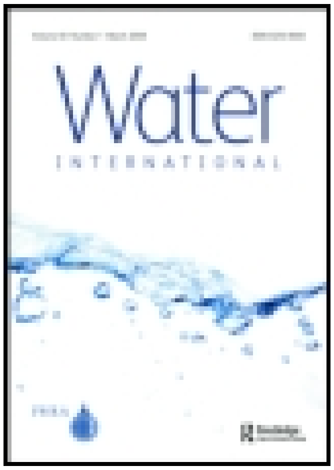

Water International
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/rwin20

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Published online: 22 Jan 2009.

To cite this article: Christos A. Karavitis & Petros Kerkides (2002) Estimation of the Water Resources Potential in the Island System of the Aegean Archipelago, Greece, Water International, 27:2, 243-254, DOI: 10.1080/02508060208686998

To link to this article: http://dx.doi.org/10.1080/02508060208686998

International Water Resources Association
Water International, Volume 27, Number 2, Pages 243–254, June 2002

Estimation of the Water Resources Potential in the Island System of the Aegean Archipelago, Greece

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Abstract: *The present paper tries to estimate the surface water resources potential in some of the major Aegean islands in an effort to provide a means for the continuous development of the region, and, by extension, for similar areas around the world. The islands have to confront the challenge of surviving in a semiarid environment under the constraints of uneven water resources distribution both in space and time. In addition to these, tourism development, industrialization and highly water consumptive life styles have exacerbated perennial problems in water resources and water resources management. The framework of the present effort has a two-prong emphasis. In the first part, a simulation model is presented, which tries to estimate the potential surface runoff under physical, structural organizational, and institutional constraints. The methodology and the premises of the simulation process are delineated. In the second part, the results of the model's application in distinct cases are demarcated. The final product, namely the model and the resulting runoff coefficients, are presented in the form of a standard, which may provide practitioners in the field as well as decisionmakers the means for an initial reference in pertinent developmental efforts. Finally, the conclusions and recommendations raise the question of ecosystem resilience and point towards the urgent and continuous need for the application of integrated water resources management principles.*
Keywords: *Water resources estimation, surface runoff coefficient, management in island systems, simulation models, semi-arid environment, Aegean islands, Greece.*

Introduction

The difficulty in studying water resources in general, and in the islands of the Aegean Archipelago in particular, includes not only an assessment of their natural state, territorial distribution, and fluctuations in time, but also their dependence on human socio-economic activities. In recent decades, the intensified exploitation of water resources for urban, agricultural and industrial uses, the population redistribution and growth, as well as alarming indications about climatic shifts (greenhouse effect, droughts, etc.) have started to elicit significant impacts on the state of the available freshwater, despite the ability of stream and groundwater flow for renewal and recharge.

The Aegean Archipelago, as a part of Greece, belongs to the Mediterranean region. In this region water is used in an unsustainable manner. The Mediterranean landscape as a whole is ecologically fragile and seriously endangered by prevailing social and economic trends. In this regard, the future of the islands may be threatened by increasing coastal areas stress, expanding deferences between tourist areas and the rural hinterlands, serious water resources interdependencies, high susceptibility to pollution, and by the sensitivity between the water and soil equilibrium. The soils in the islands are extremely vulnerable to erosion with resulting problems in developing the water resources (reservoir sedimentation, streambed stability, etc.). Most of the population is concentrated in the coastal zone, and increasing tourism causes a strong, seasonal water demand. Thus, uneven water demands in both space and time greatly increase the cost of making water accessible. Wastewater management problems proliferate with the expanding urban population during the summer and effluents are deteriorating the quality of coastal waters. Summarizing the key conflicts and concerns combining integrated water resources management and a sustainable development orientation in the Aegean Archipelago and by extension to similar areas, a few interrelated crises and issues may be demarcated in relation to some more extensive comments made by Vlachos and Braga (2001):

- A demand and water supply crisis representing, primarily, an engineering dimension. Such a dimension incorporates measures of water consumption reduction and water supply augmentation;

- A deteriorating water quality crisis producing an ecological dimension. Issues including, lack of adequate safe drinking water supplies in the needed space and time, groundwater deterioration and contamination, and interference of water resources development systems with the natural environment cycles are surfacing;
- An organizational crisis transforming into a management dimension. Attention is needed in combining competent personnel, facilities and processes, the promotion of more desirable levels and patterns of use, as well as the legal and administrative guidelines (capacity building); and
- An information and data crisis, regarding their validity, reliability, availability, and comparability, as well as combining data and judgement, modeling, and the building of applicable Decision Support Systems. In this context, all the pertinent factors point towards timely, contingency oriented and anticipatory water resources planning and management for the islands rather than waiting for even more serious water shortages, pollution and land erosion to occur.

The total water resources potential of Greece, including the Aegean islands, has different estimates throughout the literature (Karavitis, 1999b). In this context, the total water resources potential of the Aegean islands sector (one of the 14 water sectors into which Greece has been divided based on the major watersheds) is estimated at about 1.25 x 10^9 m^3/yr with the various abstractions already accounted for. Of that amount, approximately 250 x 10^6 m^3/yr or 20 percent is stored as groundwater and the remaining 1.0 x 10^9 m^3/yr is believed to constitute the surface water potential. Crete (the largest Greek island and one of the largest in the Mediterranean region) constitutes another one of the Greek water sectors, and thus it is not consider as a part of the Aegean islands. However, a few of its watersheds were included in the present effort in order to have a more complete representation of the whole area. In this regard, it is pointed out that the total water resources potential of Crete is estimated at about 2.6 x 10^9 m^3/yr. Approximately 1,3 x 10^9 m^3/yr or 50 percent is stored as groundwater and the remaining 1.3 x 10^9 m^3/yr constitutes the surface water potential. The Aegean islands water sector uses approximately 80 x 10^6 m^3/yr for irrigation, 33 x10^6 m^3/yr for domestic water supply, and only about 1 x 10^6 m^3/yr for industrial purposes. The pertinent values for Crete water sector are 220 x 10^6 m^3/yr, 33 x 10^6 m^3/yr, and 2 x 10^6 m^3/yr, respectively. Overall, the Aegean islands sector exhibits a total water use of 114 x 10^6 m^3/yr predominantly from groundwater, leaving almost all of the potential surface water available for further development. However, as in every surface water resources development effort, additional site-specific constraints are present, such as geology, morphology, environmental requisites, etc., which may render the overall effort extremely difficult. Nevertheless, the estimation of the surface runoff should be a priority in all the efforts of evaluating the potential water resources in the islands.

Hence, the estimation of the total volume of the abstractions from a given precipitation volume in a watershed may lead to the estimation of the surface water volume. Abstractions may be accounted for by means of runoff coefficients. Therefore, by estimating the runoff coefficient, it is believed that an initial approximation of the surface water may be given for further use, in all development efforts.

Methodological Procedures

Problem Definition and Objectives

The Aegean Archipelago of about 3,000 islands presents a case of many "closed" island systems in a common enough environment located in the eastern part of Greece. The axis of the area from north to south is approximately 700 km, where the zone from west to east has a width of about 300 km. A map of the islands are illustrated on Figure 1. The islands present a unique diversity in their climatic conditions, geologic characteristics, flora, and fauna. However, they exhibit some common trends being mostly semiarid and exposed to almost identical economic and social problems. Therefore, vulnerability raises the question of ecosystem resilience, especially because of periodic floods, droughts, and increasing an-

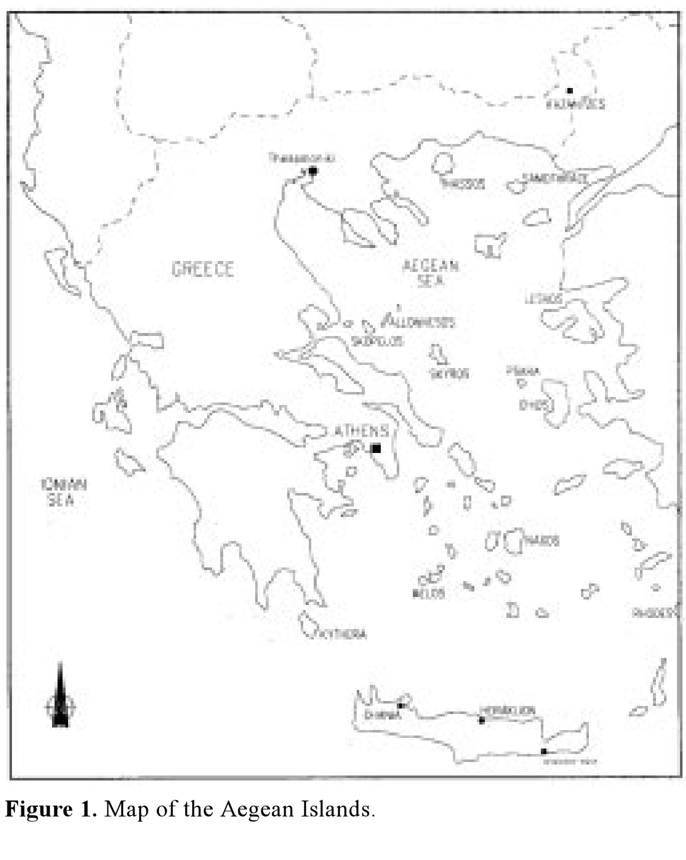

Figure 1. Map of the Aegean Islands.

Table 1. Indicative Water Demand in Various Watersheds of Selected Aegean Islands and in the Crete Water Sector in 10^6 m^3/yr

Island, Watershed Area	*Irrigation*	*Urban and Industrial*	*Total*
Skyros, Ferekampos	1.5	0.8	2.3
Allonesos, Kastanias,	1.6	0.7	2.3
Lesvos	46.0	7.0	53.0
Thassos, Limenaria	4.0	1.0	5.0
Melos	0.9	0.6	1.5
Naxos	15	1.8	16.8
Thassos, Theologos	5.0	0.8	5.8
Thassos, Prinos	3.0	0.8	3.8
Rhodes (UNEP, 1996)	16.0	11.0	27.0
Samothrace	3.2	0.5	3.7
Skopelos	2.4	0.7	3.1
Aegean Islands (total)	151	64	215
Crete (total)	415	66	481

thropogenic disturbances (Vlachos, 1995). The 1999 water demand estimates in some of the islands are presented in Table 1. The same table also reflects the water demand in the whole Aegean islands and Crete water sectors (Bosdogianni, 1994; Karavitis, 1994; Karavitis, 1999b). It is again pointed out that Crete water sector is divided into separate watersheds due to its size. All in all, water resources management efforts have to concentrate so as to breach the gap between water availability and the escalating water demand, before it becomes chasmic through time. Given the state of overexploitation of groundwater resources, surface water resources may offer an alternative for the pertinent efforts.

In this regard, the main challenge of this research has been to estimate the overall surface water resources potential in some of the major islands, in order to relate present resources with on-going and future water demands in an already stressed environment. The surface water runoff constitutes one of the major components of the islands water balance, and has to be identified for any water related development projects. The precipitation and the majority of surface runoff takes place in the winter months, creating a strong time demand for water in the dry summer season, where most of the activities are concentrated. Given the size of the islands, the corresponding small size of the watersheds (average area less than 15 km^2), and the morphologiacal characteristics, the surface runoff is usually quickly lost to the sea. The absence of runoff measurements (except for a few cases), the overall data deficiencies, as well as the ephemeral character of the streams giving often winter floods and completely drying up in the summer are additional constraints. At the same time, the continuing deforestation of the recent decades has increased the estimated surface runoff creating also severe flood and erosion hazards (e.g., Thassos Island).

In order to identify the annual surface runoff, the annual surface runoff coefficient was chosen to be estimated. The estimated runoff coefficients are plotted and the resulting curve may provide a handy reference for an initial estimation of the runoff. The literature review has indicated that only sporadic efforts have been undertaken towards this objective in the area (Karavitis, 1999a; Kerkides et al, 1996; UNEP, 1996). Thus, it is believed that the overall approach may produce a tool for practitioners in the field, managers, and other decision makers in the form of a standard for the Aegean Archipelago and, by extension, for other regions around the world facing similar problems.

Methodological Framework

The estimation of the runoff coefficient was based on the utilization of simple general principles in the areas under study. Hence, a simulation of the water balance process has been chosen to be applied. The criteria for such an application were the standardization of the procedure, common inputs, and an accurate as possible representation of the reality, given the limited meteorological and hydrological databases. In this context, the basic water balance equation fulfills the pertinent criteria, even though it is a very well known technique. However, the absence of any pertinent hydrological information in most of the area may point towards the necessity of such an effort. Thus, despite the plethora of the existing modeling tools, it was decided to develop a simulation model based on the pertinent premises in order to approximate as closely as possible the context of the area. The process has followed the principles of systems engineering techniques as a part of an integrated water resources management approach (Grigg, 1996). The methodological framework may be briefly delineated as follows:

- problem definition and objectives;
- area identification and data collection;
- evaluation of the meteorological parameters;
- application of the Penman method for the estimation of evaporation and evapotranspiration;
- estimation of the runoff coefficients; and
- results and evaluation (including feed-back loop).

All the pertinent steps are summarized in the next sections.

Area Identification and Data Collection

The estimation of the annual surface runoff coefficients involved the islands and regions, which are presented in Table 2. The area of the Kazantzes River, a tributary of Erythropotamos in the Evros river watershed (Thrace), has also been chosen for the application of the method. This area would serve as a reference for the Northeastern inland part of the country, for the necessary comparisons to be drawn. Elements of the effort were parts of a greater project for the development of water resources in the islands by the Ministry of Agriculture. The current study took place from 1993 to 1999. Numerous visits have been conducted in every area of interest, and the watersheds, their morphology, and geology have been explicitly studied. Flow data, where available, and meteorological information have been collected. Demographic, economic, and agricultural conditions have been recorded. Finally, information was also collected through the local authorities and agencies (MECPPW, 1993; Michailidis, 1994; Kerkides et al., 1996; Karavitis, 1994; 1996; 1997).

Meteorological Parameters

The necessary meteorological data included precipitation, sunshine hours, and solar radiation, humidity, temperature, and wind velocity. The values were average monthly ones. The precipitation data for the various areas were taken from a number of stations presented on Table 3. Wherever needed (and possible), the Thiessen method for aerial average rainfall was applied and/or elevation rainfall correction was computed. The final rainfall values used are presented on Table 6.

Estimation of Evapotranspiration

The modified Penman method was used for the estimation of the evaporation and consequently of the evapotranspiration (Cuenca, 1989). The general form of the Penman equation used is (Kerkides et al., 1996):

$$\mathrm{PEVT} = \frac{(\Delta * \mathrm{R} + \mathrm{E_a} * \gamma)}{\Delta + \gamma} \qquad (1)$$

Where *PEVT* is the potential evapotranspiration (mm day^{-1}); Δ is the slope of the saturation vapor pressure-temperature curve calculated at mean air temperature (*hPa* K^{-1}); Δ is the psychometric constant (*hPa* K^{-1}); and R_n is the net long-wave and short-wave radiation (mm day^{-1} water equivalent) given by:

$$\mathrm{R_n} = (1 - \mathrm{r})\mathrm{R_s} - \sigma \mathrm{T_a^4}(0.34 - 0.44(\mathrm{e_a})^{1/2})(0.10 + 0.90\mathrm{n}/\mathrm{N}) \qquad (2)$$

Table 2. Islands, Regions, and Key Characteristics

Island or Region (North to South)	*Area km²*	*Population*	*Water Resources Characteristics*
Thassos	380.1	13,527	Groundwater, springs, ephemeral streams
• Prinos watershed	4.0		
• Limenaria watershed	7.4		
• Theologos watershed	9.4		
Samothrace	178.0	3,083	Springs, streams, groundwater
• Karavi watershed	8.0		
• Xeropotamos watershed	9.0		
Lesvos	1626.0	87,151	Groundwater, springs, ephemeral streams
• Eastern part	1081.0		
• Western part	545.0		
Allonnessos	129.6	2,985	Groundwater, torrents
• Kastanias watershed	4.5		
Skopelos	96.3	4,658	Groundwater, torrents
• Panormos watershed			
Skyros	223.1	2,901	Groundwater, torrents
• Ferekampos watershed	13.0		
Chios	842.6	51,746	Groundwater, springs, ephemeral streams
• Scardanas watershed	34.1		
Psara	37.5	438	Groundwater, springs, ephemeral streams
Naxos	428.0	14,838	Groundwater, springs, ephemeral streams
• Apeiranthos watershed	10.2		
Melos	151.0	4,390	Groundwater, springs, torrents
Kythera	279.6	3,021	Groundwater, torrents
Rhodes	1400.0	98,181	Groundwater, springs, ephemeral streams
Chania Region (Crete)	625.8	93,394	Springs, streams, groundwater
Heraklion Region (Crete)	184.3	137,111	Groundwater, springs, ephemeral streams
Ierapetra Region (Crete)	237.3	21,025	Groundwater, springs, ephemeral streams
Kazantzes Area (Thrace)	76.0	1,281	Streams, groundwater

Table 3. Meteorological Stations Used for Rainfall Data

Area	*Station*	*Lat. (N)*	*Elevation in m a.s.l.*	*Average Annual Rainfall in mm*	*Time Period*
Thassos	Thassos (NMS)	40°46’	2	786.2	1932-41, 1960-92
	Kavala (NMS)	40°51’	60	592.7	
Samothrake	Alexandroupolis (NMS)	40°51’	3	551.0	1978-87, 1931-93
	Thassos			786.2	
	Kavala (NMS)			592.7	
Lesvos	Mytilene (NMS)	39°04’	3	618.2	1961-1990, 1975-
	Antessa (M.A.)	39°13’	150	424.9	1997-1999
Alonnessos	Skopelos (NMS)	39°59’	11	774.8	1931-1994
	Skyros (NMS)	38°54’	4	462.2	
Skopelos	Skopelos (NMS)			774.8	1932-39, 1955-94
Skyros	Skyros			462.2	1931-94, 1950-92,
	Chios (NMS)	38°21’	60	579.0	1955-94
	Skopelos (NMS)			774.8	
Chios	Chios			579.0	1950-92, 1931-40,
	Samos (NMS)	37°46’	48	735.3	1946-92
	Mytilene (NMS)			579.0	
Psara	Chios (NMS)			600.8	1931-39, 1951,
				1953-1980	
Naxos	Naxos (NMS)	37°06’	9	351.2	1980-92, 1970-90
	Melos (NMS)	36°44’	182	411.0	
Melos	Melos (NMS)			411.0	1960-1987
Kythera	Kythera (NMS)	36°08’	167	544.0	1960-1987
Rhodes	Rhodes (NMS)	36°24’	35	712.0	1960-1987
Chania	Chania (NMS)	35°30’	62	518.0	1960-1987
Heraklion	Heraklion (NMS)	35°20’	39	543.0	1960-1987
Ierapetra	14 Stations (MECPPW, MA)	35°00’	3 to 1150	413.0 to 1320.0	1931-1992
Kazantzes	9 Stations (NMS< MECPPW, Sugar Ind., S.A.)	(41°21’)	44 to 380	505.0 to 860.0	1932-1996

M.A.- Ministry of Agriculture. MECPPW - Ministry of Environment, City Planning and Public Works. NMS - National Meteorological Service a.s.l. - above sea level. The latitude values in paraentheses are apprxoiate of the whole area.

where *r* is the surface albedo (0.06 for water surface and 0.25 for short green cover); *s* is the Stefan-Boltzman constant (mm day^{-1} water equivalent K^{-4}); T_a is the mean air temperature (*K*) and *n/N* is the ratio of actual to possible hours of sunshine; and R_s is the incident short-wave solar radiation (mm day^{-1} water equivalent) estimated by:

$$R_s = R_a(a + bn / N) \quad (3)$$

R_a is the extraterestrial radiation received at the top of the atmosphere (mm day^{-1} water equivalent), and *a* and *b* are coefficients derived for various locations in Greece (Kerkides et al., 1996). Furthermore, E_a is the aerodynamic vapor transport term (mm day^{-1}) expressed by:

$$E_a = f(u)(e_s - e_a) \quad (4)$$

Again, e_s is the saturated vapor pressure and e_a the actual vapor pressure, both in (*hPa*) and evaluated at mean air temperature and at 2 m above the ground or the water surface. The term *f(u)* is given by:

$$f(u) = 0.263(a_u + b_u u) \quad (5)$$

Suggested values for the empirical coefficients a_u and b_u are 1 and 0.537, respectively, when *u* is measured in m/sec at 2 m above the ground or the water surface (Brutsaert, 1982). The stations for each area that were used for the necessary data input are presented in Table 4 and the results are shown in Table 6.

Surface Runoff Estimation

Model Architecture

The water balance model is a simulation model that may perform a rainfall runoff budget for a watershed on a monthly basis. The current approach treats each island as either a single unified region, or considers the presented watershed(s) as representative and typical for the whole island. Such an approximation has been accepted due to: the limited meteorological and hydrological data, the areal extent of the predominant geological formations, which in most cases were not corresponding to the watershed barriers and finally, the common physical characteristics among the various watersheds in a given island. The islands Lesvos, Naxos, and Rhodes were examined in detail taking into consideration all the major watersheds. The model estimates the runoff, the groundwater recharge and the

Table 4. Stations Used for the Penman Method

Area	*Station*
Thassos	Thassos, Alexandroupolis
Samothrake	Thassos, Alexandroupolis, Lemnos
Lesvos	Mytilene
Alonnesos	Skopelos, Skyros
Skopelos	skopelos, Skyros
Skyros	Skyros
Chios	Chios
Psara	Chios
Naxos	Naxos
Melos	Melos
Kythera	Kythera
Rhodes	Rhodes
Chania	Chania
Heraklion	Heraklion
Ierapetra	Ierapetra
Kazantzes	Orestias

actual evapotranspiration. Each year's values are based on the values of the previous one, in order to achieve a continuous time series. The only exception is the value of the simulated field capacity (FC) of the first month of the first year, which is the mean of the corresponding months after the initial run of the model (the initial value of FC is an arbitrary approximation). A schematic representation of the model is shown in Figure 2, and a more detailed description of the model and its parameters is demarcated in the following sections. The runoff estimation was performed based on the evapotranspiration method. The equation used for the simulation of the water balance (for a given time step) is delineated in the following equation:

$$P = R + I + AEVT \quad \Delta S \tag{6}$$

where P is the total precipitation; R is the surface runoff;

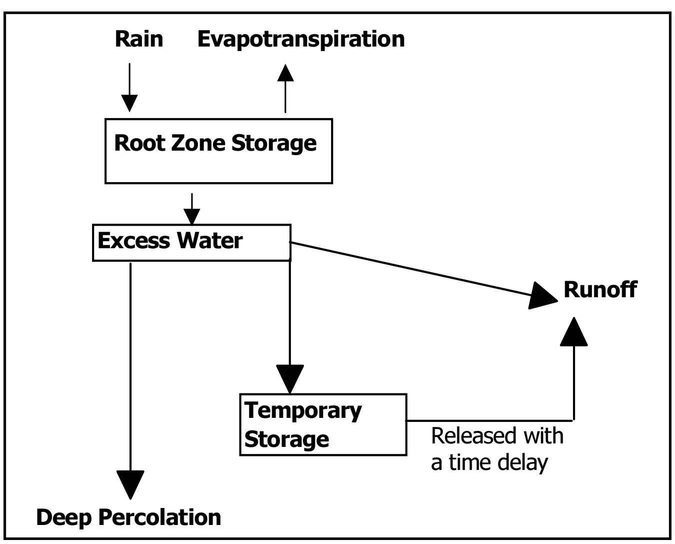

Figure 2. Schematic representation of the Water Balance Model.

I is the infiltration (including deep percolation); $AEVT$ is the actual evapotranspiration; and ΔS is the change in the soil moisture content

The actual evapotranspiration depends, in part, on the precipitation and the soil moisture content. In this regard, at some stages of crop or plant growth and in low soil moisture conditions, the potential evaporation rate is not realized. As soil moisture is gradually depleted, suction increases, and soil hydraulic conductivity acquires smaller and smaller values. And although the potential gradient from the soil water to the leaves increases, the leaves water potential decreases, and, therefore, the moisture flow rate decreases. The effect is the reduction of evapotranspiration from the potential rate (*PEVT*) to some other value (*AEVT*).

Various soil suction/plant evapotranspiration curves exist ranging from a horizontal line at *AEVT/PEVT* equal to 1.0, indicating equal availability of water from field capacity to permanent wilting point, to a line joining *AEVT/PEVT=1.0* at field capacity, to the point *AEVT/PEVT=0*, at permanent wilting point (Withers and Vipond, 1988). The model accepts the linear relationship based on the pertinent declining line. Hence, the estimation of *AEVT* is being preceded by the calculation of field capacity (FC). Such a calculation is based on the following premises:

$$FC = \sum_{i=1}^{n} (\varphi u d_i c_i), \qquad n=1,2,3 \tag{7}$$

where (McWhorter and Sunada, 1988; Danalatos, et al., 1994; Kosmas, et al., 2000) ϕ is the average porosity value of the soils equal to 0.45; u is the available for extractable water pore volume equal to 0.6, if it is assumed that the capillary water and the air entrapped in the soil, they each have an average value of 0.2 of the porosity; d_i is the depth of the root system approximately equal to 1.0 m for the forest, 0.60 m for the bushes, and 0.20 m for the plants with a shallow one (i signifies forest, bushes, and shallow plants); and c_i is the percentages of plant cover differ for each island catchment and they are estimated based on the available information.

The resulted various field capacities are presented on Table 5. For the estimation of *PEVT*, the modified Penman method was used as it was previously described. The estimation, then, of the surface runoff, may proceed based also on the following prepositions:

- The monthly rainfall satisfies first of all the field capacity. Thus, the soil moisture is estimated on the first and thirtieth of each month. Then, the average value of soil moisture dictates the *AEVT* according to the already described methodology.
- Runoff is generated only when both the field capacity and the evapotranspiration components are satisfied.

Hence, the soil moisture for the consequent month would become

$$SM_{i+1} = SM_i + P_i - AEVT_i - R_i \quad (8)$$

where SM_i is the soil moisture at a given time increment; SM_{i+1} is the soil moisture on the next time increment; $AEVT_i$ is the actual evapotranspiration, which in the cases of runoff becomes $PEVT_i$, P_i is the rainfall; and R_i is the potential surface runoff (excess water equal to zero, if the field capacity and the evapotranspiration component are not satisfied by the amount of rainfall).

- Provision has been taken in the model's code for the cases where the soil moisture may exceed the field capacity so that in the various calculations the soil moisture reaches only its maximum value, the field capacity.
- On the next step, 5 percent of the potential surface runoff is lost due to deep percolation. For a loss it is supposed that water leaves the system and feeds very deep strata and formations, which are not considered aquifers for the area. In situ investigations as well as the pertinent literature have pointed towards such an estimate (McWhorter and Sunada, 1988; Danalatos et al., 1994; Michailidis, 1994).
- The various watersheds differ also in their geology. In some of the areas the geologic formations are aquifer materials, while in some others are not. The model, hence, has a different approach for each one of the pertinent cases. In this regard, if the geology dictates the presence of aquifers, a percent of the excess water, depending on the specific area, is lost to the groundwater recharge, and it does not correspondingly contribute to the surface runoff. If the geologic strata are not aquifer materials, then the model takes into consideration the generation of groundwater flow in the upper part of the formations in the shallow water tables that are usually formed. Hence, the simulation process has considered that on a monthly time step certain percent of the remaining potential surface runoff feeds the shallow water table. The percent was chosen due to the geology of each area in accordance with pertinent studies (Michailidis, 1994). Table 4 presents these parameters. Furthermore, this amount of water was also considered that returns to the surface runoff with a certain time delay, as diffuse discharge to the drainage points. The delay pattern may be described

$$Rn_i = a_i\, GF_i + a_{i-1}\, GF_{i-1} \ldots + a_{i-n}\, GF_{i-n} \quad (9)$$

where Rn_i is the total delayed monthly component of the surface runoff from roundwater; GF_i is the total groundwater flow in a given time step (in this case a month); and a_i,...i-n are the percentages of the total groundwater flow returning in each time step chosen specifically for every case according to the geology where $a_i + a_{i-1} + \ldots a_{i-n}$ are equal to 1.

All of the above model parameters are presented in Table 5. The percentages have been converted on the same unit base. The average monthly runoff was computed solving Equation 6 for R_i, where the infiltration component I_i (including losses to deep percolation) was adjusted by subtructing Rn_i if any. $AEVT_i$ (the actual evapotranspiration) in the cases of runoff becomes $PEVT_i$, hence:

$$R_i = P_i - (I_i - Rn_i) - PEVT_i - ?S \quad (10)$$

The component ΔS reflects the amount of water (coming from P_i) that has been consumed so as the SM_i value to reach field capacity (FC) according to the previously stated premises. Provision has been taken so as monthly runoff does not take negative values. Finally, the annual runoff coefficient (f) was computed using the formula:

$$f = \frac{\sum_{i=1}^{n} R_i}{\sum_{i=1}^{n} P_i}, \quad n = 12 \quad (11)$$

where R_i is the potential average monthly surface runoff in mm, and P_i is the average monthly rainfall in mm. The model application based on the pertinent premises is presented in the following section.

Model Application

The model has been designed to run in Microsoft EXCEL under Windows. It is believed that the spreadsheet format allows for a user-friendlier interface particularly for the non-expert user, a standardized output presentation, and a built-in communication capability with other office automation tools (Word, etc.). Given such considerations, the various inputs and outputs of the model are presented in the next paragraphs.

Inputs

Since the model operates on a monthly time step (sec. 3.1) all the input constant physical paramaters (deep percolation, excess stored water, etc.) are expressed in the corresponding time dimension. Furthermore, the model requires the following data input:

- *Rainfall*: Rainfall data on monthly average values are necessary. Ideally, for each watershed rainfall data within the watershed should be provided. However, in the absence of such information, watershed rainfall was assumed to be given by point rainfall measured at the closest existing station.
- *Potential Evapotranspiration*: Average monthly potential evapotranspiration data are required. Again different evapotranspiration rates should be used

calculated or measured within the watershed. Instead, the values discussed in sec. 2.5 and 3.1 were used, with all the resulting constraints.

- *Field Capacity*: The field capacity values estimated in sec. 3.1 were used as input and presented in Table 5.

Finally, the parameters presented in Table 5 were used accordingly for the calculation of the annual runoff coefficients.

Output

For the simulated years in each case the model produces distinct tables for each year. Hence, each annual table presents the actual evapotranspiration, the runoff, the ground water recharge (if any), and finally the runoff coefficients. The total number of the generated tables is a few hundred with the corresponding values of annual runoff coefficients, for all the pertinent years and island cases. Table 6 summarizes the results of all the areas, presenting only the final average annual values. The estimated average annual runoff coefficients are plotted against the pertinent values of rainfall for each area and a trendline is calculated. The best-fit line was found to be a logarithmic curve, with an R^2 of 0.5855. The pertinent effort is presented in Figure 3.

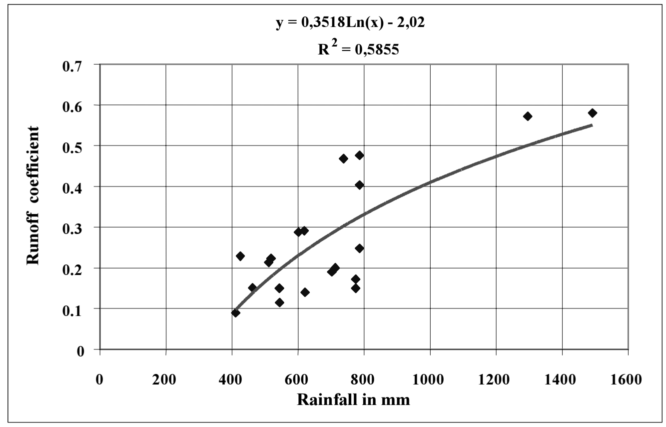

Figure 3. Average annual rainfall (x) vs. average annual runoff coefficients (y) and trendline.

Table 5. Input Parameters

Area	*Field Capacity (FC) mm*	*Predominent Geological Formations*	*Deep Percolation %*	*Aquifer System Recharge %*	*Excess Water Stored Temporarily in Shallow Acquifers and Released Gradually (Rn) %*
Thassos					
• Prinos	187	Gneisses, Schists	5	40	
• Limenaria	195	Gneisses, Schists	5		40
• Theologos	184	Gneisses, Schists, Marbles			
Samothrace					
• Karavi	102	Ophiolites, Basalt,	5		20
• Xeropotamas	150	Schist	5		20
Lesvos					
• Eastern part	230	Limestone, Schists, Volcanites, Alluvial	5	40	
• Western part	105	Volcanic, Igneous	5	10	
Chios	194	Schists, Limestones	5	30	
Psara	139	Gneisses, Schists, Rhyolites	5	30	
Allonnessos					
• Kastanias	162	Limestones, Phyllites	5	60	
Skopelos					
• Panormos	257	Limestones, Flycsh	5	60	
Skyros					
• Ferekampos	171	Marbles, Phyllites, Ophiolites	5	30	
Naxos					
• Apeiranthos	140	Schists, Quartz, Marbles	5		30
Melos	140	Volcanic (rhyolites, dacites, andecites)	5		20
Kythera	182	Limestones, Phyllites	5	40	
Rhodes	226	Flycsh, Marbles, Alluvial	5	40	
Crete					
• Chania	183	Marbles, Schists	5		10
• Heraklion	150	Marbles, Alluvial	5		10
• Ierapetra	172	Marbles, Phyllites	5		10
Kazantzes	225	Marbles, Schists	5		5

Table 6. Estimated Average Annual Runoff Coefficients, Evaporation, Potential, and Actual Evaportranspiration

Area	*Average Annual Rainfall (P) mm*	*Average Annual Evaporation mm*	*Average Annual Potential Evtrsp. (PEVT) mm*	*Average Annual Actual Evtrsp. (AEVT) mm*	*Average Annual Runoff Coefficient (f)*
Thassos					
• Prinos	786.2	1180	684.0	393.0	0.476
• Limenaria	786.2	1180	684.0	470.9	0.403
• Theologos	786.2	1180	684.0	467.4	0.248
Samothrake					
• Karavi	(737.8) 1295.4*	1298	764.7	539.8	0.572
• Xeropotamos	(737.8) 1491.7*	1298	764.7	591.0	0.580 (0.608)
Lesvos					
• Eastern part	618.2	1554	895.5	439.0	0.291
• Western part	424.9	1554	895.5	323.7	0.229
Allonnessos					
• Kastanias	774.8	1278	732.7	446.3	0.172
Skopelos					
• Panormos	774.8	1278	732.75	502.6	0.150
Skyros					
• Ferekampos	462.2	1341	773.7	366.5	0.151
Chios					
• Scardanas	579.0	1430	1056	336.0	(0.2-0.45)
Psara	600.8	1384	1033.23	341.07	0.288
Naxos					
• Apeiranthos	(351.2) 737.5•	1624	937.2	373.8	(0.083) 0.468
Melos	411	1487	1090	365.0	0.09
Kythera	544	1532	1125	434.0	0.115
Rhodes	712	1621	1199.7	465.8	0.20
Rhodes (UNEP data)	620.9	1720	1270.9	468.9	0.14
Crete					
• Chania	518	1275	946	396.0	0.223
• Heraklion	543	1581	1159	459.0	0.15
• Ierapetra	511	1784	1320	397.0	0.213
Myrtos	740.4**	2096	-	-	(0.173)
Kalamaukianos	721.44**	-	-	-	(0.255)
Kazantzes	665.0**	1245	710.0	489.5	0.252

1. The values in parenthesis are from the closest station or presenting existing measurements (Samothrace, Ierpetra, Chios).
2. *The values used after the elevation correction.
3. **The values are estimated using the Thiessen method.

It is pointed that the simulation process output is presented and compared with existing river flow measurements for Samothrace and Ierapetra, and existing runoff estimates for Chios and Rhodes.

Sensitivity Analysis

The built-in disadvantages of the modeling techniques are also present in the current effort. Specifically, the simulation was based on a set of mathematical expressions, which represent reality only to a certain degree and are based on simplified concepts. In addition to such a pitfall, some other sources of ambiguity producing also the corresponding risks for the application of the overall approach, are presented here:

- The existing hydrological databases are incomplete and sometimes conflicting. Therefore, the lack of suitable, reliable, and systematically collected data, such as discharge measurements, groundwater levels, soil moisture etc., has minimized the efforts of validating the model and estimating parameter values. In such an absence, the best that could be achieved with the model were magnitude estimates of the major components of the water balance, predictions eliciting from invalidated parameter values and a nascent form of sensitivity analysis.
- There is an absence of any rainfall measuring stations (and by extension of any meteorological stations) within the watersheds, with the exception of Ierapetra.

Given, then, the above considerations, a sensitivity analysis was attempted. The constraints and premises of the applied method as well as the obtained results are briefly illuminated:

- All the input values have been kept constant (rainfall, evapotranspiration, etc.), and only the field capacity has been allowed to vary. The model reacted positively, producing lower values of runoff and higher actual evapotranspiration for higher values of field capacity. The opposite results were recorded for lower values of field capacity. The same values of field capacity produced the same results in the corresponding model subsections.

- All the input values were kept constant and the percentage of excess water feeding the aquifers was varied. Again the model reacted positively with less runoff for a higher infiltration rate and more runoff for a lesser one.

The model reacted positively on certain key hydrological years. Namely in 1989 to 1990, 1991 to 1992, and 1992 to 1993, the years of the severe consecutive droughts, it produced minimum runoff as it was recorded on the available databases.

The estimated average annual runoff coefficients show a range from 0.08 to 0.58. Such variability may be primarily attributed to the geology of each area, if it would be considered that the rainfall and the evapotranspiration exhibit such a variability to a lesser degree. Thus, the average annual runoff coefficients for the cases that aquifers have not been present in the watersheds, were plotted against the corresponding rainfall of each area and a trendline is calculated. The trendline was found to be a logarithmic curve, with an R^2 of 0.8801. Such a result fortifies the initial premise and may be considered as an advantage of the overall methodology. The pertinent effort is presented in Figure 4. It is also pointed out, that such areas with impermeable strata are usually the prime candidates for any future surface water resources develoment schemes. Finally, the extreme variability of the runoff coefficients for the cases where aquifers were present was prohibitive for the pertinent plot, fortifying the strong geological bond of the results.

Overall, it may be pointed out that the model reacts well to the choice of parameters (Table 6) and the hydrological inputs. Based on the available information, it follows reasonably the variability of the year-to-year hydrological fluctuations. However, it cannot be independently validated at the present stage, except for Samothrace, Chios, Rhodes, and Ierapetra. In these cases, it presented a close approximation of the existing conditions for the given data and time series. Namely, for Samothrace the model value of average annual runoff coefficient was 0.580, whereas flow measurements by Public Power Corporation indicated one of 0.608 (Bosdogianni, 1994). For Chios, the model predicted an average value of 0.19 and the existing estimates in Skardanas river watershed gave annual values between 0.2 and 0.45 (CP, 1993). For Rhodes, the model produced a value of 0.20, which is close enough to the value of 0.159 that the UNEP (1996) study has estimated applying another modeling approach. However, using the original data of the UNEP study (Table 6) the model gave a runoff coefficient value of 0.14. Such a value is practically the same with the value of the UNEP study and may add towards the validity of the whole effort, as it produced similar results with another independent approach. Finally for Ierapetra (lower watershed) the model produced a value of 0.213, while measurements in the upper watersheds of rivers Myrtos and Kalamaukianos have values of 0.173 and 0.255 (MECPPW, 1993). Thus, it seems that the model consistently arrives at an acceptable approximation. If flow measurements are also carried out in the other islands (an effort that would require time and resources considering the current state of the organizational, political, and institutional environment), it may be possible to arrive to a more accurate model development. Nevertheless at this stage, it seems that the model may well serve as a decision support tool, an aide in estimating the approximate magnitude of the various water balance parameters.

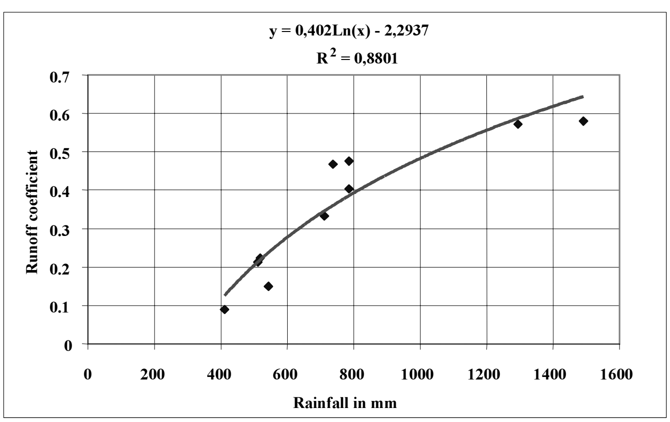

Figure 4. Average annual rainfall (x) vs. average annual runoff coefficients (y) and trendline with impermeable strata in the watersheds.

Conclusions and Recommendations

In a fast changing era, any present or future oriented water resources development and management scheme should be also able to cope with the larger aims of social and economic dimensions. In this dynamic environment one should incorporate both "structural" and "non-structural" mechanisms as vital components of an integrated water resources planning and management policy. At the same time, supply augmentation and demand reduction measures are both influencing the rate and the extent of change in the environment. Underlying all such considerations is the centrality of sustainability and equitable sharing of water resources.

The key point to be made is that ecological values and the quest for sustainable development require a balanced combination of data and judgement. The recently adopted Water Framework Directive (WFD, 2000) in the European Union emphasizes the protection of quantity and quality of surface and groundwater, introduction of water pricing policies, integrated watershed management, and the strengthening of public participation. In this regard, it becomes more than necessary that decision making should move beyond considerations of only economic tradeoffs and traditional methodologies into considering underlying water resources development goals and strategies, as well as shared societal visions. Thus, alternative water resources policy options (e.g., reservoir storage, conservation, reuse, desalination, transport of water from other areas; conjunctive water use with withdrawals from aquifers, etc.) emerge as results of the application of an integrated water resources planning and management methodology.

Given such considerations, the approach suggested in the present work seems to address more completely the challenges associated with the surface water resources potential in an island environment. The effort resulted in estimating the annual surface runoff coefficients, potential and actual evapotranspration, using the developed and described simulation model. The various premises and estimates were presented. Summarizing, key aspects of the final output may be delineated in the following:

- The precipitation and the majority of surface runoff takes place in the winter months, creating a strong temporal water deficit in the dry summer season, where most of the activities are concentrated;
- The estimated average annual runoff coefficients represent a range from 0.08 to 0.58. Such variability may be primarily attributed to the geology of each area, if it would be considered that the rainfall and the evapotranspiration exhibit a similar variability to a lesser degree. Both are generally decreasing from north to south and such a trend may also be demarcated in the average annual runoff coefficients values.
- The average annual runoff coefficients were plotted against the corresponding rainfall of each area and a trendline is calculated as a handy and quick means for an initial reference.
- The lack of suitable, reliable, and systematically collected over a period of time data leads towards the corresponding quasiness in the estimated runoff coefficients.

The attempt to model the water cycle processes within an island has resulted in fortifying the realization that this is a closed rainfall-runoff system, which in the natural state (before human intervention) it exhibits a fragile balance. In this context, the system has very limited resilience if the pertinent cycle is interrupted. Finally, a standard (in the form of a model and its output) can be a valuable tool for the application of holistic water resources management techniques. Such a modeling effort indicates also the range of hydrologic parameters, in the attempt to respond to the complex interactions of a fast changing socio-economic and water stressed environment.

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Discussions open until December 1, 2002.

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