Using Remote Sensing technology with SWAT hydrological modeling to estimate soil moisture of an insular basin

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Abstract

The knowledge of soil moisture (SM) is important in the whole range of environmental applications, and management methods, but adequate monitoring and modeling of this parameter is difficult because of its large spatial and temporal variability. A new methodology for the soil moisture estimation in insular basins is developed where there is little available data. The methodological approach involves three steps: (a) soil sampling and the gravimetric determination of soil moisture content in the laboratory, (b) remote sensing estimation of SM based o the method of spectral indices tracking, (c) execution of the distributed hydrological model SWAT, to simulate the long term trends in SM for surface soil layers and the spatiotemporal variability of SM in the island.

The results showed a strong correlation, R^2 0.7, between the surface temperature of the soil from the weather station and the satellite data. Also there is a high correlation, 0.8 between soil moisture data from field sampling and the data acquired from the soil moisture map.

The meteorology developed can be used in the future steps, but it must be improved in terms of calibration parameters of the model, and land use and geology of the area and the completeness of Meteorological data and run off field measurements.

Keywords: surfacesoil moisture, monitoring, satellite remote sensing, GIS, SWAT

Introduction

Surface soil moisture is one of the fundamental variables in hydrological processes, which influences the exchanges of water and energy fluxes at the land surface/ atmosphere interface. Accurate estimate of the spatial and temporal variations of soil moisture is critical for numerous environmental studies, including meteorology, hydrology, agriculture, and climate change.

Direct measurements of soil moisture are currently restricted to discrete measurements at specific locations, and such point-based measurements do not represent the spatial distribution, because soil moisture is highly variable both spatially and temporally (Engman, 1997, Ahmad et al. 2011) and are therefore inadequate to support regional and global studies. The use of satellite remote sensing, as a mean to estimate surface soil moisture, began in mid70's. Satellite remote sensing used for the estimation of soil moisture after processing the images that have been recorded by their receivers. The sensors do not record the content of soil moisture, but with the use of mathematical models the relationship between the signal recorded and the content of soil moisture can be described (De Troche et al., 1996, Moran S. et al., 2004, Wang L. and Qu J., 2009).In this way controlled and the sensitivity of the channels to the change in soil moisture. Numerous researchers have shown that surface soil moisture content can be estimated by optical and thermal infrared remote sensing, as well as passive and active microwave remote sensing techniques (Liu W. et al., 2003, Lakshmi, 2013).

The SWAT (Soil and Water Assessment Tool)model predicts the impact of land management practices on water, sediment, and agricultural yields in large complex watersheds with different soils types, land use and management conditions over long periods of time (Singh, J. et al., 2004, Moran S et al. 2004, Ramos et al. 2014). It takes into account data of the soil, of the land use and of climate in a basin and gives results about the runoffs and the quality parameters of surface water, chemical and organic concentrations, at the outlet of the basin but also at intermediate points. The model uses the leaf area index (LAI) or soil cover fraction (SC) to calculate the potential transpiration and evaporation of a partly covered soil. It uses water balance equation: $SW_t = SW + S(R_{day}\text{-}Q_i\text{-}E_a\text{-}P_i\text{-}QR_i)$, where SW: soil water content, t: time R_{day} :amount of precipitation, $Q_{i:}$ amount of surface runoff, $E_{a\,:}$ amount of evapotranspiration, $P_{i:}$ amount of percolation, $QR_{i:}$ amount of return flow (http://swat.tamu.edu/)The SWAT model works on Geographic Information Systems (GIS) and is an open source model.

Study area

Lesvos Island belongs to the islands of the eastern Aegean Sea, and is the third largest island of Greece. The climate of Lesvos is mild, Mediterranean climate, with great sunshine throughout the year, and the mean annual rainfall is 750mm. The territory of Lesvos is mountainous and hilly, while the low lands are formed near the coast. The main occupation of the people in the villages is focused on the primary sector, namely agriculture and animal husbandry.

The study area is Tsiknias River, which crosses the central part of the island of Lesbos, and empties into the Gulf of Kalloni (Fig.1). The basin is bounded to the north of the island and throughout the basin is constructed mainly of volcanic rocks. The hydrographic network can be described as complex. The western part belongs to the dendritic type while the east is close to the radial one.

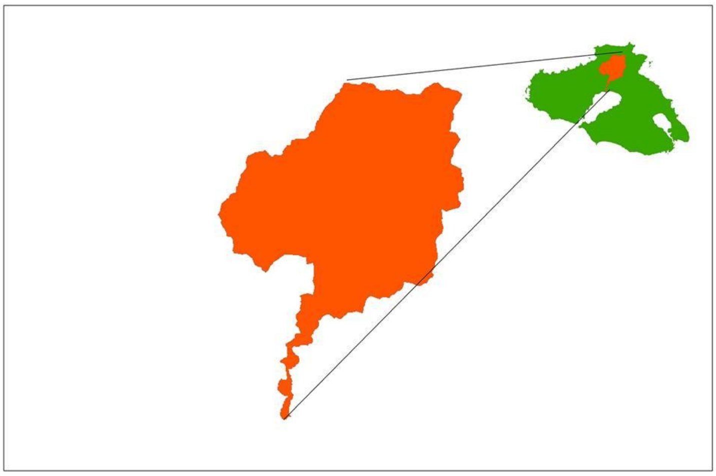


Figure 1. Study area, Tsiknias River

The majority of land use is olive groves, land principally occupied by agriculture with significant areas of natural vegetation and natural grasslands. Λιγότερη land use are with coniferous forest, complex cultivation patterns and transitional woodland-shrub. The highest elevation is 943meters and the lowest are -1.4meters.

The purpose of this study is the development of a new methodology for estimating soil moisture in island watersheds where there is little available data. The aim is to use satellite technology, GIS, and field data to estimate the temporal variation of soil moisture.

Methodology/ Experimental

The methodological approach involves three steps. In the first step soil samples were collected, with a selected sampling grid of the study area, during the wet period between 2014-15, for the determination of soil moisture in the laboratory. Samplings have been selected for different land uses and soil type in order for better differences in soil humidity to be seen, in the different land use types. The data selection in the field has been achieved using five different sampling points and this has been repeated five times. The soil samples have been dried in the lab and the soil moisture of the sampling points has been evaluated. At the same time the value of soil moisture was determined in-situ with the soil moisture tensiometer of Delta-T. The second step was the use and processing of satellite images of Landsat 5, Landsat 7TM and Landsat 8.

The estimated Surface soil moisture from remote sensing data was compared with in situ measurements of soil moisture. In the third stage the daily values of meteorological data from Agia Paraskevi station (2003-2014) and spatial data (land use, soil types and the digital terrain model) were used to perform the hydrological model SWAT. Data derived from the first two stages were used to calibrate the SWAT model.

In Table 1, presented are the equations that are used to compute NDVI from NIR and IR. Equation 2 is the converted calibrated digital numbers in spectral radiation. Also, used is the equation of converting the spectral radiation in ºC temperature. Finally, also is used the equation of calculation of soil moisture index.

Table 1. Equations

Equations	*Definition*
$\text{NDVI} = \frac{NIR-RED}{NIR+RED}$	Normalized Difference Vegetation Index
$L_\lambda = \frac{Lmax_\lambda - Lmin_\lambda}{Q_{calmax} - Q_{calmin}} \quad Q_{cal} - Q_{calmin} \ + Lmin_\lambda$	Convert calibrated Digital Numbers
$\text{T} = \frac{K2}{\ln(\frac{K1}{L_\lambda}+1)}$	Convert spectral radial transmitted in temperature
$\text{SMI} = \frac{T_{smax}-T_S}{T_{smax}-T_{smin}}$	Soil Moisture Index
$T_{smax} = a_1\text{NDVI} + b_1$	T_{smax} is the maximum surface temperature for a given NDVI
$T_{smin} = \text{a2NDVI} + b_2$	T_{smin} is the minimum surface temperature for a given NDVI

Model setup

Thirty two sub-basins were identified within the study basin. Smaller sub-basins have been developed in the area where the sampling took place in order to have a deeper study of the parameters of the soil characteristics, the land cover types and the area inclination.

In the areas where sample collections took place, new smaller sub-basins were created in order to have further examination according to land use and to soil. In Table 2, the sampling sites are presented with the different geological characteristics and the different land cover.

Table 2. Samplings data

Samplings	Geological characteristics	Land use	Sub-basin_SWAT
S1	Lowest lava stone	Olive groves, Sclerophyllous vegetation, non-irrigated arable land	27
S2	Ashes, red clays, sand and pebbles	Olive groves, non-irrigated arable land	21
S3	Pyroclastic, lowest lava stone, dacitic, latite rock, quartz and andesitic lava, Ignimbrites	Olive groves, non-irrigated arable land, natural grasslands, land principally occupied by agriculture, with significant areas of natural vegetation.	17
S4	Dacitic, latitite rock, quartz and andesitic lava, Ignimbrites	Olive groves, non-irrigated arable land.	15
S5	Lowest lava stone, Ashes, red clays, sand and pebbles	Olive groves, coniferous forest	11

Model performance was defined based on two statistical methods: the Nash-Sucliffe efficiency (NSE; Nash & Sutcliffe 1970) and the ratio of the root mean square to standard deviation (RSR).

Results and discussion

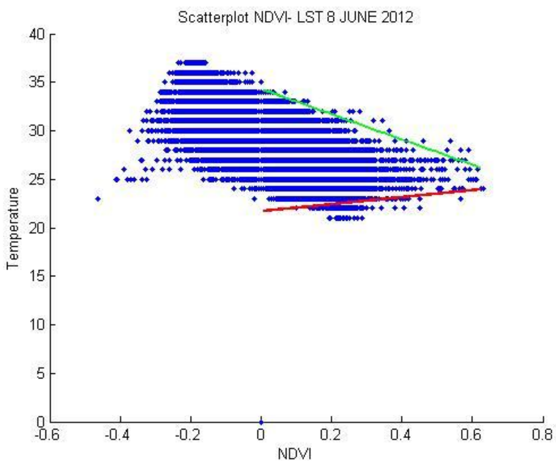
The comparison of satellite data which have the soil temperature and the data from the station of Agia Paraskevi showed that there is a high correlation, where Pearson correlation coefficient was 0.7. Furthermore, the comparison of data of soil moisture from the sampling stations and the calculated soil moisture index from the satellite images also showed a high linear correlation between them, where Pearson correlation coefficient was 0.8.

In Figure 2(a), red circles correspond to minimum temperature values for each category NDVI, which are used to calculate the wet end (lower limit of the chart) by linear regression. The green circles correspond to the maximum temperatures for the NDVI, which are used to calculate the dry end (upper limit) by means of linear regression. Ts_{max} and Ts_{min} are the maximum and minimum surface temperature for a given NDVI, and Ts is the remotely-sensed data-derived surface temperature at a given pixel for a given NDVI. In Figure 2(b) presented the soil moisture map.

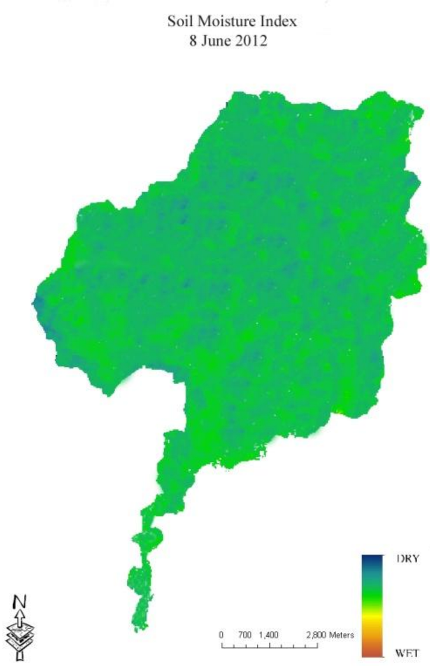
$$T_{smax} = -24.1*NDVI + 40.4$$

$$T_{smin} = 3.9*NDVI + 25.1$$

$$SMI = (T_{smax} - T_s) \;/\; (T_{smax} - T_{smin})$$



(a)



(b)

Figure 2.(a) Scatter plot of LST and NDVI, (b) map of Soil Moisture Index, Date 8June 2012

Figure 3 presents the values of soil moisture, both the observed and simulated. Finally, presented the rainfall values which occurred in those days. The simulated values are the values which result from the calibration of the several parameters.

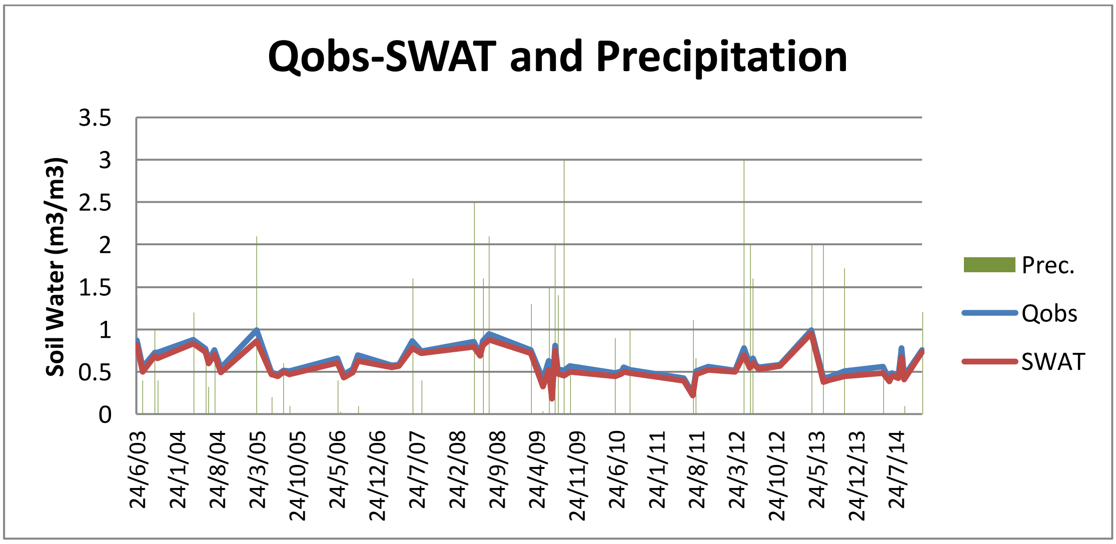


Figure 3. Compare observed with calibrated data

Conclusions

In this study a computational system has been developed, which distributes the hydrological balance in the geographical area of a small basin, using hydrometeorological data as input and outputting geographically distributed information levels for fifteen basins which have been created. The study focused more on the methodological part of creating the hydrological simulation model and qualitative investigation of various parameters of Tsiknia's basin in Lesvos Island and less on quantitative piece of data. The results are although satisfactory but could be better if there was more and accurate field data.

The results showed a strong correlation between the soil surface temperature measurements from the weather station and the satellite data. Also there is a high correlation between soil moisture data from field sampling and the data acquired from the soil moisture map (satellite processing).

From the current analysis can be drawn the conclusion that the model gives a satisfactory fit for hydrological segment balance. The methodological approach for the SWAT rating and the use of detailed soil data enabled the appropriate runoff rates and reasonably good predictions. This agrees with the worst performance of other rivers and sediment production forecast found in Mediterranean regions. The aggrement between the results of the SWAT application in this case study and other studies on other areas with Mediterranean conditions suggest the strength of scoring method proposed for small basins (Rossi et al. 2009; Arnold et al. 2010).

The advantages of the methodology used were the use of remote sensing data, which had zero market cost, and timeless collection of data at different seasons of the year. Disadvantages are the existence of dependence potential of satellite sensors, the presence of cloud cover or shadows. Finally, it should be noted that it is not possible to evaluate and verify the results of the processing of satellite data in the absence of field data or data from weather stations.

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