Evaluation of water use efficiency in irrigated agriculture supported by satellite images

• Enrique Palacios-Vélez •
Colegio de Postgraduados, Carretera México-Texcoco, Mexico

• Luis A. Palacios-Sánchez •
Servicios de Estudios en Ingeniería y Sistemas, S. A. de C. V., Hermosillo, Mexico

• José L. Espinosa-Espinosa* •
Colegio de Postgraduados, Carretera México-Texcoco, Mexico
*Correspondence author

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Abstract

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To evaluate the water use efficiency is a necessary condition to improve water productivity. The overall water use efficiency is the product of conveyance efficiency in the largest and minor irrigation canal systems, multiplied by the application efficiency at the users´ plots. Conveyance efficiency is achieved by measuring the water delivered at the irrigated plots between the amounts of water taken from the sources of supply. These measurements are generally carried out by the personnel operating the irrigation systems. In most of the districts, these measurements are usually carried mandatory to report to the National Water Commission, with a variable precision. However, the water application efficiency in the users´ plots is much more difficult to be done, because the measurement of water consumption by plants is not easy to assess. Indeed, the efficiency in plot irrigation, is the ratio of crop water evapotranspiration between the amounts of water applied, both measurements are difficult to perform. However, in recent years it has been possible to estimate water consumption by crops using satellite imagery. Thus, in this paper, a methodology used in the Mayo River Irrigation District in Sonora, Mexico is shown for the last agricultural cycle 2015-2016 using Landsat 7 and 8 satellite images, with acceptable results. This methodology is based on the PLEIADES project 2007 – 2010.

Keywords: *NDVI*, evapotranspiration, *Kc*, water use efficiency.

Resumen

Palacios-Vélez, E., Palacios-Sánchez, L. A., & Espinosa-Espinosa, J. L. (enero-febrero, 2018). Evaluación de la eficiencia del uso del agua en la agricultura apoyada por imágenes de satélite. Tecnología y Ciencias del Agua, *9(1), 31-38, DOI: 10.24850/j-tyca-2018-01-02.*

Evaluar la eficiencia del uso del agua es una condición necesaria para mejorar la productividad del agua. La eficiencia total es el producto de la eficiencia de conducción tanto de canales de riego mayores y menores, multiplicado por la eficiencia de aplicación a nivel parcelas. La eficiencia de conducción se logra mediante la medición del agua entregada en las parcelas al ser extraída de las fuentes de abastecimiento. Estas mediciones son hechas por lo general por el personal que opera los sistemas de riego en los distritos y unidades de riego. En la mayoría de los distritos de riego estas mediciones suelen ser obligatorias para reportarse a la Comisión Nacional del Agua, con una variable de precisión. Sin embargo, la eficiencia en la aplicación del agua en las parcelas de los usuarios es mucho más difícil de llevarse a cabo, porque la medición del consumo de agua por las plantas no es fácil de evaluar. En efecto, la eficiencia de riego parcelaria es la relación entre el agua evapotranspirada por los cultivos entre el agua aplicada en el riego; ambas mediciones son difíciles de efectuar. Sin embargo, en los últimos años se ha logrado estimar el consumo de agua por los cultivos mediante el uso de imágenes satelitales. Así, en el presente trabajo se muestra una metodología empleada en el Distrito de Riego Río Mayo en Sonora, México, para el último ciclo agrícola 2015-2016, utilizando imágenes de satélite Landsat 7 y 8, con resultados bastante aceptables. Esta metodología se basa en el proyecto PLEIADES 2007-2010.

***Palabras clave**: NDVI, evapotranspiración,* Kc, *eficiencia uso del agua.*

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Introduction

Estimation of the water use efficiency at the farm level has been a challenge, because it is not easy to measure crop evapotranspiration. The gravimetric method, which involves taking soil samples to determine moisture content by weighing the wet and then the dry soil, and to estimate the specific gravity for each sample at various places on a plot, are very difficult and expensive. Due to the spatial variability of soil, it requires taking several samples from each plot of each crop which would involve many people to do this task.

The use of lysimeters is another method that requires the construction of these devices which is usually done in research institutions, but its use is not possible in every crop or plot of interest. Turbulent flow measure devices (Eddy Correlation) are also used, but the cost is high and is generally used to calibrate other more simplistic methods.

There are several empirical or semi-empirical methods that have been used to estimate water use of crops for many years, among them, the method of Thornthwaite, Blaney and Criddle, Penman-Monteith, which generally attempt to estimate the potential or reference evapotranspiration, which measures the evapotranspiration demand by climatic factors. On the other hand, the crop evapotranspiration is generally very variable since it depends on the crop vegetative development, on the spatial variability of soil, on water stress in the plant and many other factors whose variability is difficult to assess. Currently available automatic weather stations can be used to estimate the reference evapotranspiration by the Penman-Monteith equation, with software that is installed in the automatic weather station (Palacios, 2002).

As mentioned before, the crop evapotranspiration is highly variable and it is usually estimated, affecting the reference evapotranspiration by a dimensionless factor called crop coefficient (*Kc*) (Allen, Pereira, Raes, & Smith, 1998). The crop coefficient changes according to the crop development. Interestingly, this factor can be estimated based on a vegetation index called *NDVI*, which can be obtained using satellite images. In this regard, it should be noted that compared with METRIC, a model developed by the University of Idaho, the method described in this article is easier to develop and gives similar results in the estimation of the water use efficiency when used properly (Palacios & Flores, 2013).

Materials and methods

The overall water use efficiency in irrigated agriculture is defined as the ratio of the volume of water used by the crops, also referred as consumptive use, and the amount of water taken from the sources of supply, in addition to the effective rainfall for irrigation. It is represented by the following function:

$$Ewu = \frac{V}{Ve + Vpe} \quad (1)$$

Where:

Ewu - Water use Efficiency, dimensionless.

Vu - Volume used by the crops, m^3.

Ve - Volume extracted from different sources, m^3.

Vpe - Volume of effective rainfall, m^3.

It should be noted that in several cases it is also considered the amount of water required by the crop for washing salts, but in this case it has not been taken into consideration.

The assessment of the overall efficiency of the water is important because it allows us to estimate the water that is wasted, which is vital in the case of Mexico, there are already major water shortages in most of the agricultural areas of the country where it has been noted with concern that the irrigated area in the past 30 years has not changed despite huge investments that have been made.

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In the irrigation districts of Mexico, the water is obtained from different sources, in general it can be measured and it is usually measured or estimated with acceptable accuracy. The volume of effective rainfall is difficult to estimate, but there are several empirical methods that can do a reasonable approximation. Estimation of the water used by every planted crop and every plot is the most difficult task to achieve.

There are several methods to estimate water consumption by plants (*ETc*), but one of the most commonly used methods is the product of the so-called reference evapotranspiration (*ETr*) multiplied by a crop coefficient, dimensionless *Kc*, so the function for the calculation is:

$$ET_c = K_c ET_r \qquad (2)$$

Potential evapotranspiration and more recently called reference *ETr*, is a crop that has no restriction of water generally of small size as grass or alfalfa, which completely covers the ground as defined by Rosenberg (1974). Nowadays, this variable can be calculated with the Penman- Monteith method, which can already be obtained from an automatic weather station in which the software for this calculation has been incorporated.

The value of *Kc* coefficient is more difficult to be obtained because it involves the measurement of actual evapotranspiration of a crop, which requires special equipment, such as a weighing lysimeter with unchanged soil structure or using a turbulent flow measurement station (Eddy Correlation). However, the water consumption of each crop can be highly variable, since it depends not only on the crop but also on other variables such as fertilization, and water stress, among others, therefore calculation can be made using different methods, as proposed by the FAO (Allen *et al*., 1998), it considers crops grown under standard conditions, which take place in vast fields under agronomic excellent condition without limitations of soil moisture.

In the year 2000, the project "*DE*monstration of *E*arth observation *T*echnologies in *R*outine irrigation advisory services" (DEMETER) financed by the European Commission, supported to the Mediterranean Nations of Europe to improve water use efficiency. During five years, several researches were performed, among them, one research was to look for a linear relationship between the vegetation index *NDVI* and the *Kc*.

The *NDVI* is calculated from the reflectance of the red and infrared bands of satellite images according to the following function:

$$NDVI = \frac{\rho_{ir} - \rho_r}{\rho_{ir} + \rho_r} \qquad (3)$$

Where:

ρ_{ir} – Infrared band reflectance.

ρ_r – Red band reflectance.

Thus, D'Urso and Calera (2006), in the *Proceedings of the AIP Conference* discussed, in some detail, this linear relationship between *NDVI* and *Kc* and derived general function relating these two variables as shown below:

$$Kc = 1.25NDVI + 0.2 \qquad (4)$$

Subsequently, Calera and Gonzalez (2007), in a document from the project "Participatory multi-Level EO-assisted water Tools for Irrigation Management and Agricultural Decision-Support" (PLEIADES), also funded by the European Commission, presented a similar function as:

$$Kc = 1.15NDVI + 0.17 \qquad (5)$$

This linear relationship between *NDVI* and *Kc*, can be clearly seen by plotting the figure mentioned in the FAO publication (Allen, Pereira, Smith, Raes, & Wright, 2005) and adding the position of the *NDVI* values obtained from satellite images as shown in figure 1.

As part of the PLEIADES (2007-2010) project, measurements were carried out in the Irrigation District of the Rio Yaqui, Sonora State, as an investigation of three Mexican Institutions

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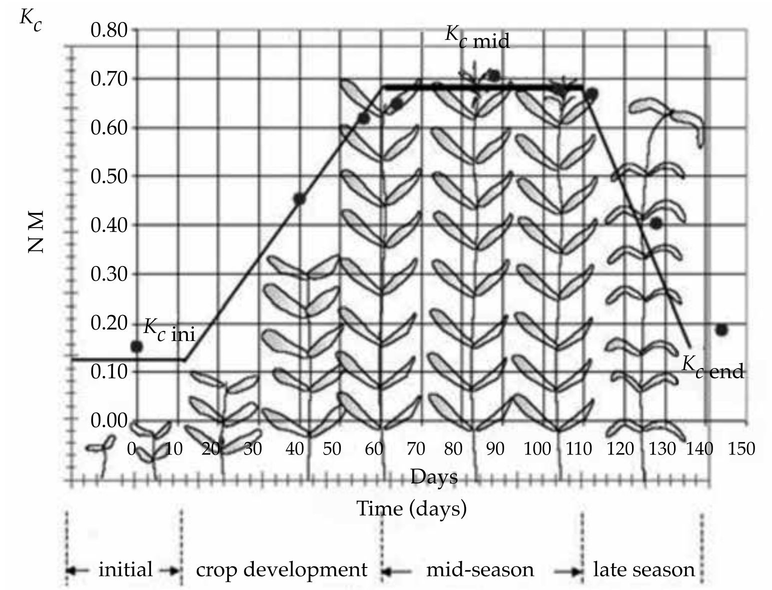

Figure 1. Points represent *NDVI* values obtained from satellite images.

(Colpos, Itson and Uson), with additional support from IRD from France with an experiment to measure evapotranspiration in four blocks of the district, including the use of four Scintilometers.

In such experiment, the crop evapotranspiration of wheat was also measured with Eddy Correlation equipment and *NDVI* indices were calculated, using 10 images from the Landsat 5 satellite. It was obtained similar results as that from Calera and Gonzalez (2007). The relationship is described in an article by Palacios, Palacios and Palacios (2011), whose graph is shown in figure 2.

On the left of the figure, it is shown the variation of *Kc* during the growing season of wheat and dark points are the *NDVI* values obtained from 10 images of Landsat 5 and 7 satellites.

The function obtained by Calera and Gonzalez was used to estimate water consumption for all crops, using *ETr* information from an automatic weather station. In a WEB page from the University Castilla la Mancha in Spain, an online system has been developed for DEMETER and PLEIADeS Projects to show the crop conditions and evapotranspiration estimations using this methodology. Now, an improved display is being used in a new project called Sustainable Irrigation water management and River-basin governance: Implementing User-driven Services (SIRIUS).

The online system (viewer), called SPIDER, uses various types of images and geographic information systems, and allows to its users (all members of the consortium SIRIUS, including Mexico), to observe the state of their plots and calculate their water consumption by crops through an ingenious method of graphical integration, using the function (5).

It is considered that this function is only valid for crops that entirely cover the soil surface when they reach flowering. For other perennial crops such as orchards, which generally do not fully cover the ground, is required to calculate other functions. As an example, it can

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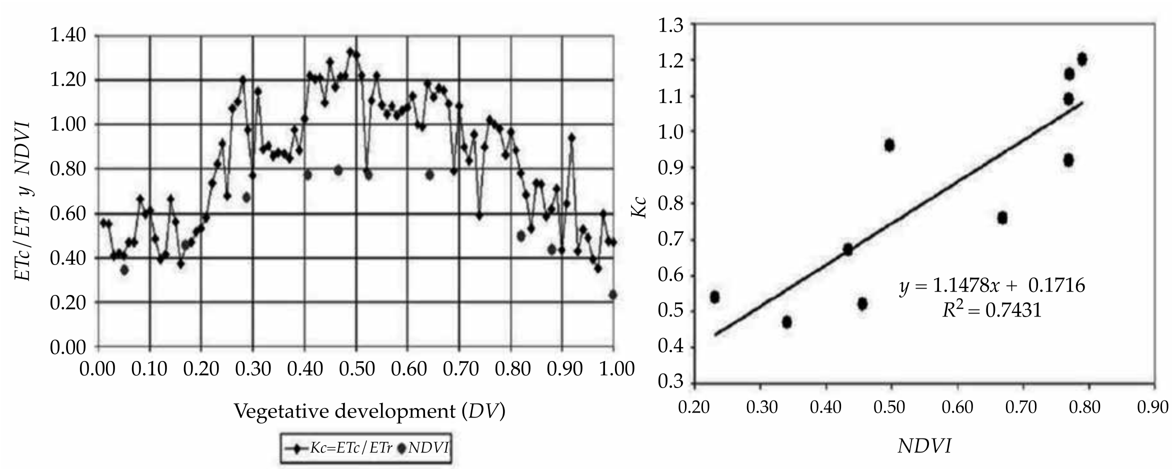

Figure 2. *NDVI* and *Kc* relationship in a wheat crop.

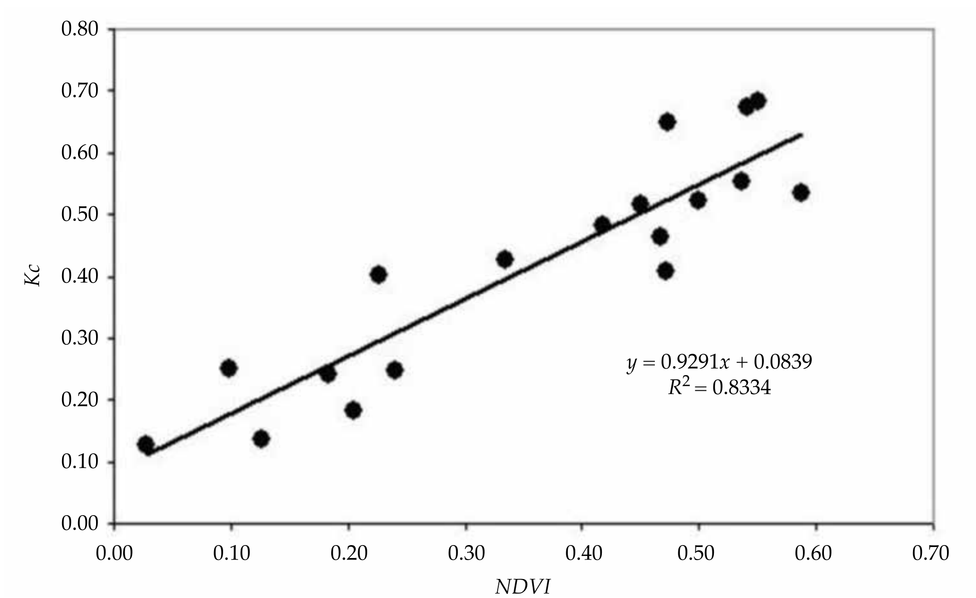

Figure 3. Linear relationship between *Kc* and *NDVI* for table grapes.

be mentioned the function found by Rodriguez, for growing table grapes, presented in an article by Palacios, Palacios, Rodriguez and Palacios (2010). This function obtained in the "Costa de Hermosillo Irrigation District" is shown in figure 3.

Considering that the function (5) can be valid to estimate the annual water consumption of crops that cover the entire irrigated area when reach flowering, then it could be used to calculate water consumption on each plot of an irrigation district.

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Under this assumption, then it is possible to integrate the total water consumption by crops in an irrigation district.

Results

This methodology has been tested in the Rio Mayo irrigation district in the Sonora state, in northern Mexico, where over 95% of the irrigated area is occupied by annual crops, predominantly wheat and safflower. The total water use efficiency in this irrigation district was calculated.

To evaluate the water use efficiency at plot level, software was developed by one of the authors of this report, which allows to calculate the average value of *NDVI* (per pixel) within the perimeter of each plot, using a geographic information system (GIS) of the irrigation district. Subsequently, a database with the average *NDVI* values per plot for each date of the satellite image was generated. Then, using the calculated *ETr* of a grass crop by the Penman-Monteith formula and climatic data registered in a weather station situated in the central part of the district, the evaluation of the water consumption in each plot was obtained.

Finally a database with average values of *NDVI* and *ETc* per plot was obtained, which allowed evaluating water consumption for irrigation in each module in which the district has been divided. In this area, however, the rain as a source of water during crop development is not significant, therefore the total water use efficiency of the irrigation is achieved by the two sources of irrigation supply for this District, the "Adolfo Ruiz Cortines" dam and 130 deep wells to supplement Irrigation needs.

All this information could be available to the water user associations in the district. To show to any water user who requests information about the status of their plots, it is possible to display satellite pictures with this information on a computer, using the " ArcView ® " or other GIS software such as the open source QGIS. The information is also available on the viewfinder SPIDER Internet, which is located on the web site of the Castilla La Mancha University, www.zeus.idr-ab.uclm.es/public. Additionally there is other viewer developed by the doctoral student José Luis Espinosa also available in Internet in:

http://hidro.colpos.mx:8080/sig-mon/

In addition, Excel sheets were generated to show the evaluation of the irrigation efficiencies at module level at the irrigation district Río Mayo in the cycle 2015-2016 using Landsat 7 and Landsat 8, shown in the Appendix section of this article.

Conclusions

It is possible to estimate crop evapotranspiration, at plot level, in Irrigation modules and in Irrigation Districts, using satellite images to calculate the *NDVI* indices and then the crop coefficients Kc. It is also necessary to have climatic data to estimate daily reference evapotranspiration through all the agricultural cycle. In the state of Sonora there is a network of automatic weather stations that can be used to get this climatic data, "Red de Estaciones Meteorológicas Automáticas de Sonora" (REMAS) www.siafeson.com/remas/.

To make a growing crop follow-up, such as the one described in the article, it is necessary to obtain satellite images, such as the new Landsat 8. The images of the new Landsat 8 are obtained every 16 days; the images of satellite Sentinel 2A, every 10 days with spatial resolution of 10 meters. Both Landsat 8 and Sentinel 2A have no cost. SPOT satellite images obtained from "Ermex". They are free if provided by means of a government office, or an educational or research institution. The DEIMOS satellite can be another option, it has a spatial resolution of 22 meters, but these images have an approximated cost of 0.15 € per km^2.

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Appendix

Río Mayo Irrigation Distric Agriculture year 2015-2016

Area in hectares and volume in cubic hectometers.

Module	Module area	Cropped area	Volume extrac.	Vol.To module	Conv. losses	Conv. Effic.	Etc vo-lume	Irrig. losses	Irrig. effi-ciency
1	8 030	7 481	62 217	40,720	21 497	0.65	32 903	7 817	0.81
2	8 808	9 057	81 669	53,452	28 218	0.65	42 917	10 534	0.80
3	5 256	5 422	51 060	33,418	17 642	0.65	26 608	6 810	0.80
4	5 803	4 859	45 165	29 560	15 605	0.65	21 326	8 234	0.72
5	5 169	3 992	33 050	21 631	11 419	0.65	16 186	5 445	0.75
6	7 901	7 284	61 093	39 985	21 108	0.65	31 089	8 896	0.78
7	8 138	8 712	81 062	53 054	28 008	0.65	46 784	6 270	0.88
8	3 606	3 081	35 938	23 521	12 417	0.65	14 792	8 729	0.63
9	6 073	7 032	65 605	42 938	22 667	0.65	34 201	8 736	0.80
10	5 004	5 179	46 733	30 586	16 147	0.65	25 928	4 658	0.85
11	5 122	5 075	44 011	28 805	15 206	0.65	26 934	1 870	0.94
12	6 887	6 400	58 693	38 414	20 279	0.65	29 851	8 562	0.78
13	6 570	6 202	54 841	35 893	18 948	0.65	32 135	3 758	0.90
14	4 687	4 833	45 101	29 518	15 583	0.65	20 747	8 771	0.70
15	6 040	5 804	55 532	36 345	19 187	0.65	30 838	5 507	0.85
16	3 981	2 252	21 629	14 156	7 473	0.65	8 380	5 777	0.59
	97 074	92 664	843 400	551 995	291 405	0.65	441 620	110 375	0.80

	Water losses	Volume	% losses	Efficiency (%)	Note: The apparent high values of irrigation efficiency observed in some modules could be to the use of water which was reported as conveyance losses
	From dam-Tesia	68 600	14.6	97.7	
	Canal losses	291 405	62.0	65.5	.
	Irrigation losses	110 375	23.5	80.0	
	Total losses	470 380	100.0	51.1	
	From Dam	824 000			
Withdrawal	From wells	88 000			
	Total	912 000			

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Institutional address of the authors

Ph.D. Enrique Palacios-Vélez
M.C. José L. Espinosa-Espinosa

Colegio de Postgraduados
Hidrociencias Department
Carretera México-Texcoco km 36.5
56230 Mexico State, Mexico
epalacio@colpos.mx
espinosa.jose@colpos.mx

Ph.D. Luis A. Palacios-Sánchez

Servicios de Estudios en Ingeniería y Sistemas,
S. A. de C. V.
Tezozmoc 55, Fraccionamiento Cuauhtémoc
83294 Hermosillo, Sonora, Mexico
luispalacios@seissa.com.mx

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