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DETERMINATION OF HYDROLOGIC CHARACTERISTICS OF SİNOP DEMİRCİKÖY WATERSHED AND PRODUCTION OF MONTHLY SATURATION DEGREE MAPS

Mustafa Can CANOĞLU[a*]

[a] *Sinop University, Faculty of Engineering and Architecture, Environmental Engineering Department Osmaniye Village, Nasuhbaşoğlu District, 57000, Sinop/TURKEY. orcid :0000-0003-4028-0046*

Research Article

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ABSTRACT

The aim of this study is to determine the hydrologic characteristics and to analyze the temporal saturation degree variations of Demirciköy Watershed which is located in Sinop City and subjected to rapidly increasing population. This study is important in terms of preventing the natural disasters such as flood, storm water, landslide and mitigation of damages within the frame of watershed planning concept. This study consists of field, office and laboratory stages. In context of field studies, representative soil samples are taken from study area. Within the scope of laboratory studies, soil hydrologic properties are characterized with the determination of soil texture of the soil samples handled from study area. The results of the laboratory tests are utilized as part of office studies with the use of the Soil Moisture Distribution and Routing (SMDR) model in Geographic Information Systems (GIS) environment considering the meteorological data such as precipitation, temperature and evapotranspiration. Spatial and temporal variation of saturation degree in Demirciköy Watershed is determined with SMDR model. The obtained monthly saturation degree maps show the variation of soil moisture in a year and allow determining the potential runoff generation zones. The results of the study show that soil moisture in South part of watershed is lower than in North part.

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1. Introduction

In Turkey, cities are enlarging based on the rapidly increasing population and rural areas get involved in city boundaries. Population of Sinop city increased in a short span of time in connection with the touristic benefits, new constructed highways and continuously developing university. Under the circumstances, the needs of increasing urbanization should be satisfied. Watershed planning have a great importance on the prediction of natural disasters such as flood, landslide etc. as well as the water demand. For this reason, it is important to determine the hydrologic characteristics of Demirciköy Watershed, located in Sinop City which enlarge unrestrainedly trough the Southwest.

Geographical Information Systems (GIS) are utilized by many researchers in watershed planning and hydrogeological investigations in Turkey (Kurtuluş, 2012; Kurtuluş and Flipo, 2012; Kurtuluş and Razack, 2010, Canoğlu, 2015). Furthermore, the SMDR model which is based on GIS is also used by several researchers in hydrological modelling of unsaturated zone (Easton et al., 2007; Alwis et al., 2007; Campos et al., 2008; Rao et al., 2009; Frey et al., 2009; Canoğlu, 2017).

Hydrologic conditions of Demirciköy Watershed which is located in southeast of Sinop city are modeled spatio-temporally by use of SMDR model and water content variations of vadose zone are determined. This study consists of office works, field works and laboratory works. Within office studies, literature review, the data collection about Demirciköy Watershed, thematic map production by GIS, processing SMDR model and evaluation of obtained results are performed. Field works include observations on landslides and soil sampling from 10 representative points (Figure 1). Basic soil mechanics tests are performed on the samples in context of

* *Corresponding author: Mustafa Can CANOĞLU, e-mail: mccanoglu@sinop.edu.tr*
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laboratory works and the results of these tests are utilized as input data of SMDR model.

The monthly mean moisture content maps obtained from SMDR model provide the opportunity of determination of potential runoff productive areas in Demiciköy Watershed during a year. In this way, critical locations which can produce natural disasters such as landslide, flood etc. are determined by modeling and possible solutions are suggested.

1.1. General Characteristics of Study Area

Study area is located in north of Turkey, Karadeniz region. The climate is typical Karadeniz climate with hot-damp summers and cold-rainy winters (Atalay, 1997). Karadeniz region is the most rain receiving geographic region. Snowfall can be occurred rarely and severe between December and March. A number of landslide events have been recorded due to the severe and unstable rainfall and snowfall in Sinop city and it the surrounding area (Ertek et al., 1993; Işık et al., 2004; Özdemir, 2005, 2007; Canoğlu, 2017). The residential areas in Sinop city are shifted through the Demirciköy Watershed. Demirciköy Watershed delineation is determined by ArcGIS 10.0 software. It covers an area of 8,71 km^2 and is located 11,2 km southwest of Sinop City center (Figure 1).

2. Geological Setting of Study Area and Surrounding

Sinop tectonic basin represents sedimentary units which is subsided between Lias – Quaternary period (Gedik et al., 1984; Gedik and Korkmaz, 1984). Geological formations of the basin are generally discordant within each other.

Stratigraphy of Sinop starts with Boyabat metamorphites as substratum. Outcrops of metamorphic rock units are observed extensively in south and west zones of Boyabat – Durağan and Saraydüzü district. These units are formed by metamorphism of schist facies with high pressure and temperature in a large period of time (Çellek, 2013).

Jurassic aged Akgöl and Bürnik formations overlap Boyabat metamorphics. Akgöl formation is formed by sandstone, siltstone and shale intercalations and Bürnük formation is formed only by gravelstone. The limestone within the lower Cretaceous aged İnaltı formation overlaps Jurassic aged units discordantly. Çağlayan formation formed by the marl, shale, sandstone and limestone covers İnaltı formation concordantly. Paleocene aged Akveren formation which is formed by limestone, shale, marl and mudstone overlaps all these units discordantly. In this region Eocene aged limestone, sandstone, marl and gravelstone can be also observed. Miocene aged Sinop

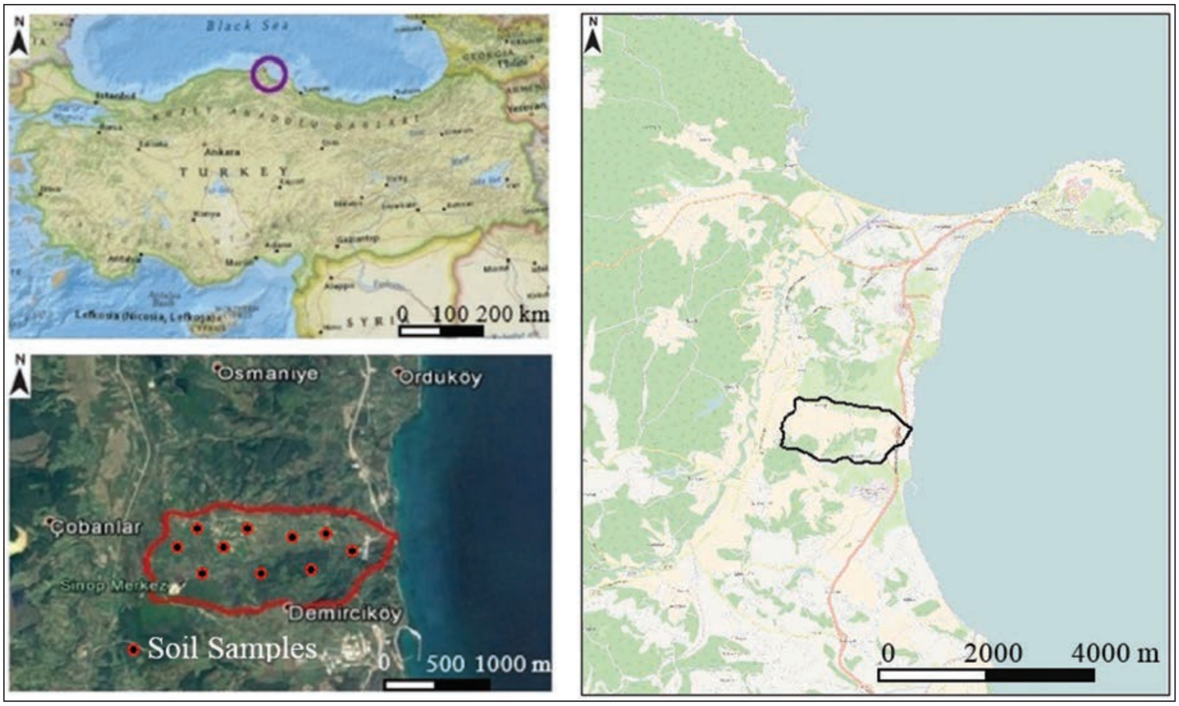

Figure 1- Location map of study area.

formation is formed by sandstone, limestone and marl and Plio-Quaternary aged Sarıkum formation is formed by sandstone, gravel and sand. Finally, alluvium covers all these units discordantly (modified from Çellek, 2013).

In Demirciköy watershed weathering products of Miocene aged Sinop formation formed by sandstone, limestone and marl units are observed (Figure 2). Sandstones and marls crop out in the watershed. Apart from these, 6 landslides are recorded within the weathered units of Sinop formation.

3. Material and Methods

The SMDR model (Soil and Water Lab., 2003) is employed in order to model the water flux of the vadose zone and to specify the potential runoff generating areas in Demirciköy Watershed. The SMDR model is created for the determination of spatio-temporal characteristics of variable source areas. This approach is developed for the soils which have vegetational activities, gentle slope and high infiltration capacity. Different watersheds can be modeled by the modular structure of the model. According to Gerard-Marchant et al. (2006) no calibration need of the model and already present electronic input data are the important advantages.

3.1 Structure of SMDR Model

The Soil Moisture Distribution and Routing (SMDR) model is based on a water balance and hydrologic model for soils within each pixel of watershed. In this model, when defining the soil hydrologic parameters, watershed is divided up to square cells (pixels) and geological, topographic and hydrologic parameters of each cell assumed as homogenous. In water mass balance calculation, water incomes to a cell are daily precipitation and lateral flow from upslope cell. As for water outputs, lateral outflow to downslope cells, percolation and evapotranspiration are considered (Figure 3).

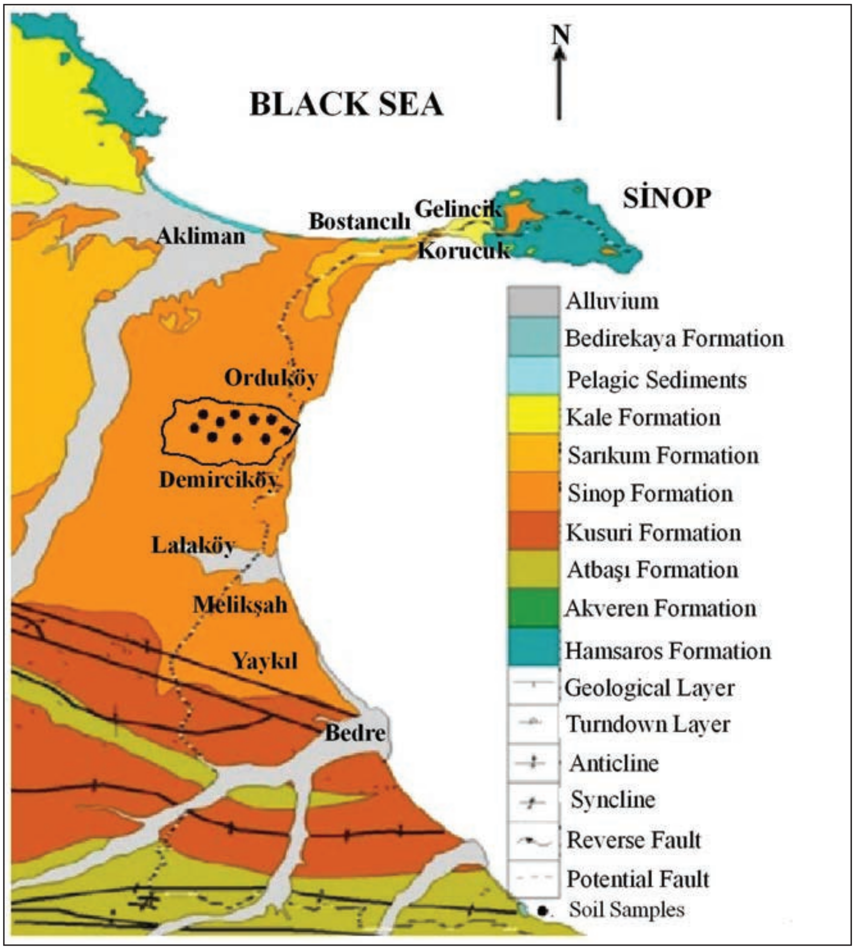

Figure 2- General geology map of the study area and its near environ (modified from Çellek, 2013).

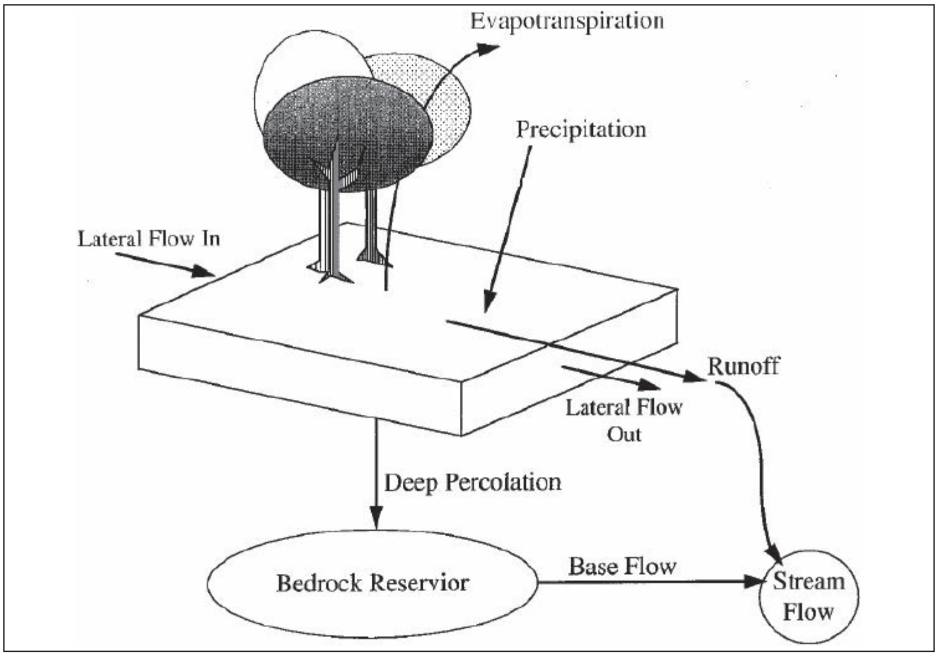

Figure 3- Hydrological processes of a cell used in SMDR model (Modified from Frankenberger et. al., 1999.

Water mass balance equation calculated for each cell from SMDR model is given below;

$$W^2 |\Theta(t) - \Theta(t - \Delta t)| = |RF(t) + SM(t)| + Qi(t) - Qo(t) - ET(t) - P(t) - SE(t) \quad \text{(equation 1)}$$

In this equation, *W* is cell size of a square cell (m), Θ is mean moisture content ($cm^3.cm^{-3}$), Δt is time interval (day), *RF* is rainfall (volume), *SM* is snowmelt (volume), *Qi* is water income from upslope cell (volume), *Qo* is water output to downslope cell (volume), *ET* is evapotranspiration (volume), *P* is percolation (volume), *SE* is saturation excess runoff (volume). In equation 1 soil thickness is considered as 1m and unit of volume is m^3.

In SMDR model, the defined meteorological information is assumed as the same for each pixels. In the model, effect of the local elevation variations on daily mean temperature is corrected by adiabatic deviation ratio (6,5 x 10^{-3}) (Boll et al., 1988). If daily mean temperature is lower than 0 C, the model assumes that it snows and no snowmelt occurs until the daily mean temperature becomes more than 0°C. The snowmelt *SM* in SMDR model is calculated by the temperature index method proposed by US Army Corps of Engineers (1960).

The underground lateral flow is calculated by Darcy's law. Water output (*Qo*) expressed with the equation 2 is calculated with the assumption that the local slope is equal to hydraulic gradient. In other words, hydraulic gradient can be interpreted as the angle between the horizontal of each cell. This assumption is not completely correct with regard to Darcy's law but the SMDR model represents unsaturated soil conditions and Richard's equation is utilized in the model instead of Darcy equation. For this reason, using local slope in lieu of hydraulic gradient gives real-like results.

$$Q_o = -\kappa K(\theta) \; W \beta \Delta t \qquad \text{(equation 2)}$$

In this equation K is the mean hydraulic conductivity of the cell ($m.day^{-1}$). κ is a factor dependent of cell depth (it changes typically between 2 and 10) employed for the transmissivity correction for the macroporosity inflow (Boll et. al., 1998). Hydraulic conductivity of the unsaturated zone in the model is determined as follow:

$$\begin{aligned} &\theta < \theta_f && \text{for} \quad K(\theta) = 0 \\ &\theta_f \le \theta < \theta_m && \text{for} \quad K(\theta) = K_s \exp \alpha \frac{(\theta - \theta_s)}{(\theta_s - \theta_f)} \\ &\theta_m \le \theta && \text{for} \quad K(\theta) = K_m + K_s \frac{(\theta - \theta_m)}{(\theta_s - \theta_m)} \end{aligned} \qquad \text{(equation 3)}$$

In this equation, Θf, Θm, Θs are field capacity, macropore drainage limit and saturated moisture content respectively. In addition, $K_s=K(\Theta_s)$ and $K_m=K(\Theta_m)$ are hydraulic conductivity for saturated conditions and for moisture content of macropore drainage limit. The parameter α shown in the equation 3 is a universal constant specified as 13 for many soil types (Bresler et al., 1978; Steenhuis and van der Molen, 1986). Distribution of the lateral outflow from a cell is determined by D∞ algorithm (Tarboton, 1997).

In SMDR model calculation of evapotranspiration is realized based on the method proposed by Thornthwaite and Mather (1957) in which the potential evapotranspiration, moisture content of soil and vegetation cover are considered. Percolation is expressed by the equation below:

$$P = min[K(\theta); K_{sub}]W^2 \Delta t \qquad \text{(equation 4)}$$

In equation 4 K_{sub} is the hydraulic conductivity of the unit under the cell (m.day^{-1}).

In SMDR model, if the mean moisture content of a cell is lower than field capacity, percolation stops. The saturation excess water at the end of the time interval is added to runoff component.

3.2 Parametrization and Input Data of SMDR Model

The SMDR model utilizes two types input data, such as raster maps and tables. Raster maps are digital elevation model, watershed boundary map, soil type map, aspect map and vegetative characteristics map. And tables are soil characteristics table, vegetation characteristics table and meteorological data table.

Digital elevation map is obtained from digitizing of the E34-a1 named 1:25,000 scale topographic map (National Mapping Agency, 1993) (Figure 4a). Watershed boundary and aspect maps are reproduced from digital elevation model with the use of ArcGIS 10.0 (ESRI, 2010) (Figure 4b). In SMDR model, geological, topographic and hydrologic parameters are assumed homogenous for each cell, for this reason cell sizes are set to the minimum possible. All maps prepared as input data for SMDR model have 10m x 10m horizontal resolution. In addition, in some ancient cell based models it is revealed that, enlarging the cell size, decreases the resolution of the curvilinearity and soil moisture content and evapotranspiration rate cannot be correctly represented (Kuo et. al., 1999).

Vegetative cover map and vegetation characteristics table are generated based on the information gathered from Sinop City Regional Directorate of Forestry. As for the soil characteristics table, the sieve analysis and hydrometer tests are performed on the soil samples handled from Demirciköy Watershed according to ASTM D-422-63 standards. Soil texture of the samples is specified based on the grain size distributions (Figure 5) and USDA (United States Department of Agriculture) soil texture classification system (Figure 6). Thereafter, soil characteristics table is generated as an input data of the SMDR model with the use of the soil hydrologic properties index table which base the soil texture proposed by Rawls and Brakensiek (1982, 1985) (Table 1). This soil characteristics table

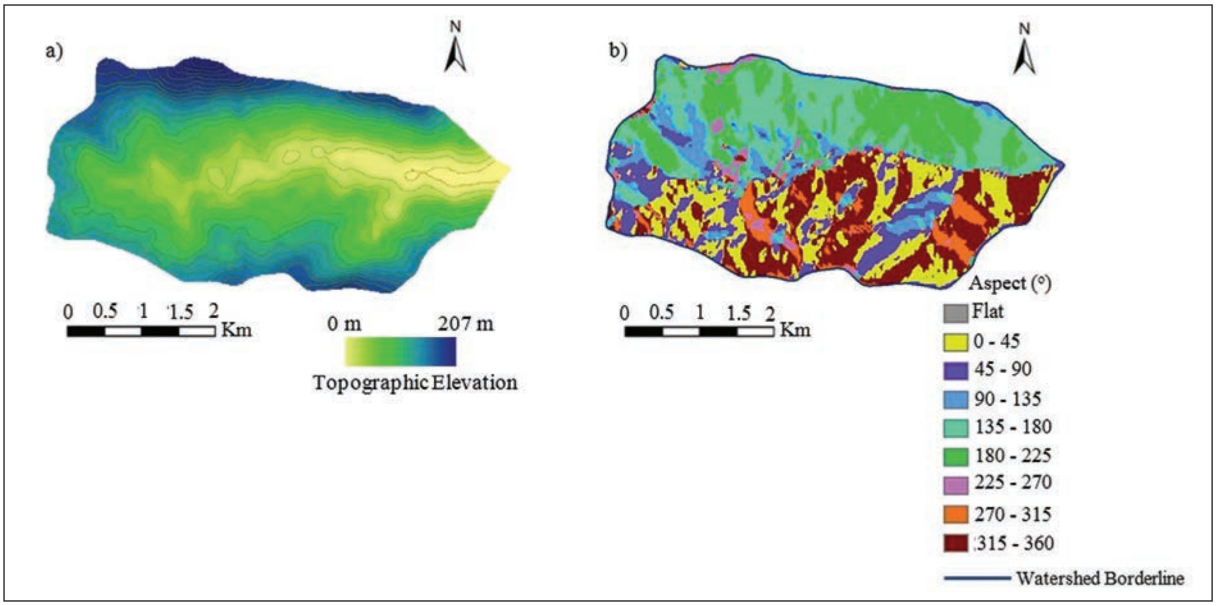

Figure 4- Digital elevation model map (a), aspect map and the watershed boundary (b).

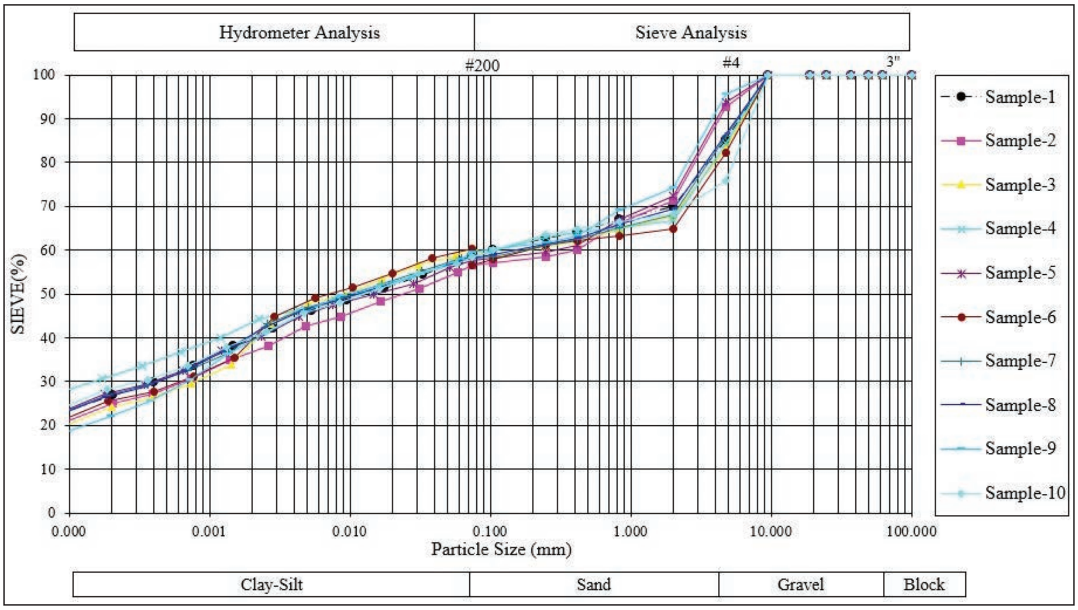

Figure 5- Grain size distributions of soil samples handled from study area.

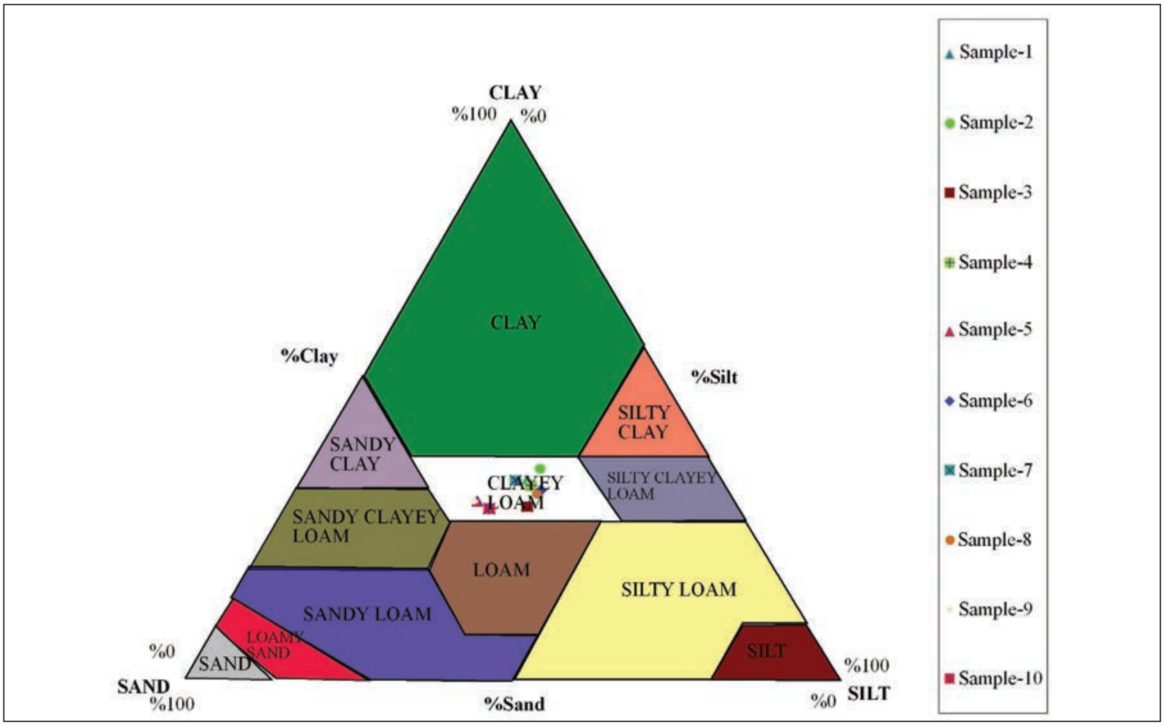

Figure 6- Textural classification of soil samples handled from the study area based on USDA soil texture classification system.

generating method is also proposed by Soil and Water Lab. (2003) in user manual of SMDR model.

As can be seen in figures 5 and 6, the soil material within Demirciköy Watershed is “clayey loam” according to USDA soil texture classification system and represented in only one textural class. Due to the domination of a monotype soil texture in Demirciköy Watershed, soil characteristics map is homogenous and represents only one soil type. Soil hydrologic properties of clayey loam are given in soil hydrologic properties index table proposed by Rawls and Brakensiek (1982, 1985) (Table 1).

As for meteorological data are obtained from General Directorate of Meteorological Affairs Sinop

Table 1- Soil hydrologic properties index table based on soil texture

Textural Class	Porosity (cm^3/cm^3)	Residual water content (%)	Wilting point (%)	Field capacity (%)	Water content at saturation (%)	Maximum available water content (%)	K_{sat} vertical (mm/d)
Clayey Loam	46,4	7,5	19,7	31,8	39	31,5	48

Station (MGM, 2010). These daily meteorological data are handled between the years 1975 – 2010 are monthly mean precipitation, daily temperature and monthly mean potential evapotranspiration and these data is prepared as an input data of SMDR model (Table 2). The SMDR model is run on a daily time step and the obtained daily saturation degree maps are transformed to monthly saturation degree maps by ArcGIS 10.0 software.

Table 2- Monthly meteorological data of Sinop city (1975-2010 General Directorate of Meteorological Affairs)

	Monthly Mean Precipitation (mm)	Monthly Mean Daily Temperature (C°)	Monthly Mean Potential Evapotranspiration (mm)
January	71,2	7	0
February	49,2	6	0
March	49,3	7	0
April	37,7	11	16
May	33,1	15	24
June	35,3	20	29
July	36,3	23	37
August	42,2	23	27
September	66,0	20	22
October	91,4	16	14
November	87,3	12	0
December	82,3	9	0
Yearly	681,3	14	169

4. Results and Discussion

The Soil texture of each soil sample handled from the field is specified based on the sieve analysis. Hydrologic properties of soil sample are determined according to in soil hydrologic properties index table proposed by Rawls and Brakensiek (1982, 1985). Thereafter, water balance elements are modelled with the use of SMDR model considering the processes schematized in figure 3 and monthly saturation degree maps of Demirciköy Watershed are generated (Figure 7). In this way, the variations of saturation excess runoff generating areas are determined during a year.

Following results and conclusions can be deduced from this study:

– The soil structure is homogenous within the watershed and specified as clayey loam according to USDA soil texture classification system. In this context, there is no spatial variation of the soil hydrologic properties within the watershed.

– The saturation degree of north faced hillsides are fewer (Figure 7). This shows that the effect of solar radiation on evaporation is not very crucial and saturation degree is not decreased importantly by solar radiation. In addition, the expression such as the moisture in the air is splashed on north faced hillsides utilized generally for Blacksea Region does not reflect the reality. However, considering the low saturation degree in botanically active regions, the effect of evapotranspiration on the saturation degree can be remarked. Under these circumstances, it can be drawn that transpiration is more effective than evaporation in terms of saturation degree.

– The saturation degree in May and August are generally low within the watershed. Evapotranspiration effect in May and high daily mean temperatures for August can decrease the saturation degree. In addition, it is observed that saturation degree is locally low for March, October, November and December. However, for these months the saturation degree of some pixels decreases, in some of them increases and becomes nearly saturated.

– The saturation degree in June and September are higher than other months. It can be said that high precipitation and water income from the upslope pixels augment the moisture content. Besides, the saturation degree values in January, April and July are also high as a result of high precipitation during subjected months and relatively decreasing evapotranspiration.

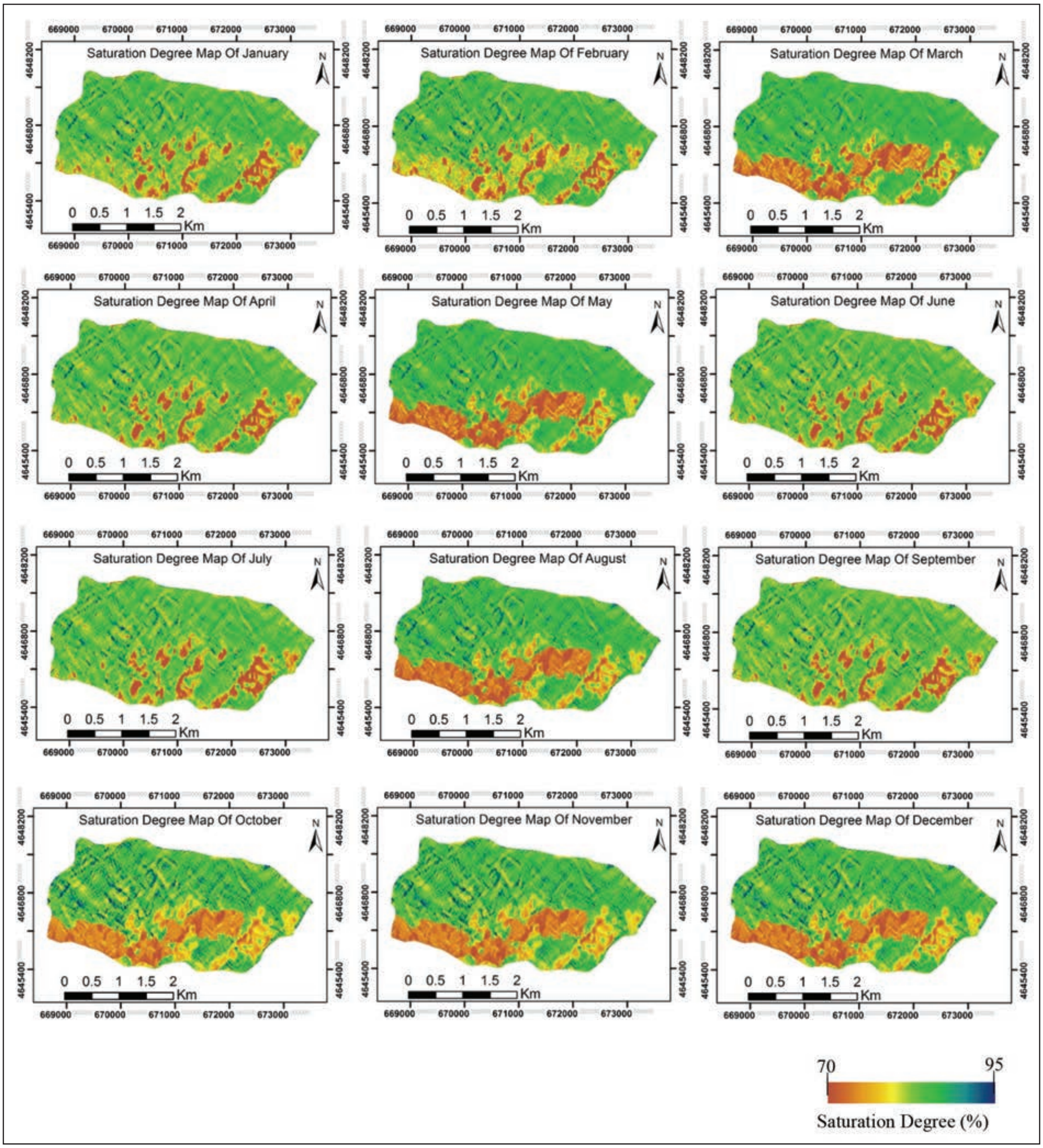

Figure 7- Monthly saturation degree variations of Demirciköy Watershed.

- The high potential of saturation excess runoff generation for south faced hillsides does not mean that these hillsides produce flood and overflows. The reason is that the floods and overflows cannot be explained by saturation excess runoff concept but the infiltration excess runoff mechanisms may sort out this situation. For the infiltration excess runoff initiation, rainfall intensity should be more than infiltration capacity of soil.
- There is no any pixel that reaches saturation and generates runoff in Demirciköy Watershed, modeled with the monthly mean meteorological data. Therewithal, it can be inferred that the pixels giving more than 90% moisture content have the potential of runoff generation with the increasing rainfall intensity especially for June which is higher saturation degree than other months (Figure 8). Additionally, some landslides are observed in the zones concentrated with

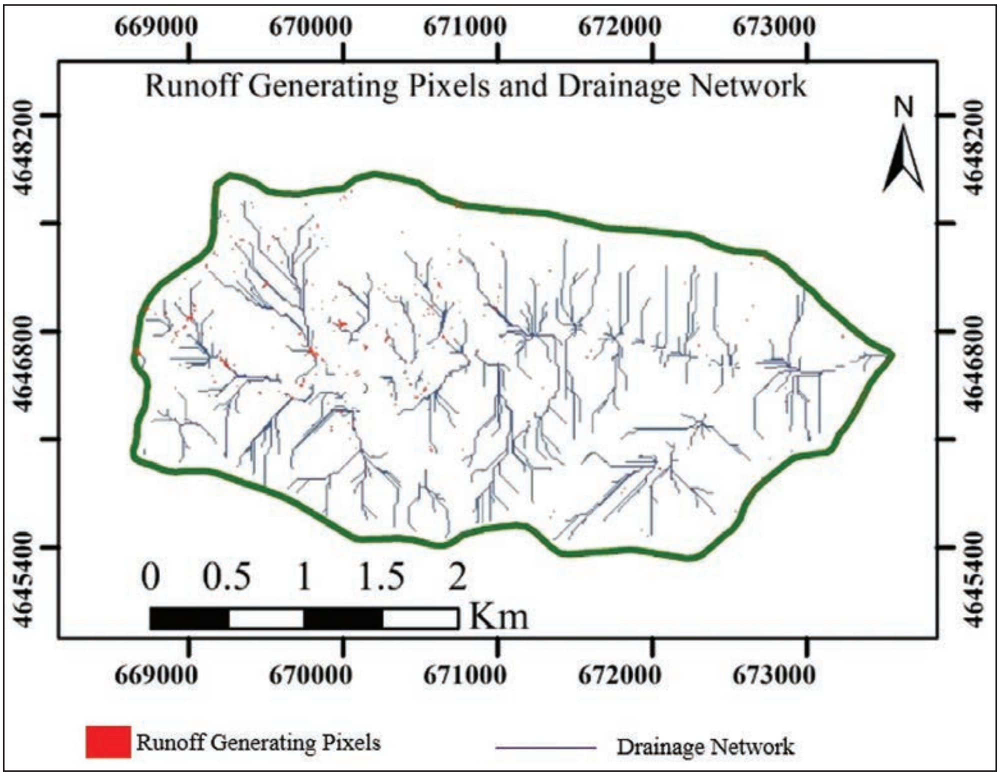

Figure 8- Potential runoff generating pixels map of June and Drainage network

these pixels. Comparison of the zones with a high degree of soil saturation with areas subject to landslide processes may be treated as the perspective of future research works.

- Finally, application of this method is simple and expeditious for the countries which have a soil characteristics database (such as SSURGO). However, application of this method in Turkey requires funding and takes time due to the absence of soil characteristics database.

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