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INDEX

PAGE **SESSION 5A : Waste Management Legislations**

450-454 Keynote_EU's Green Deal and the Waste Framework Directive
O. Tabasaran

455-460 Circular Economy goes beyond Waste Management
A. Mihajlov, A. Mladenovic, F. Jovanovic

461-468 The Use of Decision Support Systems for Evaluating Municipal Solid Waste Management Options
S. Öztaş, N. Bektaş

469-475 The Agricultural Waste Inventory On the Regional Basis in Turkey: Valuation of Agricultural Waste with Zero-Waste Concept in the Scope of Circular Economy
S. Sertgümeç , A.N. Usta , C. Özarpa

476-483 Factors Influencing Community Participation in Waste Reduction through Waste Bank
C. Meidiana, T. Sekito, S. Hariyani

PAGE **SESSION 5B : Biological Methods for Waste Treatment - 3**

485-492 Performance Evaluation of a Non-Odorous Compost Barrel for Household Purposes
M.N. Lunag Jr , M.M.M. Boado

493-499 Hazelnut Husk Based Acclimatization Soil for in-vitro Propagated Ornamental Plants
S. Ozdemir , M. Ozdemir

500-502 Role of Microbial Culture in Composting of Garden Waste
S. K. Mishra , K.D. Yadav

503-513 Sensitivity of the SWAT Model to Soil Data Parameterization; Case Study in Saz - Çayırova Stream, Turkey
H.N. Oruç , M. Çelen, F. Gülgen , M.S. Öncel, S. Vural, B. Kılıç

514-514 Effect of Methanol-Organosolv Pretreatment on Anaerobic Digestion of Lignocellulosic Materials
A. Oliva, L.C. Tan, S. Papirio, G, Esposito, P.N.L. Lens

PAGE **SESSION 5C : Membrane Technologies**

516-518 The Effects of Pretreatment on Performance of Direct Contact Membrane Distillation Treating Cooling Tower Blowdown Water
Y. A.Uslu , H. Yaşar , M. İnce, E. İnce

519-521 Investigation of Membrane Fouling in Membrane Distillation Bioreactor
H. Yaşar , Y. A.Uslu , M. İnce, E. İnce

522-527 Estimating The Adsorption Capacity of Mining Waste –Leonardite- For Treatment of Copper
Z. Kurt

528-532 Performance Comparison of Conventional Membrane Bioreactor and Moving Bed Membrane Bioreactor for the Treatment of Synthetic Textile Wastewater
A. Soysaloglu , B. Takatas, H. Sari Erkan, A. Çaglak, G. Onkal Engin

533-542 Boron Rejection from Aqueous Solution and Wastewater by Direct Contact Membrane Distillation
B. Tan , U. Selengil , T. Ennil Bektaş

543-548 Energy Production by Reverse Electrodialysis Fed with Treated Wastewater by Advanced Biological Process
A. Zoungrana , O. K. Türk , M. Çakmaci

549-558 Treatment of Nanofiltration Concentrate Discharge Water For 2nd Class Sanitary Landfill Facility Leachate
F.Çoker

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Sensitivity of the SWAT Model to Soil Data Parameterization; Case Study in Saz - Çayırova Stream, Turkey

Halil Nurullah Oruç[1], Meltem Çelen[1], Fatih Gülgen[2], Mehmet Salim Öncel[3], Sinem Vural[3], Batuhan Kılıç[2]

Abstract

The accuracy of hydrological models such as SWAT model depends on a well-defined physical property of the watershed such as land cover, soil properties, topography and meteorological factors. The objective of this study is (i) to model the hydrological processes of Saz - Çayırova Stream where located in north-west parts of Turkey, (ii) to analyze the soil physicochemical characteristic of the catchment area with laboratory and field studies, (iii) to evaluate the effect of specified soil database and the FAO soil database over streamflow using SWAT model without calibration. Twenty-nine soil sampling points were identified to represent the whole of the catchment. Among the required soil parameters clay, silt, sand, rock / gravel, bulk density, organic carbon, maximum rooting depth and depth from soil surface to bottom of layer determined by field observations and laboratory analyzes. The most noticeable difference among these parameters is the clay and sand content. While the average clay and sand contents were measured 5.1% and 43.3%, respectively, in the SSM database, these values were defined as 31% and 27%, respectively, in the FAO database. Runoff values produced using FAO and SSM databases were compared with observation data without applying any manual or automatic calibration technique, because calibration processes mask differences which can occur as a result of soil data sets. Determination coefficient (R2), Nash-Sutcliffe coefficient of efficiency (NSE) and Root Mean Square Error (RMSE) values were used to evaluate the model results. NSE value was calculated 0.19 and 0.48 for FAO and SSM, while RMSE value was 0.34 and 0.25, respectively. In this respect, while the SSM database was making acceptable estimates even before calibration, the found NSE values between the runoff values produced using the FAO database and the observation data remained below the acceptable threshold value (0.36). Forming unique soil structure of the watershed, dominated by residential and industrial areas such as Saz-Çayırova stream, with laboratory and field studies allows the calibration processes to be made more consciously.

Keywords: FAO, Soil Datasets, SWAT, Watershed

1. INTRODUCTION

Many physical-based models have been developed to examine the hydrological processes of water resources with their watersheds. The Soil and Water Assessment (SWAT) model is one of the most widely used of these hydrological models. The main input parameters of SWAT; Digital Elevation Model (DEM), land cover

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data, soil properties and meteorological parameters. While many studies are performed about land use/land cover changes in last decades([1], [2], [3], [4]), studies evaluating the performance of the hydrologic models with using soil database which comprised of laboratory analysis and field observations are very limited [5]. Soil physicochemical information is one of the crucial inputs needed to assess the sensitivity and analyzing the output of hydrologic models. For instance, assuming that no significant effect from the factors controlling hydrodynamics such as crusting and aggregation in sandy and clay soils, sandy soils allow a high rate of infiltration and generate less surface runoff, while soils formed from poorly drained clay soils produce low infiltration and produce more runoff.

The widely used digitized soil database for hydrological modeling are State Soil Geographic Database (STATSGO), Soil Research Geographic Database (SSURGO) and the Food and Agricultural Organization (FAO). In the United States, STATSGO maps are compiled by the US Natural Resources Conservation Service (NRCS) [6]. FAO maps are on the scale of 1: 1 000 000 and consider dominant soil structure over the study area. In addition to these database, digitized national soil database on the scale of 1/25 000, considering the Old American Classification Systems (Soil Taxonomy), was produced by the Turkey General Directorate of Rural Services. Parameters of this attribute table; Main soil groups, soil characteristics, area types (rubble areas, ricer flooded areas, sandy shores, reed bed on muddy areas etc.), subgroups of land capability classes. Although these parameters are useful for interpreting the input parameters of hydrological models such as SWAT, the input parameters should be modified by field and laboratory studies.

Hydrological modelling studies were examined to assess the effect of the Global Soil Database on the surface runoff in the literature. Levick et al. [7] compared effects of FAO, STATSGO and SSURGO soil databases in the Walnut Gulch Watershed in Arizona. High surface runoff was estimated in STATSGO database relative to SSURGO. In addition, about two times more streamflow was estimated using FAO compared to SSURGO. The difference in streamflow is explained by the difference in data resolution. In order to examine the effects of these soil databases on hydrological model results SWAT was mostly used ([8], [9]).

Setegn et al. [10] generated the soil structure of the Upper Mississippi River Basin by field and laboratory studies and created its hydrological budget with the Soil and Water Assessment (SWAT) model. The critical point in this study is that no calibration and validation processes have been performed for the model. It was emphasized that similar results were obtained when compared with the results of three different past studies performed for the basin, and that the model yielded acceptable results for hydrological components without applied any calibration techniques.

Few studies about this subjects indicated that variability in the surface runoff produced from the global soil databases have been explained by the climatic conditions and differences of the soil types. In general, these studies also indicated that the reliability of the model results correlated with the soil database and climate conditions ([5], [11]). In this context of this summarized information, the aim of this study is; (i) modeling the hydrological processes of Saz - Çayırova Stream where located in north-west parts of Turkey, (ii) analyzing the soil physicochemical characteristic of the catchment area with laboratory and field studies, (iii) to evaluate the effect of FAO and soil database produced from this study on streamflow using SWAT model without applied any calibration techniques.

2. MATERIAL AND METHOD

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2.1. Study Area

Saz - Çayırova river system is located in the Marmara Basin, northwest parts of Turkey (Figure 1). Saz-Çayırova Stream which is heavily affected by environmental factors and runs along the Kocaeli-Istanbul border, one of the most important industrial regions of Turkey, has been selected as study area. The length of the Saz stream is about 10 km and its width varies between 2-20 m. The catchment area is approximately 50 km^2 and is classified as a small-scale basin [12]. Saz- Çayırova Stream network are mostly included in the industrial and residential areas and it has become difficult to detect these networks visually without using Geographic Analysis Tools.

Studies for the stream have generally focused on water quality and land cover changes. Hız [13] conducted heavy metal analysis at 15 points determined by the stream and stated that the metals show complex relationships with each other and these relations cannot be explained by bilateral correlations. Atasayan et al. [12] analyzed the change in the natural landscape by detecting the changes in its natural vegetation as a result of anthropogenic activities for the years between 2003-2013 in the Saz Stream protection band. The only one discharge station belongs to the General Directorate for Hydraulic Works (GDHV) on Saz Stream is currently closed, where flowrate measurements were made between 1982 and 1986. There are no studies on the region

that assess the effect of physical parameters prepared by laboratory and field studies on hydrological processes by means of modelling or to establish the region's water budget.

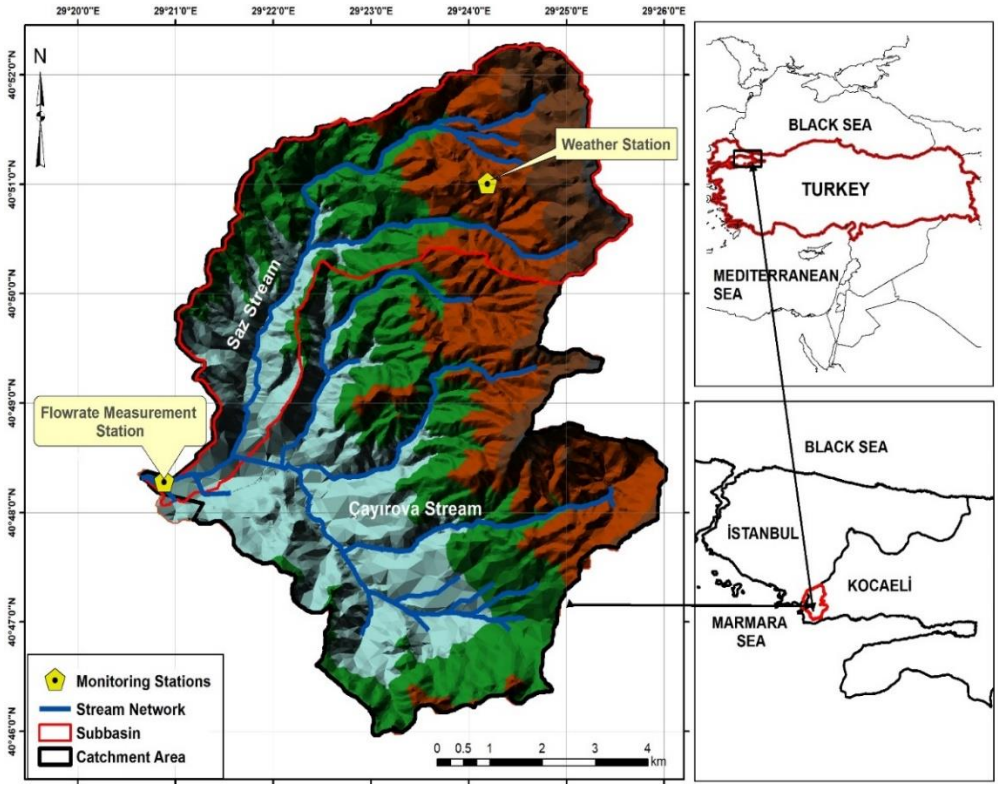

Figure 1. Location map of Saz - Çayırova river system, northwest parts of Turkey.

2.2 Soil Data Preparation

Soil structure is a critical factor for understanding processes such as surface run off, infiltration, crop growth and soil water. It is a fact that knowing the soil properties provides indication while understanding complicated watersheds. According to the soil maps prepared by Turkey General Directorate of Rural Services (TNSD), Saz-Çayırova Stream Watershed includes 3 main soil groups; Rendzinas (R), Brown forest soil without lime (N) and brown soils without lime (U). However, approximately 35% of the soil database is described as a residential area and soil data is not defined. In addition, the parameters required for SWAT are limited in this soil database. Therefore, field studies and laboratory studies were carried out to obtain the required parameters for the SWAT. The generated soil database was digitized in the GIS environment.

Many soil physicochemical properties that interact directly or indirectly each other are used as input variables in SWAT (Table 1). For instance, the erodibility factor of the studied region is a fraction of soil texture (clay, silt, sand and rock content) and of organic carbon content [14]. Hydrological group values produced by NRCS and determined by considering the soil infiltration rate were obtained from the TNSD soil database. According to TNSD the dominant hydrological group of the catchment area is C (Infiltration rate ranges between 0.8 - 3 mm/hr). Fraction of porosity from which anions are excluded and maximum crack volume values are assumed as 0.5. The available water content parameter is defined as the difference of field capacity saturation and wilting point saturation. These parameters were obtained from the SWAT documentation [15].

Firstly, the analysis of soil texture which directly affects other variables and is critical for their determination was made. After determination of rock (particle diameter > 2mm) and sand (particle diameter ranges between 2 and 0.5 mm) percentages by wet sieve analysis, clay and silt content of soil samples were determined using Mastisizer-2000 Malvern device (Gebze Technical University Materials Science and Engineering Laboratory). According to these percentages, soil textures were determined on the soil texture triangle system [15]. Total organic matter content was analyzed according to the Loss-on-Ignition method ([16], [17]). The organic carbon content determined according to the following equation.

Organic matter content (% soil weight) = 1.72 * Organic carbon content (1)

USLE soil erodibility factor is measure of the sensitivity of soil particles to separation and transport by precipitation and discharge. Texture of soil is an important parameter affecting this variable as well as structure of soil, organic matter content and permeability. The following equations were used to calculation USLE_K which represent the soil erodibility [14].

$$K_{USLE} = f_{csand} \times f_{cl-si} \times f_{orgc} \times f_{hisand} \quad (2)$$

Where; f_{csand} is a factor that gives low soil erodibility factors for high-coarse sand soils and high values for low-sand soils. $f_{(cl\text{-}si)}$ is low erodibility factor in soils with high clay-silt rate. f_{orgc} is a factor that reduces soil erodibility for soils with high organic carbon content and f_{hisand} is a factor that reduces soil erodibility in soils with extremely high sand content.

$$f_{csand} = \left(0.2 + 0.3 \times exp\left[-0.256 \times m_s \times \left(1 - \frac{m_{silt}}{100}\right)\right]\right) \quad (3)$$

$$f_{cl-si} = \left(\frac{m_{silt}}{m_c + m_{silt}}\right)^{0.3} \quad (4)$$

$$f_{orgc} = \left(1 - \frac{0.25 \times orgC}{orgC + exp[3.72 - 2.95 \times orgC]}\right) \quad (5)$$

$$f_{hisand} = \left[1 - \frac{0.7 \times \left(1 - \frac{m_s}{100}\right)}{\left(1 - \frac{m_s}{100}\right) + exp\left[-5.51 + 22.9 \times \left(1 - \frac{m_s}{100}\right)\right]}\right] \quad (6)$$

Where; m_s is the percent sand content (0.05-2.00 mm diameter particles), m_{silt} is the percent silt content (0.002- 0.05 mm diameter particles), m_c is the percent clay content (< 0.002 mm diameter particles), and org C is the percent organic carbon content of the layer (%).

Soil bulk density expresses the ratio of mass of solid particles to the volume of the soil. In this study, bulk density was determined by ratio of mass of soil after the oven dry and total volume of soil. Saturated hydraulic conductivity is an important physical property that controls the permeability properties of the soils and therefore the transportation and washing of salt and agricultural chemicals in the soils. It is also important parameter for drainage problems [18]. In this study, hydraulic conductivity derived according to the soil texture [15].

Table 1. Description, units and determination methods of soil parameters required for SWAT

Description	Determination Method
Hydrologic group	Turkey General Directorate of Rural Services
Depth from soil surface to bottom of layer (mm)	Field studies
Maximum rooting depth (mm)	Field studies
Fraction of porosity from which anions are excluded	Neitsch et al. [15]
Maximum crack volume (m^3/m^3)	Neitsch et al. [15]
Bulk density (g/cm^3)	Laboratory Analysis
Available water content (mm/mm)	Neitsch et al. [15]
Saturated hydraulic conductivity (mm/h)	Neitsch et al. [15]
Organic Carbon content (%)	Laboratory Analysis
Clay, silt, sand, rock/gravel content (%)	Laboratory Analysis
Albedo	Neitsch et al. [19]
USLE soil erodibility factor	Calculate according to Williams et al. [14]

Depth from soil surface to bottom of layer refers to the depth from the soil surface to the layer that prevents the plant roots of developing downwards. Plants supply water and nutrients from the upper soil, and a depth of up to 150 cm significantly affects plant growth. In this study, maximum rooting depth is accepted as soil profile depth. The depth of the soil profile as determined by field studies compared and verified to soil depths of Turkey National Soil Database.

2.3 Model Input Parameters

The SWAT model requires six meteorological parameters and DEM, soil, land use/land cover parameters as input data. The 5 m DEM was generated using digital topographic vector data on the scale of 1/25,000 which were taken from Turkish General Command of Mapping. The elevation contours and hydrographic features were the fundamental data. The topo to raster tool of ArcGIS 10.4.1 was used in DEM generation process.

Then, the stream burning process was applied to the DEM data derived with the topo to raster to obtain the hydrologically corrected DEM to be used in the analysis process. The resulted DEM is used to calculate sub-basin parameters such as slope, slope lengths, and streamflow network properties, i.e. channel slope, length and width. The DEM for Saz-Çayırova Stream Watershed is shown in Figure 2. The elevations of the watershed range from about 0, which is the sea level, and 311 m. The variation in elevation are relatively high. This especially affects the amount of water to surface runoff. Slope classes were determined, after determining the basin boundaries and stream network properties.

The land use data was derived from the Coordination of Information on The Environment (CORINE) data reflecting the year 2018. The CORINE method is based on remote sensing techniques [2]. The CORINE Land Cover classification is based on a three-level hierarchical basis, and each level corresponds to an individual scale. Level III mapped on the scale of 1/100,000 and has information in 44 categories. Level II corresponds to 1/500,000 and Level I mapped on the scale of 1/1,000,000. In this study, the Level I is considered. According to CORINE 73 % of the basin consists of built-up lands, 15 % agricultural lands, %10 rangeland, %2 road and rail networks. The study area is dominated by industrial and residential areas. In the Level III classification, 11- class land cover classification scheme applied over the study area is illustrated in Figure 2.

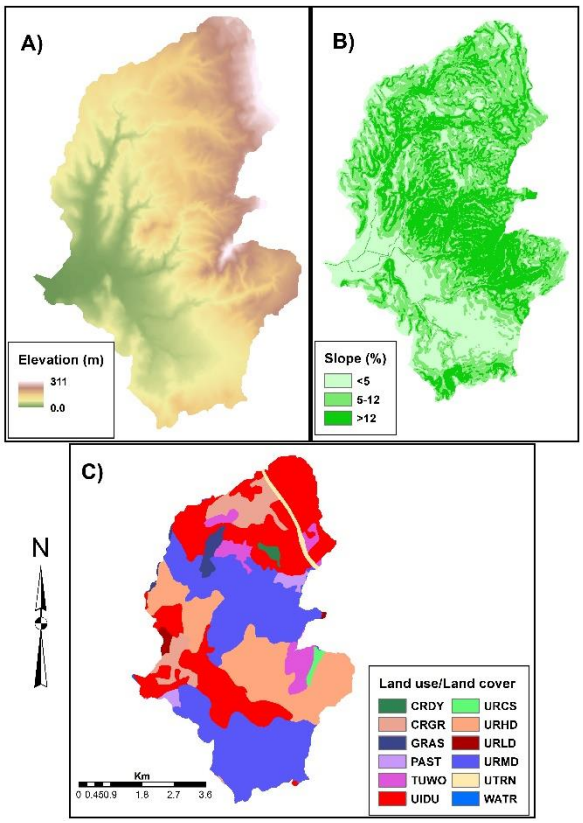

Figure 2. Map showing A) Digital elevation model, B) slope ranges, and C) Land use/land cover classifications (CRDY, dryland cropland and pasture; CRGR, cropland/grassland mosaic; GRAS, grassland; PAST, pastures; TUWO, wooded tundra; UIDU, industrial; URCS, construction sites; URHD-URMD-URLD, residential high-medium-low density; UTRN, transportation; WATR, water)

SWAT requires daily values of weather as input data. These data are precipitation, maximum and minimum temperature, solar radiation, relative humidity and wind speed. To run SWAT one can either prepare a file that contains observed data, or use daily values obtained by any re-projection data such as NCEP, GLCC [20]. Meteorological data were obtained from weather stations of Turkish General Directorate of Meteorology (TMMS), located in the catchment area. In addition, the meteorological data produced by the National Environmental Prediction Center (NCEP), which operates in connection with the National Oceanic and Atmospheric Office (NOAA) established to investigate the weather and sea events in the world, was used. TMMS data were utilized to create files for minimum and maximum daily precipitation and temperature. The rest of the meteorological parameters such as solar radiation, wind speed and relative humidity were simulated by using NCEP. The obtained dataset consists of a 4-year (2016 - 2020) period. In this data set, the first two years were used as a warm-up time in order to increase the performance of the model.

Hydrologic response unit (HRU), which is defined as the piece of land that gives the same response to weather data, was determined by SWAT, taking into account the sub-basins created and other land-based input data. In this study, the threshold value of 200 ha assigned by default was decreased to 30 and the number of sub bases was determined as 91. Neitsch et al. [20] stated that the number of sub-basins defined by the model is insufficient to examine the unique features produced in the dataset. Thus, the number of sub-basins was increased to 91 by decreasing the threshold value to 30 ha.

Since the modeling period is determined according to the time interval of meteorological input data, the authors chose the period between 1 January 2016 and 31 December 2019 in this study. Also, the flowrate values measured by Kocaeli Water Works between 2017 and 2019 were used to compare observed and predicted flowrates

3. RESULTS

3.1. Preparation of Soil Map

In the study area, 29 soil sampling points considering the main soil group and slope/depth combinations derived from Turkey National Soil Maps were identified to simulate the whole catchment area (Figure 3).

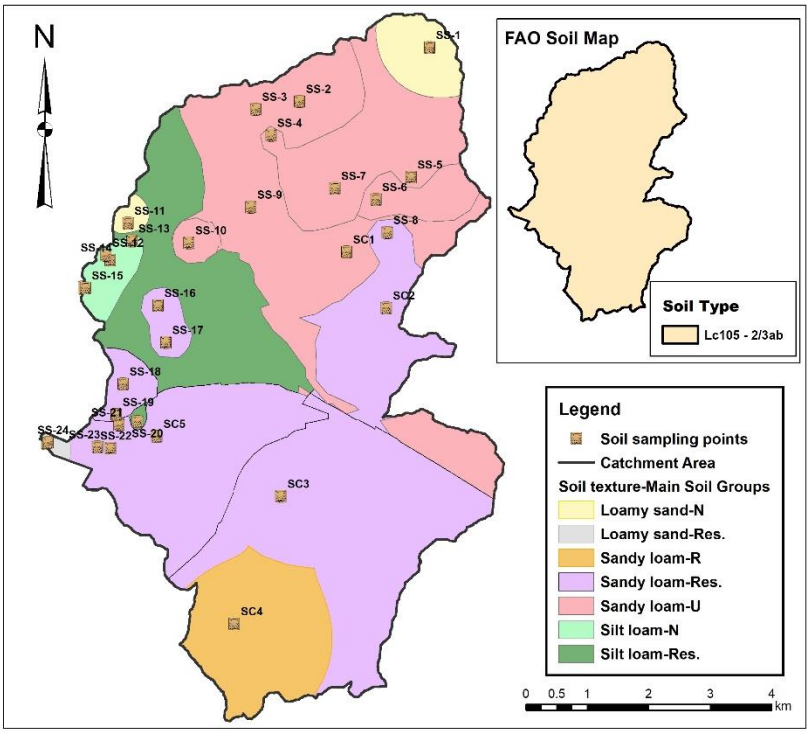

Figure 3. Soil sampling points.

All the physicochemical properties of the soil required for the SWAT model are available in the FAO soil database in appropriate format. Firstly, FAO map was used to observe the effect of soil properties on

streamflow. The dominant soil type of the studied area is classified as Chromic Luvisols according to FAO [21] with medium to fine texture (sandy-loam), undulating to rolling, and reddish to brown color (Figure 3). Secondly, the effect of the soil database, which was created by laboratory analysis / field observations and has more heterogeneity than the FAO, on the surface flow of the basin was investigated. To identify the characteristics of basin soil categories, representative stations for each soil category was determined as given in Figure 3.

Fraction of porosity from which anions are excluded and maximum crack volume parameters were not specified for the studied watershed. Default value (0.5) was used for the two parameters. Hydrologic group values were determined by considering the combination of main soil group and slope values derived from Turkey General Directorate of Rural Services (TNSD) legend. Dominant hydrologic groups of the watershed are C (Minimum infiltration rate: 0.8 - 3 mm / hr). One of the main differences between the FAO and the specified soil database is the hydrological group. While the dominant group was D (Minimum infiltration rate: 0 - 0.8 mm / hr) in the FAO database, dominant group was accepted C (Minimum infiltration rate: 0.8 -

3 mm / hr) in the TNSD. As a result of the laboratory studies 3 types of soil textures were determined; sandy loam, silt loam and loamy sand, while the soil texture of the watershed was determined as clay loam in FAO soil database. Saturated hydraulic conductivity, available water content and albedo parameters were determined according to soil texture ([15], [19]).

Soil profile depth (mm), erodibility factor, organic carbon (%) and clay (%) content values of the sampling points in the study area were classified using the Inverse Distance Weighted interpolation technique (IDW), which shows the distribution optimally in the ArcGIS 10.4.1 (Figure 4). The maximum profile depth (900 mm) was observed in the northeast part of the watershed when the minimum soil profile depth has lowest value (250 mm) in the residential areas. The erodibility factor represents not only the susceptibility of the soil to erosion but also the runoff. The erodibility factor varies between 0.23 and 0.53 throughout the watershed. High erodibility factor was calculated in the Çayırova sub-basin comparing to Saz sub-basin. The organic carbon content of the watershed is relatively low. While high carbon content appears in the south parts of the Saz sub-basin (1.91 - 4.26%), organic carbon contents of the remaining areas are generally varied between 0.3 - 1.1%. Clay content of the catchment area was varied 8.7% and 1.12%. Lower clay content is observed at higher elevations, while the southern part of the basin has a relatively higher clay content. In addition, the soil texture within the catchment area is rich in terms of sand and silt content.

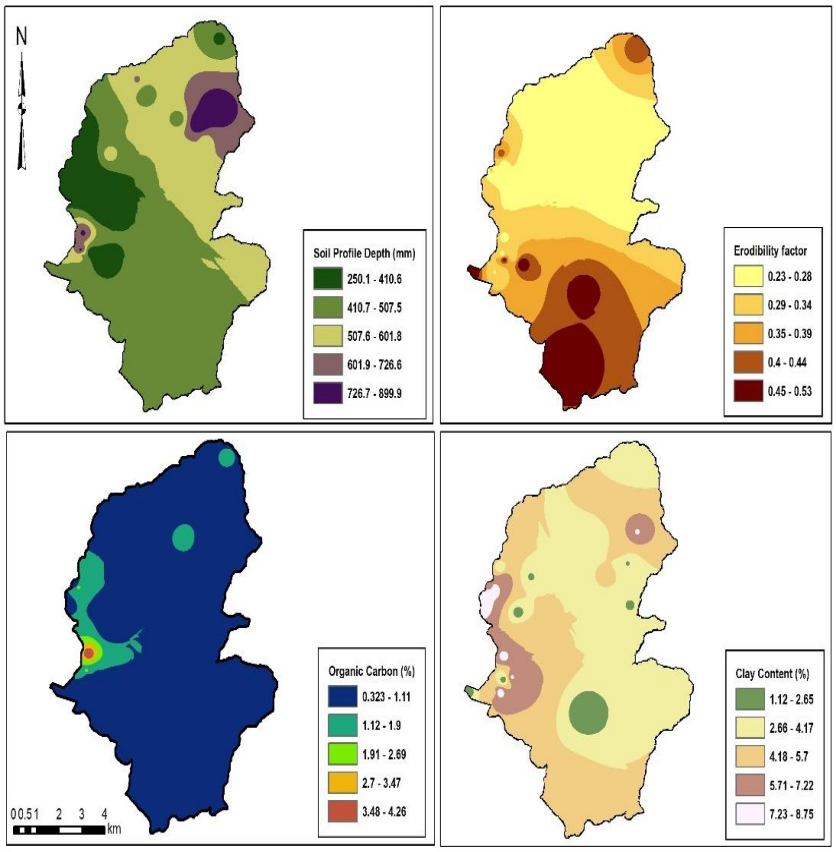

Figure 4. Spatial distribution of soil properties in the Saz-Çayırova catchment.

Specified soil database by help of laboratory analysis and field studies is shown in Table 2. Soil profile depth and maximum rooting depth (mm) are selected equal. The depth values in the specified soil database were found almost half of the values given in FAO database. While soil texture (sand, silt and clay) values are almost evenly distributed in the FAO database, sand and silt content are formed about 78% of the specified soil database. Additionally, 5 time differences were observed in percent clay content values between the two soil database. These differences observed in depth and texture values can be explained by the fact that the FAO database accepts average values for the whole of the Marmara Basin.

Table 1. Summarized results of specified soil database and FAO database for required parameters in SWAT

Sampling ID	Specified Soil Database (SSM)		FAO Database
	Average	Min. - Max.	Value
Profile Depth - Maximum rooting depth (mm)	493	250-900	840
Bulk density (g/cm^3)	1.4	1.12 - 1.63	1.3
Organic Carbon (%)	1.1	0.32 - 4.28	1.2
Rock/ Gravel (%)	17.6	5.55 - 34.9	10
Sand (%)	43.3	17.9 - 75.5	31
Silt (%)	34.1	12.7-58.7	32
Clay (%)	5.1	1.1-8.7	27
USLE soil erodibility factor	0.29	0.23-0.53	0.25

3.2. Evaluation Model Performance without Applied Any Calibration Techniques

Model outputs were compared for both soil database sets without applying automatic or manual calibration processes. Examining uncalibrated model outputs is significant for evaluation the predictive performance of model because of fact that calibration processes mask differences which can occur as a result of soil data sets. In another respect, the uncalibrated model outputs represent the runoff estimation performance of used soil dataset, which is the required effort for calibration. In this study, surface runoff was better estimated by using specified soil database and require less effort for calibration processes (Figure 5).

Runoff values produced from two soil databases were overestimated the observation values. Generated runoff values considering the SSM was overestimated comparing to the runoff values produced using FAO database. In addition, generated runoff from two databases have similar trend. The determination coefficient (R^2) value of them was calculated 0.66. One possible explanation for this result is similar values for some parameters of two databases such as organic carbon content, soil erodibility factor.

In seasonal approach, the surface runoff was observed highest in winter season (especially January), lowest values were observed in summer season (especially July). In contrast, two episodes in terms of surface runoff were observed in May, 2018 and 2019. While Episode in 2018 can be explained by the industry and residential discharge over the watershed, episode in 2019 can be defined by average monthly precipitation (142 mm). Relationship between observation or predicted surface runoff and precipitation has high variation. This relationship is independent from each other especially in the autumn season, while they have similar trend during the winter months. While the R^2 value between precipitation and observation runoff is 0.26, it is approximately 0.11 between the predicted runoff values and precipitation. The main reason for the low determination coefficient values can be explained that studied watershed is dominated by industry and residential areas (about 73%).

Model results obtained using two different soil database were compared to observed values, without applying any calibration techniques (Figure 6). The proximity of the scattered points to the 1: 1 ($y = x$) line shows the predictive performance of the model. Low runoff values were observed relatively closer to the trend line than higher runoff values for both soil databases. Also, high runoff effects the surface flow conditions and low runoff effects the base flows because of increasing infiltration period. In this context, the observed relatively good results for low runoff conditions indicates that the model prediction performance at the baseline flow better than the high runoff conditions.

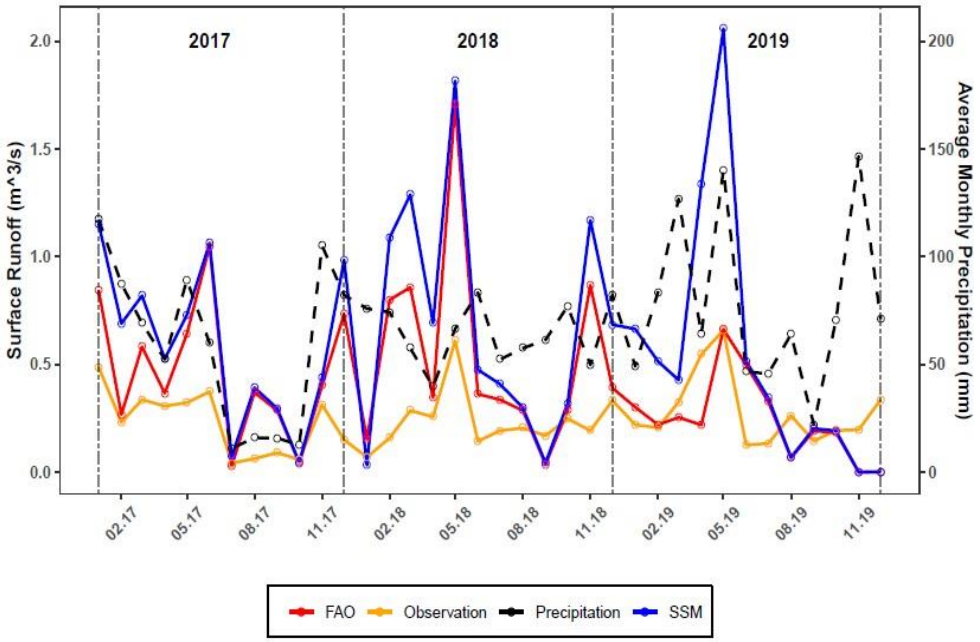

Figure 5. Average monthly time series of observed streamflow and predicted runoff that produced from FAO and Specified Soil Database (SSM)

Determination coefficient (R^2), Nash-Sutcliffe coefficient of efficiency and Root Mean Square Error (RMSE) values were used to evaluate the quality of model results without applied any calibration techniques. Motovilov et al. [22] stated that if the NSE value produced after calibration was between 1 and 0.75, the flow estimate was excellent and the NSE value between 0.75 and 0.36 was acceptable. The NSE value calculated as 0.19 and 0.48 for FAO and SSM, respectively. In this respect, while the SSM database was making acceptable estimates even before calibration, the found NSE values between the runoff values produced using the FAO database and the observation data remained below the acceptable threshold value (0.36). The RMSE value close to zero indicates that the error values between the observation and estimated data are low. RMSE values are 0.34 and 0.25, for FAO and SSM respectively. Additionally, it has been observed that the runoff values estimated from both soil databases have a significant relationship with the observation data, but the outlier values affect the determination coefficient value as they directly affect the model performance.

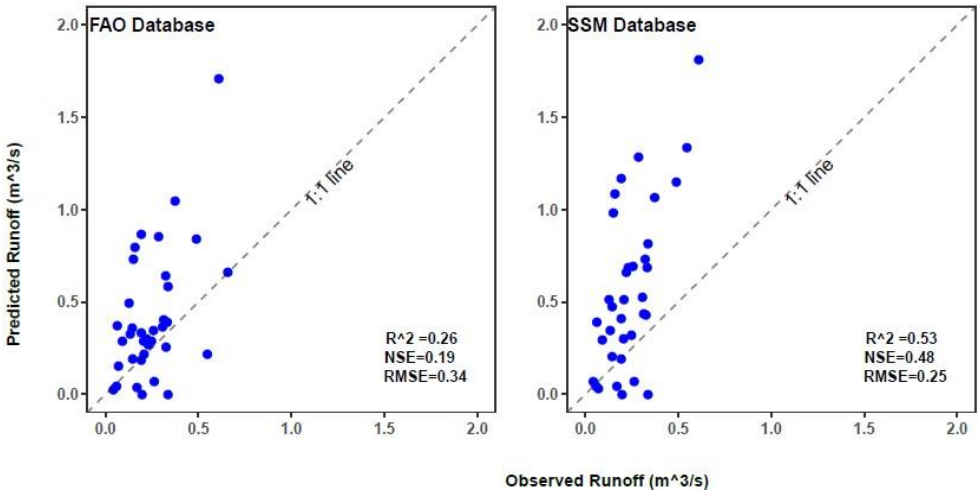

Figure 6. Scatter plot of monthly average observed and predicted runoff for specified soil database (SSM) and FAO.

4. CONCLUSION

In this study, 29 soil samples were collected, representing the whole of Saz-Çayırova Stream, and digital soil map was created by considering required soil parameters of SWAT with field observation and laboratory analyzes. Soil texture of the watershed was dominated by sand and silt content, while the clay content was found to be lowest throughout watershed. However, high clay contents were observed in Gebze Technical University Campus, which forms the delta of the Saz-Çayırova stream. The reason for this result is that stream energy decreases, thereby increasing the tendency of suspended solids to precipitate. The SSM map was created using the data obtained and the results were compared with the data of FAO. The most noticeable difference among these parameters is the clay and sand content that changes soil texture and directly affects stream flows. Main reason of the differences is that FAO has only one soil type (Lc-105-2/3ab) for the entire Marmara basin.

Stream flow was predicted and compared for the watershed by using specified soil database and FAO soil database. The comparisons were made without calibration in order to observe the differences when all variables such as land use/land cover, slope are the same but only soil datasets are different. The predicted runoff values using the two soil databases were observed higher than the observation values. Study conducted by Mengistu et al. [5] was compared STATSGO and SSURGO soil database which are default datasets in SWAT model and stated that the model results are overestimated for both soil databases. The reason for this situation was explained by the infiltration into the soil can be diverted by bedrock to the stream because of proximity of bedrock to the surface. This explanation also true this study's result.

NSE value calculated between the predicted dataset produced using SSM and observation runoff was in acceptable range, while this value was below the threshold value (0.36) for FAO dataset. Generally, NSE values were found high, about 0.6, relative to this study in runoff prediction studies using STATSGO and SSURGO soil databases without calibration ([23], [5], [7]). This is because STATSGO and SSURGO soil databases are highly detailed databases embedded in the SWAT model. In addition, the runoff values used for comparison in these studies are based on a longer measurement period.

In the light of this information, the obtained NSE value (0.48) using SSM database in this study was considered as a good predict without calibration processes. It is concluded that better results can be obtained in future studies by comparing the results with long-term measured flow rates.

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