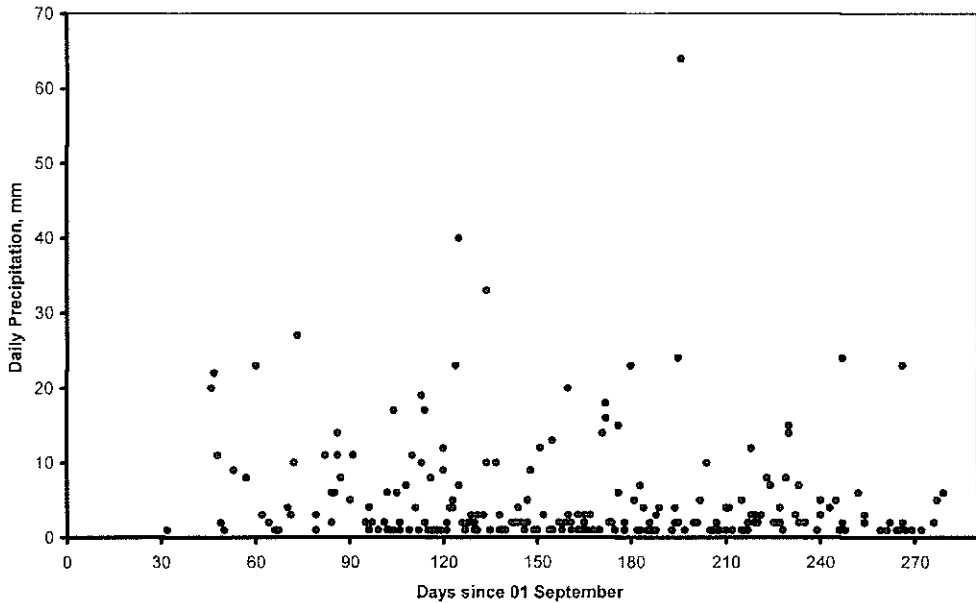


Fig. 2 Daily precipitation records of the Eilat station of the Israeli Meteorological Service (rain years 1950–1994).

The meteorological stations in Israel record precipitation amounts exceeding 0.1 mm day^{-1} . Such an amount of rain evaporates immediately after it reaches the ground in the hot and dry environment of Eilat. Therefore, only rain events exceeding 1 mm day^{-1} were included in the database, as was also recommended by Katsnelson (1979, p.60). Sharon (1979) used a higher (3 mm day^{-1}) threshold for a significant rain event. Karni (1992, p.43) preferred a threshold of 5 mm day^{-1} .

Rain events

The typical duration of local convective rain showers over the Eilat station is 5–15 min, whereas low-intensity regional rainfall events cover much larger areas for several hours (Sharon, 1979). The average duration of a rain event in Eilat is 5 h 20 min, with a standard deviation of 7 h, and a median of 3 h (Karni, 1992). Therefore, for modelling purposes, it was assumed that each rain event is confined within one-day time steps, and is not connected to either the previous rain event or the following one. Henceforth a precipitation event exceeding 1 mm of rain per day is referred to simply as a rainy day or a rain event.

RESULTS AND DISCUSSION

Simulating rainfall time series in dry climates

The stochastic modelling of rainfall time series has been an active research topic in hydrology for many years (Cowpertwait *et al.*, 1996a,b). More recently the importance

of a single storm and the importance of the length of the dry spell within a sequence of storms has been emphasized in soil modelling (Marion *et al.*, 1985; Mayer, 1986; Marion & Schlesinger, 1994; O'Connell & Todini, 1996). The number of rain events is considered as important to the understanding of climate as the rain depth itself, and perhaps even more. The method of an inter-arrival time lag technique is used to simulate rainfall time series in both wet and dry climates (Marion *et al.*, 1985; Marion & Schlesinger, 1994; Cowpertwait *et al.*, 1996a,b). However, it was noted that the synthetic time series derived from this method when using pure statistics tend to be unstable and differ from the actual data even in wet climates when the dry spells are long. The reason being that most of the series is composed of zero rainfall amounts (Cowpertwait *et al.*, 1996a).

Therefore, when this method is used, models must be modified and trimmed. Marion *et al.* (1985) adopted a more empirical approach for their CALDEP model for the formation of soils in the United States southwestern deserts ($80\text{--}380\text{ mm day}^{-1}$). They divided the year into seasons and calculated the cumulative distribution of inter-arrival time lag between rains. A random number generator was used to draw a proper time-interval for every iteration. In the hyperarid climate of the southern Arava even this method is problematic. An approach based on sampling from the distributions of rain-day inter-arrival times tested for southwest Saudi Arabia was unsatisfactory. Difficulties arose owing to the carry-over of long dry periods from dry to wet months (Wheater *et al.*, 1991a).

The average number of rainy days per year in Eilat is five and the average interval is 34 days (Table 2; Fig. 3). Furthermore, over the entire 45 year record there were only 22–28 rainy days in each of the winter months, an average of half a rainy day per winter month each year. The fall and spring months witnessed a total of only 7–16 rainy days over the entire record. Two of the winter seasons were totally dry, 23 and 24 of the fall and spring seasons, respectively, were dry. Twelve years had both dry fall and dry spring (Table 2). Thus the use of an inter-arrival time approach for this area is inappropriate. Here we present a method that approaches the problem in a different and more appropriate way for extreme arid environments.

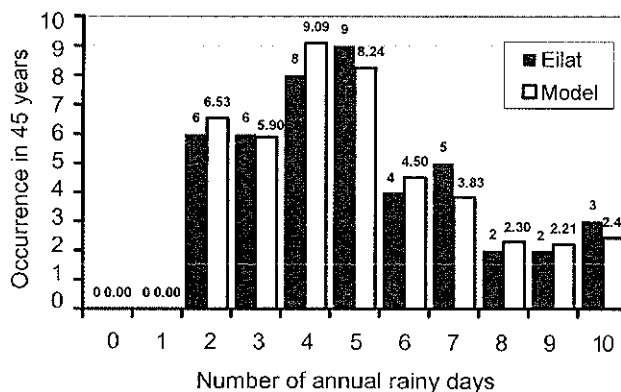


Fig. 3 The rain-days distributions of the Eilat station and the 1000 years synthetic series (the calculated synthetic-series probabilities multiplied by 45).

Table 2 Recorded distributions of rain events within a rain year, grouped by seasons, for the Eilat rainfall station (rain years 1950–1994). The table lists number of yearly rain events (Total), the distribution of the events according to the seasons (Fall, Winter, Spring), number of similar occurrences (Occurrences), and their rank (Rank).

Total	Fall	Winter	Spring	Occurrences	Rank
2	0	1	1	1	1
2	0	2	0	3	2, 3, 4
2	1	0	1	1	5
2	1	1	0	1	6
3	0	2	1	1	7
3	0	3	0	2	8, 9
3	2	0	1	1	10
4	0	3	1	3	11, 12, 13
4	0	4	0	3	14, 15, 16
4	1	2	1	1	17
4	1	3	0	1	18
4	2	1	1	1	19
5	0	4	1	2	20, 21
5	0	5	0	2	22, 23
5	1	4	0	4	24, 25, 26, 27
5	2	3	0	1	28
6	0	5	1	1	29
6	1	5	0	1	30
6	2	2	2	1	31
6	2	3	1	1	32
7	0	3	4	1	33
7	0	4	3	1	34
7	0	7	0	2	35, 36
7	2	3	2	1	37
8	1	6	1	1	38
8	1	7	0	1	39
8	2	5	1	1	40
9	0	6	3	1	41
9	1	8	0	1	42
10	1	4	5	1	43
10	2	8	0	2	44, 45

Rain events: temporal and magnitude distributions

The rain years within the database were ranked according to the number of rainy days per year (Table 2). A rain year is a period of 365 days starting on 1 September and ending on 31 August.

As mentioned earlier, a difference between the rain producing mechanisms is evident for the different seasons. Hence, following Karni (1992), the rainy days were grouped for each rain year according to the seasons, fall: October, November; winter: December, January, February and March; spring: April and May. The outcome of these

two procedures is a ranked list of 45 possibilities of mother-type rain years. Each mother-type year represents a group of rain years that have the same number of rainy days for each season and, therefore, the same number of rainy days per year.

These 45 mother-type rain years are used to produce a synthetic precipitation time series. The synthetic series is a string of years where each and every one of them can be grouped to one of the mother-type rain years listed in Table 2.

Each of the synthetic years which the model produces is similar, but not identical to, a mother-type year in the database. The synthetic rain years and their mother-type year share the same number of rainy days per season. However, each synthetic year has a different rain-day distribution within each season. Therefore, the dates of rain events within a season are random.

The dates for the rain events within each season are chosen using a uniform distribution and then rain amounts for each event are produced. Each amount is calculated separately from a monthly log normal distribution (Table 3). The log normal distributions parameters were calculated based upon a dataset containing all the rainy days that occurred during each month. Hence, the probability of a rain event of a certain magnitude is more closely related to the changing patterns within the seasons.

Creation of the synthetic rain-years series

The procedure uses the mother-type rain-years and the log normal distributions of the rain amounts that were discussed above. The procedure is described step by step below (see example in Fig. 4).

- (a) Select a mother-type year by choosing a random number from 1–45 (from Table 2).
- (b) Read number of rain events during the fall. If none, go to step (e).
- (c) Read number of rain events during the winter. If none, go to step (h).
- (d) Read number of rain events during the spring. If none, go to step (m).
- (e) Select fall rain event date by choosing a random number between 1–60 (October and November).
- (f) If there are more rain events during the fall, repeat step (e). If the date selected was selected previously, repeat step (c).
- (g) Select winter rain event date by choosing a random number between 1–120 (December, January, February and March).
- (h) If there are more rain events during the winter, repeat step (g). If the date selected was selected previously, repeat step (g).
- (i) Select spring rain event date by choosing a random number between 1–60 (April and May).
- (j) If there are more rain events during the spring, repeat step (i). If the date selected was selected previously, repeat step (i).
- (k) Fit to each of the rain events a probability (a random number between 1–100).
- (l) Fit each probability with the proper amount of precipitation according to the log normal distribution function of the month.
- (m) End of procedure.

Table 3 Log normal distribution of daily rainfall amounts for each month in Eilat. All daily rainfall amounts (rain years 1950–1994) are given and ranked for each month. The parameters of the log normal distribution are given for each month and for each season.

Rank	October	November	December	January	February	March	April	May
1	23	27	40	33	64	18	34	11
2	22	14	23	20	24	16	24	9
3	20	11	19	13	23	15	23	7
4	11	11	17	12	15	14	20	6
5	9	11	17	10	10	12	6	5
6	8	10	14	10	7	8	5	4
7	2	8	12	9	6	8	5	3
8	1	6	11	5	5	7	4	2
9	1	6	10	4	5	7	3	2
10	1	5	9	3	4	5	3	2
11		4	8	3	4	4	2	1
12		3	7	3	4	4	2	
13		3	7	3	3	4	2	
14		3	6	3	3	4	2	
15		2	6	3	2	3	2	
16		2	6	3	2	3	1	
17		2	5	3	2	3	1	
18		1	4	2	2	3	1	
19		1	4	2	2	3	1	
20		1	4	2	2	3	1	
21		1	4	2	2	2	1	
22			3	2	2	2	1	
23			3	2	2	2	1	
24			2	2	2	2		
25			2	2	1	2		
26			2	2	1	2		
27			2	1	1	2		
28			2	1	1	2		
29			2	1	1	2		
30			2	1	1	1		
31			2	1	1	1		
32			2	1	1	1		
33			2	1	1	1		
34			2	1	1	1		
35			1	1		1		
36			1	1		1		
37			1	1		1		
38			1	1		1		
39			1	1		1		
40			1	1		1		
41			1	1				
42			1	1				
43			1	1				
44			1	1				
45			1					
46			1					
47			1					
48			1					
49			1					
50			1					
51			1					
52			1					
Average	0.7204	0.609 359	0.465 863	0.358 958	0.456 356	0.450 909	0.470 086	0.572 738
Stdev.	0.583 022	0.427 238	0.458 535	0.407 286	0.462 850	0.390 059	0.503095	0.325 115
Average	Fall	0.645 209		Winter	0.432 774		Spring	0.503 297
Stdev.		0.475 869			0.429 586			0.450 714

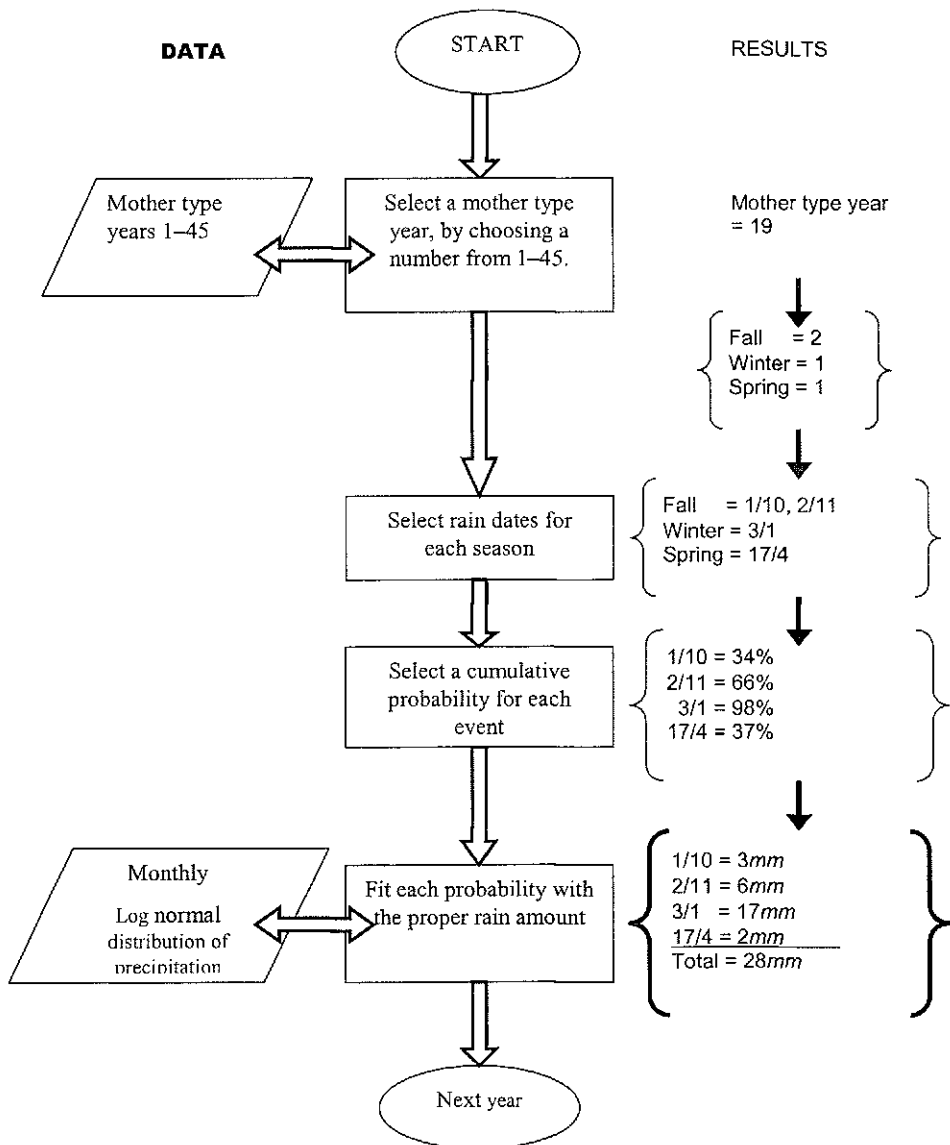


Fig. 4 A flow chart outlining the procedure constructed for producing synthetic rain-years series for the southern Arava. Data sets are shown at the left side and an illustration of the results is shown in brackets.

Model validation

The properties of a synthetic 1000 year daily precipitation record are compared with the actual data set from Eilat.

- The annual rainy day distribution of the synthetic series and the actual data are similar. This indicates that the rainy day generator of the synthetic series is stable and produces a good representation of the original data set (Fig. 3).

- The average annual precipitation record (>1 mm) at Eilat is 28 mm per year. The 1000 years average is 27.5 mm year⁻¹ (Fig. 5). This is very similar to the actual data.
- The stochastic precipitation procedure accurately simulated both the mean and the variance of annual precipitation amounts (Fig. 5).

Therefore we conclude that the synthetic time series generator represents well the precipitation in the southern Arava.

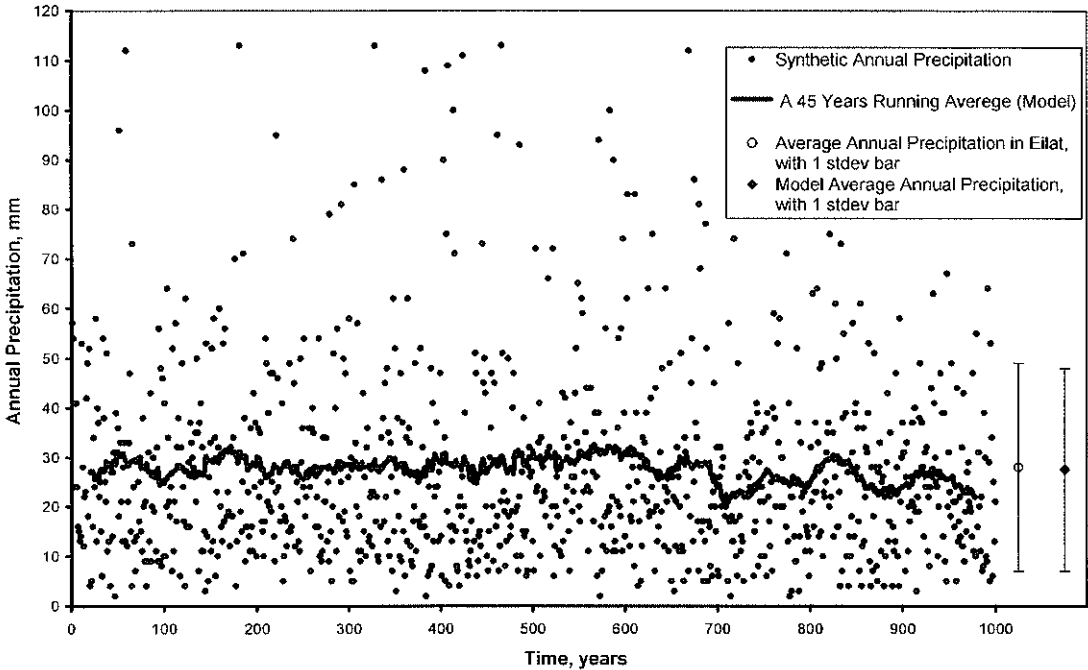


Fig. 5 The average annual precipitation in Eilat, compared to the running 45 years average and an overall average of the synthetic time series.

Changing rainfall properties

Several approaches have been used to achieve a good analogue for the change in rainfall properties due to a climatic change. One approach was to use contrasting sets of actual precipitation data from widely different regions to simulate changes between warm/dry and cold/moist climatic regions (e.g. Mayer *et al.*, 1988). Another approach was to create new rainfall datasets by modifying data for a single site. It is done either by arbitrarily decreasing and/or increasing monthly precipitation values by a factor (McFadden, 1982; McFadden & Tinsley, 1985; Mayer *et al.*, 1988) or by changing the number of rainy days (Marion *et al.*, 1985; Marion & Schlesinger, 1994). A third approach was to typify wet and dry conditions by the use of actual data sets of daily precipitation years representing current wet and dry years (McDonald *et al.*, 1996).

The method we propose allows one to simulate alternative precipitation hypotheses by doing one of the following: (a) increasing or decreasing the daily precipitation

amounts for each month, season or year, by a factor, or (b) altering the number of events by changing the probability of scoring any year of the 45 years within the database. This approach allows for better sensitivity analyses since the basic parameters (such as seasonality, rainfall amounts, number of rain days, daily rainfall amounts) can be tested separately or combined with other parameters in terms of the impact on the model outcome.

CONCLUDING REMARKS

The overall objectives of the rainfall modelling are to summarize the essential characteristics of daily rainfall in stochastic formulations that provide the basis for generating synthetic rainfall sequences as an input to another model (Wheater *et al.*, 1991a).

As in all hyperarid environments of the world, the rainfall properties in the southern Arava are difficult to simulate in the long-term. While the inter-arrival time lag technique was found inappropriate, we offer another data-related method for the extreme arid environment of the southern Arava.

A 1000 year run demonstrated that the resulting synthetic time series is stable and its properties resemble the statistical properties of the database it originated from.

The method we propose allows a simple way of simulating alternative precipitation hypotheses by changing either the magnitude or frequency of the daily precipitation amounts. This approach permits better sensitivity analysis of the modelled environmental parameters.

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