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Articles

Water use analysis in the Cuauhtemoc Aquifer, Chihuahua, Mexico

Análisis del uso del agua del acuífero Cuauhtémoc, Chihuahua, México

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Abstract

Chihuahua is an arid state that have few sources of surface water and uses mainly underground water for irrigation. The volume extracted of these sources has an increasing tendency. The Cuauhtémoc aquifer was overexploited for several decades mainly for the water supply for irrigation and usually the extraction of water volume is much greater than the recharge, which has generated overexploitation with wide abatements of the static levels. In the irrigated areas, it has not been possible to quantify regularly the variation of the irrigated area as well the volume of water used. The estimation of the water volume used for irrigation has been based in the irrigated areas. For 2012, 1,317 irrigated units were located, supplied by 1,818 water exploitations, covering a physical area of 55,555 hectares, where 92% of the water used is underground, also, more than 62,000 hectares are rain-fed agriculture. The cultivated area is concentrated in two crops: corn (87.0%) and apple (11.9%). However, by quantifying the areas of standing crops carried out for the years 2015 and 2016, it is show that the agriculture has grown outside the areas defined in 2012, which implies a greater consumption of groundwater.

Keywords: Aquifer Cuauhtemoc, water balance, cultivated area.

Resumen

Chihuahua es un estado árido que cuenta con pocas fuentes de agua superficial y utiliza para el riego principalmente fuentes de agua subterránea, cuyo volumen extraído tiene tendencia creciente. El acuífero Cuauhtémoc se ha explotado por varias décadas, en particular para el suministro de agua en la agricultura, y registra extracciones de volúmenes de agua mayores a la recarga, lo que ha generado sobreexplotación, con notables abatimientos de los niveles de bombeo. En las zonas de riego no ha sido posible cuantificar con regularidad la variación en superficies sembradas y regadas, así como el volumen empleado de agua. La estimación de estos volúmenes de agua se hizo a partir de la ubicación de los pozos usados para el riego y la evaluación de las superficies cultivadas. Para 2012 se ubicaron 1 317 unidades de riego abastecidas por 1 818 aprovechamientos de agua, cubriendo una superficie física de 55 555 hectáreas regadas, donde 92% del agua utilizada es subterránea; además, se cultivan de temporal poco más de 62 mil hectáreas; sin embargo, el reporte del SIAP para ese año fue de 47 792 hectáreas regadas, 7 763 menos que las detectadas. La superficie cultivada se concentra en dos cultivos: maíz (87.0%) y manzana (11.9%). Sin embargo, mediante la cuantificación de las superficies de cultivos en pie realizado para los años 2015 y 2016, se aprecia que la agricultura ha crecido por fuera de las áreas delimitadas en 2012, lo que implica un mayor consumo de agua subterránea.

Palabras clave: acuífero Cuauhtémoc, balance de agua, superficie cultivada.

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Introduction

The state of Chihuahua has sources of surface water and groundwater and, since rainfall is low in these areas, the greater water use is of subterranean origin.

The Cuauhtémoc aquifer has been exploited for several decades, mainly for the supply of water used in agriculture, and to a lesser extent, it is used to provide water to the population. In the irrigation areas it has not been possible to regularly quantify the variation in the area sown, the volume of irrigation water, and in the same way, the efficiency degree in the water use is unknown. In this aquifer, rainfall plays an important role in agricultural production by providing a considerable amount of water to crop requirements, particularly in the summer spring cycle and in second crops, requiring less irrigation stretches than those used in autumn-winter crops. With the large surface irrigated with water from the aquifer, volumes have been extracted larger than the recharge volume, which has led to severe overexploitation, which in many places results in notable declines in static levels, which in turn generate social and economic problems.

Pineda-Pastrana (2011) points out that analyzing land use change requires accurate and consistent tools. Remote sensors and geographic information systems are an option for quantifying changes in a territory, which are difficult to understand and need to be studied holistically.

The agricultural area cannot be seen as a separate system of social process; it must be conceived as a whole, composed of a natural and a social part, which are both dynamic, and subject to transformations over time. Mapping land uses been an accepted practice since 1940 through the use of aerial photographs, physical changes in land use have been identified through the maps obtained by these methods and have allowed inferences to be made about the economic and social reasons involved in such changes. One way to evaluate the changes in land use is from the measurement of the changes in the vegetation cover thereof. Traditionally, the measurement of changes in vegetation cover and land use is based on information generated from remote sensing (usually aerial photographs and satellite images). Understanding the causes behind the change in land use and coverage means studying the environmental and socio-economic factors that affect land use.

For their part, Ponvert and Lau (2013) point out that many of the impacts, from the use of agricultural technologies, are susceptible to be detected by the footprint it produces to the environment by sensor systems such as aerial photographs and satellite images; as well as by direct observation “in situ” using field survey techniques. Also, the different spatial variables can be converted into layers of information that are stored, processed and analyzed using Geographic Information Systems (GIS).

Advances in the monitoring of crops and using the methodologies of Precision Farming (PF) in the primary production, and mapping of the land cover can make monitoring possible, as an example, the estimation of the state that is a crop like sugarcane in a given region, at a homestead-scale or production unit, due to the longevity of the crop, the low-cost acquisition of images, its spatial coverage and the possibility of generating its spectral bands indexes (Zhang, Anderson, Huang, & Myneni, 2005).

Aguilar, Galindo, Fortanelli and Contreras (2010) points out that the techniques of Remote Sensing (RS) with Landsat images and Geographical Information Systems (GIS), as well as with the Geo-Positioning Systems (GPS), are useful tools in the identification and monitoring of large agricultural areas, estimation of the production, detection of diseases and stress, through the analysis of the spatial distribution, the mapping of the various productive areas, addressing sampling and observation in the field, promoting a further evaluation of the productive potential of the sown areas within Precision or Site-Specific Farming, based on the spatial variability of the soil parameters and field crops.

Hatfield, Gitelson, Schepers y Walthall (2008) points out that geographical information systems provide the possibility of linking spatially distinct sources of information, and from the analysis of the images generated by remote sensors, it is possible to obtain information on the vegetation's characteristics, using different image processing techniques; among them, the calculation of vegetation indexes from the values of reflectivity at different wavelengths and to extract the information related to vegetation, minimizing the influence of other external factors in decision-making.

As Pineda-Pastrana (2011) points out, the use of geographic information systems and remote sensing techniques represents a clear vision for temporary monitoring in agricultural areas during the crops' development phases.

In the Cuauhtémoc aquifer, various studies have been carried out by federal agencies. In 1973, the Ministry of Hydraulic Resources (SRH) has agreed to a study from the point of geo-hydrological view, whose objective was to carry out a census of groundwater use and to know the existing exploitation conditions in regional aquifers; for 1982, the Secretary of Agriculture and Hydraulic Resources (SARH) contracted a study that included the Cuauhtémoc aquifer, whose objective was to know the degree of aquifer exploitation, determine the behavior and evolution of water levels, assess the potentiality of the aquifer to determine the water volumes available, define the water quality and make recommendations for areas with good quality in order to plan their rational use (SARH, 1982).

Starting with the creation of the National Water Commission (CONAGUA), many studies have been conducted by firms or public institutions contracted, such as the one conducted in 1991 for the update of the geohydrological study and analysis of the operation policies, in addition to developing a project management of the aquifer, it was a study of geohydrologica update and modeling, hired by the necessity of having the technical elements to make decisions before the obvious symptoms of an over-exploitation of the aquifer; for 1998, we worked on the formation of the model of hydrodynamic simulation of the Cuauhtémoc aquifer; for the year 2000 a study was performed whose main objective was to ascertain the magnitude and spatial distribution of extractions from the aquifer, identify suitable sites to implement specific development or preservation actions, as well as to propose and plan future aquifer management strategies; for 2001, the update study of piezomtric measurements in several aquifers; for the year 2002, we performed the determination of the availability of water in the Cuauhtémoc aquifer, in 2005 was the delineation of the aquifer, based on the collection and analysis of previous studies, to define the hydrogeological knowledge situation at that time, for 2009, the update of the ground-water annual average availability was reported, this document indicates that the aquifer has a deficit of 207.1 hm^3/year, which points to the severity of the situation, it additionally reports that the extraction is 190.9 hm^3/year and the concessioned volume of 322.3 hm^3/year, and for 2010 we conducted a study and measurement of electromechanical efficiencies in 63 pumping equipment within the aquifer, especially wells for the supply of drinking water.

Purposes

The purpose of this work was to analyze the use of water in the agricultural irrigation zones of the Cuauhtémoc aquifer, taking the balance of the aquifer, the estimation of sown areas and volumes of water used as reference, the above based on the use of remote sensing techniques and geographic information systems.

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General characteristics of the Cuauhtémoc aquifer

The Cuauhtémoc Valley aquifer, numbered 0805 by the National Water Commission (DOF, 2001), is located in the central part of the Chihuahua State between the 28° 15' and 28° 57' parallels as well as between the meridians 106° 30' and 107° 11' west longitude (DOF, 2009), and cover an area of 3,411 km^2, Figure 1. This aquifer covers almost the entire municipality of Cuauhtémoc and partially the municipalities of Riva Palacio, Cusihuirachi, Bachiniva and a very small area of the municipalities of Chihuahua and Guerrero.

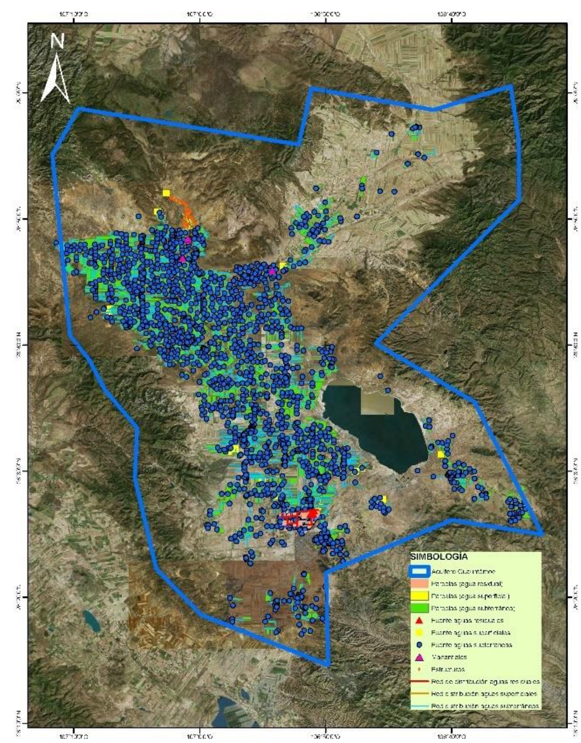

Figure 1. Water use and agricultural area within the official polygonal of the Cuauhtémoc aquifer. Source: Own elaboration with field information.

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Analysis of the current situation of groundwater and surface water use in the Cuauhtémoc aquifer

For the analysis of water use in the Cuauhtémoc Aquifer, in 2012 we carried out the building of a hydro-agricultural infrastructure in the irrigation units, which according to the DOF (2016) are “agricultural areas with infrastructure and irrigation systems, other than an irrigation district, and commonly of a smaller surface area than the other one; which can be integrated by associations of users or other figures of producers' organizations that are associated with each other freely to provide the irrigation service with autonomous management systems that operate the works of hydraulic infrastructure for the recruitment, referral, conduct, regulation, distribution, and eviction of the national waters intended for the irrigation in agriculture”. The use of surface and underground water, irrigation surface (land delimitation), conduction network and structures, irrigation systems and type of cultivation were identified in these irrigation units as well as the use of existing urban public use and residual use.

Agricultural use

Within the aquifer 1,317 irrigation units were located, Table 1 whereas the classification of these uses by type of use and volume awarded is presented in Table 2.

Table 1. Exploitation Census Cuauhtémoc aquifer. Source: Own elaboration with field data.

Type of use	Number of uses	Physical surface	Number of irrigation units

			(ha)	
	Total	**Inactive**		
Surface	30	3	801	
Residual	1		573	
Agricultural underground	1,783	82	54,133	
Urban public underground	142	5		
Spring	4		48	
Total	**1 960**	**90**	**55 555**	**1 317**

Table 2. Use of resources in irrigation units of the Cuauhtémoc aquifer. Source: Own elaboration with field data.

Year	Use	Number of active uses	Volume (hm^3)	Agricultural area (ha)
2012	Agricultural underground	1 701	352.7	54 133
	Urban public underground	137	18.6	
	Livestock underground		5.0	
	Agricultural Springs	4	0.3	48
	Agricultural surface	27	4.8	801
	Agricultural residual	1	3.6	573
	TOTAL	**1 870**	**385.0**	**55 555**

Other results of the infrastructure in irrigation units show the area sown and its crop pattern with the corresponding type of use, Table 3. Table 4 shows the irrigation systems found in the irrigation units and their respective crop.

Table 3. Planted area and crop pattern. Source: Own elaboration with field data.

Crop	**Area by type of use (ha)**			
	Underground	**Surface**	**Residual**	**Total**
Corn	47 106.83	670.75		47 777.58
Apple	6 459.17	168.25	572.88	7 200.30
Beans	218.60	10.00		228.60

Oats	215.00			215.00
Crop Association*	51.00			51.00
Other crops**	82.80			82.80
Total	**54 133.40**	**849.00**	**572.88**	**55 555.28**

* Two crops planted together

** Other crop: cherry, peach, beans, vegetables, tomato, sorghum, grape.

Table 4. Area sown by crop type and irrigation system. Source: Own elaboration with field data and the geographic information system of the Cuauhtémoc aquifer, 2012.

Crop	Intermittent irrigation		Micro sprinkler irrigation		Central pivot		** Other irrigation		Total	
	(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)
Corn	44 554.73	80.20	45.50	0.08	1 722.70	3.10	1 317.45	2.37	47 640.39	85.75
Apple	776.13	1.40	5 810.66	10.46	0.00	0.00	613.50	1.10	7 200.29	12.96
* Another crop	383.60	0.69	10.00	0.02	81.00	0.15	240.00	0.43	714.60	1.29
Total	**45 714.46**	**82.29**	**5 866.16**	**10.56**	**1 803.70**	**3.25**	**2 170.95**	**3.90**	**55 555.28**	**100.00**

* Another crop: alfalfa, oats, oats and wheat, cherry, peach, beans, vegetables, tomato, corn, fodder maize, corn and oats, corn and beans, sorghum, tomato, grape.

** Other types of irrigation: Sprinkling, sprinkling and intermittent, front advance, drip, gravity, micro-operation and intermittent piping, central pivot and intermittent piping.

Since the main and largest user of water in the Cuauhtémoc aquifer is the agricultural sector, the volume of water extracted from raw irrigation plates determined in Conagua's work (2000) was estimated and the current irrigation systems considered. For corn, the total irrigation efficiency was considered to be 55% and for other crops, 49%, Table 5 shows the extraction volumes in the agricultural sector used for the volumes calculation of 2012.

Table 5. Irrigation stretches and estimated volumes. Source: Own elaboration with Conagua data (Conagua, 2000).

Crop	Corn	Other crops	Apple
Number of risks	6	5	21
Irrigation requirement (cm)*	34.4	26.8	74.0
Total irrigation efficiency**	55%	49%	90%
Stretch gross irrigation (cm)***	63	53	82
Area (ha)	47,107	567	6,459
Volume (hm^3/year)	296.7	3.0	53.0
Total volume extracted (hm^3/ year)	352.7		

* Irrigation requirement is the amount of water needed for the crop to survive, varying with environmental, climatic and soil factors.

** Total irrigation efficiency is equal to the product of application conducting and efficiency.

*** Gross irrigation stretch is the net irrigation stretch affected by the total irrigation efficiency.

Urban public use

Concerning urban public use, 142 uses were located, of which 76 have concession title, covering a volume of approximately 11 hm^3/year. However, extraction for this use (which includes 5 hm^3/year for livestock use) has been estimated at 23 hm^3/year as extraction.

Bans for the exploitation of groundwater

A relevant aspect is that practically all the Cuauhtémoc aquifer is banned for the extraction of groundwater, only a small part in the northeast is not, which makes possible the implementation of a Specific

Regulation of water use in this area, or simply an agreement with the users.

Annual groundwater average availability

According to the annual average availability update of groundwater from the Cuauhtémoc aquifer (0805), published in the year 2009, there is no availability for the granting of new awards for the exploitation of this resource in the mentioned aquifer (DOF, 2009).

This publication mentions a total recharge of 115.2 hm^3/year, a null committed volume and a concession volume of 322.3 hm3/year, resulting in a deficit of 207.1 hm^3/year, according to the standard. In addition to a volume of extraction recorded in technical studies of 190.9 hm^3/year (Conagua, 2002).

Integration and analysis of a water balance model in the Cuauhtémoc aquifer

The extraction of groundwater in the Cuauhtémoc aquifer has increased considerably, considering that the information available to analyze the historical development of the extractions corresponds to the period from 1973 to 2000, it was determined that the extraction goes from 97.9 hm^3/year to 381.3 hm^3/year and currently up to 352.7 hm^3/year.

The average depths of the static level show an increasing decline from 1973 to date. The behavior of the depths of the static level, between 1973 and 2012, is presented in Figure 2.

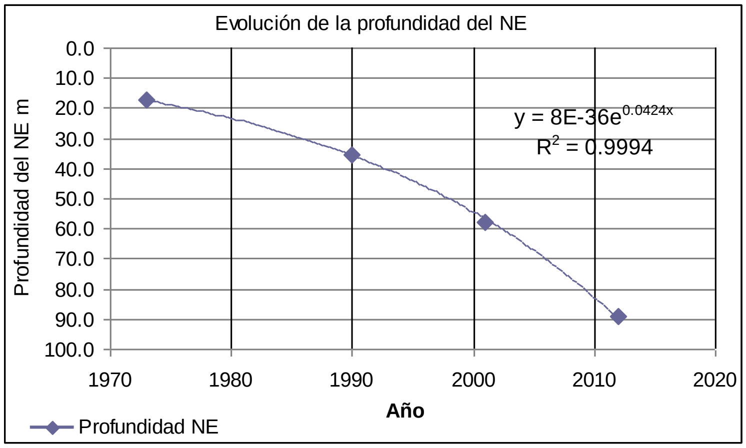

Figure 2. Mean depth of static level observed in Cuauhtémoc. Source: Own elaboration with study data.

Currently, the aquifer has really variable depths of its static levels, ranging from 20 m to about 200 m. The depths of 20 m are located near the Bustillo Lagoon, while to the northeast of the town Reforma, the highest depths of the static level are observed, ranging from 130 to 210 m.

Groundwater balance of the Cuauhtémoc aquifer

As part of the analysis of the Cuauhtémoc aquifer, the conceptual model of the aquifer was elaborated, and in order to know the order of the water volumes that recharge the aquifer, it is essential to note that the average annual rainfall in the region is of the order of 492 mm/year and that the average annual temperature is 13.2°C, so it is estimated that the infiltration is approximately 100 hm^3/year that corresponds to 6% of the precipitated volumes. This information is incorporated into the groundwater balance.

The groundwater balance area is considered both the upper parts with an area of 1,649 km^2, and those of the valley (1,762 km^2) that are included within the aquifer polygonal, therefore, the total area is 3,411 km^2. The groundwater balance includes the scenarios for the years

1973, 1991, 2000 and 2012, as information from the studies for those years was available (Table 6).

Table 6. Groundwater Balances. Source: Own elaboration with data from various studies.

Year		**1973**(1)	**1991**(2)	**2000**(3)	**2012**(4)
Total aquifer area	km^2	3 411	3,411	3,411	3 411
Natural rain recharge	hm^3/year	52.7	52.7	52.7	52.7
Horizontal entries	hm^3/year	51.5	51.5	51.5	51.5
Total natural recharge	**hm^3/year**	**104.2**	**104.2**	**104.2**	**104.2**
Total return	hm^3/year	17.5	25.1	67.6	55.5
Total entries	**hm^3/year**	**121.7**	**129.3**	**171.8**	**159.7**
Springs	hm^3/year				0.3
Evapotranspiration	hm^3/year	34.6	34.61	6.20	3.5
Horizontal outputs	hm^3/year				0.0
Gross total extraction	**hm^3/year**	**97.9**	**151.2**	**381.3**	**376.2**
Agricultural	hm^3/year	61.6	111.6	324.2	352.7
Urban public	hm^3/year	5.1	15.4	15.4	18.6
Industrial	hm^3/year	25.0	18.0	35.4	
Other	hm^3/year	6.2	6.3	6.3	5.0
Total discharge	hm^3/year	132.5	185.8	387.5	380.0
Mined	**hm^3/year**	**-10.9**	**-56.5**	**-215.7**	**-220.3**
Net total extraction	hm^3/year	**115.0**	**160.7**	**319.8**	**324..5**
Natural recharge	hm^3/year	**104.2**	**104.2** (65%)	**104.2** (33%)	**104.2** (32%)
Aquifer mining	hm^3/year	**-10.9**	**-56.5** (35%)	**-215.7** (67%)	**-220.3** (68%)
Drawdown in the period		**1.07**	**2.06**	**2.81**	

(1) SRH, 1973.

(2) Conagua, 1991.

(3) Conagua, 2000.

(4) Study data.

Alternative solutions to the Cuauhtémoc aquifer problems

Given the problem of the Cuauhtémoc aquifer, it is necessary to carry out the analysis of the productivity of irrigation in the Cuauhtémoc Aquifer, which will allow the generation of irrigation water management alternatives that allow the efficient use of irrigation water, and lead to an increase in that resource's productivity. The management options for water resources focus primarily on subsoil resources and for agricultural use, which account for 92% of total water resources used in the region. During the field work, the cost and value of the production was obtained through interviews with the producers. Table 7 shows the value of production in crops irrigated exclusively within the aquifer limits.

Table 7. Irrigated crops with groundwater harvesting.

Crop	Area (ha)	Percentage (%)	Production cost (Million $)	Production value (Million $)	Volume (hm^3/year)	Benefit ($/ha)	Profit ($/$m^3$)
Corn	47,107	87%	755.2	1 446.9	296.7	14 684	2.33
Apple	6,459	12%	515.3	1 065.5	53.0	85 183	10.39
Other crops	567	1%	9.2	21.5	3.0	21 693	4.09
Total	54,133	10000.%	1 279.7	2 533.9	352.7	23 169	3.56

If the current conditions of overexploitation continue, the drawdowns of the static level will continue at a significant rate, in thirty years the average depth of the static level will double, from 90 meters to 170 meters on average, within the aquifer exploitation zone (Figure 3).

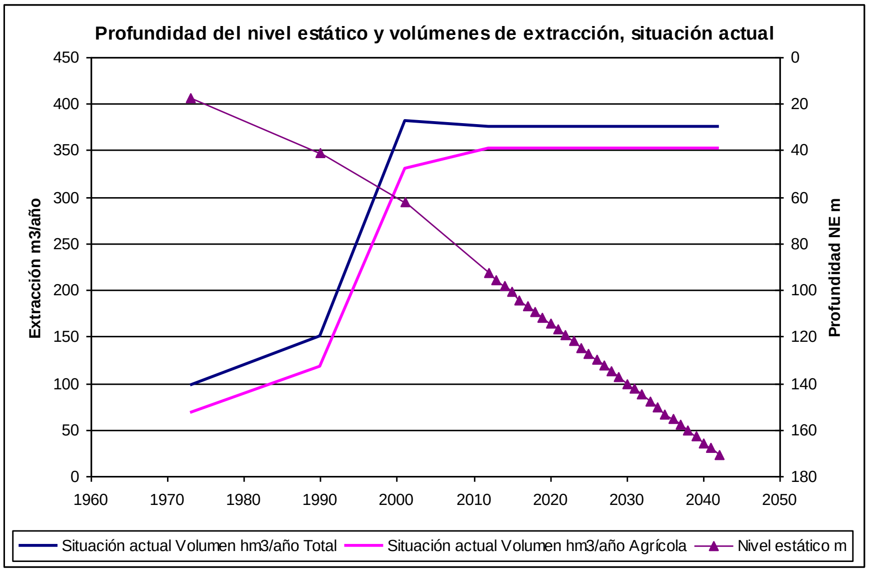

Figure 3. Groundwater extraction under the current situation and projection of the static level. Source: Own elaboration with study data.

Adjustment of awards to the extraction volume

To modify the drawdowns mentioned above, the current extraction of 352.7 hm^3/year should be reduced to 189.4 hm^3/year, by adjusting the extraction volumes to the award volume of 206.1 hm^3/year, minus 16.7 hm^3/year, for concessional volumes not used.

To achieve this purpose, a series of actions will have to be taken to demonstrate to users, through measurements, that the volume they use exceeds the award, the measurements can be either directly with meters or indirectly, such as irrigation plates or electrical energy consumption, and with the support of remote sensing techniques and using the geographic information systems platform.

In the second case, all wells will necessarily have to be calibrated and a constant of proportionality between energy consumption and extraction obtained, constant that must be corrected at least annually due to the deterioration of the well and/or pumping equipment, as well as the increase in the pumping level, and it will also be necessary to demonstrate that the energy meter works correctly.

Also, the anomalies mentioned above should be corrected in the Public Register of Water Rights (REPDA). In this planning exercise, a time of five years has been considered to achieve this adjustment and to order the administrative system of CONAGUA.

Aquifer stabilization

Subsequently, an attempt will be made to stabilize the aquifer, which means equating the recharge with the extraction, that is, bringing the extraction to a value close to 100 hm^3/year, corresponding to the natural recharge, actions for which another five years have been considered.

Economic effects

In the first stage of adjusting concessions to the volume of extraction, the value of production would decrease from 2,534 to 1,392 million pesos per year, with the consequent decrease in the profits of farmers. In this case the extraction volume would decrease from 352.7 hm^3/year to 189.4 hm^3/year.

Subsequently, a second phase is proposed to stabilize the aquifer where the gross volume used would decrease to 86.6 hm^3/year. In this case, the corn area would go from 25,100 ha to 8,860 ha, the area planted with apple is preserved.

Both phases would only affect the agricultural sector, which means respecting the volumes of water used in urban public use. The quantification of costs and benefits is presented in Table 8.

Table 8. Proposal for stabilization. Source: Own elaboration with study data.

Crop	Area (ha)	Percentage area (%)	Gross volume (hm^3/year)	Production cost (million $)	Production value (million $)	Benefit (Million $)	Profit ($/$m^3$)
Situation (2012)							
Corn	47,107	87%	296.7	755.2	1,446.9	691.7	2.3
Apple	6,459	12%	53.0	515.3	1,065.5	550.2	10.4
Other crops	567	1%	3.0	9.2	21.5	12.3	4.1
Total	**52,121**		**-1659.3**	**-732.3**	**521.9**	**-757.8**	**3.6**
Adjustment of awards (2013-2017)							
Corn	25,100	87%	158.2	404.2	770.7	366.5	2.3
Apple	3,650	13%	29.9	298.5	607.7	309.2	10.3
Other crops	250	1%	1.3	6.1	14.0	7.9	5.9
Total	**133,238**		**-3133.2**	**-759.8**	**2,432.2**	**-836**	**3.6**
Recharge stabilization = extraction (2018-2022)							
Corn	8,860	70%	55.9	145.6	272.1	126.5	2.3
Apple	3,650	29%	29.9	298.5	607.8	309.3	10.3
Other crops	160	1%	0.8	2.2	5.9	3.7	4.4
Total	**279,142**		**-6 183.8**	**-1 077.3**	**5 746.2**	**-1 236.5**	**5.1**

However, in the second stage it requires the cancellation of concessions (103 hm^3/year), which represents a reduction in the net benefit of farmers in the order of 240 million pesos per year, a figure to be paid, since there are legal concessions.

Analysis of water use in Cuauhtémoc aquifer agriculture

From the updating of the model and the balance of the aquifer, the analysis of the change in the area sown in the Cuauhtémoc aquifer was carried out. Analysis tools such as remote sensing techniques, Geographic Information Systems and Landsat 8 satellite imagery were used for various dates in the years 2015 and 2016, as shown in Table 9.

Table 9. Landsat 8 images used in the quantification of the area sown in the Cuauhtémoc aquifer. Source: Own elaboration.

ID	Key	Name	Date
1	LC80330402015163LGN00	LC0803304020150612	12/06/15
2	LC80330402015243LGN00	LC0803304020150831	31/08/15
3	LC80330402015307LGN00	LC0803304020151103	03/11/15
4	LC80330402016054LGN00	LC0803304020160223	23/02/16
5	LC80330402016166LGN00	LC0803304020160614	14/06/16
6	LC80330402016198LGN00	LC0803304020160716	16/07/16
7	LC80330402016294LGN00	LC0803304020161020	20/10/16
8	LC80330402017056LGN00	LC0803304020170225	25/02/17

The Landsat 8 satellite images are processed by the application of the Normalized Difference Vegetation Index (NDVI) to quantify the surface that was sown in the cropping zones demarcated through the model of geographic information system. The atmospheric correction of satellite images and the Ortho-rectification of satellite images was carried out using the orthophotos reference of the National Institute of Statistics, Geography and Informatics (INEGI).

The integration of the information of the irrigation units in the GIS model allowed to detect that during the time of spring-summer, there is a large area that is susceptible to sow, and that is additional to that contained in the GIS. Using the false color image and a Spot 5 image with a resolution of 2.5 m, all plots within the polygonal of the Cuauhtémoc aquifer were digitalized. This allowed to know the data of total physical area susceptible to cultivation.

The calculation of the NDVI was performed from the values of reflectance in the red and near-infrared bands, using a filter of 0 for values of NDVI lower than 0.25. Subsequently, the number of pixels was quantified in each of the polygons corresponding to plots by using the software ERDAS, the allocation of the sum of pixels of NDVI to the database of parcels.

The estimate of the area sown was made from the multiplication of the number of pixels of each plot by the area of the pixel (0.09 ha), then a filter is made to prevent the area sown from being larger than the physical area. Once this has been done, the percentage between the two areas was calculated and values less than 30% of the sown area are filtered, to which a value of zero is assigned. Finally, the sum of the area of each plot was made to obtain the total sown area.

For the analysis of Agriculture in the 2012, 2013 and 2014 cycles, the images for the spring-summer period (June–August) had a large cloud coverage, so they were omitted from the surface quantification.

For the year 2015 and 2016, during the spring-summer period (June–August) Landsat 8 satellite images were located with low cloud cover that allowed to quantify the area planted. For these cycles we observed a planted area with greater coverage than that used by irrigation units located in 2012 with fieldwork. For this reason, it was necessary to generate an additional layer of information in the geographic information system model, which included the areas cultivated in the summer period, even if in much of this area the type of culture developed is temporary, and the irrigated area cannot be quantified or differentiated. This layer of information served as a reference for later quantifying the cultivated area through remote sensing techniques with satellite images and NDVI calculation. For the years 2015 and 2016 it was determined that there exists an additional area outside the perimeter of the irrigation units considered; however, the type of crop and the volumes of water used are not exactly known. In this case, the plant cover that exists within lands located and visible in the agricultural area of the aquifer was estimated. The above is shown in the figures 4, 5, 6, 7, 8, 9, 10 and 11, and the results in Table 10.

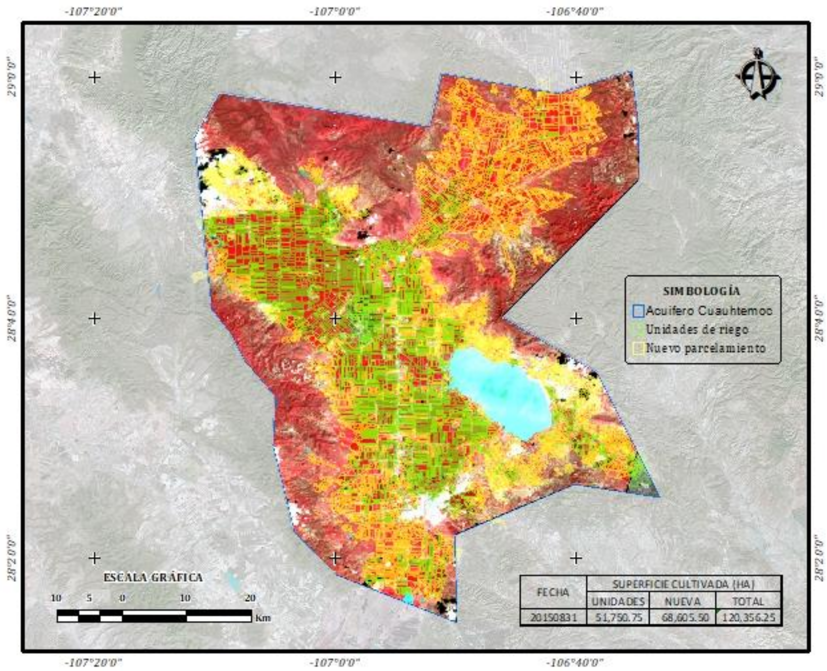

Figure 4. Composite image NDVI Landsat 8 (31/08/2015) - parceling in irrigation area (2012) and outside the irrigation area. Source: Own elaboration.

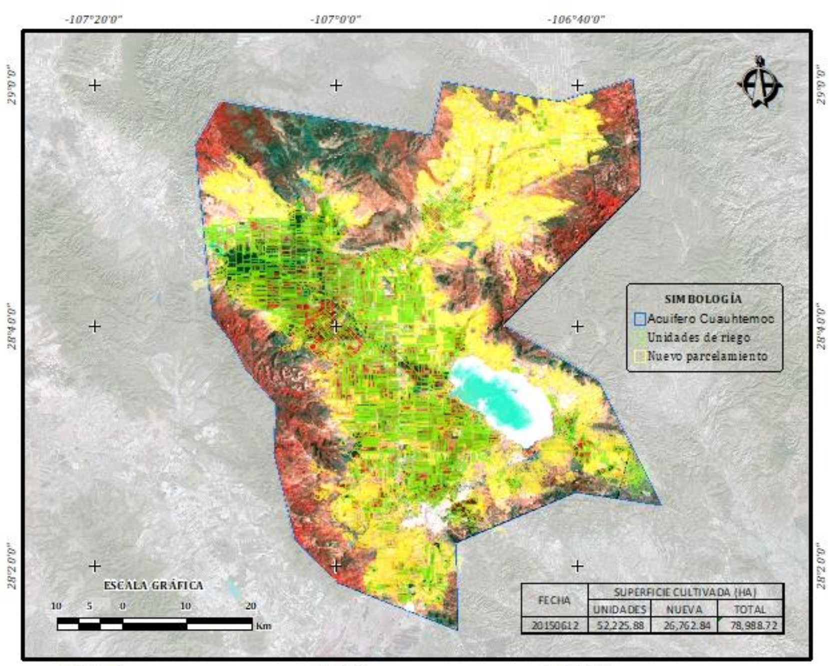

Figure 5. Composite image NDVI Landsat 8 (12/06/2015) - parceling in irrigation area (2012) and outside the irrigation area. Source: Own elaboration.

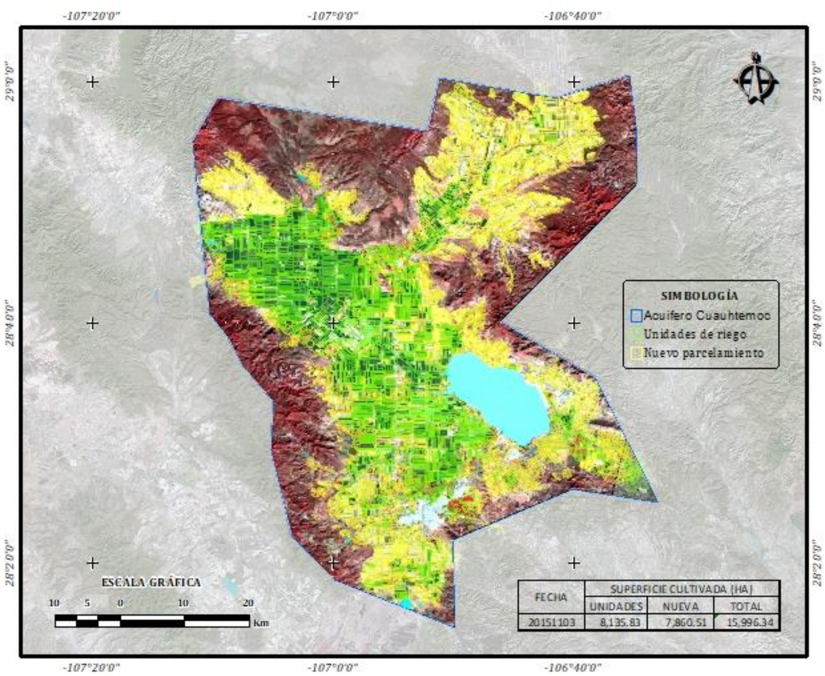

Figure 6. Composite image NDVI Landsat 8 (03/11/2015) - parceling in irrigation area (2012) and outside the irrigation area. Source: Own elaboration.

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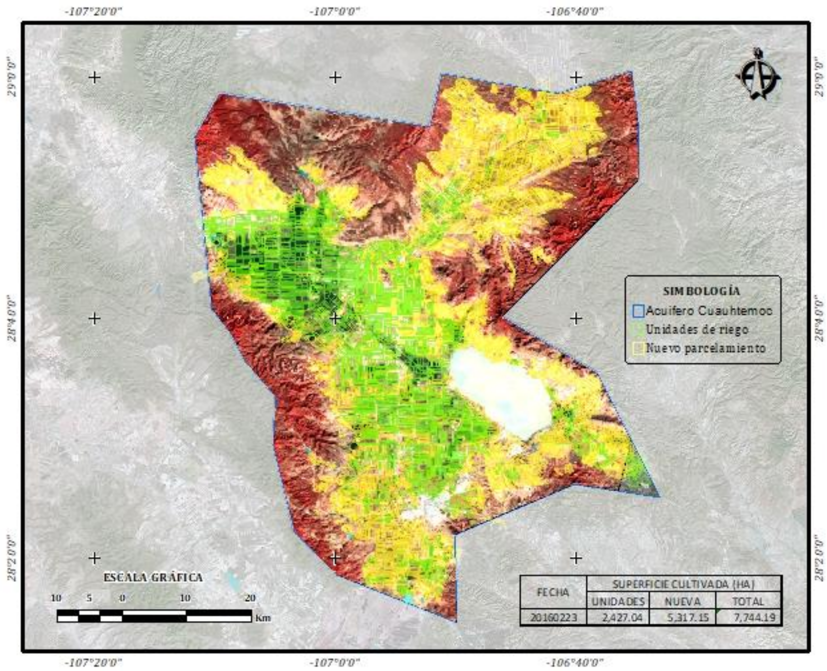

Figure 7. Composite image NDVI Landsat 8 (23/02/2016) - parceling in irrigation area (2012) and outside the irrigation area. Source: Own elaboration.

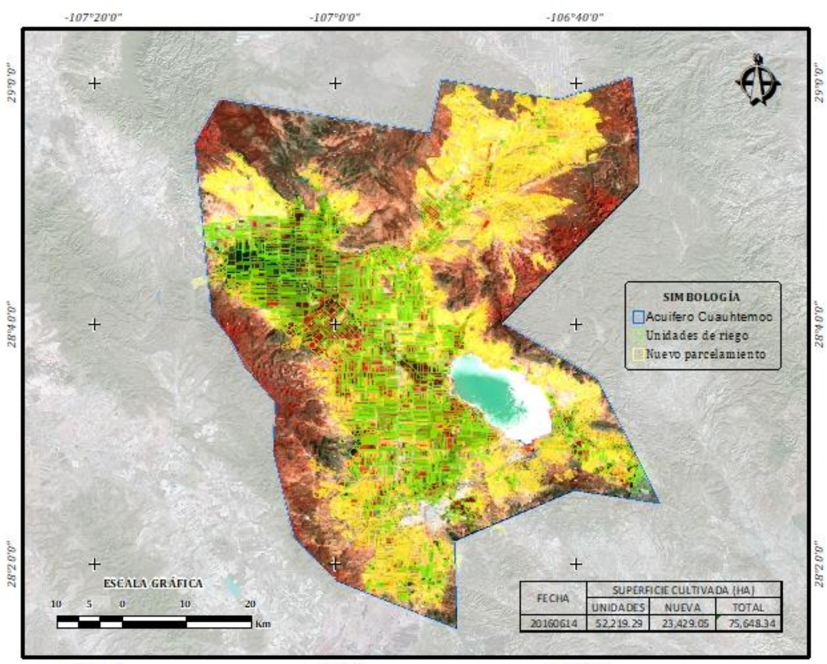

Figure 8. Composite image NDVI Landsat 8 (14/06/2016) - parceling in irrigation area (2012) and outside the irrigation area. Source: Own elaboration.

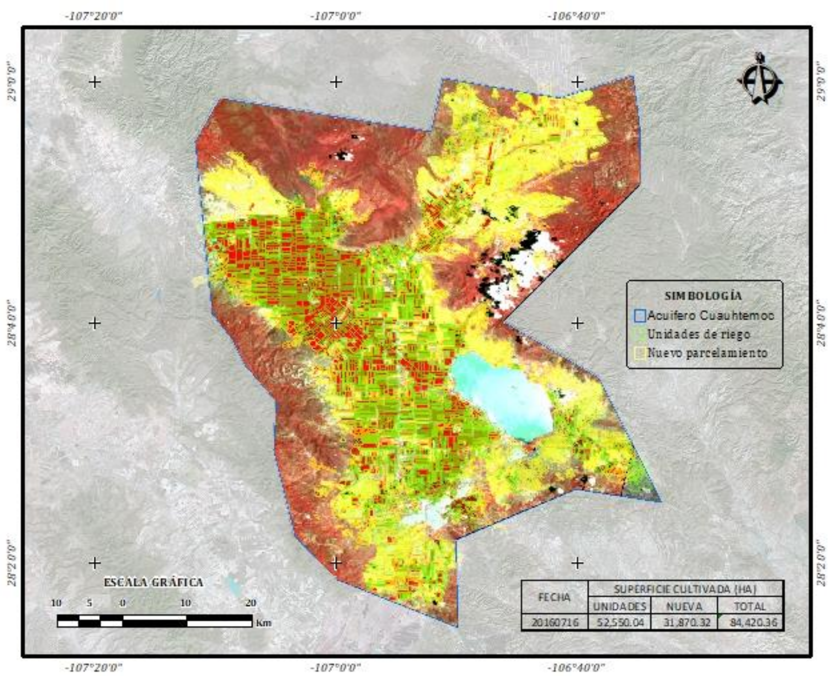

Figure 9. Composite image NDVI Landsat 8 (16/07/2016) - parceling in irrigation area (2012) and outside the irrigation area. Source: Own elaboration.

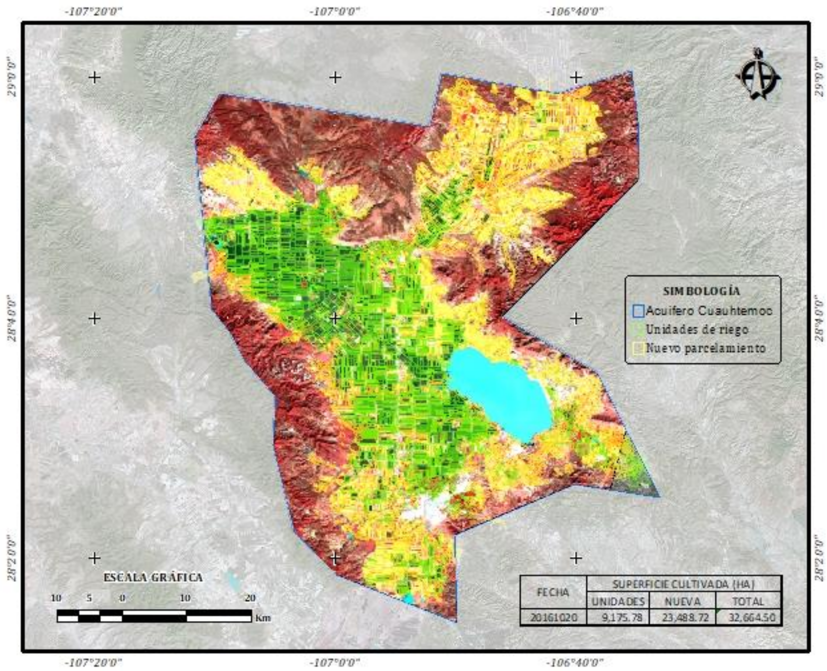

Figure 10. Composite image NDVI Landsat 8 (20/10/2016) - parceling in irrigation area (2012) and outside the irrigation area. Source: Own elaboration.

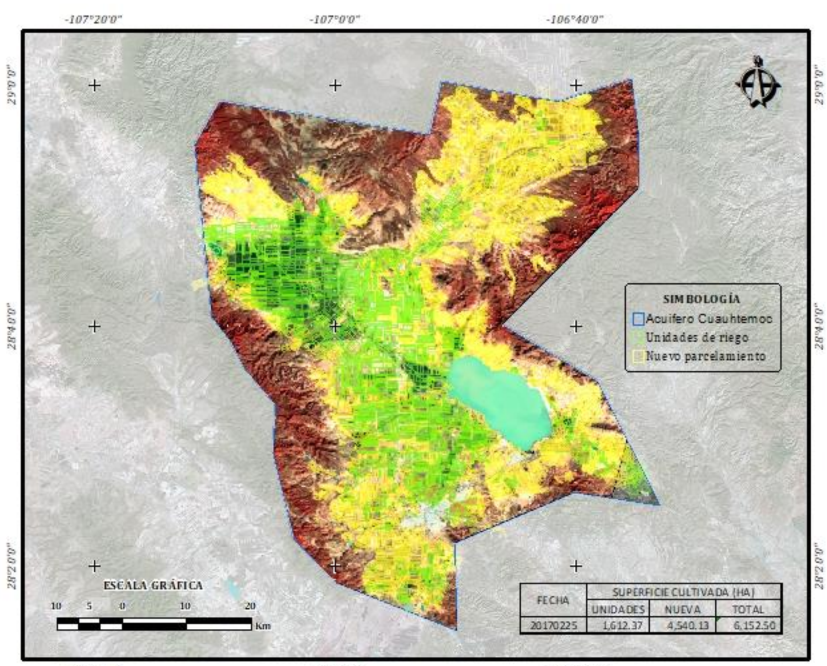

Figure 11. Composite image NDVI Landsat 8 (25/02/2017) - parceling in irrigation area (2012) and outside the irrigation area. Source: Own elaboration.

Based on the results generated, Table 10 and Figure 12 are presented.

Table 10. Estimated area under cultivation in the Cuauhtémoc aquifer, for different dates in 2015 and 2016). Source: Own elaboration.

Date	Acreage				
	Irrigation units		Outside the irrigation area		Total
	(ha)	(%)	(ha)	(%)	(ha)
20150612	52 225.88	66.12	26 762.84	33.88	78 988.72
20150831	51 750.75	43.00	68 605.50	57.00	120 356.25
20151103	8 135.83	50.86	7 860.51	49.14	15 996.34
20160223	5 317.15	68.66	2 427.04	31.34	7 744.19
20160614	52 219.29	69.03	23 429.05	30.97	75 648.34
20160716	52 550.04	62.25	31 870.32	37.75	84 420.36
20161020	9 175.78	28.09	23 488.72	71.91	32 664.50
20170225	4 540.13	73.79	1 612.37	26.21	6 152.50

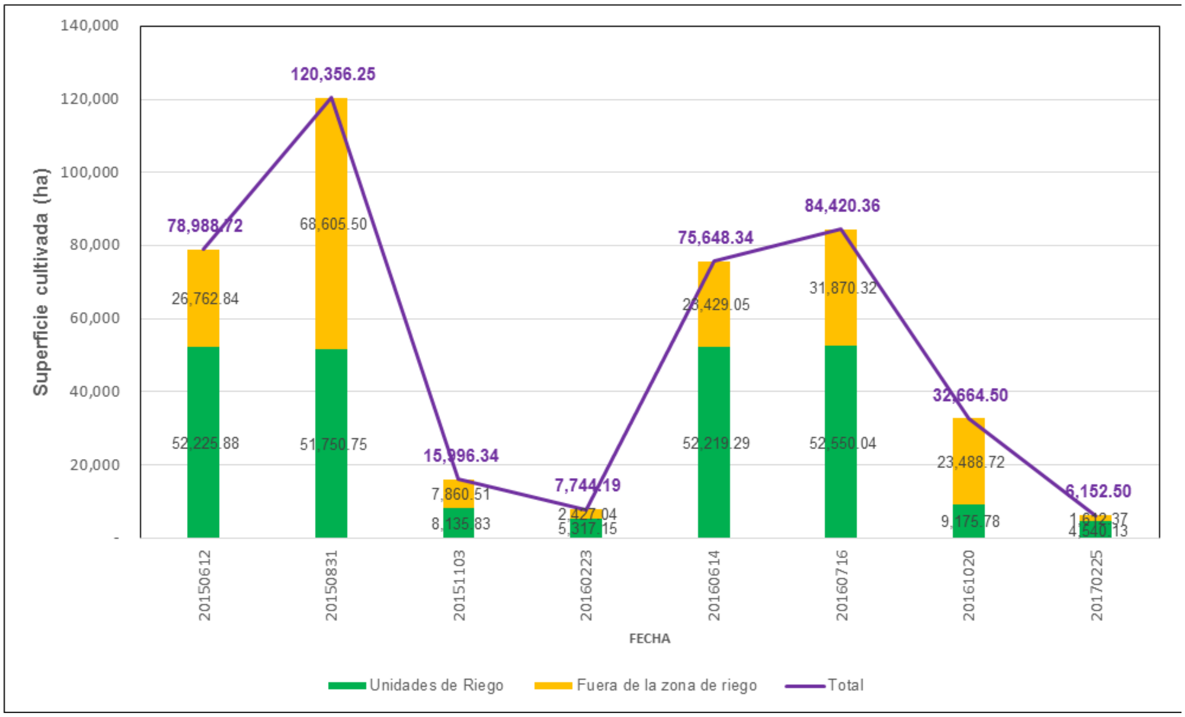

Figure 12. Area planted determined through the NDVI for different dates in the irrigation area (2012) and outside the irrigation area. Source: Self-elaboration with study results.

Because the image with higher visibility for the estimation of surface is presented for the images of August 31, 2015 and July 16, 2016, the corresponding results to that date are presented in the Table 11.

Table 11. Planted area and crop pattern in 2015 and 2016. Source: Own preparation with estimated Landsat 8 satellite image data.

	Cultivated area (ha)	
Crop	**2015$^{(1)}$**	**2016$^{(2)}$**
Corn	44 897.11	45 653.13
Apple	6 377.58	6 449.82
Beans	202.41	176.16
Oats	165.75	157.25
Crop Association*	40.66	43.27
Other crops**	67.24	70.41

Total	51 750.75	52 550.04
Area detected outside the UR ***	68.605.50	31 870.32
Total cultivated area	**120 356.25**	**84 420.36**

(1) Estimated Landsat 8 satellite image area of August 31st, 2015.

(2) Estimated Landsat 8 satellite image area of July 16th, 2016.

* Two crops planted together.

** Other crop: cherry, peach, vegetables, tomato, sorghum, grape.

*** Area sown outside the polygonal parcel of the aquifer GIS model.

It is possible to determine that more than 120,000 hectares are planted in the aquifer for the Spring Summer cycle. 43% of the planted surface in the aquifer is cultivated within the previously defined irrigation unit areas. While 57% of the sown area is cultivated in areas where it is difficult to quantify the irrigation-temporal effect, since it is likely that part of this area is present irrigation of aid considering the time in which it is sown and given the crops of the region and the climatic conditions, irrigation is imperative for the installation of crops in the months of May-June.

Also, the statistics of the Ministry of Agriculture, Livestock, Rural Development, Fisheries and Food (Sagarpa) for the municipality of Cuauhtémoc are presented in Table 12.

Table 12. Agricultural Statistics of the municipality Cuauhtémoc cycle 2015. Source: Own elaboration with data from Sagarpa (2017). http://infosiap.siap.gob.mx/aagricola_siap_gb/ientidad/index.jsp

Crop	**Area (ha)**		**Production (Ton)**	**Production value (thousands of pesos)**
	Sow	**Harvest**		
Irrigation mode				
Forage oats	332.00	332.00	11,365.00	4,724.06
Grain oats	50.00	50.00	225.00	787.50
Oats seed grain	45.00	45.00	171.00	837.90
Cherry	12.00	12.00	48.00	4,560.00
Peach	13.00	9.50	152.00	1,216.00
Corn	118.21	118.21	2,646.92	17,352.88

Crop	Area (ha)		Production (Ton)	Production value (thousands of pesos)
	Sow	Harvest		
Strawberry	1.75	1.75	52.75	1 751.38
Beans	100.25	100.25	150.00	1 252.50
Apple	8 311.71	7 948.71	190 892.00	1 086 689.40.
Grain corn	37 740.00	36 651.00	378 735.90	1 108 342.64
Pasture	25.00	25.00	630.00	201.60
Red tomato	9.75	9.75	3 855.00	64 144.44
Wheat grain	339.00	339.00	1 974.00	6 281.40
Apple nurseries	4.00	4.00	180 000.00	6 480.00
Subtotal irrigation	**47 101.67**	**45 646.17**	**770 897.57**	**2 304 621.70**
	41.51%	**41.59%**	**50.81%**	**86.54%**
Temporary mode				
Green forage oats	41 300.00	41 294.00	683 195.00	219 873.50
Beans	16 827.00	14 592.00	12 204.17	105 137.83
Green fodder maize	3 000.00	3 000.00	33 000.00	17 487.03
Grain corn	4 200.00	4 180.00	3 822.00	11 092.50
Green forage sorghum	1 051.00	1 051.00	14 240.00	4 969.14
Subtotal temporary	**66 378.00**	**64 117.00**	**746 461.17**	**358 560.00**
	58.49%	**58.41%**	**49.19%**	**13.46%**
TOTAL	**113 479.67**	**109 763.17**	**1 517 358.74**	**2 663 181.70**

The comparison of the areas reported by Sagarpa in 2015 and the estimation of the area by satellite images of the same year is presented in Table 13.

Table 13. Comparative Agricultural Statistics of Sagarpa and results of the quantification of area planted with satellite images, in 2015. Source: Own elaboration with Sagarpa data and surface quantification results using Landsat 8 satellite images of August 31, 2015.

Concept	Area sown	
	Data reported by Sagarpa, 2015	Quantification with satellite images of August 31st, 2015

		Irrigation	Temporary	Total	Irrigation units	Outside the irrigation area	Total
Surface	(ha)	47,101.67	66,378.00	113,479.67	51,750.75	68,605.50	120,356.25
	(%)	41.5%	58.5%	100.0%	43.0%	57.0%	100.0%

According to the results of Table 13, there is a difference of 6,900 ha in the area sown in the Cuauhtémoc aquifer area, and most of this area corresponds to the irrigation area since the difference between the statistics of Sagarpa and the quantification carried out is slightly greater than 4,600 ha, which represents 9 percent of the irrigation area that remains to be considered in the Sagarpa statistics. On a global level, Sagarpa statistics lack to consider an additional 5.7% of sown area.

It is pertinent to note that the area quantified as irrigated, through the use of satellite images, is strictly related to the area considered as irrigation from the information layers of the geographic information system model of the Cuauhtémoc aquifer, 2012. However, there may be area planted outside these polygons that would be susceptible to being sown with irrigation.

Conclusions

The use of Information Technologies, both geographic information systems and remote sensing techniques, is now a fundamental tool in the integration and analysis of information for the realization of various studies. However, it is essential that the platform has duly validated field information.

In the Cuauhtémoc aquifer, the fieldwork carried out to identify the water uses allowed to integrate the information of users, type of use, and in the case of agricultural users: surface, production and production value. This made it possible to ascertain the current state of agricultural production and water use in the aquifer.

The quantification of areas harvested within the Cuauhtémoc aquifer area showed that the area reported by Sagarpa statistics for the Cuauhtémoc aquifer, is less for at least 10 percent in the irrigation area, compared to the area sown and quantified through the use of satellite images, compared to the total area sown in the aquifer that includes irrigation and temporal, was found to be approximately 6 percent less than that quantified with remote sensing.

The area dominated by irrigation units within the Cuauhtémoc aquifer, of the 2012 GIS model, is lower than the area quantified through Landsat 8 satellite imagery for the years 2015 and 2016. However, the total area is not fully quantifiable because of the lack of total information on potential irrigation areas.

The development of the management proposal for the Cuauhtémoc aquifer should consider the current state of the aquifer, since it is located in a banned zone for the delivery of groundwater. According to the groundwater availability update (2009), there is no availability for new concessions.

The extraction of groundwater in the Cuauhtémoc aquifer has had a considerable increase, for the period from 1973 to 2000, it was determined that the extraction goes from 97.9 hm^3/year to 381.3 hm^3/year and currently up to 352.7 hm^3/year, thus the groundwater levels have gone from average depths of about 20 m in 1973 to 90 meters currently and in the future it will increase.

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