Trend analysis of soil wetness index derived from optical satellite data

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ABSTRACT:

Due to the importance of soil moisture for plants growth and in the biology interactions, it is considered as a key factor in agriculture sector. In this research, to evaluate the trend of soil moisture changes, a Soil Wetness Index was derived from reflective and thermal bands of MODIS data. For this purpose, 8-day-products of land surface reflectance and land surface temperature over Esfahan in the period of 2000-01(dry) and 2004-05 (wet) were used. The trend of soil moisture changes was evaluated using statistical methods such as Mann-Kendall and Linear regression. The results derived from Mann-Kendall and Linear regression methods indicated that pixels without considerable changes cover a large portion of areas in the both dry and wet periods (67 and 41 % respectively). However a declination of 26 % has occurred in number of these pixels from dry to wet years. Instead number of pixels with negative amount of trend increased from 23% in the dry year to 53% in the wet period. The number of pixels with positive amount of trend was almost constant during the both periods. These pixels are limited only in the low eastern parts, Zayande roud river side and Gawkhoni swamp. High percent of area with negative trend in the wet year is due to moisture availability and high atmosphere demand.

1. Introduction

Moisture content generally assigned to the water content in the upper 1-2 m of soil profile. This moisture is generally available for crop growth and can be transported to the atmosphere through evapo-transpiration process (Verstraeten, 2006). Due to the importance of soil moisture for crop development and biological process, it is considered as a key factor in the agricultural sector. Soil moisture monitoring using point and laboratory methods is expensive, time consuming and impossible in the vast practical application. In addition, use of point methods for moisture measurements and interpolation of these data using geo-statistical methods to the regional scale has no adequate quality due to high uncertainty. Therefore, there is need for special tools which able us to spatially and temporally monitor soil moisture changes in the large areas. In contrast to point measurements and simulation models, methods based on remote sensing technique are preferred in the regional scale studies due to high spatial and temporal resolution, accessibility and acceptable accuracy. Over the past two decades, numerous remote sensing based method such as ground based, air born and space born have been implemented for soil moisture derivation, using reflective (Peters et al., 1991;Wang et al., 2007), thermal infrared , passive and active microwave (Mattia et al., 2008 ; Moran et al., 2004) and radio electromagnetic radiation (Scheftic et al., 2008). Remote sensing methods based on optical and thermal imagery has more limitations in comparison to radar and microwave imagery. These limitations consist of low surface penetration, high scatter in interaction with aerosols, water vapor and surface vegetation covers. However, high potential capacity, high spatial and temporal resolution, high correlation between soil moisture and surface temperature has raised the implementation of methods based on optical and thermal imagery (Verstraeten, 2006).

Plants are sensitive to water stress and amount of stress can be detected using vegetation indices derived from satellite data (Marshall, 2005). Vegetation indices derived from spectral analysis are the most common techniques for estimation of crop physical characteristic such as moisture content in the leaves and pigment concentration (Cheng et al., 2008; Ustin et al., 2004; Peñuelas et al., 1997; Huete et al., 1997; Gao, 1996). For instance, NDVI (Normalized Difference Vegetation Index) is one of the famous vegetation indices which show a high correlation with short term variation of soil moisture especially in semi-arid regions (Wang et al., 2007; Peters et al., 1991). NDVI is an alternative measure of vegetation amount and condition that obtained by combination of channel one (~660 nm) and two (~860 nm), visible and near infrared respectively of MODIS data. Adegoke and Carleton (2002), and Wang et al. (2007) studied direct relation between soil moisture and NDVI, and confirmed delay effect of soil moisture on NDVI. Wang et al. (2007) indicated also relationship between NDVI and soil moisture is more reliable with less delay in the semi-arid regions.

Land surface temperature (LST) depends on soil moisture and fractional vegetation cover. However, no universal and direct relation between LST and soil moisture has been reported yet (Mallick et al., 2009). In many studies, the physical relationship between vegetation index (NDVI) and LST in the form of scatter plot has been demonstrated (Stisen et al, 2008; Wang et al., 2006). However, in the arid region, due to increase of land surface temperature over area with low NDVI a negative relation between LST and NDVI is expected.

Although many studies have reached to the promising results, but due to the environmental factors, atmospheric effects, satellite noises and mixed pixels, uncertainties in estimation of absolute soil moisture from satellite data is still high. Instead, evaluation of short and long term soil moisture trends is more reliable for the environmental applications. Parametric and non parametric statistical tests can be implemented on soil moisture time series to monitor the trend of its changes pixels by pixel. For practical application of this theory, we can refer to Robock et al., (2005). They used the 10-day-soil moisture data set from 141 agricultural stations collected during 1958 to 2002 in Ukraine and indicated an overall upward trend due to greenhouse effect. Upward trend of soil moisture can be caused by upward trend of rainfall (Vinnikov et al., 1991).

In this research, to evaluate the trend of soil moisture changes, a Soil Wetness Index (SWI) was derived from reflective and thermal satellite data using a triangular variant of trapezoidal concept. For this purpose, 8-day-products of land surface reflectance (MOD09Q1) and temperature (MOD11A2) were received from MODIS satellite data over Esfahan in the period of 2000-01(dry) and 2004-05 (wet). Thereafter, the trend of soil moisture was evaluated using statistical methods: Mann-Kendall and Linear regression.

2. Material and methods

2.1 Study area

The study area, Isfahan province, is located in the central parts of Iran with 214503 km2. It covers an area from 30.6 N to 34.58 N and from 49.6 E to 55.5 E. The area has a semi-arid climate with a limited amount of precipitation (130 mm per year which generally occurs in winter from December to April. The cultivated area (609250 ha) contains 6 percent of total area from which 95% assigned to the irrigated lands and 5% assigned to rain-fed lands. Maximum temperature reaches to 30 oC in July and minimum temperature falls to 3 oC in January.

2.2 Data preparation and image processing

Optical-thermal infrared band data from moderate resolution (250 m to 1km) sensors (e.g. MODIS Terra and AQUA) having two overpasses per day provide a unique opportunity to monitor frequently short term variation of soil moisture in vegetated areas with greater details (Mallick et al., 2009). Therefore, in this study MODIS products of adjusted surface reflectance (Mod09Q1) in bands of visible and near infrared with 250 meter spatial resolution and LST product (Mod11A2) with 1 km spatial resolution were implemented. These data were ordered for the period of Sep 2000 to Jul 2001 and Sep 2004 to Jul 2005 over Isfahan (tile h22v05) from WIST gateway. NDVI was obtained by combination of channel one (~660 nm) and two (~860 nm), visible and near infrared respectively of MODIS data. LST data was decoded using scale and offset factors derived from file header. The data was geometrically corrected and its projection system was converted from Sinusoidal to UTM. To overlay the LST data on the NDVI maps, the images was resembled into 250 spatial resolutions using nearest neighbourhood method. The operations of image processing were performed using an automatic program developed in MATLAB. Table 1 shows the characteristic of satellite data implemented in this study.

Satellite	Sensor	Spatial resolution (m)	Temporal resolution (day)	Selected products	Acquisition dates
Terra	MODIS	250 1000 Resampled to 250 m	8 8	MOD09Q1 , MOD11A2	2000-2001 From Sep to Jul And 2004-2005 From Sep to Jul

Table 1. Characteristic of satellite data used for computing Soil Wetness Index

2.3 Soil Wetness Index (SWI)

To extract soil moisture, a triangular variant of trapezoidal concept between LST and NDVI data was implemented. As shown in figure 1, the highest LST along the dry edge represents the driest soil condition when soil wetness is near zero. The wettest (near saturated) soil conditions are represented through the minimum LST along the wet edge when surface soil wetness is the highest. It is assumed that moisture availability varies linearly from the dry edge to the wet edge.

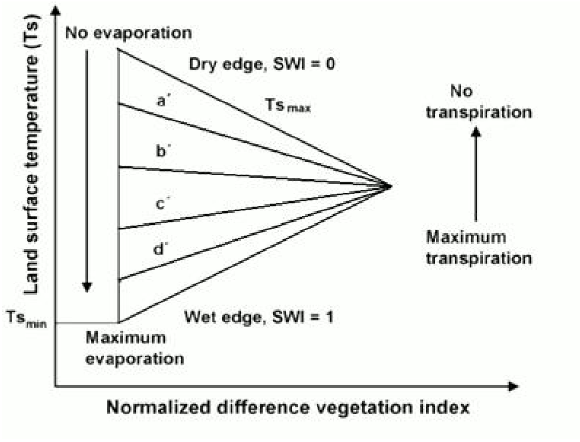


Figure 1. Conceptual diagram of triangular variant of trapezoidal concept for Soil Wetness Index. Zero indicates Soil Wetness Index along the dry edge and 1 show Soil Wetness Index along the wet edge

With this assumption, Soil Wetness Index (SWI) can be computed for each pixel as:

$$SWI_i = \frac{T_{max(i)} - T_{s(i)}}{T_{max(i)} - T_{min(i)}} \qquad (1)$$

Where i indicate pixel number, Ts(i) is the LST for ith pixel, Tmin(i) and Tmax(i) are minimum and maximum values of observed LST for ith NDVI. Tmin and Tmax can be derived using linear relations between NDVI and LST on the dry and wet edges as below:

$$T_{max(i)} = b + a\left(NDVI_{(i)}\right) \qquad (2)$$

$$T_{min(i)} = d + c\left(NDVI_{(i)}\right) \qquad (3)$$

Where a, b, c and d are slope and offset values of diagonal lines on the dry and wet edges respectively.

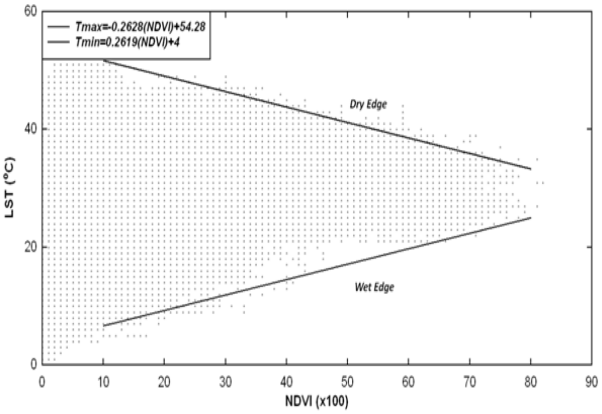


Figure 2. A sample of triangular variant between Land Surface Temperature and Normalized Difference Vegetation Index over Isfahan on a clear day (DOY 105: 15 Apr 2005).

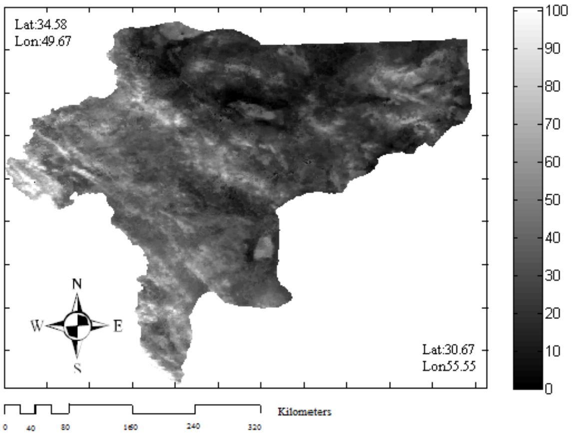


Figure 3. A sample of spatial distribution of Soil Wetness Index over Isfahan on a clear day (DOY 81: 22 May 2001)

To see the validation of results derived from SWI, the correlation of cumulated SWI with cumulated rainfall in end of both dry and wet periods were analyzed (Figure 4 a and b). As we expected the cumulated rainfall and SWI were highly matched to each other (R2 = 0.8) which confirm the effect of rainfall on SWI. However, in the dry period, correlations reach to only 50 percent. This shows that in the dry period, radiation and temperature affects the soil water contents more than rainfall.

Figure 4a-Comparison of cumulated rainfall and SWI in 2004-05

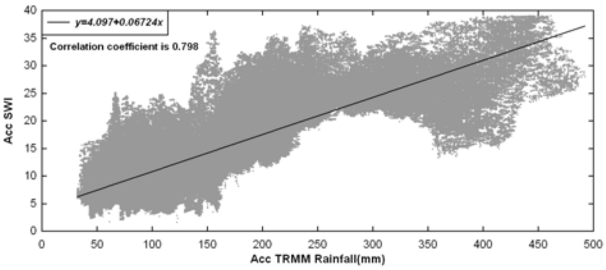
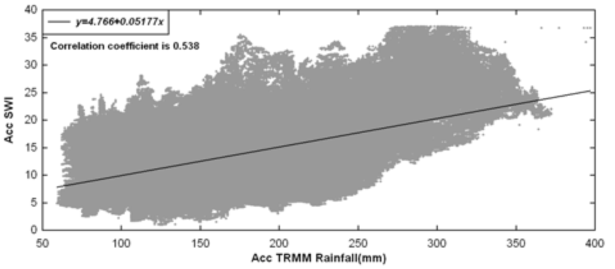


Figure 4a-Comparison of cumulated rainfall and SWI in 2001-02



2.4 Trend analysis of soil moisture changes

Trend of soil moisture changes in dry and wet periods was evaluated using two well-known statistical methods: Linear regression and Mann-Kendall. However, the study mainly relied on the linear regression method and other method was just used for comparison.

2.4.1 Linear regression

Linear regression is a common method for trend analysis of climatic parameters (e.g,. Chattopadhyay and Hulme, 1997). However, linear regression depends on existence of normal data series. Therefore, a K.S normal test was first applied to the soil moisture data series to see whether the data are normal or not. This test removed each time step, whenever it did not follow the normality (Pajand, 2000).

In linear regression, a regression line separates the differences between independent (time; Y) and dependent (moisture; X) variables. Intercept and line slope can be calculated through error minimization. Afterwards t statistics is computed using slope of the regression line (b) and standard deviation of the data Sb as follow:

$$S_b^2 = \frac{\left(\frac{\sum(x-x_i)^2}{n-2}\right)}{\sum(Y-Y_i)^2} \quad , \quad t = \frac{b}{Sb} \qquad (4)$$

Whenever | t | > t1-α,n-2 from the t-student table (n is sample size and α is level of significant) the slope of the trend line is significantly different from zero and a trend is observed (Ghahraman, 2006).

2.4.2 Mann-Kendall test

The Mann-Kendall test is a non-parametric test for identifying the trends in time series data. The test compares the relative magnitudes of sample data rather than the data values themselves (Gilbert, 1987). The Mann-Kendall statistic (t) is given by:

$$t = \sum_{i=1}^{n-1} \sum_{k=i+1}^{n} sign(x_k - x_i) \qquad (5)$$

Where, x represents the soil moisture data set e.g. x1, x2, x3,…,xn and function of sign is defined as:

$$sign(x_k - x_i) = \begin{cases} 1 & if\ (x_k - x_i) > 0 \\ 0 & if\ (x_k - x_i) = 0 \\ -1 & if\ (x_k - x_i) < 0 \end{cases} \quad (6)$$

High positive value of t indicates upward trend, and low negative value of t shows a downward trend has occurred.

To statistically quantify the significance of trend intensity, it is necessary to compute the probability associated with a normalized test statistic Z as follows:

$$Z = \begin{cases} \frac{t-1}{\sqrt{Var(t)}} & t > 0 \\ 0 & t = 0 \\ \frac{t+1}{\sqrt{Var(t)}} & t > 0 \end{cases} \quad (7)$$

Where:

$$Var(t) = {}^{1}/_{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p(t_p-1)(2t_p+5)\right] \quad (8)$$

where n is the number of data time series , q is the number of tied groups (a tied group is a set of sample data having the same value), and tp is the number of data time series in the pth group.

As result, the trend is downward (or upward) when the absolute computed Z is greater than 1.96 (for 95 % level of significance) and Z is negative (positive), and finally there is no trend when the absolute computed Z is less than 1.96.

3. Results and discussion

SWI values in 8-day steps were derived from satellite data by triangular variant between LST and NDVI maps (figure 2) using an automatic program written in MATLAB. In figure 3, spatial distribution of SWI values are shown as an example. Global mean of SWI values over Isfahan province in the 8-day-steps has been also shown in figure 5. This figure compares the variation of SWI in the period of 2000-01 (dry) and 2004-05(wet). The horizontal axis indicates day number in Julian which starts from 273th day in 2000(or 2004) and ends to 209th day in 2001(or 2005).

The variation of SWI in the dry and wet periods was compared using Duncan test. For this purpose, each time step was considered as one block and each period (dry or wet) was defined as one variety. The results indicated that the differences between global means are significant (at 0.05 level of significance). This confirm that amount of soil moisture in the period 2004-05 vary considerably from its values in the period of 2000-01 (figure 5, table 2).

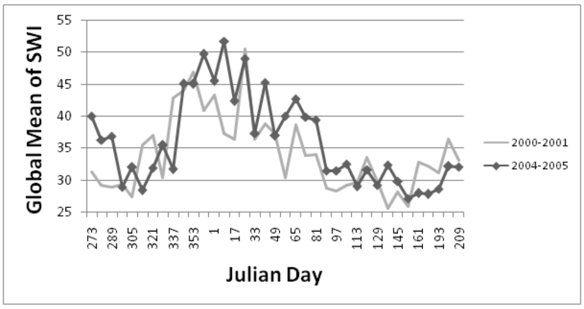


Figure 5. Global mean of Soil Wetness Index of Isfahan province in the periods of 2000-01(Dry) and 2004-05(Wet).

Table 2. Comparison of global mean of Soil Wetness Index in the period of 2000-01 and 2004-05 over study area (positive sign indicates existence of a significant difference) using Duncan method

Parameter	***LEVEL***		***Mean***		***Error Freedom Degree***	***CV***
	0.05	***0.01***	***2000-01***	***2004-05***		
Global SWI	+	-	0.34	0.36	36	10.6

To evaluate the trend of soil moisture variations in the dry and wet years, statistical methods of Mann-Kendall and linear regression was performed on the SWI dataset. Spatial distribution of trends in the periods of 2000-01 (dry) and 2004-05 (wet) has been shown in the figures of 6 and 7 respectively. These figures map the spatial distribution of trends in three classes of upward, downward and without trend.

To investigate the correspondence of two methods, the resulted trend maps were crossed to each other and spatially comparison was performed pixel by pixel. The results indicated that Mann-Kendall and Linear regression presents a strong agreement (91.2 %) and shows more or less the same pattern of trend distribution (Figure 6 and 7). Therefore, both methods are recommended for routing of soil moisture trend in this area.

As shown in the figures 6 and 7, a large portion of lands do not show any sensible trend in the both periods. The areas without trend in 2000-01 cover the whole part of province except the highlands in North West parts. However, in 2004-05, these areas are limited to the only low dry lands in the East parts. It may be due to the low available soil moisture caused by precipitation shortage in this region. The rest of region had a downward trend except small sparse areas in the low eastern parts, Zayande roud river beaches and Gawkhoni swamp which had an upward trend probably due to irrigation. As mentioned in the Table 3, number of pixels with downward trend has increased from 23% in the period of 2000-01 to 53% in the period of 2004-05. The number of pixels with upward trend was almost constant during the both periods. Instead, number of pixels without considerable trend showed a declination from 67 to 41 percent from period of 2000-01 to 2004-05 respectively.

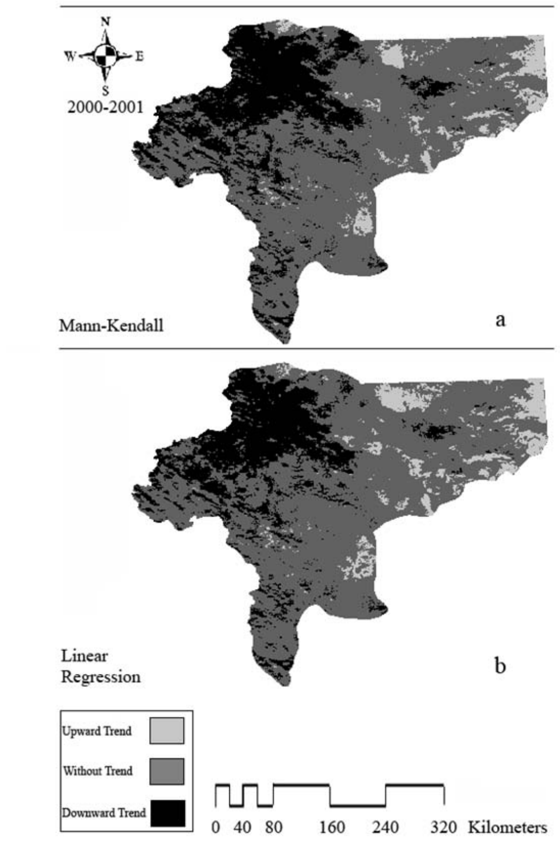


Figure 6. Spatial distribution of soil moisture trend in the wet period (2000-01) retrieved by applying Mann-Kendall(a) and linear regression (b) methods to the SWI data set.

Contrary to initial thought, less number of points with downward trend in the dry year was observed. This event can be described by long period of rainfall shortage and in result very low moisture in the root zone which caused to a generally insignificant trend. So with long term lack of precipitation, soil moisture is reached to the residual value and there is no moisture to be lost. While in the wet period, there is consistently enough moisture available for evaporation. Although, global mean of soil moisture in the wet period is significantly higher than dry period (figure 4, table2), but wider areas shows downward trend in this period.

In Figures of 8 and 9, the spatial distribution of regression line slope with their histogram for the both periods has been shown. The regression line slope in the linear regression method indicates the intensity of trend (upward or downward) for each pixel. As shown in these figures, the range of trend intensity varies from -1.45 to 0.9 (median =0) in 2000-01 and from -1.88 to 1.45 (median = -0.3) in 2004-05. Spatial distribution and histogram of slope values, and amplitude changes indicate that in country to the dry year, in the period of 2004-05 both the extent and intensity of downward trend has increased.

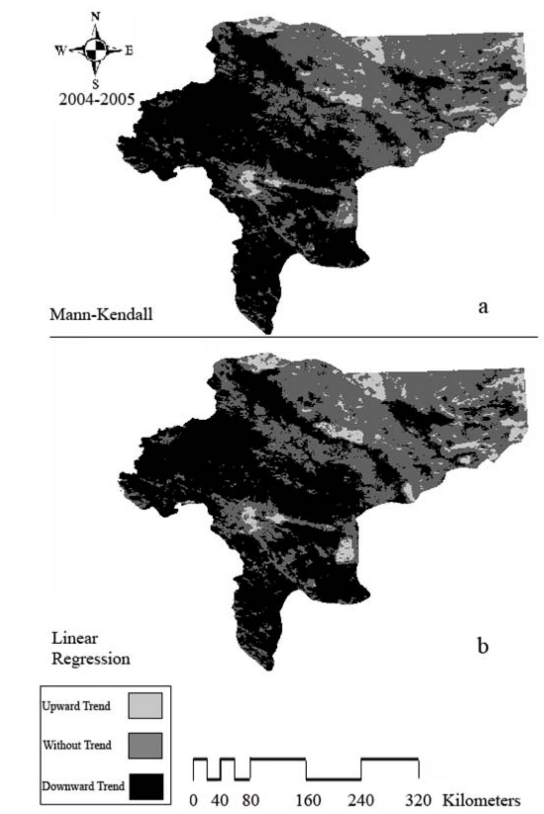


Figure 7. Spatial distribution of soil moisture trend in the wet period (2004-05) retrieved by applying Mann-Kendall(a) and linear regression (b) methods to the SWI data set.

Table 3. Trend analysis of soil moisture changes using Mann-Kendall and Regression methods at 5% level for dry (2000-01) and wet (2004-5) periods

Method	Upward Trend (%)	Downward Trend (%)	No-Trend (%)
2000-2001			
Mann-Kendall	**6.2**	**26.7**	**67.1**
Linear regression	**7.1**	**23.2**	**69.7**
2004-2005			
Mann-Kendall	**5.1**	**53.5**	**41.4**
Linear regression	**5.7**	**53.5**	**40.8**

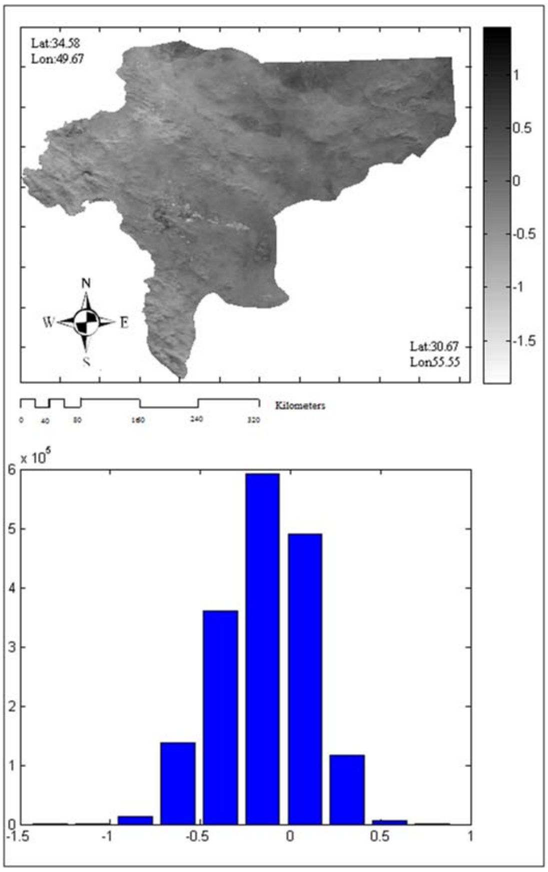


Figure 8. Spatial distribution of slope of regression line with its histogram over the Isfahan in the period of 2000-01.

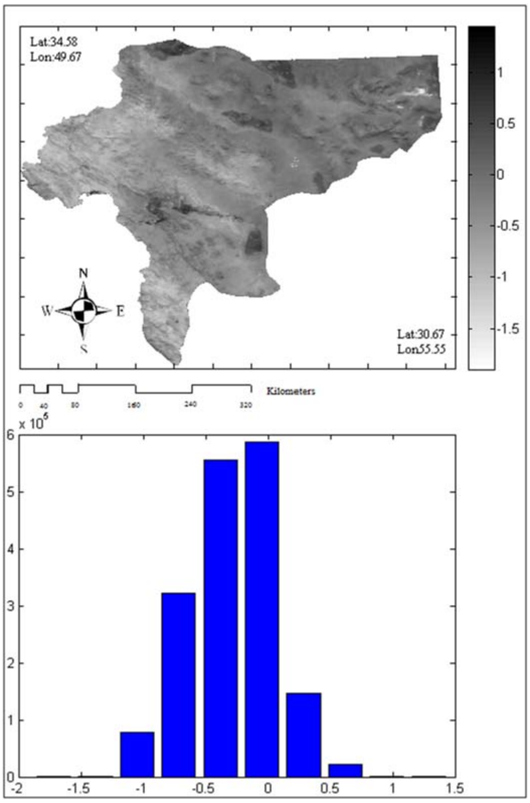


Figure 9. Spatial distribution of slope of regression line with its histogram over the Isfahan in the period of 2004-05.

4. **Conclusion**

Triangular distribution of LST (land surface temperature) and NDVI (normalized difference vegetation index) were mapped to retrieve the time series of SWI (Soil Wetness Index). Then the trend of soil moisture changes was evaluated using statistical methods of Mann-Kendall, linear regression at 5% level of significant. Review of trends showed that more than 40 percent of the areas have no significant trend and changes in SWI values don't follow a specific pattern in this area. In the dry period, an increase of 53 percent was observed for the number of pixels with a downward trend. Number of pixels with downward trend was limited to 24 percent in the dry period. The pixels with downward trend are geographically located in the western and central areas mainly. The Pixels with upward trend are limited to only small parts of eastern low areas around the Zayande Roud River and marshes Gavkhoni. High percent of area with negative trend in the wet year is due to moisture availability and high atmosphere demand.

Finally, for the regions like Iran with lack of historical soil moisture record, retrieval of soil moisture from satellite data and analysis of its trend is a valuable alternative approach instead of direct sampling of soil moisture. It is also recommended to study the trend of soil moisture changes using long term data set.

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