BGSG

Volume 51

Research Paper

Correspondence to:
Aikaterini-S. Partsinevelou
spartsi@geol.uoa.gr

DOI number:
http://dx.doi.org/10.12681/bgsg.11960

Keywords:
Naxos Island, fractured rocks, groundwater exploration, hydrology modeling, SWAT model

Citation:
Partsinevelou, A.-S, (2017) Using the SWAT model in analyzing hard rock hydrogeological environments: Application in Naxos Island, Greece, Bulletin Geological Society of Greece, 51, 18-37.

Publication History
Received: 01/04/2017
Accepted: 15/09/2017
Accepted article online: 04/10/2017

The Editor wishes to thank Section Editor K. Voudouris for his work with the scientific reviewing of the manuscript

Using the SWAT model in analyzing hard rock hydrogeological environments: Application in Naxos Island, Greece

Aikaterini – S. Partsinevelou [1]
[1] National and Kapodistrian University of Athens,
spartsi@geol.uoa.gr

Abstract

The main parameter that controls the groundwater flow regime in fractured aquifers is the fracture pattern. Its description is crucial for a hydrogeological study, as the hydraulic properties of hard rocks are mainly controlled by fracturing. The parameters of the fracture pattern that were analyzed in the study area were the frequency and spatial location of the fractures, the density of fractures and the degree of fracture intersection.

Furthermore, a straight link between the fracture pattern and the hydrological conditions is important for a first analysis of the potential groundwater zones and their vulnerability in hard rock environments. To study this link, the SWAT hydrology model was applied in the study area. Using suitable territorial and meteorological data, the model simulates the parameters of the hydrological balance in each catchment of the hydrographical network.

The analysis of the fracture pattern revealed that the fragmentation in all lithologies is characterized by high degree of uniformity. Very high density and interconnection density of the fractures are observed in areas where the alternations between different lithologies are very intense. Also, the application of the SWAT model showed that the calculated hydrological parameters could be related to the fracture pattern, as high infiltration rates occur in areas where the density and the degree of interconnection of the fractures are also high.

Keywords: *Naxos Island, fractured rocks, groundwater exploration, hydrology modeling, SWAT model.*

Περίληψη

Η κύρια παράμετρος που ελέγχει το καθεστώς ροής των υπόγειων υδάτων σε υδροφορίες σκληρών διερρηγμένων πετρωμάτων είναι το μέσο ασυνεχειών. Η περιγραφή του μέσου ασυνεχειών είναι σημαντική σε μια υδρογεωλογική μελέτη, καθώς οι υδραυλικές ιδιότητες των σκληρών διερρηγμένων πετρωμάτων ελέγχονται κυρίως από τον κατακερματισμό αυτών. Οι παράμετροι του μέσου ασυνεχειών που αναλύθηκαν στην περιοχή μελέτης ήταν η συχνότητα και η γεωγραφική κατανομή των ασυνεχειών, η πυκνότητα των ασυνεχειών και ο βαθμός διασύνδεσης των ασυνεχειών.

Επιπλέον, μια άμεση σύνδεση μεταξύ του μέσου ασυνεχειών και των υδρολογικών συνθηκών σε σκληρά διερρηγμένα πετρώματα είναι σημαντική για μια πρώτη εκτίμηση των πιθανών ζωνών εύρεσης υπόγειων υδάτων, καθώς και της τρωτότητάς τους. Για να μελετηθεί η σύνδεση αυτή, εφαρμόστηκε το υδρολογικό μοντέλο SWAT στην περιοχή μελέτης. Χρησιμοποιώντας κατάλληλα γεωλογικά και μετεωρολογικά δεδομένα, το μοντέλο προσομοιώνει τις παραμέτρους του υδρολογικού ισοζυγίου σε κάθε υδρολογική λεκάνη του υδρογραφικού δικτύου.

Η ανάλυση του μέσου ασυνεχειών έδειξε ότι ο κατακερματισμός σε όλες τις λιθολογίες χαρακτηρίζεται από υψηλό βαθμό ομοιομορφίας. Πολύ υψηλή πυκνότητα και βαθμός διασύνδεσης των ασυνεχειών παρατηρούνται σε περιοχές όπου οι εναλλαγές μεταξύ διαφορετικών λιθολογιών είναι πολύ έντονες. Επίσης, η εφαρμογή του μοντέλου SWAT έδειξε ότι οι υπολογιζόμενες υδρολογικές παράμετροι μπορεί σχετίζονται με το μέσο ασυνεχειών, καθώς υψηλές τιμές κατείσδυσης παρατηρήθηκαν σε περιοχές όπου η πυκνότητα και ο βαθμός διασύνδεσης των ασυνεχειών είναι επίσης υψηλές.

Λέξεις κλειδιά: *Νήσος Νάξος, σκληρά διερρηγμένα πετρώματα, έρευνα υπόγειων αποθεμάτων, υδρολογικά μοντέλα, μοντέλο SWAT.*

1. Introduction

Naxos is the largest island in the Cyclades island group, which is located in the central Aegean Sea, southeast of the mainland of Greece. Its area reaches about 430 km^2 and its circumnavigation is equal to 81 km. One of the key morphological features of the island is a central mountain range (Fig. 1), which crosses the island from North to South, having the highest altitude (1001 m) in the central part of the range, at Zeus peak (Evelpidou et al., 2005; Partsinevelou et al., 2011).

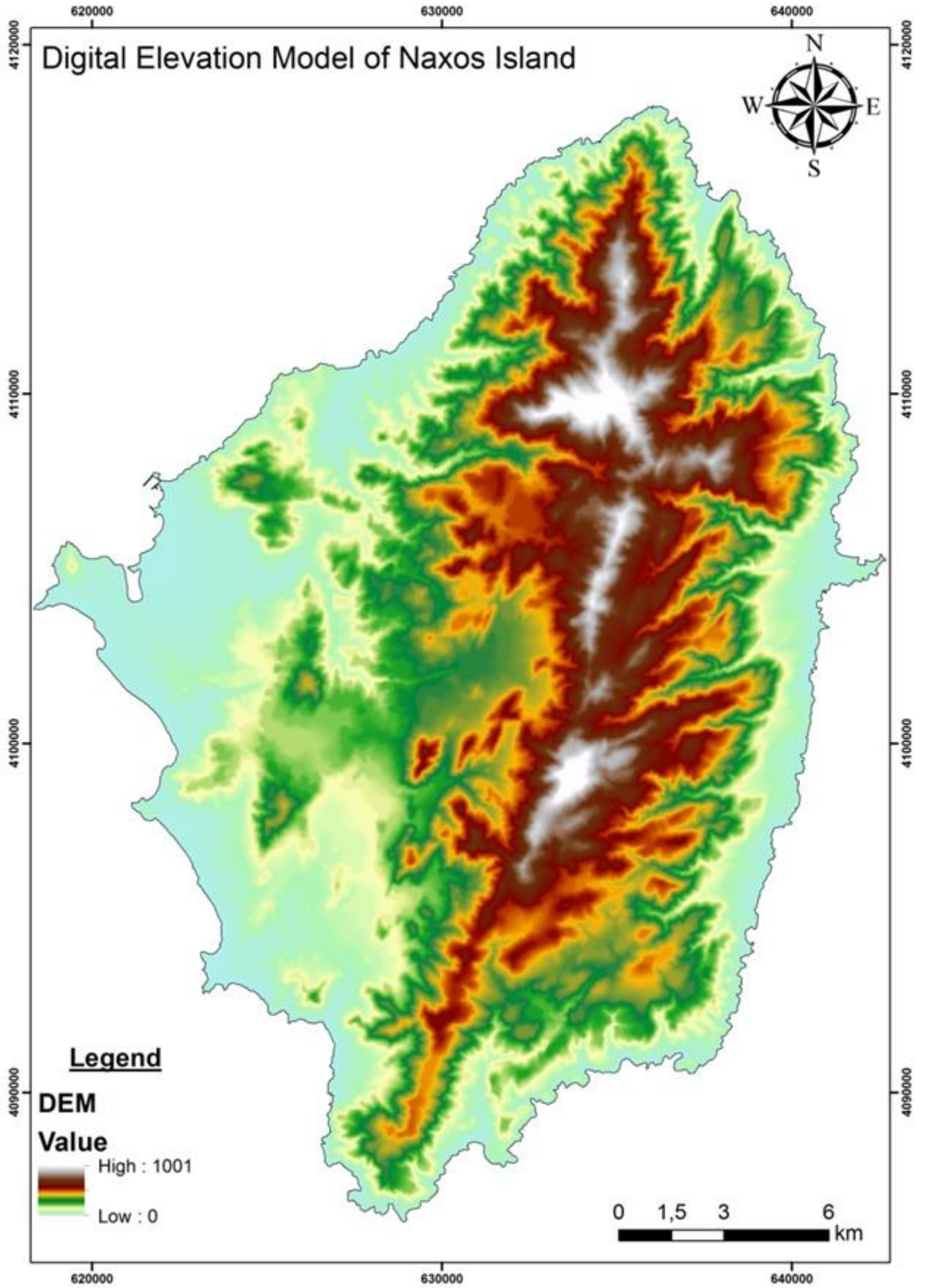

Fig.1. Digital Elevation Model (DEM) of Naxos Island.

The water resources in Naxos Island are extremely limited and the secure of the water needs is very difficult. Surface water is available only for a few days after heavy rains and the water needs are mainly fulfilled by the groundwater resources. However, groundwater resources are also limited, due to natural and anthropogenic causes, such as the climate, the pollution and abstraction of the aquifers, the small water capacity of the geological formations, the high morphological slopes and the low vegetation (Partsinevelou, 2012).

This increasing need of groundwater for water supply, leads to a continuous interest for groundwater exploration, especially in hard rock hydrogeological environments. The study area is consisted mainly by igneous and metamorphic rocks, which are in direct connection to the term hard rocks (Krasny 1996 2002). Although it is observed that hard rocks have often low permeability, they may host important water resources (Singhal and Gupta 2010), as the groundwater flow regime in this case is depended mainly by several factors of the fractured media, including the density and the degree of interconnection of the fractures (Stournaras et al., 2003, Botsialas et al., 2005).

The aim of this study was to determine if a continuous-time and semi-distributed model like SWAT can be used to simulate the hydrological parameters, especially the water infiltration, in a fractured media. SWAT model is often being used in areas with the presence of thick soil layers. But in the study area there are not any thick soil layers and the infiltration is correlated directly with the fractured media. For this purpose, the fracture pattern of Naxos Island was analyzed, by emphasizing on the density and degree of intersection of the fractures. Also, the hydrological model SWAT was applied to determine the parameters of the hydrological balance in each catchment of the study area and to correlate the infiltration values with the fracture pattern.

The above correlation should be a part of an integrated analysis and description of any hard rock hydrogeological environment, as the infiltration of water and pollutants through any type of fractures is the basic characteristic of these environments. Fractures provide direct connections between surface water and groundwater, increasing the vulnerability of the aquifers. Thereby, a further hydrogeological study should be made in these areas, where high values of infiltration and fractures' density are observed. Also, a first estimation of the available groundwater sources could be made, using the results of the SWAT model.

2. Geological and Hydrogeological Setting

Naxos Island is described as an elliptic dome with a main direction N15^{o}E (Evelpidou 2003), which is consisted mainly from igneous and metamorphic rocks of different age and deformation. Geologically, the study area is part of the Attic-Cycladic Massif, which has been developed by thrust faulting, ductile thinning and normal faulting (Jansen, 1977).

In general, the geological formations of Naxos Island can be divided into three main units (Brichau, 2004):

- The upper non-metamorphic unit

- The Cycladic blueschist unit
- The granodiorite massif

The upper non-metamorphosed nappe is very thin and it is consisted by Miocene – Pliocene sedimentary rocks. This nappe overlies the Cycladic blueschist unit and the allochthonous granodiorite massif. The Cycladic blueschist unit is a metamorphic complex mainly characterized by a migmatite core, which is surrounded by a multifolded sequence of marbles, metapelites, schists, amphibolites and gneiss. At the superiorly part of this unit metabauxites and meta-conglomerates are appeared. At the west of the island the granodiorite massif is observed and it is consisted of an I-type granite which intrudes the Cycladic blueschist unit (Fig. 2). Both the Cycladic blueschist and the granodiorite unit constitute the autochonous unit of the island. Also, undeformed intrusives, mainly S-type granites, are observed in the northern part of the island (Galanos and Rokkos, 1999).

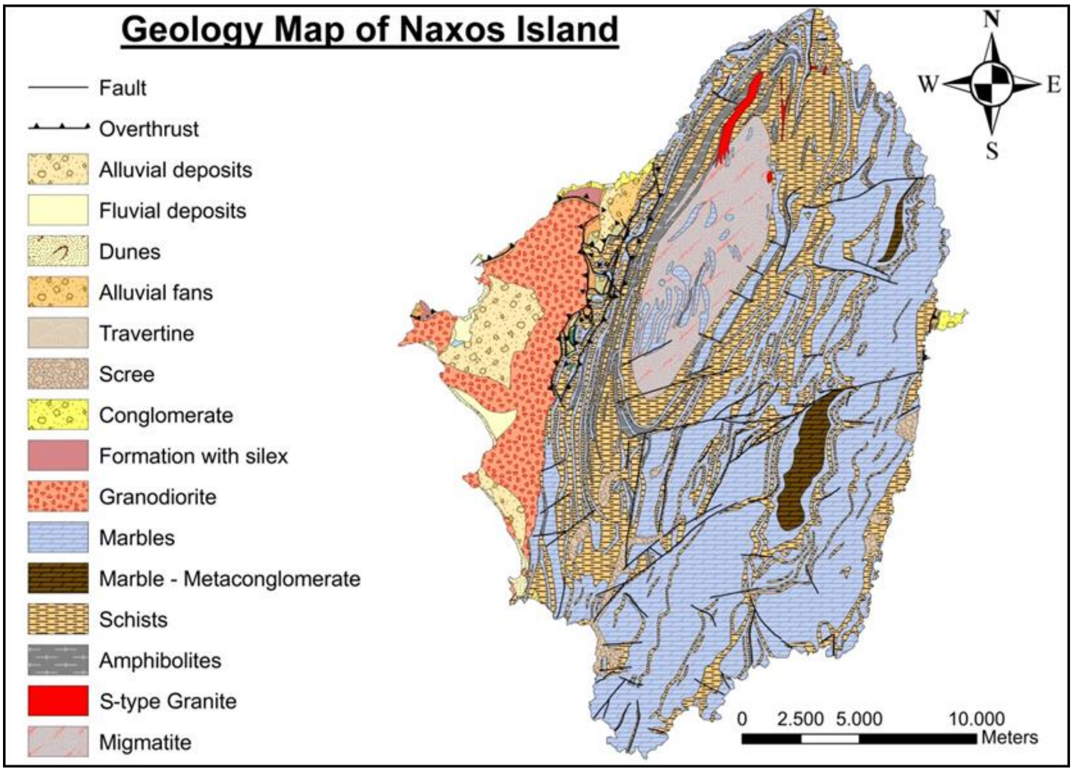

Fig.2. Simplified geological map of Naxos Island (Jansen 1977, modified).

Naxos has a semi-arid Mediterranean climate, which is characterized mainly by dry hot summers and mild winters with very low precipitation rates and strong winds. The mean annual rainfall is approximately 400 mm, while the mean annual temperature is 18 ^{o}C. These climatic conditions favor the high evapotranspiration that occurs in the study area (Partsinevelou, 2012). Moreover, the combination of low precipitation rates and high morphological slopes results a very low water infiltration, especially in mountainous areas. Infiltration is also controlled by the hydrolithology and the fracture pattern of the study area, as the geological formations and the fractures show different hydraulic behavior.

As it is already mentioned, the island of Naxos is consisted mainly by igneous and metamorphic rocks strongly welded. The hydrogeological behavior of these rocks is depended mainly by the secondary porosity (number of discontinuities, cracks, etc.). The hydrogeological environment in these cases is often characterized by the occurrence of local and shallow aquifers and a secondary process of dissolution and expansion of the fractures is creating favorable conditions for the underground flow. (Krasny, 1996; Botsialas, 2007).

According to all the above geological characteristics, the geological formations of Naxos island are classified into different categories, according to their permeability. In this study the geological formations were classified into 4 categories, as seen in Fig. 3.

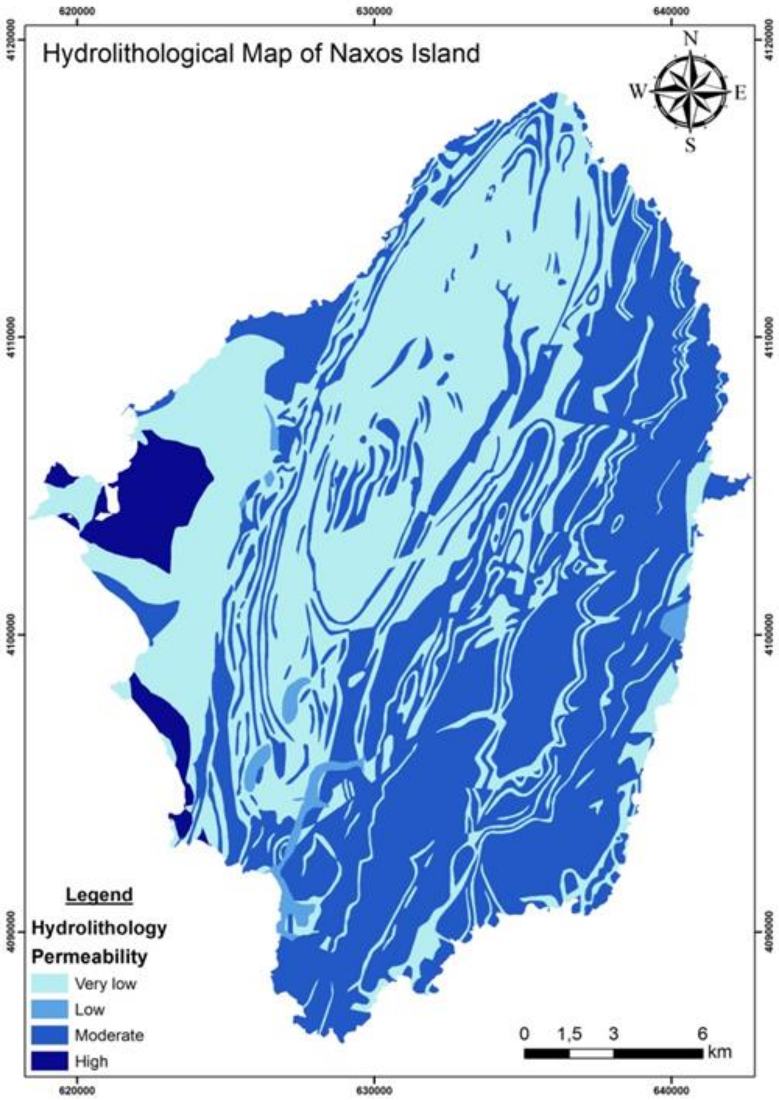

Fig.3. Simplified hydrolithological map of Naxos Island (Partsinevelou, 2016).

3. Methodology

The description and analysis of the hard rock hydrogeological environment is very important, especially in cases where the water resources are limited. Its description is based mainly on the characteristics of the fractures, such as the frequency, orientation, dimensions, density and degree of intersection of the fractures. Although a comprehensive analysis could be done using these parameters, the hydrological and hydrochemical conditions could give more information about the initial connection between the groundwater and the fractured media.

This study was developed in three stages. In the first stage the fracture pattern was determined, described and analyzed using remote sensing and GIS techniques. In the second stage the SWAT model was applied in the study area and in the third stage, the correlation between the hydrological conditions and the fracture pattern was made.

For the study of the fracture pattern, one dataset of Landsat 7 – ETM+ was subset and a combined satellite image of Naxos Island was produced with a resolution of 15m per pixel and 8 available spectral bands to combine. The georeferenced images were orthorectified using a digital elevation model with a cell size of 10m and finally projected on the Hellenic Geodetic Reference System (GGRS'87). Also, a set of aerial photographs (with scale 1:30000) was orthorectified at the same projection and an orthophoto mosaic was produced, reaching a high resolution of 5 meters per pixel. The high and the low resolution images were merged and a final image has been created with a better resolution and the same spectral characteristics with the Landsat 7– ETM+. This image was used for the lineaments extraction and interpretation.

Also the Soil and Water Assessment Tool (SWAT 2005) was used to simulate the parameters of the water balance equation (precipitation, infiltration, surface runoff, evapotraspiration, lateral flow and percolation) in the study area for the period 1958 - 2010. For the application of the SWAT model in the study area, a version of ArcSWAT was used, which works as an extension of the ArcGIS software. ArcSWAT gives the opportunity to insert different parameters by inserting tables or existing shapefiles in any SWAT project.

To run the SWAT model for the entire study area, the digitation of the 25 main catchments of the island was necessary (Fig. 4). Every catchment was manually input and the model run separately for each catchment. Using the values of water percolation every catchment of Naxos Island, the correlation between these values and the fractured media was able to carry out.

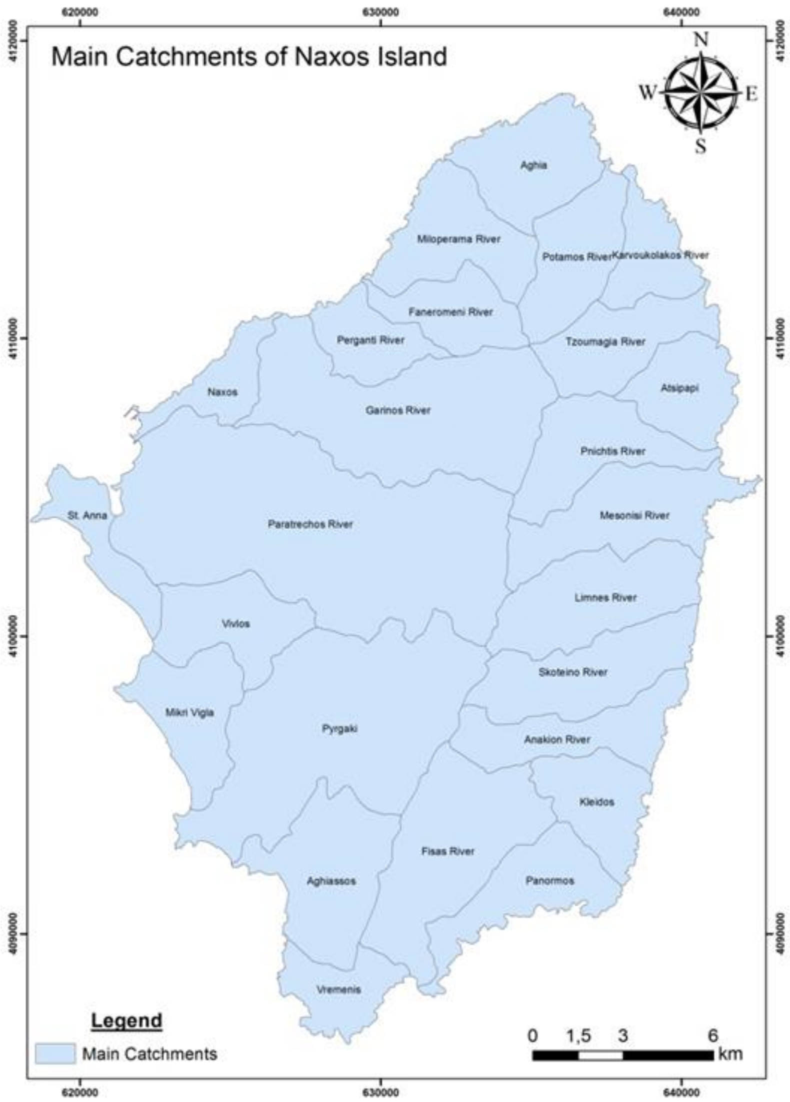

Fig.4. The 25 main catchments of Naxos Island.

4. Description and analysis of the fracture pattern

Lineaments in general are defined as mapable linear surface features, which differ distinctly from the patterns of adjacent features and presumably reflect subsurface phenomena (O' Leary et al., 1976; Scanvic, 1997). There are many types of lineaments such as lineaments controlled by geological structures (faults and fractures), lineaments resulted from morphological effects (stream channels) and lineaments caused by human activity (roads). These types of lineaments can exist simultaneously in the same region and it is important to characterize properly each lineament during their mapping (Gülcan, 2005).

The lineaments map of the island, as shown in Fig. 5, demonstrates 887 features which have been extracted from satellite images and aerial photographs and correspond to the fractures of the study area, which are the result of post-alpine movements.

4.1. Frequency and spatial location of the fractures

The lineament map shows that the fracture distribution is hardly homogeneous. The frequency of the lineaments is high in the biggest part of the island with an exception in the west of the study area, where the frequency of the fractures is very low to zero. The majority of the fractures are located on igneous and metamorphic rocks (Fig. 5). Therefore, the discussed character represents an initial indication for the unified tectonic and hydrogeologic behavior of the hard rock environment. The minority of the fractures is located on the granodiorite massif and post-alpine sediments.

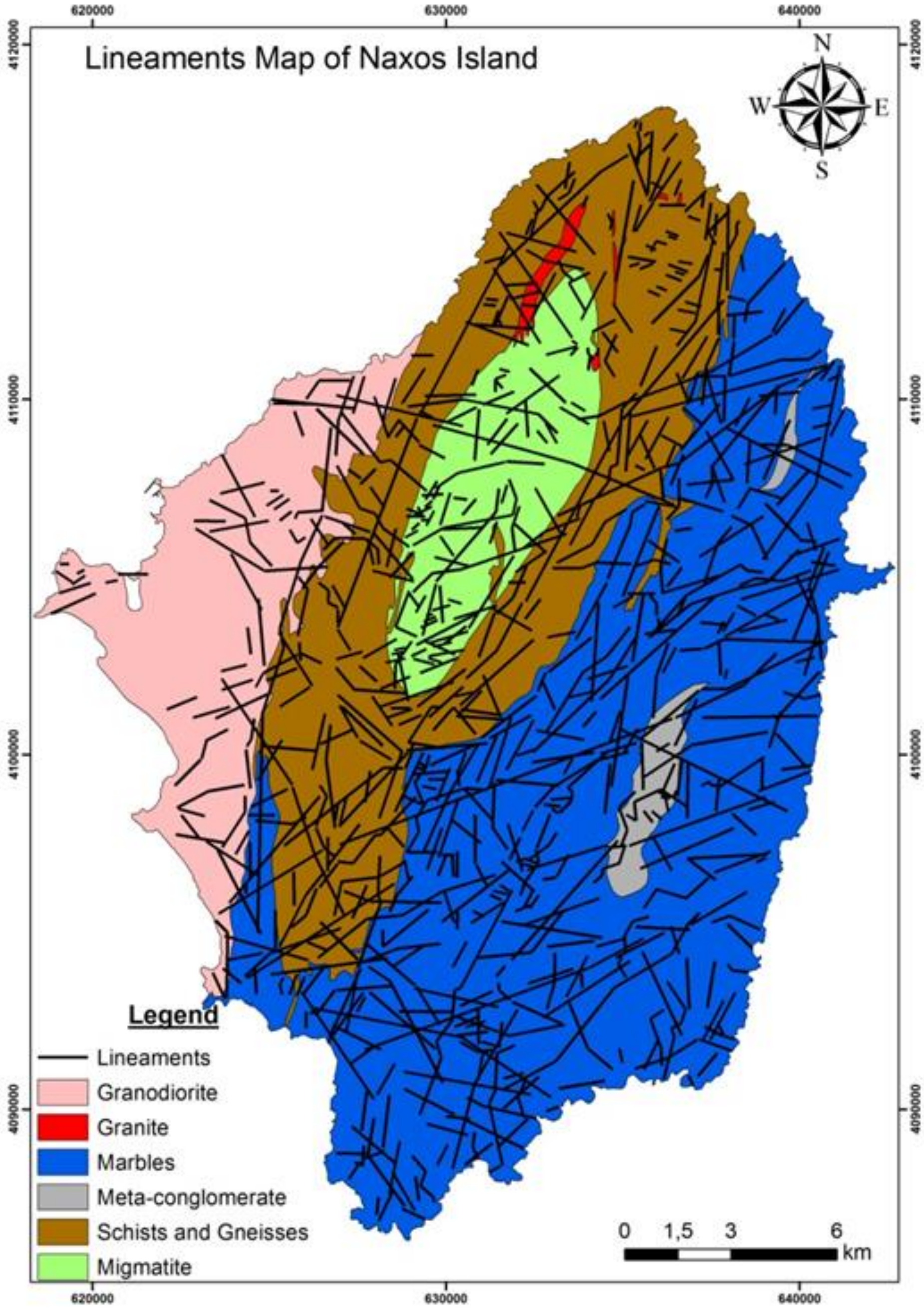

Fig.5. Lineaments map of Naxos Island related with the dominant lithology.

4.2. Density of the fractures

The purpose of the fracture density analysis is to calculate frequency of the fractures per unit area. With this analysis a map has been produced showing concentrations of the lineaments over the study area (Fig. 6), in which very high density (3.97 – 6.54 km/km^2) is observed in areas where the alternations between marbles, schists and amphibolites are very intense, citing the high degree of hydraulic interconnection between the above lithologic units as surface water circulates through these discontinuities. This is verified in the next consideration (degree of fractures intersection). On the other hand, very low density (0 – 0.95 km/km^2) is observed in granodiorites, post-alpine sediments and in areas where one lithology dominates. This verifies that these lithologies are not much affected by tectonic activity.

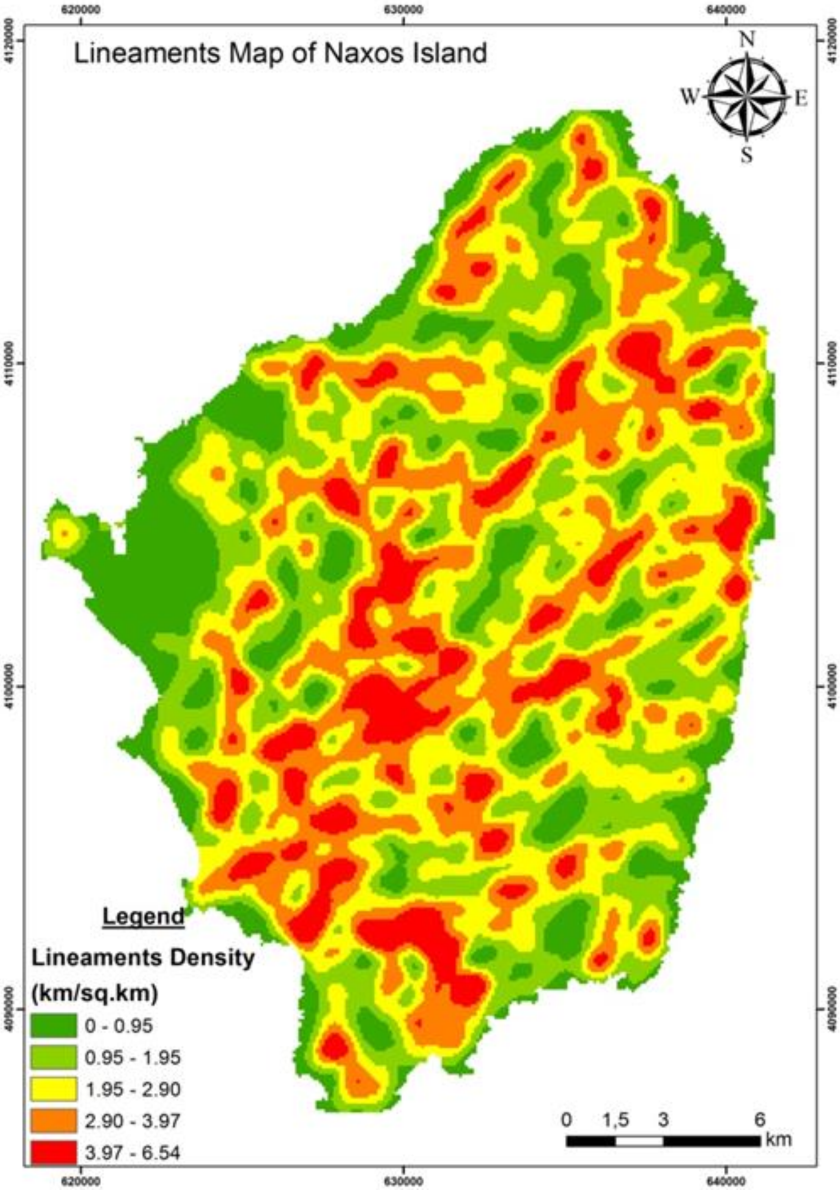

Fig.6. Density of the fractures in Naxos island.

4.3. Interconnection density of the fractures

The density of fractures along with the interconnection density of the fractures determine the degree of anisotropy of groundwater flow in the fracture network, as in environments with high degree of interconnection, groundwater flow is smoother and more uniform.

Fracture interconnection density is a parameter showing the frequency of intersections that occur in a unit cell. The purpose of using intersection density map is to estimate the areas of diverse fracture orientations. If the fractures do not intersect in an area, the resultant map will be represented by a plain map with almost no density contours and the fractures are almost parallel or sub-parallel in an area.

The fractures intersection map of the study area (Fig. 7) indicates high and very high intersection density in the same areas where very high fracture density is observed.

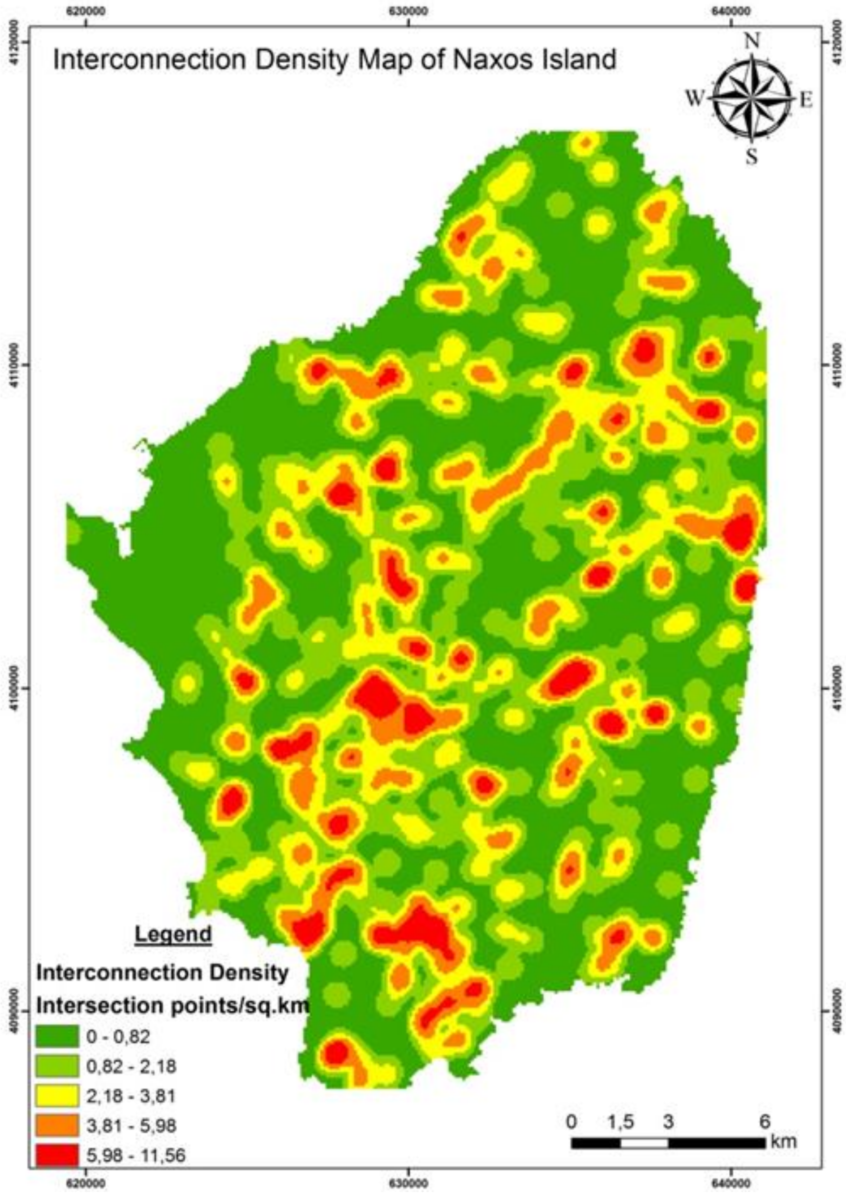

Fig.7. Interconnection density of the fractures in Naxos island.

5. Application of the SWAT model

The Soil and Water Assessment Tool (SWAT), is a continuous time, spatially semi-distributed model, developed to simulate the impact of management decisions on water, sediment and agricultural chemical yields in river basins in relation to soil, land use and management practices (Arnold et al., 1998; Bouraoui et al., 2005). The hydrologic model is based on the water balance equation in the soil profile, where the processes which are simulated in each catchment, are precipitation, infiltration, surface runoff, evapotranspiration, lateral flow, percolation and the movement and transformation of nitrogen (N) and phosphorus (P).

Although the program requires a large amount of spatial and meteorological data to simulate the hydrologic balance, however, the implementation is quite easy, because many of the problems of the past in earlier versions have been overcome, and the successive steps of the model are performed serially. This means that the program does not allow the user to proceed to the next step if it does not perform successfully the previous (Zheng et al., 2010; Kalogeropoulos, 2011).

For the application of the hydrological model in the study area, a version of ArcSWAT was used, which works as an extension of the ArcGIS software. This particularly facilitates the users of this program, as the input of spatial and meteorological data and the monitoring of the actions is done by direct visualization of the results in a relatively easy and familiar environment (Jacobs et al. 2007; Kalogeropoulos, 2011). For the successful execution of the program using ArcSWAT, it is necessary a series of tasks to be followed (Fig. 8).

Before starting the application, it is necessary to create the SWAT project, in which the processed data will be saved. The first analysis that is taking place is the hydrological analysis, which is based on the digital elevation model (DEM), the hydrographic network and the catchments of the study area. The Digital Elevation Model was created from digitized contour maps, in scale 1: 50000. The analysis of the DEM mosaic is a critical for the simulation, as is affects the accuracy of the results that will be provided by the model (Geza and McGray, 2008). For this reason, the analysis of the DEM that has been used in this case is 25x25 pixel, which covers the needs of the work, since three-dimensional soil models with this analysis give satisfactory results (Chaplot, 2005).

After the hydrological analysis, the creation of the hydrological response units (HRUs) is taking place automatically, based on land use and soil maps. But, as Naxos Island is characterized by the absence of thick soil layers, it was considered crucial to use at this stage the hydrolithological maps of the study area, which has been constructed according to the detailed geological map. This consideration was made by the fact that the high values of fractures' density are even higher in larger scale, and the hydrolithology could be considered as a soil in enlargement, and the soil data was inserted by correlating the permeability with the characteristics of soils given in SWAT. Lithologies with low permeability were characterized as Windsor soils, lithologies with medium permeability were characterized as Vergennes soils, while lithologies with high permeability were characterized as Covington soils.

The above consideration is the reason why no modification was made in the model, while in applications of the SWAT model in karst aquifers the model was modified to simulate quick movement of water where karstic features were observed (Baffaut & Benson, 2009; Afinowicz et al., 2005). Both karstic and fractured media have similar characteristics regarding the water flow, but in the case of karstic aquifers, features such us sinkholes provide larger direct connections between surface water and groundwater.

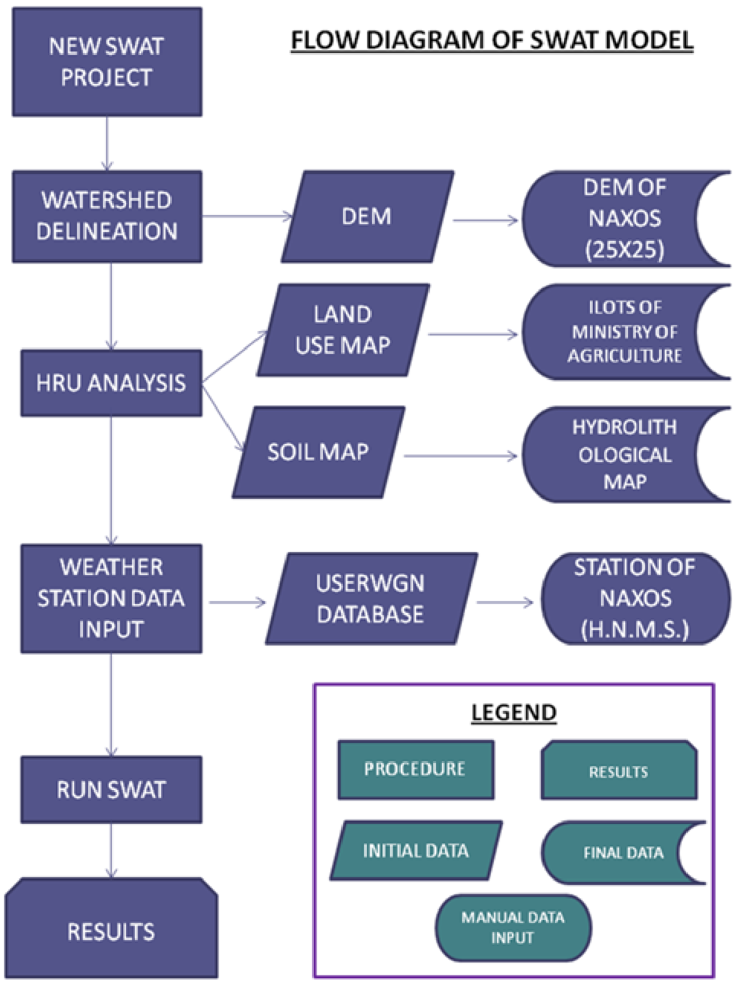

Fig. 8. Flow diagram of SWAT model.

For the simulation of the hydrological balance it is necessary to insert in the model a large amount of meteorological data of the study area. Climatic parameters such as temperature, rainfall, humidity and wind speed data are taken from the meteorological station of Naxos Island and the available time series of these parameters covered the period 1958 – 2010. Other atmospheric parameters such as the solar radiation, have been chosen from the database of SWAT by selecting a weather station with the same latitude with the meteorological station of study area.

Model equations are given in the SWAT theoretical documentation (http://swatmodel.tamu.edu) and in Arnold et al. (1998).

6. Results

For the present study only the results of the parameters of the hydrologic balance were discussed, i.e. the precipitation, the runoff, the infiltration and the actual evapotranspiration, in order to correlate the hydrological conditions with the fracture pattern in Naxos Island. According to the above results, it is possible to modulate the hydrological balance on an annual basis for the period 1958 - 2010 for the study area (Table 1 and Table 2). These results show that evapotranspiration and surface runoff are quite high in the region (respectively 69% and 29% of precipitation), while infiltration is quite low, at 2% of precipitation.

Table 1. Total annual average volume of water for each parameter of the hydrological balance for the island of Naxos, but for each major drainage basin separately for the period 1958-2010.

Catchment	P ($x 10^6 m^3$)	E ($x 10^6 m^3$)	R ($x 10^6 m^3$)	I ($x 10^6 m^3$)
Aghia	5	2.5	2.7	0
Potamos River	5	2.5	2.5	0
Karvoukolakos River	3	2.7	0.3	0.1
Tzoumagia River	5	3.4	1.1	0.1
Atsipapi	4	3.3	0.4	0.1
Pnichtis River	5	3.9	1.1	0.3
Mesonisi River	6	5.1	1.3	0.2
Limnes River	7	5.6	0.9	0.2
Skoteino River	6	5.4	0.6	0
Anakion River	5	4.3	0.3	0.1
Kleidos	4	3.5	0.4	0.1
Panormos	5	4.2	0.6	0.1
Fisas River	9	8.1	0.9	0.2
Vremenis	3	2.7	0.3	0.1
Aghiassos	7	5.8	1	0.2
Pyrgaki	17	12.9	4.2	0.1
Mikri Vigla	5	3	1.6	0.2
Vivlos	5	3	1.6	0.3
St. Anna	3	2.3	0.5	0.1
Paratrechos River	25	14.8	10	0.6
Naxos	3	1.3	1.7	0
Garinos River	14	6.7	6.8	0.2
Perganti River	3	1.6	1.5	0
Faneromeni River	4	1.5	2	0
Miloperama River	5	2.4	2.9	0
Total	163	112.5	47.2	3.3

Table 2. Hydrological balance of the island of Naxos on an annual basis for the period 1958-2010.

Parameter	P	E	R	I
Water Volume (x 10^6 m^3)	163	112,5	47,2	3,3
Percentage (%)	100%	69%	29%	2%

After running the SWAT model and processing the results, it is estimated that the water infiltration is very low throughout the study area, which is justified by the large spread of geological formations with very low permeability (schists, migmatite, etc.). But in the case of Naxos Island, which characterized by a low to moderate potentiality of groundwater presence, the infiltration is also dependent by the fractures' density and the degree of interconnection, the climatic and geologic conditions.

Furthermore, using the values of infiltration for every catchment and constructing a water infiltration map, the direct relationship between the infiltration and the fracture pattern of Naxos Island could be made. Analytically, high infiltration rates occur in areas where the density and the degree of interconnection discontinuities are also high (Fig. 9). Exception is the western part of the island, where high values of infiltration are observed in areas with quite low fractures' density, due to the change of the lithology (alluvial deposits and conglomerates).

Also, zones with high fractures' density and low infiltration are observed, especially in the mountainous area of the island. In this case infiltration is unfavorable due to the lithology and the high morphological slopes, resulting an episodic runoff. But in general, it is observed that the infiltration in the eastern part of Naxos is larger than the western part, due to the presence of marbles in this section, in relation to the prevalence of mica schist in the west.

Overall, the results of the application of the hydrological model ArcSWAT in the study area, appear that are quite satisfactory, as the infiltration could be associated directly with the fracture pattern of the study area. Thereby, areas with high values of water infiltration could be characterized as groundwater potential and vulnerable zones. Also, a verification of the results was made by correlating the high or low infiltration values with the presence of aquifers in low or high depth respectively. The main drawback of simulation models is the lack of data. Therefore, field measurements (e.g. surface flow) in the future are necessary in order to verify and/or calibrate the results of this model overcoming the drawbacks of this study.

7. Conclusions

The hydrogeological conditions in a hard rock environment are strictly connected with the hydrological conditions and the characteristics of the fractured media of the study area. A thorough study of the fractured media and its correlation with the hydrological conditions is practical for the right exploration of groundwater supplies in regions with water scarcity problems.

The analysis of the fractures in Naxos Island revealed that the fragmentation in all lithologies is characterized by high degree of uniformity and high values of density and interconnection density of the fractures are observed in areas where the alternations between marbles, schists and amphibolites are very intense.

The correlation between the hydrological conditions and the basic characteristics of the fractured media in Naxos Island using the SWAT model revealed that the infiltration could be associated directly with the fractured media. This suggests that the SWAT model is suitable for a first study of hard rock environments by indicating groundwater potential zones, which could help in a further investigation of the available water supplies. Furthermore, as the groundwater potential zones are most vulnerable and as SWAT model simulates by default the movement and transformation of nitrogen (N) and phosphorus (P) in each catchment, a first estimation of the pollution from agriculture and the vulnerability of the groundwater systems could be made also.

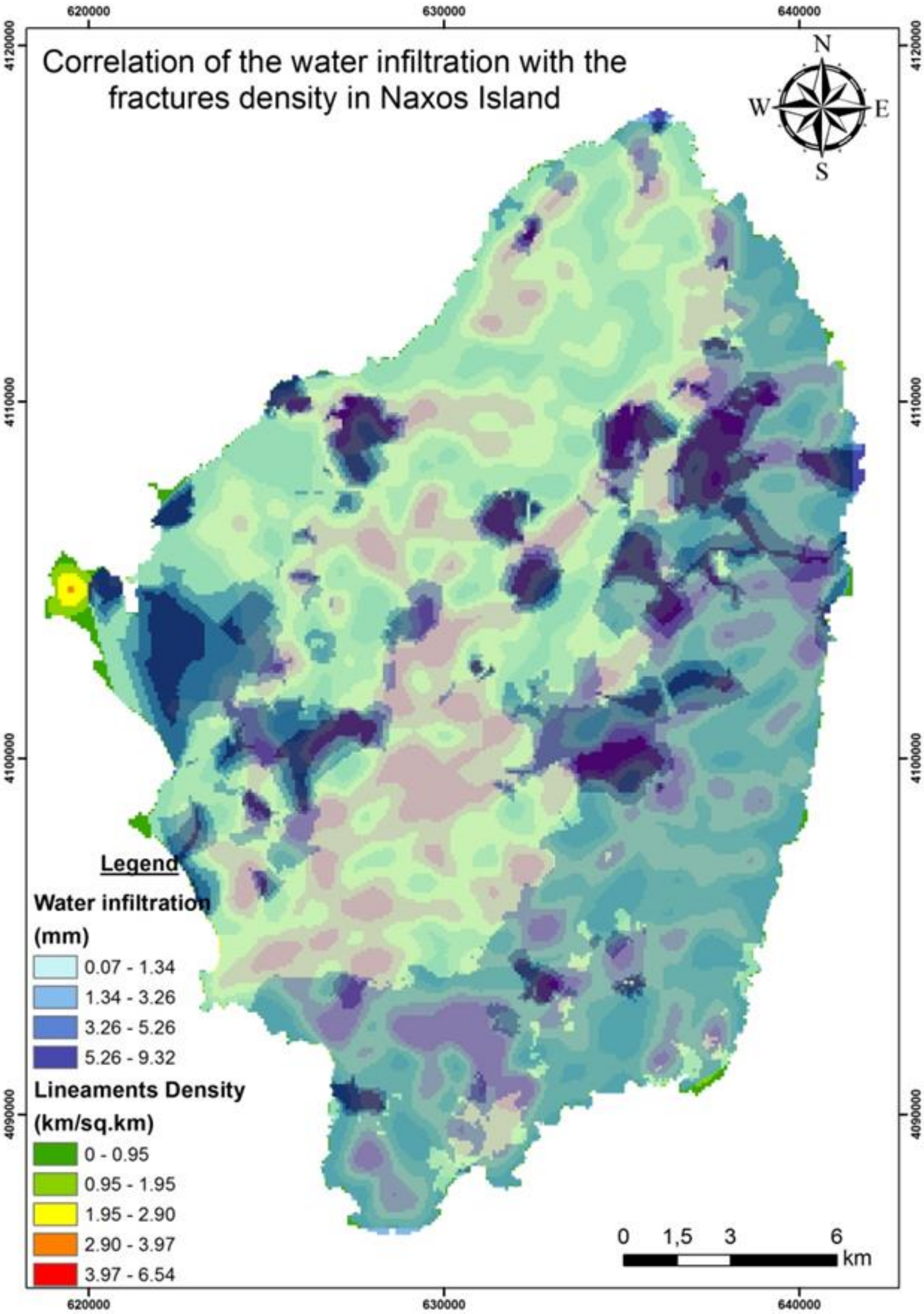

Fig. 9. Relationship of the water infiltration with the fractures density in Naxos Island.

References

Afinowicz J. D., Munster C. L., Wilcox B. P., 2005. Modeling effects of brush management in the rangeland water budget: Edwards Plateau Texas. *J. American Water Resources Assoc.*, 41 (1), 181-193.

Arnold J.G., Srinivasan R., Muttiah R.S., Williams J.R., 1998 Large area hydrologic modeling and assessment part I: model development. *J. Am. Water Resour. Assoc.*, 34 (1), 73-89.

Baffaut C., Benson V.W., 2009. Modeling flow and pollutant transport in a karst watershed with SWAT. *Transactions of the American Society of Agricultural and Biological Engineers,* 52 (2), 469-479.

Botsialas K., Vassilakis E., Stournaras G., 2005. Fracture pattern description and analysis of the hard rock hydrogeological environment, in a selected study area in Tinos island, Hellas. 7th Hellenic Hydrogeological Conference - Athens 2005, Volume II, pp. 91-100.

Botsialas K., 2007. Analysis, interpretation and estimation of the hydrogeological and geotechnical environment of the fractured media. Application in the schist system of Tinos Island. PhD Thesis, N.K.U.A., Greece.

Bouraoui F., Benabdallah S., Jrad A., Bidoglio G., 2005. Application of the SWAT model on the Medjerda river basin (Tunisia). *Physics and Chemistry of the Earth*, 30, 497-507.

Brichau St, 2004. Constraining the tectonic evolution of extensional fault systems in the Cyclades (Greece) using low-temperature thermochronology. PhD Thesis, Mainz University.

Chaplot V., 2005. Impact of DEM size and soil map on SWAT runoff, sediment and NO3-N loads predictions, *Journal of Hydrology*, 132, 207-222.

Evelpidou N., 2003. Geomorphological and geographical observations on Naxos Island, using Remote Sensing and G.I.S. methods, PhD Thesis, N.K.U.A., Greece.

Evelpidou N., Leonidopoulou D., Vassilopoulos A., Stournaras G., 2005. Procedures concluded to erosion geomorphological characteristics of Naxos, Mykonos, Tinos islands (Aegean Sea). 7th Hellenic Hydrogeological Conference - Athens 2005, Volume II, 117-125.

Galanos I., Rokkos D., 1999. Exploring the possibility of lithological and structural mapping using principal component analysis on Landsat TM images of Naxos island. *Tech. Chron. Sci. J. TCG*, I, No 3, 89-91.

Geza M., McCray J., 2008. Effects of soil data resolution on SWAT model stream flow and water quality predictions. *Journal of Environmental Management*, 88, 393-406.

Gülcan S., 2005. Lineament analysis from satellite images, north-west of Ankara, MSc Thesis, Middle East Technical University.

Jacobs J., Angerer J., Vitale J., Shrinivasan R., Kaitho R., 2007. Mitigating Economic Damage in Kenya's Upper Tana River Basin: An application of Arc-View SWAT, *Journal of Spatial Hydrology*, Vol.7, No.1.

Jansen J., 1977. The geology of Naxos. Institute of Geological and Mining Research, Greece.

Kalogeropoulos K., 2011. Exploitation of the hydrological model SWAT in the investigation of water reservoirs. Master Thesis, Harokopio University, Athens.

Krasny J., 1996. Hydrogeological Environment in Hard Rocks: An attempt at its schematizing and terminological consideration. *Acta Univesitatis Carolinae Geologica*, 40, 115-122.

Krasny J., 2002. Hard Rock Hydrogeology. 1st Workshop on Fissured Rocks Hydrogeology Proceedings, Athens, 11-18.

O'Leary D.W., Friedman J.D., Pohn H.A., 1976. Lineament, linear, lineation: Some proposed new standards for old terms. *Geological Society America Bulletin*, 87, 1463-1469.

Partsinevelou A.-S., Lozios S., Stournaras G., 2011. Fracture pattern description and analysis of the hard rock Hydrogeological environment in Naxos Island, Hellas. *Advances in the Research of Aquatic Environment*, 2, 45-52.

Partsinevelou A.-S., 2012. Tectonic and microtectonic approach of the groundwater systems in the metamorphic complex of Naxos Island. Master Thesis, N.K.U.A., Greece.

Partsinevelou A.-S., 2016. Investigation and simulation of aquifers in heterogeneous fractured media. Application in Naxos Island (Aegean Sea). PhD Thesis, N.K.U.A., Greece.

Scanvic J.Y, 1997. Aerospatial remote sensing in geology. Rotterdam, Balkema, 239 p.

Singhal B.B.S., Gupta R.P., 2010. Applied hydrogeology of fractured rocks. Springer, pp. 1-11.

Stournaras G., Alexiadou Ch., Leonidopoulou D., 2003. Correlation of hydrogeologic and tectonic characteristics of the hard rock aquifers in Tinos Island (Aegean Sea, Hellas). International Conference on Groundwater in Fractured Rocks, Prague.

Zheng J., Li G., Han Z., Meng G., 2010. Hydrological cycle simulation of an irrigation district based on a SWAT model, *Mathematical and Computer Modeling*, 51, 1312-1318.