

A multiple linear regression GIS module using spatial variables to model orographic rainfall

S. Naoum and I. K. Tsanis

ABSTRACT

This paper aims to document the development of a new GIS-based spatial interpolation module that adopts a multiple linear regression technique. The functionality of the GIS module is illustrated through a test case represented by the island of Crete, Greece, where the models generated were applied to locations where estimates of annual precipitation were required. The response variable is 'precipitation' and the predictor variables are 'elevation', 'longitude' and 'latitude', or any combination of these. The module is capable of performing a sequence of tasks which will eventually lead to an estimation of mean areal precipitation and the total volume of precipitation. In addition, it can generate up to nine predictor variables and their parameters, and can estimate areal rainfall for a user-specified three-dimensional extent. The developed module performed satisfactorily. Precipitation estimates at ungauged locations were obtained using the multiple linear regression method in addition to some conventional spatial interpolation techniques (i.e. IDW, Spline, Kriging, etc.). The multiple linear regression models provided better estimates than the other spatial interpolation techniques.

Key words | ArcView GIS, mean areal precipitation, multiple linear regression

S. Naoum

I. K. Tsanis (corresponding author)
Department of Civil Engineering,
McMaster University,
1280 Main Street West,
Hamilton, Ontario,
Canada L8S 4L7
Tel: +(905) 525 9140 ext. 24415
E-mail: tsanis@water.eng.mcmaster.ca

INTRODUCTION

The rapid development in geographic information systems (GIS) originally inspired hydrologists to develop new models to work within the GIS environment. GIS can integrate databases, extract the parameters needed for different modelling applications, and process and display the results. However, current GIS packages are sometimes difficult to use and offer limited functions to support environmental modelling (Strebel *et al.* 1994; Steyaert & Goodchild 1994; Maidment 1996; Sui & Maggio 1999; Paniconi *et al.* 1999). Such limitations include a lack of efficient data conversion algorithms, static representations of multiple temporal and spatial data, weak tools for information extraction and aggregation, limited capabilities for managing large numbers of data sets and dealing with relationships among the data sets, and no facility to assess and communicate uncertainties introduced by imprecision and incompleteness (Jelinski *et al.* 1994; Stafford *et al.* 1994; Burrough *et al.* 1996;

Goodchild 1996; Taylor *et al.* 1999; Paniconi *et al.* 1999; He *et al.* 2001). To overcome these problems, four approaches are presented in the literature to link GIS to environmental modelling. (1) Embedding GIS-like functionality into the models where GIS is used as a mapping tool only. This approach lacks the capacity to manage and visualize spatial data. (2) Embedded modelling in GIS such as ESRI's ArcStorm[®] and ArcView[®] Hydrological Modelling. This approach utilizes the full capabilities of GIS, but the modelling functionalities tend to be simplistic and need to be validated. (3) Loose coupling, where GIS is used to generate model input files and display model output data which are independent of the models. (4) Tight coupling, where GIS and the models are integrated via a common user interface that is developed by either GIS macros and scripts or by conventional programming. User-written libraries or routines are incorporated into a GIS and are

called through the pull-down menu of the GIS package (Sui and Maggio 1999; He *et al.* 2001).

In this paper, the tight coupling approach is adopted using ArcView Avenue (ArcView GIS programming language) scripts, Fortran, IMSL Stat Library, ArcView Dialog Designer, and batch programming through a developed drop-down menu. The ArcView project consists of six modules: (1) spatial input data preparation; (2) database accessing tool; (3) parameter generator; (4) model executor; (5) output visualizer; (6) output report generator, that includes spatial statistical information in addition to a printing tool. The ArcView GIS Regression Utility (AVRU) was developed to accommodate the large amount of work that initially had to be done using different software simultaneously, including ArcView, S+ for ArcView, Minitab, and MS Office (Word and Excel). The functionality of this module is presented in an application of the spatial variation of orographic precipitation in the island of Crete by means of the multiple linear regression method.

BACKGROUND

Many hydrological processes are subject to chance in the sense that they exhibit substantial variability that cannot adequately be accounted for by physical laws. The difficulty in explaining or predicting hydrological variables arises for three reasons. The first is the inherent randomness of the driving variables and the hydrological system. The second is sampling error—the measurements that hydrologists have to work with are only a small sample from an infinite population. The third is a result of an incorrect understanding of the processes involved. This means that, even if sampling errors were eliminated, there would still be errors in estimating or predicting system outputs from system inputs (Hirsch *et al.* 1993).

A common type of multiple linear regression model in hydrology is the stream-flow basin characteristics model (Sauer *et al.* 1983; Stedinger & Tasker 1985). Some stream-flow statistics are estimated as a function of drainage basin area, average basin altitude and percentage of basin forested. A similar approach is the basin yield–basin characteristics model (Peters 1984) in which, for example, the yield of dissolved solids in the basin is estimated as a

function of average rainfall, percentage of basin area underlain by carbonate rocks and basin population.

Precipitation can also be estimated using multiple linear regression, especially in mountainous regions (Hay *et al.* 1998) where elevation, range, slope, aspect, exposure, barrier and orientation are used as explanatory (independent) variables. Spatially distributed precipitation is needed to estimate runoff accurately in mountainous terrain. In many cases, a standard (e.g. monthly) precipitation–elevation relation is used to interpolate precipitation for use in distributed rainfall–runoff models (Risley 1993; Nakama & Risley 1993; Jeton *et al.* 1995). Often, this approach does not accurately represent the spatial distribution of precipitation because the monthly derived precipitation–elevation relation may not be accurate on a daily basis. More complicated methods for distributing precipitation in mountainous regions are available (Daly *et al.* 1994; Garen *et al.* 1994; Hevesi *et al.* 1992). For example, Garen *et al.* (1994) present a method that uses detrended kriging to estimate precipitation based on specific precipitation–elevation relations for each time step. They conclude that smoothed elevation and other topographic characteristics such as slope or aspect may be better indicators of orographic effects than elevation alone. Some studies have related topographic characteristics to precipitation (Spren 1947; Linsley 1958; Schermerhorn 1967; Storr & Ferguson 1972). For western Colorado, Spren (1947) showed that mean winter precipitation was highly correlated with station elevation, maximum elevation within an 8-km radius (barrier height), the fractional circumference of a circle (32 km in radius) not containing a barrier more than 300 m higher than the station (exposure), and the direction of the sector of greatest exposure (orientation). Schermerhorn (1967) found that simple indices of terrain and barrier elevation, as well as a latitude index, explained most of the variation in precipitation among over 280 stations in western Oregon and Washington.

METHODOLOGY

Regression analysis

For any system in which variable quantities change, it is of interest to examine the effects that some variables exert on

others, since these often result in a complicated relationship. In such a case we may approximate the relationship by a simple mathematical function such as regression. Regression analysis is a statistical technique that is used to analyse raw data and search for the messages they contain. The method of analysis used is the method of least squares (LS), which is simply a minimization of the sum of squares of the deviations of the observed response from the fitted response. The model function is of a specified form that involves both the predictor variables and the parameters. Interaction effects between the variables can also be considered. These would be represented in the models by adding three more terms. The use of a second-order model is also a useful possibility. Second-order models with three predictor variables, as in this case, are particularly useful in response-surface studies, where it is desired to graduate, or approximate to, the characteristics of some unknown response surface by a polynomial of low order. Note that all possible second-order terms will be included in the model, thus leading to ten-parameter models. The general form of the final product is

$$\begin{aligned}
 p = & \beta_0 + \beta_1x_1 + \beta_2x_2 + \beta_3x_3 \\
 & + \beta_4x_1^2 + \beta_5x_2^2 + \beta_6x_3^2 \\
 & + \beta_7x_1x_2 + \beta_8x_1x_3 + \beta_9x_2x_3
 \end{aligned} \quad (1)$$

where p is precipitation (mm yr^{-1}), x_1 is altitude (m), x_2 is longitude (km) and x_3 is latitude (km).

AVRU also evaluates the R^2 statistic (coefficient of determination) for each case as a convenient measure of the success of the regression equation in explaining the variation in the data. This is expressed as the percentage ratio of the sum of squares caused by the regression to the total sum of squares. The value of R^2 should not be 100% no matter how well the model fits.

ArcView GIS project

The AVRU is a project set up to perform the tasks in sequence through a drop-down menu in the ArcView GIS package. An ArcView project in its basic format is a collection of views, tables, scripts, layouts and charts. The saved project with all its contents is transferable under the con-

dition that the source location of the themes displayed in the views is transferred along with it. Upon opening the project, all information is retrieved and redisplayed in the same fashion. The project also works as a communication medium between the user, the PC and the project contents. For example, the user can generate a tool in the project which, upon being selected, will create a new working directory in a specified location. The new work performed within the project can be stored in that new folder. If the project is transferred, it will still perform the same tasks on another PC. The AVRU project is set up as described below.

1. The initial step deals with a projection of the view where the work is taking place. The projection is of primary importance since the longitude and latitude variables are extracted based on the map units according to the projection.
2. The digital elevation model (DEM) is the backbone of the project as it provides numerical values for variables containing elevation, and its grid cells are the platform of the execution stage when mean areal precipitation is estimated. The DEM can be generated, clipped to the desired shape, and modified to a set resolution.
3. The rain gauges shapefile is the connection between the database accessing tool and the parameter generator. The user is able to derive the three spatial predictor variables of the gauges (x, y, z). The three variables will be derived and stored in three columns in the attribute table of the shapefile.
4. The database is then accessed in order to extract the user-specified data (i.e. the response variable precipitation), which can be either monthly or yearly. Similarly, the response variable is stored as a column in the attribute table of the rain gauges shapefile.
5. The parameter generator uses the information derived in the previous steps to generate the parameters based on the least-squares (LS) method. The parameters and the coefficient of determination are then stored in one file.
6. Using the parameters generated and the DEM, the mean areal precipitation (in mm) and the total volume of precipitation water (in m^3) are estimated.

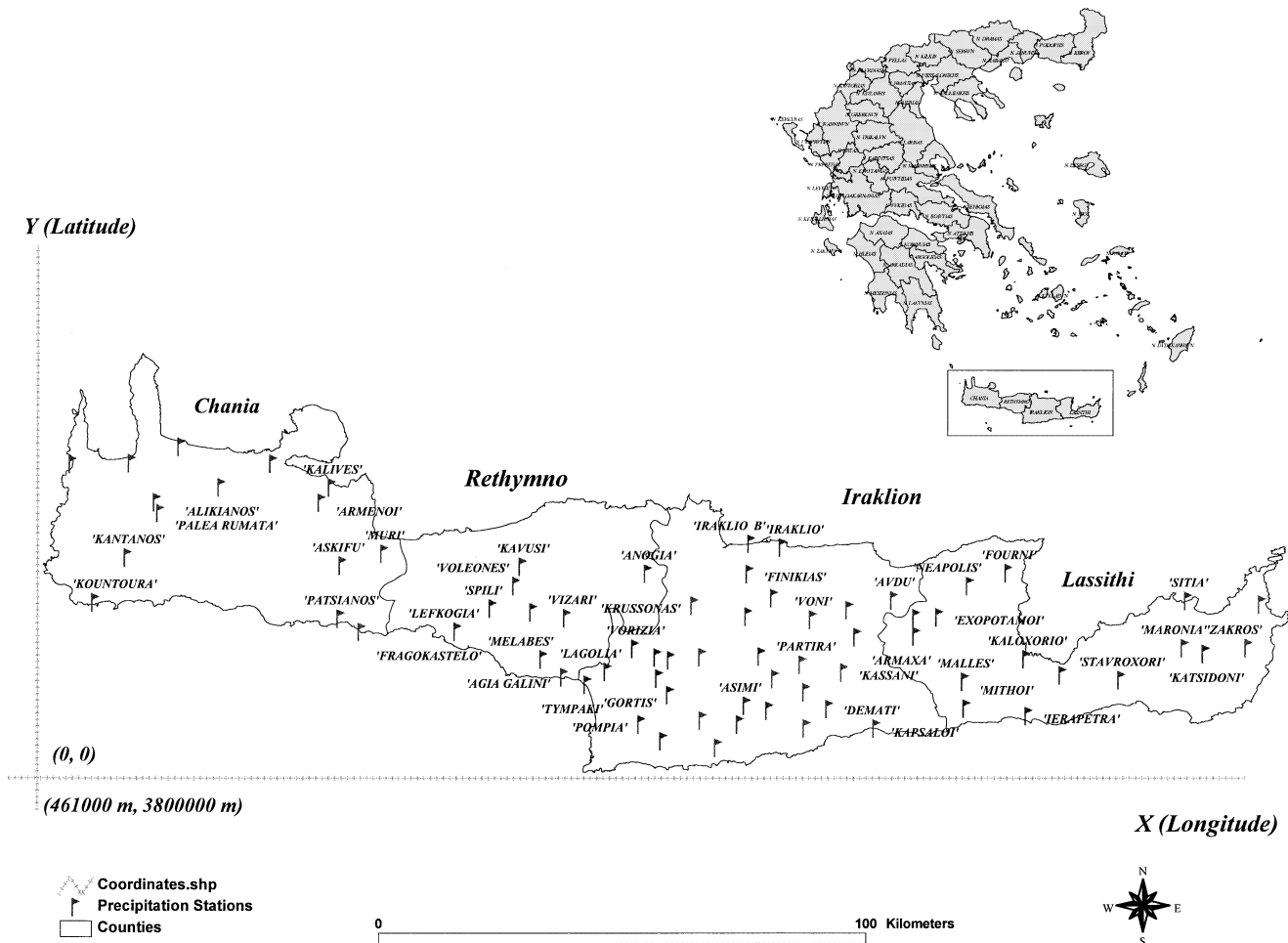


Figure 1 | Precipitation stations in the four prefectures of Crete.

7. A point shapefile is generated with the amounts of precipitation recorded in one column at each point for future reference.
8. A text format report summarizing the results for the case under investigation is generated, and can be printed from within ArcView.

TEST CASE

The island of Crete, in Greece, occupies the southern part of the country of Greece (as shown in Figure 1) with an area of 8,265 km², which is almost 6.3% of the area of Greece. Crete has a mean elevation of 482 m and an average slope of 228 m km⁻¹. The island is divided into

four counties: Lassithi, Iraklio, Rethymno and Chania. Most agricultural activity takes place in the county of Iraklio (2,626 km²). The remaining counties, in order of agricultural activity, are Lassithi (1,810 km²), Chania (2,342 km²) and Rethymno (1,487 km²).

Monthly precipitation data were compiled by the Hellenic National Meteorological Service and other government agencies for 77 precipitation stations throughout the island (see Figure 1). The locations of the stations were provided in degrees, minutes and seconds. The stations mainly cover the eastern part of the island, which has a higher level of agricultural activity and tourism than the western part. The counties of Iraklio, Lassithi, Chania and Rethymno were covered by 35, 17, 16 and 9 gauges,

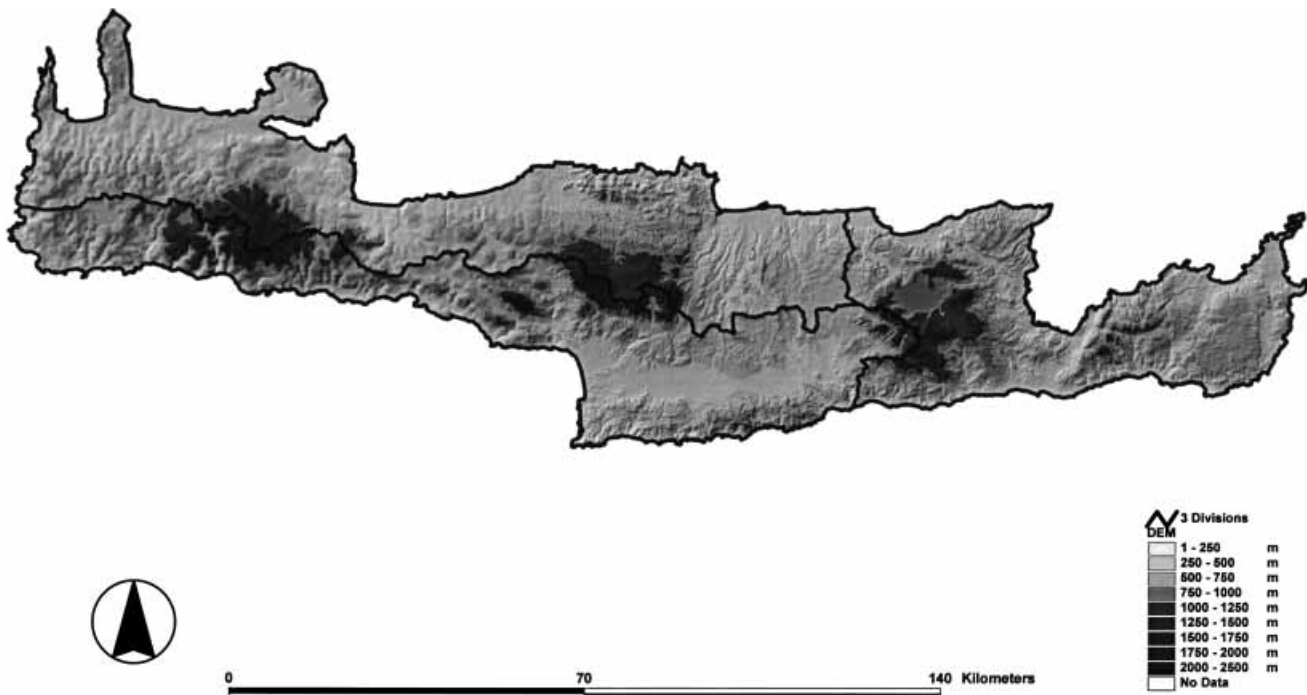


Figure 2 | Digital elevation model (DEM).

respectively. Six gauges (two in Iraklio, one in Lassithi and three in Chania) recorded for only 4 or 5 years, while the rest recorded for 12–50 years. The gauges were located at elevations that ranged from mean sea level (MSL) in the county of Iraklio to 905 m above MSL in the county of Lassithi. The GIS coverages used in this study were based on maps developed by the Greek Army Geographical Service.

A digital elevation model (DEM) with a cell size of 30 m and a grid of 3,027 rows and 8,659 columns was generated from the spot elevation values and a 20-m contour map. As can be seen in Figure 2, a chain of high elevations lies across the island. The island receives fairly high amounts of precipitation i.e. orographic, and produces runoff that is generally greater in the western and northern parts of the island.

AVRU STRUCTURE

A geographic information system becomes more powerful when it is tightly coupled with different programming

techniques, resulting in a sound decision support system. The drop-down menu of the project is shown in Figure 3 using the ArcView Avenue scripts, which provide a well-defined mechanism for allowing user-written routines to be called from within the normal user interface of the GIS package. In addition, this language also provides a menu-driven graphic interface that makes it possible to guide the user with prompts and explanations throughout the application. In order for this project to work properly, the ArcView Extensions Dialog Designer and Spatial Analyst were loaded into the project.

In addition to the shapefiles and DEM used for the analysis, the project 'mlr.apr' is composed of ten other facilities.

1. Sixty-six Avenue scripts. The scripts are generic, but in some cases they are modified versions of scripts that existed in the ArcView on-line help. Some scripts may run independently to perform an individual task, and some can run in sequence to perform one or several task(s).

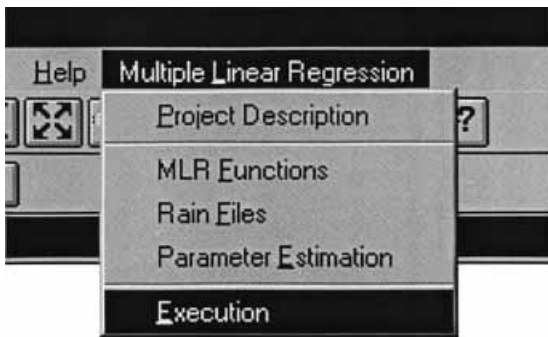


Figure 3 | The main drop-down menu representing the ArcView regression utility.

2. Seven dialogs, which are used to facilitate program–user interaction and execute the scripts.
3. One IMSL Stat Library (RLSE). This library uses the least-squares method to estimate the parameters for multiple linear regression.
4. Five input files which are generated by ArcView GIS. Four of these are used by 'mlr.exe' (msize.dat, multi.dat, multx.dat, multy.dat) and the fifth (xy.dat) is used by ArcView. The 'msize.dat' file stores the sample size (n), which is also the dimension (x) of the arrays. The 'multi.dat' file stores the data required by the library, which includes the number '1' if there is an intercept in the model or the number '0' if there is no intercept, the number of variables (up to nine), the sample size and the number of terms in the equation (which is equal to the number of parameters). The 'multx.dat' has the numerical values for the predictor variables, and the 'multy.dat' stores the observed values for response variable. The 'xy.dat' holds the extent information of the DEM to be used by AVRU when estimating the mean areal precipitation.
5. One output file, generated by 'mlr.exe' (mult.out), that has the numerical values for the parameters as well as the coefficient of determination. Any unused variable is assigned a corresponding 'zero' parameter value.
6. One database file (par.dbf) in which all generated parameters are stored. The file is used in the final stage (execution) to extract the parameters.
7. An HTML file for project description (help.html). This file contains extensive documentation of the

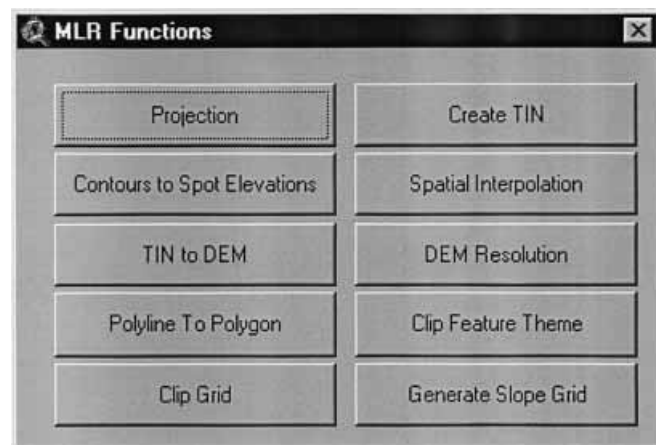


Figure 4 | The MLR functions dialog representing module 1.

- study, with text and images using the Microsoft FrontPage® HTML format providing links to the Avenue scripts and samples of input and output files.
8. Two simple Fortran codes (mlr1.f and mlr2.f). In the first file, the IMSL library is included, the dimension (x) of the arrays is read (which will be used in the second code), and the second program (subroutine) is called. The second file includes read statements for the rest of the input files, calls the external IMSL Stat Library (RLSE), and generates the output file.
9. One executable file (mlr.exe), which is generated from the Fortran code to estimate the parameters.
10. Two batch files (mlr.bat and print.bat) which were written and executed from within ArcView. The first file is to execute the 'mlr.exe' from its location, and the second is to print the report generated.

AVRU uses four main pieces of information from preparation to execution: the location of gauges, rainfall data, regional boundary and a DEM for the region. The project consists of six modules, as described below.

Spatial input data preparation

As shown in Figure 4, this module mainly deals with the DEM and the view projection. The user is prompted to specify the type of projection, which can be either EGSA87 or any other projection. EGSA87 is

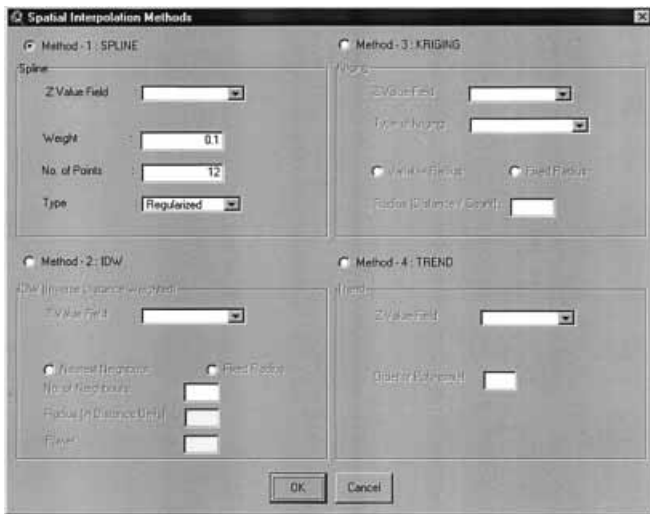


Figure 5 | The developed spatial interpolation dialog.



Figure 6 | The rain files dialog representing module 2.

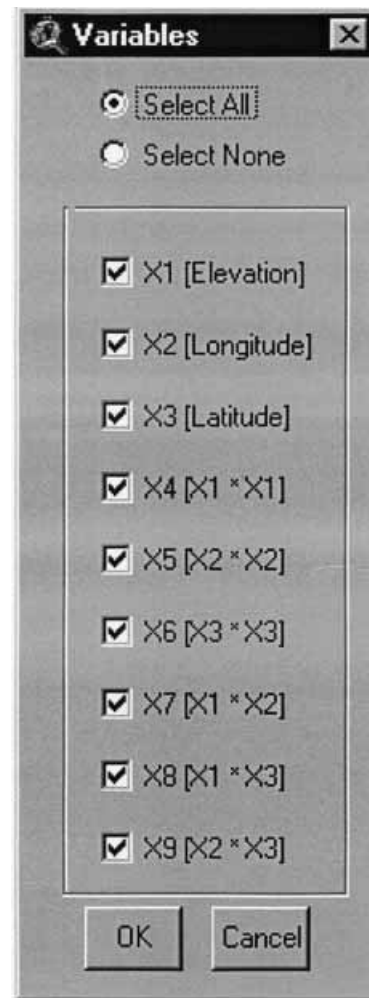


Figure 7 | The variables dialog representing the parameter generator module (module 3).

the Greek projection that has the parameters described below.

- Transverse mercator. This is a cylindrical projection with the cylinder along the meridian. The result is a conformal projection that maintains small shapes and increasingly distorts larger regions (area and shape) away from the meridian. As meridians run north and south, this projection is best suited for land masses that also stretch north to south.
- Spheroid. To make mathematical calculations easier, the Earth is often treated as a sphere with a radius

of 6,370,997 m. This assumption can be used for small-scale maps where the difference between a sphere and a spheroid cannot be detected. However, to maintain accuracy for larger-scale maps, the Earth must be treated as a spheroid (ellipsoid). For this particular case the spheroid is GRS80 (Geodetic Reference System 1980).

- Central meridian. The central meridian is centred on the region of interest. This centering on a specific region minimizes distortion of all properties in that region. For Greece, the central meridian is 24°E.
- Reference latitude. This is the angular distance in degrees north or south of the equator. For this case it is 0.

Figure 8 | The multiple linear regression execution dialog representing modules 4 and 6.

- Scale factor. This is the ratio of the scale at a particular location and direction on a map to the stated scale of the map. In this case it is 0.9996.
- False easting. This is the x -coordinate value assigned relative to the point of origin of the projection. For example, if the origin of the projection (in latitude–longitude) is in the centre of the map, all areas to the west of the origin would be negative when a false easting of zero is assigned. To make the coordinates positive for the entire map, set the false easting to a positive number. In this case the number is 500,000.
- False northing. This is the y -coordinate value assigned relative to the point of origin of the projection. For example, if the origin of the projection (in latitude–longitude) is in the centre of

the map, all areas to the south of the origin would be negative when a false northing of zero is assigned. To make the coordinates positive for the entire map, set the false northing to a positive number. In this case the number is 0.

The DEM can be generated, if it is not already available, from a triangulated irregular network (TIN), contour lines, spot elevations or a combination of these. The user can then clip the DEM to a specified extent, create a slope grid, or change the resolution of the DEM if desired. It should be noted that the resolution of the DEM has a direct effect on the model results, so higher resolutions are recommended although they may take longer to execute. The spatial interpolation tool is also available for the user to use conventional spatial interpolation techniques such

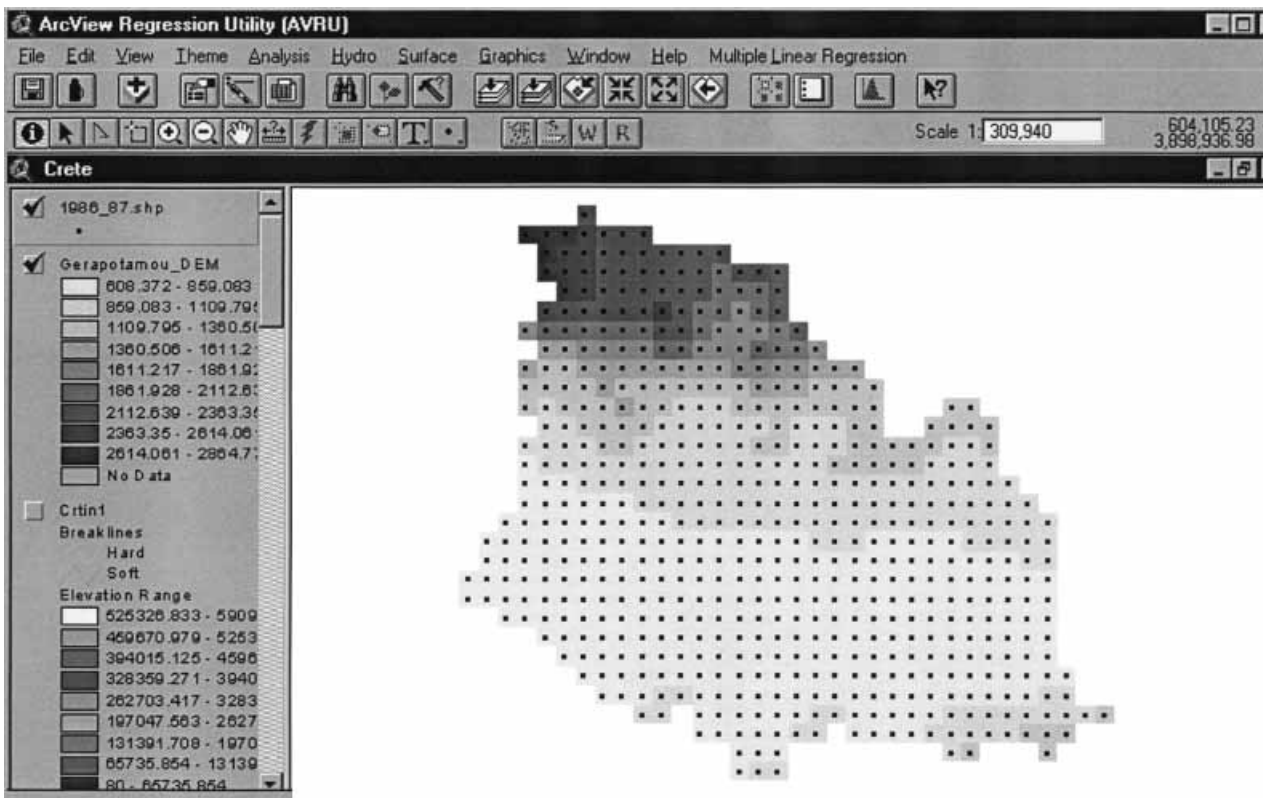


Figure 9 | Visual output for a basin in Crete representing module 5.

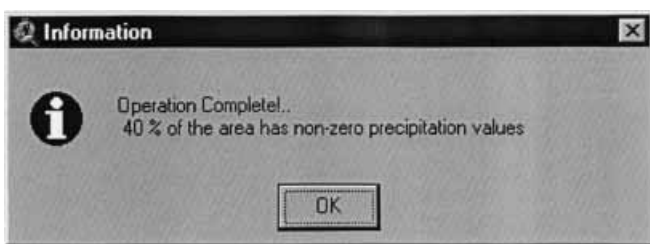


Figure 10 | An informative message shows after execution.

as kriging, spline and IDW. The dialogue, as shown in Figure 5, was developed to accommodate all the variables required to perform the interpolation. Most of the techniques use the *barrier* argument to specify the location of linear features (such as the shoreline) to interrupt the surface continuity. Barriers are set to limit the set of the input sample points used to interpolate the z -values to

only those samples on the same side of the barrier. Input sample points that lie exactly on the barrier line are included in the sample set for both sides of the barrier. However, when barriers are specified, processing time is significantly extended.

Database Accessing Tool

A shapefile that contains the locations and names of the gauges is required as input to this tool. Because the locations should be in decimal degrees in order to be visualized in ArcView, a conversion tool, as shown in Figure 6, is added to convert from units of degrees–minutes–seconds to units of decimal degrees. After the conversion, with the view already projected, the values for the predictor variables longitude and latitude (x_2 and x_3 , respectively) are extracted from the view. If the altitudes of the gauges (x_1) are not known, they can be extracted from the DEM.

1 .. General information

 Case name: 1986–87
 Number of variables: 3
 Number of gauges: 73
 Coefficient of determination: 48.7045 %
 The X-coordinate: 461000 m
 The Y-coordinate: 3.8e+006 m
 Bo: -760.584
 B1: 0.843013
 B2: 0.495441
 B3: 14.844
 B4: 0
 B5: 0
 B6: 0
 B7: 0
 B8: 0
 B9: 0

2 .. Boundary conditions

 Unconditional elevation case
 Minimum elevation: 608.372 m
 Maximum elevation: 2864.77m
 Minimum longitude: 568408 m
 Maximum longitude: 602408 m
 Minimum latitude: 3.86832e+006 m
 Maximum latitude: 3.89832e+006 m

3 .. Grid information

 Elevation grid name: Gerapotamou–DEM
 Mean elevation: 1065.19 m
 Average slope as percentage: 7.46999 %
 Average slope in degrees: 4.24133 degrees

4 .. MLR results

 Mean areal precipitation: 1412.36 mm
 Total precipitation: 854.478 mega cubic meter

End of report

Figure 11 | A sample report for one case that is generated using the MLR executor dialog.

The database accessing tool is designed to access three different types of databases where the time series data are stored, and then extract the precipitation values (y) for a user-specified period of time and possibly for a specified group of gauges rather than all the gauges.

- (a) A database that can basically be one column in the attribute table of the rain gauge shapefile. This column can represent a previous run or a one-time run.
- (b) A database that is stored in ArcView as a collection of database files (*.dbf) (77 files for our test case). This tool can browse through all the files, extract the required data and add it as a column to the attribute table of the shapefile.
- (c) A database that is stored somewhere in the computer outside ArcView. This tool can again browse through all the files, extract the required data and add it as a column to the attribute table of the shapefile.

For the purpose of the test case, and to simplify calculations, a relative coordinate system was established by locating an origin (0, 0) at the lower left corner of the island at latitude 3,800,000 m and longitude 461,000 m (see Figure 1). Subsequently, all Y-coordinates employed in the regression were the result of subtracting 3,800,000 from the original latitudes of the different stations and dividing by 1,000 to obtain latitudes in kilometres. Similarly, all X-coordinates were the result of subtracting 461,000 from the original longitudes of the different stations and dividing by 1,000 to obtain longitude values in kilometres. This manipulation of coordinates is preferable when performing the regression analysis. Using large numbers for latitude and longitude could have resulted in very small values for the model parameters (β_i), which is not desirable. Smaller numbers for parameters can be a source of error. For example, if we have a parameter that has a value of 0.000249, it can be rounded to 0.00025 or truncated to 0.00024, which when multiplied by a large number for longitude or latitude can result in noticeable errors.

Parameter generator

The number of parameters generated is one more than the number of variables included in the analysis because of

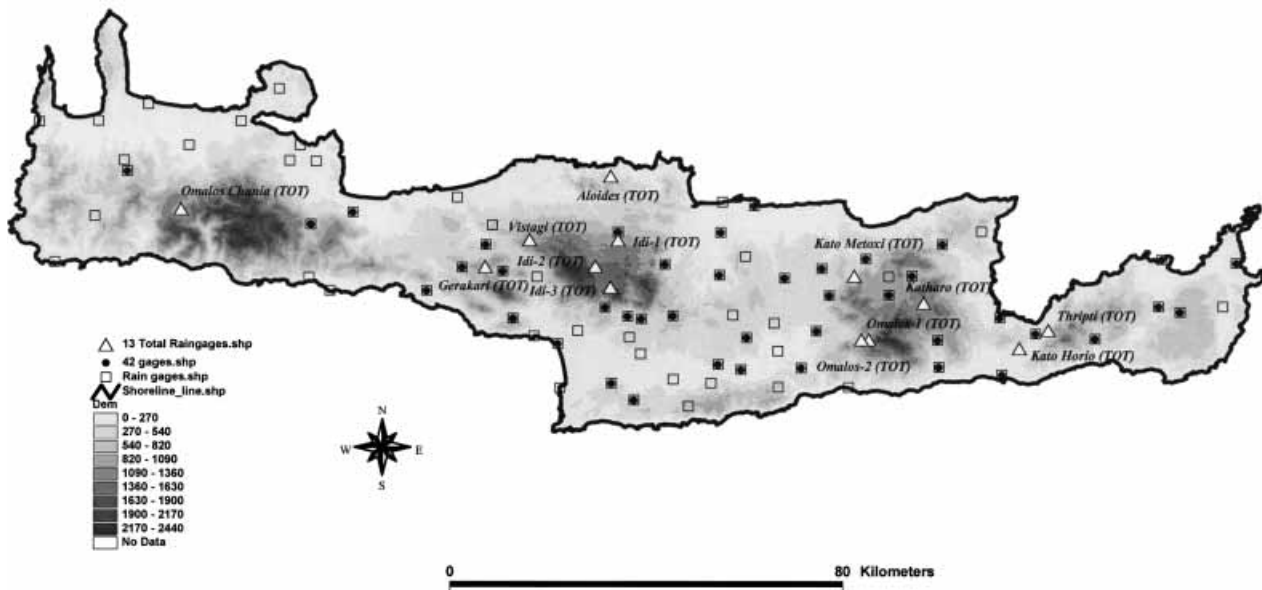


Figure 12 | The gauges used in the analysis (42 and 13) in addition to all the gauges on the island.

the intercept parameter (β_0). The user should identify the variables considered for the case being studied through the pop-up menu shown in Figure 7. The module will then generate the four input files necessary to run the executable 'mlr.exe', read the output file generated, and store the new information in the database file 'par.dbf'. Once the parameters are estimated, the regression model is complete and ready to use.

Model executor

Each grid cell in the DEM has an area, altitude, longitude and latitude. The regression models are applied for each cell in the DEM using the values of parameters generated in the previous step, and the values of the variables are extracted from each cell. The result is a mean areal precipitation value (in mm) and the total volume of precipitation (in 10^6 m^3) over the region which the DEM represents. The model executor is represented by the pop-up menu shown in Figure 8. By using the 'refresh' button, the module will extract information from the 'par.dbf' file concerning the case being studied, such as the case name, number of variables, number of gauges, coef-

ficient of determination, x -coordinate, y -coordinate and the values of the parameters generated. The user also has full control to alter the boundary conditions in the three dimensions of the study area. For example, the user can estimate the mean areal precipitation for a rectangular area within the region under consideration rather than the full extent. The user is also able to estimate the mean areal precipitation over a range of altitudes within the study area, or above or below a certain altitude. This provides the flexibility required for such a decision-support system. The module is equipped with artificial intelligence components that can recognize any mistakes made by the user and correct them automatically, or instruct the user to correct them or terminate the application. The results of the execution are then displayed at the bottom of the same pop-up menu.

Output visualizer

This is basically a point shapefile, with each point representing a grid cell in the DEM, as shown in Figure 9. The attribute table of the shapefile contains information about each cell, such as the original values for latitude and

Table 1 | Observed and estimated precipitation values for the 13 storage gauges

No	1	2	3	4	5	6	7	8	9	10	11	12	13
English name	Aloides (TOT)	Gerakari (TOT)	Idi-1 (TOT)	Idi-2 (TOT)	Idi-3 (TOT)	Katharo (TOT)	Kato Horio (TOT)	Kato Metoxi (TOT)	Omalos Chania (TOT)	Omalos-1 (TOT)	Omalos-2 (TOT)	Tiripti (TOT)	Vistagi (TOT)
Code	RG31	RG33	RG3	RG7	RG30	RG38	RG37	RG39	RG40	RG34	RG35	RG36	RG32
Prefecture	Rethymno	Rethymno	Rethymno	Rethymno	Rethymno	Lassithi	Lassithi	Lassithi	Chania	Iraklio	Iraklio	Lassithi	Rethymno
Longitude	024:52:20E	024:35:40E	024:55:16E	024:52:20E	024:50:26E	02:53:44:46E	02:54:47:20E	02:55:25:08E	02:54:20E	02:52:27:14E	02:52:26:00E	02:55:51:22E	02:44:41:00E
Latitude	35:22:20N	35:12:12N	35:15:00N	35:13:08N	35:12:15N	35:08:50N	35:03:28N	35:11:16N	35:20:50N	35:04:40N	35:04:00N	35:05:18N	35:15:50N
Egsa87-X	578283.9	552778.2	579806.0	578283.9	5752225.0	642004.4	661531.3	627845.8	490663.8	630904.6	629393.6	667435.2	561757.6
Egsa87-Y	3916356.1	3897949.9	3903582.7	3893728.9	3897969.3	3890502.2	3881286.1	3895997.2	3909639.2	3883076.2	3883076.2	3884923.7	3903410.0
Elevation (X1 in m)	460.0	1000.0	1150.0	1450.0	1350.0	1150.0	180.0	1150.0	1050.0	1350.0	1300.0	700.0	1040.0
Long (X2 in km)	117.3	91.8	118.8	117.3	114.2	181.0	200.5	166.8	29.7	169.9	168.4	206.4	100.8
Lat (X3 in km)	116.3	97.9	103.4	93.7	98.0	90.5	81.3	96.0	109.6	83.1	83.1	84.9	103.4
Agency	YEB	YEB	YEB	YEB	YEB	YEB	YEB	YEB	YEB	YEB	YEB	YEB	YEB
Start date	01/01/85	01/01/68	01/01/68	01/01/68	01/01/68	01/01/68	01/01/86	01/01/68	01/01/95	01/01/68	01/01/95	01/01/86	01/01/68
End date	01/01/96	01/01/96	01/01/96	01/01/96	01/01/96	01/01/96	01/01/96	01/01/96	01/01/96	01/01/96	01/01/96	01/01/96	01/01/96
1968-69	- 999.99	- 999.99	1910.00	2020.00	1810.00	1580.00	- 999.99	1825.00	- 999.99	- 999.99	- 999.99	- 999.99	- 999.99
Estimated	1732.45	2037.99	2283.59	2440.45	2417.14	1883.61	474.95	2029.90	2472.30	1986.72	1929.29	1169.95	2186.49
1969-70	- 999.99	1005.00	920.00	1215.00	1340.00	940.00	- 999.99	1130.00	- 999.99	925.00	- 999.99	- 999.99	1180.00
Estimated	894.92	1155.55	1232.78	1359.72	1329.37	1053.18	380.95	1109.11	1358.17	1148.84	1121.19	706.31	1196.72
1970-71	- 999.99	1545.00	1510.00	1875.00	1915.00	1230.00	- 999.99	1435.00	- 999.99	1155.00	- 999.99	- 999.99	1790.00
Estimated	1316.42	1678.35	1820.81	1998.70	1959.60	1525.84	448.59	1622.64	2007.01	1656.63	1612.51	972.62	1758.60
1971-72	- 999.99	1200.00	1185.00	1430.00	1395.00	1105.00	- 999.99	1190.00	- 999.99	915.00	- 999.99	- 999.99	1440.00
Estimated	1015.02	1282.38	1395.19	1527.95	1498.75	1177.15	360.72	1249.81	1525.75	1273.36	1239.68	759.77	1345.58
1972-73	- 999.99	1135.00	1385.00	1435.00	1350.00	1190.00	- 999.99	1220.00	- 999.99	1110.00	- 999.99	- 999.99	1465.00
Estimated	1260.15	1425.45	1559.58	1638.91	1631.94	1286.90	461.17	1383.59	1716.46	1342.42	1310.27	860.27	1512.58
1973-74	- 999.99	915.00	1480.00	1155.00	1025.00	1060.00	- 999.99	1055.00	- 999.99	940.00	- 999.99	- 999.99	1030.00
Estimated	941.46	1176.01	1307.66	1434.53	1403.11	1159.53	400.63	1214.76	1348.56	1242.29	1208.78	786.01	1243.64
1974-75	- 999.99	1190.00	1180.00	1660.00	1450.00	840.00	- 999.99	1105.00	- 999.99	880.00	- 999.99	- 999.99	1285.00
Estimated	1068.57	1371.04	1460.80	1609.24	1572.95	1262.95	493.77	1324.62	1595.72	1374.01	1342.07	867.60	1417.75
1975-76	- 999.99	1415.00	1535.00	1590.00	1450.00	1260.00	- 999.99	1415.00	- 999.99	1140.00	- 999.99	- 999.99	1605.00
Estimated	1491.43	1718.48	1877.07	1987.97	1973.16	1565.52	567.76	1675.23	2054.19	1643.39	1603.87	1052.26	1818.14
1976-77	- 999.99	1065.00	1195.00	1315.00	1160.00	815.00	- 999.99	985.00	- 999.99	670.00	- 999.99	- 999.99	1325.00
Estimated	1064.16	1248.41	1407.54	1506.53	1489.79	1188.19	331.63	1271.36	1489.39	1249.83	1213.96	760.18	1341.36
1977-78	- 999.99	2090.00	3005.00	3290.00	3770.00	1310.00	- 999.99	1790.00	- 999.99	1305.00	- 999.99	- 999.99	3110.00
Estimated	1589.53	2093.84	2230.70	2480.73	2416.09	1947.21	748.70	2033.91	2421.68	2133.23	2082.52	1334.65	2160.12
1978-79	- 999.99	1270.00	1315.00	1515.00	1410.00	1070.00	- 999.99	1500.00	- 999.99	1025.00	- 999.99	- 999.99	1570.00
Estimated	1236.65	1511.90	1689.19	1842.20	1804.33	1515.41	563.09	1583.52	1715.68	1611.29	1568.72	1051.15	1603.01
1979-80	- 999.99	1450.00	1585.00	1715.00	1570.00	1155.00	- 999.99	1580.00	- 999.99	1090.00	- 999.99	- 999.99	1715.00
Estimated	1329.01	1599.38	1801.39	1956.13	1918.27	1624.95	607.94	1697.68	1806.86	1717.59	1671.72	1133.24	1703.86

Table 1 | Continued

No	1	2	3	4	5	6	7	8	9	10	11	12	13
English name	Aloides (TOT)	Gerakari (TOT)	Idi-1 (TOT)	Idi-2 (TOT)	Idi-3 (TOT)	Katharo (TOT)	Kato Horio (TOT)	Kato Metoxi (TOT)	Omalos Chania (TOT)	Omalos-1 (TOT)	Omalos-2 (TOT)	Thripti (TOT)	Vistagi (TOT)
Code	RG31	RG33	RG3	RG7	RG30	RG38	RG37	RG39	RG40	RG34	RG35	RG36	RG32
1980-81	- 999.99	1700.00	1400.00	2310.00	3360.00	1250.00	- 999.99	1350.00	- 999.99	1070.00	- 999.99	- 999.99	1150.00
Estimated	1249.55	1611.97	1703.69	1880.24	1835.96	1481.38	618.31	1548.44	1865.63	1615.37	1579.59	1035.88	1658.19
1981-82	- 999.99	1575.00	1600.00	1750.00	1700.00	925.00	- 999.99	1465.00	- 999.99	1375.00	- 999.99	- 999.99	1775.00
Estimated	1253.04	1503.27	1563.35	1670.69	1653.78	1275.96	546.52	1362.95	1811.10	1368.20	1341.85	879.50	1547.96
1982-83	- 999.99	1200.00	1525.00	2000.00	1445.00	900.00	- 999.99	1000.00	- 999.99	750.00	- 999.99	- 999.99	1500.00
Estimated	1067.69	1351.37	1498.67	1648.44	1612.45	1304.94	403.86	1374.48	1573.85	1405.64	1366.57	856.66	1428.59
1983-84	- 999.99	1665.00	1350.00	1650.00	1650.00	1400.00	- 999.99	1225.00	- 999.99	1225.00	- 999.99	- 999.99	1425.00
Estimated	1232.40	1479.36	1636.78	1771.79	1739.80	1461.87	591.71	1528.58	1680.94	1547.92	1509.66	1034.07	1562.30
1984-85	- 999.99	1550.00	1600.00	1700.00	1900.00	1100.00	- 999.99	1000.00	- 999.99	1000.00	- 999.99	- 999.99	1900.00
Estimated	1318.26	1602.98	1750.83	1875.93	1842.24	1520.89	654.21	1592.54	1840.50	1623.00	1586.39	1083.01	1671.86
1985-86	1105.00	900.00	900.00	1100.00	1150.00	1000.00	- 999.99	925.00	- 999.99	755.00	- 999.99	- 999.99	- 999.99
Estimated	1305.61	1378.96	1461.22	1496.05	1496.29	1297.24	823.53	1356.67	1552.06	1320.50	1302.32	1052.34	1433.99
1986-87	1255.00	1500.00	1700.00	1650.00	1540.00	910.00	880.00	1425.00	- 999.99	800.00	- 999.99	1360.00	1405.00
Estimated	1663.70	1697.67	1936.32	1966.22	1979.22	1645.07	653.56	1767.99	2003.09	1644.21	1603.86	1154.59	1849.74
1987-88	970.00	1400.00	1300.00	- 999.99	1600.00	1325.00	490.00	1140.00	- 999.99	1020.00	- 999.99	900.00	1220.00
Estimated	1044.90	1438.63	1556.72	1763.10	1703.29	1423.12	550.24	1465.47	1608.17	1568.03	1528.23	992.74	1486.71
1988-89	1065.00	1075.00	1225.00	1450.00	1350.00	875.00	563.00	1150.00	- 999.99	925.00	- 999.99	975.00	1285.00
Estimated	1058.30	1298.90	1403.00	1521.30	1496.50	1191.05	432.61	1261.65	1533.68	1277.43	1246.51	801.62	1358.80
1989-90	750.00	850.00	975.00	- 999.99	1050.00	575.00	256.00	750.00	- 999.99	560.00	- 999.99	464.00	825.00
Estimated	742.85	883.34	969.75	1041.28	1027.77	823.12	290.66	876.49	1042.61	874.11	852.08	554.15	933.77
1990-91	825.00	950.00	1350.00	1450.00	1100.00	860.00	482.00	1000.00	- 999.99	700.00	- 999.99	840.00	960.00
Estimated	988.37	1134.46	1240.04	1315.68	1302.47	1074.49	460.04	1134.86	1316.03	1124.52	1099.14	764.36	1196.64
1991-92	1100.00	1115.00	1810.00	2475.00	2175.00	1050.00	572.00	1300.00	- 999.99	625.00	- 999.99	899.00	1100.00
Estimated	1280.46	1396.28	1544.52	1602.24	1602.38	1279.97	476.30	1378.21	1676.25	1315.67	1284.27	868.49	1493.22
1992-93	650.00	950.00	1100.00	- 999.99	1000.00	765.00	330.00	1025.00	- 999.99	500.00	- 999.99	670.00	775.00
Estimated	932.57	1122.37	1208.24	1295.33	1282.28	974.78	295.90	1051.39	1373.54	1042.51	1016.54	617.52	1178.70
1993-94	925.00	1235.00	1360.00	1310.00	1465.00	995.00	474.00	1175.00	- 999.99	800.00	- 999.99	780.00	975.00
Estimated	11116.87	1435.26	1549.10	1705.96	1669.70	1313.07	421.45	1389.34	1700.45	1428.83	1392.02	855.68	1497.41
1994-95	950.00	1125.00	1650.00	1475.00	1475.00	1150.00	537.00	1460.00	- 999.99	815.00	- 999.99	972.00	1175.00
Estimated	1275.80	1566.49	1771.34	1938.62	1895.42	1611.80	583.86	1678.92	1758.91	1712.18	1665.09	1118.04	1669.20
1995-96	1150.00	1475.00	1550.00	1675.00	1675.00	1340.00	636.00	1425.00	1660.00	1090.00	1110.00	1100.00	1275.00
Estimated	1262.51	1620.29	1713.64	1887.45	1844.57	1484.69	614.98	1554.21	1880.28	1616.78	1580.90	1035.14	1668.39
1996-97	1400.00	1400.00	1500.00	1475.00	1475.00	1040.00	512.00	1455.00	2370.00	810.00	820.00	883.00	1590.00
Estimated	1550.12	1830.32	2001.85	2133.31	2117.10	1607.45	431.09	1742.36	2253.07	1704.83	1659.35	994.70	1941.92

Note: - 999.99=unavailable record.

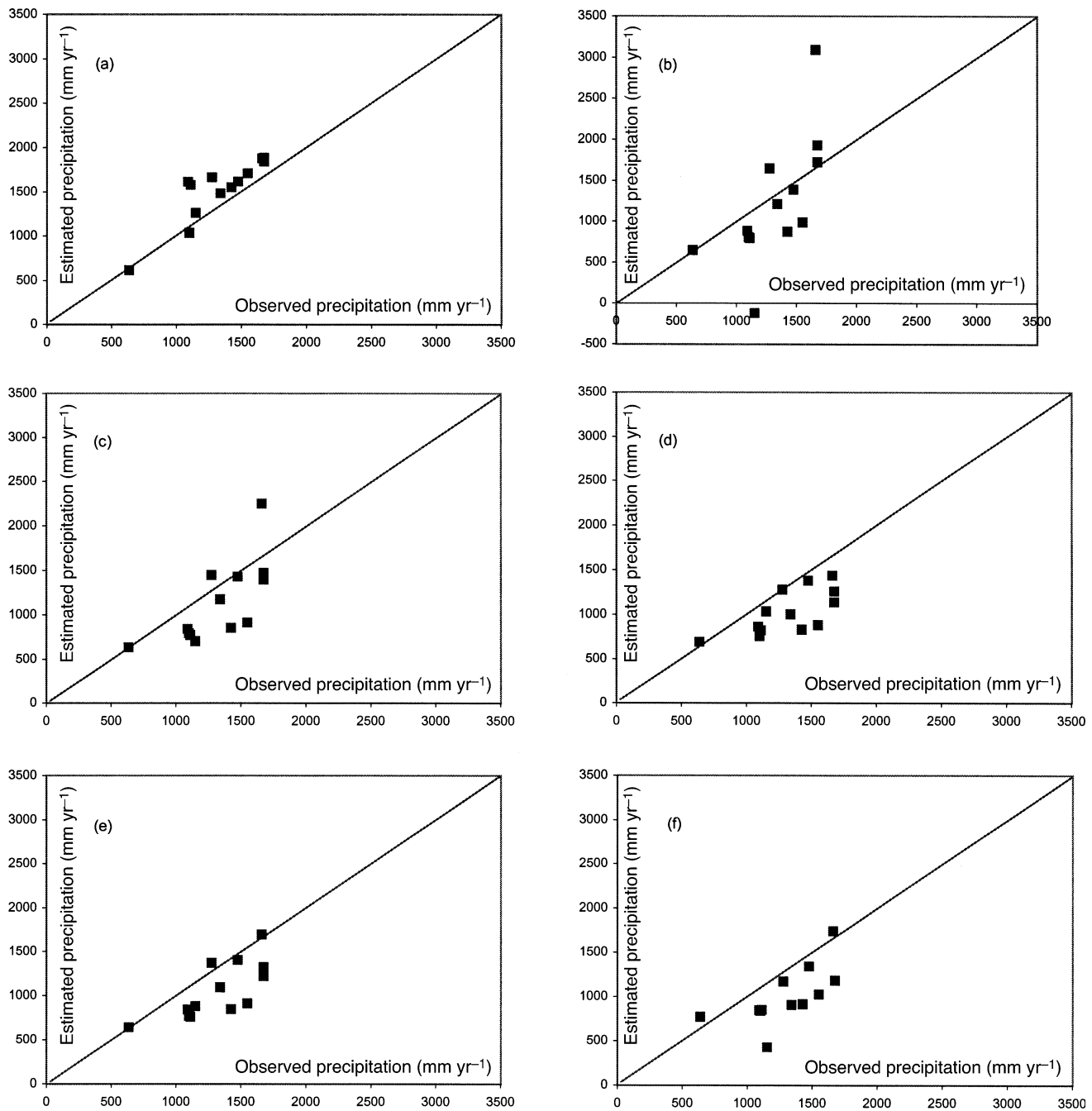


Figure 13 | A comparison between observed precipitation for the water year 1995–1996 and estimated values using the MLR models and spatial interpolation techniques.

longitude, altitude, and the x - and y -coordinates, and the estimated value of precipitation. If the user is to specify a smaller area than the full extent, the value of precipitation

is 0 outside the specified extent. The user will be informed of the ratio of the extent being analysed to the full extent, as shown in Figure 10.

Table 2 | A comparison between observed precipitation values, estimated precipitation values using Crete models, and estimated precipitation values using regional models

No.	Region	English name	Code	Prefecture	X1	X2	X3	1974–75	1977–78	1986–87
1	Observed							– 999.99	– 999.99	1255.00
	Crete	Aloides (TOT)	RG31	Rethymno	460.0	117.28	116.34	1068.57	1589.53	1663.70
	North							646.19	813.81	977.49
2	Observed							1190.00	2090.00	1500.00
	Crete	Gerakari (TOT)	RG33	Rethymno	1000.0	91.78	97.95	1371.04	2093.84	1697.67
	South							1247.49	2078.78	1529.07
3	Observed							1180.00	3005.00	1700.00
	Crete	Idi-1 (TOT)	RG3	Rethymno	1150.0	118.81	103.38	1460.80	2230.70	1936.32
	North							1325.67	1768.22	1737.55
4	Observed							1660.00	3290.00	1650.00
	Crete	Idi-2 (TOT)	RG7	Rethymno	1450.0	117.28	93.73	1609.24	2480.73	1966.22
	North							1716.21	2347.38	2162.63
5	Observed							1450.00	3770.00	1540.00
	Crete	Idi-3 (TOT)	RG30	Rethymno	1350.0	114.23	97.97	1572.95	2416.09	1979.22
	North							1588.18	2153.55	2026.85
6	Observed							840.00	1310.00	910.00
	Crete	Katharo (TOT)	RG38	Lassithi	1150.0	181.00	90.50	1262.95	1947.21	1645.07
	East							1194.84	1936.58	1542.49
7	Observed							– 999.99	– 999.99	880.00
	Crete	Kato Horio (TOT)	RG37	Lassithi	180.0	200.53	81.29	493.77	748.70	653.56
	East							563.41	791.35	783.64
8	Observed							1105.00	1790.00	1425.00
	Crete	Kato Metoxi (TOT)	RG39	Lassithi	1150.0	166.85	96.00	1324.62	2033.91	1767.99
	East							1233.00	1994.74	1603.25
9	Observed							– 999.99	– 999.99	– 999.99
	Crete	Omalos Chania (TOT)	RG40	Chania	1050.0	29.66	109.64	1595.72	2421.68	2003.09
	South							1390.49	2325.51	1790.22
10	Observed							880.00	1305.00	800.00
	Crete	Omalos-1 (TOT)	RG34	Iraklio	1350.0	169.90	83.08	1374.01	2133.23	1644.21
	South							1321.65	2198.59	1498.34
11	Observed							– 999.99	– 999.99	– 999.99
	Crete	Omalos-2 (TOT)	RG35	Iraklio	1300.0	168.39	83.08	1342.07	2082.52	1603.86
	South							1290.07	2145.15	1461.21
12	Observed							– 999.99	– 999.99	1360.00
	Crete	Thripti (TOT)	RG36	Lassithi	700.0	206.44	84.93	867.60	1334.65	1154.59
	East							877.90	1361.83	1197.81
13	Observed							1285.00	3110.00	1405.00
	Crete	Vistagi (TOT)	RG32	Rethymno	1040.0	100.76	103.41	1417.75	2160.12	1849.74
	North							1372.25	1865.25	1785.72

Note: –999.99=unavailable record.

Output report generator

Using the 'write report' button of the pop-up menu (Figure 8), the user can write a report, which is normally named '<casename.txt>', that is stored in the working directory of the project, as shown in Figure 11. The report is divided into four sections. Section 1 is the general information about the case. Section 2 is the boundary conditions of the case. Section 3 is the DEM name, mean elevation, and the average slope as a percentage and in degrees. [The slope is defined in ArcView as the maximum rate of change in value from each cell to its neighbors. The slope in degrees is 'arctan rise/run', while the slope as a percentage is 'rise/run*100%. So a slope of 45° is 100% as a percentage. Thus the slope as a percentage = TAN (the slope in degrees)*100.] Section 4 contains the results. An additional feature is added to the module that enables the user to get a hard copy of the report through ArcView by clicking the 'print report' button. The user will be prompted by a name for the default printer. If the user agrees, the printing job will take place; if not, the user will then enter a new name that can be recognized by the program and the document is sent to the printer.

DISCUSSION

AVRU was used to derive regression models for every year for the 30-year period 1967–1997. Of the 77 gauges available, only 42 recorded data for that period. The analysis was based on the data from these 42 gauges. Their locations are shown in Figure 12. Precipitation data were also collected from a set of 13 storage gauges (see Figure 12) that were mainly installed on relatively higher elevations. These gauges were read only once a year because of problems with accessibility. The models developed were used to estimate precipitation at those locations, as shown in Table 1.

Generally, the results can be considered satisfactory considering the sparse rain gauge network employed in the analysis, as well as the uncertainty associated with the data collected from the storage gauges as readings were done only once per year.

Spatially, the results obtained can be ranked as: good for the gauges Aloides, Gerakari, Idi-1, Kato Horio, Kato Metoxi, Omalos Chania and Thripti; average for the gauges Idi-2 and Vistagi; bad for the gauges Idi-3, Kathro, Omalos-1 and Omalos-2. There was a relatively high overestimation by the models for Kathro, Omalos-1 and Omalos-2, while there was a relatively high underestimation for Idi-3. Estimated values using MLR were compared with those obtained using spatial interpolation techniques. In all cases, estimates using MLR were closest to the observed values. Figure 13 shows an example for the year 1995–1996, when all observed records were available for all gauges which were compared to estimates obtained using the spatial interpolation techniques. Case (a) is MLR estimates, (b) Spline_Regularized, (c) Spline_Tension, (d) IDW, (e) Kriging, and (f) 2nd Order Polynomial.

Temporally, there was a general overestimation by the models for all years especially the years 1985–86 and 1996–97. The observed records for the year 1977–78 were significantly underestimated especially for the gauges Idi-1, Idi-2, Idi-3, and Vistagi (they are located in the middle of the island). The models, however, overestimated the records of 1977–78 for the gauges Kato Metoxi and Omalos-1 (they are both located at the eastern part of the island).

New models were developed for the regions of the island (North, South, and East—refer to Figure 2) trying to enhance the estimates. Results show that the new models provided some improvement, however the observed records for the year 1977–78 were still not matched as shown in Table 2.

CONCLUSION

Integrating GIS with statistical models, represented in this case by the multiple linear regression method, can enhance the capabilities of the GIS. The development of the ArcView Regression Utility (AVRU) enables the user to model precipitation, or any other spatial hydrological response variable, using three spatial variables (i.e. altitude, longitude and latitude). ArcView Avenue scripts, Fortran, IMSL Stat Library, ArcView Dialog Designer and

Batch Programming were used effectively and interactively to create this powerful tool. The result is a linear (in the parameters) model that is used to estimate mean areal precipitation and total precipitation volume over any specified region using its digital elevation model (DEM). A test case from the island of Crete, in Greece, was used to illustrate the capabilities of the utility. The results show that owing to the uncertainty associated with the data from storage gauges (yearly values), the comparison between observed and estimated values cannot be used either to verify the models or to provide specific recommendation for installing recording gauges on those higher altitudes. However, the differences detected between the model output and the observed values can provide general guidelines for both the models and the collected data. The procedure to be followed in this case would have three stages. (a) Investigate the site where the gauge is installed to determine the degree of exposure. Evaporation and wind currents cause the largest errors by diverting falling rain away from the instrument. (b) Conduct an experiment by installing low-cost standard gauges at higher altitudes for a short period of time to improve/verify the models. (c) Read the documentation of the gauge to see if there are any changes in the surroundings, the observer, the location of the gauge (gauge has moved) or the gauge type. Mechanical errors are also a factor. A human error in documenting the right observation should also be investigated.

REFERENCES

- Burrough, P. A., Van Rijn, R. & Rikken, M. 1996 Spatial data quality and error analysis issues: GIS functions and environmental modelling. In *GIS and Environmental Modelling: Progress and Research Issues* (ed. M. R. Goodchild *et al.*). GIS World, Fort Collins, CO.
- Daly, C., Neilson, R. P. & Phillips, D. L. 1994 A statistical-topographic model for mapping climatological precipitation over mountainous terrain. *J. Appl. Meteorol.* **33**, 140–158.
- Garen, D. C., Johnson, G. L. & Hanson, C. L. 1994 Mean areal precipitation for daily hydrologic modelling in mountainous regions. *Wat. Resources Bull.* **30**, 481–491.
- Goodchild, M. F. 1996 The spatial data infrastructure of environmental modelling. In: *GIS and Environmental Modelling: Progress and Research Issues* (ed. M. R. Goodchild *et al.*). GIS World, Fort Collins, CO.
- Hay, L., Viger, R. & McCabe, G. 1998 Precipitation interpolation in mountainous regions using multiple linear regression. *Proceedings of the HeadWater 98 Conference*, Mean/Merano, Italy, April 1998. IAHS publication No. 248, pp. 33–38.
- He, C., Shi, C., Yang, C. & Agosti, B. P. 2001 A Windows-based GIS-AGNPS interface. *J. Am. Wat. Resources Assoc.* **37** (2), 395–406.
- Hevesi, J. A., Istok, J. D. & Flint, A. L. 1992 Precipitation estimation in mountainous terrain using multivariate geostatistics. Part I. Structural analysis. *J. Appl. Meteorol.* **31**, 661–676.
- Hirsch, R. M., Helsel, D. R., Cohn, T. A. & Gilroy E. J. 1995 Statistical analysis of hydrologic data. In *Handbook of Hydrology* (ed. D. R. Maidment). McGraw-Hill, New York, Chap. 17.
- Jelinski, D. E., Goodchild, M. F. & Steyaert, L. T. 1994 Multiple roles for GIS in global change research: towards a research agenda. In *Environmental Information Management and Analysis: Ecosystem to Global Scales* (ed. W. K. Michener *et al.*). Taylor and Francis, Bristol, PA, pp. 40–56.
- Jeton, A. E., Dettlinger, M. D. & Smith, J. L. 1995 Potential effects of climate change on streamflow, eastern and western slopes of the Sierra Nevada, California and Nevada. *US Geological Survey, Water Resources Investigative Report 95-4260*.
- Linsley, R. K. 1958 Correlation of rainfall intensity and topography in California. *Trans. Am. Geophys. Un.* **39**, 15–18.
- Maidment, D. R. 1996 Environmental modelling within GIS. In *GIS and Environmental Modelling: Progress and Research Issues* (ed. M. R. Goodchild *et al.*). GIS World, Fort Collins, CO.
- Nakama, L. Y. & Risley, J. C. 1993 Use of a rainfall-runoff model for simulating effects of forest management on streamflow in the East Fork Lobster Creek Basin, Oregon. *US Geological Survey, Water Resources Investigative Report 93-4040*.
- Paniconi, C., Kleinfeldt, S., Deckmyn, J. & Giacomelli, A. 1999 Integrating GIS and data visualization tools for distributed hydrologic modelling. *Trans. GIS* **3**(2), 97–118.
- Peters, N. E. 1984 Evaluation of environmental factors affecting yields of major dissolved ions in streams of the United States. *US Geological Survey, Water Supply Paper 2224*.
- Risley, J. C. 1993 Use of a precipitation-runoff model for simulating effects of forest management on streamflow in 11 small drainage basins, Oregon Coast Range. *US Geological Survey, Water Resources Investigative Report 93-4181*.
- Sauer, V. B., Thomas, W. O., Strickler, V. A. & Wilson, K. V. 1983 Flood characteristics of urban watersheds in the United States. *US Geological Survey, Water Supply Paper 2207*.
- Schermerhorn, V. P. 1967 Relations between topography and annual precipitation in Western Oregon and Washington. *Wat. Resources Res.* **3**, 707–711.
- Spreen, W. C. 1947 Determination of the effect of topography on precipitation. *Trans. Am. Geophys. Un.* **28**, 285–290.
- Stafford, S. G., Brunt, J. W. & Michener, W. K. 1994 Integration of Scientific Information Management and Environmental Research. In *Environmental Information Management and Analysis: Ecosystem to Global Scales* (ed. W. K. Michener *et al.*). Taylor and Francis, Bristol, PA, pp. 1–19.

- Stedinger, J. R. & Tasker, G. D. 1985 Regional hydrologic analysis. 1. Ordinary, weighted, and generalized least-squares compared. *Wat. Resources Res.* **21**(9), 1421–1432.
- Steyaert, L. T. & Goodchild, M. F. 1994 Integrating geographic information systems and environmental simulation models: a status review. In *Environmental Information Management and Analysis: Ecosystem to Global Scales* (ed. W. K. Michener *et al.*). Taylor and Francis, Bristol, PA, pp. 333–355.
- Storr, D. & Ferguson, H. L. 1972 The distribution of precipitation in some mountainous Canadian watersheds. In *Distribution of Precipitation in Mountainous Areas, II. WMO/OMM 326*, pp. 243–253.
- Strebel, D. E., Meeson, B. W. & Nelson, A. K. 1994 Scientific information systems: a conceptual framework. In *Environmental Information Management and Analysis: Ecosystem to Global Scales* (ed. W. K. Michener *et al.*). Taylor and Francis, Bristol, PA, pp. 59–85.
- Sui, D. Z. & Maggio, R. C. 1999 Integrating GIS with hydrological modelling: practices, problems, and prospects. *Comput. Environ. Urban Syst* **23**, 33–51.
- Taylor, K., Walker, G. & Abel, D. 1999 A framework for model integration in spatial decision support systems. *Int. J. Geogr. Inf. Sci.* **13**(6), 533–555.