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Diagnostic Analysis of Spatial and Temporal Variations in Crop Water Productivity: a Regional Scale Analysis of the Rain Fed Wheat

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Abstract

Water productivity is a suitable indicator in water potential analysis at a location in a region. In this study, changes in water use productivity are studied in spatial and temporal scale simultaneously. To evaluate temporal changes in water productivity in Hamadan region (Iran), Standard Precipitation Index (SPI) was analyzed and evaluated for drought, wet and normal conditions. To estimate regional water productivity, GIS and Kassam methods were coupled to estimate the Potential yield of rain-fed wheat in a developed rasterized grid network with 30×30 -km resolution. Results of this study indicate that the amount of water productivity in drought condition in comparison with the other two conditions was higher and from geographical point of view the southern parts of the region have higher potential production with compare to other locations of the province. The analysis shows the variation in amount of active radiation received by the earth surface is causing these differences.

Key words

SPI, Drought, Kassam method, water productivity.

Introduction

The world‘s population has increased from 2.5 billion to more than 6 billion during the last 50 years (Billib and et al. 2009).The population in Iran has increased with the same rate from 6 million in 1956 to about 65 million in the beginning of 2001 and it is expected with the implementation of all population control programs to reach to about 100 million in 2022 (Ehsani and Khaledi, 2003). Due to increasing population and consequently water consumption in current situation, the water requirement will increase to about 266 billion cubic meters in 2022. Hence, the water resources will not be adequate to fulfill the required volume (Jahani, 2001). In order to respond to increasing demand and achieve food security of the society a comprehensive study on agricultural planning is required to reach the maximum economic use in different climatic regions of Iran and promote water productivity from 0.7 to 1.8 (to 2) kg per cubic meter of water (Nazarifar and et al. 2007). Generally speaking, the term ‘water productivity’ refers to the magnitude of output or benefit resulting from the input quantum of water as applied on a unit base. In the domain of agriculture, it is expressed as the net consumptive use efficiency in terms of yield per unit depth of water consumed per unit area of cultivation (Kjine, and et al. 2003). Agricultural water productivity can be expressed either as a physical productivity in terms of the yield over unit quantity of water consumed (tonnes per ha.cm of water or kg yield per kg water consumed) in accordance with the scale of reference that includes or excludes the losses of water or an economic productivity replacing the yield term by the gross or net present value of the crop yield for the same water consumption (rupees per unit volume of water) (Molden Sakthivadivel, 1999).

One of the researches carried out on water use efficiency for various agricultural crops in regional scale is that of Heinemann et al. (2001) in Tybajy River Basin. They combined GIS methods with plant growths models. They showed that linking the crop growth simulation models to GIS can be an effective tool determining irrigation requirement and water productivity for river basin and large catchments. Amor et al. (2001) applied crop growth simulation models coupled with geographic information system to analyze water productivity in Laoag River Basin in the Philippine in spatial and temporal dimensions, for three crops: rice, corn and peanuts, in both existing and potential agricultural areas. The results showed that temporal and spatial analysis of water productivity could provide substantial information for water saving opportunities and, hence, strategies in irrigated Agriculture. Oweis and Hachum (2004) carried out researches for Improved Water Productivity of Dry Farming Systems in West Asia and North Africa. The results showed that substantial and sustainable improvements in water productivity can only be achieved through integrated farm resources management. On-farm water-productive techniques are coupled with improved irrigation management options, better crop selection and appropriate cultural practices, improved genetic make-up, and timely socioeconomic interventions will help to achieve this objective. Conventional water management guidelines should be revised to ensure maximum water productivity instead of land productivity. Ahmad et al. (2004) carried out diagnostic analysis of spatial and temporal variations in crop water productivity for a field scale analysis of the rice-wheat cropping system of Punjab, Pakistan. to sustain and/or enhance water productivity, the management of uncontrollable factors such as climatic variability along with the improvements in controllable factors such as agronomic and water management practices need careful planning and actions. The application of a comprehensive set of water balance and water productivity indicators for spatial and temporal analysis could help in performance evaluation of irrigated crops and devising strategies for improving food production and water productivity. Hussain et al. (2007) provided an overview of the issues and approaches on measuring and enhancing the value of agricultural water in large irrigated river basins. They developed a framework and a set of indicators for valuing agricultural water by looking into various dimensions and underlying key factors that influence the value of water at micro, meso and macro levels. In addition, the research compiles recent estimates of the value of agricultural water, and it outlines measures for enhancing the value of agricultural water. Singh et al. (2006b) focused on the identification of appropriate strategies to improve water management and productivity in the Sirsa district, India. The field scale eco-hydrological model SWAP, in combination with field experiments, remote sensing and GIS, has been used in a distributed manner generating the required hydrological and biophysical variables to evaluate alternative water management scenarios at different spatial and temporal scales. Improved crop husbandry in terms of improved crop varieties, timely sowing, better nutrient supply and more effective weed, pest and disease control, will increase crop yields and water productivity in this region. The scenario results further showed that reduction of seepage losses will improve significantly the long term water productivity, halt the rising and declining groundwater levels, and decrease the salinization in Sirsa district.

There are various methods to determine water productivity to estimate the actual yield which can identify the amount of actual yield for different regions. One of the most appropriate methods is that of Kassam which has been improved by the International Institute of Reclamations (Kassam, 1977) based on land and water relation. They have calibrated and tested the method using the measured data collected from field experiments. They have extracted a linear regression model to determine the dry biomass of crops: alfalfa, corn, sorghum and wheat and proposed mathematical relationships to convert the dry biomass into marketable product. But in the modified linear model while maintaining the previous assumptions another assumption for inclusion of maximum dry biomass in maximum evapotranspiration was introduced and by applying simple correction factors the marketable crop yield could be calculated.

The purpose of this research was to study the variations in water productivity in spatio-temporal scales. In order to analyze the temporal variation of water productivity standardized precipitation index (SPI) was used and with the development of coupled GIS and combining Kassam method the spatial and temporal variations in water productivity were investigated in the region.

Methods

Hamedan province lies between longitudes 48° 28′ 30″ and 49° 1′ E and latitudes 34° 36′ and 35° 9′ N and is shown in Figure 1. The area occupies about 944 km2, with a mean altitude of 1950 m.a.s.l. The climate of the study area is considered to be semi-arid, the annual average precipitation being approximately 300 mm, of which about 37% occurs during winter. Another feature characterizing the precipitation in the study site is its irregular yearly distribution. The mean air monthly temperature is highest during August (23.45 °C) and lowest during January (−1.91 °C) with an annual average of 10.88 °C. The annual potential evaporation far exceeds the annual rainfall (Figure 2) with a mean annual amount of approximately 1505 mm (1975–2001)

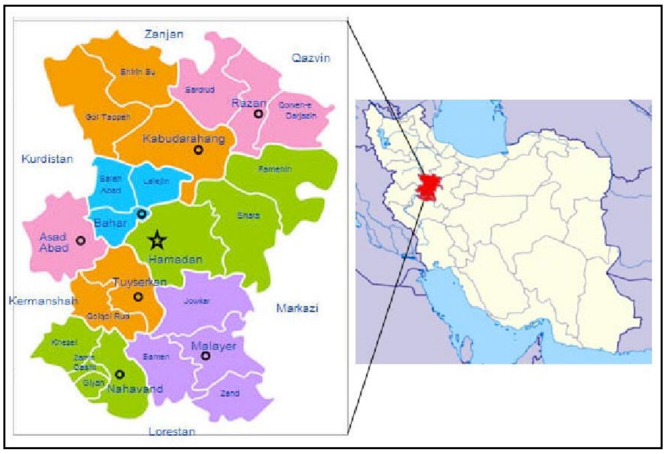

Figure 1: Location of study area.

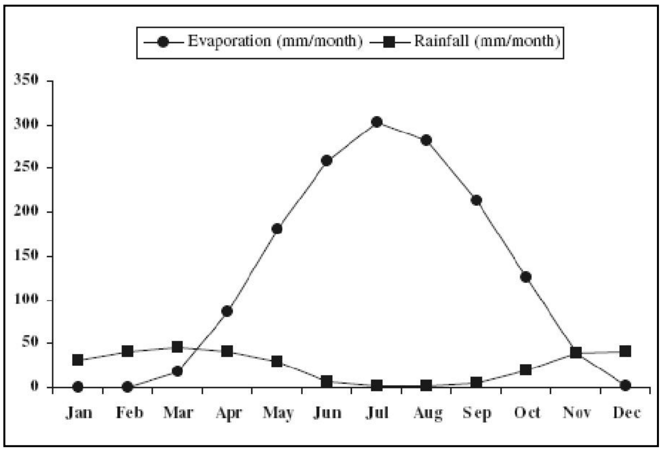

Figure 2: Monthly rainfall and evaporation in the study area.

(Zare abyaneh, 2004). The area has complicated land use characteristics, mainly consisting of agricultural and urban/residential areas. Groundwater has been used for various purposes, such as drinking, agricultural, domestic and industrial needs. The most important economic activity of the area is agriculture, the chief crops are garlic (Allium sativum), potato (Solanum tuberosum L.) and wheat (Triticum aestivum L.), with actual irrigation being lower than total theoretical demand, as there is a considerable deficit in relation to the amount of irrigated land.

The standardized precipitation index (SPI) was used for monitoring of drought, wet and normal conditions. In this study 29 years (1973-2002) precipitation data of 13 stations has been used. These stations are monitored by two separate organizations: Meteorological department and the Regional Water Company in Hamedan province. The data of seven additional adjacent meteorological stations were used as complementary data for further analysis. Annual precipitation homogeneity was confirmed through Run test.

For the reconstruction and completing the sequence of data the SPSS software was used for correlating the stations through regression analysis (Yazdani et al., 2005).

SPI was calculated for 12-month time scale. The results were analyzed to clarify the boundary conditions for “drought, wet, normal”.

To estimate regional water productivity in the region, GIS and Kassam method were coupled to estimate the Potential yield of rainfed wheat in a developed rasterized network with 30×30 -km resolutions in the region. This method, based on eco-physiological principles, is outlined below (Fischer and et al, 2001):

In order to calculate the net biomass production (B_n) of a crop, an estimation of the gross biomass production (B_g) and respiration loss (R) is required:

$$B_n = B_g - R \qquad (1)$$

The equation relating the rate of net biomass production (b_n) to the rate of gross biomass production (b_g) and the respiration rate (r) is:

$$b_n = b_g - r \quad (2)$$

The maximum rate of net biomass production (b_{nm}) is oteined when the crop fully covers the ground surface. The period of maximum net crop growth, i.e., the point in time when maximum net biomass increments occur, is indicated by the inflection point of the cumulative growth curve. When the first derivative of net biomass growth is plotted against time the resulting graph resembles a normal distribution curve. The model assumes that the average rate of net production (b_{na}) over the entire growth cycle is half the maximum growth rate, i.e., $b_{na} = 0.5b_{nm}$. The net biomass production for a crop of N days (B_n) is then:

$$B_n = 0.5b_{nm}xN \quad (3)$$

The maximum rate of gross biomass production (b_{gm}) is related to the maximum net rate of CO_2 exchange of leaves (P_m) which is dependent on temperature, the photosynthesis pathway of the crop, and the level of atmospheric CO_2 concentration.

For a standard crop, i.e., a crop in adaptability group I (FAO, 1978-81) with P_m = 20 kg ha -1 hr -1 and a leaf area index of LAI = 5, the rate of gross biomass production b_{gm} is calculated from the equation:

$$b_{gm} = Fxb_o + (1 - F)\, b_c \quad (4)$$

where:

F = the fraction of the daytime the sky is clouded, $F = (A_c - 0.5R_g) / (0.8A_c)$, where A_c (or PAR) is the maximum active incoming short-wave radiation on clear days (de Wit, 1965), and R_g is incoming short-wave radiation (both are measured in cal cm^{-2} day^{-1}).

b_o = gross dry matter production rate of a standard crop for a given location and time of the year on a completely overcast day, (kg ha^{-1} day^{-1}) (de Wit, 1965).

b_c = gross dry matter production rate of a standard crop for a given location and time of the year on a perfectly clear day, (kg ha^{-1} day^{-1}) (de Wit, 1965).

When P_m is greater than 20 kg ha^{-1} hr^{-1}, b^{gm} is given by the equation:

$$b_{gm}=F(0.8 + 0.01P_m)b_o + (1 - F)(0.5 +0.025\, P_m)b_c \quad (5)$$

When P m is less than 20 kg ha -1 hr -1 , b gm is calculated according to:

$$b_{gm} = F(0.5+0.025P_m)\, b_o + (1 - F)\, (0.05\, P_m)\, b_c \quad (6)$$

To calculate the maximum rate of net biomass production (b_{nm}), the maximum rate of gross biomass production (b_{gm}) and the rate of respiration are required. Here, growth respiration is considered a linear function of the rate of gross biomass production (McCree, 1974), and maintenance respiration a linear function of net biomass that has already been accumulated (B_m) When the rate of gross biomass production is b_{gm}, the respiration rate (r_m) is:

$$r_m = kb_{gm} + cB_m \quad (7)$$

where k and c are the proportionality constants for growth respiration and maintenance respiration respectively, and B_m is the net biomass accumulated at the time of maximum rate of net biomass production. For both legume and non-legume crops k equals 0.28. However, c is temperature dependent and differs for the two crop groups. At 30 °C, factor c_{30} for a legume crop equals 0.0283 and for a non-legume crop 0.0108. The temperature dependence of c_t for both crop groups is modeled with a quadratic function:

$$c_t = c_{30}\, (0.0044+0.0019T+0.0010T^2) \quad (8)$$

It is assumed that the cumulative net biomass B_m of the crop (i.e., biomass at the inflection point of the cumulative growth curve) equals half the net biomass that would be accumulated at the end of the crop‘s growth cycle. Therefore, we set $B_m = 0.5\, B_n$, and using (3), B_m for a crop of N days is determined according to:

$$B_m = 0.25b_{nm}xN \quad (9)$$

By combining the respiration equation with the equation for the rate of gross photosynthesis, the maximum rate of net biomass production (b_{nm}) or the rate of net dry matter production at full cover for a crop of N days becomes:

$$b_{nm} = 0.72b_{gm}/(1 + 0.25\, c_tN) \quad (10)$$

Finally, the net biomass production (B_n) for a crop of N days, where $0.5b_{nm}$ is the seasonal average rate of net biomass production, can be derived as:

$$B_n = (0.36b_{gm}xL)/(1/N + 0.25c_t) \quad (11)$$

where:

b_{gm} = maximum rate of gross biomass production at leaf area index (LAI) of 5

L = growth ratio, equal to the ratio of b_{gm} at actual LAI to b_{gm} at LAI of 5

N = length of normal growth cycle

c_t = maintenance respiration, dependent on both crop and temperature according to equation (8)

Potential yield (Y_p) is estimated from net biomass (B_n) using the equation:

$$Y_p = H_i x B_n \qquad (12)$$

where:

H_i =harvest index, i.e., proportion of the net biomass of a crop that is economically useful.

Thus, climate and crop characteristics that apply in the computation of net biomass and yield are: (a) heat and radiation regime over the crop cycle, (b) crop adaptability group to determine applicable rate of photosynthesis P_m, (c) length of growth cycle (from emergence to physiological maturity), (d) length of yield formation period,.(e) leaf area index at maximum growth rate, and (f) harvest index.

Biologically crops consume water for evapotranspiration (ET), and the rest of supplied water does not participate in the yield formation. In order to assess the productivity of ET, the following formula (13) is used (Abdullaev et al,2003):

$$Wp = \frac{Crop\,Yield}{ET} \qquad (13)$$

The maps related to the geographical and political Complications of the area were digitized and georeferenced using Er mapper software. Arcinfo software was used to change the Coordinate system. For the meteorological stations, which were identified earlier within and adjacent areas, all the required parameters were estimated. For this purpose the guide lines reported by FAO (1994b) and other standard methods were used at regional scale. To calculate B_n according to equation (1) the variables F and R_g based on radiation data should be calculated. Parameter n is the measured actual radiation, measured period in hours per day. The values of this parameter are calculated from meteorological station data. At this stage, after evaluating the values of the parameter n, as the average monthly for each station, the relevant database was created. After linking the database to Arcview software and producing the station-point layer, a monthly grid map was prepared. Finally, after determining all the required information, R_g layer of the region was created as monthly through interpolation with IDW method with 12 neighborhoods with the power 2. The next step, the data layer for the parameter F was created and after extracting the parameters bo, bc from relevant tables, B_n layer was formed. Then, the appropriate correction factors should be applied for b_O layer. In order to apply the correction factor to incorporate the crop variety and temperature, average monthly temperature of meteorological stations in the area were called from Arcview software environment and the functions comprising map calculator, map Query and Reclassify operators were used to separate the different temperature zones, create relevant layers, and other correction factors, and the layer of spatial extent of Potential yield (Y_p) for winter wheat production in the region level were produced.

To determine the productivity of water use, in addition to the actual yield which is the numerator of equation (13), the denominator of the same equation which is actual evapotranspiration has to be determined. Thus the area was delineated into the areas covered by each station using Thiessen method with Arcinfo software (Dartiguenave and Maidment, 2005). Later, potential evapotranspiration was calculated using Cropwat software (FAO, 1993) for each of these areas. These were converted into actual evapotranspiration using proposed FAO method (1998). The maps of the actual evapotranspiration were prepared by the map calculator operator. These maps were overlapped with the spatial map of actual yield and the final map of spatial zones of water productivity of wheat crop in the Hamadan region was produced.

Results and Discussion

Figure (3) shows a sample diagram of the temporal variation of SPI for 32 years span for Novejeh station. Analysis of the calculated SPI for all the stations shows that, in general, in recent years (past 10 years), the region has experienced a drought state (C1) in 1999, and wet condition (C2) in 1992 and state closed to normal in 1989 (C3).

Figure (4) shows comparative statistics of water productivity in the area for the three conditions C1, C2, C3. Figure (5) is the spatial distribution map of water productivity for drought condition.

For the condition C1, the maximum WP is 0.67

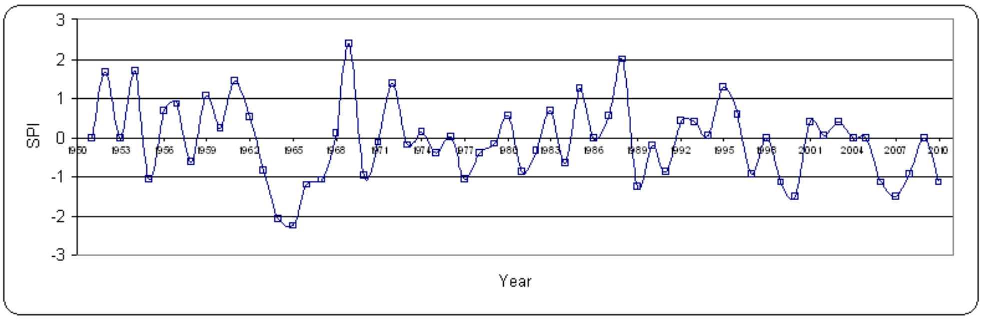

Figure 3: A sample diagram of the temporal variation of SPI for 32 years span for Novejeh station.

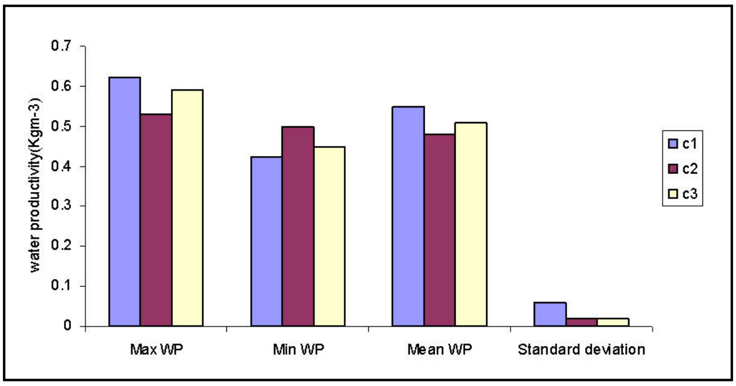

Figure 4: Comparative statistics of water productivity in the area for the three conditions C1, C2, C3.

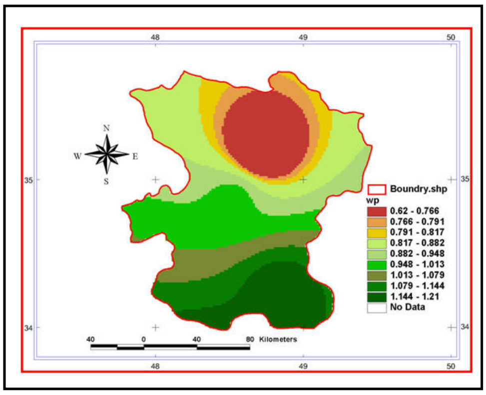

Figure 5: The spatial distribution map of water productivity for drought condition.

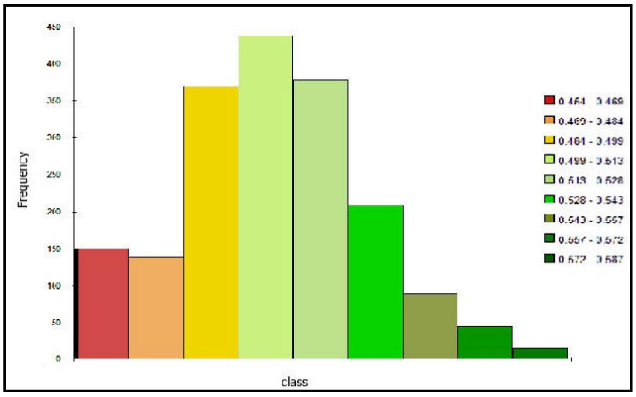

Figure 6: Frequency of water productivity in the area for drought condition.

kg/m^3 and South and South-east of the region has higher WP than the northern part. It should be noted that the standard deviation fo the WP was the highest under C1 conditions the region. Figure (6) shows that the major part of the region has forth class water productivity (0.51 to 0.49). For C2 condition, the north-east and east regions have the maximum water productivity; 0.57 Kg/m3 and most of the regional area enjoys the forth class of water productivity (0.47 to 0.48). Maximum water productivity; 0.61 Kg/m3 for the C3 condition is observed in extreme east and west of the region. These parts are placed in forth class of productivity (0.49 to 0.51).

In dry conditions, like C1, average and maximum productivities are placed at a higher level than the other two conditions, contrary to what was expected in advance. But minimum WP in wetter condition

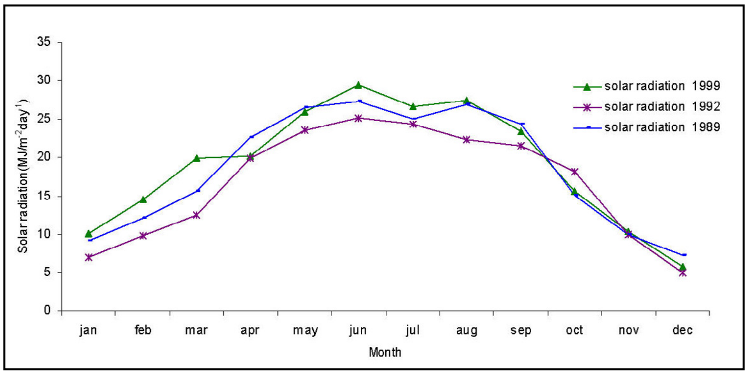

Figure 7: Variation of active Solar Radiation (SRAD) received by the earth's surface in the three conditions.

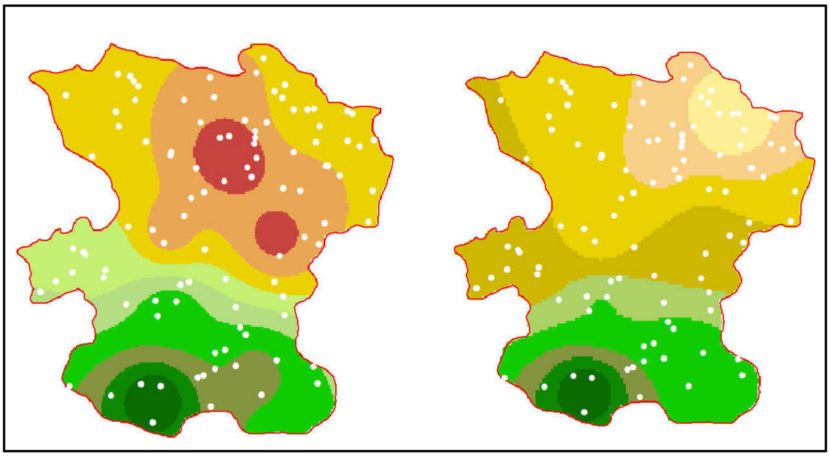

Figure 8: The extracted information from 100 randomly selected points on the two maps of WP and SRAD.

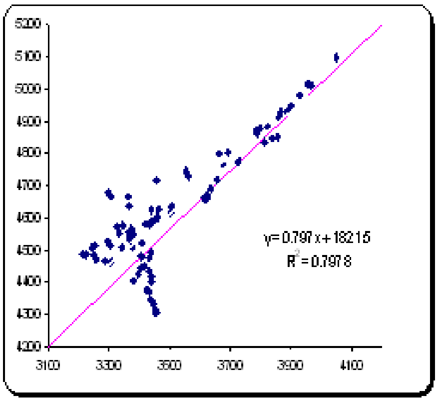

Figure 9: The regression line between Water Productivity and SRAD maps.

is higher than dry condition. The reason is that in C1 the average solar radiation is higher than the other two conditions as it is observed in Figure (7). This has affected greatly crop yield. In other words, during the drought condition, maximum level of production is higher than in other conditions due to higher amount of active Solar Radiation (SRAD) received by the earth's surface in the growth period.

Further, the analysis showed that spatial variation of WP is a function of spatial variations of solar radiation. The extracted information from 100 randomly selected points on the two maps (Figure 8) of spatial distribution of WP and spatial distribution of the active radiation as short wave reached to the Earth's surface shows a good correlation ($R^2 = 0.8$). The regression line is shown in Figure (9).

Conclusion

The simultaneous investigation of the spatial and temporal dimensions of WP leads to a more effective analysis, comprehensive and in depth understanding of the condition of resources for planning and decision making. In addition, the results of such an analysis will provide more information to adopt suitable techniques for saving water in agriculture. It is clear that WP is sensitive to solar radiation and its spatial variations.

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