Assessment of daily catchment precipitation in mountainous regions for climate change interpretation

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Abstract Many recent researchers have ventured a physical modelling of mean areal precipitation with a view to ensuring an appropriate analysis of climate change. Preliminary results of a simple, practical and dynamic integration method of incomplete daily precipitation data for a mountainous catchment are presented here. This is a combinatorial technique of the Thiessen method and precipitation gauge availability. The estimated catchment precipitation is corrected for elevation variations. This double technique preserves, to a large extent, the physical structure of precipitation information which is vital for climate change interpretation. Furthermore, the proposed method can handle successfully any change in the gauge network, the greatest limitation of the inflexible Thiessen method.

Estimation de la précipitation journalière de bassins des régions montagneuses en vue d'interpréter les changements climatiques

Résumé Beaucoup de chercheurs se sont récemment attachés à la recherche d'un modèle de précipitation régionale moyenne, ceci afin de réaliser une analyse correcte des modifications climatiques. On trouvera ici les résultats préliminaires d'une intégration simple, pratique et dynamique de données de précipitations journalières incomplètes recueillies dans un bassin montagneux. Il s'agit d'une technique combinant la méthode de Thiessen et la disponibilité des différents appareils de mesure. La précipitation sur le bassin ainsi estimée est corrigée en fonction des variations d'altitudes. Cette double technique préserve dans une large mesure la structure physique des informations concernant les précipitations, qui est fondamental pour interpréter correctement les modifications climatiques. De plus, la méthode proposée peut bel et bien s'accommoder de toute modification du réseau de mesure, modification qui limite habituellement l'inflexible méthode de Thiessen.

INTRODUCTION

The reliable assessment and prediction of mean areal precipitation in a mountainous region on a catchment scale and for a daily time interval has been one of the most difficult problems of surface hydrology. The problem becomes more acute for reasons of climate change interpretation and adjustment, which

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require areal precipitation modelling to be as physical and accurate as possible (Klemeš, 1985; Becker & Němec, 1987; Hutchinson, 1990; Barros & Lettenmaier, 1993).

The predictions of long term climate change which resulted from General Circulation Models (GCMs) are scientifically an interesting but also controversial subject. GCMs are physical-mathematical models of climate in which the equations of classical physics (including the laws of motion and the requirements for conservation of heat and mass) are solved in a three-dimensional grid with a horizontal spacing of 250-800 km (Mitchell & Qingcum, 1991). The GCM fluxes (i.e. precipitation, heat and runoff), integrated into areas of the order of 10^5-10^6 km^2, are highly simplified. Furthermore, it is doubtful whether GCM predictions on time scales shorter than one month do reflect the natural variability of field data. The few attempts to validate GCM simulations of present surface meteorological conditions using field surface meteorological data (Rind *et al.*, 1989; Grotch, 1988) are limited only to long term climatic averages over large areas.

In surface hydrology, many models are related to catchment scale (100-1000 km^2) (Gleick, 1987), with authors accepting such meteorological inputs (precipitation, temperature, etc.) as are integrated into daily time steps. These space-time necessities require reliable and accurate GCM climatic predictions which do not yet exist.

Although many publications are focused on one-way nested modelling from the macroscale to the mesoscale, and on the parameterization of land-atmosphere interaction in GCMs (e.g. Giorgi & Mearns, 1991; Thomas & Henderson-Sellers, 1991; Avissar & Verstraete, 1990), these strategies have critical shortcomings for the space-time variability of precipitation. They cannot represent the dynamic feedback between the fine and coarse scales, which, for GCM applications, is equivalent to neglecting the dynamics of land-atmosphere interactions except within a limited mesoscale region for the current time step. Further, the parameterization of subgrid-scale processes without reference to spatial location precludes preservation of consistency across scales (Thomas & Henderson-Sellers, 1991). On the other hand, statistical approaches, such as fractal and self-similar representations, may be useful for short term, localized, dynamical state-space modelling, but the lack of their physical determinism places medium and long term diagnosis or prognosis beyond their scope (Namias, 1980). This latter shortcoming is also present in the stochastic models which are used for disaggregation of GCM climate simulations to point sequences of precipitation for input to catchment scale hydrological models (e.g. Hay *et al.*, 1992; Wilson *et al.*, 1992; Bárdossy & Plate, 1991).

Thus, some studies are directed towards a coupling of atmospheric circulation simulations with surface hydrology (e.g. Becker & Němec, 1987), while some others are focused on point or areal rainfall estimation and prediction models with a sound physical interpretation (Hutchinson, 1990; Georgakakos & Bras, 1984a,b; Georgakakos & Hudlow, 1984; Georgakakos, 1986; Lee & Georgakakos, 1990; Oki *et al.*, 1991; Barros & Lettenmaier, 1993). These last are more-or-less weather models and, in a preliminary sense, they are appropriate for calibrating the rates of climate change.

The Hutchinson model, based on a three-state continuous Markov occurrence process is the only up-to-date stochastic model incorporating sound physical processes, yet it is limited to point rainfall descriptions. A multisite weather model of this kind would be more promising.

Many meteorological variables such as cloud precipitation, surface air temperature, dew point temperature, evaporation of cloud drops, etc., are parameterized in the models proposed by Georgakakos & Bras (1984a,b), Georgakakos & Hudlow (1984) and Georgakakos (1986). These models, used for hourly areal precipitation rate predictions and developed for small- and medium-sized hydrological basins (100-1000 km^2), could be promising for climate change studies, but their use of radar data (Georgakakos & Krajewski, 1991), including many measurement errors (e.g. solid precipitation effects on reflectivity), diminishes their effectiveness. The Georgakakos & Krajewski study (1991) on the worth of radar data to nonadvective physically based models does not account for systematic errors in radar data, while at the same time it underscores the importance of the investigation of errors in mean areal precipitation estimates. The consensus of the authors, that a two-dimensional model including both advection and convection dynamics of the type described by Lee & Georgakakos (1990) could statistically describe the spatial structure of radar measurement errors, must be substantiated.

The study by Oki *et al.* (1991) on spatial rainfall distribution in a storm event (with 1-hour data interval) in mountainous regions, is also a preliminary step to the interweaving of meteorology and hydrological modelling on a basin scale. A three-dimensional numerical model of the hydrostatic atmosphere, including basin orography estimated by wind direction and the area of ascending air, was used for basin orographic rainfall. This model, just as its developers recognized, is not a sound physical model, but rather a conceptual one for which the precise mechanism of action is still unknown. Had this model included water vapour, convective clouds, evaporation and such other processes as are important to intense rainfall representation, it would probably provide a strong physical structure, most appropriate for estimating the rate of climate change.

More recently, Barros & Lettenmaier (1993) used a multigrid method to better describe the numerical representation of the interaction between land-surface singularities (e.g. mountain ranges) and large-scale circulation features that control the space-time distribution of precipitation. They established "a numerical analogue of a telescope consisting of a network of grids from the GCM scale (100-500 km) to the local scale (5-10 km)". The problem with their method is that it served only the study region and did not offer any global solution, resulting in not being able to use this method for an investigation regarding the impact of land-atmosphere interactions on climate.

In addition to the models discussed above, several simpler methods for mean areal precipitation estimation, based on complete or incomplete raingauge records, are available. These methods include the common and simple techniques of arithmetic mean, Thiessen polygons (1911), inverse-distance, inverse-distance-squared, and other nearest neighbour interpolation schemes. Also, there are some other more sophisticated interpolation methods, such as surface-fitting techniques (Duchon, 1976; Paihua & Utreras, 1978), double Fourier series (Thorpe *et al.*, 1979), so called optimal interpolation (Gandin, 1965; WMO, 1970), interpolation based on empirical orthogonal functions (Holmstrom, 1963, 1977) and kriging (Matheron, 1971; Delhomme, 1978), plus co-kriging techniques (Hevesi *et al.*, 1992a,b; Phillips *et al.*, 1992).

Such methods have been widely used for annual, monthly and hourly areal precipitation computation but not for daily estimation that is particularly required for hydrological simulation on a catchment scale area. Several studies (Hughes & Lettenmaier, 1981; Creutin & Obled, 1982; Tabios & Salas, 1985; Lebel *et al.*, 1987; Phillips *et al.*, 1992) have dealt with the comparison and further development of the methods. In some cases (e.g. for medium or high density raingauge networks, large space scales, etc.), the more sophisticated of them are not necessarily more accurate than the simplest ones (Lebel *et al.*, 1987; Phillips *et al.*, 1992). While all the methods present advantages and disadvantages, the disadvantages are stronger whenever missing daily data are to be interpolated. All the point data estimation methods produce computing errors (Georgakakos & Krajewski, 1991; Wallis *et al.*, 1991). Even the purely statistical ones are not totally reliable nor more promising (i.e. the climatological kriging methods of Delfiner & Delhomme (1973); Chua & Bras (1982), Kitanidis (1983), Hevesi *et al.* (1992) and Phillips *et al.* (1992)), because they make partial use only of the global statistical information contained in the overall precipitation data. Furthermore, the statistical methods cannot preserve the physical structure of precipitation data. Thus, the daily catchment precipitation obtained with such methods is less physical and so its use in climate change studies may lead to wrong conclusions.

In this paper, the daily catchment precipitation over a mountainous region is assessed from incomplete point records with a simple and practical method aimed at preserving the physical structure of the areal data series especially required for climate change interpretation. The missing daily values of station records are not estimated, but the existing ones are integrated, introducing the concept of a "station availability condition" and using combinatorial and sorting analysis. The estimated catchment precipitation is also corrected for elevation variations. The other orographic and climatological parameters (e.g. orientation, slope, exposure, zonal index, etc.) (Oki *et al.*, 1991) are not considered in the spatial distribution of the daily precipitation in this study. On the other hand, several of the aforesaid meteorological parameters can be taken into account in snow accumulation and ablation (pseudo-precipitation) models, which accept as input the spatially distributed daily precipitation. These parameters can be estimated in the calibration process of the snowmelt models (e.g. elevation zone separation, snow corrective factor (SCF)) which consider vapour transfer, drifting, etc.

STATION AVAILABILITY AND INTEGRATION DATA

A station is available on a given day when it furnishes precipitation information for that particular day. In contrast, a station is unavailable when no daily precipitation information is known. Beyond the missing values of precipitation data in a record, there are also cases of inconsistent and suspicious values. The problem of inconsistency concerns the sum of the daily values which cannot be confirmed by the archival monthly value of the same month. Suspicious data can be spotted when daily precipitation values are negative or too high (e.g. greater than 500 mm), or when a station monthly value is recorded as 0, while nearby stations have monthly recorded values significantly greater than zero. For both these questionable cases, inconsistent and suspect daily and monthly precipitation values are rejected and it is assumed that the monthly and daily data for that month do not exist. They are represented instead by the unavailability of their corresponding stations.

In mathematical terms, an available station is represented by 1 and a non-available station by 0 (binary numbers). The juxtaposition in consecutive words of 1 or 0 items constructs the condition of station availability which, when applied to daily data, gives the condition of daily station availability. For n stations, the availability conditions based on binary number operation (Spiegel, 1974), are defined by the matrix a_{ij}, where $i = 1, 2, \ldots, (2^n - 1)$ and $j = 1, 2, \ldots, n$. If there are six stations, there are 63 availability conditions (and one completely unavailable condition). Examples of these are: 111111 which denotes that all the stations are available, 101011 which reflects that the second and fourth are unavailable (the other four being available), and 100001 which means that only the first and sixth station are actually available.

For the areal integration of daily precipitation data including missing values, station weights are evaluated through a Thiessen-like polygon method. This computation is done for all $(2^n - 1)$ combinations of station availability, thereby producing a matrix w_{ij} of all possible combinations of weights. The actual weights to be used in w_{ij} are determined through the stations' daily availability condition a_{ij} as described in the following section.

In mountainous regions, precipitation gauge stations are usually installed in the valleys of these areas and cannot possibly catch and record correctly the precipitation occurring at higher elevations. Even though there may be stations installed at high elevations, these are often susceptible to recording incorrectly. For this reason, on many occasions, one would rather compute the areal precipitation from records of stations that are installed at lower elevations, correcting accordingly for the elevation variations concerned. In hydrological modelling, the catchment precipitation is corrected for mean catchment elevation after a proper precipitation-elevation relationship has been established. In the case of incomplete records, one determines correction factors for every combination of station availability, thereby providing a λ_i matrix for all possible factor combinations. The actual factors to be used in the λ_i matrix are computed through the stations' daily availability condition a_{ij} as described below.

DAILY CATCHMENT PRECIPITATION

For determining daily catchment precipitation, the proposed method is based on an assumption similar to that of the Thiessen polygon method, i.e.:

> An available precipitation station is significant when the distance between that station and the centre of any finite element of a catchment is smaller than the corresponding distance of any other available station to that same element. Stations outside the catchment are not equally significant with respect to catchment precipitation.

In other words the significance of an available precipitation station is determined by its area of influence. For this reason, the catchment is divided into unit elements on a grid pattern as illustrated in Fig. 1. The element centres and the positions of stations are determined with the aid of x and y axes.

For every element, the distance between its centre and every available station position is computed. The weight 1 is attached to the nearest available station (the assumption). This procedure is repeated for all the unit elements. Adding up all the unit elements defines the catchment area, while the number of weight 1 elements of every available station divided by the total number of elements gives the weights of the available stations.

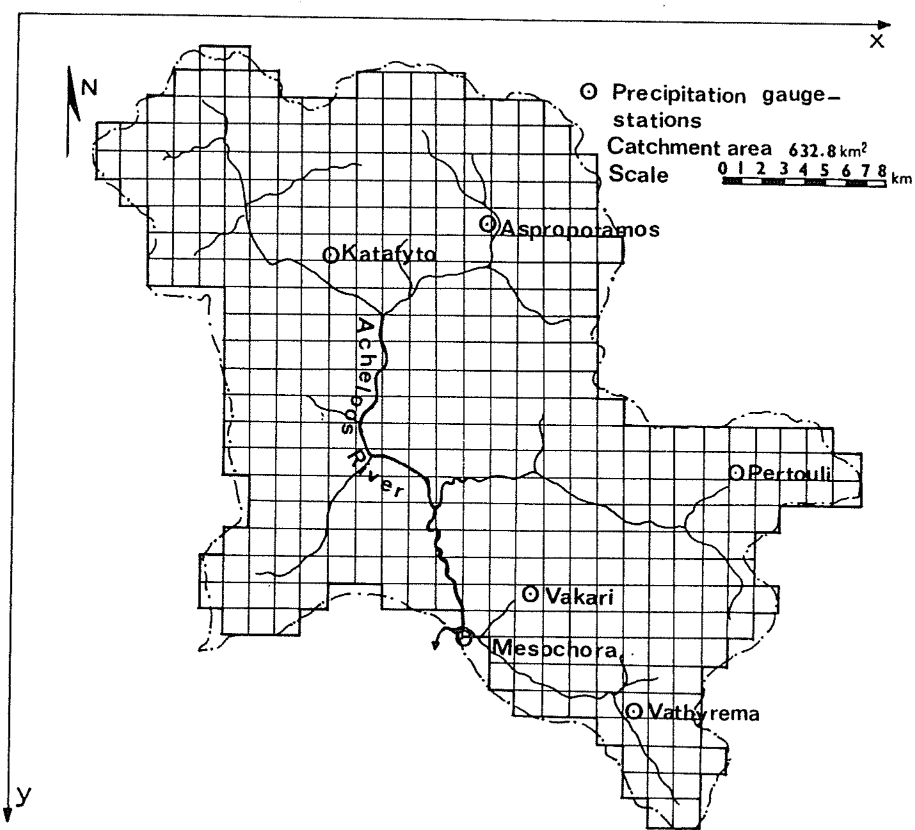

Fig. 1 Division of Mesochora catchment into 1.25 × 1.25 square unit elements.

Table 1 Station weights and correction factors

	Station availability	Station weights						Correlation coefficient	Regression line $y=\alpha x+\beta$		Corrective factor
		Aspropot	Kataphyto	Pertouli	Vakari	Mesochora	Vathyrema				
i	a_{ij}	w_{i1}	w_{i2}	w_{i3}	w_{i4}	w_{i5}	w_{i6}	R_{xy}	α	β	λ_i
1	000001	0.0	0.0	0.0	0.0	0.0	1.0				1.59360
2	000010	0.0	0.0	0.0	0.0	1.0	0.0				1.77041
3	000011	0.0	0.0	0.0	0.0	0.78272	0.21728				1.73199
4	000100	0.0	0.0	0.0	1.0	0.0	0.0				1.30311
5	000101	0.0	0.0	0.0	0.86914	0.0	0.13086				1.34113
6	000110	0.0	0.0	0.0	0.71852	0.28148	0.0				1.43465
7	000111	0.0	0.0	0.0	0.59012	0.28148	0.12840				1.47195
8	001000	0.0	0.0	1.0	0.0	0.0	0.0				1.29048
9	001001	0.0	0.0	0.68148	0.0	0.0	0.31852				1.38703
10	001010	0.0	0.0	0.36049	0.0	0.63951	0.0				1.59740
11	001011	0.0	0.0	0.33086	0.0	0.55802	0.11111				1.59198
12	001100	0.0	0.0	0.26173	0.73827	0.0	0.0				1.29981
13	001101	0.0	0.0	0.25185	0.65432	0.0	0.09383				1.32719
14	001110	0.0	0.0	0.26173	0.45679	0.28148	0.0				1.43134
15	001111	0.0	0.0	0.25185	0.37531	0.28148	0.09136				1.45801
16	010000	0.0	1.0	0.0	0.0	0.0	0.0				1.51782
17	010001	0.0	0.63704	0.0	0.0	0.0	0.36296				1.54532
18	010010	0.0	0.52099	0.0	0.0	0.47901	0.0				1.63881
19	010011	0.0	0.52099	0.0	0.0	0.26173	0.21728				1.60040
20	010100	0.0	0.51358	0.0	0.48642	0.0	0.0				1.41338
21	010101	0.0	0.51358	0.0	0.35556	0.0	0.13086				1.45140
22	010110	0.0	0.50370	0.0	0.37284	0.12346	0.0				1.46895
23	010111	0.0	0.50370	0.0	0.24444	0.12346	0.12840				1.50625
24	011000	0.0	0.61975	0.38025	0.0	0.0	0.0				1.43138
25	011001	0.0	0.59753	0.19753	0.0	0.0	0.20494				1.48844
26	011010	0.0	0.49877	0.20000	0.0	0.30123	0.0				1.54844
27	011011	0.0	0.49877	0.17037	0.0	0.21975	0.11111				1.54302
28	011100	0.0	0.50123	0.15062	0.34815	0.0	0.0	0.77543	1.03989	432.79	1.40883
29	011101	0.0	0.50123	0.14074	0.26420	0.0	0.09383				1.43621
30	011110	0.0	0.49136	0.15062	0.23457	0.12346	0.0				1.46440
31	011111	0.0	0.49136	0.14074	0.15309	0.12346	0.09136				1.49106

The values of the correction factor λ correspond to α = 1.19155 for the station availability combinations.

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Table 1 continued Station weights and correction factors

	Station availability	Station weights						Correlation coefficient	Regression line $y=\alpha x+\beta$		Corrective factor
		Aspropot	Kataphyto	Pertouli	Vakari	Mesochora	Vathyrema				
i	a_{ij}	w_{i1}	w_{i2}	w_{i3}	w_{i4}	w_{i5}	w_{i6}	R_{xy}	α	β	λ_i
32	100000	1.0	0.0	0.0	0.0	0.0	0.0				1.42941
33	100001	0.62222	0.0	0.0	0.0	0.0	0.37778				1.49144
34	100010	0.52593	0.0	0.0	0.0	0.47407	0.0				1.59107
35	100011	0.51111	0.0	0.0	0.0	0.27407	0.21481				1.55814
36	100100	0.49630	0.0	0.0	0.50370	0.0	0.0				1.36579
37	100101	0.49630	0.0	0.0	0.37284	0.0	0.13086				1.40381
38	100110	0.49136	0.0	0.0	0.35556	0.15309	0.0				1.43671
39	100111	0.49136	0.0	0.0	0.22716	0.15309	0.12840				1.47400
40	101000	0.64444	0.0	0.35556	0.0	0.0	0.0				1.38001
41	101001	0.59012	0.0	0.16790	0.0	0.0	0.24198				1.44581
42	101010	0.49136	0.0	0.17531	0.0	0.33333	0.0				1.51872
43	101011	0.49136	0.0	0.14568	0.0	0.25185	0.11111				1.51330
44	101100	0.49383	0.0	0.13086	0.37531	0.0	0.0	0.95882	6.20159	−5531.83	1.36383
45	101101	0.49383	0.0	0.12099	0.29136	0.0	0.09383				1.39121
46	101110	0.48889	0.0	0.13086	0.22716	0.15309	0.0				1.43474
47	101111	0.48889	0.0	0.12099	0.14568	0.15309	0.09136				1.46141
48	110000	0.54815	0.45185	0.0	0.0	0.0	0.0				1.46936
49	110001	0.24444	0.41481	0.0	0.0	0.0	0.34074				1.52203
50	110010	0.23457	0.32593	0.0	0.0	0.43951	0.0				1.60810
51	110011	0.21975	0.32593	0.0	0.0	0.23951	0.21481				1.57517
52	110100	0.20000	0.33333	0.0	0.46667	0.0	0.0	0.44910	1.98959	−731.33	1.39994
53	110101	0.20000	0.33333	0.0	0.33580	0.0	0.13086				1.43796
54	110110	0.20000	0.32346	0.0	0.35309	0.12346	0.0				1.45551
55	110111	0.20000	0.32346	0.0	0.22469	0.12346	0.12840				1.49281
56	111000	0.21235	0.43704	0.35062	0.0	0.0	0.0	0.29845	1.02648	232.57	1.41934
57	111001	0.21235	0.41481	0.16790	0.0	0.0	0.20494				1.47641
58	111010	0.20000	0.32593	0.17531	0.0	0.29877	0.0				1.53575
59	111011	0.20000	0.32593	0.14568	0.0	0.21728	0.11111				1.53032
60	111100	0.19753	0.33333	0.13086	0.33827	0.0	0.0	0.51220	1.91955	−660.50	1.39798
61	111101	0.19753	0.33333	0.12099	0.25432	0.0	0.09383				1.42536
62	111110	0.19753	0.32346	0.13086	0.22469	0.12346	0.0				1.45355
63	111111	0.19753	0.32346	0.12099	0.14321	0.12346	0.09136				1.48021

The values of the correction factor λ correspond to $\alpha = 1.91955$ for the station availability combinations.

The necessary computations are carried out for all possible combinations of available stations, resulting in the formation of a matrix w_{ij} that includes all the possible weights (see Table 1). The dimensions i and j in the w_{ij} matrix are the same as those of the matrix a_{ij}. The row number r_i required for any condition of station availability is determined by the following algorithm:

$$r_i = \sum_{j=1}^{n} 2^{n-j} a_{ij} \tag{1}$$

For instance, with six stations, the availability condition 111111 gives row 63 in the matrix w_{ij}, while the condition 010111 gives row 23 in the same matrix (Table 1). The station availability matrix a_{ij} is computed on a daily basis, while the w_{ij} matrix is used as a look-up table from which the actual weights for each available station configuration can be read. The weights are then used for computing the daily catchment precipitation from individual station precipitations. In addition, the monthly and annual catchment precipitation can be computed.

DAILY CATCHMENT PRECIPITATION CORRECTED FOR ELEVATION VARIATION

For adjusting daily catchment precipitation for elevation the proposed method includes:

1. Computation of mean catchment elevation (Panagoulia, 1991b,c).
2. Determination of a linear correlation between station elevation and mean annual station precipitation. The slope of the regression line constitutes an initial estimate of α, the rate of the precipitation variation with elevation. The final estimate of the rate can be determined by a trial and error procedure based on annual water balance considerations (total annual precipitation is often adjusted to achieve a long term balance between simulated and observed runoff (Lettenmaier & Gan, 1990)).
3. Evaluation of the weighted mean station elevation $\overline{e}_i$ according to station availability conditions. The matrix w_{ij} is used to estimate $\overline{e}_i$, the weighted mean elevation of stations:

$$\overline{e_i} = \sum_{j=1}^{n} w_{ij} e_j \tag{2}$$

   where, $i = 1, 2, \ldots, (2^n - 1)$, n is the number of precipitation stations and e_j is the set of station elevations. Every value of $\overline{e}_i$ is controlled by the station availability condition a_{ij} and gives the actual weighted mean elevation of available stations.
4. Estimation of correction factors λ_i for precipitation-elevation variation. Because the weighted mean station elevation depends on the station availability (step 3), a set of correction factors λ_i is defined for the variation of catchment precipitation with elevation. The set of possible

values of the correction factors λ_i is computed through the following algorithm:

$$\lambda_i = 1 + \frac{\overline{e}_c - \overline{e}_i}{h_c}\alpha \tag{3}$$

where e_c is the mean catchment elevation and h_c the annual catchment precipitation (without correction).

In general, the parameter α is a monotonic function of $(\overline{e}_c - \overline{e}_i)$, but its second derivative is negative, reflecting the fact that the rate of increase of mean precipitation with elevation decreases at high elevations. In this study, the determination of the α parameter was limited to an initial estimate derived from a linear regression of precipitation *vs* elevation for a selected group of stations.

The daily condition of station availability determines, from the set of possible correction factors, λ_i, the actual correction factor with which one multiplies the daily catchment precipitation for that day.

PROGRAMMING PROCEDURE

The method described above can be easily programmed, using five phases, (Panagoulia, 1990a; 1991b,c) namely:

(a) Station weights determination

By using the geometric characteristics of the catchment the station weights are computed and stored in order to use subsequently in the second phase. The required data are:

- Dimensions of the elements of the catchment division. (A good choice for large basins is in the order of 500-1500 m).
- Row number of elements for one of the axes x and y. Every row includes a set of elements depending on the size and shape of the catchment.
- Co-ordinates of the centre of the first and last element for every row.
- The number and co-ordinates of the precipitation stations.

(b) Determination of daily catchment precipitation

First the condition of daily station availability is determined, the actual weights for this condition are found, and then the daily catchment precipitation from the precipitation of the individual stations is computed. Subsequently the computation of monthly and annual catchment precipitation is a simple procedure. The required data are:

- Number of precipitation stations.
- Common ending year of station precipitation data.

- Beginning year of daily precipitation for every station in the files.
- Files of daily station precipitation.

(c) Computation of annual catchment precipitation

The annual catchment precipitation can be computed from the daily catchment precipitation obtained from phase (b) by a double summing. Firstly, the summing of daily catchment data for every month gives the monthly catchment precipitation, and in turn, the summation of monthly catchment precipitation over a year provides the annual catchment precipitation for that particular year.

If monthly or annual station precipitation data are independently available, the estimation procedure for annual catchment precipitation is simple and short, in contrast to use of daily station data which require more processing and computation time in order to yield the annual catchment precipitation. The mean annual catchment precipitation is the long term average of the annual precipitation.

(d) Computation of precipitation variation rate with elevation

The linear correlation line (correlation coefficient, α and β parameters) of mean annual precipitation *vs* station elevation is computed for all possible station combinations. Rejecting negative correlations (if any) assumed as not being compatible with precipitation-elevation variation reality, the focus is placed on positive correlation coefficients and slopes (the α parameter) for all possible subsets of the precipitation-elevation data (of three or more). Then, the median value of these slopes is taken as a robust estimator of the dependence of precipitation on elevation in the catchment. Thus the influence of high leverage points is diminished and does not drastically affect the estimated slope. For this phase, the required data are:

- Station availability conditions matrix.
- Mean annual station precipitation.
- Station elevations.

(e) Computation of correction factors

In this phase, the correction factors λ_i are computed. The required data are:

- Mean catchment elevation.
- Station elevations.
- α, the variation in precipitation rate with elevation.
- The annual catchment precipitation (without correction), h_c.

After this last step, firstly, the daily condition of station availability is determined; secondly, the actual factors λ_i (from the last phase) are found; and thirdly, the corrected daily catchment precipitations are computed by multiplying the daily catchment precipitation (from phase (b)) by the factors λ_i. The required data are the same as those of the second phase.

APPLICATION EXAMPLE

The method described has been applied to the Mesochora mountainous catchment of the Acheloos river in Greece (Fig. 1), on account of the projects now being constructed there for diverting the river to the arid Thessaly plain. The catchment area is 632.8 km^2 and has intense topography with strong interchanges of lower and higher elevations. The mean catchment elevation is 1390 m (Panagoulia, 1990b; 1991b,c,d). The unit elements in Fig. 1 are 1.25 × 1.25 km squares.

Inside the catchment boundary there are six hillslope precipitation stations (Fig. 1). The wind direction, orographic effects and prevailing humidity conditions of the region prevent the stations from catching and recording the true precipitation on many days in the year. These local conditions probably alter the reality of the precipitation-elevation variation. The daily station precipitation including incomplete data appear in Tables A1 to A6 of the Appendix. (Panagoulia, 1990a; 1991b,c). From the existing data, the daily precipitation-elevation relationship for the calendar year 1964 was estimated.

In the Tables, the missing data are represented by -, while the symbol • denotes the maximum daily value for every month. The availability and the possible weights of the six stations are presented in Table 1, while Table 2 includes the estimates of the daily catchment precipitation (without elevation correction) for the year 1964. The daily catchment precipitation series are complete because there were no days with missing values for all stations. So the monthly and annual catchment precipitation series are deemed to be complete, while some of the monthly and annual station precipitation series display nil data (represented by -) because daily series with no data cannot be processed.

The mean annual catchment precipitation has been estimated to be 1519.8 mm (Panagoulia, 1990b), while the linear correlation between annual precipitation and station elevation is considered for the following:

Station	Latitude	Longitude	Elevation (m)	Annual precipitation (mm)
Aspropotamos	39°39′	21°20′	1050.0	969.2
Kataphyto	39°38′	21°15′	980.0	1447.0
Pertouli	39°33′	21°28′	1160.0	1556.0
Vakari	39°30′	21°22′	1150.0	1716.7
Mesochora	39°29′	21°20′	780.0	1839.6
Vathyrema	39°27′	21°25′	920.0	2071.3

Table 2 Average precipitation (mm) for the catchment without elevation correction

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	0.00	2.59	11.63	5.07	0.53	0.00	1.65	3.08	0.00	0.00	1.40	66.67•
2	0.24	0.00	4.11	0.00	0.60	0.00	0.41	7.46•	2.96	0.00	7.23	40.71
3	6.80	0.00	0.00	0.00	0.00	0.00	0.00	0.19	20.44	0.22	9.58	13.01
4	20.94•	0.00	0.69	7.93	0.00	0.00	0.30	0.85	4.75	0.75	6.42	21.52
5	5.91	0.00	10.65	26.98•	0.00	0.00	0.00	0.00	0.00	0.00	0.83	31.12
6	0.44	0.48	1.61	3.95	0.00	0.00	0.20	0.00	0.00	7.29	51.55•	5.48
7	0.47	1.10	14.04	5.65	0.00	2.95	0.00	0.00	0.00	1.38	16.43	0.62
8	0.00	1.19	10.18	4.18	0.00	11.69	0.00	2.57	0.00	1.70	0.23	0.00
9	0.00	0.00	7.60	2.19	0.00	4.78	1.01	3.77	0.00	29.63	0.04	0.00
10	0.00	0.00	8.63	0.00	0.00	5.29	0.00	5.54	0.00	32.98•	22.37	0.00
11	0.00	0.22	0.14	0.00	0.00	3.09	0.00	3.78	0.00	0.00	29.33	0.00
12	0.00	0.00	0.27	0.71	5.88	4.01	0.28	4.85	0.00	0.00	11.07	0.00
13	0.00	0.40	2.07	0.00	0.00	2.23	0.84	0.00	0.00	0.30	21.22	0.00
14	0.00	0.00	15.35	0.00	0.00	2.81	0.00	0.00	0.00	1.48	1.22	0.00
15	0.00	0.92	1.86	0.00	0.00	8.87	0.00	0.00	0.00	6.64	0.00	0.57
16	0.00	7.26	25.83 •	0.00	4.96	0.00	0.59	0.00	0.00	0.20	0.00	0.00
17	0.00	2.54	9.70	2.48	26.81•	0.40	2.67	0.00	0.22	0.00	0.00	1.68
18	0.00	6.00	0.00	0.40	5.39	2.91	15.14•	0.00	0.00	1.53	0.00	0.08
19	0.00	13.60	0.00	5.26	0.61	0.00	0.00	0.00	0.00	14.15	0.71	0.00
20	0.00	50.24•	0.00	5.98	0.00	0.25	0.00	0.00	0.00	8.61	1.14	31.78
21	0.00	20.77	2.81	0.00	0.11	0.00	0.00	0.00	0.00	16.38	0.00	12.24
22	0.00	4.34	1.92	0.00	0.67	0.34	0.00	0.00	25.42•	5.18	0.39	14.05
23	0.00	1.58	6.22	0.00	2.57	0.04	0.10	0.00	12.66	8.37	0.11	0.00
24	0.00	0.00	0.93	0.00	3.47	15.18•	3.29	0.00	0.00	0.00	0.00	0.24
25	0.00	0.00	1.60	0.00	1.36	7.39	1.56	0.00	0.81	0.00	0.00	0.72
26	0.00	0.49	0.00	8.98	3.68	1.03	5.51	0.52	1.19	0.00	0.00	14.88
27	0.00	1.39	0.00	1.61	0.00	0.69	0.34	1.27	1.27	0.00	0.00	23.77
28	1.21	0.69	0.74	0.63	0.00	0.79	6.50	0.00	0.98	0.57	0.00	7.51
29	5.17	2.19	12.02	0.00	1.10	0.27	0.00	0.00	0.00	2.21	2.69	0.00
30	16.93		0.25	0.00	18.45	1.11	0.00	0.00	0.00	1.38	26.83	2.14
31	19.01		0.19		1.66		0.00	0.00		0.41		0.43
Σ	77.11	118.00	151.02	81.97	77.84	76.10	40.38	33.88	70.69	141.35	210.78	289.21

Table 1 gives the results of the positive linear correlation, that is the positive correlation coefficient R_{xy}, and the α and β parameters of the regression line for three or more stations. The combination of the four stations: Aspropotamos-Kataphytö-Pertouli-Vakari, was selected because this combination gave the median of the positive linear regression slopes. Consequently, the selected slope of the precipitation *vs* elevation relationship, parameter α, was equal to 1.91955.

Finally, the elevation corrected daily catchment precipitation data were computed for the calendar year 1964 (Table 3) by multiplying the corresponding daily catchment precipitation without correction (Table 2) by the actual value of the correction factor λ_i, taken from the matrix of the possible factors (Table 1) under the station availability conditions. By summing the corrected daily and monthly catchment precipitation respectively, the corrected monthly and annual values were obtained (Table 4). The same table reflects the monthly and annual station precipitation, and the monthly and annual catchment precipitation without correction (numbers in parentheses).

Also, it is to be noted that this work has been restricted to an initial estimate of the corrective factor λ_i, and did not consider proceeding to factor refinements through a trial and error approach.

Table 3 Average precipitation (mm) for the catchment with elevation correction

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	0.00	3.83	17.21	7.50	0.79	0.00	2.44	4.56	0.00	0.00	2.07	98.69•
2	0.36	0.00	6.08	0.00	0.89	0.00	0.60	11.04•	4.39	0.00	10.70	60.26
3	10.06	0.00	0.00	0.00	0.00	0.00	0.00	0.28	30.26	0.32	14.18	19.26
4	30.99•	0.00	1.02	11.73	0.00	0.00	0.44	1.26	7.03	1.11	9.16	31.86
5	8.74	0.00	15.76	39.93•	0.00	0.00	0.00	0.00	0.00	0.00	1.23	46.07
6	0.66	0.72	2.38	5.85	0.00	0.00	0.29	0.00	0.00	10.79	73.48•	8.11
7	0.69	1.63	20.79	8.36	0.00	4.36	0.00	0.00	0.00	1.97	24.31	0.91
8	0.00	1.77	15.07	6.19	0.00	17.30	0.00	3.80	0.00	2.42	0.34	0.00
9	0.00	0.00	11.25	3.24	0.00	7.07	1.50	5.57	0.00	42.23	0.05	0.00
10	0.00	0.00	12.77	0.00	0.00	7.83	0.00	8.20	0.00	47.01•	31.88	0.00
11	0.00	0.32	0.20	0.00	0.00	4.58	0.00	5.59	0.00	0.00	43.41	0.00
12	0.00	0.00	0.40	1.05	8.71	5.93	0.42	7.18	0.00	0.00	15.77	0.00
13	0.00	0.60	3.06	0.00	0.00	3.30	1.25	0.00	0.00	0.43	31.42	0.00
14	0.00	0.00	21.88	0.00	0.00	4.16	0.00	0.00	0.00	2.11	1.81	0.00
15	0.00	1.37	2.76	0.00	0.00	13.13	0.00	0.00	0.00	9.47	0.00	0.84
16	0.00	10.74	38.23•	0.00	7.33	0.00	0.88	0.00	0.00	0.28	0.00	0.00
17	0.00	3.76	14.36	3.66	41.03•	0.59	3.95	0.00	0.32	0.00	0.00	2.49
18	0.00	8.89	0.00	0.58	8.25	4.31	22.41•	0.00	0.00	2.18	0.00	0.12
19	0.00	20.13	0.00	7.79	0.90	0.00	0.00	0.00	0.00	20.17	1.05	0.00
20	0.00	74.37•	0.00	8.86	0.00	0.37	0.00	0.00	0.00	12.27	1.68	47.04
21	0.00	30.75	4.17	0.00	0.17	0.00	0.00	0.00	0.00	23.35	0.00	18.11
22	0.00	6.42	2.85	0.00	0.99	0.50	0.00	0.00	36.23•	7.39	0.58	20.79
23	0.00	2.34	9.21	0.00	3.80	0.05	0.15	0.00	18.74	11.92	0.17	0.00
24	0.00	0.00	1.37	0.00	5.14	22.47•	4.87	0.00	0.00	0.00	0.00	0.36
25	0.00	0.00	2.37	0.00	2.01	10.94	2.38	0.00	1.19	0.00	0.00	1.07
26	0.00	0.73	0.00	13.29	5.45	1.52	8.44	0.78	1.76	0.00	0.00	22.02
27	0.00	2.05	0.00	2.38	0.00	1.02	0.51	1.88	1.89	0.00	0.00	34.74
28	1.79	1.02	1.10	0.94	0.00	1.17	9.62	0.00	1.45	0.82	0.00	10.97
29	7.65	3.24	17.14	0.00	1.62	0.40	0.00	0.00	0.00	3.15	3.98	0.00
30	25.06		0.37	0.00	27.31	1.65	0.00	0.00	0.00	1.97	39.71	3.12
31	28.14		0.27		2.46		0.00	0.00		0.59		0.63
Σ	114.14	174.67	222.04	121.34	116.84	112.64	60.14	50.15	103.25	201.93	306.98	427.46

Table 4 Stations and catchment monthly and annual precipitation

Stations	Jan	Feb	Mar	Apr	May	Jun
Aspropotam	3.00	76.00	76.00	81.20	53.00	68.80
Kataphyto	105.00	91.90	136.20	82.20	67.80	75.80
Perpouli	86.00	107.80	182.80	71.40	132.40	89.40
Vakari	76.90	149.80	222.30	88.70	-	88.20
Mesochora	98.20	167.60	-	56.00	63.20	71.60
Vathyrema	98.70	197.90	218.30	121.40	107.50	62.40
Catchment	(77.11)	(118.00)	(151.02)	(81.97)	(77.84)	(76.10)
Mesochora	114.14	174.67	222.04	121.34	116.84	112.64

Stations	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Aspropotam	16.50	47.50	25.60	85.20	213.60	125.00	871.40
Kataphyto	30.20	38.70	59.90	138.50	235.60	-	-
Pertouli	52.40	39.20	82.60	139.60	210.20	342.70	1536.50
Vakari	-	16.80	91.50	163.30	215.30	444.20	-
Mesochora	69.60	20.80	-	-	-	476.30	-
Vathyrema	60.10	24.80	125.20	223.50	227.20	166.00	1633.00
Catchment	(40.38)	(33.88)	(70.69)	(141.35)	(210.78)	(289.21)	(1368.35)
Mesochora	60.14	50.15	103.25	201.93	306.98	427.46	2011.59

CONCLUSIONS

Attempting to assess accurately the areal precipitation of a mountainous catchment from incomplete point records, a new integration method has been developed. According to this method, the daily catchment precipitation was estimated from the existing data and subsequently corrected for elevation variation with a simple linear regression scheme. In this manner an attempt has been made to preserve, to a large extent, the physical meaning of areal series data, as is strongly required for climate change analysis. This latter requirement is widely recognized by such specialists as Klemeš (1985), Lettenmaier & Gan (1990), Wallis *et al.* (1991) and Hutchinson (1990), as opposed to attempts directed towards a deterministic and stochastic modelling of areal precipitation for the purpose of appropriate climate change rate estimations. The method developed allowing the areal and elevation integration of daily point precipitation data has been implemented successfully over a mountainous catchment for conceptual watershed simulation by using nine precipitation stations inside and around a catchment (Panagoulia, 1991d), as well as for climate change interpretation using 11 precipitation stations (Panagoulia, 1990b; 1991a; 1992a,b; 1994).

The proposed method is not only simple, practical and appropriate for climate change studies, but also is able to handle successfully any change in a gauge network, the greatest limitation of the inflexible Thiessen method (Linsley *et al.*, 1988).

Because the integration method deals with incomplete daily records, it is possible for some daily maximum precipitation values to be lost. To counter this likelihood the existence of a dense network is deemed necessary.

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APPENDIX

Table A1 Daily precipitation (mm) for Aspropotamos station

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	0.0	0.0	15.0	0.0	0.0	0.0	0.0	15.6•	0.0	0.0	0.0	55.0•
2	0.0	0.0	8.0	0.0	0.0	0.0	0.0	0.0	9.2	0.0	0.0	0.0
3	3.0•	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.2	0.0	15.2	0.0
4	0.0	0.0	0.0	34.0•	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	8.0	0.0	0.0	0.0	0.0	0.0	0.0	4.2	0.0
6	0.0	0.0	0.0	2.0	0.0	0.0	0.0	0.0	0.0	13.4	45.2	0.0
7	0.0	0.0	0.0	0.0	0.0	8.4	0.0	0.0	0.0	0.0	8.4	0.0
8	0.0	0.0	5.0	0.0	0.0	5.2	0.0	13.0	0.0	3.0	0.0	0.0
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	47.2•	0.0	0.0
10	0.0	0.0	0.0	0.0	0.0	4.4	0.0	13.7	0.0	0.0	65.6	0.0
11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.2	0.0	0.0	0.0	0.0
12	0.0	0.0	0.0	0.0	0.0	8.6	0.0	0.0	0.0	0.0	0.0	0.0
13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
14	0.0	0.0	0.0	0.0	0.0	6.2	0.0	0.0	0.0	3.2	0.0	0.0
15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
16	0.0	0.0	29.0•	0.0	11.0	0.0	3.0	0.0	0.0	0.0	0.0	0.0
17	0.0	0.0	8.0	5.0	8.0	0.0	13.5•	0.0	0.0	0.0	0.0	0.0
18	0.0	15.0	0.0	2.0	5.6	0.0	0.0	0.0	0.0	3.2	0.0	0.0
19	0.0	14.0	0.0	16.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
20	0.0	47.0•	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15.2	0.0	40.0
21	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	30.0
22	0.0	0.0	8.0	0.0	3.4	0.0	0.0	0.0	10.2•	0.0	0.0	0.0
23	0.0	0.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
24	0.0	0.0	1.0	0.0	4.6	24.6•	0.0	0.0	0.0	0.0	0.0	0.0
25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
26	0.0	0.0	0.0	11.0	2.4	3.2	0.0	0.0	0.0	0.0	0.0	0.0
27	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
28	0.0	0.0	0.0	3.2	0.0	4.0	0.0	0.0	0.0	0.0	0.0	0.0
29	0.0	0.0	0.0	0.0	5.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
30	0.0		0.0	0.0	12.6•	4.2	0.0	0.0	0.0	0.0	75.0•	0.0
31	0.0		0.0		0.0		0.0	0.0		0.0		0.0
Σ	3.0	76.0	76.0	81.2	53.0	68.8	16.5	47.5	25.6	85.2	213.6	125.0

Table A2 Daily precipitation (mm) for Kataphyto station

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	0.0	8.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	70.2•
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.3	0.0	0.0	14.0	60.3
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.2	0.0	0.0	5.7
4	38.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	14.5	0.0	17.2	27.4
5	10.0	0.0	30.0•	30.0•	0.0	0.0	0.0	0.0	0.0	0.0	0.0	40.1
6	0.0	0.0	0.0	4.3	0.0	0.0	0.0	0.0	0.0	4.8	61.0•	8.0
7	0.0	0.0	0.0	9.5	0.0	0.0	0.0	0.0	0.0	1.9	19.4	0.0
8	0.0	0.0	0.0	10.1	0.0	19.8•	0.0	0.0	0.0	0.0	0.0	0.0
9	0.0	0.0	7.5	5.2	0.0	0.0	0.0	10.6	0.0	59.0•	0.0	0.0
10	0.0	0.0	14.0	0.0	0.0	8.6	0.0	7.8	0.0	0.0	0.0	0.0
11	0.0	0.0	0.0	0.0	0.0	1.9	0.0	0.0	0.0	0.0	48.5	0.0
12	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15.0•	0.0	0.0	33.2	0.0
13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	30.3	0.0
14	0.0	0.0	26.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
15	0.0	0.0	0.0	0.0	0.0	8.2	0.0	0.0	0.0	12.3	0.0	0.0
16	0.0	0.0	28.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
17	0.0	0.0	9.4	4.6	35.0•	0.0	0.0	0.0	0.0	0.0	0.0	0.0
18	0.0	0.0	0.0	0.0	5.2	0.0	21.2•	0.0	0.0	0.0	0.0	0.0
19	0.0	18.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	22.6	0.0	0.0
20	0.0	39.0•	0.0	18.5	0.0	0.0	0.0	0.0	0.0	6.5	0.0	12.5
21	0.0	19.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	24.3	0.0	7.8
22	0.0	3.0	0.0	0.0	0.0	0.0	0.0	0.0	3.2	0.0	0.0	13.0
23	0.0	0.0	10.3	0.0	5.6	0.0	0.0	0.0	35.7•	7.1	0.0	0.0
24	0.0	0.0	0.0	0.0	0.0	19.5	9.0	0.0	0.0	0.0	0.0	0.0
25	0.0	0.0	0.0	0.0	0.0	17.8	0.0	0.0	1.3	0.0	0.0	0.0
26	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.0
27	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-
28	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-
29	0.0	4.2	10.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-
30	13.0		0.0	0.0	19.2	0.0	0.0	0.0	0.0	0.0	12.0	-
31	44.0•		0.0		2.8		0.0	0.0		0.0		-
Σ	105.0	91.9	136.2	82.2	67.8	75.8	30.2	38.7	59.9	138.5	235.6	-

Table A3 Daily precipitation (mm) for Pertouli station

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	0.0	0.0	13.4	9.2	0.0	0.0	4.6	0.0	0.0	0.0	0.0	69.5•
2	2.0	0.0	4.0	0.0	0.0	0.0	0.0	26.0•	0.0	0.0	0.0	50.3
3	16.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	30.4	0.0	15.0	25.0
4	28.0•	0.0	2.0	2.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	18.0
5	0.0	0.0	0.0	31.2•	0.0	0.0	0.0	0.0	0.0	0.0	0.0	24.5
6	0.0	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.8	48.4•	5.0
7	0.0	0.0	49.0•	7.5	0.0	0.0	0.0	0.0	0.0	1.0	17.0	0.0
8	0.0	0.0	24.6	0.0	0.0	5.4	0.0	0.0	0.0	1.0	0.0	0.0
9	0.0	0.0	10.2	0.0	0.0	15.3•	7.8	0.0	0.0	0.0	0.0	0.0
10	0.0	0.0	16.7	0.0	0.0	1.5	0.0	0.0	0.0	70.4•	30.2	0.0
11	0.0	0.0	0.0	0.0	0.0	3.2	0.0	8.6	0.0	0.0	43.0	0.0
12	0.0	0.0	0.0	2.3	28.0	12.7	0.0	0.0	0.0	0.0	0.0	0.0
13	0.0	0.0	0.0	0.0	0.0	4.6	0.0	0.0	0.0	0.0	35.8	0.0
14	0.0	0.0	19.4	0.0	0.0	9.8	0.0	0.0	0.0	7.0	0.0	0.0
15	0.0	0.0	0.0	0.0	0.0	15.2	0.0	0.0	0.0	0.0	0.0	0.0
16	0.0	16.3	25.0	0.0	8.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
17	0.0	1.0	0.0	0.0	32.4•	3.0	0.0	0.0	0.0	0.0	0.0	0.0
18	0.0	8.4	0.0	0.0	13.7	1.5	22.0•	0.0	0.0	7.4	0.0	0.0
19	0.0	0.0	0.0	8.4	3.2	0.0	0.0	0.0	0.0	2.0	2.0	0.0
20	0.0	23.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.0	3.0	37.5
21	0.0	28.0•	0.0	0.0	0.0	0.0	0.0	0.0	0.0	14.0	0.0	10.6
22	0.0	17.4	0.0	0.0	0.0	0.0	0.0	0.0	38.0•	4.6	0.0	22.0
23	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.0	0.0	0.0
24	0.0	0.0	0.0	0.0	5.2	6.5	0.0	0.0	0.0	0.0	0.0	0.0
25	0.0	0.0	0.0	0.0	6.3	4.8	0.0	0.0	0.0	0.0	0.0	3.0
26	0.0	0.0	0.0	0.0	11.4	1.4	11.0	0.0	4.2	0.0	0.0	24.0
27	0.0	8.0	0.0	10.5	0.0	4.5	2.3	4.6	3.4	0.0	0.0	43.5
28	10.0	0.0	0.0	0.0	0.0	0.0	4.7	0.0	6.6	0.0	0.0	8.4
29	26.0	0.0	18.5	0.0	0.0	0.0	0.0	0.0	0.0	9.4	0.0	0.0
30	4.0		0.0	0.0	23.6	0.0	0.0	0.0	0.0	0.0	15.8	1.4
31	0.0		0.0		0.0		0.0	0.0		0.0		0.0
Σ	86.0	107.8	182.8	71.4	132.4	89.4	52.4	39.2	82.6	139.6	210.2	342.7

Table A4 Daily precipitation (mm) for Vakari station

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	0.0	0.0	18.5	13.5	0.0	0.0	1.0	0.0	0.0	0.0	0.0	83.3•
2	0.0	0.0	6.0	0.0	4.2	0.0	0.0	3.6	3.0	0.0	0.4	40.8
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	37.0	0.0	16.7	16.7
4	15.4	0.0	0.0	6.5	0.0	0.0	0.0	4.5	0.4	0.0	0.8	31.2
5	7.1	0.0	3.9	36.0•	0.0	0.0	0.0	0.0	0.0	0.0	0.0	48.1
6	0.0	0.0	3.3	2.3	0.0	0.0	0.0	0.0	0.0	8.4	58.6•	10.1
7	1.7	1.7	27.2	9.0	0.0	0.2	0.0	0.0	0.0	1.7	21.2	4.3
8	0.0	0.0	37.5•	1.0	0.0	7.9	0.0	0.0	0.0	2.7	1.5	0.0
9	0.0	0.0	15.0	1.2	0.0	5.2	0.3	0.8	0.0	1.0	0.0	0.0
10	0.0	0.0	14.5	0.0	0.0	7.5	0.0	1.2	0.0	78.7•	13.7	0.0
11	0.0	0.0	0.0	0.0	0.0	10.0	0.0	1.7	0.0	0.0	45.9	0.0
12	0.0	0.0	0.0	1.3	10.1	4.7	1.3	0.0	0.0	0.0	0.0	0.0
13	0.0	1.6	0.0	0.0	0.0	4.0	2.1	0.0	0.0	0.0	30.0	0.0
14	0.0	0.0	10.0	0.0	0.0	1.4	0.0	0.0	0.0	0.0	0.0	0.0
15	0.0	0.0	13.0	0.0	0.0	10.9	0.0	0.0	0.0	10.0	0.0	0.0
16	0.0	17.3	30.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
17	0.0	6.0	13.8	0.0	-	0.0	0.0	0.0	0.0	0.0	0.0	5.0
18	0.0	6.0	0.0	0.0	-	10.7	16.5•	0.0	0.0	0.0	0.0	0.3
19	0.0	9.3	0.0	2.1	0.0	0.0	0.0	0.0	0.0	16.8	0.0	0.0
20	0.0	64.0•	0.0	0.0	0.0	0.7	0.0	0.0	0.0	5.0	5.4	53.8
21	0.0	26.0	0.0	0.0	0.8	0.0	0.0	0.0	0.0	18.0	0.0	9.4
22	0.0	4.8	1.1	0.0	0.0	0.8	0.0	0.0	41.2•	4.5	0.0	26.6
23	0.0	5.5	6.5	0.0	1.4	0.0	0.0	0.0	2.8	15.6	0.8	0.0
24	0.0	0.0	1.0	0.0	3.2	14.8•	1.6	0.0	0.0	0.0	0.0	0.9
25	0.0	0.0	0.5	0.0	3.8	6.5	-	0.0	2.0	0.0	0.0	1.3
26	0.0	0.0	0.0	15.0	5.6	0.0	-	0.0	0.8	0.0	0.0	29.8
27	0.0	0.0	0.0	0.8	0.0	1.0	-	5.0•	3.4	0.0	0.0	56.7
28	0.0	4.8	0.0	0.0	0.0	0.0	8.0	0.0	0.9	0.7	0.0	20.7
29	8.9	2.8	20.5	0.0	0.2	1.9	0.0	0.0	0.0	0.0	4.8	0.0
30	28.4•		0.0	0.0	19.5•	0.0	0.0	0.0	0.0	0.2	15.5	3.9
31	15.4		0.0		5.3		0.0	0.0		0.0		1.3
Σ	76.9	149.8	222.3	88.7	-	88.2	-	16.8	91.5	163.3	215.3	444.2

Table A5 Daily precipitation (mm) for Mesochora station

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	0.0	0.0	20.7	0.0	4.3	0.0	5.3	0.0	0.0	0.0	0.0	94.2•
2	0.0	0.0	9.6	0.0	0.0	0.0	3.3	8.5•	5.8	0.0	0.4	52.7
3	30.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	44.0•	0.0	19.2	16.6
4	0.0	0.0	3.6	0.0	0.0	0.0	2.4	1.7	0.0	0.0	-	41.1
5	8.0	0.0	0.0	24.3•	0.0	0.0	0.0	0.0	0.0	0.0	0.0	60.5
6	3.6	0.0	0.0	0.0	0.0	0.0	1.6	0.0	0.0	0.0	-	6.8
7	1.8	0.0	0.0	0.7	0.0	10.2	0.0	0.0	0.0	-	0.6	0.0
8	0.0	5.0	0.0	3.2	0.0	9.8	0.0	0.0	0.0	-	0.1	0.0
9	0.0	0.0	10.5	2.7	0.0	9.9	0.2	1.8	0.0	-	-	0.0
10	0.0	0.0	0.0	0.0	0.0	3.1	0.0	1.1	0.0	-	-	0.0
11	0.0	0.0	1.1	0.0	0.0	0.6	0.0	7.3	0.0	-	0.0	0.0
12	0.0	0.0	2.2	1.0	2.5	0.8	0.8	0.0	0.0	-	-	0.0
13	0.0	1.4	6.3	0.0	0.0	8.9	1.2	0.0	0.0	-	0.3	0.0
14	0.0	0.0	-	0.0	0.0	1.6	0.0	0.0	0.0	-	0.0	0.0
15	0.0	0.6	0.0	0.0	0.0	12.0•	0.0	0.0	0.0	-	0.0	0.0
16	0.0	19.5	0.0	0.0	7.3	0.0	0.0	0.0	0.0	-	0.0	0.0
17	0.0	0.5	14.5	0.0	19.3•	0.3	0.0	0.0	0.0	-	0.0	7.8
18	0.0	5.6	0.0	0.0	0.0	9.7	16.6	0.0	0.0	-	0.0	0.3
19	0.0	9.8	0.0	2.8	0.0	0.0	0.0	0.0	0.0	-	0.0	0.0
20	0.0	80.0•	0.0	0.0	0.0	1.2	0.0	0.0	0.0	-	0.0	55.3
21	0.0	35.0	22.8•	0.0	0.0	0.0	0.0	0.0	0.0	-	0.0	9.4
22	0.0	0.8	1.5	0.0	0.0	1.8	0.0	0.0	-	-	0.0	27.3
23	0.0	2.5	0.6	0.0	2.2	0.3	0.8	0.0	4.0	-	0.0	0.0
24	0.0	0.0	0.0	0.0	7.3	1.4	1.2	0.0	0.0	-	0.0	0.9
25	0.0	0.0	12.4	0.0	0.4	0.0	4.0	0.0	0.8	-	0.0	1.4
26	0.0	0.0	0.0	19.5	8.3	0.0	18.0•	0.4	0.5	-	0.0	7.8
27	0.0	3.4	0.0	1.8	0.0	0.0	0.0	0.0	0.6	-	0.0	63.2
28	0.0	0.0	6.0	0.0	0.0	0.0	14.2	0.0	0.4	-	0.0	22.7
29	0.0	3.5	-	0.0	0.0	0.0	0.0	0.0	0.0	-	7.8	0.0
30	40.0•		2.0	0.0	11.6	0.0	0.0	0.0	0.0	-	20.4•	6.7
31	14.8		1.5		0.0		0.0	0.0		-		1.6
Σ	98.2	167.6	-	56.0	63.2	71.6	69.6	20.8	-	-	-	476.3

Table A6 Daily precipitation (mm) for Vathyrema station

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	0.0	0.0	20.1	22.1	0.0	0.0	3.2	0.0	0.0	0.0	15.3	12.4
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.3•	0.0	0.0	28.4	30.3
3	6.2	0.0	0.0	0.0	0.0	0.0	0.0	2.1	34.2	2.4	0.0	40.5•
4	33.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.2	5.2	10.3
5	7.3	0.0	4.2	41.2•	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.1
6	0.0	0.0	12.4	20.1	0.0	0.0	0.0	0.0	0.0	10.3	16.3	0.0
7	0.0	9.4	46.2•	3.2	0.0	0.0	0.0	0.0	0.0	2.1	36.4•	0.0
8	0.0	6.3	9.3	4.1	0.0	13.8	0.0	0.0	0.0	3.2	0.0	0.0
9	0.0	0.0	5.4	0.0	0.0	10.5	0.0	0.0	0.0	4.1	0.4	0.0
10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	47.4•	24.2	0.0
11	0.0	2.4	0.0	0.0	0.0	6.4	0.0	6.2	0.0	0.0	20.4	0.0
12	0.0	0.0	0.0	1.3	8.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
13	0.0	0.0	14.1	0.0	0.0	0.0	4.3	0.0	0.0	3.2	30.2	0.0
14	0.0	0.0	16.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.4	0.0
15	0.0	9.3	0.0	0.0	0.0	14.6•	0.0	0.0	0.0	0.0	0.0	6.2
16	0.0	4.4	40.0	0.0	9.2	0.0	0.0	0.0	0.0	2.1	0.0	0.0
17	0.0	16.4	14.4	0.0	44.0•	0.0	0.0	2.4	0.0	0.0	0.0	0.0
18	0.0	5.2	0.0	0.0	5.2	0.0	13.2	0.0	0.0	0.0	0.0	0.0
19	0.0	26.3	0.0	4.8	2.4	0.0	0.0	0.0	0.0	22.4	5.1	0.0
20	0.0	70.4•	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.2	0.0	8.4
21	0.0	33.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	21.4	0.0	0.0
22	0.0	5.2	0.0	0.0	0.0	0.0	0.0	0.0	77.4•	37.1	4.3	0.0
23	0.0	4.0	16.3	0.0	3.1	0.0	0.0	0.0	2.4	15.2	0.0	0.0
24	0.0	0.0	6.4	0.0	6.3	10.2	0.0	0.0	0.0	0.0	0.0	0.0
25	0.0	0.0	0.0	0.0	0.0	1.3	6.2	0.0	0.0	0.0	0.0	0.0
26	0.0	5.4	0.0	24.6	0.0	2.5	0.0	5.2	5.5	0.0	0.0	38.4
27	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.3	0.0	0.0	6.3
28	0.0	0.0	0.0	0.0	0.0	0.0	33.2•	0.0	0.0	4.2	0.0	0.0
29	8.2	0.0	13.2	0.0	0.0	0.0	0.0	0.0	0.0	11.4	11.4	0.0
30	35.4•		0.0	0.0	29.2	3.1	0.0	0.0	0.0	14.2	16.2	4.1
31	8.2		0.0		0.0		0.0	0.0		4.4		0.0
Σ	98.7	197.9	218.3	121.4	107.5	62.4	60.1	24.8	125.2	223.5	227.2	166.0