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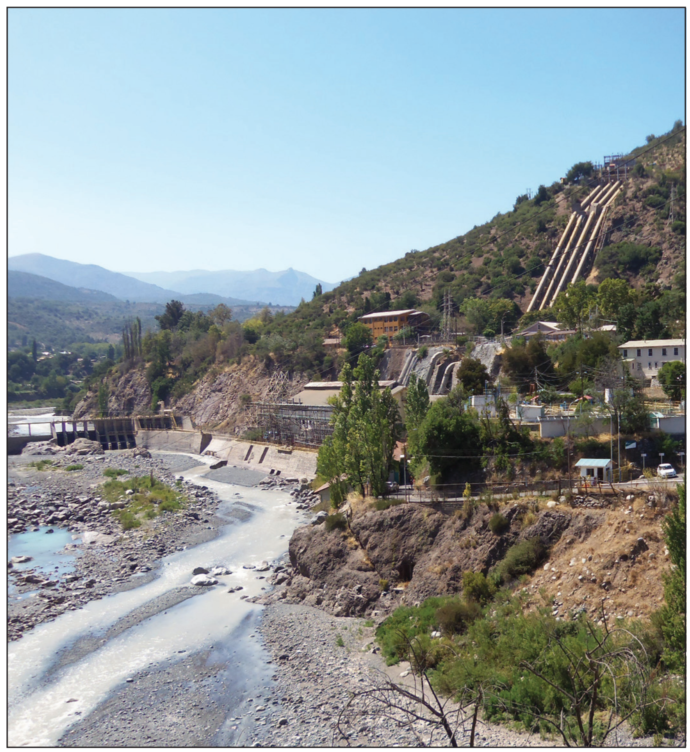

Cover: high section of the Cachapoal river, Andes precordillera, Machalí commune, Chile, where the hydroelectric power station of Coya pass is located, 30 km from Rancagua, whose operations date back to 1911 and supplies power to the mining company Codelco, Copper producer.

The assessment of the availability of water in a basin is a complex challenge because it has to do with the geographical characteristics of the place, use and behavior of the hydrological cycle, affected by processes of variability and climate change. Agriculture depends on climatic conditions, as fluctuations or variabilities have a significant effect on crop yields. Therefore, the evaluation of the use of the water resource during the agricultural production process, considering the climatic variability, would contribute to encourage a better management in the water management practices in an area. In this context, the water footprint has been proposed as a tool that identifies the use of water and the effects of agricultural production, providing information for decision making. See the article "Variability of the water footprint of the cereal crop, Cachapoal river, Chile" by Vanessa Novoa *et al*. (pp. 35-49).

Photo: Vanessa Novoa.

Hydroponic cultivation of celery in the Campo de Cartagena, Murcia, Spain.

Photo: José Luis García Aróstegui.

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Sustainable Crop Irrigation and Overexploitation of Aquifers

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Abstract

Palacios-Vélez, O. L., & Escobar-Villagrán, B. S. (March-April, 2016). Sustainable Crop Irrigation and Overexploitation of Aquifers. *Water Technology and Sciences* (in Spanish), 7(2), 5-16.

This article discusses the basic premises of "sustainable development" and mentions some of the enormous challenges that need to be addressed to achieve such development. A study by the Stockholm Environment Institute and the Tellus Institute of Boston (Great Transition. The Promise and Lure of the Times Ahead) presents three possible scenarios related to this topic: a) conventional, b) catastrophic and c) a "great transition." The need and importance of crop irrigation in the majority of regions in the country is then discussed, and the hydraulic infrastructure built up to 2013 is summarized. The main challenges involved in crop irrigation are also mentioned, including: a) lack of social awareness about the real value of water on the part of authorities as well as agricultural and urban users; b) changes in the amount and quality of runoff from rivers; c) overexploitation of aquifers, d) salinization of soils, e) contamination of aquifers and surface water bodies and f) conflicts between agricultural water users and industrial and municipal users. The increasingly intensified use of groundwater has resulted in an overexploitation of many aquifers, although it is difficult to correctly evaluate the degree of overexploitation. Two methods to evaluate this are presented —hydrological balance and evolution of groundwater levels— based on the example of the Texcoco aquifer. Lastly, some recommendations are presented to address the problem of overexploitation of aquifers.

Keywords: Sustainable development, crop irrigation, overexploitation of aquifers.

Resumen

Palacios-Vélez, O. L., & Escobar-Villagrán, B. S. (marzo-abril, 2016). La sustentabilidad de la agricultura de riego ante la sobreexplotación de acuíferos. Tecnología y Ciencias del Agua, *7(2), 5-16.*

Se discuten los supuestos básicos del "desarrollo sustentable" y se comentan algunos de los enormes retos que deberán afrontarse para alcanzar ese desarrollo. Sobre este punto se comenta un estudio realizado por el Stockholm Environment Institute y el Tellus Institute de Boston (Great Transition. The Promise and Lure of the Times Ahead) en relación con tres escenarios posibles: a) escenario convencional, b) escenario catastrofista y c) escenario gran transición. Después se expone la necesidad e importancia de la agricultura de riego en la mayor parte del país, y se presenta un resumen de la infraestructura hidráulica construida hasta 2013. Se comentan también los principales retos a la que se enfrenta la agricultura de riego, como son: a) falta de una conciencia social sobre el valor real del agua tanto por parte de la autoridad como de los usuarios agrícolas y urbanos; b) alteraciones a la cantidad y calidad del escurrimiento de los ríos; c) sobreexplotación de acuíferos; d) ensalitramiento de los suelos; e) contaminación de acuíferos y cuerpos superficiales de agua, y f) conflictos entre el uso agrícola del agua, y los usos industrial y municipal. El empleo cada vez más intenso de las aguas subterráneas ha generado la sobreexplotación de muchos acuíferos, aunque es difícil evaluar de forma correcta el grado de sobreexplotación. Se exponen dos métodos para llevar a cabo esta evaluación: a) balance hidrológico y b) evolución de niveles de agua subterránea, tomando como ejemplo el acuífero de Texcoco. Por último, se dan algunas recomendaciones para enfrentar el problema de la sobreexplotación de acuíferos.

Palabras clave: *desarrollo sustentable, agricultura de riego, sobreexplotación de acuíferos.*

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Introduction

Agricultural activities in general, particularly irrigation, have significantly changed the landscape of our planet. They have also altered many delicate ecosystems that have existed well before the rapid growth in human development that occurred over the past 200 to 250 years —a completely insignificant amount of time compared to the estimated age of the earth. The development of communities, communications and industry along with energy generation and agriculture, particularly highly technified and irrigated crop production, have exponentially increased over the past 100 or 150 years, of which the last decades are of most concern. A series of problems have arisen along with this exponential growth that are threatening growth itself and must be very carefully analyzed. One problem is the exploitation of aquifers by both agricultural as well as industrial and urban water users.

The overexploitation of aquifers is a problem that needs to be solved in order to achieve "sustainable development," defined as development that satisfies the needs of the current generation while not compromising the ability of future generations to similarly have their needs met. Sustainable development should be *socially acceptable, economically viable and environmentally responsible*, although strictly speaking it is not certain whether these three conditions can be simultaneously met. This concept was popularized at the 1992 United Nations Conference on Environment and Development, commonly known as the Río de Janeiro Summit, or Earth Summit. The Sustainable Development Division of the United Nations Department of Economic and Social Affairs ((http://www. un.org/esa/sustdev/documents/docs_sdissues.htm) lists 42 areas of activity required to achieve this type of development. Similarly, Agenda 21, which is a series of proposals by the 1992 Conference on the Environment and Development (http://www. un.org/esa/sustdev/documents/agenda21/english/agenda21toc.htm), presents actions in 40 different areas or subjects that need to be addressed to achieve this type of development. Perhaps including a high number of actions to be met complicates monitoring and evaluation. It seems to us that four key action areas should be emphasized: 1) eradicating poverty, 2) conservation of natural resources, 3) preventing and combating pollution and 4) combating global warming. These are briefly discussed below.

1. *Eradicating poverty.* There seems to be a consensus that to achieve sustainable development the participation of all sectors of the society is needed, particularly the most numerous, which tends to be the poorest. Nevertheless, this participation will be achieved only after first reducing the enormous social and economic inequalities between rich and poor countries as well as within each nation. In the richest countries, the *per capita* annual gross domestic product is 30 000 to 100 000 U.S. dollars per inhabitant, and exceeds 100 000 in the case of Luxemburg. Meanwhile, the income of the poorest nations is under 1 000 US dollars per inhabitant annually, that is, at least 30 times less (http://datos.bancomundial.org/indicador/NY.GDP.PCAP.CD). Enormous differences also exist within each country, which have been increasing year after year. As in other countries in Latin America, nearly half of the population in Mexico lives in conditions of poverty or extreme poverty. Obviously those who have the least are only thinking about how to feed their families. They cannot be expected to be concerned about the environment, global warming or what could happen to future generations. Poverty and social inequality are therefore the main obstacles to sustainable development.

2. *Conservation of natural resources.* This action is practically synonymous with sustainable development, since overexploitation and even depletion would mean real catastrophe for humanity. Therefore, natural resources urgently need to be carefully and efficiently used with good planning and monitoring, particularly water, soil, subsoil resources and the biota. Meanwhile, demographic growth over the past 100 years is placing great stress on natural resources, especially in less developed countries. Thus, this growth urgently needs to be reduced.

3. *Conservation of natural resources.* This action is practically synonymous with sustainable development, since overexploitation and even depletion would mean real catastrophe for humanity. Therefore, natural resources urgently need to be carefully and efficiently used with good planning and monitoring, particularly water, soil, subsoil resources and the biota. Meanwhile, demographic growth over the past 100 years is placing great stress on natural resources, especially in less developed countries. Thus, this growth urgently needs to be reduced.

4. *Combating global warming.* While it is recognized that developing countries contribute to the emission of greenhouse gases and global warming, their part is much less than that of developed countries such as the United States, China and Japan, as well as the European Union. We must increase our efforts to reduce energy consumption that is dependent on oil and increase the use of alternative energies such as wind, solar and geothermal, as well as energy from biomass. It must be recognized that oil will be depleted sooner or later and that it will become increasingly inaccessible. Thus, the use of biofuels urgently needs to be encouraged, learning from the experience in Brazil, a country that has made considerable progress in this regard. This will contribute to decreasing the accumulation of greenhouse gases and reducing global climate change.

Environmental awareness must be created in order to obtain broad participation from society. All those who have had the opportunity to work on these problems, to lesser or greater degrees, should participate in this effort. To this end, all means need to be used to explain the risks posed by overexploiting natural resources, pollution and global warming —for the survival of humans, animals and vegetation. Promoting changes in lifestyles is crucial in order to begin substituting values based on consumerism and individualism with those involving cultural, artistic and intellectual development, as well as social solidarity with less advantaged classes.

Contributions by the Stockholm Environment Institute and the Tellus Institute, Boston

When contemplating the problems involving sustainable development, it is normal to question whether we are capable of overcoming all the obstacles and attaining an ecological balance that will enable us to live well without endangering future generations; or whether we will continue deteriorating, with the possibility that organized society will disappear. Research groups from universities and scientific institutions are trying to answer this question, including a study performed by the Stockholm Environment Institute and the Tellus Institute in Boston, Massachusetts. With the support of these institutions, a group of researchers headed by Paul Raskin (2002) produced a report entitled "Great Transition: The Promise and Lure of the Times Ahead." This study considers three plausible scenarios: evolutionary, catastrophic and "a great transition."

According to this study, *evolutionists* are optimistic. They think the prevailing patterns seen today can generate prosperity, stability and ecological health with no big surprises or major disruptions. They believe incremental adjustments in markets and government policies will be able to control social, economic and environmental problems.

The *catastrophists*, on the other hand, fear that social, economic and environmental tensions will not be resolved and will result in terrible consequences for the future of the world. There will be a division into two opposing levels —a few fortified enclaves for the privileged elites and large chaotic and anarchistic sectors for the impoverished majority.

Lastly, those hold the perspective of the *great transition* share these fears but also believe that through active participation —primarily by young people and non-governmental organizations (NGO)— and with the wide use of social networks and new information technologies we will be able to influence how governments and large corporations act, to the point of achieving the changes and transformations needed to renew society and attain sustainable development. Nevertheless, this will be accomplished only after a serious global crises, which are expected to occur around the year 2015 (study performed in 2002).

These scenarios represent three possible worlds: one with incremental adjustments, another cataclysmic and the third with structural changes and renewal.

Crop Irrigation

Problems related to sustainability can be analyzed according to sectors of human activity. The main sector with the greatest impact on the environment is agriculture, and irrigation in particular. In the specific case of Mexico, irrigation is indispensable or necessary for the majority of the country, which has an annual mean rainfall of roughly 772 mm. Nevertheless, usually water is not spatially distributed evenly throughout the country. Large regions in northwestern Mexico have an annual mean rainfall of less than 200 mm while the southeastern portion of the country has over 3 000 mm. Precipitation also has wide seasonal variations including dry periods with virtually no rain and regions with monthly precipitation of roughly 500 mm. These natural conditions have led to increased irrigation as population growth and economic development have raised demand for agricultural products. Although there are regions in the country where seasonal farming is successful, the irrigation of crops such as corn, sorghum, wheat and beans generally provides 2 to 3 times more yields than seasonal farming. More revealing of the importance of irrigation is that, in 2014, the total value of agricultural production was estimated at $238 559 104.00 of which 64% ($152 310 412.00) corresponded to irrigated crops and only 36% ($86 248 692.00) to seasonal crops. It is important to add that 4 119 605 hectares of irrigated crops and 10 980 356 ha of seasonal crops were harvested. (http://www.siap.gob.mx/cierre-de-laproduccion-agricola-por-estado). This explains the rapid development of irrigation in our country since the founding of the National Irrigation Commission in 1926 and the creation of the Ministry of Water Resources in 1947. The data demonstrate the importance of fostering the productive potential of irrigated land and improving the efficient use of water. This will make it possible to increase the irrigation area and the production of crops, since population growth and the urgency to increase buying power will continue to raise the demand for all types of agricultural products. Table 1 presents a summary of the main hydraulic infrastructure built as of 2013 for different users in the country.

Challenges Faced by Crop Irrigation

A series of challenges will have to be faced in order to achieve sustainable crop irrigation.

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Some of these include:

a) *Lack of awareness about the real value of water.* The first problem facing water policies in Mexico is the lack of awareness about the real value of water on the part of the authorities as well as agricultural and urban users. This is evident in the inefficient and often careless use of water.

b) *Gravity Irrigation Systems and Changes in the Quantity and Quality of Runoff from Rivers*. The purpose of irrigation systems in arid and semiarid zones is to collect, store, transport and distribute rainwater, channeling it to crop fields to meet the water requirements of crops and thus generate and improve yields. Irrigation systems are usually composed of a dam and its reservoir located in a topographically suitable area in a river channel, and a system of canals and hydraulic structures for its operation. Drainage systems complement irrigation systems. This includes drainage of parcels, sometimes using buried plastic tubes, as well as collector drainage with different arrangements that send the drainage water to a receiving body such as the ocean, an inland lake or the river itself. From the environmental perspective, a very important characteristic to be considered is that the soluble salt contents of drainage water are always higher than the original water from the river. This is because the crops' evapotranspiration process uses water while leaving soluble salts behind in the drainage that flows into water tables, aquifers or drains. This drainage also contains different agrochemical residues from substances used in modern agriculture. All of this means that a river ends up with less water after it is taken out for irrigation, and poorer quality water when the river receives drainage from irrigation systems. This situation can dramatically worsen if the river has a cascade of irrigation systems, something which is beginning to be seen more often as crop irrigation has developed over the past 100 years.

Irrigation systems are as old as humanity itself. Some very old systems are still in operation, such as the Nile River system in Egypt, while many others have disappeared, such as in Mesopotamia and ancient Persia. Others have serious problems or are en route to extinction after having provoked unprecedented ecological catastrophes. It is of particular interest that irrigation specialists know about

Table 1. Hydraulic infrastructure build in Mexico as of 2013.

Hydraulic infrastructure 5,163 water storage dams and dikes, with a total storage capacity of roughly 150 km^3, equivalent to 10% of the annual precipitation	
Agricultural Infrastructure	**Urban Infrastructure**
6.4 million hectares irrigated, of which 3.4 million correspond to 85 irrigation districts and 3 million to over 39 000 small "irrigation units."	742 drinking water purification plants in operation.
A water volume of 62 km^3/year is used for irrigation, of which 21 km3/year is extracted from aquifers.	2 287 municipal wastewater treatment plants in operation and 2 617 industrial wastewater treatment plants in operation; 3 000 km of aqueducts.

Source: Semarnat-Conagua, 2014.

these experiences in order to be aware of the hazards involved in irrigation and the excessive use of agrochemicals, to attempt to prevent similar tragedies.

The most serious ecological catastrophe caused by an irrigation system occurred in the Amu Darya and Syr Darya rivers that empty into a large lake called the Aral Sea (because its original size was large). These rivers irrigate land in the former Soviet republics of Tadzhikistan, Kyrguistán, Uzbequistan,Turkmenistan and Kazajstan . The irrigation system began to be built in the 1930s, but there was a marked rise in the 1960s when the Soviet authorities decided to substantially increase cotton production to export the product as well as meet the growing internal demand. This crop is known to require large irrigation volumes and the use of many agrochemicals such as fertilizers, insecticides, pesticides and herbicides. This increased irrigation greatly reduced the amount of runoff that reached the Aral Sea, decreasing the area and volume of the lake. In addition, the small runoff volumes had higher contents of soluble salts and hazardous agrochemical residues. Therefore, not only did the lake become smaller but the quality of the water worsened, harming the fish and the health of the population. The damage was really incalculable, not only in economic terms but also socially and politically. Much has been written lately about this problem, and while several courses of action to mitigate the damage have been mentioned they all require large investments and a good deal of time. It suffices to say that in January 1994, the republics of Kazajstan, Uzbequistan, Turkmenistan, Tadzhikistan and Kyrguistan signed an agreement to allocate 1% of their budgets to help to reverse the damage. By 2006, the restoration projects by the World Bank, particularly in the northern portion of the lake, were bringing about some improvements, providing unexpected relief to what was an extremely pessimistic situation (http://www.answers.com/aral+sea?cat=travel&gwp=11&method=3&ver=2.3.0.609). In Mexico, this should serve as a warning as to what could happen with the Chapala, Cuitzeo and Patzcuaro lakes, which have seen decreases in the quantity and quality of the runoff that reaches them and are now polluted by urban, agricultural and industrial wastewater.

c) *Pumping Irrigation Systems and Overexploitation of Aquifer*. As mentioned, one-third (21 km3) of the total water (some 62 km^3) used for crop irrigation in our country comes from the subsoil. In its evaluation of water availability in 2013, published in the Official Journal of the Federation (DOF, Spanish acronym),the National Water Commission (Conagua, Spanish acronym) identified and delineated 653 aquifers, 106 of which are overexploited. That is, the water extracted from these aquifers exceeds the estimated mean recharge, and therefore the piezometric levels are decreasing from year to year. Since this extraction scheme cannot last indefinitely, pumping wells need to be deepened and relocated. The situation in the Valley of Mexico is really quite critical, in states such as Queretaro, Guanajuato and Aguascalientes where most of the water is used for municipal and industrial purposes. Sonora and Baja California Sur are also facing a critical situation. The problem with sustainable development is that "some experts think that to maintain food security an increase of 15 to 20 percent in water extraction is needed until 2025, [while] some environmentalists believe that extractions need to be decreased by at least 10% during this same period in order to conserve already stressed water resources" (Castro et al., 2006). Since many of the overexploited aquifers are a significant or only source of water for populations, the solution cannot consist of only eliminating the price subsidies for water and for the energy used for pumping, letting market forces discard users who obtain fewer benefits per cubic meter of water utilized. Rather, increasing water fees for agricultural as well as domestic users (besides the industrial users who already have much higher fees) is a necessity that society must now confront.

d) *Irrigation and Salinization of Soils.* The biggest risk for irrigated soil in arid and semiarid regions is probably the accumulation of soluble salts, which causes lower yields for the majority of crops. The accumulation process is well known and is especially problematic when irrigating with groundwater which tends to have higher soluble salt contents than surface water. Irrigation water is used by the crops' evapotranspiration processes while the salts in solution tend to accumulate on the top layers of the soil. Soluble salts can leach into the subsoil in arid and semiarid zones where rainfall is scarce, as well as when applying "over-irrigation" which is sometimes added to irrigation. If the water table levels remain near the surface of the soil (especially at least 1.5 m deep), the soluble salts return to the top layers through capillary rise. The drainage from irrigated zones keeps water table levels down to prevent or decrease the capillary rise of saline water and thereby prevent the salinization of soil. Nevertheless, because of a variety of economic reasons and a lack of appreciation of the benefit of drainage, only around 1% of the irrigated area in Mexico has piped underground drainage. It is important to mention that the existing collector drainage is made up of large ditches with an average spacing of roughly 1 km, which also keeps water table levels low and controls salinity. These are, in principle, aimed at draining parcels, and their wide spacing and frequently poor maintenance limits their desalinization capacity.

e) *Irrigation Systems and Pollution of Aquifers and Surface Water Bodies*. It is virtually impossible to prevent all of the irrigation volumes applied from percolating into the water table, even with drip irrigation. In addition, percolated water always contains soluble salts and residues from the different agrochemicals used in agriculture, particularly nitrogenated fertilizers which often are applied in larger amounts than other agrochemicals. Percolated water can primarily follow two routes, it can flow through existing drainage systems into water bodies that receive drainage effluents or it can percolate into aquifers. The drainage systems are the only routes through which soluble salts and agrochemical residues reach water bodies and pollute them. This type of pollution is different than that caused by urban and industrial drainage. It is also not as noticeable visually (and in terms of odors). But it can have catastrophic consequences for the environment, as was seen in the Aral Sea. Another negative effect on the environment is produced by nitrogenated fertilizers which contribute to the formation of algae in water bodies, which in turn clouds the water and deteriorates it in various ways, altering wild aquatic life. These problems are caused not only by the drainage of irrigation areas but also by all agricultural drainage in general, through which the fertilizers in the water reach rivers and lakes. All developed countries are addressing these problems by returning the water bodies to the states they were in before the exponential increase in the use of fertilizers during the second half of the 1900s. Another portion of the water that percolates into the water table does not flow through the drainage systems but rather continues to descend until reaching the aquifers. As is known, many water supply systems use groundwater that may be polluted by agrochemical residues and could affect the health of humans and animals.

f) *Conflicts between Agricultural, Industrial and Municipal Water Users*. Crop irrigation tends to use most of the water resources, although urban and industrial sectors are beginning to use more than the agricultural sector in several metropolitan regions in our country. As the population has grown and the economy developed, conflicts over the use of scarce water resources have intensified. In this battle, the agricultural sector will eventually have to considerably improve its water management efficiency and reduce its consumption of water for the benefit of domestic and industrial users, who have priority over agricultural users according to the National Waters Law (2013). These adjustments will require large investments to modernize and technify irrigation systems (as well as drinking water supply systems). It must be recognized that, among the measures that will have to be taken sooner or later, the most important will be an increase in fees for irrigation services, particularly pumping, as well as fees for portable water. Fees that discourage wasting water is the best incentive to use it more carefully and efficiently.

Gravity and Pumping Irrigation System

Crop irrigation was first developed using water directly from rivers. More complex irrigation systems then began to be built, composed of storage dams and networks of diverters and canals to distribute water to plots. Nevertheless, groundwater began to be pumped as surface runoff became more scarce. Some of the costs related to exploitation by pumping water for agriculture are higher than taking water from rivers or dams, such as higher fees for the use of groundwater than for surface water, as established by the Federal Tax Law (2014). Pumping costs also add to the expense of groundwater, which depends on the cost of energy and the pumping depth. Pumping depths have exceeded 200 m in some overexploited regions, including the Valley of Mexico, Bajío and some farming areas in northern and northwestern Mexico. Meanwhile, Davis and DeWiest (1966) reported that using groundwater has more advantages than surface water since the chemical composition of groundwater is less variable over time and more water is generally stored in the subsoil than on the surface. It is therefore easier to exploit since long pipelines are not needed and it is immediately available. In addition, surface water is more exposed to the pollution which is currently present and therefore its use requires additional treatment and pipeline costs. Extracting water from the subsoil continues to be less expensive, given its better quality it is not necessary to investment in treatment.

Nevertheless, depending on groundwater for irrigation faces the increasing problem of overexploitation of aquifers. The stress on the aquifers has grown not only because of excessive extraction but also because of reduced recharge from infiltration as a result of deforestation and land use changes. The number of overexploited aquifers in Mexico has increased substantially since 1975: from 32 in 1975 to 36 in 1981, 80 in 1985, 97 in 2001 and 106 in 2013 (Semarnat-Conagua, 2014). Due to overexploitation, the groundwater reserve in the country is decreasing at a rate of nearly 5 km3/year. Nationally, the recharge of aquifers is estimated at 77 km3/year, and extractions at 27 km3/year, which is roughly 33.3% of the recharge. Although the balance

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seems to be positive, this is a national average and does not reflect the critical situation in some of the aquifers located in arid regions where the balance is negative. Some of the most overexploited aquifers are in the Lagunera region in the state of Coahuila, Costa de Hermosillo in Guaymas, Caborca in the state of Sonora, Celaya and Irapuato in the state of Guanajuato and the Valley of Mexico.

Uncertainty about the Degree of Overexploitation: the case of the "Texcoco Aquifer"

The first problem with combating the overexploitation of aquifers is the large degree of uncertainty about the estimated values of the components of the water balance and the geohydrological characteristics of the aquifers, based on which groundwater inflows and outflows are calculated. The problems with estimating the overexploitation of an aquifer can be demonstrated with the particular case of the Texcoco aquifer. This aquifer is the primary source of water for 12 municipalities in the eastern portion of the Valley of Mexico, with a population of roughly 1.5 million inhabitants. The economic development of this region is closely related to the ability to sustainably manage the aquifer. Determining a reliable overexploitation value is entirely indispensable to the capacity to develop and implement a sustainable aquifer management plan (Escobar & Palacios, 2012).

The data published in the *Official Journal of the Federation* (DOF, Spanish acronym) in 2003 and 2009 (Figure 1) show the high degree of uncertainty in the recharge and extraction values calculated for the Valley of Mexico aquifers.

In 2003, this aquifer was reported to be the most overexploited of the 14 aquifers in the Valley of Mexico, with groundwater extractions estimated at 9 times recharge. Nevertheless, a later study in 2007 (published in the 2009 DOF) estimated extraction at roughly 15% more than recharge. This enormous difference in reported extractions is largely because the municipality of Ecatepec and the district of Iztapalapa —with extractions of over 300 hm^3/year —were reassigned from the Texcoco aquifer to different nearby aquifers. What is less understood is the enormous increase in the estimated recharge (from 49 hm^3/year in 2003 to 161 hm^3/year in 2007). Since no significant recharge works were produced during that period, the differences in these amounts may be due to how they were calculated, given that:

a) The calculation of real evapotranspiration —subtracting atmospheric precipitation to evaluate vertical recharge— is generally determined using imprecise methods, such as that by Turc (Conagua, 2006). It should also be mentioned that more precise models such as Penman-Monteith are more difficult to use because of a lack of the information required.
b) The calculation of groundwater flow using the Darcy equation requires knowledge of the potential gradient at the boundary of the aquifer and transmissivity, neither of which are reliably known.
c) The calculation of the extracted volume is based on an incomplete and outdated census of pumping wells, and the actual number of unauthorized wells is unknown.
d) Surface flow gauges often do not exist to calculate the inflow and outflow of surface water.

Methods to Evaluate the Degree of Overexploitation of an Aquifer

The degree of overexploitation can be quantified using two approaches (Escobar & Palacios, 2012):

a) The first is based on the study of the water balance of an aquifer, according to the general equation:

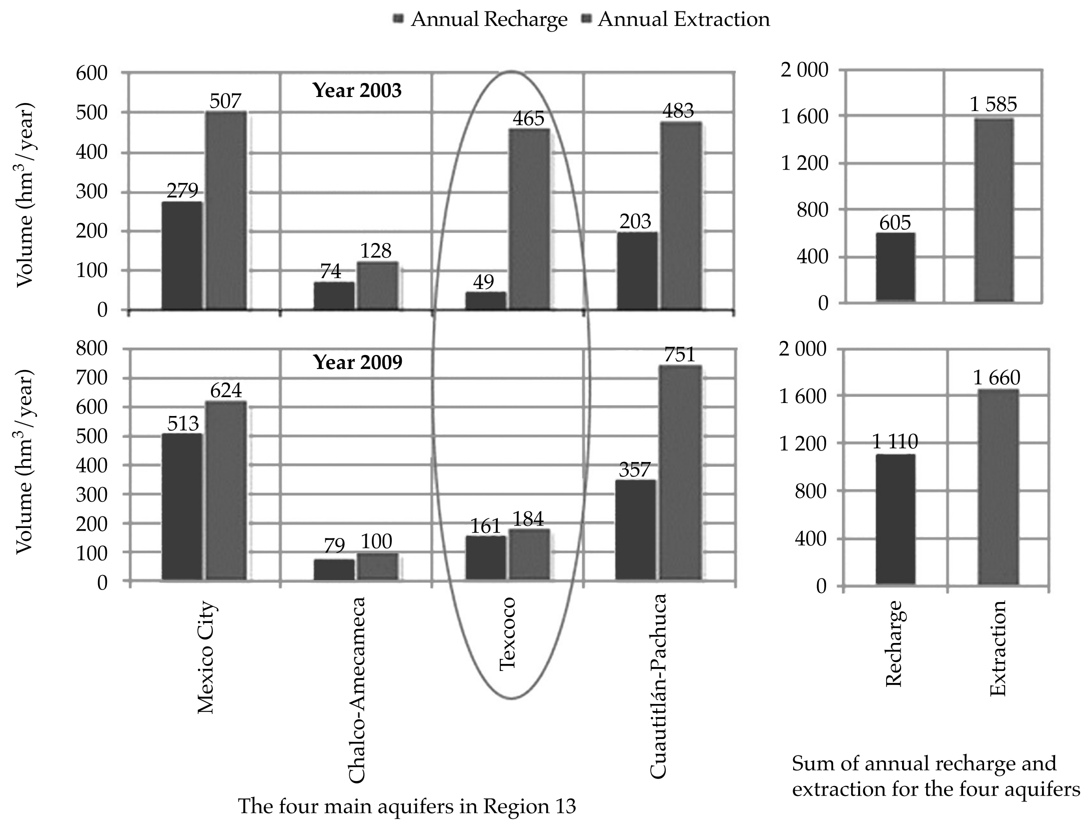

Figure 1. Comparison of extraction and recharge for the main aquifers in the Valley of Mexico.

$$I - O = \Delta S \qquad (1)$$

where:

I = total inflows of water into the aquifer.

O = total outflows of water from the aquifer.

ΔS = change in storage (overexploitation when $O > I$).

And:

$$I = \Delta P + I_{grn} + L_{IR} + L_{PWN} \qquad (2)$$

where:

ΔP = the fraction of precipitation that infiltrates.

I_{grn} = lateral inflow of groundwater.

L_{IR} = losses from infiltration in the irrigation network.

L_{PWN} = losses from infiltration in the drinking water network.

$$O = P + O_{grn} + O_{sur} \qquad (3)$$

where:

P = extractions of water by pumping.

O_{grn} = lateral outflow of groundwater.

O_{sur} = lateral outflow of surface runoff.

Overexploitation occurs when there is more outflow of water than inflow. Unfortunately, with the exception of atmospheric precipitation, the calculation or measurement of the components of the water balance usually present several problems —particularly the scarce or uncertain quality of the available information. In addition, to calculate groundwater inflow and outflow, knowledge about transmissivity and its variations in the aquifer is necessary, as well as about the water levels on the periphery, in order to determine gradients and calculate flows using the Darcy Law.

b) The second approach is based on the analysis of the evolution of the water levels in the aquifer, according to the following formula:

$$\Delta S = \pm \sum_{i=1}^{na} a_i h_i S_i \qquad (4)$$

where:

ΔS = change in storage (overexploitation when ΔS is negative).
a_i = area assigned to the i^{th} observation site.
h_i = mean evolution or variance of hydraulic recharge in well i.
S_i = storage coefficient.
na = number of elements into which the aquifer is divided.

If the trend in the water level data is negative, this clearly represents a decrease in the aquifer over time. This method requires a network of wells and piezometric devices to observe hydraulic recharge levels as well as pumping tests to determine the storage coefficient of the aquifer. For more information, see Conagua (2007), and Escobar and Palacios (2012).

Possible Solutions to the Overexploitation of Aquifers

A series of measures are described below, categorized according to technical studies and operational actions that can be used as a basis to develop a sustainable aquifer management plan.

Technical Studies

- Update the census of pumping wells.
- Estimate volumes extracted from unauthorized wells based on electric consumption data.
- Studies of the components of the hydrological water balance.
- Establish a network of wells and piezometric devices to monitor the hydraulic head that extends out to the boundary of the aquifer.
- Pumping tests to determine transmissivity and the aquifer's storage coefficient.

Operational Actions

- Promote the formation of a technical groundwater committee responsible for the management of the aquifer, including the identification and removal of unauthorized wells and ensuring that extractions do not exceed the volumes allotted.
- Foster a culture of paying for water services in cities and irrigation regions.
- Reduce the subsidies for irrigation and urban water services as well as for energy consumption to pump water.
- Artificial aquifer recharge projects (reforestation, recharge lagoons, absorption wells).
- Encourage the collection and use of rainwater for domestic consumption and vegetable gardens.

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Rural Drinking Water Systems. Institutions, Organizations, Government, Administration and Legitimacy

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Abstract

Galindo, E., & Palerm, J. (March-April, 2016). Rural Drinking Water Systems. Institutions, Organizations, Government, Administration and Legitimacy. *Water Technology and Sciences* (in Spanish), 7(2), 17-34.

Field information obtained from 12 systems located in 5 municipalities was used to analyze the size or number of intakes supplied and the type of organization, for the purpose of management, governance and administration, as well regulations for access to and exclusion from piped water service. The objective was to compare management models to determine the ones that are most suitable, effective and legitimate. Two factors were compared for their contribution to improving conditions —professionalization of the administration under the direction of managers versus the users themselves based on local knowledge systems. According to the evidence, we can state the following: no direct correlation exists between the number of intakes supplied and the type of organization; various systems can have a single centralized administration; the institutional structure designed by the users themselves represent more legitimacy; and this affects the efficiency of applying the regulations related to access and exclusion.

Keywords: decentralized operating entities, municipal departments, users committees, self-management, self-government, neo-institutionalism.

Resumen

Galindo, E., & Palerm, J. (marzo-abril, 2016). Sistemas de agua potable rurales. Instituciones, organizaciones, gobierno, administración y legitimidad. Tecnología y Ciencias del Agua, *7(2), 17-34.*

Con información obtenida en campo para doce sistemas localizados en cinco municipios, analizamos tamaño o número de tomas servidas y tipo de organización, para su manejo, gobierno y administración, así como las reglas de acceso y exclusión al servicio de agua entubada. El objetivo es comparar cuáles pueden ser los modelos de gestión más apropiados, eficaces y legítimos, y en la práctica quién hace mejor las cosas: la profesionalización de la administración bajo la dirección de gerentes o los mismos usuarios con base en sistemas de conocimiento local. Las evidencias nos permiten afirmar que no existe una correlación directa entre número de tomas servidas y tipo de organización; varios sistemas pueden tener una sola administración centralizada; el arreglo institucional diseñado por los mismos usuarios presenta mayor legitimidad, y ello se traduce en eficiencia para aplicar las reglas de acceso y exclusión.

Palabras clave*: organismos operadores descentralizados, direcciones municipales, comités de usuarios, autogestión, autogobierno, neo institucionalismo.*

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Introduction

Mexico has a long tradition of studying hydraulic works and their management (Bribiesca, 1958; Palerm, 1972), but little focus has been placed on small water systems for human consumption in both rural and urban areas (Ávila, 1996, 2002; Burguete, 2000; Birrichaga, 2007; Galindo & Palerm, 2007).

While urban water management studies reflect significant advances in administration and operations, as well as in terms of fees, financial efficiency and equitable supply, these only correspond to large-scale systems (Pineda, 1998, 2002, 2006; Martínez, 2002; Solís, 2005; Barkin, 2006; Soto, 2007; Saldívar, 2007) —that is, in cities— while little discussion has been focused on small-scale systems, which can also be called rural drinking water systems.

In order to contribute to knowledge about this subject, the objective of this article is to compare management models and field information to determine which are most suitable, effective and legitimate and to document which group performs better —professional administration by municipal departments, manager-run operating entities or the users themselves based on local knowledge systems with users committees.

Emergence of the OCSAS and the OLPE

Political scientist Elinor Ostrom (2011:7) categorically stated that, in spite of their enormous contributions, community organizations that provide water and sanitation services (OCSAS, Spanish acronym) are rarely discussed in texts about governability. She also commented that the systematic study of these organizational arrangements may be pertinent because they significantly contribute to achieving local self-government.

With respect to Latin America, the AVINA Foundation (2015) reported on their website that these organizations service 20 to 30% of the population in rural and peri-urban areas in Latin American countries and over 80 000 are quietly operating, many times with no knowledge on the part of decision-makers. This same foundation calculates that these organizations serve at least 70 million persons throughout the region, according to figures by international organizations,

With regard to the community-based management model, Enrique Aguilar (2011:62) indicated that while this is not the only option for rural systems in Latin America, in some countries it is the preferred option or the only one available.

Thus other organizational forms to ensure small-scale domestic water supply are possible. These include public, private or mixed operators that provide service in rural, peri-urban and small urban communities with under 30 000 residents. These organizations are known as small-scale operating entities (OLPE, Spanish acronym), about which important references have also been made (World Bank, 2008; Aguilar, 2011).

For the specific case of Mexico and this work in particular, as was already mentioned, of interest are systems that supply small populations and are managed by users committees, municipal departments or operating entities.

With regard to the emergence of the OCSAS and the OLPE, this may have arisen from interest over recent years in rural drinking water systems as a result of the controversy generated by the municipalization of these systems in some parts of the country (Galindo & Palerm, 2007; López, Martínez, & Palerm, 2013; Vargas, 2015). One example of this is the increasing number of national and local news articles (Sánchez, 2015).

In addition to the controversy between community and municipal organizations, some publications have documented management by users committees versus operating organizations or municipal departments (Sandoval, 2011; Pimentel, Velázquez, & Palem, 2012; Galindo & Palerm, 2012), as well as the participation of women, or lack thereof, in decision-making about community water management (García & Vázquez, 2013; Gutiérrez, Nazar, Zapata, Contreras, & Salvatierra, 2013). The consensus indicates that, in general, self-management includes

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democratic principles and effectively achieves compliance with regulations and agreements.

Municipality, Decentralization or Self-management. The case of Hidalgo

Before entering into the subject in detail, it is relevant to define what is officially understood as a rural drinking water system. According to the National Water Commission (Conagua, Spanish acronym), this type of supply refers to drinking water coverage for populations under 2 500 inhabitants, for those who have implemented public policy through the Program for Sustainable Drinking Water and Treatment Services in Rural Communities (Prosappys, Spanish acronym).

This program has existed since 1999 and is aimed at modernizing domestic water systems. For example, in 2014 the objective was to provide distribution to 600 000 residents and treatment to another 390 000 in rural and impoverished areas by promoting community management of the systems (Conagua, 2014).

With regard to the legal framework that regulates the provision of water for domestic use, it is worth mentioning that the 1980s and 1990s represented a turning point in which legal changes mandated administration and operations to be performed by local governments, as well as the maintenance of local piped water systems in their municipal jurisdiction (Procuraduría Agraria, 1992; Conagua, 2004).

Nevertheless, some studies on the subject report that state governments have legislated the possibility of users continuing to manage these systems on a small scale. For example, Jacinta Palerm (2014) mentions Chihuahua, Guanajuato, San Luis Potosí and Tabasco, and notes significant differences between a state entity and others.

As can be seen, the debate about the national legal framework for the management of water for domestic users and its implementation in the states is interesting, but we now want to focus specifically on institutional or organizational frameworks that can supply water for human consumption in small towns in the state of Hidalgo.

In Hidalgo, national laws are complemented by the 1999 State Water and Sewer Law and its respective Regulation (Periódico Oficial del Estado de Hidalgo, 1999). As a consequence, the resulting institutional arrangement in this state is clear, establishing that the supply of water for domestic use is a public service and permitting them to be run by only five types of public water and sewer services: municipalities, operating entities, inter-municipal operating entities, the State Water Commission, or licensed organizations with notarized articles of incorporation and registered with the federal treasury department (Galindo & Palerm, 2012; Rodarte, Galindo, Díaz, & Fernández, 2012)

Although this institutional arrangement and the corresponding organizations seem suitable in theory, the evidence found in the field shows that community organizations known as "users committees" are also present, which generally are created and operated outside the current legislation.

Methodology

Field information was gathered to compare the number of intakes receiving water service from a system and the type of organization that managed 12 of those systems. We also compared governance, administration and operations as well as the legitimacy of the regulations and the organizations responsible for their enforcement.

To identify the type of governance, attention was placed on the capacity to make decisions as well as the authority to issue orders related to the management of a system or systems run by a specific organization. From its inception, this investigation considered

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that governance may be limited by existing legislation or by regulations and restrictions established by the users themselves. Therefore, we classified self-governing systems as those managed by users based on a system of local knowledge, and bureaucratic systems as those run by municipal departments or operating entities designed in accordance with the regulations issued by the current legislation on drinking water.

The analysis of the administration was focused on a set of activities, such as provision of contracts, charging for the service and fines, conflict resolution, payment for electricity consumption and staff salaries when applicable, purchasing of supplies to maintain the infrastructure, payment for office rental and telephone services, and the accounting corresponding to the system or systems of piped water managed by a particular organization.

The operational activities are different than the activities performed by office staff, and include the extraction of groundwater from deep wells equipped with electric pumps or, when applicable, piped water from a spring; distribution of the water to the intakes through a network of pipelines and storage tanks; maintenance and rehabilitation of infrastructure and equipment; installation or removal of an intake and, when applicable, periodic measurement of water consumed by each one to calculate the respective charges.

To identify the regulations corresponding to access to and exclusion from the system, we specifically focused on agreements and regulations regardless of whether or not they were written. This made it possible to document the procedure used by an individual to obtain the category of "user," as well as the reasons why an individual could lose that categorization.

In order to investigate the legitimacy of the regulations and the organizations responsible for enforcing them, special attention was placed on two aspects —one was the designers of the regulations and where they were issued, and the other was those who designated or chose the persons responsible for enforcing the regulations, as well as their jurisdiction or area of influence.

The field information needed to conduct the study was collected through formal and informal interviews with administrators and operators. Field surveys were also conducted to identify the hydraulic infrastructure in each particular system and record the tasks performed by operations staff to ensure the extraction and distribution of water, as well as those related to the maintenance and rehabilitation of equipment and pipes. Lastly, in order to identify and document the administrative tasks by office staff, we visited the field sites on the days when the staff was working.

Results and Discussion

Size and Type of Organization

At least 46 piped water systems exist in the five municipalities chosen as the study area, with service provided for 144 to 3 000 intakes, as shown in Table 1. Users committees were responsible for 34 of those intakes, municipal departments for 8 intakes and decentralized municipal operating entities for only 4. This information enables us to state small-scale systems are being managed by bureaucratic as well as self-managed organizational frameworks.

Table 2 summarizes the 12 systems analyzed and the type of organizations responsible for their management. According to the data regarding the number of intakes receiving water service, we can state that the systems studied are small-scale, since 10 range between 500 and 2 500 intakes and only two fall outside that range (Santa María-Río Verde Hydrographic System María and El Rincón, with 3 080 and 144, respectively).

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Table 1. Organizations and Systems for Piped Water in the Study Area.

Municipality	Type of Organization	Organizations	Systems Managed
Ajacuba	Municipal Department	1	3
	Users Committee	1	1
Arenal	Municipal Department	1	2
	Users Committee	4	4
Cardonal	Operating Entity	1	1
	Users Committee	10	11
San Salvador	Municipal Department	1	3
	Operating Entity	1	2
	Users Committee	9	9
Santiago A.	Users Committee	10	10
	Totales	**39**	**46**

Source: Field Data.

Table 2. Intakes receiving water service, per system and type of organization responsible for their management.

System	Intake	Organization	System	Intakes	Organization
San Salvador Santa María	560 3 080 **3 640**	Water and Sewer Comission, Municipality of San Salvador Hidalgo (CAAMSSH)	Pozo 2	144 **144**	El Rincon Users Committee (CUR)
Cardonal	650 ***650***	Cardonal Operating Entity (OOC)	Santiago de Anaya	980 ***980***	Santiago de Anaya Users Committee (CUSA)
Ajacuba Tezontlale Tecomatlan	2 286 1 242 1 097 ***4 625***	Ajacuba Municipal Potable Water Department (DMAPA)	Yolotepec	700 **700**	Yolotepec Users Committee (CUY)
20 de Nov. Bocja-Chimilpa	1 479 454 ***1 933***	El Arenal Municipal Potable Water Department (DAPMA)	San Miguel Tlazintla	1 697 ***1 697***	San Miguel Tlazintla System Users Committee (CUSMT)

Source: Field Data.

Based on this information, it can be said that the scale or number of intakes receiving water service from the portable water systems analyzed is not directly related to the type of organization that manages the system.

Thus the discussion presented so far indicates differences in the study area in terms of the implementation of the organizational framework established by national and state legislation for domestic water services. This is demonstrated by the cases found in the

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field such as Santiago de Anaya where all the systems are managed by users committees and San Salvador which has a municipal department and operating entities as well as nine users committees.

Governance, Administration and Operations

In the four systems that are managed by committees, the users themselves are in charge of the administration of piped water and the operations of the infrastructure.

In order to ensure that all the tasks required of the administration are performed, the users create a type of organization in which honorary positions are determined by elections and are rotated on a regular basis. Two mechanisms for the operational tasks were identified. The most common procedure is to name one or two users who receive financial pay for their activities, and the other was unpaid work, known locally as *faena*, performed by all the users according to a work scheduled determined in advance by the committee.

In the municipal water departments and operating entities in all of the eight systems, the administrative and operations work was performed by full-time staff employed for a determined period, depending on whether the system was run by the municipal government or by a government board.

Self-Management of Systems

As indicated in Table 3, for the operations of the Yolotepec and Santiago de Anaya systems, the administrative committees name two users, one to be responsible for managing the pumping equipment and the distribution of the water and the other for the maintenance and rehabilitation of the infrastructure. In the El Rincon system, only one user performs both tasks. The San Miguel Tlazintla system requires unpaid work by users according to a rotation schedule for ongoing work and special projects, as applicable.

Table 3 also indicates that the general users assembly delegates authority to the administrative committee, and both office tasks and operations are coordinated by the respective committees. Three of the four systems that are self-governed are organized by neighborhood or by blocks, according to the territorial divisions of the respective community. San Miguel Tlazintla, which supplies eight localities, has two organizational levels —a single community and a multi-community level.

The work, responsibilities and authority of the operators in these types of systems is specified —that is, they work under a system of subordination and supervision, but not a chain of command given that one or two people are involved. Those responsible for the wells and the pipelines necessarily have to be users of the system in question, and this does not require previous technical or professional experience.

Bureaucratic Systems

The information in Table 3 indicates that 9 systems are managed by bureaucratic organizations in the form of municipal departments or decentralized municipal operating entities, as established by current state and national legislation.

Therefore, according to Article 25 and 38 of the state of Hidalgo water and sewer law, the municipal president is responsible for hiring the director or manager of the municipal drinking water department or operating entity, as applicable (POEH, 1999: 13-16). The president also participates in decisions regarding the number of persons to be hired for administration, operations and maintenance, as well as their salaries and the amount of time they will be employed.

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Under this arrangement, the local governments of El Cardonal and San Salvador have transferred the administration and operations to their respective operating entities, but continue to govern them and, therefore, the municipal presidents directly participate in decision-making.

In systems governed by local governments, the municipal treasurer is responsible for paying the management costs, which generally include salaries for staff involved in the management of the drinking water system, electricity used to extract and distribute the water, and material to maintain and rehabilitate the hydraulic infrastructure.

In the case of Arenal, the municipal treasurer also collects the fees for piped water service and only assists the payment department with processing contracts for new service. In Ajacuba, the two secretaries who work in the water department collect payments for piped water service and also process and deliver new contracts. They are also required to submit cash balance statements and report income obtained by the three systems for which they are responsible.

Thus, a small bureaucracy is in charge of the administration and operations of the systems managed by the municipal water departments. This bureaucracy is contracted by the local government and is part of the office staff of the municipal presidents.

A technocracy runs the two systems managed by the San Salvador operating entity. The office staff includes a professional in accounting and one in information systems, and is supervised by the Administrative Sub-Department and the Commercial Sub-Department, respectively. The former is responsible for the accounting and payments of salaries, electricity, office rent and providers. The information systems specialist measures the water consumed by each intake, determines the corresponding charge and collects the respective payments.

In El Cardonal, an accounting firm performs the accounting for the operating entity, which is hired specifically for that task. The assistant director and secretary are responsible for the processing of new contracts for piped water service and charging for the service provided. At the time the interviews were conducted, the staff did not include professionals or technicians, although the state of Hidalgo's water law indicates that operating entities must hire professionals with proven experience. Therefore, it can be said that the administrative structure in this type of system is designed to be managed by a technocracy.

To conclude this section, it is important to clarify that the administration and operations by self-managed versus bureaucratic systems are different, and there is very little or no rotation in operations staff, which is generally composed of persons responsible for the wells and the pipelines. Those responsible for the wells operate the hydraulic pumps installed in the wells and verify water levels when filling the distribution tanks. The latter are responsible for maintaining the pipelines in the network and minor maintenance of the values that regulate water pressure.

The case of administrators is completely opposite that of the operators, given the high turnover of staff employed in the municipal department and operating organizations. This is because a new town council is elected every three years which generally appoints a new manager or director, depending on the case, with their respective assistant directors. These become part of the administrative structure. The committees also have a high degree of turnover since they are composed of honorary positions that must be occupied by users. In any one of the systems studied, once a person officially becomes a user that person is required to serve on the administrative committee when the users assembly indicates.

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Table 3. Characteristics of the organizations that manage the systems studied.

Organization (systems)	Governance/ administration	Chain of command	Staff hired	Organization (systems)	Governance/ administration	Chain of command	Paid users
CAAMSSH (2)	Technocratic Board	Board Director Assistant director Area head Office workers Operators	- 1 3 3 6 10 **23**	CUR (1)	Self- management by users	Users Operating Committee	- 0 1 **1**
OOC (1)	Bureaucratic board	Board Director Assistant director Office workers Operators	- 1 1 1 5 **8**	CUSA (1)	Users Self- management	Users Operating Committee	- 0 2 **2**
DMAPA (3)	Bureaucratic Local Government	Local Government Director Assistant director Office workers Operators	- 1 1 2 13 **17**	CUY (1)	Users Self- management	Users Operating Committee	- 0 2 **2**
DAPMA (2)	Bureaucratic Local Government	Local Government Director Operators	- 1 5 **6**	CUSMT (1)	Users Self- management	Users Operating Committee	- 0 0 **0**

Source: Field data.

Regulations and Agreements — Legitimacy and Equity

As shown in Table 4, the municipal departments and operating entities are governed by the current water legislation. Meanwhile, the committees are run according to agreements made by general users assemblies, and in the case of the San Miguel Tlazintla by a regulation created by the users themselves.

This has implications for each of the two cases analyzed, since regulations regarding access and exclusion are defined according to the type of organization responsible. In addition, as indicated in this table, the users in the four self-governed systems determine the fee categories and amounts for the piped water service. This situation does not occur in systems managed by municipal departments or operating entities, given article 134 of the State Drinking Water and Sewer Law, which stipulates that the state congress approves the type and amount of fees that these organizations can charge for this service (POEH, 1999: 37).

Self-Managed Systems

The regulations established for this type of system recognize two categories of users: locally born and resident. The latter category serves to assign the person arriving as a new resident to one of the localities supplied by the system, for the purpose of requesting piped water service.

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In the four systems studied, the category of "resident" serves as a mechanism to regulate access to piped water service as well as access to the locality in question, given that someone who is not born in the locality must request access to the system through the respective administrative committee, and request access to the locality through their legal representative, who may be a municipal councilperson, communal land commissioner or common property commissioner, depending on the case. Once the person not born in the locality has access to the piped water system, that person is assigned the category of "resident" in the locality in question.

The procedure and requirements for a possible user to obtain the category of "resident" are as follows. The administrative committee has a historical registry of the community work and the monetary contributions each user has given to the system in question. The legal representative of the locality also keeps records of the unpaid work by users (faenas) and monetary contributions made by each citizen to improve the systems. Based on these registries, the legal representative of the locality determines the monetary amount to be paid by the person not born in the locality, who is considered to be a resident. The administrative committee determines the conditions for access to the piped water system by taking into account the registries mentioned and determines the amount applicable to the contracts.

The procedure described requires the users categorized as "resident" to contribute money as a form of compensation for the monetary contributions and community work performed previously by the users categorized as "locally born."

As shown in Table 4, the users of the Yolotepec and Santiago de Anaya systems have sub-divided the category "locally born," which applies different costs for those requesting to contract a new water intake under this category. In Yolotepec, the amount paid by a user who is born in the community for a contract for a piped water intake is determined based on the users' participation in unpaid work and their financial contributions. In Santiago de Anaya, the criterion is having held an honorary position in one of the committees in the locality, such as the drinking water committee, the collaboration council or the religious festivities board.

In San Miguel Tlazintla, the users have established mechanisms to compensate for participation in administrative tasks. This is because all the users under 60 years of age are required to participate in one of the 10 committees that exist, as well as to perform unpaid work tasks once they are 18 years old. Under this institutional arrangement, users who serve as president of the general committee or as president of the monitoring committee have a lifetime exemption from performing unpaid work tasks or from participating in one of the 10 committees, regardless of their age when occupying those positions.

Table 5 summarizes the requirements to maintain the users category in self-governed systems, in the El Rincon and Yolotepec systems as indicated. These requirements are: performing the unpaid work tasks needed to improve the systems; providing monetary contributions when required; and paying the monthly or annual fee for the piped water service, as applicable. Users in the Santiago de Anaya system do not perform unpaid work tasks or make monetary contributions. The only requirement is to pay the annual fee for piped water service and the annual fee to cover unforeseen costs.

The San Miguel Tlazintla system is also worth mentioning, because unpaid work by users is more important than the annual fee to maintain the "user" category. That is, in this system the manual work performed by a user to maintain and rehabilitate the hydraulic infrastructure is more useful than the payment of the annual fee for the piped water service.

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Table 4. Institutional and Organizational Frameworks. Type of users, fees and costs.

Organization, legal framework	Type of user	Fee ($)	Cost of intake ($)
CAAMSSH State Potable Water and Sewer Law, state of Hidalgo National Water Laws and their Regulations	 Domestic Retired Commercial Industrial Periodic Inactive intake	Monthly 46.00 23.00 132.00 324.00 55.00 17.00	New contract and installation 800.00
OOC State Potable Water and Sewer Law, state of Hidalgo National Water Laws and their Regulations	Domestic Commercial	Monthly 50.00 150.00	New contract and installation 2 000.00
DMAPA State Potable Water and Sewer Law, state of Hidalgo National Water Laws and their Regulations	Domestic Commercial Industrial	Monthly 50.00 50.00 50.00	New contract 300.00
DAPMA State Potable Water and Sewer Law, state of Hidalgo National Water Laws and their Regulations	Domestic Commercial Industrial	Monthly 40.00 40.00 40.00	New contract 800.00
CUR Users Assembly agreements	Resident Locally-born	Monthly Variable	New contract and installation 3 920.00 1 320.00
CUSA Users Assembly agreements	Resident Locally-born no payment Locally-born with payment	Fixed Annual 500.00 Unforeseen expenses 150.00	New contract and installation 10 000.00 5 000.00 3 000.00
CUY Users Assembly agreements	Resident Locally-born non-participating Locally-born participating	Fixed Monthly 45.00	New contract and installation 1 000.00 1 000.00 500.00
CUSMT Internal regulations	Domestic Public hydrant	Fixed annual 120.00 50.00	900 Minimal salaries Unpaid work by users

Source: field data.

As shown in Table 5, the exclusion of users is one of the sanctions imposed in the El Rincon and San Miguel Tlazintla systems.

Meanwhile, no exclusions exist in the Yolotepec and Santiago de Anaya systems, but that does not necessarily mean that the users comply with the regulations and agreements established. For instance, in Santiago de Anaya, if a user stops paying for piped water service, for however long he or she wants, in order to rectify the situation the user's repayment will be based on current fees, which are adjusted every three years. In the case of Yolotepec, at the time of the interviews there were users who had not paid for 4 months, given that no sanctions exist for late

Table 5. Regulations for Access and Exclusion.

Organization	Access	Failure and sanctions
CAAMSSH	Proof of community authorization Contract Payment of fee Payment for material	Sanctions established by the State Drinking Water and Sewer Law are not enforced
OOC	Proof of community authorization Contract Payment of fee Payment for material	$10.00 for non-payment within first 10 days of month $200.00 for one month unpaid $2 200.00 for two consecutive months unpaid. Includes costs of new contract and reconnection
DMAPA	Proof of community authorization Contract Payment of fee Payment for material	Sanctions established by the State Drinking Water and Sewer Law are not enforced
DAPMA	Proof of community authorization Contract Payment of fee Payment for material	No se aplican las sanciones establecidas en la Ley Estatal de Agua Potable y Alcantarillado
CUR	Proof of community authorization Contract Unpaid work by users Financial Contributions Payment of fee Payment for material Member of the administrative committee at least once	$10.00 fine per day beginning day four after payment date $150.00 for three consecutive months unpaid Disconnection: $200.00 Reconnection: $150.00 Unauthorized intake, removed and service is denied
CUSA	Proof of community authorization Contract Payment of fee Payment for material Member of the administrative committee at least once	More than three years unpaid, annual payments are charged at the current rate
CUY	Proof of community authorization Contract Unpaid work by users Financial Contributions Payment of fee Payment for material Member of the administrative committee at least once	No sanctions but the committee ending its term may not pass on debts to the incoming committee.
CUSMT	Proof of community authorization Contract Unpaid work by users Financial Contributions Payment of fee Payment for material Member of the administrative committee at least once	Debts owed for service are charged at double the current fee Five minimum salaries for water leaks inside or outside a home, and service is suspended if it occurs twice

Source: field data.

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payments, and the payment can also be made at the end of the committee's administration term. Nevertheless, users are not permitted to miss more payments, since the outgoing committee is not permitted to carry any debts over to the new administration.

The fact that there are users behind on their payments did not affect the functioning of the Yolotepec or Santiago de Anaya systems, since some of the members of the administrative committee can loan money when the committees does not have sufficient funds. The members of these committees can even request a loan from other users in the system and pay it back at the end of the calendar year or the end of the committee's term.

Meanwhile, even though the possibility of suspending water service to a user exists in El Rincon and San Miguel Tlazintla, this rarely occurs, and according to the interviews, the administrative committee had not used this sanction. In El Rincon, this does not occur often because unauthorized intakes are uncommon, since the residents there also receive water from artesian wells and the established late fees and fines are effective for collecting the monthly fees. In San Miguel Tlazintla, the unpaid work by users is more important than the annual payments for piped water service. And while the eight towns supplied by this system have a high migration index, the users who are absent pay someone in the locality to perform their work tasks. The absent user thereby maintains the right to belong to the system.

Given what was described in this section, we can state that compliance with established regulations and the legitimacy of users committees and operations staff are factors that contribute to self-governed systems not applying the maximum sanctions (exclusion). Thus, the organizational frameworks designed by the users themselves effectively achieved the goals of the organization, that is, the supply of water for human consumption.

With the information presented, we demonstrated that informal organizations —that is, unwritten agreements by users assemblies— provide effective game rules for the management of piped water systems. In this case, these are seen as a commonly-used resource for users to govern their drinking water systems and to create non-bureaucratic organizations for their administration and operations.

Lastly, with regard to self-managed systems, we can confirm that none of the cases analyzed contain measuring devices to regulate water consumption, and the fees established by state legislation have not been imposed. Rather, agreements exist that prevent excessive water consumption and waste, including a set of fees established according to the needs of each specific system.

Bureaucratic Systems

For systems managed by municipal departments or operating entities, Article 3 of the State Drinking Water and Sewer Law defines four types or categories of water usage: commercial, industrial, domestic and public (POEH, 1999: 3).

In terms of charges for piped water serviced, the above law stipulates the fees through an authorized table that sets payments for each type of user based on consumption level, with prices per unit of service for each one. In addition, Article 124 stipulates that seniors, persons with disabilities and retired people will receive a subsidy for domestic service fees, and official schools will be charged the minimum fee when consumption is under 50 cubic meters per month. Article 133 states that the fees should enable the entity providing the service to be financially self-sufficient and they should be approved by the state congress (POEH, 1999: 3, 35 and 37).

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The sanctions for non-compliance on the part of users and the service provider's authority to enforce them are described as follows:

> "Article 140. With respect to non-payment by non-domestic users on two consecutive occasions, the service provider is authorized to suspend public services until payment is received in full. In the case of domestic users, non-payment on two consecutive occasions will result in suspension of the service and failure to pay the balance within 30 calendar days will result in suspension from the distribution network; (…) Article 145. Service providers (…) can implement the practice of site visits for inspection and verification of services by authorized personnel; Article 146. Site visits will be conducted to verify: I. That the public services are used in accordance with the contract; II. The hydraulic installations are functioning in accordance with the authority granted; III. Functioning of meters and causes of high or low consumption; IV. Exact diameter of intakes and discharge connections; V. No unauthorized intakes or diversions exist; VI. The presence of water leaks; (…) Article 164. With regard to infractions of this law: I. Persons who are required and fail to solicit water service in a timely manner (…); II. Persons who install or obtain unauthorized water supplies (…); II. Users who cause or allow failures in a meter (…); IV. Users who in any way alter the consumption recorded by meters or prevent the inspection or verification of data by inspectors; V. Any person who themselves or through a third party removes a meter without authorization or temporarily or permanently changes its location; (…) VIII. Owners or those in possession of properties in front of which a leak is located and has not been reported to the service provider in a timely manner; IX. Those who waste water; (…) XII. Those who build or operate systems to provide public services without having the corresponding license; Article 165. Infractions of this article shall be administratively sanctioned by the operating entities with fines that shall be equal to the following number of days equivalent to the minimum salary rate currently established in the geographic area and at the moment that the infraction is committed: 1) 10 to 50 days for a violation of sections I through V and VII through X; 2) 50 to 75 for a violation of sections VI and XI; (…) Article 167. In cases of sections I, IV, VIII, IX and XII of article 164, and in the case of reoccurrence, the operating entity may also impose the temporary or permanent suspension of the service (POE, 1999).

As noted in Table 4, the government board of the El Cardonal operating entity established two categories or types of users, domestic and commercial. The government board of the San Salvador operating entity created three additional categories: retired, which applies to piped water intakes owned by persons 60 years of age or older; periodic, which applies to intakes that do not receive water continuously but rather at regularly scheduled times; inactive intake which corresponds to users who utilize the service sporadically.

The two operating entities studied comply with the state legislation in the sense that all of the intakes supplied have meters to measure the consumption of water. But, as indicated in Table 5, the San Salvador operating entity does not enforce the sanctions established by the Water and Sewer Law of the state of Hidalgo and the users categories corresponding to the El Cardonal operating entity do not include all the options specified by this law.

Some of the ways in which the San Salvador operating entity do not enforce the sanctions established by the legislation, and some of the reasons for this are: unauthorized intakes exist; users do not pay fines for water leaks or excessive consumption; users object when attempting to suspend the water service; users individually ask for help from the municipal president to intervene and their payments are waived or, in extreme cases, users protest as a group before the municipal president.

Furthermore, employed personnel visit residences only to read the meters because the users do not allow the inspection and verification visits stipulated by law.

Based on the above, it can be said that the fees and meters in the San Salvador and Santa Maria systems do not achieve their function as mechanisms to regulate water consumption, and the sanctions are not enforced because the users oppose them or the municipal president intervenes. Therefore, in these systems a user who violates the law or who is late on their payments for piped water service cannot be excluded, which contradicts the legislative framework.

The situation was different at the El Cardonal operating entity. Its government board establishes more sanctions than what are indicated by the state water law, which are defined in the contract issued to each user. One includes a maximum penalty of cancelling the contract and disconnecting the water intake if the fee for water consumption is not paid for two consecutive months.

Thus, in the system managed by the El Cardonal operating entity, a user who is behind on payments can be excluded, but neither the fees nor the meters fulfill their function as mechanisms to regulate water consumption since seven of the eight localities receive water service under a periodic supply system and are provided with water every three days. That is, the government board and the hired personnel decided to provide the service every three days and, rather than the fees and meters, this decision is what determined the amount of water consumed by the intakes.

In addition, the government board of the El Cardonal operating entity does not apply the fee rates corresponding to retired users or inactive intake, even though the eight localities supplied by this provider contain housing owned by persons 60 years or older as well as homes that use the services only during certain periods of the year.

One regulation related to access in the San Salvador, Santa Maria and El Cardonal systems is requiring that those who want to obtain water service request written authorization from the legal representative of the locality where the property or home is located. Others include the need to request a contract from the operating entity in question and purchase the material needed to install the intake.

Once access to the San Salvador and Santa Maria systems is obtained, the category of "user" is maintained even when the fee is not paid on time. Whereas in the El Cardonal system, this category is forfeited when the fee for water consumption is not paid for two consecutive months. To regain service, a request for a new contract and a new intake is required.

The local governments of El Arenal and Ajacuba established three users categories for charges —domestic, commercial and industrial. A single, fixed fee was assigned to the three categories or types of users, specifically: $50.00 in the three systems managed by the Ajacuba Drinking Water Department and $40.00 in the two systems managed by the El Arenal Drinking Water Department.

This means that these two municipal governments established equal fees for all intakes. Nevertheless, Table 5 indicates that neither organization enforces the sanctions stipulated by the state water law because the users oppose it. Thus, large inequalities in fees exist, but the two organizations mentioned that they lack the legitimacy to enforce the regulations related to maintaining the category of "user," and they are unable to exclude those who do not comply.

Under these circumstances, the users of the Tezontle, Tecomatlán, Veinte de Noviembre and Bocja-Chimilpa systems pay the same fees regardless of how much water they consume or the purpose for which it is used. In other words, the fee does not function as a mechanism to regulate water consumption in these systems, as intended by the Hidalgo's water and sewer law. Thus, those with industrial and domestic intakes pay the same amount.

This situation is possible because the intakes served by the four systems mentioned lack meters. Therefore, these two municipal departments do not comply with the law requiring the measurement of drinking water consumption. It is worth mentioning that of the five systems managed by the municipal government, only Ajacuba has installed meters, which are read by personnel on a monthly basis.

The municipal directors of the respective organizations indicated that the lack of meters is due to the users objecting to their installation, and when these devices had been installed the users removed them or stopped paying for water.

Another reason why these two municipal departments do not entirely comply with state law is that they do not conduct inspection visits or remove the intakes from violators. This is because the users do not recognize the authority of the personnel who work for the local government, and therefore they do not permit access to their home, let alone the disconnection of their water intakes from the distribution network.

The users' opposition to the installation of meters and the inability to inspect water consumption and intakes led the El Arenal local government to establish one single fee for the two systems it manages. The users have more or less complied with this, although fees continue to be paid late. Although it was not possible to obtain the percentage paid monthly, in the interviews the water director commented that it is very low.

It is worth mentioning that the Ajacuba local government and the municipal director of the drinking water system allow users to participate in the decision-making regarding the fees to be applied at the time of the interviews. And as the fieldwork documented, through this negotiation it was possible to increase the monthly fee by $10.00. The percentage of the monthly fees collected also increased considerably in the three systems managed by this organization.

While consulting with the users enabled the Ajacuba municipal water department to increase the fee and the percentage of payments collected, inspections are still not conducted in Tecomatlan and Tezontlale and there are no devices to measure water consumption, since this was decided by the users.

In terms of regulations related to access, Table 5 shows that two municipal departments require that authorization to receive water be requested in writing from the legal representative of the locality where the property or home is located. And once the possible user obtains authorization, a contract that determines the price of the service has to be requested from the respective Drinking Water Department. Thus, the El Arenal and Ajacuba local governments are also flexible when enforcing existing legislation in the sense that they allow the participation of community authorities when a water intake is requested. In fact, authorization from the legal representative in the locality is the first requisite in both municipal departments, before beginning the process to obtain a contract for the intake.

Lastly, neither the Ajacuba or El Arenal municipal departments exclude users who are behind on payments or who do not comply with the law, even though that is one of the sanctions established by the legislation governing them and gives them that authority. Thus, once someone enters the piped water systems managed by these organizations, they are not likely to forfeit the category of "user," even when they do not pay on time or in accordance with the monthly fees established, or when not complying with the state water law.

Conclusions

According to what was found in the field, it can be stated that the users in self-governed systems create horizontal administrative and operating structures. In addition, in all the cases analyzed, the owner of the intakes receiving service can join the administrative committee or serve as operations personnel to conduct tasks related to extracting and distributing water or maintaining the infrastructure.

Meanwhile, systems governed by local governments or government boards have a vertical administrative and an operations structure in which users do not participate in decisions. The operations and administrative tasks are organized and carried out by a small full-time bureaucracy hired as part of the municipal president's office staff, or a decentralized technocracy paid with municipal funds and directed by managers.

Therefore, we conclude that the type of governance of rural drinking water systems directly influences their administration and operations in terms of the number of employees hired as well as the chain of command.

With regard to regulations, given the data presented it can be categorically stated that the instruments that represent the "user" category and the fees in self-governing systems present principles involving equality and legitimacy. This does not occur in bureaucratic systems because the users do not consider these instruments as legitimate, since they do not participate in the process to develop or implement them.

We have sufficient evidence to support the position that the institutional framework established by the current legislation creates organizations that are not suitable to managing small-scale drinking water systems. Thus, the current management model based on municipal departments or operating entities is not the most suitable or legitimate for all cases, nor is it the most effective or equitable.

Finally, for the specific case of the state of Hidalgo, it can be said that the users in some municipalities prefer self-management based on local knowledge, which responds to the particularities of each drinking water system, as opposed to the institutional and organizational frameworks based on managers, offered by the current legislation.

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Variability in the Water Footprint of Cereal Crops, Cachapoal River, Chile

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Abstract

Novoa, V., Rojas, O., Arumí, J. L., Ulloa, C., Urrutia, R., & Rudolph, A. (March-April, 2016). Variability in the Water Footprint of Cereal Crops, Cachapoal River, Chile. *Water Technology and Sciences* (in Spanish), 7(2), 35-50.

The water footprint was calculated to evaluate the effects of climate variability on the water consumed during the production of cereals. This methodology considered three precipitation scenarios: a) rainy year, b) normal year and c) dry year. It also included two yield conditions —constant and a 20% reduction (projecting for the effect of climate change)— for three sections of the Cachapoal River basin. In addition, virtual and apparent water productivity were calculated to demonstrate the effect of climate variability on water productivity of cereal crops. The analysis of percentiles found that the year 2005 corresponded to a rainy year, 2006 to a normal year and 2007 to a dry year. Under constant yield conditions, the water footprint of the cereals was larger during the rainy year (1 064 m3/ton), while under reduced yield conditions it was larger during the dry year (1 633.9 m^3/ton). For both conditions, the largest blue water footprint estimated corresponded to a dry year and the largest green water footprint to a rainy year. Nevertheless, no differences among the sections of the basin were observed. During a rainy year, the largest amount of virtual water (14 325 000 m^3/year) would be exported and the lowest apparent water productivity (92.8 \$/m^3) would be produced. This information is crucial to develop sustainable agricultural systems.

Keywords: Water footprint, precipitation, climate variability, yields.

Resumen

Novoa, V., Rojas, O., Arumí, J. L., Ulloa, C., Urrutia, R., & Rudolph, A. (marzo-abril, 2016). Variabilidad de la huella hídrica del cultivo de cereales, río Cachapoal, Chile. Tecnología y Ciencias del Agua, *7(2), 35-50.*

Se evaluaron los efectos de la variabilidad climática en el consumo de agua para la producción agrícola de cereales, a través del cálculo de la huella hídrica, metodología que consideró tres escenarios de precipitación: (a) año húmedo, (b) año normal y (c) año seco, y bajo dos condiciones de rendimiento (constante y disminución de 20%, proyectando el efecto de cambio climático), en tres secciones de la cuenca del río Cachapoal. Además, se calculó el agua virtual y la productividad aparente del agua para evidenciar el efecto de la variabilidad climática en la productividad del consumo del agua en el cultivo de cereales. El análisis de percentiles determinó que el año 2005 correspondió a húmedo, 2006 a normal y 2007 a seco. La huella hídrica de los cereales, bajo un rendimiento constante, fue mayor en el año húmedo con 1 064 m^3/ton; en cambio, con una disminución del rendimiento, fue mayor en el año seco (1 633.9 m^3/ton). Para ambas condiciones, la mayor huella hídrica azul se estimó en un año seco y la mayor huella hídrica verde en un año húmedo. Sin embargo, no se observaron diferencias entre las secciones de la cuenca. En un año húmedo se habría exportado la mayor cantidad de agua virtual con 14 325 000 m^3/año, y se habría producido la menor productividad aparente del agua, 92.8 \$/m^3, información fundamental para determinar sistemas agrícolas sustentables.

***Palabras clave**: huella hídrica, precipitación, variabilidad climática, rendimiento.*

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Introduction

One of the greatest challenges to the sustainability of water resources worldwide is related to the inexorable increase in water demand to satisfy the growing needs of the population. Globally, an estimated 70% of water is used for agriculture, 22% for industrial activities and 8% for domestic purposes (Strzepek & Boehlert, 2010; Konar *et al*., 2011). In middle- and low-income countries, over 82% of the water extracted is used in agricultural (Pfister, Bayer, Koehler, & Hellweg, 2011; Mubako & Lant, 2013).

The evaluation of water availability in a basin is a complex challenge since it depends on the geographic characteristics of the location, its use and how the behavior of the hydrological cycle is affected by climate variability and climate change (Gleick, 2010). Agriculture is dependent on climate conditions in that fluctuations or variability in the climate significantly affects crop yields (Costanzo, Bonel, & Montico, 2009). Therefore, taking into account climate variability when evaluating the use of water for crop production will contribute to better water management practices in a region (FAO, 2011; Herath *et al*., 2013; Sun *et al*., 2013). The water footprint has been proposed as a tool to identify the use of water and the effects of agricultural production, providing information for decision-makers.

This methodology can differentiate between the sources of water needed for crops, making it possible to compare productivity, efficiency and vulnerability to water availability on the local, national and global scales, while also considering the differences among countries or geographic areas (Bulsink, Hoekstra, & Booij, 2010; Mekonnen & Hoekstra, 2011; Montesinos, Camacho, Campos, & Rodríguez-Díaz, 2011). The analysis includes variables such as the growing period, irrigation efficiency and yields on the level of a hydrographic basin, and includes characteristics related to monthly regional climate variability (Hoekstra, 2014).

The water footprint has three components: 1) green water footprint, which is the volume of water consumed by the production process through the moisture in the soil in an unsaturated area, which is composed of precipitation and water available for plants; 2) blue water footprint, which is irrigation water composed of surface water (rivers, lakes, wetlands) or groundwater (aquifers) that is consumed in the production process, taking into account the water lost from the system through evaporation processes in crops; and 3) grey water footprint, which is the amount required to assimilate pollutants generated by crop production (Hoekstra, 2013; Vanham & Bidoglio, 2013).

Conventional agriculture has emphasized water management for consumptive use (Mekonnen & Hoekstra, 2014). Nevertheless, crops receive blue water (from irrigation) as well as green water (soil moisture), and therefore all the components in the water cycle need to be included (Willaarts, Volk, & Aguilera,2012), as well as hydrological flows, outflows and changes in storage (Deurer, Green, Clothier, & Mowat, 2011). The impact of agriculture on water resources also needs to be indicated (Ridoutt & Pfister, 2010).

A large diversity of hydrographic systems exists throughout the broad range of latitudes in Chile (17° S to 56° S), with large variations in precipitation, regimes and maximum flow periods (Oyarzún, Alvarez, Arumí, & Rivera, 2008). Given these climatic conditions, 45% of the total crops produced nationally is grown between the Aconcagua (32° S) and Maule (35° S) rivers in central Chile, an area where irrigation and dryland systems co-exist. Irrigation represents an estimated 84.5% of consumptive water uses nationally, with a mean flow of 546 m^3/s applied to 2 million hectares (Gleick, 2010; Donoso, Blanco, Foster, Franco, & Lira, 2012).

Global climate change projections (HadCM3 model, A2 scenario) for latitudes between 30°S and 40°S indicate robust signs of a decreased precipitation, from 5 to 10% in the short-term and 20 to 30% for a long-term scenario (CEPAL, 2012). An increase in the zero isotherm has been found in rivers in the central region, with a clear glacial retreat over the past 100 years (Carrasco, Casassa, & Quintana, 2005; Bown, Rivera, & Acuña, 2008). This is important given that nival-glacial water availability supplies 67% of the surface runoff during dry periods associated with La Niña (climate variability) (Peña & Nazarala, 1987). According to the trends presented, the water supply is expected to decrease 40% in the year 2016 (DGA, 2012; Pizarro *et al*., 2013), whereas the water demand for irrigation is expected to increase 4 billion m^3 over the next 40 years (Neuenschwander, 2010).

This study evaluated the water footprint of crop production in the Chachapoal River (34°), which covers approximately 161 500 ha, of which 29 713 ha are used for cereal crops such as corn and legumes, which represent 73% of the national production. The water use pattern in this basin is determined by the irrigation area, specifically, furrow irrigation by gravity, drip micro-irrigation and traditional mechanical aspersion (Censo Agrícola, 2007). With respect to water availability in the basin, interior dryland areas and intermediate depressions with water deficits or soil dryness have been reported, with a negative correlation between these indices and precipitation, limiting the use of irrigation (DGA, 2012; Sánchez & Carvacho, 2013).

Therefore, the effects of climate variability on water consumption for crop production was evaluated by calculating the water footprint under three precipitation scenarios: a) rainy year, b) normal year and c) dry year. These were selected from 34 years of recorded precipitation data and under two yield conditions (normal and the projected effect of climate change). The water footprint was calculated with indicators that differentiate between green and blue water sources in the three sections of the Cachapoal River. Virtual water and apparent productivity were also calculated to determine the effect of climate variability on water productivity for cereal crop production..

Methodology

Study Area

The Cachapoal River Basin (34° S, 70° W) is the most productive agricultural region in south-central Chile. It covers 38% of the area of Region VI, with 6 370 km^2. The population of the basin is 542 901 inhabitants, 30% of which work in activities related to agriculture. The climate is temperate with variations due to the effect of the topography, in which a rise in elevation changes the temperature and rainfall. Above 3 500 m, the climate becomes harsher, until reaching glacial conditions (MOP, 2013).

The analysis divided the Cachapoal River Basin into three sections (1st, 2nd and 3rd) according to the differences in altitude (Figure 1). Agricultural data were also needed, including the cultivated area, yield and irrigation techniques in the different sections of the Cachapoal Basin (INE, 2007) (Table 1).

Determination of Climate Variability

The meteorological data used were selected from nine weather and rain gauge stations run by the General Water Department (DGA, Spanish acronym), with 34 years of records. This study used the information from the stations most representative of each section of the basin (Table 2). The study and correction of the monthly rain gauge statistics for each section were performed with the mass curve method.

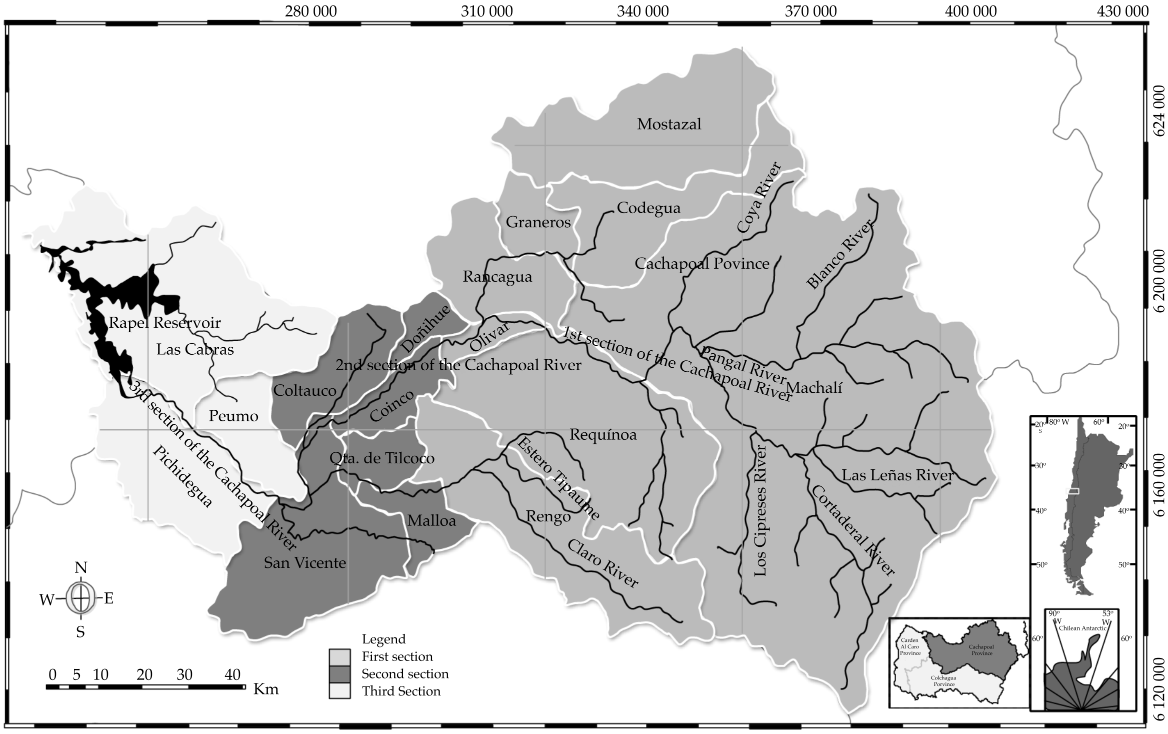

Figure 1. Cachapoal River Basin. For this study, the sections of the basin were identified with different shades of gray as first, second and third, from right to left.

Table 1. Location of the weather stations in each section analyzed, planted area, production, yield of cereals and irrigation techniques used per irrigated area in the Cachapoal River Basin. Source: 2007 Agriculture census (DGA, 2012).

Cachapoal Basin	Location		Cultivated area (ha)	Total production (qqm)	Yield (ton/ha)	Irrigated area (%)		
						Gravity Irrigation	Mechanical Irrigation	Micro-irrigation
1st section	34° 45′ 31.01″ S	70° 45´ 24.65″ O	7 473.4	775 333	10.37	75.7	0.4	24
2nd section	34° 17′ 30.03″ S	71° 04´ 52.22″ O	12 263.8	1 518 158	12.38	82.6	0.8	16.7
3rd section	34° 17′ 29.29″ S	71° 24´ 24.18″ O	9 975.3	1 170 822	11.74	62.8	1.2	36.4

Box plots were used to analyze precipitation, which provided information about the behavior of seasonal cycles and the extreme values observed (Guenni, Degryze, & Alvarado, 2008). Years were classified as dry, normal and rainy according to the percentiles, which resulted in the definition of five categories: very dry (0-20th percentile), dry (20-40th percentile), normal (40-60th percentile), rainy (60-80) and very rainy (80-100) (Valiente, 2001).

Calculation of the Water Footprint for Ceral Crops (WF$_{crop}$)

The water footprint was evaluated for each of the sections in the basin under climate condi-

Table 2. Weather station, annual precipitation (prec), reference evapotranspiration (Eto), effective precipitation (Eff Prec), evapotranspiration of ceral crops (Etc) and irrigation requirement (Irr Req), for the years 2005, 2006 and 2007 in the different sections of the Cachapoal River.

Years	Section	Representative Station	Prec. (mm)	ETo (mm/day)	Eff Prec (mm)	ETc (mm/dec)	Irr Req (mm/dec)
2005	1st section	La Rufina	1 405	2.84	715.7	398.0	246.2
	2nd section	Contaulco	822	2.81	546.7	395.6	264.0
	3rd section	Pichidegua	680	2.79	518.8	423.7	285.7
2006	1st section	La Rufina	1 212	2.82	672.1	390.2	310.6
	2nd section	Contaulco	704	2.78	531.6	384.7	343.8
	3rd section	Pichidegua	597	2.67	464.7	384.7	315.8
2007	1st section	La Rufina	488	2.68	400.0	401.7	395.4
	2nd section	Contaulco	318	2.73	279.9	396.7	396.6
	3rd section	Pichidegua	366	2.63	309.9	396.2	395.0

tions for rainy, dry and normal years, defined according to the climate analysis. Two yield conditions were also considered —constant yields in the three sections (1st, 2nd and 3rd) of 10.4, 12.4 and 11.7 ton/ ha, respectively (Odepa, 2014), and a 20% decrease in yields per year according to projections by climate change scenario A2 for cereal crops (CEPAL, 2012).

The methodology proposed by Hoekstra, Chapagain, Aldaya and Mekonnen (2011)was used to calculate the water footprint, taking into account the sum of the green and blue components (Figure 2):

$$WF_{crop}\,(m^3/ton) = WF_{green} + WF_{blue} \quad (1)$$

Both components were determined based on the following equations:

$$WF_{green} = \frac{CWU_{green}}{Y}(m^3/ton) \quad (2)$$

$$WF_{blue} = \frac{CWU_{blue}}{Y}(m^3/ton) \quad (3)$$

Where Y (ton/ha) = crop yield (Table 1) and CWU = crop water use according to source (precipitation or irrigation), expressed in m^3/ha (Allen, Pereira, Raes, & Smith, 1998).

Calculation of the Crop Water Use (CWU) (m³/ha)

The following equations were used:

$$CWU_{green} = 10 \times \sum_{d=1}^{lgp} ET_{green}\left[\text{volume/area}\right] \quad (4)$$

$$CWU_{blue} = 10 \times \sum_{d=1}^{lgp} ET_{green}\left[\text{volume/area}\right] \quad (5)$$

Where Σ = the crop's growth cycle, that is, from planting (day 1) to harvest; lgp = length, days in each stage of the cycle; ET_c = evapotranspiration of the crop (mm/day).

Estimation of the Crop's Evapotranspiration (ET_c) *(Green and Blue)*

The water demand of the cereal crop was determined based on the crops' water requirements (CWR) using Cropwat 8.0 software. Under ideal growth conditions, ET_c is considered equal to the CWR and would correspond to evapotranspiration. The calculation of ET_c was performed over 10-day periods, in relation to irrigation efficiency. This methodology assumes that the losses from irrigation remain in or return to the basin:

$$ET_c\left[mm/day\right] = Kc * ET_o \quad (6)$$

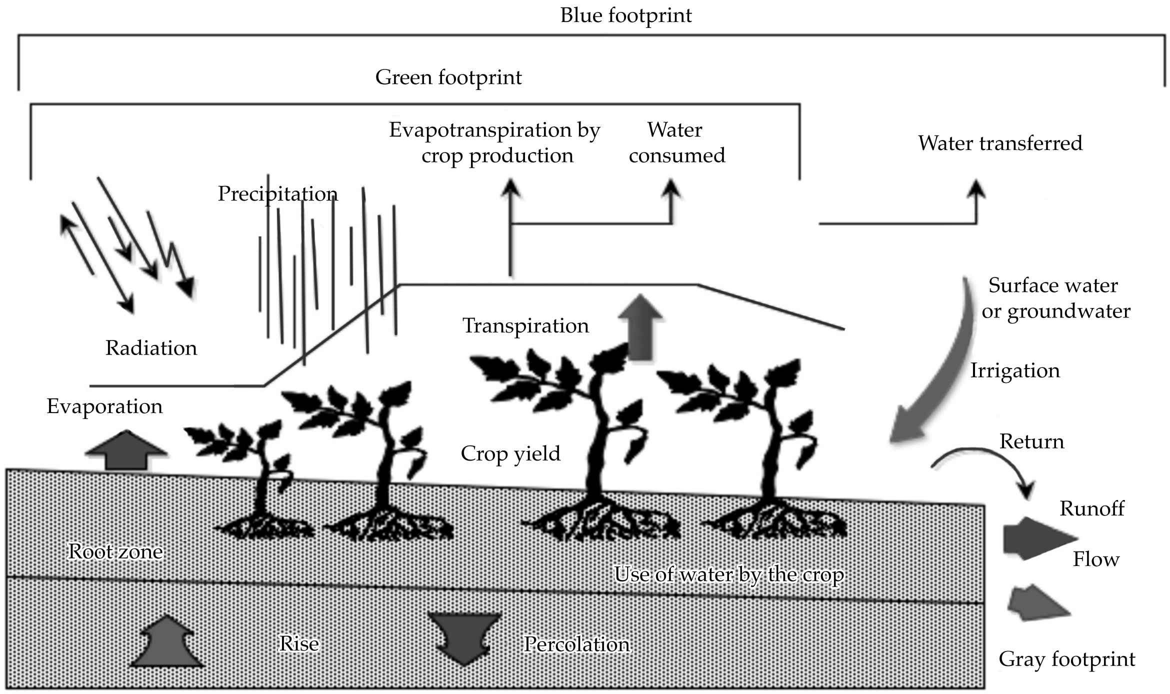

Figure 2. Layout of the components of the water footprint of crops.

$$ET_c[\text{mm/dec}] = ET_c[\text{mm/day}]$$

$$\text{*days in each 10-day period} \qquad (7)$$

Where Kc = crop coefficient; ET_o = reference evapotranspiration (mm day^{-1}).

The estimation of ET_{green} is:

$$ET_{\text{green}}[\text{mm/dec}] = ET_c[\text{mm/dec}] - \text{Irr req}[\text{mm/dec}] \qquad (8)$$

Irrigation Requirement (Irr reg)

Where:

$$\text{Irr req}[\text{mm/dec}] = ET_c[\text{mm/dec}] - \text{Peff}[\text{mm/dec}] \qquad (9)$$

Effective precipitation (P_{eff}) calculated by the program.

The estimation of ET_{blue} is:

$$ET_{\text{blue}}[\text{mm/dec}] = \text{Irr req}[\text{mm/dec}] \qquad (10)$$

The sum of ET_{blue} (mm/10-day period) and ET_{green} (mm/10-day period) equals ET_c (mm/10-day period).

Calculation of evapotranspiration (ET_o)

The Penman-Monteith method and the Cropwat 8.0 program were used. Climate data related to latitude and period were taken from the DGA. The information was georeferenced using the Climwat 2.0 program, where:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T-273} u(e_s - e_a)}{\Delta + \gamma(1 + 0.34u)} \qquad (11)$$

ET_o = reference evapotranspiration (mm day^{-1}); R_n = net radiation on the surface of

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Water

the crop (MJ m^{-2} day^{-1}); R_a = extraterrestrial radiation (mm day^1); G = flow of heat in the soil (MJ m^{-2} day^{-1}); T = mean air temperature (C°); u = wind speed (ms^{-1}); e_s = saturated vapor pressure (kPa); e_a = real vapor pressure (kPa); $e_s - e_a$ = vapor pressure deficit (KPa); Δ = slope of the vapor pressure curve (kPa °C^{-1}); Γ = psychrometric constant (kPa°C^{-1}).

Calculation of Virtual Water (VW)

This refers to the water volume embedded in a product that was used for its production, in the context of exported water flow (Hoekstra, 2014). This is calculated using the equation described by Salmoral *et al*. (2011):

$$VW_{\text{exp}} = WF\left(\text{m}^3/\text{ton}\right) \times E \qquad (12)$$

Where VW_{exp} = virtual water exported (m^3/year), E = quantity of exported products (ton/year). The quantity exported (E) was taken from the regional forestry and agriculture exports report (Informe Regional de Exportaciones Silvoagropecuarias (Odepa, 2013b)).

Apparent Water Productivity (AWP)

According to Salmoral *et al.*(2011), this is the economic value of crop production per cubic meter of water used. It was calculated based on:

$$AWP = \frac{\sum\left(Pr \times T_l\right)}{WF} \qquad (13)$$

Where AWP is the apparent water productivity ($/$m^3$) in Chile for the years analyzed; Σ (*Pr x T)* is the market price of the crop ($/ton); WF = water footprint of the crop production (m^3/ton). The AWP values in Chile for the years studied were taken from the regional forestry and agriculture exports report (Informe Regional de Exportaciones Silvoagropecuarias (Odepa, 2013b).

Statistical Analysis

In the evaluation of the water footprint, the Shapiro-Wilk test was used to analyze the normality of the data. The feasibility of using an additive model was analyzed by applying the Tukey test for additivity. A two-way analysis of variance was performed to compare factors —for example, among years (three levels, 2005, 2006, 2007) and sections (1^{st}, 2^{nd}, 3^{rd})— and the Tukey test was applied *a posteriori*. A one-way analysis of variance was performed to analyze the results for virtual water and apparent water productivity. The Statistica version 6.0 program was used (StatSoft Inc. 2001).

Results

Climate Behavior in the Cachapoal Basin

Figure 3 shows the spatial variation of precipitation at the weather stations selected as a reference in the Cachapoal basin, over the 34 years analyzed. The first section (mountainous) had the highest precipitation, with a mean of 1.119 ± 409 mm (R^2 = 0.999; cv = 36.5), and a minimum of 311 mm during very dry years and a maximum of 2.082 mm during very rainy years. The second section had a mean precipitation of 649 ± 293 mm (R^2 = 0.997; cv = 45) , with a minimum of 117 mm and a maximum of 1.517 mm. The third section (with coastal influence) had the lowest annual precipitation, with 549 ± 230 mm (R^2 = 0.998; cv = 41), and a minimum of 145 mm and a maximum of 1.022 mm. At the intra-annual level, the greatest variability in precipitation was registered during the winter.

According to the analysis of percentiles, extreme conditions were observed during the years 2005 and 2007 (Table 2). The year 2005 was characteristic of a rainy year, with a mean precipitation of 969 mm, while 2007

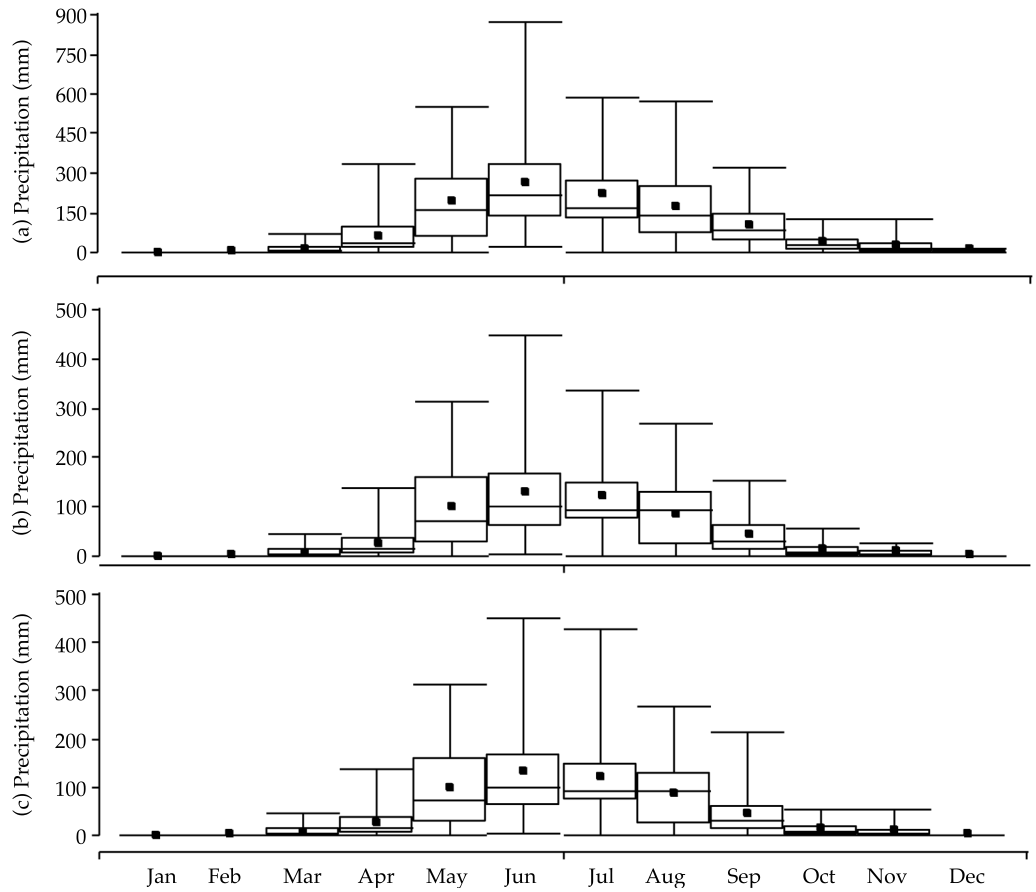

Figure 3. Box plots of monthly precipitation for a period of 34 years in the Cachapoal basin (mm): (a) first section, La Runia station; (b) second section, Coltauco station; (c) third section, Pihidegua station. The horizontal line and the square inside the box indcate the median and the mean. The bottom and top of the box correspond to the 0.25 and 0.75 percentiles, respectively. The bottom and top bars correspond to the 0.05 and 0.95 percentiles, respectively.

represented dry conditions, with 391 mm. The year 2006 was selected for normal rainfall (see Table 2), with a mean precipitation of 838 mm.

Water Footprint of the Cereal Crop (WF_{crop})

Table 2 summarizes the information required to calculate the water footprint for each section in the Cachapoal basin. The results demonstrate that ET_o, ET_c and effective precipitation were greater in the year 2005 (rainy year), and the irrigation requirement was higher in the year 2007 (dry year).

The crop cycle for corn was estimated to be 125 days, with the following stages: initial = 20 days, development = 35 days, maturity = 40 days, aging = 30 days. The three crop coefficients (Kc) were 0.30 for initial, 1.20 for the middle stage and 0.35 for the final stage, for the period September-December (Figure 4).

An additive model was considered for the analysis since no significant ($p > 0.05$) evidence was found from the application of the Tukey test for additivity. In addition, no evidence was found that contradicted the hypothesis of normality, thereby supporting the supposition of a normal distribution ($p > 0.05$) according to the Shapiro-Wilk test (Table 4).

Table 3. Calculation of evapotranspiration for the growth period (ET_c), crop water use (CWU) and the water footprint (WF) for the cereal crop during the years 2005, 2006 and 2007 in the different sections of the Cachapoal River, under conditions of constant yield (a) and a scenario with a 20% decrease in yields (b).

(*Y*)	Years	Sections	ET_c (mm/growth period)		CWU (m^3/ha)			Water footprint (m^3/ton)		
			Green	Blue	Green	Blue	Total	Green	Blue	Total
Constant yield (a)	2005	1st section	151.8	246.2	1 518	2 462	3 980	146.4	237.4	383.8
		2nd section	131.6	264	1 316	2 640	3 956	106.4	213.4	319.8
		3rd section	138	285.7	1 380	2 857	4 237	117.6	243.4	361
		Total						370.3	694.3	1 064.6
	2006	1st section	79.6	310.6	796	3 106.4	3 902.4	76.8	299.6	376.3
		2nd section	40.9	343.8	409	3 438	3 847	33.1	277.9	311
		3rd section	68.9	315.8	689	3 158	3 847	58.7	269.1	327.8
		Total						168.5	846.6	1 015.1
	2007	1st section	6.3	395.4	63	3 954	4 017	6.1	380.19	386.3
		2nd section	0.1	396.6	1	3 966	3 967	0.1	320.5	320.5
		3rd section	1.2	395	12	3 950	3 962	1	337.6	338.6
		Total						7.2	1 038.3	1 045.4
Decrease (20%) in yields (b)	2005	1st section	151.8	246.2	1 518	2 462	3 980	146.4	237.4	383.8
		2nd section	131.6	264	1 316	2 640	3 956	106.4	213.4	319.8
		3rd section	138	285.7	1 380	2 857	4 237	117.6	243.4	361
		Total						370.3	694.3	1 064.6
	2006	1st section	79.6	310.6	796	3 106.4	3 902.4	95.9	374.4	470.4
		2nd section	40.9	343.8	409	3 438	3 847	41.3	347.4	388.7
		3rd section	68.9	315.8	689	3 158	3 847	73.4	336.3	409.7
		Total						210.7	1 058.2	1 268.8
	2007	1st section	6.3	395.4	63	3 954	4 017	9.5	595.8	605.3
		2nd section	0.1	396.6	1	3 966	3 967	0.1	501.1	501.2
		3rd section	1.2	395	12	3 950	3 962	1.6	525.8	527.4
		Total						11.2	1 622.7	1 633.9

As observed in Table 3, under a scenario with constant yields the total water footprint of the cereal crop was estimated to be 064.6 m^3/ton for a rainy year (2005), 1 015.1 m^3/ton for a normal year (2006) and 1 045.4 m^3/ton for a dry year (2007). Consumption was 49.5 m^3/ton higher in a rainy year than a normal year and only 30.3 m^3/ton higher in a dry year, with significant differences among the years analyzed. No significant differences in the total water footprint were found among the sections (1st, 2nd, 3rd) (see Table 4).

The largest blue water footprint was observed in the year 2007 (dry year), with 1 038.3 m^3/ton, corresponding to irrigation water (Table 3). The Tukey test showed significant differences among a rainy, normal and dry year. Nevertheless, no significant differences were found among the sections (1st, 2nd, 3rd) (see Table 4). The largest green water footprint was observed in 2005 (rainy year) with 370.3 m^3/ton (see Table 3). The statistical analysis showed significant differences among a rainy, normal and dry year. Nevertheless, no

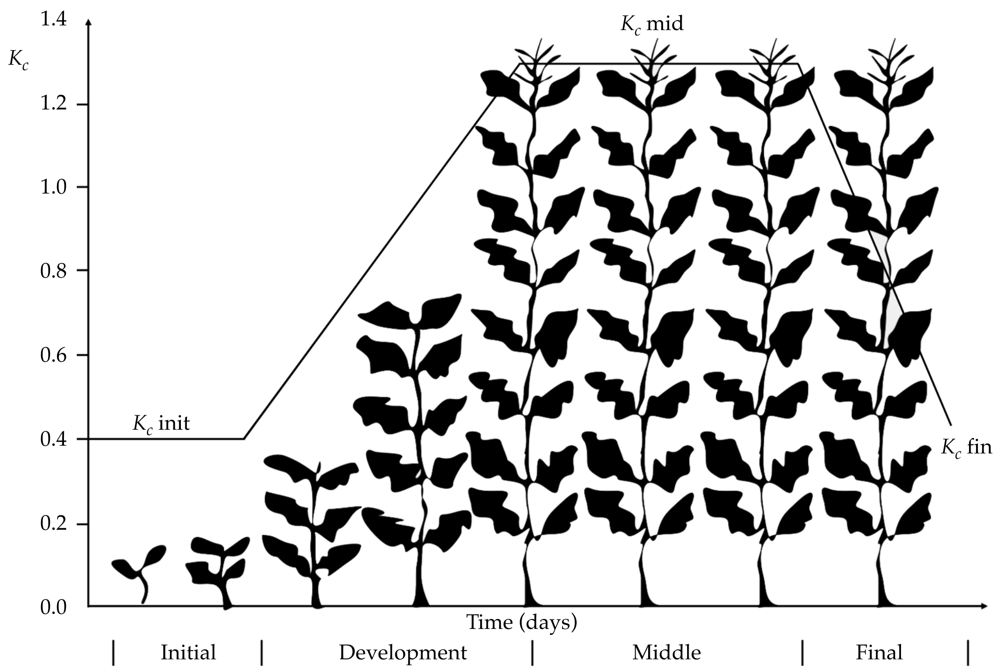

Figure 4. Stages and estimated coefficients (Kc) of the corn crop (September 28 - December 30).

Table 4. Summary of the results obtained from the statistical analysis of the water footprint, by year and section, with a constant yield (a) and a 20% decrease in yield (b).

			Green footprint		Blue footprint		Total footprint	
FV		*gl*	*F*	*p*-value	*F*	*p*-value	*F*	*p*-value
Constant yield (a)	Year	2	91.1473	0.0005	40.0632	0.0023	48.0072	0.0016
	Section	2	5.5836	0.0696	3.8352	0.1175	3.0923	0.1543
	Tukey test for additivity Shapiro-Wilk test		0.1438 0.9587		0.2196 0.117		0.1543 0.0764	
Decrease in yield (20%) (b)	Year	2	72.6504	0.0007	123.1527	0.0003	127.1361	0.0002
	Section	2	6.1044	0.0609	3.1464	0.151	24.5216	0.0057
	Tukey test for additivity Shapiro-Wilk test		0.2082 0.5855		0.0697 0.5243		0.1249 0.7036	

significant differences were found among the sections (1st, 2nd, 3rd) (see Table 4).

The trends observed in the blue and green water footprints (see Table 3) during a rainy, normal and dry year showed an increase in the blue footprint (694.3-1 038.3 m^3/ton) and a decrease in the green footprint (370.3-7.2 m^3/ton).

Under the scenario with a 20% lower yield, the total water footprint of the crops was estimated to be 1 064 m^3/ton for a rainy year, 1 268.8 m^3/ton for a normal year and 1 633.9 m^3/ton for a dry year (see Table 3). Consumption was 365.1 m^3/ton higher in a dry year than a normal year, but 204.2 m^3/ton less in rainy year, with significant differences detected among the years analyzed. In addition, the statistical analysis showed significant differences among the sections, in which the water footprint in the 1st section was larger for the different years analyzed (see Table 4).

Under a scenario with 20% less crop yields (see Table 3), the largest blue water footprint was also detected during a dry year, with 1 622.7 m^3/ton of irrigation water and with significant differences among a rainy, normal and dry year. Nevertheless, no significant differences were found among the sections. The largest green water footprint was also seen during the rainy year, with 370 m^3/ton and with significant differences among a rainy, normal and dry year. The statistical analysis did not identify significant differences among the sections (see Table 4). Under this condition, while the blue footprint increased, the green footprint decreased, similar to the trend detected in the previous scenario.

Virtual Water (WV)

The largest amount of total virtual water would have been exported during a rainy year, with significant differences with respect to a dry year (ANOVA $F_{(2,4)}$ = 6 293; P = 0.0001). This largest amount of total virtual water would correspond to green water from precipitation, with significant differences among the years analyzed (ANOVA $F_{(2,4)}$ = 2 347; P = 0.0001). The majority of blue water would have been exported during a dry year, which would correspond to the addition of irrigation water, with significant differences among the years analyzed (ANOVA $F_{(2,4)}$ = 3 215; P = 0.0001) (Figure 5).

Apparent Water Productivity (AWP)

The *AWP* during the study period varied in relation to market prices. In terms of the

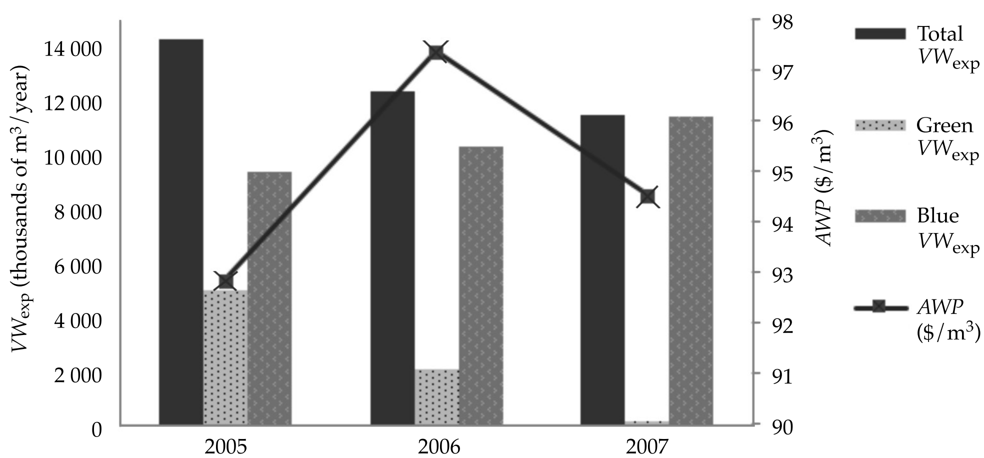

Figure 5. Estimation of the exported virtual water (VW_{exp})content and apparent water productivity (*AWP*) in the production of cereals, during a rainy year (2005), normal (2006) and dry year (2007), in the Cachapoal River Basin.

water footprint of cereals, it would have been less during a rainy year (2005), calculated at 92.8 $/m^3, and more in a normal year (2006), calculated at 97.4 $/m^3, with significant differences detected among the years studied [(2005, 2006, 2007 (94.5 $/m^3)] (ANOVA $F_{(2,4)} = 39.02$; $P = 0.0004$) (see Figure 5).

Discussion

In a hydrographic basin, it is crucial to consider agriculture as the productive and economic activity most dependent on local climate conditions, and these conditions are the primary reason for variations in the annual production of crops (Gil, Lozada, López, Marquez, & Salazar, 2012). Precipitaiton is the main climate factor responsible for periodic changes in yields. Its influence is even greater in basins with dryland and irrigated crops, such as the Cachapoal River Basin.

The analysis of 34 years of precipitation data in the area demonstrates that the climate in the Cachapoal River basin is similar to the Mediterranean, with rainfall during the cold season (May-August) and a dry period during the hot season (November-February) (Figure 3). In addition, there are notable hydric differences among the 1st section, the Andean region (with the most precipitation) and the 3rd section which receives the least precipitation (52% less), the sector through which the coastal mountains drain. The behavior of rainfall in the basin could also be categorized according to rainy, normal and dry years, which ranged from 117 to 1.517 mm. This region produces 73.2% of the Chilean cereal crops, which is attributed to a set of factors, including soil conditions (alluvial) and climate (Osorío, 2013).

To demonstrate the effect of the climate on the water footprint of the crops under the constant yield scenario, extreme climate conditions —that is, rainy and dry years— were found to have water footprints over 1 064 and 1 045 m^3/ton, respectively, whereas a normal year had 1 015 m^3/ton (see Table 3). These results regarding the variation among rainy, normal and dry years observed by this study were similar to those described by Rodríguez-Casado, Garrido, Llamas and Varela-Ortega (2008) for a basin in Spain, in which the water footprint for a rainy year was larger than that of a normal year.

The use of water was found to be less productive under a scenario with a 20% decrease in crop yields (situation projected given climate change), since water consumption was higher per ton of product generated (larger water footprint) (Table 3), demonstrating that the sustainability of the water footprint of a cereal crop should take into account the efficiency of the water resource as well as the climate situation.

Under both yield scenarios (constant and 20% reduction) a dry year had a larger blue water footprint (more irrigation) and a rainy year had a larger green water footprint (more precipitation), indicating that the availability and source of water are key to sustainability. The use of water for irrigation is affected by a) changes in hydrological regimes (for example, variations in precipitation, potential and real evaporation, and/or runoff on a basin scale); b) increased competition among water users (Schmidhuber & Tubiello, 2007), and c) the planting period, growth and harvesting methods (Xiong *et al*., 2010), which the present study estimated as 120 days (Figure 4).

In agriculture, roughly 40% of the water extractions return to rivers and/or local aquifers, becoming reusable. Therefore, the calculation of the volume of water consumed provides a solid basis to estimate the extraction of the resource (Hoekstra, Mekonnen, Chapagain, Mathews, & Richter, 2012). The estimation of virtual water is thus crucial during dry periods since it makes it possible to estimate how the demand of exportable products may affect hydrological systems in exporting regions (Chen & Chen, 2013).

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This study found that the largest amount of total virtual water exported (VW_{exp}) would have occurred during a rainy year (2006) and the least during a dry year (2007), given the lowest supply of green virtual water. Likewise, the largest amount of blue virtual water exported would occur during a dry year, when irrigation is used to compensate. In particular, in 2007 (dry year), the north-central portion of the country registered strong frost conditions during the second week of July, when the Cachapoal Basin was affected by very low temperatures which seriously compromised crop production (Odepa, 2013a). This was compensated by increased irrigation, as reflected by this indicator (Figure 5).

The apparent water productivity (AWP) values were not found to be affected by the climate, given that the AWP was less for a rainy year such as 2005 even though the exportation of cereals required a higher virtual water content (Figure 5). Donoso *et al*. (2012) suggest that the economic sectors that use the most water in Chile, such as agriculture, would have a lower AWP. Nationally, the apparent productivity of cereal crops is estimated at 110 /m^3, a value similar to that calculated by the present analysis of the Cachapoal River Basin.

The largest water footprint in the country corresponding to the agricultural sector was found in the region between O'Higgins and Araucanía (Donoso *et al*.,2012). The water volume used in this region is 6 676.74 million m^3/year, representing 70.2% of the total water volume used by the agricultural sector (Hadjigeorgalis & Riquelme, 2002). Improving the efficiency of the use of water in Chile is a challenge due to low crop yields. Because of the passage of Law 18.450, for products with high export value the O'Higgins region is incorporating technologically better irrigation methods. Changes in the types of irrigation have been registered (gravity -41%; mechanical -8), with a 75% increase in the use micro-irrigation. Nevertheless, this effort is not reflected in lower water consumption. Therefore, the optimization of the productivity of water should be considered for the development of sustainable crop systems (Postle, George, Upson, Hess, & Morris, 2012) since water is the resource that links productive activities with changes in environmental conditions. An essential component to address the challenges created by water security is the generation of knowledge and innovation: "better knowledge about the natural and social processes involved in the occurrence and management of water is indispensable, as is the anthropogenic processes involved (Martínez-Austria, 2013). In addition, Chile requires more innovation in technology and water management methods, training, social organization, adequate legal frameworks and the development of institutions such as the Superintendencia del Agua proposed by the current government in the 2015 National Water Resource Policy.

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Virtual Water in an Input-Output Framework for the Valley of Mexico Basin

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Abstract

Rodríguez-Tapia, L., Morales-Novelo, J. A., Sosa-Rodríguez, F. S., Altamirano-Cabrera, J. C., & Torres-Ayala, F. (March-April, 2016). Virtual Water in an Input-Output Framework for the Valley of Mexico Basin. *Water Technology and Sciences* (in Spanish), 7(2), 51-66.

The Valley of Mexico basin (VMB) is located in central Mexico and produces one-fourth of the total national production. The overexploitation of its aquifers has been registered as the highest nationwide. This article introduces a methodology to estimate virtual water multipliers (VWM) for the economic activity in the basin based on an input-output matrix for the VMB for 2008. The VWM takes into account the virtual water related to the economic activities of a region, with the rest of the economy of Mexico and the world. The results identified the economic activities with low- and high-intensity water usage that are prevalent in the basin. In addition, based on the balance between virtual water imports and exports in the basin, it is concluded that goods with high water contents are imported and goods with low water contents are exported. This behavior describes the basin as a net importer of virtual water, which is a positive characteristic that helps to compensate for the water stress in the basin. This finding appears to confirm the Heckscher-Ohlin theorem of international trade, suggesting the economic rational of a region which is experiencing the highest water stress nationwide.

Keywords: Virtual water trade, Valley of Mexico basin, input-output in the Valley of Mexico basin, input-output model, virtual water multipliers.

Resumen

Rodríguez-Tapia, L., Morales-Novelo, J. A., Sosa-Rodríguez, F. S., Altamirano-Cabrera, J. C., & Torres-Ayala, F. (marzo-abril, 2016). Agua virtual en un marco insumo-producto para la cuenca del valle de México. Tecnología y Ciencias del Agua, *7(2), 51-66.*

La cuenca del valle de México (CVM) se ubica en la región central de México, genera la cuarta parte de la producción total nacional y registra la mayor sobreexplotación de sus acuíferos en el país. Este artículo introduce la metodología para estimar los multiplicadores de agua virtual (MAV) de cada actividad económica de la cuenca a partir de la matriz insumo-producto de la cuenca del valle de México 2008. Los MAV contabilizan el agua virtual involucrada en las actividades económicas dentro de la región, con el resto de la economía de México y el mundo. Los resultados identifican las actividades económicas de baja y alta intensidad en el uso del agua que predominan en la cuenca. Asimismo, haciendo el balance entre exportaciones e importaciones de agua virtual en la CVM, se concluye que se importan bienes con alto contenido de agua y se exportan bienes con bajo contenido del recurso. Dicho comportamiento describe a la cuenca como una región importadora neta de agua virtual, lo cual es una característica positiva que ayuda a compensar el estrés hídrico que sufre la cuenca. Este hallazgo parece confirmar el teorema de Heckscher-Ohlin del comercio internacional, sugiriendo la racionalidad económica de una región que enfrenta el mayor estrés hídrico del país.

***Palabras clave**: comercio de agua virtual, cuenca del valle de México, insumo-producto en la CVM, modelo insumo-producto, multiplicador de agua virtual.*

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Introduction

The Valley of Mexico Basin (VMB) is the most important economic region in Mexico, and its water resources are also the most overexploited. Water scarcity affects the well-being of various population groups and limits economic growth. To better analyze how to reduce water stress in the VMB, we are interested in investigating the structure of virtual water consumption and the efficient use of water by economic activities.

This article is organized into five sections. First, in the introduction, the characteristics of the economy and the water in the VMB are described, demonstrating a complex relationship between a limited water supply *versus* high water demand. The concept of "virtual water" is also presented. The second section describes the methodology used to estimate virtual water. The third section applies that methodology to the VMB and estimates direct water coefficients and virtual water multipliers, as well as the final water demand for all sectors. The fourth section discusses the results, analyzes the structure of the VBM's external virtual water trade and how this can help mitigate water stress in the valley. The conclusions are then presented in the last section.

Characteristics of the Economy and the Water in the Valley of Mexico Basin (VMB)

The VMB covers a total area of 9 738 km^2, which includes portions of the state of Mexico, Hidalgo, Tlaxcala (composed up of 85 municipalities) and the 16 districts in Mexico City. The topography of the VMB is characterized as endorheic, concave in shape and surrounded by a mountain chain with no natural outlets. This requires the building of large infrastructure projects to expulse rainwater and wastewater from the valley (beginning with the construction of the Nochistongo Canal in the 18th century), as well as bringing water in from other basins (Lerma and Cutzamala).

The VMB has a population of 20.59 million, the majority (97%) of which is located in an area measuring 7 854 km^2 (Conagua, 2009), called the Metropolitan Area of the Valley of Mexico (MAVM), giving it the characteristic of an urban area (INEGI, 2010). This city is the largest in the country and is comparable to the largest in the world.

Based on 2008 statistics from what is called the input-output matrix (IOM) of the Valley of Mexico Basin (IOM-VMB-2008), we have estimated the gross value of production (GVP) generated in the basin at $5.085 trillion Mexican pesos. This represents one-fourth of the country's production and demonstrates the importance of the economic activity in this region to the economic growth of Mexico. Three sectors represent the majority of the production in the VMB —the *service* sector with nearly half the gross value of production (GVP) (48.6%), *industrial manufacturing* with roughly one-fifth of production (19.2%) and the *commercial* sector with 14.5%. *Agriculture* and *primary production* represents only 1.5% of production. This structure is consistent with the urban profile of the VMB.

Water Stress in the VMB

In 2008, the extensive economic activity taking place in the valley and consumption by over 20 million people together created a demand for 2 902.29 cubic hectometers (hm^3/year) of water (Conagua, 2009). Forty-three percent of this volume was consumed for urban public use and 57% for economic activities (Rodríguez & Morales, 2013). Meanwhile, the sources of the water supply in the VMB mainly come from the valley itself (73%), while roughly one-fifth is imported (21%) and roughly 6% of the total supply comes from reuse (Conagua,2009, 2010).

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The problem is that the average yearly volume of water consumed in the VMB is twice as much as that which ensures its sustainable use. The rational use of water in a basin is determined by the mean natural availability (MNA). An MNA of 1 404.68 hm^3 has been calculated for the basin, obtained from the sum of the mean natural surface runoff and annual groundwater recharge. Both amounts reflect water volumes that are renewed each year and indicate the water's condition as a natural renewable resource. The total water required in the VMB, 2 902.29 hm^3, is double the MNA. By applying the well-known Falkenmark index to measure water stress, the valley is classified by extreme scarcity, having reached an annual per capital water MNA of 68.2 m^3/inhabitant/year, much less than the 1 000 m^3/inhabitant/year that defines this category.

The source that provides most of the water for the VMB is the basin itself. Specifically, according to Conagua (2009, 2010), 90% comes from aquifers (underground) and 10% from surface water. In effect, groundwater is the main source of water in the basin. In 2008, 1 903.8 hm^3 were extracted (Conagua 2009, 2010), which is 2.1 times the natural recharge of the aquifer. Extraction exceeded natural recharge by 1 010.35 hm^3, thereby reflecting an overexploitation of this source of 113%. This imbalance is classified as a predatory use of groundwater resources having significant collateral effects, such as the sinking of large urban areas as well as a decrease in the quality of the water and higher extraction costs.

Concept of Virtual Water

The concept of "virtual water" was presented by Allan (1997, 1999) and refers to the amount of *water used* to produce a particular product or service. The adjective "virtual" refers to the fact that only some of the water used to produce the product is contained in the final product, and this part is often insignificant in comparison to the virtual water content (Hoekstra & Chapagain, 2008). For example, it has been estimated that 114 liters (l) of water are needed to produce one cup of coffee, and 1 to 3 cubic meters (m^3) of water are necessary to obtain one kilogram of rice (Chapagain & Hoekstra, 2004). In effect, the amount of water required in the production process of any good or service can be calculated. Thus, the concept of *water used* does not only refer to the physical content of water in a product but also includes all of the water that is consumed during the process to produce the particular product, as well as the water used to produce the inputs for its production process.

The concept of virtual water is particularly important in terms of trade (Lenzen & Foran, 2001). For example, a region or country can save water by replacing some of its water-intensive domestic products with imported goods from regions with a relative abundance of water. Thus, the concept of virtual water can be used to measure the amount of water involved in the exportation and importation of goods and services, which reflects an application of the Heckscher-Ohlin theory to water, suggesting that countries with a relative abundance of water export relatively water-intensive goods and services (Debaere, 2014). The virtual water contained in exports and imports also plays an important role in the determination of the water footprint (Chapagain & Hoekstra, 2004). For example, the water footprint of a nation indicates the total amount of water used by its inhabitants in the consumption of goods and services. These inhabitants consume imported products and therefore external virtual water, while domestic water used to produce products that are exported are consumed by those outside the region.

Work by Debaere (2014) shows that water actually provides a comparative advantage and that countries with more available water per capita tend to export more water-intensive goods. Findings indicate that the global proportion of exports by countries with an abundance of water tends to increase with the water intensity of the goods they export. The methodology and estimation of virtual water exports and imports will be described next.

Methodology

The focus on virtual water is aimed at estimating the direct and indirect consumption of water (by production). The method consists of quantifying the amount of water directly used in the production of a primary good or service, as well as the water required to produce the inputs used in its production process. The concept of virtual water refers to the estimation of the amount of water directly and indirectly used in the production of a good or service based on an input-output matrix (IOM).

An input-output matrix is a suitable tool to determine the virtual water content corresponding to a monetary unit of final demand for a specific sector or activity. This is called the virtual water multiplier (VWM). That is, the VWM represents the amount of water directly used in the process to produce the final unit of demand for sector *i*, plus the water required to produce the goods *k* used as inputs in the process to produce *i*, plus the water consumed to produce the inputs *n* used in the production of goods *k*, etcetera. Adding all the direct and indirect water requirements results in the total amount of water used for the final unit of demand for sector *i*, which is referred to as the VWM. In brief, the virtual water multiplier (VWM) is defined as the amount of water directly and indirectly required to produce a final unit of demand corresponding to a specific economic activity.

The idea of using the concept of virtual water using an input-output structure is to analyze direct and indirect relationships among sectors in order to trace the destination of water according to the components included in the final unit of demand (for domestic use or an external sector). This perspective can be used to determine the trade of direct and indirect water used in, for example, exported goods and services.

Estimation of a Virtual Water Multiplier

The work developed herein is focused on the destination of the water used in the VMB after it has been incorporated into the production of goods and services. The amount of water attributed to the final demand is calculated using an input-output matrix, distinguishing between destinations within the Valley of Mexico Basin, to the rest of the country and to the rest of the world. Thus the water trade can be determined, for example, through goods and services.

The methodology uses an input-output matrix of the Valley of Mexico Basin from 2008 (IOM-VMB, 2008). This data is used to identify the economic structure of the region and record the activity that receives and supplies water. The water flow data corresponding to the VMB for 2008 was obtained from Conagua (2009) for consistency with the IOM-VMB-2008 input-output matrix. Since measuring water trade among sectors is more complicated, this investigation relied on information from the VMB water model database (UAM, 2010) and applied adjustments to large clusters.

Based on the IOM-VMB-2008, the Leontief inverse matrix was estimated, which indicates the interdependence among the different activities in the region and makes it possible to identify the direct and indirect effects of production, as in the case of water. Specifically, this work estimates the VWM for the economic activities in the basin, which are used to calculate the virtual water involved in trade with economies in the rest of Mexico

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and the world. Thus, the effects of trade on water savings in a region with a water deficit can be analyzed. The application of the methodology to the calculation of the VWM is based on work by Dietzenbacher and Velázquez (2007).

How the effects of the indirect use of water are analyzed using an input-output matrix (IOM) is explained next. The IOM is composed of the sub-matrices shown in Figure 1.

The elements z_{ij} are inter-activity flows that define matrix Z, having dimensions n x n, where n indicates the number of economic activities in the VMB. That is, z_{ij} denotes the inputs from activity i for activity j in the same basin (i,j range from 1,…n).

In matrix F, having size n x k, the elements f_{ij} denote the inputs in the VMB from sector i for the different categories that make up the final demand j (where $j = 1,\ldots k$). The final demand categories are private consumption, government consumption, exportations to the rest of the Mexican economy, exportations to the rest of the world, gross capital and variation in stocks.

Vector v' (row) contains the value added for each activity (salaries and pay, depreciation, operating profit, indirect taxes minus subsidies). The sum of this vector results in the value added for the VMB, which is the Regional Gross Product (RGP), also known as the Gross Domestic Product (GDP).

The typical elements m_{ij} in vector M (row) denote the importation from an external sector j (rest of the Mexican economy or rest of the world) that are purchased by sector i in the VMB (imported inputs).

The elements x_i in the column vector X denote the gross product corresponding to activity i in the VMB. The value of the product of each activity can be obtained by adding the rows or columns in the matrix. Adding the columns produces the following equation:

$$x_i = \sum_j z_{ij} + \sum_j f_{ij}$$

where $z_{ij} = a_{ij} x_j$ and f_{ij} is the final demand.

The coefficients of the indirect inputs are defined as $a_{ij} = z_{ij}/x_j$, and indicate the (additional) inputs from sector i, in monetary units (Mexican pesos), required to produce one additional peso of product for sector j in the VMB. When using this definition and adding the categories in the final demand (for example, $f_i = \Sigma_j f_{ij}$), the equation for the sector's product can be rewritten as:

$$x_i = \sum_j a_{ij} x_j + f_i$$

or using matrix notation:

$$x = Ax + f$$

If matrix A of direct inputs coefficients is known and is presumed to be constant, the production in the different sectors can be determined for any given final demand vector

Z	F	x
v'		
M		
x'		

Figure 1. Input-output matrix.

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$(\tilde{f})$ (for example, exogenously specified). The solution produces:

$$\left(1-A\right)^{-1}\tilde{f}=L\tilde{f}=x$$

where $L = (1 - A)^{-1}$ denotes the Leontief inverse or *matrix of multipliers*. Taking $\tilde{f}$ = 0,…0,1…)′, for example, the j^{th} unit element of the final demand provides the interpretation of the elements in the Leontief inverse. Each element l_{ij} in the Leontief inverse provides the (extra) product for sector i needed to generate one (extra) peso of final demand for sector j. Those L elements include all the direct and indirect effects needed to produce one unit of final demand. The multipliers of the product are obtained by adding the columns in the Leontief inverse That is, $\sum_i l_{ij}$ indicates the total (extra) product that needs to be produced for one additional peso of final demand for sector j.

The amount of (extra) liters of water directly and indirectly consumed by sector i to generate one additional monetary unit of final demand in sector j is obtained in the same way by multiplying the elements l_{ij} (column in the Leontief inverse) by the direct water input coefficients y_{ji} (transposed vector) (for example, $y_j l_{ij}$). The extra amount of virtual water to produce one additional peso of final demand in sector j, or the virtual water multiplier (VWM), is obtained by adding the results from the vector related to i. The virtual water multipliers for the economic activities or sectors in the VMB are shown in Table 1, column 4 (for example, $\Sigma_i y_j l_{ij}$) and a multiplier per economic activity is obtained.

Results

Direct Water Coefficients and Virtual Water Multipliers

This section describes the use of water by the economic activities in the VMB. The information shown in Table 1 was generated based on the IOM-VMB-2008 and data from Conagua for the year 2008. The information is presented using the nomenclature from the input-output matrices.

i: economic activities per row.
j: economic activities per column.
w_j: row vector for direct water consumption (primary water use) per economic activity.
x_j: row vector for production per economic activity.
$y_j = w_j / x_j$: direct water coefficients vector, define water consumption in liters per monetary unit of production.
l_{ij}: production multipliers in the IOM from column j.
$\Sigma_i y_j l_{ij}$: virtual water multipliers (VWM) per economic activity.

Table 1. Direct water coefficients and virtual water multiplier per economic activity in the Valley of Mexico Basin (VMB), 2008.

Activities J	**(1) Use of water millions of m³ (hm³)**		**(2) GVP millions of pesos ($)**		**(3) Direct Coefficients liters/peso (l/$)**	**(4) Virtual water multiplier IOM-VMB liters/peso (l/$)**
	w_j	%	x_j	%	$y_j = (w_j/x_j)$	$VWM = \sum_j[y_j * l_{ij}]$
Agricultural and other Primary Activities (a)	145.25	9.35	58 034	1.14	2.50	3.67
Livestock	218.22	14.04	19 581	0.39	11.14	11.44

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Table 1 (continued). Direct water coefficients and virtual water multiplier per economic activity in the Valley of Mexico Basin (VMB), 2008.

Activities J	(1) Use of water millions of m³ (hm³)		(2) GVP millions of pesos ($)		(3) Direct Coefficients liters/peso (l/$)	(4) Virtual water multiplier IOM-VMB liters/peso (l/$)
	w_j	%	x_j	%	$y_j = (w_j/x_j)$	$VWM = \sum_j [y_j * l_{ij}]$
Total Agriculture and Other Primary Activities	**363.47**	**23.39**	**77 615**	**1.53**	**-**	**-**
Average	**-**	**-**	**-**	**-**	**4.68**	**7.68**
Total electric, water and gas generation and supply	**1.49**	**0.10**	**19 689**	**0.39**	**0.08**	**0.22**
Total Construction	**30.26**	**1.95**	**380 663**	**7.49**	**0.08**	**0.09**
Food Industry	36.88	2.37	221 606	4.36	0.17	0.99
Drinks and Tobacco Industry	20.68	1.33	54 918	1.08	0.38	0.65
Manufacturing of Textile Inputs	2.77	0.18	18 427	0.36	0.15	1.05
Manufacturing of textile products	0.86	0.06	6 970	0.14	0.12	0.25
Manufacturing of Clothing	4.62	0.30	38 617	0.76	0.12	0.24
Manufacturing of leather products	0.67	0.04	3 747	0.07	0.18	0.44
Wood Industry	0.18	0.01	6 249	0.12	0.03	0.07
Paper Industry	9.91	0.64	37 394	0.74	0.27	0.39
Printing and Related Industries	4.73	0.30	20 096	0.40	0.24	0.34
Other Industries	46.46	2.99	569 206	11.19	0.08	0.16
Total Manufacturing Industries	**127.77**	**8.22**	**977 229**	**19.22**	**-**	**-**
Average	**-**	**-**	**-**	**-**	**0.13**	**0.23**
Total Commerce	**4.27**	**0.27**	**735 024**	**14.45**	**0.01**	**0.07**
Total Transportation, Mail and Storage	**217.90**	**14.02**	**424 896**	**8.36**	**0.51**	**0.71**
Film, Video and Sound Industry	44.17	2.84	33 097	0.65	1.33	1.44
Social Assistance and Health Care Residences	1.36	0.09	578	0.01	2.35	2.40
Other Social Assistance Residences	1.83	0.12	648	0.01	2.83	2.90
Entertainment Services in Recreational Facilities and Other Recreactional Services	24.92	1.60	9 407	0.18	2.65	2.77
Temporary Housing Services	32.92	2.12	16 489	0.32	2.00	2.06
Food and Drink Preparation Services	44.03	2.83	52 622	1.03	0.84	0.89
Associations and Organizations	62.86	4.05	39 049	0.77	1.61	1.69
Other Services	597	38.39	2 318 415	45.59	0.26	0.44
Total Services	**808.60**	**52.04**	**2 470 305**	**48.58**	**-**	**-**
Average	**-**	**-**	**-**	**-**	**0.33**	**0.55**
Total of 80 Activities	**1 554**	**100**	**5 085 421**	**100**	**-**	**-**
Average	**-**	**-**	**-**	**-**	**0.31**	**0.48**

(a) Includes agricultural, livestock, forest, fishing and mining activities.

Source: developed based on the 2008 IOA of the VMB (MIP-CVM, Spanish acronym).

The first column in Table 1 shows the consumption of primary water used by each economic activity (w_j), in hm^3. The column with the corresponding percentages shows each activity's proportion of the total of primary water used in the basin. The activities in the service category are seen to represent the largest percentage (52.04%), followed by agriculture and livestock (23.39%), transportation, mail and storage (14.02%), manufacturing (8.22%), construction (1.95%), and lastly commercial (0.27%).

The second column indicates the gross value of production (GVP) for each activity (x_j) and its corresponding proportion of the gross value of production in the basin. Although agriculture and livestock have a very low proportion of the production (1.53%), they are found to be responsible for nearly one-fourth (23.29%) of direct water use in the entire basin. Commercial activity has the opposite behavior, with only 0.27% of the total primary water use and producing 14.45% of the value of production in the basin. Service activities are responsible for half of the GVP and half of the direct water use. The manufacturing activities represent one-fifth of the GVP and 8.22% of the primary water use. These last two groups include economic activities with high variations in water usage and production depending on the particular production conditions of each activity.

The third column shows the direct water coefficient vector (y_j) and indicates how many liters of primary water use are required by each economic activity to produce one peso of the gross value of production. The value of y_j for the entire basin is 0.31 liters, which indicates that 310 milliliters (ml) of water (or 310 liters of water per thousand pesos of GVP) must be directly used to produce one peso of gross value of production. The direct water required by the different economic activities vary greatly. For example, 2.5 liters are needed in order for the agricultural activity to produce one peso of gross value of production, and 11.14 liters are needed for livestock activities. These values are much higher than the average for the economy, and are therefore classified as water-intensive activities. The direct water requirements by these service sector activities vary widely, with a mean of 0.33 liters, placing it slightly above the mean of the basin. Other findings that stand out include: other services and social assistance requiring 2.83 liters, entertainment and recreational services requiring 2.65 liters, social assistance and health care residences requiring 2.35 liters, and temporary housing services that require 2 liters of water per monetary unit of the GVP for the respective sector. The manufacturing activities have a mean value of 0.130 liters per peso produced, placing it below the mean of the economy, while the coefficients of the specific activities vary depending on the type of manufacturing. The drinks and tobacco industry requires 0.380 liters while the food industry requires 0.170 liters per peso of the gross value of production. The wood industry is below the mean, with 0.03 liters per peso of GVP.

Agricultural activity has an intensive primary water use (a high direct water usage coefficient), and in turn, its production is used as input in the food industry. This relationship explains the food industry's intensive use of water to produce goods. This effect of the indirect use of water is precisely what is identified by the indicator called the virtual water multiplier (VWM).

Lastly, the calculation of the VWM for each activity is shown in Table 1, column 4.

The VWM values range from 0.07 liters for the wood industry to 11.44 liters for livestock, which indicate the total amount of water required by both activities (directly and indirectly) to produce one monetary unit of final demand. The VWM for the food industry is 0.99 liters (990 ml) and indicates 170 ml of primary water use (direct) and 820 ml of indirect water use. Therefore, the VWM will always be greater than or equal to the direct water coefficient. The VWM for the basin is 57% more than the coefficient of the direct water requirements.

In addition, agricultural and other primary activities have a VWM of 3.67 liters, which is 46.8% larger than the coefficient of the direct water requirement (2.50 liters), since their production requires inputs that demand a large amount of water. Livestock has a high direct water coefficient (11.14), while its VWM increased by only 0.26%.

Commercial activity has a VWM of 0.07 liters, much higher than its direct requirement of only 0.01 liters, given that a large amount of water is needed to produce commercial goods and services —for example, agricultural products and livestock, processed foods and products pertaining to the chemical industry, among others.

With regard to manufacturing activities, the food industry has a VWM of 0.99 liters —495% higher than its direct coefficient (0.17 liters) since it requires agricultural inputs and, therefore, needs a large amount of water for its production.

Some of the services that stand out due to their high VWM are social assistance (2.90 liters) and entertainment (2.77 liters), from the use of water directly incorporated into the production process.

Virtual Water Contents in the Final Demand in the VMB

The virtual water used to produce the final demand is estimated based on the VWM. For calculation purposes, total final demand corresponding to the IOM-VMB-2008 was divided into three categories:

a) Domestic consumption in the VMB (f^{vmb} vector) which includes private consumption, government, investment and variations in stocks.

b) Exports to the rest of Mexico (F^{RMEX}).

c) Exports to the rest of the world (F^{RW}).

The virtual water for each category was estimated for each economic activity. These monetary amounts are multiplied by the corresponding VWM. For example, exports to the rest of Mexico are multiplied by their VWM $\sum_{i=1}^{80} y_j l_{ij} f_j^{\text{RMEX}}$ for $j = 1, \ldots, 80$. The result is the amount of virtual water used in the production of the exports for each activity j. The final demand is calculated in the same way for the categories below.

Table 2a shows the virtual water estimations for the VMB in 2008. The first three columns contain each component and the fourth column contains the total final demand. This table shows that 43.51% of the manufacturing production is exported, the majority to the rest of the world and a lesser amount to the rest of Mexico, while the remaining 56.48% is consumed domestically. Columns 5 through 8 in Table 2a present the amount of virtual water estimated per sector. For example, the food industry exports a value equal to \$6 806 million pesos to the rest of the world which requires 6.74 hm^3 of virtual water to produce.

Table 2 presents a summary of Table 2a, in which the activities are grouped into the agricultural sectors and other primary activities; generation and supply of electricity, water and gas; construction; manufacturing industries; commerce; transportation, mail and storage; and services. The data shows percentages of the total final demand (3.209 trillion pesos) and the total virtual water required to produce it (1 260 hm^3).

Table 2 shows that the domestic consumption of agricultural goods and primary activities represents 1.34% of the total final demand and requires 8.28 of the total virtual water used, indicating that this component of demand is water-intensive. Likewise for domestic consumption of manufacturing products, which represents 9.67% of the final

Table 2. Grouped Results for the Final Demand and Virtual Water for the Valley of Mexico, 2008 (percentages).

Sectors	Components of final demand			
	Domestic consumption a)	Exportation to the rest of the Mexican economy	Exportation to the rest of the world	Final Demand
Final demand				
% of total final demand				
Agriculture and other primary activities	1.34	0.00	0.14	**1.48**
Generation a supply of electricity, water and gast	0.21	0.00	0.00	**0.22**
Construction	10.90	0.00	0.00	**10.90**
Industrial manufacturers	9.67	1.05	6.40	**17.12**
Commerce	11.45	0.44	2.68	**14.57**
Transportation, mail and storage	6.64	1.84	1.08	**9.56**
Services	35.26	10.14	0.76	**46.16**
Total	75.47	13.47	11.05	**100**
Virtual water contents in the final demand				
% of the total virtual water				
Agriculture and other primary activities	8.28	0.24	0.89	**9.40**
Generation a supply of electricity, water and gast	0.07	0.00	0.00	**0.07**
Construction	4.43	0.00	0.00	**4.43**
Industrial manufacturers	15.00	0.49	3.66	**19.15**
Commerce	1.90	0.07	0.44	**2.42**
Transportation, mail and storage	7.57	3.40	2.01	**12.98**
Services	39.99	11.03	0.53	**51.54**
Total	**77.24**	**15.24**	**7.53**	**100**

a) Domestic consumption includes private consumption by families, government consumption, gross fixed capital formation and variations in stocks.
Source: developed based in the IOM-VMB-2008.

demand and 15% of the total virtual water in the basin.

The construction sector represents 10.9% of the total final demand and 4.43% of the total virtual water, and the entire sector was consumed domestically. Services explain 35% of the total final demand (directed towards domestic use) and requires 39.99% of the total virtual water, suggesting that some of its activities are water-intensive.

Commerce explains 11.45% of the final demand for domestic consumption and only 1.90% of the total virtual water, demonstrating low water requirements. The exports from the commerce sector represent 3.12% of the final demand and 0.52% of the total virtual water used by that demand.

What is most interesting is that manufacturing exports represent 7.45% of the final demand and only 4.15% of the virtual water used by the final demand, suggesting a certain degree of specialization in exporting goods with low water contents.

Virtual Water Trade by the VMB

The above results indicate that the agricultural and manufacturing processes directed towards domestic consumption are produced with large amounts of water. In this section, it

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Table 2a. Virtual water contents in the components of final demand in the Valley of Mexico Basin.

Activities	Consumption a)	Exports to the rest of the Mexican economy	Exports to the rest of the world	Final demand	Domestic Consumption a)	Exports to the rest of the Mexican economy	Exports to the rest of the world	Final demand
	Millions of pesos				Virtual water (hm^3)			
Agriculture and other primary activities b)	35 643	53	3 926	39 622	21.29	3.02	5.75	30.06
Livestock	7 259	0	473	7 732	83.04	0.00	5.41	88.45
Total agriculture and other primary activities	**42 902**	**53**	**4,399**	**47 354**	**104.33**	**3.02**	**11.16**	**118.51**
Total generation and supply of electricity, water and gas	**6 861**	**0**	**61**	**6 921**	**0.94**	**0.00**	**0.01**	**0.94**
Total Construction	**349 985**	**0**	**0**	**349 985**	**55.83**	**0.00**	**0.00**	**55.83**
Food Industry	145 053	1 147	6 806	153 006	143.65	1.14	6.74	151.52
Drinks and Tobacco Industry	31 706	1 469	4 899	38 074	20.74	0.96	3.20	24.91
Manufacturing of Textile Inputs	2 906	0	5 994	8 900	3.04	0.00	6.28	9.32
Manufacturing of textile products	891	0	3 400	4 290	0.23	0.00	0.87	1.09
Clothing Manufacturing	10 818	0	22 993	33 811	2.59	0.00	5.51	8.10
Manufacturing of leather products	1 963	0	520	2 483	0.87	0.00	0.23	1.10
Wood Industry	1 024	0	363	1 387	0.07	0.00	0.03	0.10
Paper Industry	5 144	0	4 000	9 143	2.00	0.00	1.55	3.55
Printing and Related Industries	3 142	766	2 519	6 427	1.06	0.26	0.85	2.17
Other Industries	107 746	30 349	153 851	291 946	14.75	3.83	20.86	39.44
Total Manufacturing Industry	**310 393**	**33 731**	**205 344**	**549 469**	**189.00**	**6.19**	**46.12**	**241.31**
Total Commerce	**367 454**	**14 070**	**86 028**	**467 552**	**23.93**	**0.92**	**5.60**	**30.44**
Total Transportation, Mail and Storage	**213 003**	**58 983**	**34 705**	**306 692**	**95.38**	**42.87**	**25.37**	**163.62**
Film, Video and Sound Industry	7 206	20,926	53	28,185	10.36	30.08	0.08	40.52
Social Assistance and Health Residences	442	136	0	578	1.06	0.33	0.00	1.38
Other Social Assistance Residences	648	0	0	648	1.88	0.00	0.00	1.88
Entertainment and Recreational Services	5 207	4 200	0	9 407	14.40	11.62	0.00	26.02
Temporary Housing Services	14 003	0	0	14 003	28.83	0.00	0.00	28.83
Food and Drinks Preparation Services	46 934	0	0	46 934	42.00	0.00	0.00	42.00
Associations and Organizations	22 319	10 139	0	32 458	37.75	17.15	0.00	54.90
Other Services	1 034 964	290 180	24 211	1 349 355	367.68	79.84	6.55	454.06
Total Services	**1 131 723**	**325 580**	**24 264**	**1 481 567**	**503.96**	**139.01**	**6.62**	**649.59**
Total 80 Activities	**2 422 322**	**432 417**	**354 801**	**3 209 540**	**973.36**	**192.01**	**94.88**	**1 260.25**

a) Domestic consumption includes private consumption by families, government consumption, gross fixed capital formation and variations in stocks.
Source: developed based in the IOM-VMB-2008.

is of interest to investigate whether external trade with the VMB has a net export or import of virtual water.

According to Heckscher-Ohlin's international trade theory, a country exports the products that give it a comparative advantage. These are the products that intensively use the factors of production that are relatively abundant in the country. Meanwhile, countries import products that are made with an intensive use of factors that are scarce. Considering water as a factor of production, the VMB does not have a comparative advantage in producing water-intensive goods.

This section estimates the virtual water used in exports and imports. According to the combination of products that make up current exports, for example with the rest of the world, they are expected to increase one million pesos. Therefore, a vector $\bar{f}^{\text{RMEX}}$ is constructed with the same distribution as f^{RMEX}, but with its elements adding up to one million pesos. That is:

$$\bar{f}_j^{\text{RMEX}} = (1\,000\,000)\, f_j^{\text{RMEX}} \Big/ \sum_i f_j^{\text{RMEX}}$$

The water requirements (or virtual water contents) of additional exports of product j are therefore obtained by:

$$\sum_{i=1}^{80} y_i l_{ij} \bar{f}_j^{\text{RMEX}}$$

Leaving the balance of regional trade unaffected, the imports (in this case from the rest of Mexico) are also assumed to increase by one million. This means that these products to not need to be produced in the VMB and thus the regional water requirements decrease. Denoting the import vector as $\bar{m}_j^{\text{RMEX}}$ the increase in one million pesos in imports corresponds to an increased importation of products j of:

$$\bar{m}_j^{\text{RMEX}} = (1\,000\,000)\, m_j^{\text{RMEX}} \Big/ \sum_i m_j^{\text{RMEX}}$$

Therefore, the water requirements decrease by:

$$\sum_{i=1}^{80} y_i l_{ij} \bar{m}_j^{\text{RMEX}}$$

due to the increased importation of products j.

The total water requirements from additional exports are given by:

$$\sum_{j=1}^{80} \sum_{i=1}^{80} y_i l_{ij} \bar{f}_j^{\text{RMEX}}$$

and the total water reduction from additional imports is:

$$\sum_{j=1}^{80} \sum_{i=1}^{80} y_i l_{ij} \bar{m}_j^{\text{RMEX}}$$

Using matrix notation, we have $y'L\bar{f}^{\text{RMEX}}$ and $y'L\bar{m}^{\text{RMEX}}$, respectively.

According to the Hecksher-Ohlin theory, a region with a scarcity of water would expect to save water by increasing trade. That is:

$$y'L\bar{m}^{\text{RMEX}} > y'L\bar{f}^{\text{RMEX}}$$

In other words, the virtual water contents of imports should be greater than the virtual water contents of exports.

Table 3 shows the virtual water contents from trade between the VMB and the rest of Mexico and the rest of the world, as well as total trade. The import vector only includes products produced in the basin. The virtual water trade balance with the rest of the Mexican economy shows that virtual water imports are 1.39 times exports, and 2 times more exports for the trade balance with the rest of the world. For the total balance, 1.65 times more water is imported than exported, confirming the Heckscher-Ohlin theory that a region with water scarcity (as is the case in the VMB) tends to import products with high water contents.

Table 3. Virtual water contents in one million pesos of exports and imports, Valley of Mexico Basin, 2008.

Activities	Exports		Imports		Sectoral Virtual Water Balance
	Monetary structure a)	Virtual Water Contents	Monetary structure a)	Virtual Water Contentse agua virtual	
	%	m³	$	m³	m³
Trade with the rest of the Mexican Economy					
Agricultural and Other Primary Activities	0.01	6.98	12.73	337.22	-330.23
Generation and Supply of Electricity, Water and Gas	0.00	0.00	4.33	4.93	-4.93
Construction	0.00	0.00	0.19	0.25	-0.25
Manufacturing Industries	7.80	14.31	32.20	165.14	-150.83
Commerce	3.25	2.12	34.52	22.48	-20.36
Transportation, Mail and Storage	13.64	99.14	6.73	28.84	70.30
Services	75.29	321.48	9.30	58.98	262.49
Total of 80 Activities	**100**	**444.03**	**100**	**617.84**	**-173.81**
Trade with the Rest of the World					
Agricultural and Other Primary Activities	1.24	31.45	3.92	313.57	-282.12
Generation and Supply of Electricity, Water and Gas	0.02	0.02	0.00	0.00	0.01
Construction	0.00	0.00	0.00	0.00	0.00
Manufacturing Industries	57.88	129.99	83.67	176.12	-46.13
Commerce	24.25	15.79	0.00	0.00	15.79
Transportation, Mail and Storage	9.78	71.51	0.66	3.72	67.79
Services	6.84	18.66	11.75	44.78	-26.12
Total of 80 Activities	**100**	**267.41**	**100**	**538.19**	**-270.78**
Total Trade					
Agricultural and Other Primary Activities	0.57	18.01	10.97	332.48	-314.47
Generation and Supply of Electricity, Water and Gas	0.01	0.01	3.47	3.94	-3.94
Construction	0.00	0.00	0.15	0.20	-0.20
Manufacturing Industries	30.37	66.45	42.50	167.34	-100.89
Commerce	12.72	8.28	27.61	17.98	-9.70
Transportation, Mail and Storage	11.90	86.68	5.51	23.81	62.87
Services	44.44	185.00	9.79	56.14	128.86
Total of 80 Activities	**100**	**364.43**	**100**	**601.89**	**-237.47**

a) Domestic consumption includes private consumption by families, government consumption, gross fixed capital formation and variations in stocks.
Source: developed based in the IOM-VMB-2008.

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For the total balance, in terms of trade in one million pesos of exports and imports, the net balance of virtual water is 237.47 m^3 imported into the VMB. The basin is a virtual water importer because it imports agricultural products (and other primary activities) from the rest of Mexico as well as the world (-314.47 m^3 total balance). The importation of manufacturing products is the second largest explanation for the water importation structure, with a total virtual water balance of -100.89 m. Meanwhile, a factor that is placing pressure on the exportation of virtual water is the service sector, which has a positive water balance of 128.83 m^3, which suggests that it is important for this sector to increase its water use efficiency.

Conclusions

The amount of water resources available in the VMB (2 902.29 hm^3) cannot be increased over the mid-term, while at the same time water demand exceeds supply given the growing economic activity in the region and because it is the largest urban region in the country (MAVM).

Over half of the economic structure of the VMB is explained by a variety of services, followed in importance by commercial and manufacturing activities, while agricultural plays a marginal role in this region. The amount of stress on water resources from the economic activities is consistent with their order of importance of the activity in the economic structure. The specific economic activities that place the most stress on the water resources in the basin are more accurately identified by estimating their respective VWM, an indicator of the amount of liters of water used by each economic activity (directly and indirectly) to generate one additional peso of its respective final demand. The results show an average VWM in the basin of 0.310 liters, indicating that the region needs 310 ml of water to produce one peso of the value of production. The activities registered as requiring the most water for their production processes (that is, higher VWM) are agricultural and livestock production, followed by housing services and some of the food, paper and textile manufacturing activities. At the other extreme are the activities with the lowest VWM, which are associated with commerce.

An interesting finding by the investigation is that the basin uses water for low water-intensive activities, such as commerce and manufacturing activities for exportation. Manufacturing exports in the basin represent 7.45% of the total final demand and only require 4.15% of the virtual water contents, suggesting that the region specializes in the exportation of goods with low water contents.

What is of most interest is that the VMB region is classified as a net virtual water importer, given that the region exports low water-intensive goods and services (manufacturing products) while importing high water-intensive goods and services (agricultural products and livestock). This finding appears to confirm the Heckscher-Ohlin theory of international trade in the sense that we import goods with high contents of a scarce resource, in this case water, and which explains the economic rational of a region with the greatest water stress in the country.

The key conclusion of this investigation is that special attention needs to be paid to the economic activities that contribute a small percentage to the production structure of the VMB while also consuming a considerable portion of the water resource. For example, agriculture produces 1.34% of the total final demand and requires 8.28% of the virtual water to produce the final demand in the basin. Another red flag is the case of manufacturing products for domestic consumption, which explain 9.67% of the final demand and 15% of the total virtual water in the basin. These results have interesting implications for water

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management in the VMB, since they indicate the specific activities that should be addressed by water policies aimed at achieving the efficient use of the resource or providing special incentives for their relocation.

In addition to considering the favorable impacts of promoting the import of virtual water in the basin, another set of public policies are suggested to help reduce water stress in the VMB. The first is the promotion of technological changes by adopting new water-savings technologies for production processes, such that the amount of water directly used in each production process is reduced. This requires additional investments in the affected sectors. The second is to provide incentives to restructure production to encourage low water-intensive activities, as is beginning to occur. The third is the introduction of an increase in the price of water for economic activities with the expectation that producers will use the resource more efficiently, for example, by wasting less water. The fourth is to encourage the use of treated water for suitable industrial processes by providing economic incentives to adopt this strategy.

Finally, it is important to expand the current trend in reducing the exportation of virtual water in the VWM, because this is done at the cost of greater overexploitation of aquifers and imported water resources.

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Assessment of Sustainability in Semiarid Mediterranean Basins: Case Study of the Segura Basin, Spain

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Abstract

Senent-Aparicio, J., Pérez-Sánchez, J., & Bielsa-Artero, A. M. (March-April, 2016). Assessment of Sustainability in Semiarid Mediterranean Basins: Case Study of the Segura Basin, Spain. *Water Technology and Sciences* (in Spanish), 7(2), 67-84.

Ever since the concept of sustainable development was introduced by the Brundtland Report in the late 1900s, many scientists have worked on objectively measuring sustainability based on indices. The application of these indices to water resource management makes it possible to evaluate the current state of this resource and provides a tool to help decision-makers. One of the most common indices is the Watershed Sustainability Index. This has been applied by various investigators in a large number of basins throughout the world, and particularly in Central and South America. Nevertheless, references to its application in Europe have not been found. The objective of this study was to apply the Watershed Sustainability Index in a semiarid Mediterranean basin, such as the Segura Basin in Spain. Some of the indicators were adapted to the characteristics of the case study. The Segura Basin has a large water deficit and is subject to the requirements stipulated by the Water Framework Directive. A sustainability index of 0.64 was obtained for the Segura Basin during the period 2006-2010, which is equal to an intermediate sustainability level. The methodology proposed can be used for many other European Mediterranean basins with hydrological, environmental, social and political conditions that are very similar to those of the case study.

Keywords: Hydrology, Segura basin, sustainability index, pressure-state-response model, integrated watershed management.

Resumen

Senent-Aparicio, J., Pérez-Sánchez, J., & Bielsa-Artero, A. M. (marzo-abril, 2016). Evaluación de la sostenibilidad de cuencas mediterráneas semiáridas. Caso de estudio: cuenca del Segura, España. Tecnología y Ciencias del Agua, *7(2), 67-84.*

Desde la introducción del concepto de desarrollo sostenible en el Informe Brundtland a finales del siglo pasado, numerosos científicos han trabajado en la medición objetiva de la sostenibilidad mediante índices. La aplicación de estos índices a la gestión de los recursos hídricos permite evaluar el estado actual de los mismos y servir como herramienta de ayuda a la toma de decisiones por parte de los organismos competentes. Uno de los índices más utilizados es el Índice de Sostenibilidad de Cuencas. Este índice ha sido aplicado por distintos investigadores en numerosas cuencas a lo largo de todo el mundo, principalmente América Central y Sudamérica. Sin embargo, no se han encontrado referencias sobre su aplicación en Europa. El objetivo de este estudio es la aplicación del Índice de Sostenibilidad de Cuencas en una cuenca mediterránea semiárida, como es la cuenca del Segura (España). Se han adaptado algunos de los indicadores a las características del caso de estudio. La cuenca del Segura se caracteriza por su alto déficit hídrico y por estar sometida a los requisitos exigidos por la Directiva Marco del Agua. Se ha obtenido un valor del índice de sostenibilidad para la cuenca del Segura durante el periodo 2006-2010 de 0.64, lo que equivale a un nivel intermedio de sostenibilidad. La metodología propuesta puede ser utilizada en numerosas cuencas mediterráneas europeas que presentan condiciones hidrológicas, ambientales, sociales y políticas muy similares a las del caso objeto de estudio.

Palabras clave*: hidrología, cuenca Segura, índice de sostenibilidad, modelo presión-estado-respuesta, gestión integrada de cuencas.*

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Introduction

The United Nations (UN) Conference on the Human Environment held in Stockholm in the year 1972 was the first major UN conference on international environmental issues, marking a turning point in the development of international policies on the environment. Years later, as a result of this conference, the Brundtland Report was published in which the concept of sustainable development was first introduced (Brundtland, 1987).

Ever since the publication of this report many institutions and organizations have dedicated great effort to objectively measuring sustainability. One clear example of this is the development of evaluation tools based on sustainability indicators known as sustainability indices. By applying these indices to water resources, all of the factors that contribute to improving the water resources can be identified. That information can then be used so that users in a given region become aware of the current state of the water resources in their area, and to aid decision-making by organizations dedicated to water resource management (Juwana, Muttil, & Perera, 2012).

In 2005, the UNESCO created the International Hydrological Programme (IHP) as an instrument through which its member states aim to improve knowledge about the water cycle and better manage and exploit their water resources (UNESCO, 2005). The goal of this program is to minimize the risks to which water resource systems are exposed while taking into account the demands, social interactions and development methods that contribute to the rational management of water resources, including environmental protection. To achieve this objective, a watershed sustainability index was needed which integrated not only purely hydrological questions but also the different socioeconomic and environmental factors that affect the sustainable management of water resources in a basin (Chaves & Alipaz, 2007). All these aspects were included in the Watershed Sustainability Index (WSI), selected by the UNESCO for their IHP.

As can been seen in the literature consulted, the WSI has been applied by different researchers in many basins throughout the world, and particularly in Central and South America (Chaves, 2009; Catano, Marchand, Staley, & Wang, 2009; Cortés *et al*., 2012; Preciado-Jiménez, Aparicio, Güitrón- De-Los-Reyes, & Hidalgo-Toledo, 2013; Elfithri, 2013; Firdaus, Nakagoshi, & Idris, 2014). Nevertheless, this index has not yet been applied to European basins. The objective of the work herein is to analyze the sustainability of water resource management in a semiarid Mediterranean basin as well as to adapt the parameters proposed by Cahvez and Alipaz to the climatic, political and social conditions that impact the management of water resources in the study area.

Description of the Study Area

The Segura River Basin is located in southeastern Spain (Figure 1). It has an area of approximately 20 234 km^2 (19 025 km^2 when only considering the continental region, excluding coastal waters) and affects four autonomous communities: Murcia, Andalucía (the provinces of Jaén, Granada and Almería), Castilla-La Mancha (Albacete province) and Valencia (Alicante province). As can be seen in Figure 1, the basin can be divided into 14 different zones for the purpose of their hydrological functioning and in accordance with the Hydrological Plan for the Segura Basin (HPSB) (CHS, 2013).

The mean annual precipitation is roughly 382 mm, characterized by large seasonal imbalances and clear spatial contrasts among the headwaters, middle and lower portions of the basins. A typical characteristic of precipitation in the basin is the occurrence of strong

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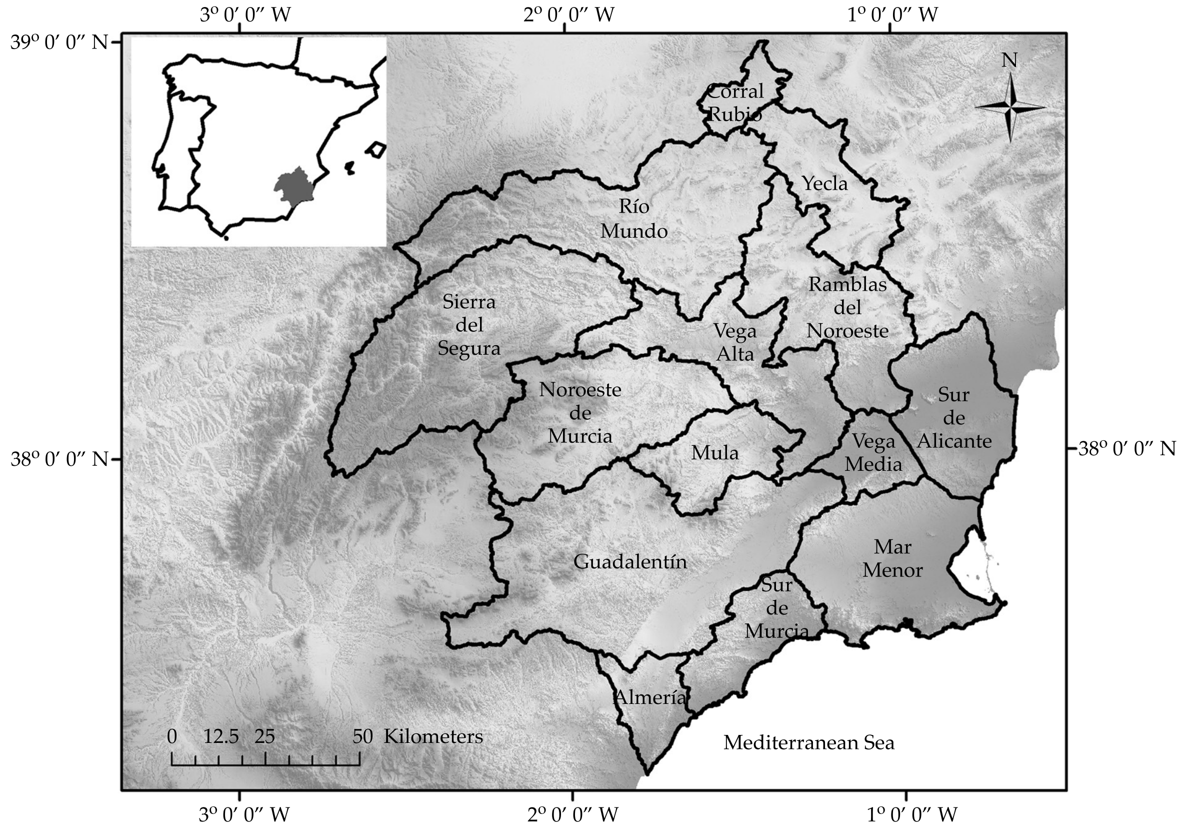

Figure 1. Map of the locations and definitions of the hydrological zones.

rainfalls —known as "cold rains"— with short and very intense durations that cause large and notably torrential floods. This type of event occurs during the autumn months. In addition, periods of drought are common during the summer months with virtually no precipitation, in addition to inter-annual droughts.

Both rainfall and temperatures are highly influenced by the orography. Extreme temperatures range from a mean annual isotherm of 10°C in the Sierra del Segura to a mean annual temperature of 18°C in Sur de Alicante and some coastal regions. In terms of evapotranspiration, mean potential values are roughly 992 mm and annual real evapotranspiration has been estimated to be 339 mm. The total mean runoff represents 13% of the total mean precipitation, which is the lowest percentage on the Iberian Peninsula (CHS, 2013).

During the late 1900s, the total water demand in the Segura River Basin increased to such an extent as to exceed the limits established for existing natural resources, creating an entirely unsustainable structural deficit (Martínez- Fernández, Esteve-Selma, & Calvo-Sendín, 2000). While this deficit has been mitigated by measures driven by the enactment of the Water Framework Directive (WFD), the problem has not yet been resolved.

The Segura River Basin is one of the regions in Mediterranean Europe with high water stress. In overall terms, the current total demand is 1 800 hm^3/year, 86% of which corresponds to agricultural demand and 10% to urban demand. In contrast, natural supplies are roughly 800 hm^3/ year (CHS, 2013). Great effort has been taken over recent years to decrease this deficit by using non-conventional water resources to the extent possible, including the reuse of treated water, desalination and the transfer of water resources from nearby basins.

Methodology and Data

General Description of the WSI

The Watershed Sustainability Index (WSI) presumes that a basin's sustainability as a resource depends on its hydrology (*H*), environment (*E*), life (*L*) and the water policies enacted (*P*) (Chaves and Alipaz, 2007). With these four indicators, the WSI can be obtained by applying the following equation:

$$\text{WSI} = \left(H + E + L + P\right) / 4$$

Where *H* is the hydrology indicator (0-1); *E* is the environment indicator (0-1); *L* is the life indicator (0-1) and *P* is the policy indicator (0-1). This equation implies that the same weight is given to each one of the indicators and that, as with the rest of the indicators, the WSI will vary between 0 and 1. Each of these indicators are analyzed separately with a pressure-state-response model (PSR). To this end, Chavez and Alipaz propose a series of parameters that make it possible to adequately represent the individual processes reflected by each indicator (Table 1). In addition, these parameters provide a certain degree of flexibility in terms of their adaptability to the particular conditions of the basin for which the WSI is to be calculated. In this regard, the authors suggest a maximum basin area of 2 500 km^2 for its correct application.

The PSR model was developed by Raport and Friend (1979) and has been widely used throughout the world as a result of its implementation by the Organization for Cooperation and Economic Development (OCED) as a model for the development of environmental indicators. It consists of analyzing the relationships between human activities (pressure) and their impact on the state of the environment (state), causing a series of actions to be performed to solve the problems generated (response). The advantage of using this type of model is that, by incorporating cause-effect relationships, it identifies the users and decision-makers involved in the relationships among the different parameters and thus helps to establish policies or redirect those that have been enacted (OCDE, 2003).

Table 1. WSI Indicators and Parameters.

Indicator	Pressure	State	Response
(*H*) Hydrology	Variation in per capita water availability during the period	Water availability *per capit*a in the basin	Evolution in water use efficiency during the period analyzed
	Variation in the BOD_5 during the period in relation to the average	BOD_5 of the basin (average and long-term)	Evolution in treatment/disposal of wastewater
(*E*) Environment	EPI (rural and urban)of the basin during the period	% of the basin with natural vegetation	Evolution of protected areas in the basin (reserves, BMPs)
(*L*) Life	Variation in the (GDP) per capita in the basin during the period analyzed	IDH of the basin during the previous period (weighted)	Evolution of the IDH of the basin during the period analyzed
(*P*) Policies	Variation in the IDH-Ed during the period analyzed	Legal and institutional capacity in IWRM in the basin	Evolution of the costs of IWRM in the basin during the period analyzed.

Tables 2, 3 and 4 show the levels and the respective scores proposed by Chaves and Alipaz (2007). Based on these, the score of each one of the indicators is obtained and then the equation mentioned earlier is applied. Once the final value of the WSI is determined, the sustainability could be considered *low* if WSI < 0.5, *intermediate* if it ranges from 0.5 to 0.8 and *high* if the WSI > 0.8.

Adaptation of the Methodology to the Case Study and Data Used

The present study applies the WSI to the Segura River Basin. Since the area of this basin exceeds the maximum limit established by the methodology to calculate the WSI, the methodology was applied to each of the 14 sub-basins defined by the HPSB (CHS, 2013). Thus the areas of all the sub-basins analyzed are under 2 500 km^2, with the exception of the Guadalentin sub-basin which is slightly larger (3 000 km^2), and the Sierra del Segura sub-basin with an area of 2 600 km^2. Therefore, the WSI will be calculated by sub-basin to subsequently obtain the mean WSI of the entire Segura Basin. Since some of the indicators used by the methodology are available on a basin or province scale, this spatial reduction in scale will make it difficult to obtain them. In addition, there is no history of applying the WSI to the Segura Basin or to semiarid Medi-

Table 2. Description of pressure, level and score parameters.

Indicator	Pressure parameters	Level	Score
(*H*) Hydrology	Δ1 per capita change in available water in the basin during the study period, relative to the long-term average (m^3/year·person)	Δ1 ≤ −20%	0.00
		−20% < Δ1 ≤ −10%	0.25
		−10% < Δ1 ≤ 0%	0.50
		0% < Δ1 ≤ +10%	0.75
		Δ1 > +10%	1.00
	Δ2 BOD_5 change in the basin during the study period, or in another critical parameter, relative to the long-term (or historical) average	Δ2 ≥ 20%	0.00
		20% > Δ2 ≥ 10%	0.25
		10% > Δ2 ≥ 0%	0.50
		−10% ≤ Δ2 < 0%	0.75
		Δ2 < −10%	1.00
(*E*) Environment	EPI of the basin (rural and urban) during the study period	EPI ≥ 20%	0.00
		20% > EPI ≥ 10%	0.25
		10% > EPI ≥ 5%	0.50
		5% > EPI ≥ 0%	0.75
		EPI < 0%	1.00
(*L*) Life	Change in the HDI-GDP-Index of per capita income (PCI) during the study period, relative to the previous period.	Δ ≤ −20%	0.00
		−20% < Δ ≤ −10%	0.25
		−10% < Δ ≤ 0%	0.50
		0% < Δ ≤ +10%	0.75
		Δ > +10%	1.00
(*P*) Policies	Change in the HDI-education (EI) during the study period, relative to the previous period	Δ ≤ −20%	0.00
		−20% < Δ ≤ −10%	0.25
		−10% < Δ ≤ 0%	0.50
		0% < Δ ≤ +10%	0.75
		Δ > +10%	1.00

Table 3. Description of state, level and score parameters.

Indicator	State Parameters	Level	Score
(*H*) Hydrology	*Wa* - Water availability per capita (m³/person annually) in both area and sources of grounwater during the historical period	$Wa \leq 1.700$	0.00
		$1\,700 < Wa \leq 3\,400$	0.25
		$3\,400 < Wa \leq 5\,100$	0.50
		$5\,100 < Wa \leq 6\,800$	0.75
		$6\,800 < Wa$	1.00
	Average BOD_5 (mg/l) of the basin, long-term (or another critical parameter)	$BOD_5 \geq 10$	0.00
		$10 > BOD_5 \geq 5$	0.25
		$5 > BOD_5 \geq 3$	0.50
		$3 > BOD_5 \geq 1$	0.75
		$BOD_5 < 1$	1.00
(*E*) Environment	Percentage of the area (*Av*) of the basin with natural vegetation	$Av \leq 5\%$	0.00
		$5\% < Av \leq 10\%$	0.25
		$10\% < Av \leq 25\%$	0.50
		$25\% < Av \leq 40\%$	0.75
		$Av > 40\%$	1.00
(*L*) Life	Weighted HDI of the basin during the previous period (weighted for the population)	HDI ≤ 0.5	0.00
		0.5 < HDI ≤ 0.6	0.25
		0.6 < HDI ≤ 0.75	0.50
		0.75 < HDI ≤ 0.9	0.75
		HDI > 0.9	1.00
(*P*) Policies	Legal and institutional capacity in IWRM in the basin (legal and organizational)	Very poor	0.00
		Poor	0.25
		Average	0.50
		Good	0.75
		Excellent	1.00

terranean regions. Therefore, as mentioned throughout this section, it was necessary to make a series of adjustments to the data based on the physical, environmental and socioeconomic conditions in the study area.

Hydrology: Amount of Water

In order to determine the pressure and state parameters, the per capita water availability (surface water + groundwater) was calculated for the study period (2006-2010) and its historical average (1996-2010) was determined. Total runoff flows were obtained using the raster available from the Integrated Water Information System of Spain's Secretary of Agriculture, Food and the Environment (Magrama, 2013). The population associated with each of the sub-basins was determined using data about the evolution of the population at the municipal scale, available from the National Statistics Institute (INE, 2014). For the case of municipalities located in portions of the various sub-basins, the criteria followed was to assign the municipality's population to the sub-basin in which the primary geographic center of the municipality was located.

With regard to the response parameters, Chaves and Alipaz (2007) suggest to evaluate improvements in the efficient use of water resources. Accordingly, and taking into account

Table 4. Description of the response, level and score parameters.

Indicator	Response parameters	Level	Score
(*H*) Hydrology	Evolution of water use efficiency in the basin during the period analyzed, a period of five years with respect to the historical period	Very poor	0.00
		Poor	0.25
		Average	0.50
		Good	0.75
		Excellent	1.00
	Evolution of the treatment/disposal of wastewater in the basin during the period analyzed	Very poor	0.00
		Poor	0.25
		Average	0.50
		Good	0.75
		Excellent	1.00
(*E*) Environment	Evolution of areas for basin conservation (protected and BMP areas) during the period	$\Delta \leq -10\%$	0.00
		$-10\% < \Delta \leq 0\%$	0.25
		$0\% < \Delta \leq +10\%$	0.50
		$+10\% < \Delta \leq +20\%$	0.75
		$\Delta > +20\%$	1.00
(*L*) Life	Change in the HDI in the basin during the period (weighted)	$\Delta \leq -10\%$	0.00
		$-10\% < \Delta \leq 0\%$	0.25
		$0\% < \Delta \leq +10\%$	0.50
		$+10\% < \Delta \leq +20\%$	0.75
		$\Delta > +20\%$	1.00
(*P*) Policies	Evolution of the IWRM expenses (legal and organizational) in the basin during the period	$\Delta \leq -10\%$	0.00
		$-10\% < \Delta \leq 0\%$	0.25
		$0\% < \Delta \leq +10\%$	0.50
		$+10\% < \Delta \leq +20\%$	0.75
		$\Delta > +20\%$	1.00

the background mentioned in the description about the study area, the efficiency in the use of natural water resources in the basin is characterized as very high and constant over the past 30 years (Grindlay, Zamorano, Rodríguez, Molero, & Urrea, 2011). It was therefore decided to analyze this parameter from a more quantitative perspective by calculating the non-conventional water resources obtained in each basin through the reuse of wastewater (*R*), desalination (*D*) and transfers from nearby basins (*T*) and determining the score according to the percentage of the non-conventional resource obtained with respect to the natural water availability per capita (Table 5).

Hydrology: Water Quality

The pressure and state parameters were calculated based on available data about the biochemical oxygen demand at 5 days (BOD_5) at the water quality control stations managed by the Segura Hydrographic Confederation (CHS, Spanish acronym), organization responsible for the management of the basin. In terms of improvements in the treatment of wastewater, the criteria used by Preciado-Jiménez *et al*. (2013) was used, in which the number of wastewater treatment stations (WTS) available in each sub-basin was evaluated. In addition, the volume of treated wastewater in each sub-basin was

Table 5. Modified response parameters for the hydrological-quantity indicator.

Indicator	Response Parameters	Level	Score
(*H*) Hydrology	Evolution of the per capita water availability from non-conventional resources during the study period	Non-conventional resources not created	0.00
		0% ≤ Δ < +5%	0.25
		+5% ≤ Δ < +10%	0.50
		+10% ≤ Δ < +20%	0.75
		Δ > +20%	1.00

also taken into account. As a result of the development of the General Treatment and Purification Plan for the Region of Murcia (BORM, 2003), an area encompassing 61.42% of the total basin, the purification of the water has been improved by adding tertiary treatment to the existing treatment and substituting lagoon techniques with more effective systems. Therefore, although the number of WTS or amount of treated water have been reduced in some cases, this does not necessarily signify poorer quality of the treated water intended for subsequent reuse. Considering all of this, the criterion that was followed was to establish a middle baseline score of 0.5 for all sub-basins, and raising that according to increases in the number of available WTS and the volume treated.

Environment

The Environment Pressure Index (EPI) is calculated as the mean change over the study period in the area of the basin used for agriculture and livestock and in the population residing in the basin. These changes were obtained for each sub-basin based on population data from the INE and land use maps of the Segura Basin obtained with remote sensing by Alonso-Sarría, Gomariz-Castillo and Cánovas-García (2010). These land use data also served to determine the percentage of natural vegetation in each sub-basin. In terms of the response parameter, the data available from the EUROPARC-Spain Foundation were used (EUROPARC, 2014).

Life

This was based on human development indices (HDI) published by the Valencian Economic Research Institute (Herrero, Soler, & Villar, 2012). These indices are calculated at a provincial scale and, therefore, to obtain the indicators for each sub-basin, a weighted mean was calculated according to the origin of the population in each sub-basin.

Policies

The pressure indicator associated with this parameter is the human development index for education (HDI-Education), which was determined in the same way as the life indicators mentioned earlier. To analyze the political response, data were used from the organizations responsible for managing the basin (CHS) in terms of investments in the basin's water resources during the study period.

With respect to the institutional capacity of the basin, the WSI represents a quantitative score ranging from poor (0.0) to excellent (1.0), recognizing that if there are some existing laws related to water resource management that have not yet been implemented or enforced, an intermediate score (0.5) may be assigned. This study case uses the intermediate score as a baseline for the entire basin, which will be increased according to the institutional capacity and level of public participation. To this end, the analysis includes the meetings held in the different sectors involved, the number of goals discussed in the meetings and the participation of the actors involved in the process.

Results and Discussion

Hydrology: Amount of Water

The semiarid climate conditions of the Segura Basin are seen by analyzing the annual per capita water availability for each sub-basin (Table 6). The water availability in most of the sub-basins is under 500 m^3/inhab/year, which in terms of the water stress index (Falkenmark, Lundquist, & Widstrand, 1989) could be categorized as absolute scarcity, and hence the state indicators present very low scores. Water is more available only in the sub-basins located in the headwaters of the basin (Sierra del Segura, Corral Rubio and Río Mundo) because of their lower population density combined with more precipitation. The basins with water availability under 100 m^3/inhab/year are Vega Media and Sur de Alicante with 18 and 58 m^3/inhab/year, respectively. In the case of Vega Media, this value is a reflection of the most populated city in the Segura Basin being located in this basin (Murcia with roughly 450 000 inhabitants). Sur de Alicante is a coastal sub-basin where the population density is also very high and therefore the availability is low. In terms of pressure indicators, the study period generally had more availability than the historical period, which explains the high scores obtained.

Table 7 shows the response parameters calculated according to the non-conventional resources generated. It is worth mentioning that treated wastewater is being reused in every sub-basin. Most of the desalination and transfer efforts are in the places with less water availability, where in many cases there are more of these types of resources than natural water availability.

Table 6. Values of pressure and state parameters obtained for the hydrology-amount indicator.

Sub-basin	Water availability per capita (m^3/inhab year) (1996-2010)	Water availability per capita (m^3/inhab year) (2006-2010)	Δ (%)	Pressure score	State score
Río Mundo	2 054	2 532	23.27	1	0.25
Corral Rubio	1 811	1 897	4.73	0.75	0.25
Yecla	360	390	8.28	0.75	0
Ramblas del Noroeste	474	571	20.50	1	0
Sur de Alicante	58	53	-8.62	0.50	0
Vega Media	18	19	3.78	0.75	0
Mar Menor	106	90	-15.42	0.25	0
Guadalentín	469	580	23.68	1	0
Sur de Murcia	183	184	0.63	0.75	0
Almería	623	737	18.44	1	0
Mula	1 134	1 134	0.04	0.75	0
Vega Alta	235	271	15.29	1	0
Noroeste de Murcia	1 453	1 746	20.20	1	0
Sierra del Segura	25 413	33 712	32.66	1	1

Hydrology: Water Quality

Table 8 presents the results from the variation in the biochemical oxygen demand (BOD_5 in mg/l) over the study period (2006-2010) as well as the historical average. The concentrations are seen to be decreasing significantly in a large portion of the sub-basins, creating high pressure scores. Nevertheless, the records analyzed during the historical period show very high concentration values (low state scores), which demonstrates that actions by the CHS to control discharges, driven by the enactment of the Water Directive Framework (WDF), are bringing about very beneficial results.

The reuse of wastewater is one of the main objectives of organizations responsible for water resources management in the Segura Basin. According to the results presented in Table 7, all the sub-basins are reusing treated water as one of the means available to reduce the water deficit in the basin. In order to increase the volumes of reused water, more investments have been made in wastewater treatment over recent years. These investments are reflected in the number of WTS and the amount of treated wastewater in the basin (Table 9), which in most cases have increased considerably, obtaining very high response levels.

Environment

Table 10 shows the calculation of the EPI for each of the sub-basins in the Segura Basin. Analyzing this table, it can be seen that the farming and livestock areas have decreased over the study period. The main reason for this reduction is the abandonment of agricultural work due to water scarcity. The only sub-basins not following this trend are the Sierra del Segura, with the highest water availability in the basin (Table 6) and the Sur de Murcia and Almeria sub-basins whose water supplies come primarily from desalination (Table 7). In terms of population, this has increased between 0 and 10% in practically all the sub-basins.

In terms of the natural vegetation cover in the basin (Table 11), the pressure parameters

Table 7. Values of response parameter obtained for the hydrology-amount indicator.

Sub-basin	Mean annual population (2006-2010)	Non-conventional resources					Δ (%)	Response score
		T (hm^3)	*R* (hm^3)	*D* (hm^3)	Total (hm^3)	Per capita (m^3/inhab year)		
Río Mundo	50 700		2.23		2.23	44	1.74	0.25
Corral Rubio	2 505		0.06		0.06	25	1.32	0.25
Yecla	36 907		1.78		1.78	48	12.31	0.75
Ramblas del Noroeste	51 806	0.96	6.37		7.33	142	24.87	1
Sur de Alicante	380 764	47.46	19.34	53	119.80	315	594.34	1
Vega Media	495 328	28.69	4.05		32.74	66	347.37	1
Mar Menor	361 745	49.01	19.73	92	158.74	439	487.78	1
Guadalentín	171 063	25.26	6.60		31.86	186	32.07	1
Sur de Murcia	67 522	3.71	2.24	61.50	67.45	999	542.93	1
Almería	8 014	3.87	0.29	7	11.16	139	18.86	0.75
Mula	24 264	2.69	1.10		3.79	156	13.76	0.75
Vega Alta	174 926	22.83	11.42		34.25	196	72.32	1
Noroeste de Murcia	73 166	4.02	3.08		7.10	97	5.56	0.50
Sierra del Segura	17 774	0.15	0.84		0.99	55	0.16	0.25

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Table 8. Values of pressure and state parameters obtained for the hydrology-quality indicator.

Sub-basin	BOD_5 Concentration (mg/l)(1979-2010)	BOD_5 Concentration (mg/l)(2006-2010)	Δ (%)	Pressure score	State score
Río Mundo	1.43	0.69	-51.75	1	0.75
Corral Rubio	13.33	13.33	0.00	0.75	0
Yecla	23.98	6.78	-71.73	1	0
Ramblas del Noroeste	3.76	3.76	0.00	0.75	0.50
Sur de Alicante	18.37	2.75	-85.03	1	0
Vega Media	38.97	3.02	-92.25	1	0
Mar Menor	3.81	3.81	0.00	0.75	0.50
Guadalentín	181.10	47.44	-73.80	1	0
Sur de Murcia	0.00	0.00	0.00	0.75	1
Almería	23.98	6.78	-71.73	1	0
Mula	14.84	3.18	-78.57	1	0
Vega Alta	5.17	0.80	-84.53	1	0.25
Noroeste de Murcia	5.98	2.33	-61.04	1	0.25
Sierra del Segura	1.02	0.21	-79.41	1	0.75

Table 9. Values of the response parameters obtained for the hydrology-quality indicator.

Sub-basin	No. of WTS (2006)	Volume (hm^3) (2006)	No. of WTS (2010)	Volume (hm^3) (2010)	ΔWTS (%)	Δvol. (%)	Response score
Río Mundo	6	4.29	15	4.70	+150.00	+9.56	1
Corral Rubio	0	0	3	0.15			1
Yecla	3	2.03	2	1.79	-33.33	-11.82	0.50
Ramblas del Noroeste	6	5.13	17	6.46	+183.33	+25.93	1
Sur de Alicante	30	26.33	32	24.88	+6.67	-5.51	0.75
Vega Media	9	39.47	7	44.60	-22.22	+13.00	0.75
Mar Menor	23	27.76	27	26.02	+17.39	-6.27	0.75
Guadalentín	14	7.35	13	7.00	-7.14	-4.76	0.50
Sur de Murcia	3	3.91	3	4.17	0.00	+6.65	0.75
Almería	1	0.31	2	0.36	+100.00	+16.13	1
Mula	3	3.05	6	3.08	+100.00	+0.98	1
Vega Alta	10	13.95	11	15.13	+10.00	+8.46	1
Noroeste de Murcia	7	3.21	11	5.19	+57.14	+61.68	1
Sierra del Segura	7	2.20	8	1.67	+14.29	-24.09	0.75

could be classified as acceptable, considering that the Corral Rubio is the only sub-basin with under 10%, and thus is very anthropized. The Sierra del Segura stands out as the other extreme, which has the largest protected nature area (PNA). Spain approved most of the PNA during the 1990s (Vacas-Guerrero, 2005), and so very little changes in this aspect occurred during the period analyzed.

Life

Table 12 presents the pressure parameters. The human development index associated

Table 10. Values of pressure parameters obtained for the environment indicator.

Sub-basin	Farming/livestock area (km²)			Population (inhabitants)				Pressure score
	2006	2010	Δ (%)	2006	2010	Δ (%)	EPI	
Río Mundo	1 020	1 004	-1.57	50 146	51 067	+1.84	+0.14	0.75
Corral Rubio	234	198	-15.38	2 545	2 403	-5.58	-10.48	1
Yecla	553	502	-9.22	36 284	37 246	+2.65	-3.29	1
Ramblas del Noroeste	799	706	-11.64	49 458	53 744	+8.67	-1.49	1
Sur de Alicante	612	572	-6.54	354 153	398 132	+12.42	+2.94	0.75
Vega Media	192	173	-9.90	479 584	509 179	+6.17	-1.87	1
Mar Menor	1 101	1 166	+5.90	348 893	374 466	+7.33	+6.62	0.50
Guadalentín	1 668	1 579	-5.34	167 811	174 810	+4.17	-0.59	1
Sur de Murcia	205	352	+71.71	63 291	70 364	+11.18	+41.45	0
Almería	210	245	+16.67	7 537	8 429	+11.83	+14.25	0.25
Mula	351	338	-3.70	23 530	24 640	+4.72	+0.51	0.75
Vega Alta	608	555	-8.72	166 301	181 529	+9.16	+0.22	0.75
Noroeste de Murcia	798	771	-3.38	71 045	74 467	+4.82	+0.72	0.75
Sierra del Segura	391	599	+53.20	18 086	17 368	-3.97	+24.62	0

with income (HDI-income) decreased from 1 to 1.5% during the study period in nearly all the sub-basins analyzed, primarily because of a period of economic crisis in Spain. The sub-basin associated with the province of Almeria is the only one where this index improved (+0.4%).

With respect to the state and response parameters (Table 13), all the provinces in the study area present very similar HDIs and evolved similarly across the study area. The range in variation was between 0.823 and 0.853, while the increase in the HDI varied between 0.84 and 2.87%.These results demonstrate the socioeconomic homogeneity of the study area in spite of the large area analyzed.

Policies

The human development index associated with education (HDI-education) is similar to the above HDI results, with little variation across the study area and a slight increasing trend, as seen in Table 14.

To accomplish the public participation processes set forth by the WFD, 50% of the organizations, administrations and entities involved have participated in different territorial roundtables organized during the study period, according to the different meeting minutes reviewed. Hence, the legal and institutional capacity can be considered to be good (score of 0.75). Furthermore, based on the objectives discussed during these roundtables some of the sub-basins can be classified as excellent, as seen in Table 15.

Investments in integrated water resource management in the basin (Table 16) have increased over the study period in all of the sub-basins analyzed. As can be expected, smaller investments were made in sub-basins located in the headwaters (Sierra del Segura and Rio Mundo) while larger investments were made in the coastal sub-basins where the water stress is greater (Sur de Alicante, Sur de Murcia and Almeria).

Table 17 presents a summary of the parameters obtained for each of the indicators in the 14 sub-basins studied. The WSI for the individual sub-basins ranged from 0.56 to 0.70, with a global WSI for the entire Segura Basin of 0.64, which would be classified as

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Table 11. Values of state and response parameters obtained for the environment indicator.

Sub-basin	Area (km²)	*Av* (%) (2006-2010)	State score	ENP (2006) (km²)	ENP (2010) (km²)	Δ (%)	Response score
Río Mundo	2 414	46.86	1	74.14	77.09	+3.98	0.50
Corral Rubio	272	5.45	0.25	3.42	3.42	0.00	0.25
Yecla	843	23.65	0.50	8.99	8.99	0.00	0.25
Ramblas del Noroeste	1 497	32.11	0.75	115.20	116.16	+0.83	0.50
Sur de Alicante	1 016	15.16	0.50	143.25	145.29	+1.42	0.50
Vega Media	412	24.73	0.50	31.17	31.17	0.00	0.25
Mar Menor	1 602	17.08	0.50	105.99	105.99	0.00	0.25
Guadalentín	3 343	37.55	0.75	410.96	411.08	+0.03	0.50
Sur de Murcia	690	49.13	1	45.30	45.30	0.00	0.25
Almería	452	42.43	1	0.67	0.67	0.00	0.25
Mula	708	36.25	0.75	44.72	44.72	0.00	0.25
Vega Alta	1 389	41.13	1	41.54	41.54	0.00	0.25
Noroeste de Murcia	1 688	41.52	1	0.08	0.08	0.00	0.25
Sierra del Segura	2 605	75.24	1	737.74	737.74	0.00	0.25

Table 12. Values of the pressure parameters obtained for the life indicator.

Sub-basin	Province	Population		HDI-Income		Weighted HDI - income			Pressure score
		2006	2010	2006	2010	2006	2010	Δ (%)	
Río Mundo	Albacete	50 146	51 067	0.768	0.759	0.768	0.759	-1.17	0.50
Corral Rubio	Albacete	2 545	2 403	0.768	0.759	0.768	0.759	-1.17	0.50
Yecla	Murcia	33 964	34 945	0.789	0.779	0.788	0.778	-1.27	0.50
	Albacete	2 320	2 301	0.768	0.759				
Ramblas del Noroeste	Murcia	39 122	42 413	0.789	0.779	0.790	0.780	-1.27	0.50
	Alicante	10 336	11 331	0.794	0.782				
Sur de Alicante	Alicante	354 153	398 132	0.794	0.782	0.794	0.782	-1.51	0.50
Vega Media	Murcia	479 584	509 179	0.789	0.779	0.789	0.779	-1.27	0.50
Mar Menor	Murcia	329 315	351 911	0.789	0.779	0.789	0.779	-1.27	0.50
	Alicante	19 578	22 555	0.794	0.782				
Guadalentín	Murcia	155 244	162 083	0.789	0.779	0.790	0.781	-1.14	0.50
	Almería	12 567	12 727	0.800	0.803				
Sur de Murcia	Murcia	63 291	70 364	0.789	0.779	0.789	0.779	-1.27	0.50
Almería	Almería	7 537	8 429	0.800	0.803	0.800	0.803	+0.38	0.75
Mula	Murcia	23 530	24 640	0.789	0.779	0.789	0.779	-1.27	0.50
Vega Alta	Murcia	166 301	181 529	0.789	0.779	0.789	0.779	-1.27	0.50
Noroeste de Murcia	Murcia	71 045	74 467	0.789	0.779	0.789	0.779	-1.27	0.50
Sierra del Segura	Albacete	14 046	13 666	0.768	0.759	0.764	0.756	-1.05	0.50
	Jaén	4 040	3 702	0.752	0.748				

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Table 13. Values of the state and response parameters obtained for the life indicator.

Sub-basin	Province	HDI		Weighted HDI			State score	Response Score
		2006	2010	2006	2010	Δ (%)		
Río Mundo	Albacete	0.826	0.837	0.826	0.837	+1.33	0.75	0.50
Corral Rubio	Albacete	0.826	0.837	0.826	0.837	+1.33	0.75	0.50
Yecla	Murcia	0.838	0.845	0.837	0.845	+0.96	0.75	0.50
	Albacete	0.826	0.837					
Ramblas del Noroeste	Murcia	0.838	0.845	0.838	0.847	+1.07	0.75	0.50
	Alicante	0.839	0.853					
Sur de Alicante	Alicante	0.839	0.853	0.839	0.853	+1.67	0.75	0.50
Vega Media	Murcia	0.838	0.845	0.838	0.845	+0.84	0.75	0.50
Mar Menor	Murcia	0.838	0.845	0.838	0.845	+0.84	0.75	0.50
	Alicante	0.839	0.853					
Guadalentín	Murcia	0.838	0.845	0.837	0.845	+0.96	0.75	0.50
	Almería	0.823	0.847					
Sur de Murcia	Murcia	0.838	0.845	0.838	0.845	+0.84	0.75	0.50
Almería	Almería	0.823	0.847	0.823	0.847	+2.92	0.75	0.50
Mula	Murcia	0.838	0.845	0.838	0.845	+0.84	0.75	0.50
Vega Alta	Murcia	0.838	0.845	0.838	0.845	+0.84	0.75	0.50
Noroeste de Murcia	Murcia	0.838	0.845	0.838	0.845	+0.84	0.75	0.50
Sierra del Segura	Albacete	0.826	0.837	0.824	0.837	+1.58	0.75	0.50
	Jaén	0.820	0.837					

Table 14. Values of pressure parameters obtained for the policy indicator.

Sub-basin	Province	HDI-Education		Weighted HDI-Education			Pressure score
		2006	2010	2006	2010	Δ (%)	
Río Mundo	Albacete	0.753	0.781	0.753	0.781	+3.74	0.75
Corral Rubio	Albacete	0.753	0.781	0.753	0.781	+3.74	0.75
Yecla	Murcia	0.782	0.797	0.780	0.796	+2.04	0.75
	Albacete	0.753	0.781				
Ramblas del Noroeste	Murcia	0.782	0.797	0.780	0.799	+2.45	0.75
	Alicante	0.772	0.806				
Sur de Alicante	Alicante	0.772	0.806	0.772	0.806	+4.46	0.75
Vega Media	Murcia	0.782	0.797	0.782	0.797	+1.92	0.75
Mar Menor	Murcia	0.782	0.797	0.781	0.798	+2.06	0.75
	Alicante	0.772	0.806				
Guadalentín	Murcia	0.782	0.797	0.779	0.796	+2.19	0.75
	Almería	0.741	0.783				
Sur de Murcia	Murcia	0.782	0.797	0.782	0.797	+1.92	0.75
Almería	Almería	0.741	0.783	0.741	0.783	+5.72	0.75
Mula	Murcia	0.782	0.797	0.782	0.797	+1.92	0.75
Vega Alta	Murcia	0.782	0.797	0.782	0.797	+1.92	0.75
Noroeste de Murcia	Murcia	0.782	0.797	0.782	0.797	+1.92	0.75
Sierra del Segura	Albacete	0.753	0.781	0.756	0.787	+4.04	0.75
	Jaén	0.767	0.807				

intermediate sustainability by the Chaves and Alipaz classification.

Conclusions

Segura is characterized as being among the basins experiencing the greatest water stress in the European Mediterranean region. The high stress on water resources have caused many political, economic, social and environmental problems. In order to evaluate the sustainability of water resource management in the basin, the WSI methodology was applied and satisfactory results were obtained,

Table 15. Values of state parameters obtained for the policy indicator.

Sub-basin	Goals discussed at the territorial roundtables					State score
	Environmental	Rational use	Extremes	Governance	Total	
Río Mundo	4	0	1	0	5	0.75
Corral Rubio	4	0	0	0	4	0.75
Yecla	1	1	0	1	3	0.75
Ramblas del Noroeste	1	1	0	1	3	0.75
Sur de Alicante	11	2	0	0	13	1
Vega Media	4	1	0	0	5	0.75
Mar Menor	5	1	0	0	6	1
Guadalentín	5	2	0	0	7	1
Sur de Murcia	5	2	0	0	7	1
Almería	5	2	0	0	7	1
Mula	4	1	0	0	5	0.75
Vega Alta	11	2	0	0	13	1
Noroeste de Murcia	4	1	0	0	5	0.75
Sierra del Segura	4	0	1	0	5	0.75

Table 16. Values of response parameters obtained for the policy indicator.

Sub-basin	Population		Investment (thousand €)		Δ (%)	Pressure score
	2006	2010	2006	2010		
Río Mundo	50 146	51 067	434	445	+2.51	0.50
Corral Rubio	2 545	2 403	1 202	1 307	+8.71	0.50
Yecla	36 284	37 246	870	953	+9.58	0.50
Ramblas del Noroeste	49 458	53 744	1 186	1 376	+16.00	0.75
Sur de Alicante	354 153	398 132	8 492	10 191	+20.01	1
Vega Media	479 584	509 179	11 500	13 034	+13.34	0.75
Mar Menor	348 893	374 466	8 366	9 586	+14.58	0.75
Guadalentín	167 811	174 810	4 024	4 475	+11.21	0.75
Sur de Murcia	63 291	70 364	1 518	1 801	+18.68	0.75
Almería	7 537	8 429	181	216	+19.39	0.75
Mula	23 530	24 640	564	631	+11.79	0.75
Vega Alta	166 301	181 529	3 988	4 647	+16.53	0.75
Noroeste de Murcia	71 045	74 467	1 704	1 906	+11.89	0.75
Sierra del Segura	18 086	17 368	434	445	+2.51	0.50

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Table 17. WSI in the Segura Basin.

Sub-basin	Pressure	State	Response	Hydrology quantity	Pressure	State	Response	Hydology quality	Pressure	State	Response	Environment	Pressure	State	Respuesta	Life	Pressure	State	Response	Policies	WSI
Río Mundo	1	0.25	0.25	0.50	1	0.75	1	0.92	0.75	1	0.50	0.75	0.50	0.75	0.50	0.58	0.75	0.75	0.50	0.67	0.68
Corral Rubio	0.75	0.25	0.25	0.42	0.75	0	1	0.58	1	0.25	0.25	0.50	0.50	0.75	0.50	0.58	0.75	0.75	0.50	0.67	0.56
Yecla	0.75	0	0.75	0.50	1	0	0.50	0.50	1	0.50	0.25	0.58	0.50	0.75	0.50	0.58	0.75	0.75	0.50	0.67	0.58
Ramblas del Noroeste	1	0	1	0.67	0.75	0.50	1	0.75	1	0.75	0.50	0.75	0.50	0.75	0.50	0.58	0.75	0.75	0.75	0.75	0.70
Sur de Alicante	0.50	0	1	0.50	1	0	0.75	0.58	0.75	0.50	0.50	0.58	0.50	0.75	0.50	0.58	0.75	1	1	0.92	0.66
Vega Media	0.75	0	1	0.58	1	0	0.75	0.58	1	0.50	0.25	0.58	0.50	0.75	0.50	0.58	0.75	0.75	0.75	0.75	0.63
Mar Menor	0.25	0	1	0.42	0.75	0.50	0.75	0.67	0.50	0.50	0.25	0.42	0.50	0.75	0.50	0.58	0.75	1	0.75	0.83	0.59
Guadalentín	1	0	1	0.67	1	0	0.50	0.50	1	0.75	0.50	0.75	0.50	0.75	0.50	0.58	0.75	1	0.75	0.83	0.69
Sur de Murcia	0.75	0	1	0.58	0.75	1	0.75	0.83	0	1	0.25	0.42	0.50	0.75	0.50	0.58	0.75	1	0.75	0.83	0.64
Almería	1	0	0.75	0.58	1	0	1	0.67	0.25	1	0.25	0.50	0.75	0.75	0.50	0.67	0.75	1	0.75	0.83	0.66
Mula	0.75	0	0.75	0.50	1	0	1	0.67	0.75	0.75	0.25	0.58	0.50	0.75	0.50	0.58	0.75	0.75	0.75	0.75	0.63
Vega Alta	1	0	1	0.67	1	0.25	1	0.75	0.75	1	0.25	0.67	0.50	0.75	0.50	0.58	0.75	1	0.75	0.83	0.70
Noroeste de Murcia	1	0	0.50	0.50	1	0.25	1	0.75	0.75	1	0.25	0.67	0.50	0.75	0.50	0.58	0.75	0.75	0.75	0.75	0.66
Sierra del Segura	1	1	0.25	0.75	1	0.75	0.75	0.83	0	1	0.25	0.42	0.50	0.75	0.50	0.58	0.75	0.75	0.50	0.67	0.61
Cuenca del Segura	0.82	0.11	0.75	0.56	0.93	0.29	0.84	0.68	0.68	0.75	0.32	0.58	0.52	0.75	0.50	0.59	0.75	0.86	0.70	0.77	**0.64**

demonstrating the sustainable management of the resource over recent years. A WSI of 0.64 was obtained for the entire basin, which places it at an intermediate sustainability level. The greatest strengths pertained to political indicators while the greatest weaknesses were related to hydrological quantity indicators, primarily due to water scarcity. No large differences were observed among the sub-basins analyzed, which indicates a certain degree of homogeneity in the sustainable management level of the basins.

The primary contribution of the work presented herein is the adaptation of the WSI to climate conditions in a semiarid basin subject to the obligations enacted by the European WFD. To this end, the indicators that are more qualitative in nature were modified based on the conditions in the study area, in order to reflect efforts taken to generate non-conventional resources as well as the obligations defined by the WFD for public participation.

According to the literature consulted, this methodology has not previously been applied in Europe, and therefore could be used in many European Mediterranean basins with climate, social and legal conditions very similar to those of the case study.

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Methodology to Delimit and Characterize Wetlands at Scales of 1:50 000 and 1:20 000

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Abstract

Brena, J., Castillo, C., & Wagner, A. (March-April, 2016). Methodology to Delimit and Characterize Wetlands at Scales of 1:50 000 and 1:20 000. *Water Technology and Sciences* (in Spanish), 7(2), 85-98.

This work analyzes the past and current state of the wetlands located in the study area, on the Pacific slope of the state of Chiapas, Mexico. To this end, remote sensing techniques were applied using satellite images taken in 1986, 2004 and 2010. This was used along with digital thematic mapping processed with a geographic information system to prospectively evaluate the trends in the wetlands' behavior through the year 2030. As result, a methodology was obtained to delimit wetlands at scales of 1:50 000 and 1:20 000. Land use and vegetation maps for the three basins in the study area were used as well as a trend map for the year 2030. The temporal analysis of vegetation cover, location and topographical morphology detected problems and threats. A map of critical areas was generated to inform environmental recovery actions and reduce erosion and the risk of landslides which threatens specific localities. It is concluded that a diagnostic of the environmental health of a wetland reflects the effects of the actions taken in different parts of a basin. The information obtained is crucial to evaluate sectoral strategies and develop an integral resource management plan that promotes the economic growth of the region as well as its sustainable use.

Keywords: Wetlands, integrated water management, remote sensing.

Resumen

Brena, J., Castillo, C., & Wagner, A. (marzo-abril, 2016). Metodología para la delimitación y caracterización de humedales en escalas 1:50 000 y 1:20 000. Tecnología y Ciencias del Agua, *7(2), 85-98.*

Se analiza la situación retrospectiva y actual de los humedales localizados en la zona de la Vertiente Pacífica del estado de Chiapas, México, para lo cual se aplicaron técnicas de percepción remota empleando imágenes satelitales tomadas en 1986, 2004 y 2010, que junto con cartografía temática digital procesada en un sistema de información geográfica permitió la evaluación prospectiva del comportamiento tendencial de los humedales al año 2030. Como resultado, se obtuvo una metodología para delimitar humedales en escalas 1:50 000 y 1:20 000, los mapas de uso de suelo y vegetación de las tres cuencas que integran la zona de estudio y un mapa tendencial para el año 2030. Del análisis temporal de las coberturas, su localización y la morfología del relieve, se detectaron problemas y amenazas, elaborándose un mapa de áreas críticas para orientar acciones de recuperación ambiental, reducir la erosión y el riesgo de deslizamientos que amenazan a localidades específicas. Se concluye que el diagnóstico de salud ambiental de un humedal refleja los efectos de las acciones hechas en las diferentes partes de una cuenca. La información obtenida es básica para evaluar estrategias sectoriales y desarrollar un plan de manejo integral de los recursos que promueva el crecimiento económico de la región y su aprovechamiento sustentable.

Palabras clave*: humedales, percepción remota, recursos naturales.*

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Introduction

The Ramsar Convention defined wetlands as "areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six meters" (Ramsar Convention Secretariat, 2010b). This definition includes both continental (lakes, rivers and salt marshes) and coastal wetlands (tidal flats, mangrove swamps, saltwater marshes and coral reefs).

Wetlands are some of the most important areas in the world for biodiversity and serve as the primary habitat for numerous species. They are also particularly important as providers of ecosystem services related to water, regulating the amount of surface water, purifying it, and contributing to groundwater recharge. In some cases, wetlands also help to control floods and reduce the impact of storms, increasing the ability to withstand torrents. They also play an important role in the recycling of nutrients, climate change and food and work security.

Worldwide, an estimated 50% of the wetland area has been lost over the past 100 years. This mainly occurred in temperate regions in the northern hemisphere over the first half of the 19th century, while tropical and sub-tropical wetlands began to disappear quickly around 1950, particularly swamp forests and mangroves (Stolk, Verweij, Stuip, Baker, & Oosterberg, 2006). With respect to mangroves, 20% of the total area (3.6 million hectares) was lost worldwide between 1980 and 2007, and an estimated 1.5% per year (13 000 hectares) in Mexico from 2000 to 2005 (FAO, 2007). The degradation of the wetlands that remain can produce losses in biodiversity and change ecological functions and the flows of ecosystem services, with subsequent effects on health, means of survival, the well-being of communities and economic activity.

Mexico has a total 10 033 623 hectares of wetland area (González, 2012). Many of these ecosystems are undergoing severe deterioration, overexploitation and pollution of the water, and are being drained to build urban and tourist infrastructure or converted for economic activities (agriculture, aquaculture and livestock). To reverse the loss of wetlands in the country, conservation policies are needed that are based on updated inventories and that support, on real bases, the implementation of programs to manage wetlands at the local, regional and national levels (Semarnat, 2008).

The *National Wetland Inventory* (scale of 1:250 000) has systematized information with which to locate, indentify and classify the objects they contain with maps that show the location, size, shape and type of wetlands in a geographic area, as well as the area covered by each wetland type. Thus, the inventory helps to develop and implement policies pertaining to these systems (Conagua, 2012).

Accurate inventories of these systems are needed (at a 1:50 000 scale a the basin level and 1:20 000 at the wetland level) in order to propose regulations for the protection, restoration and use of wetlands, as well as to establish the nature protection area or perimeter of a wetland zone, for the purpose of preserving their hydrological and ecosystem conditions.

Methodology

The boundaries, inventory and characterization of the wetlands in the study area were determined based on methodologies developed by the National Institute for Statistics and Geography (INEGI, 2006) as well as by the National Autonomous University of Mexico and the National Water Commission (UNAM, 2011). Both methodologies include

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the elements in the geographic landscape that are directly related to water and can be cartographed, thereby selecting themes: edaphology, vegetation and land use, climate, hydrography, topography and ecological regions. It is important to mention that while both methodologies can be applied using a multi-scale cartography, they were applied in the country with a scale of 1:250 000 (INEGI, 2007; Conagua, 2012). Therefore, the contributions offered by the present work is the incorporation of hydrological and topographical elements that can be systematically used by various institutions to delineate wetlands within a hydrographic basin, at scales of 1:50 000 and 1:20 000, and taking into account the coherence of the data at each change in scale.

The wetlands were delineated with the use of a geographic information system (GIS), obtaining an area of 51 983.7 ha at a 1:250 000 scale and 54 649.4 ha at the 1:20 000 scale. Figure 1 presents a flow diagram of the methodology applied to delineate the wetlands in the study area.

To aid in the analysis of the dynamics of vegetation and land use in the study area, Landsat images TM21-49 and 21-50 were used, taken February 4, 1985 and January 15, 1986, respectively, as well as multispectral SPOT images 603/319, 603/320, 604/319 and 604/320 (taken on the date indicated in Table 1). Land use maps for 1986, 2004 and 2010 were generated based on the classification and analysis of these images. This methodology was aimed at representing the changes produced by the extreme hydrometeorological events occurring in 1989 and 2005 that significantly impacted the study area.

Delineation of Wetlands in the Study Area

The process to establish the boundaries of the area of interest at scales of 1:50 000 and 1:20 000 was supported by the *National Wetland Inventory*, which simplifies the locating and delineating work. This process also adapts, complements and incorporates hydrological

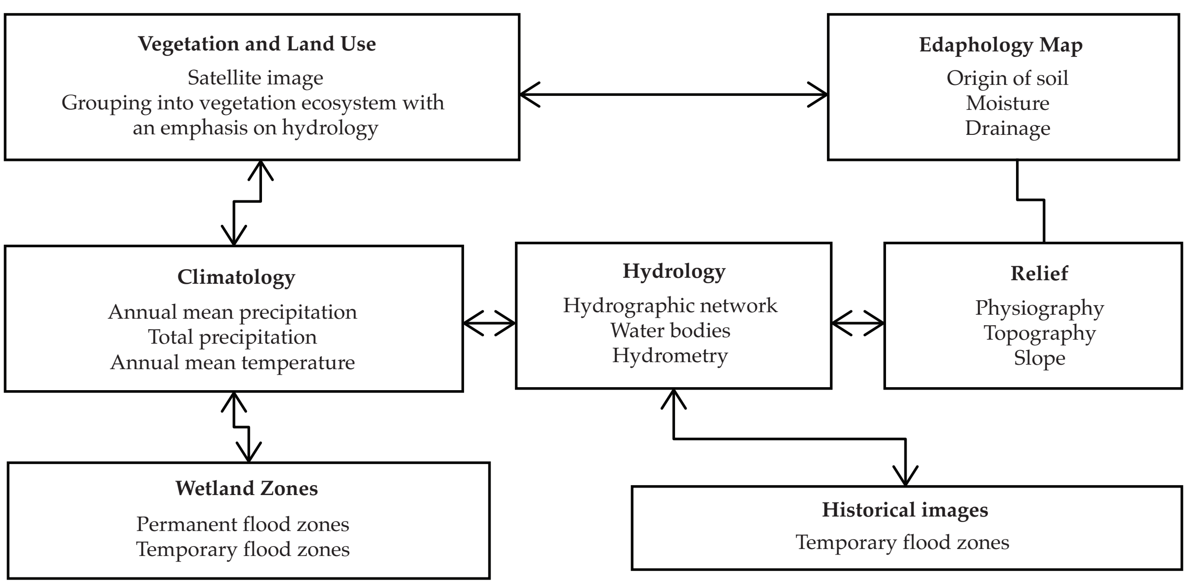

Figure 1. Methodological diagram of the spatial analysis for the delineation of wetlands.

Table 1. SPOT XS images used in the study.

Image	Date taken (*K/J*)	
603/319	April 16, 2004	January 15, 2011
603/320	March 10, 2004	November 25, 2009
604/319	March 11, 2004	November 19, 2009
604/320	January 24, 2004	December 05, 2009

and topographic elements not included in the methodologies *Mapping of Potential Wetlands 1:250 000* (INEGI, 2006) and the *National Wetland Inventory* (UNAMConagua, 2012). The wetlands in the area of interest were located and delineated by superimposing the maps of the hydrological boundaries of the sub-basin with the *National Wetland Inventory* at a scale of 1:250 000 using a geographic information system (Alonso-EguíaLis *et al*., 2013).

Delineation of the Perimeter of the Wetlands Zone at a scale of 1:50 000

Given the limits imposed by the spatial resolution (minimum area of a cartography) at a scale of 1:250 000, an analytical process needed to be performed using a GIS so that the original perimeter would meet the requirements of the 1:50 000 scale as well as those involving the incorporation of zones subject to temporary flooding (Moreno *et al*., 2009). To this end, three sources of information were used:

a) *National Surface Water Data* (Bandas, GAS-IR) and the *Rapid Extractor of Climatological Information* (ERIC, IMTA) to indicate and select the hydrometric and climatological stations in the study area, analyze the behavior over time and determine the period with the most precipitation and runoff in the river basins that feed into the wetlands.
b) Landsat satellite information bank of images (IMTA and EROS), which provided the images acquired during the periods with the highest precipitation (Alonso-EguíaLis *et al*., 2013) and runoff, identified by *Bandas* and *ERIC*, to evaluate the spatial behavior of the region of the study area that is prone to flooding (Figure 2).
c) The *Inter-Connected Hydrographical Network* (IHN), version 2, developed by the National Institute for Statistics and Geography (INEGI, 2010), which relates the hydrographic elements with the sub-basin location, providing an element for the nomenclature that identifies the wetlands and for the polygons corresponding to lotic and lentic water, adjusted for their incorporation and analysis and later used to obtain the coverage of water bodies at a scale of 1:50 000.

The polygon defining the boundary of the flood zone seen in the satellite image taken during the rainy season was then generated using computer-aided interpretative techniques with the use of a GIS. Then, the polygons of the water bodies from the coverage in the IHN were superimposed and analyzed, omitting the present ones and incorporating the missing ones in the working map. Lastly, the coverage was fused to generate a new one which integrated the databases from the fused layers and conserved and associated the data for later use for the nomenclature and classification of the wetlands. The wetlands were located and delineated by superimposing the maps of the hydrological boundaries of the sub-basins in the study area with the

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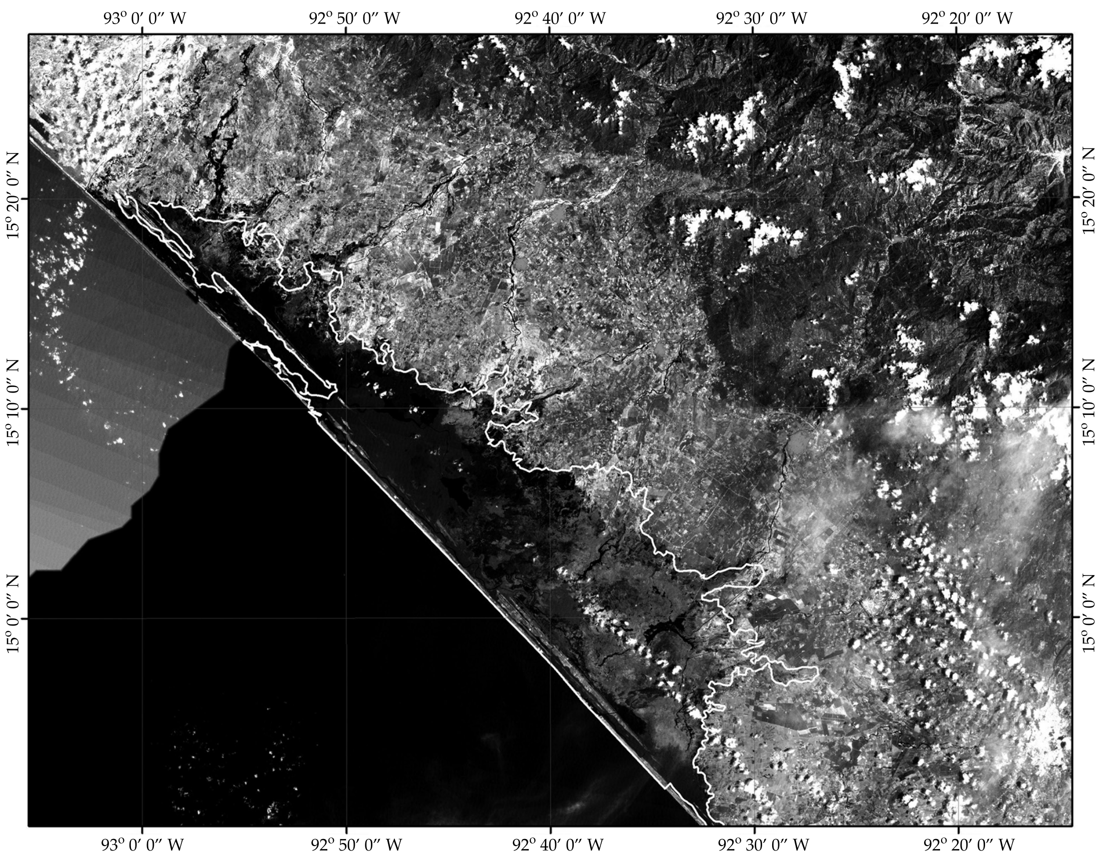

Figure 1. Recording of floodable zones by the Landsat image, compared to the INEGI perimeter of the wetland at a scale of 1:250 000.

National Wetland Inventory at a 1:250 000 scale, developed based on different thematic layers (edaphology, climatology, hydrology topography and ecological regions) using a geographic information system.

Characterization of the Wetlands at a Scale of 1:50 000

The different vegetation covers and land uses in the wetlands were obtained from the land use and vegetation map initially developed to characterize the study area, through a process of cropping and extracting performed based on the polygon that delineated the wetland zone.

Field Verification

Data was loaded into a laptop computer prior to field verification. The coverage of the perimeter of the wetlands, the vegetation layer and land use was verified with supplemental information about coverage obtained from the digital topographic map at a scale of 1:50 000 which shows the urban areas, rural communities, communication routes and toponymy. A project was opened in a portable mapping environment where the previously loaded coverage was organized and configured. The points of interest were located and identified by consensus among the specialists who participated in the project's different themes,

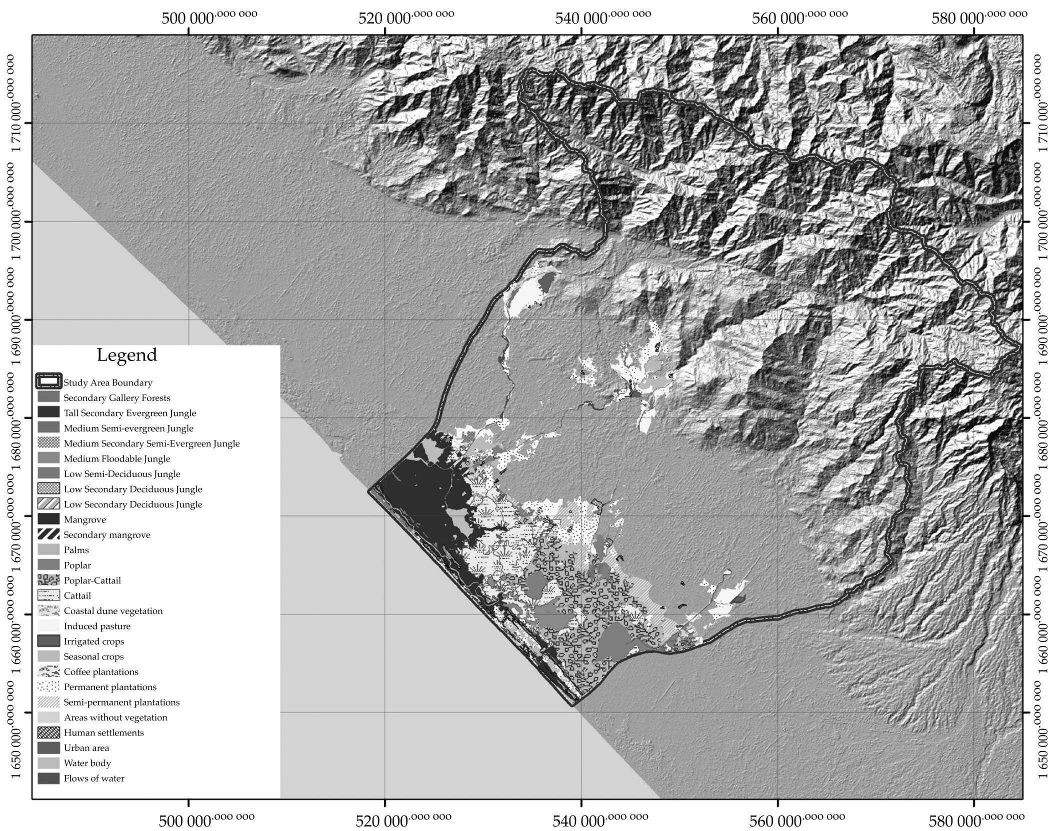

Figure 3. Distribution of the wetlands in the study zone and vegetation coverage.

for which field records needed to be obtained. Lastly, a field survey was performed.

Delineation of the Perimeter of the Wetland Zone at a Scale of 1:20 000

The boundary obtained at a scale of 1:50 000 was used as the basis to reduce the wetland area to a scale of 1:20 000, refining the delineation and conserving the coherence between the two scales, with the following information:

a) Coverage in the *Inter-Connected Hydrographic Network* (IHN). This coverage determined the order of magnitude of each water channel in the hydrographic network, which was superimposed with the satellite image to define the order of magnitude of the water channel meeting the minimum area required at the 1:20 000 scale, thereby selecting the fluvial wetlands to be mapped at that scale.

b) Survey of the topographic sections. After selecting the flows of water considered to be fluvial wetlands, that met the scale requirements, the area of influence of the area of water on both banks of each water channel was defined based on the order, topography type and location in the basin. To this end, of the three basins in the study area, the Huixtla River Basin was selected since it had the best access for performing the topographic work. The results obtained served as a basis to determine the dimensions of the areas of influence of the wetlands and were extrapolated to other basins.

c) High-resolution satellite image. The 2.5 m resolution of the SPOT 5 was indispensible to the characterization of the wetlands at the present scale of analysis, enabling an adequate interpretation of the different elements that compose the delineated area and supporting the classification of the wetlands complex (Alonso-EguíaLis *et al*., 2013).

d) Land use and vegetation map at a scale of 1:50 000. The high-resolution image of the perimeter obtained at a 1:50 000 scale was superimposed with the IHN using a geographic information system and the perimeter of the wetland area was determined. The vegetation coverage and land use classes inside the polygon were reclassified (Yang, 2007) to meet the requirements of the 1:20 000 scale. Lastly, the resulting map was reviewed and incorporated into the project's geographic database (Figure 4).

Land Use and Vegetation in the Hydrographic Basin

This analysis was aimed at spatially observing the biophysical and socioeconomic conditions in the basins in the study area in order to characterize each basin's historical, current and future use of the resources that affect the health of the wetlands located therein, and their continued existence. Land use and vegetation maps were generated by processing satellite images and the state of the natural vegetation in the study area was evaluated for

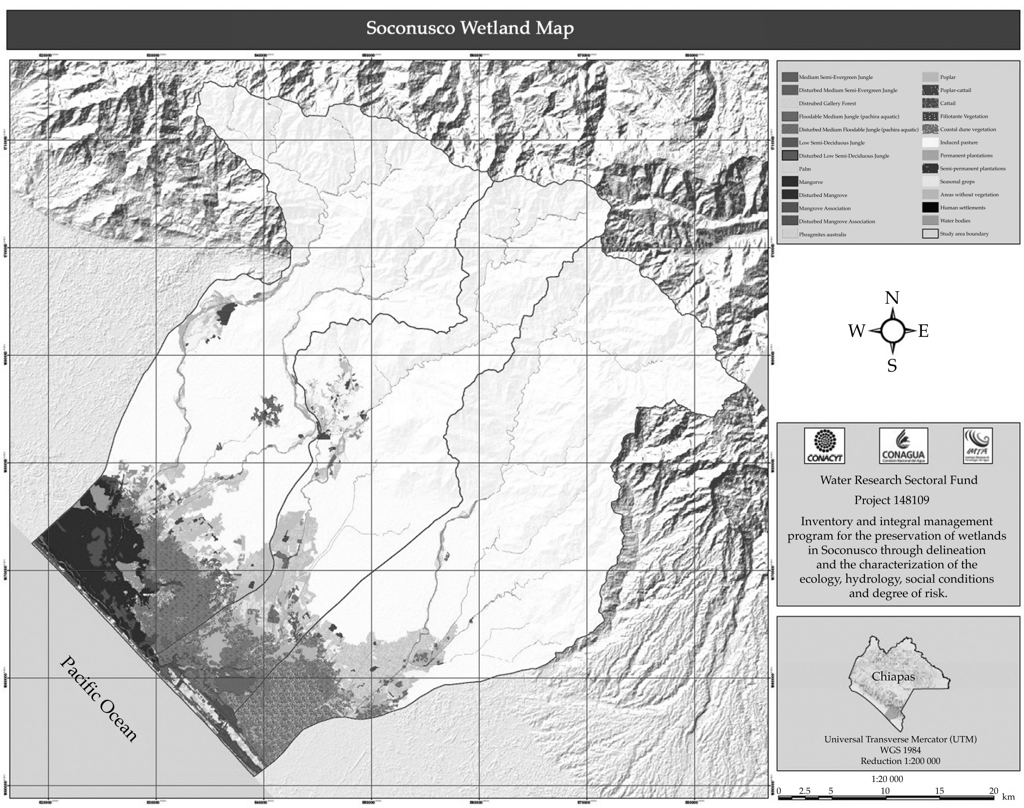

Figure 4. Map of Wetlands at a scale of 1:20 000.

Table 2. Areas quantified per class for the years 1986, 2004 and 2010.

Classes evaluated	1986		2004		2010	
	Area		Area		Area	
	ha	%	ha	%	ha	%
Irrigated crops	1 456	1	1 320	1	2 747	1
Seasonal crops	9 885	4	6 039	3	5 791	2
Human settlements	1 808	1	4 885	2	5 954	3
Gallery Forest	75	0	7	0	6	0
Disturbed Gallery Forest	694	0	456	0	606	0
Mesophyll Mountain Forest	7 926	3	4 969	2	2 960	1
Disturbed Mesophyll Mountain	13 466	6	14 356	6	14 974	6
Temperate Forest	4 654	2	3 664	2	2 433	1
Disturbed Temperate Forest	11 974	5	10 242	4	10 773	5
Coffee plantations	31 134	13	33 299	14	40 874	18
Water body	2 835	1	2 674	1	3 579	2
Mangrove	7 994	3	8 123	3	7 907	3
Disturbed mangrove	1 469	1	541	0	560	0
Induced pasture	29 179	13	34 843	15	32 172	14
Plantations	44 901	19	49 677	21	50 504	22
Poplar	5 541	2	5 139	2	2 650	1
Poplar-cattail	4 940	2	6 418	3	8 612	4
Deciduous Forest	996	0	607	0	707	0
Disturbed deciduous forest	4 842	2	4 113	2	3 701	2
Evergreen Jungle	2 662	1	1 676	1	1 419	1
Disturbed Evergreen Jungle	33 183	14	29 649	13	23 743	10
Bare Soil	238	0	607	0	1 726	1
Cattail	10 543	5	9 088	4	8 001	3
Costal dune vegetation	98	0	99	0	92	0

the years 1986, 2004 and 2010 (Ramsar Convention Secretariat, 2010a). Table 2 shows the determination of the classes and areas and the quantification of the percentage of coverage. Figure 5 presents the distribution of the land use and vegetation classes obtained for 2004.

The net rate of change in coverage was then evaluated for each class during the period 1986 to 2004 and from 2004 to 2010, presented in Tables 3 and 4, respectively.

Future Land Use

The future cartographies of the study area were obtained by applying the following analysis modules: Markov chains and stochastic projection; multi-criteria analysis and multi-objective evaluation; Markov chains coupled with a cellular automata algorithm (Paegelow, Camacho-Olmedo, & Menor-Toribio, 2003).

The Ca-Markov process was used to determine future land use and vegetation, with maps generated for 1986 and 2010 to identify the possible distribution of land uses and vegetation for the year 2030, the period established by the Water Agenda.

The algorithm used Markov chains to calculate the probability of a change from one class to another based on the change matrix

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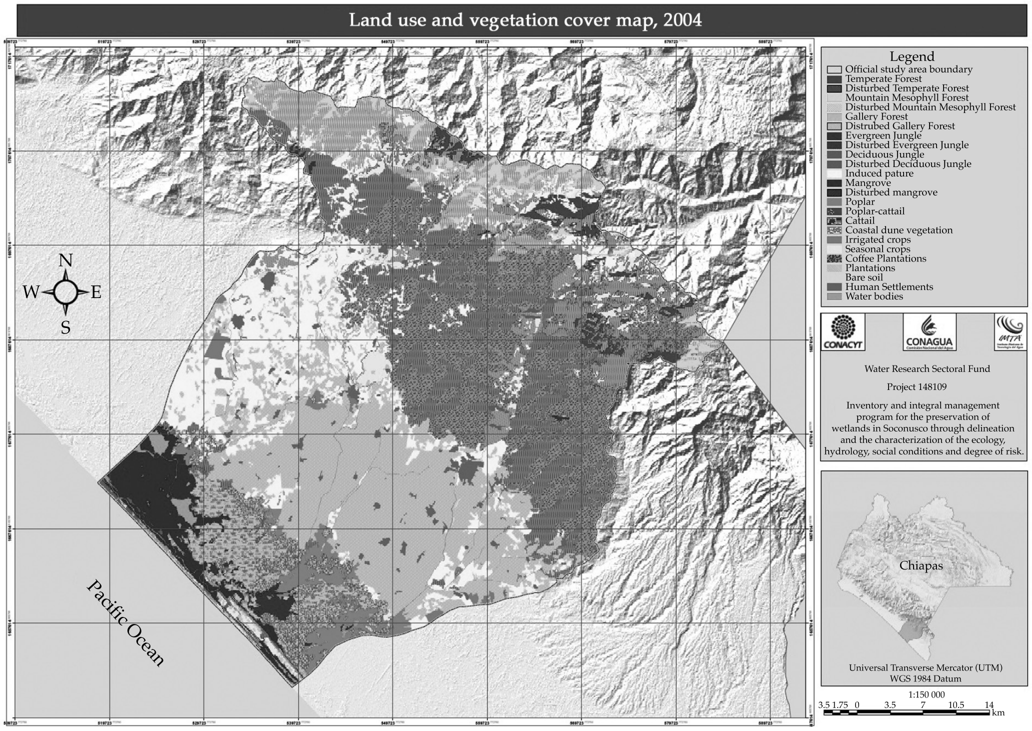

Figure 5. Distribution of land use and vegetation classes for 2004.

Table 3. Evaluation of the exchange rate in the period 1986-2004 by class.

Classes evaluated	Area (ha) Year		Net rate exchange (ha)	Annual rate exchange (ha/year)	Annual index exchange (%)
	1986	2004			
Irrigated crops	1 456	1 320	-136	-8	-1
Seasonal crops	9 885	6 039	-3 846	-214	-2
Human settlements	1 808	4 885	3 077	171	9
Gallery Forest	75	7	-68	-4	-5
Disturbed Gallery Forest	694	456	-238	-13	-2
Mesophyll Mountain Forest	7 926	4 969	-2 957	-164	-2
Disturbed Mesophyll Mountain Forest	13 466	14 356	890	49	0
Temperate Forest	4 654	3 664	-990	-55	-1
Disturbed Temperate Forest	11 974	10 242	-1 732	-96	-1
Coffee Plantations	31 134	33 299	2 165	120	0
Water body	2 835	2 674	-161	-9	0
Mangrove	7 994	8 123	128	7	0
Disturbed mangrove	1 469	541	-928	-52	-4
Induced pasture	29 179	34 843	5 664	315	1
Plantations	44 901	49 677	4 776	265	1
Poplar	5 541	5 139	-402	-22	0

Table 3 (continued). Evaluation of the exchange rate in the period 1986-2004 by class.

Classes evaluated	Area (ha) Year		Net rate exchange (ha)	Annual rate exchange (ha/year)	Annual index exchange (%)
	1986	2004			
Poplar-cattail	4 940	6 418	1 478	82	2
Deciduous Jungle	996	607	-389	-22	-2
Disturbed Deciduous Jungle	4 842	4 113	-730	-41	-1
Evergreen Jungle	2 662	1 676	-986	-55	-2
Disturbed Evergreen Jungle	33 183	29 649	-3 534	-196	-1
Bare Soil	238	607	370	21	9
Cattail	10 543	9 088	-1 455	-81	-1
Costal dune vegetation	98	99	1	0	0

Table 4. Evaluation of the exchange rate in the period 2004-2010 by class.

Classes evaluated	Area (ha) Year		Net rate exchange (ha)	Annual rate exchange (ha/year)	Annual index exchange (%)
	2004	2010			
Irrigated crops	1 320	2 747	1 427	238	18
Seasonal crops	6 039	5 791	-248	-41	-1
Human settlements	4 885	5 954	1 068	178	4
Gallery Forest	7	6	-2	0	-3
Disturbed Gallery Forest	456	606	149	25	5
Mesophyll Mountain Forest	4 969	2 960	-2 008	-335	-7
Disturbed Mesophyll Mountain Forest	14 356	14 974	618	103	1
Temperate Forest	3 664	2 433	-1 231	-205	-6
Disturbed Temperate Forest	10 242	10 773	531	89	1
Coffee plantations	33 299	40 874	7 574	1 262	4
Water body	2 674	3 579	905	151	6
Mangrove	8 123	7 907	-215	-36	0
Disturbed mangrove	541	560	19	3	1
Induced pasture	34 843	32 172	-2 671	-445	-1
Plantations	49 677	50 504	827	138	0
Poplar	5 139	2 650	-2 490	-415	-8
Poplar-cattail	6 418	8 612	2 194	366	6
Deciduous Jungle	607	707	100	17	3
Disturbed Deciduous Jungle	4 113	3 701	-411	-69	-2
Evergreen Jungle	1 676	1 419	-257	-43	-3
Disturbed Evergreen Jungle	29 649	23 743	-5 905	-984	-3
Bare Soil	607	1 726	1 119	186	31
Cattail	9 088	8 001	-1 087	-181	-2
Costal Dune Vegetation	99	92	-7	-1	-1

for a particular period. The underlying idea is that the changes observed during one period of time tend to repeat at a later period of time. For this application, a transition matrix was generated based on an image from one initial moment (the land use and vegetation from 1986) and the current image (land use and vegetation in 2010). For each category, the area having the same land use throughout the period considered was calculated as was the area in which land use changed to another category. Based on this transition matrix, the program then generated a probability of change matrix for the 24 classes that had been established. The probabilities of change from one class to another were obtained by dividing the area that changed from one class to another by the total area of the class in the past.

After defining the areas for the future trends scenario, the program required elements to identify the zones where these changes will occur. An aptitude map was required for each class to evaluate the probability that a class exists at some point based on the characteristics of this point.

Figure 6 presents the potential distribution of the land uses and vegetation for 2030, obtained by applying the Ca-Markov process. Table 5 shows the potential distribution of the areas, grouped by general vegetation types, which detected increased land use for farming and livestock at the expense of losses in natural vegetation cover.

According to the resulting data, a declining trend in the area corresponding to natural vegetation classes has continued — mainly jungles, forests and hydrophytic vegetation— which can clearly be seen in the trends graph shown in Figure 7. Meanwhile, the coverage of farming and livestock activities presented an increasing trend (Figure 8).

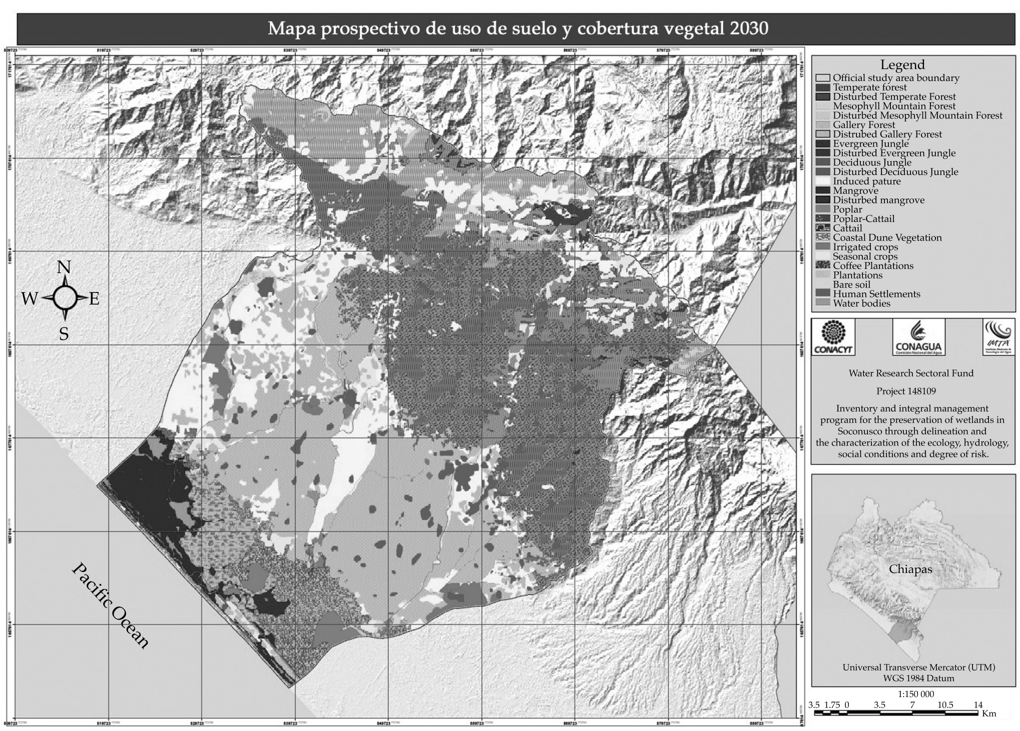

Figure 6. Spatial distribution of vegetation cover and land use by 2030.

Table 5. Area evaluated by class and exchange rate in the period.

Classes Evaluated	Area (ha) year		Net rate exchange	Annual rate exchange	Net rate exchange
	2010	2030	(ha)	(ha/year)	(%)
Irrigated Crops	2 747	3 245	498	25	1
Seasonal Crops	5 791	4 691	-1 100	-55	-1
Human Settlements	5 954	9 065	3 111	156	3
Gallery Forest	6	5	-1	0	-1
Disturbed Gallery Forest	606	560	-45	-2	0
Mesophyll Mountain Forest	2 960	1 534	-1 426	-71	-2
Disturbed Mesophyll Mountain Forest	14 974	15 039	65	3	0
Temperate Forest	2 433	1 626	-807	-40	-2
Disturbed Temperate Forest	10 773	8 914	-1 859	-93	-1
Coffee Plantations	40 874	41 929	1 055	53	0
Water body	3 579	3 724	145	7	0
Mangrove	7 907	7 406	-501	-25	0
Disturbed mangrove	560	436	-124	-6	-1
Induced pasture	32 172	32 507	334	17	0
Plantations	50 504	52 516	2 012	101	0
Poplar	2 650	2 315	-335	-17	-1
Poplar-Cattail	8 612	8 654	42	2	0
Deciduous Jungle	707	418	-289	-14	-2
Disturbed Deciduous Jungle	3 701	3 266	-435	-22	-1
Evergreen Jungle	1 419	876	-543	-27	-2
Disturbed Evergreen Jungle	23 743	22 230	-1 513	-76	0
Bare Soil	1 726	2 305	579	29	2
Cattail	8 001	7 033	-968	-48	-1
Costal Dune Vegetation	92	207	115	6	6

The spatial analysis of natural resource usage in the basin indicates high direct and indirect stress on aquatic systems. In the case of direct affects, a reduction in the wetland area was detected as a result of the drainage of areas and changes in land use. And as indirect affects, a large proportion of the usage in the upper, middle and lower basins was not ecologically compatible with the use of the soil, causing landslides and erosion in the upper basin which deposit sediments particularly in the coastal wetland area in the lower basin, continuously deteriorating the conditions of the aquatic habitat.

Conclusions

Applying hydrometeorological information to the selection of satellite images and analyzing the distribution and behavior of floodable zones substantially improved the delineation of the marshy and fluvial wetlands located in

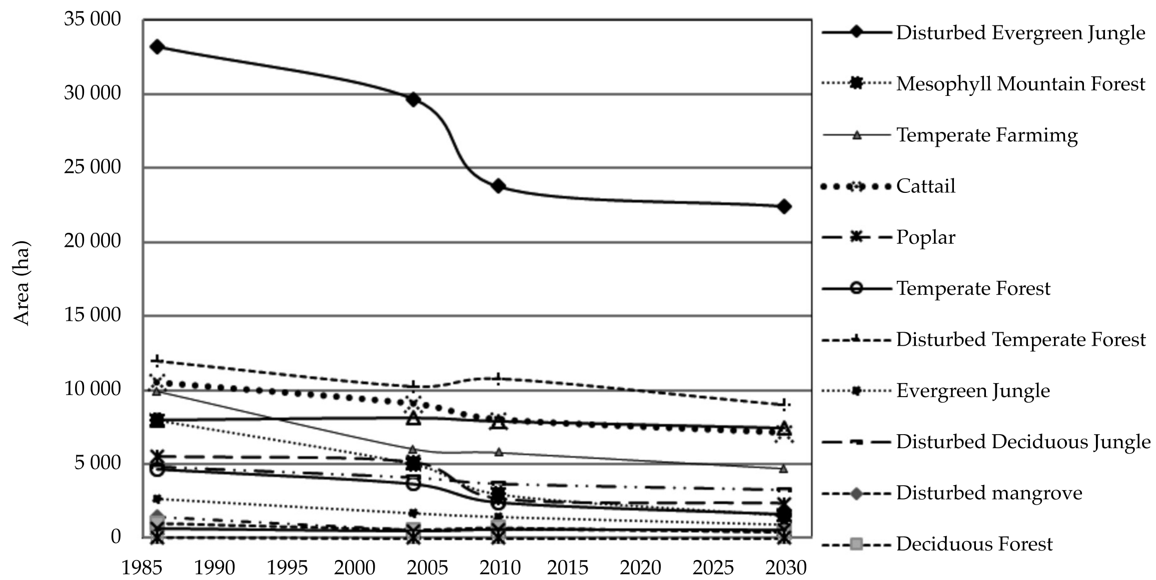

Figure 7. Cover with tendency to decrease.

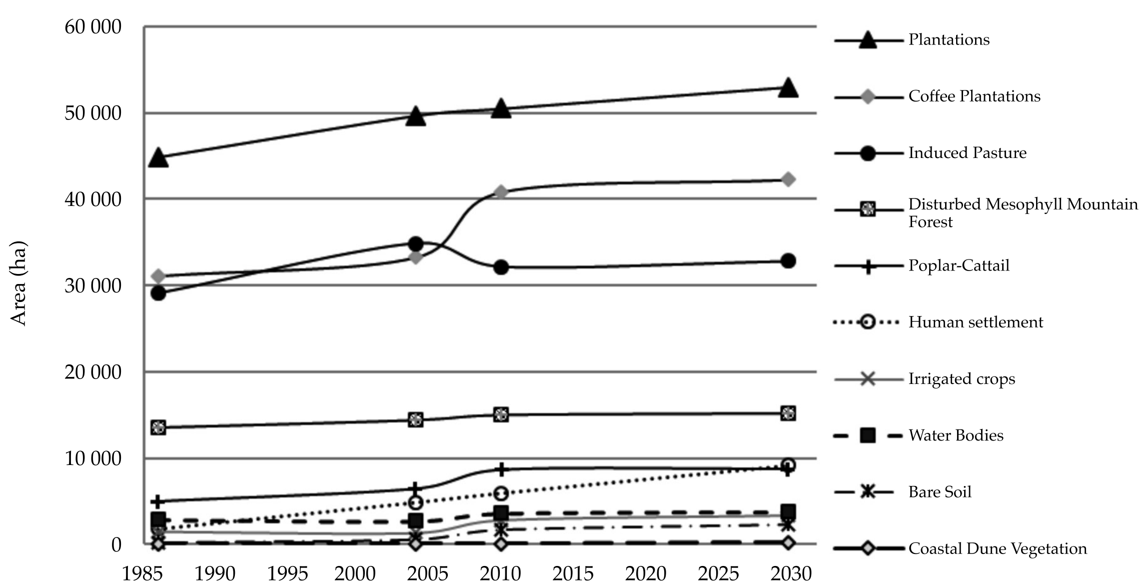

Figure 8. Cover with tendency to increase.

areas with shallow slopes in the lower river basins. This was accomplished by comparing the boundaries obtained with those from maps generated by the INEGI (2007) and by Conagua-UNAM (González, 2012). The methods applied in this study also contributed to the congruency of the cartographic representations at each change in scale.

The field work, and in particular the hierarchical selection survey of the topographic sections of the channels, enabled establishing criteria to adequately choose the water channels to be cartographed. It also made it possible to define the dimensions of the area of influence of the fluvial wetlands at a scale of 1:20 000, which is an original contribution by the present work to procedures performed in Mexico to delineate fluvial wetlands.

This type of study makes it possible to dimension, delineate and characterize regions containing wetlands. It also provides the supplemental information needed to propose actions and programs aimed at sustainably using and managing the natural resources and the richness and biodiversity in wetlands and the hydrographic basins.

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Flood Risk Modeling for the State of Tabasco, 1961-2007

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Abstract

Reyes-Olvera, A. L., & Gutiérrez-González, E. (March-April, 2016). Flood Risk Modeling for the State of Tabasco, 1961-2007. *Water Technology and Sciences* (in Spanish), 7(2), 99-114.

This paper proposes a flood risk indicator for hydrographic region 30 and a portion of 29, located in the state of Tabasco, Mexico. The indicator takes into account three factors: vulnerability, cost and hazards. Vulnerability measures the susceptibility of a region to flooding, which includes social and natural elements —that is, the services available to the population and the hydrological resources that pass through the region, respectively. In terms of cost, this takes into account the amount and type of damage from flooding, including the number of inhabitants and goods possessed by the population. The third factor, hazards, is based on annual maximum precipitations from 1961 to 2007, taken from the Maya v. 1.0 database, to calculate the probability of the occurrence of flooding and its return periods. For the hazards, a bootstrap goodness-of-fit test was proposed based on the sample correlation coefficient, using simulation to estimate the size and statistical power of the test. The distribution parameters were estimated according to maximum likelihood and the test verified that the observations fit the Gumbel distribution or generalized extreme values selected by the log-likelihood, AIC and correlation criteria.

Keywords: Risk index, vulnerability, cost and hazard, extreme value, bootstrap test, risk level map and return periods, principal components.

Resumen

Reyes-Olvera, A. L., & Gutiérrez-González, E. (marzo-abril, 2016). Modelación del riesgo de inundaciones en el estado de Tabasco en el periodo 1961-2007. Tecnología y Ciencias del Agua, *7(2), 99-114.*

En este trabajo se propone un indicador del riesgo de inundación en la región hidrográfica 30 y parte de la 29 que se encuentran en el estado de Tabasco, México, considerando tres factores: vulnerabilidad, costo y peligro. En el caso de la vulnerabilidad, se medirá la susceptibilidad de una región frente a una inundación; para esto se consideran elementos sociales y naturales, en donde el primero mide la disposición de los servicios con los que cuenta la población y el segundo incluye los recursos hidrológicos que atraviesan la región de estudio. Para el costo se considera cuánto y cómo afecta el daño provocado por una inundación, tomando en cuenta dos factores: número de habitantes y bienes que posee la población. En el tercer factor se consideran las precipitaciones máximas anuales de 1961 a 2007 tomadas de la base de datos Maya v. 1.0, para calcular la probabilidad de ocurrencia de inundación y sus periodos de retorno; para el peligro se propone una prueba de bondad de ajuste bootstrap, basada en el coeficiente de correlación muestral, estimando el tamaño y la potencia de la prueba usando simulación. Los parámetros de la distribución fueron estimados por máxima verosimilitud y con la prueba se verificó que las observaciones cumplieran con la distribución Gumbel o de valores extremos generalizada, elegidas por los criterios log-verosimilitud, AIC y correlación.

Palabras clave: *índice de riesgo, vulnerabilidad, costo y peligro, valores extremos, prueba bootstrap, mapa de riesgo, niveles y periodos de retorno, componentes principales.*

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Introduction

Given the social and economic benefits from the conscious exploitation of water, it is one of the most valuable natural resources for any country. Nevertheless, not only benefits but also extreme situations exist, such as floods and droughts (Zucarelli, 2013).

Globally, floods are increasing more rapidly than any other disaster and have caused severe social and economic problems. This is why a variety of investigations have been developed to analyze extreme events and different ways to evaluate the risk of flooding. In Mexico, Uribe-Alcántara, Montes-León and García-Celis (2010) proposed a flood index map to identify zones prone to flooding.

The study of floods is complex. For example, the direct economic damage to a flooded building not only depends on the water depth but also on how the building is used. Other important factors include the characteristics of the building, socioeconomic variables and the quality of the emergency response, among others (Smith, 2001). In Mexico City, Baró-Suárez, Díaz-Delgado, Calderón-Aragón performed research about the most likely cost of damage in residential zones and proposed a characterization of the cost based on an urban marginalization index.

Different methods can be used to examine floods. The analysis by Hunt considers them to be natural disasters for which it is necessary to identify the hazards and the vulnerability in terms of the ability to overcome them (Hunt, 2002). Meanwhile, the National Center for Disaster Prevention (Cenapred, 2006) does not treat disasters as natural but rather as a product of conditions related to vulnerability and exposure. Therefore, when wanting to prevent disasters, it is necessary to talk about risk. Various definitions can be mentioned that mainly refer to the factors on which the estimation is based. It is also important to mention that the effects of floods in society cannot be represented by a monetary value (Green, Van Der Veen, Wiertra, & Penning-Rowsell, 1994)

In other works, Herrera-Díaz, Rodríguez-Cuevas, Couder-Castañeda and Gasca-Tirado (2015), Flowers-Cano, Jeffrey-Flowers and Rivera-Trejo (2014) and Young (2002) combined statistical and deterministic methods to analyze past data and predict flood and river levels. Meanwhile, Bayliss and Reed (2001) discussed different ways to study historical floods and reviewed methods to incorporate historical data into flood frequency analyses. Meteorological data can be incorporated to strengthen the estimation of risks and rainfall can be a remarkably reliable indicator of floods (Duncan, 2002). Nevertheless, risk includes two factors —hazard (H) and vulnerability (V) (Mileti, 1999)— and although this is not the only definition of risk it is one of the most commonly used. Ordaz includes a third factor in the calculation of risk from the occurrence of a natural event (Ordaz, 1996), which is the cost (C) or value of the goods exposed. So then, risk is a product of three factors: $R = V \times C \times H$. Note that this is really the same definition, since vulnerability is composed of two elements —potential exposure or damage and susceptibility or loss (Merz, Thieken, & Gocht, 2007). Therefore, these three latter factors should be included in the measurement of risk.

Given the impact of floods on society and the monetary losses, it is important to construct a vulnerability index (Tapsell, Penning-Rowsell, & Tunstall, 2002). Vulnerability refers to different concepts. For example, Blaikie, Wisner, Cannon and Davis (1994) analyzed the socioeconomic conditions that increase the degree of vulnerability.

In terms of hazard, it is necessary to calculate the probabilities that an event will occur that can damage what is exposed (Ordaz, 1996). For floods, risk can be a result of rainfall, tropical cyclones or failures in hydraulic works.

The present article studies floods when extreme rainfall values are recorded, and thus the theory of extreme values will be introduced herein.

Fisher and Tippett (1928) derived the limiting form of the distribution of the maximum value from a random sample with three possible distributions: Gumbel, Weibull and

Frechet. Based on this, other contributions of interest were developed, such as those by Gumbel (Gumbel, *Les moments des distribution limite du terme maximum dune sèrie alèatoire*, 1934), who also presented the first important book (Gumbel, *Statistics of Extremes*, 1958) in which his work with extreme events considered several applications. In a general form and with a rigorous test, Gnedenko presented the theorem of the types of distributions for extreme values proposed by Fisher and Tippett (Gnedenko, 1943). Another important contribution was that of Von Mises (1936) and Jenkinson (1955), who through their work on the distribution of extreme values proposed a distribution that combines three families of extreme value distributions, known as GEVD. Significant statistical advances were made in this field between 1990 and 2011, such as Tawn (1992), Rosbjerg and Madsen (1996), Coles and Dixon (1999, Likelihood-Based Inference for Extreme Values Models) and Coles (2001, An Introduction to Statistical Modeling of Extreme Values), among others.

Having obtained a measurement of risk, flood hazards and risk maps are generated to determine the different risk categories for the zones and to develop a management plan. Tawatchi and Mohammed (2005) and Lehner and Döll (2001) provided an example of how to approach this analysis on a global scale using maps of the flood situation in Europe. Meanwhile, Mexico has flood risk maps at the municipal scale (Cenapred, 2006).

In Mexico, floods have occurred over recent years in the Grijalva-Usumacinta region of the state of Tabasco. One of these, in 2007, was one of the most intense floods over the past 50 years (Rivera-Trejo, Soto-Cortés, & Barajas-Fernández, 2009). Arreguín-Cortés, Rubio-Gutiérrez, Domínguez-Mora and Luna-Cruz (2014) analyzed the factors that influence floods on the Tabasco plains, such as a lack of adequate land-use planning and the deforestation of the upper portion of basins.

Therefore, the present investigation calculated flood risk indices and return periods for four hazards scenarios: 100, 150, 200 and 250 mm. To this end, the use of a parametric bootstrap goodness-of-fit test was proposed based on the sample correlation coefficient, with the verification of the size and power of the test through simulations with 10 000 replications.

Overall Objective

To model the risk of floods due to extreme weather in the state of Tabasco.

Specific Objectives

- Propose a statistical model based on the extreme values theory in order to determine the behavior and trends in extreme rainfall.
- Calibrate the statistical model using a historical rainfall database and hydrometric levels in the state of Tabasco.
- Generate a flood risk map of the state of Tabasco, by municipality.

Methodology

Usually, a hazard is believed to be the only factor responsible for disasters, but to a large extent it is society that exposes itself to high-risk events through its infrastructure, organization and culture. Therefore, disasters should be understood not only as natural but also as the product of conditions involving vulnerability and exposure (Cenapred, 2006).

Therefore, a measurement that represents risk and its changes over time needs to be found. And though it may be statistically difficult to model the large amount of variables involved in a model, the introduction of index numbers may be one way to handle the solution and make it more manageable. Ever since they appeared, indices have become increasingly important as indicators of the different changes that society undergoes.

The present work constructs risks indices and maps at the municipal scale for the state of Tabasco. The definition of risk by Ordaz (1996) will be used, who treats it as the product of three factors (see expression (1)). An indicator will be calculated for each one of these:

$$R = V \times C \times H \quad (1)$$

In which V represents vulnerability, C represents the value of the cost of the exposed goods and H is the hazard or probability that an event will occur that can damage what is exposed.

Vulnerability

Vulnerability can be described by different concepts. The article herein considers it as a measure of the susceptibility of an exposed good to the occurrence of a disruptive event (Ordaz, 1996). Two variables are included in this analysis —the community's services (electricity, drinking water and drainage) and its primary hydrological resources (rivers and lagoons).

In the case of services, an index of services is constructed with three variables:

PO_WOE: percentage of occupants without electricity.
PO_WOPW: percentage of occupants without piped water.
PO_WOD: percentage of occupants without drainage.

These factors are weighted using a multivariate principal components (PC) analysis. The use of the PC ensures a linear combination with a maximum variance to provide the best coefficients and to adequately explain the community's situation.

The second variable, hydrological resources in each municipality, is included since the region of Tabasco is very near sea level. It is a region with rivers, lagoons and marshes. In addition, throughout its history Tabasco has experienced floods from the overflowing of the rivers that run through the state. For example, the flood of 2007 (Rivera-Trejo *et al*., 2009) in the municipality of Paraiso was caused by rainfalls that coincided with a storm surge in the Gulf of Mexico which prevented the Grijalva and Carrizal rivers from emptying into the sea. Therefore, for the hydrological resources, a river index was constructed by weighting each municipality according to the number of rivers located therein and the capacity of each river based on its normal maximum water level (NMWL).

Cost of Goods Exposed

The cost component, C, in equation (1) measures the degree of susceptibility to being affected by the occurrence of a disruptive event (Ordaz, 1996). Thus, the construction of a cost indicator takes into account the goods possessed by the population (television, washing machine, refrigerator, computer, car) and the number of inhabitants per community. The number of inhabitants is included given the supposition that "the larger the population, the greater the wealth." So then, the cost index for exposed goods is constructed based on the following five indicators of goods, which is later weighted using principal components:

POWT: porcentaje de ocupantes que dispone de televisión.
POWR: porcentaje de ocupantes que dispone de refrigerador.
POWM: porcentaje de ocupantes que dispone de lavadora.
POWC: porcentaje de ocupantes que dispone de computadora.
POWV: porcentaje de ocupantes que dispone de automóvil o camioneta.

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Hazard

In the context of this investigation, hazards, H, from flooding is defined as the probability of the occurrence of a flood situation that has the potential to damage a given area and for a certain specified period. For the analysis of this component, the information to be used will depend on the type of flood analyzed, which can be defined as:

- The duration of floods (slow or sudden).
- The mechanism that produces them (pluvial, fluvial, coastal or the failure of hydraulic works).

In this case, the value of the hazard is calculated by considering rainfall as a reliable indicator of flooding. The floods that have occurred from failures of hydraulic works are not directly studied, although it is important to note that these failures are highly probably when rainfall values are extreme. Thus, rainfall data in Tabasco and nearby areas are analyzed in order to calculate the hazard factor. Nearby areas are included since floods depend not only on local precipitation but also on the precipitation in basins upstream from the overflow point.

Precipitation Data

Precipitation data was obtained from daily rainfall measurements between 1961 and 2007 from the weather stations belonging to the National Weather Service (NWS), with the interpolated version of CLICOM with a standard grid of 0.2 degrees longitude by 0.2 degrees latitude (*Maya* v. 1.0).

A region was delineated for each municipality in order to obtain databases for each one. This was performed with the help of information from the sub-basins whose flows partially or totally influence the municipality studied. In the event that a portion of a sub-basin enters a municipality but its flow does not have an influence, only the nodes found within the municipality are included. The nodes that have an influence on the analysis are thereby determined, and there will be as many data series as there are number of nodes included in the study. A linear combination of the nodes involved is then performed until obtaining one suitable series. To this end, the principal components theory is again used. In this case, the variables are the nodes in the municipality. The resulting PC corresponds to the weights assigned to each node to obtain the linear combination desired which, finally, represents the data series that represents the municipality.

Data Analysis

Maximum annual rainfall was extracted from the data series for each municipality. Let x_1, x_2,... x_m be a sample of the random variable X_i, precipitation in municipality i. Then, two vectors are created $x^{(1)} = (x_1^1, ..., x_n^1)$, $x^{(2)} = (x_1^2, ..., x_n^2)$, $x^{(k)} = (x_1^k, ..., x_n^k)$. The vectors are used to calculate the annual maximums $M_{n,i} = \text{máx}\{x_1^i, ..., x_n^i\}$, where $i = 1, ..., k$, which are considered *iid* (independent and identically distributed) according to the theory of extreme values. Then $F(x) = P(M \leq x) = \{F(x)\}^k$. The theorem by Fisher and Tippett (1928) assumes that $M_{n,i}$ fits one of the extreme value distributions (GEVD) shown in (2), (3) and (4):

$$\text{Gumbel: } F(x) = \exp\left\{-\exp\left[-\left(\frac{x-\mu}{\sigma}\right)\right]\right\}, \quad x \in \mathbb{R} \quad (2)$$

$$\text{Fréchet: } F(x) = \begin{cases} 0 & x \leq \mu \\ \exp\left[-\left(\frac{x-\mu}{\sigma}\right)^{-\varepsilon}\right] & x > \mu \end{cases} \quad (3)$$

$$\text{Weibull: } F(x) = \begin{cases} 0 & x < \mu \\ 1-\exp\left\{-\left(\frac{x-\mu}{\sigma}\right)^{\varepsilon}\right\} & x \geq \mu \end{cases} \quad (4)$$

with parameters $\mu \in \mathbb{R}$, $\sigma > 0$ and $\varepsilon > 0$, or with the generalization given by Gnedenko, the generalized extreme values distribution (GEVD) shown in (5):

$$F(x) = \exp\left\{-\left[1+\varepsilon\left(\frac{x-\mu}{\sigma}\right)\right]_{+}^{-\frac{1}{\varepsilon}}\right\} \tag{5}$$

where $y_{+} = \max\{y, 0\}$, $\mu \in \mathbb{R}$, $\sigma > 0$ and $\varepsilon \in \mathbb{R}$.

This investigation studied the fit with the Gumbel distribution, since this is one of the most widely used distributions to study floods in Mexico, and the GEVD which has been increasingly used in recent years but has not been applied much to maximum precipitation in Mexico. The parameters μ, σ and ε are estimated using the maximum likelihood method to take advantage of the asymptotic properties of these estimators and simplify the calculation of confidence intervals. The log-likelihood function for the GEVD and the Gumbel distribution are given by (6):

$$l(\mu,\sigma,\varepsilon;\mathbf{x}) = \begin{cases} -n\log(\sigma) - \left(\frac{1}{\varepsilon}+1\right)\sum_{i=1}^{n}\log\left[1+\varepsilon\left(\frac{x_i-\mu}{\sigma}\right)\right] \\ -\sum_{i=1}^{n}\left[1+\varepsilon\left(\frac{x_i-\mu}{\sigma}\right)\right]^{1/\varepsilon} & \text{if } \varepsilon \neq 0 \\ -n\log(\sigma) - \sum_{i=1}^{n}\exp\left[\frac{-x_i-\mu}{\sigma}\right] - \sum_{i=1}^{n}\left[\frac{-x_i-\mu}{\sigma}\right] & \text{if } \varepsilon = 0 \end{cases} \tag{6}$$

where $(\hat{\mu},\hat{\sigma},\hat{\varepsilon})$ are the maximum likelihood estimators (MLE) of (μ, σ, ε), which are calculated with the *evd* libraries and the VGAM R package. The intervals are estimated based on the fact that the MLE have an asymptotic normal distribution $\hat{\theta} \sim N_d\left(\theta, \mathbf{I}^{-1}(\hat{\theta})\right)$ where $\mathbf{I}(\hat{\theta})$ is the Fisher information matrix. Then, the confidence interval (1-α)100% for each component of θ is given by $\hat{\theta}_i \pm Z_{\alpha/2}\sqrt{c_{ii}}$, where $Z_{\alpha/2}$ is the value of the standard normal variable with a right area equal to $\alpha/2$, and c_{ii} is the i$^{\text{th}}$ element of the diagonal $\mathbf{I}^{-1}(\hat{\theta})$.

Model Selection

The model was selected primarily based on the Akaike information criterion (AIC) AIC(k) = –2log(L(θk)) + 2k, where k is the number of parameters of the model and log(L(θ_k)) is the logarithm of the likelihood of the model, taking as the preferred model the one with a lower AIC. A second criterion for models with the same number of parameters is the value of the logarithm of the likelihood (log-likelihood), choosing the model with the highest log-likelihood value. The third criterion assumes a linear relationship between the empirical and theoretical distributions, Gumbel (2) or GEVD (5), which uses the sample correlation coefficient (7) as a measure of the association and the preferred model is the one with the sample correlation coefficient closest to one:

$$r_n(\mathbf{Y},\mathbf{Z}) = \frac{\sum_{i=1}^{n}(Y_i-\bar{Y})(Z_i-\bar{Z})}{\sqrt{\sum_{i=1}^{n}(Y_i-\bar{Y})^2(Z_i-\bar{Z})^2}} \tag{7}$$

Bootstrap Test Based on the Sample Correlation Coefficient

Let $X_{1,\ldots,}X_n$ be a random sample of a distribution function $F_x(x) = P(X \leq x)$. The contrast of the hypothesis to be tested is given by:

$$H_0: f(x) \in \mathbf{F}^*(x) \quad vs. \quad H_1: f(x) \notin \mathbf{F}^*(x) \tag{8}$$

where $\mathbf{F}^*(x)$ denotes a family of specific densities, in this case the Gumbel density function and the GEVD.

The densities analyzed by this investigation are locality and scale (Gutiérrez-González, Panteleeva, & Córdoba- Lobo, 2012) when the value of the shape parameter is fixed. Thus, based on the invariance under the transformation of the locality and scale parameters, a parametric bootstrap goodness-of-fit test is proposed with the sample correlation coefficient as a statistical test. A similar test for the generalized log-gamma distribution was presented by Gutiérrez-González, Villaseñor-Alva, Panteleeva and Vaquera-Huerta (2013).

If H_0 in (8) is true, then the distribution of $f(x)$ is such that $F(x;\mu,\sigma,\varepsilon)=F_*\left(\frac{x-\mu}{\sigma};\varepsilon\right)$. Then, for a random variable X with a density function $f(x)$, the function $F_*(x;\varepsilon)$ corresponds with the inverse function $F_*^{-1}(y;\varepsilon)$ at y.

Let $X_{(1)},\ldots, X_{(n)}$ be the order statistics of a random variable, then the corresponding empirical distribution function is given by:

$$F_n(x)=\begin{cases} 0 & \text{if} \quad x<x_{(1)} \\ \dfrac{i+0.5}{n_1} & \text{if} \quad x_{(i)}\le x<x_{(i+1)} \\ 1 & \text{if} \quad x>x_{(n)} \end{cases}$$

where $x_{(i)}$ is the value of the ith order statistic.

Based on the Glivenko-Cantelli theorem, a nearly certain convergence is established between the empirical distribution $F_n(x)$ and the theoretical distribution as $n\to\infty$, which can be $F(x)$ or $G(x)$. Therefore, the following can be established for the GEVD:

$$G_n(x)\approx G(x)\Rightarrow\frac{1}{\varepsilon}\left[-\log\left[G_n(x)\right]\right]^{-\varepsilon}-\frac{1}{\varepsilon}\approx\frac{1}{\sigma}x-\frac{\mu}{\sigma}$$

Similarly, for the Gumbel distribution we have:

$$F_n(x)\approx F(x)\Rightarrow\log\left\{-\log\left[F_n(x)\right]\right\}\approx-\left(\frac{x-\mu}{\sigma}\right)$$

Both expressions can be rewritten as $Y=\beta+\alpha Z$ and given H_0, a strong linear relation is expected between Y and Z when substituting parameter ε with a consistent estimator $(\hat{\varepsilon})$. Then, to test the contrast of the hypothesis (8), the sample correlation coefficient given in (7) is proposed as the test statistic where, given H_0, the distribution of $r_n(\mathbf{Y},\mathbf{Z})$ is expected to be concentrated around 1. Therefore, the decision rule for a test of size α, with a known value $\alpha\in(0,1)$ consists of rejecting H_0 when $r_n(\mathbf{Y},\mathbf{Z})<r_\alpha$.

The bootstrap test based on the MLE is performed using the next steps:

1. Given the observations $x_1,\ldots x_n$, a value of the estimator ε is calculated, denoted as $\tilde{\varepsilon}_0$.
2. With the observations, the sample correlation coefficient r_0 is calculated.
3. The bootstrap cycle is initiated beginning with $\tilde{\varepsilon}_0$.
   a) A bootstrap sample is generated, of size n, of the GEVD or the Gumbel distribution, as applicable.
   b) Based on the sample from step 3a), the shape parameter is estimated, denoted by $\tilde{\varepsilon}_1$.
   c) Based on $\tilde{\varepsilon}_1$ from step 3b), the sample correlation coefficient $\hat{r}_1$ is calculated.
4. The bootstrap cycle from step 3 is repeated m times to calculate $\hat{r}_1,\ldots,\hat{r}_m$, in which m is the number of bootstrap estimations to determine the bootstrap quantile.
5. With the completed cycle, $\hat{r}_1,\ldots,\hat{r}_m$ are put in non-decreasing order, denoted by $\hat{r}_i$. Then $\hat{r}_1\le\hat{r}_2\le\cdots\le\hat{r}_m$ and the quantile α is obtained, which is $\hat{r}_\alpha$.
6. The decision rule. Compare r_0 with quantile α from step 5.
   a) If $r_0\le\hat{r}_\alpha$, reject H_0 at a significance level α.
   b) If $r_0>\hat{r}_\alpha$, do not reject H_0 at a significance level α.

Before beginning the tests, it is determined whether these conserve the nominal size of the test and if their powers are good.

Table 1 presents the results from the sizes of the tests for both distributions, with 10 000 replications. It can be concluded that the bootstrap test conserves the nominal size of the test of the Gumbel and GEVD distributions.

Table 1. Sizes of the tests for the GEVD and the Gumbel Distribution.

	GEVD wit ε = 0.1					GEVD wit ε = 0.5					Gumbel Distribution				
n	0.010	0.025	0.050	0.075	0.100	0.010	0.025	0.050	0.075	0.100	0.010	0.025	0.050	0.075	0.100
30	0.012	0.026	0.040	0.060	0.086	0.004	0.011	0.039	0.059	0.084	0.008	0.023	0.039	0.060	0.082
50	0.008	0.016	0.030	0.046	0.064	0.004	0.012	0.038	0.063	0.095	0.010	0.030	0.055	0.080	0.100
75	0.002	0.010	0.020	0.036	0.050	0.006	0.018	0.038	0.058	0.086	0.012	0.021	0.043	0.069	0.097
100	0.004	0.016	0.026	0.046	0.062	0.006	0.018	0.041	0.059	0.085	0.010	0.018	0.046	0.078	0.100
150	0.004	0.010	0.044	0.058	0.070	0.007	0.020	0.046	0.069	0.096	0.011	0.029	0.053	0.077	0.104

In terms of the power of the test, three different distributions were used: standard normal, Student-*t* with 4 gl and Cauchy (0.2). The results with 10 000 replications are shown in Table 2.

Return Periods

To analyze the hazard factor, it is of interest to know the average waiting time for the occurrence of extreme rainfall that can cause a flooding problem. The return period is the mean time in which a similar event is repeated. Then, let $X_1, X_2, \ldots$ be a successions of random *iid* variables with a continuous distribution function F and $\mu \in \mathbb{R}$. Where $\{X_i > u\}$ is an extreme event, the time of the first exceedance is defined as $T(u) = \min\{i \geq 1 : Xi > u\}$. With this, the average waiting time for the occurrence of an extreme event is $E[T(u)]$.

Table 2. Power corresponding to the test of the GEVD.

n	α	Alternative		
		Normal (0.1)	*Student-t* (4)	Cauchy (0.2)
30	0.010	0.376	0.398	0.658
	0.050	0.662	0.610	0.824
	0.075	0.734	0.660	0.862
	0.100	0.774	0.704	0.882
50	0.010	0.534	0.396	0.884
	0.050	0.850	0.704	0.964
	0.075	0.900	0.782	0.976
	0.100	0.924	0.814	0.981
75	0.010	0.536	0.420	0.960
	0.050	0.930	0.790	0.996
	0.075	0.956	0.856	0.998
	0.100	0.964	0.892	1.000
100	0.010	0.552	0.604	1.000
	0.050	0.976	0.862	1.000
	0.075	0.992	0.894	1.000
	0.100	0.992	0.930	1.000
150	0.010	0.574	0.781	1.000
	0.050	0.994	0.966	1.000
	0.075	0.998	0.987	1.000
	0.100	1.000	0.992	1.000

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If the probability of the event $\{X * i > u\}$ is p, its return period is p^{-1}. Then, using the accumulated probability distribution, the return period for event $\{X_i > u\}$ is calculated with (9):

$$\tau_x = \frac{1}{1-F(x)} \quad (9)$$

Specifically, the return level associated with return period p^{-1} is the $(1 - p)^{th}$ quantile of the distribution. In the case of the Gumbel distribution and the GEVD, the $1 - p$ quantile is given in (10):

$$x_p = \begin{cases} \mu - \frac{\sigma}{\varepsilon}\left[1-\{\log(1-p)\}^{-\varepsilon}\right] & \text{if } \varepsilon \neq 0 \\ \mu + \sigma\left[-\log\{-\log(1-p)\}\right] & \text{if } \varepsilon = 0 \end{cases} \quad (10)$$

The quantiles are calculated based on the estimations of the parameters.

Results and Discussion

The risk index was calculated using formula (1). For the vulnerability and cost factors, two indicators were constructed, which were based on the availability of services, the goods that the population possesses and the number of inhabitants per municipality. The information was taken from the INEGI database corresponding to the 2010 Population and Housing Census.

Vulnerability Index

Vulnerability is composed of two factors: social and natural. The social factor refers to the services indicator (Ind_{serv}) which was obtained from a linear combination of the three variables PO_WOE, PO_WOPW and the PO_WOD. The linear combination was weighted according to the PC. The covariance matrix was calculated with the information from those three variables, and from that the values of each one of the variables were obtained, resulting in 290.367, 6.808 and 1.228, respectively. The values themselves were then weighted to obtain the weights of each one of the three variables. Table 3 shows the results corresponding to the Ind_{serv}.

The use of the river indicator was proposed (Ind_{riv}) as the natural factor, which takes into account the main hydrological resources in each municipality. This indicator was constructed by weighting the number of rivers in a municipality and the capacity of each one, measured by the normal maximum water level. The results of the Ind_{riv} are shown in Table 3.

Lastly, both Ind_{serv} and Ind_{riv} were weighted to obtain the vulnerability indicator (Ind_{vuln}). These results are shown in Table 3.

Cost Index

Two variables are of interest when analyzing the cost factor. First, there is the logarithm for the number of inhabitants in each municipality, which is primarily based on the supposition that the larger the population the greater the wealth. The logarithm of the population ($\log_{pop}$) is used only to maintain the most suitable scale. These results are shown in Table 4.

The second variable is an indicator of the goods (Ind_{goods}) possessed by the population in the municipality under study. The generation of this indicator included five goods that would be exposed to some degree of damage in the event of a flood: televisions (POWT), refrigerators (POWR), washing machines (POWM), computers (POWC) and vehicles (cars or trucks, POWV). The calculation of the indicator of goods took into account the percentage of the population that possessed one of these.

To obtain a suitable linear combination of these five variables, a PC analysis was per-

Table 3. Vulnerability Index.

No.	Municipalities	Ind_{serv}	$Ind_{ríos}$	Ind_{vuln}	Category
1	Balancán	0.282	0.128	0.221	Medium
2	Cárdenas	0.403	0.785	0.556	Very high
3	Centla	1.000	0.161	0.664	Very high
4	Centro	0.000	0.957	0.526	Very high
5	Comalcalco	0.242	0.552	0.366	High
6	Cunduacán	0.531	0.785	0.632	Very high
7	E. Zapata	0.001	0.161	0.065	Low
8	Huimanguillo	0.810	0.101	0.526	Very high
9	Jalapa	0.123	0.827	0.405	High
10	Jalpa	0.166	0.684	0.373	High
11	Jonuta	0.123	0.161	0.138	Low
12	Macuspana	0.496	0.665	0.564	Very high
13	Nacajuca	0.016	0.392	0.166	Low
14	Paraíso	0.112	1.000	0.467	High
15	Tacotalpa	0.367	0.000	0.220	Medium
16	Teapa	0.166	0.060	0.124	Low
17	Tenosique	0.256	0.161	0.218	Low

Table 4. Cost Index.

No.	Municipalities	log_{pop}	Ind_{goods}	Ind_{cost}
1	Balancán	4.754	0.274	2.514
2	Cárdenas	5.395	0.514	2.955
3	Centla	5.009	0.238	2.624
4	Centro	5.806	1.000	3.403
5	Comalcalco	5.285	0.447	2.866
6	Cunduacán	5.102	0.412	2.757
7	E. Zapata	4.470	0.672	2.571
8	Huimanguillo	5.254	0.286	2.770
9	Jalapa	4.561	0.593	2.577
10	Jalpa	4.921	0.546	2.734
11	Jonuta	4.470	0.156	2.313
12	Macuspana	5.185	0.428	2.806
13	Nacajuca	5.061	0.742	2.901
14	Paraíso	4.938	0.702	2.820
15	Tacotalpa	4.666	0.000	2.333
16	Teapa	4.729	0.400	2.564
17	Tenosique	4.771	0.421	2.596

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formed to produce the appropriate weights of each variable. Similar to the case of services, a covariance matrix was generated and the values themselves were calculated for the five variables mentioned above, resulting in 243.062, 17.619, 5.178, 3.471 and 1.405, respectively. The weights of each of the five variables were obtained by weighting based on the values themselves. The results are shown in Table 4.

Lastly, to obtain the cost indicator (Ind_{cost}) the $\log_{pop}$ and Ind_{goods} factors that influence this indicator were weighted. It is worth mentioning that there is no pertinent reason to give more weight to a particular factor, therefore the same weight (0.5) was applied to both. The results are shown in Table 4.

Hazards Factor

Obtainment of Information

To calculate the hazard indices, rainfall information was obtained from the measurements between 1961 and 2000 contained in the National Weather Service database (managed with *CLICOM*), using the interpolated version with a standard grid of 0.2 degrees longitude by 0.2 degrees latitude (called *Maya* v. 1.0). The information was obtained from over 5 000 weather stations contained in the database. The most recent information (2001-2007) came from daily measurements of a subset of weather stations that reported in practically real-time. These data were obtained based on their longitude and latitude.

The data used correspond to pluvial precipitation and have a node-by-node presentation. There is a list of 4 542 text files, each one of which corresponds to one node and contains a series of pluvial precipitation data from January 1961 to December 2000. In addition to this information, precipitation from 2001 to 2007 at the stations in Mexico was known. There is a file for each year, each one with the following fields: latitude, longitude, code and name of the station, elevation, month and days. The stations around the node were also included in order to take advantage of the extra information. For each node in the analysis, a maximum precipitation value was calculated from 2001 to 2007 and the precipitation corresponding to the node of interest was obtained.

The nodes of interest are those that influence each municipality. To this end, the location of the basins in the state of Tabasco were identified. Most of the area of the state (75.22%) is located in Hydrographic Region 30, or the Grijalva-Usumacinta Region System, composed of the Grijalva and Usumacinta hydrographic basins and those of the Términos Lagoon, which occupy 41.45, 29.24 and 4.53% of the state of Tabasco, respectively. The remaining 24.78% of the state is located in Hydrographic Region 29, or the Coatzacoalcos Region. This region is composed of two basins —Coatzacoalcos (Tonalá) and the Carmen lagoons and the Machona basin, the latter being the only one inside the state. Both regions are considered to be the rainiest in the country, in first and second place, respectively.

With the information known about the vulnerability and cost, the work then proceeds by municipality. To obtain rainfall data for each municipality, information from the sub-basins that are part of each one is used, whether completely or partially located therein, taking into account those with flows that affect the municipality under study.

Analysis of Information

The analysis of the data requires a series of observations for each municipality, where in this case there is the same number of series as there are number of nodes involved. Then, to obtain a single series, a linear combination was performed of the nodes that entered each

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municipality, until finding one that was suitable. To obtain the best linear combination, a PC was used with the nodes in each municipality, which provided the final precipitation data series for the municipality of interest.

For the hazards factor, the annual maximums were extracted from the precipitation data and fitted to a Gumbel distribution and a GEVD. Point and interval estimations were performed with both. The three criteria mentioned previously in the earlier section were taken into account and the model having two or more criteria favorable to modeling the municipality of interest was chosen.

Tables 5 and 6 show the results from these estimations and Figure 1 presents the graphs corresponding to the municipality of Balancan, Tabasco. The same estimation was performed with the remaining 16 municipalities. Table 7 shows four municipalities as examples of the models chosen.

After obtaining the models of the 17 municipalities, their respective return periods were calculated. Table 8 presents the results for four hazard scenarios: 100, 150, 200 and 250 mm. For example, for Balancan the average time for a rainfall equal to or over 150 mm to occur is 3.5 years.

Finally, the Flood Risk Index was constructed with the results from the three factors. For the hazard factor, the probability p of the event $\{X_i > x\}$ was used, where $x = 150$

Table 5. Estimation of parameters.

Estimation of parameters, Balancan						
Distribution	**Scale**	**Shape**	**Locality**	**Log-likelihood**	**AIC**	**Correlation**
GEV	27.840	0.129	117.294	-234.053	474.106	0.974
Gumbel	29.368	.	119.298	-234.831	473.662	0.972

Table 6. Confidence Intervals.

CI	GEV	Gumbel
Scale	(21.002, 34.678)	(27.172, 31.564)
Shape	(-0.092, 0.351)	.
Locality	(108.315, 126.274)	(110.456, 128.139)

Table 7. Models chosen per municipality.

Municipality	Model chosen
Balancán	$F(x) = \exp\left\{-\left[1+0.129\left(\frac{x-117.294}{27.84}\right)\right]^{-\frac{1}{0.129}}\right\}$
Centro	$G(x) = \exp\left\{-\exp\left[-\left(\frac{x-142.057}{30.375}\right)\right]\right\}$
Huimanguillo	$G(x) = \exp\left\{-\exp\left[-\left(\frac{x-163.261}{53.403}\right)\right]\right\}$
Tenosique	$F(x) = \exp\left\{-\left[1+0.282\left(\frac{x-91.188}{29.447}\right)\right]^{-\frac{1}{0.282}}\right\}$

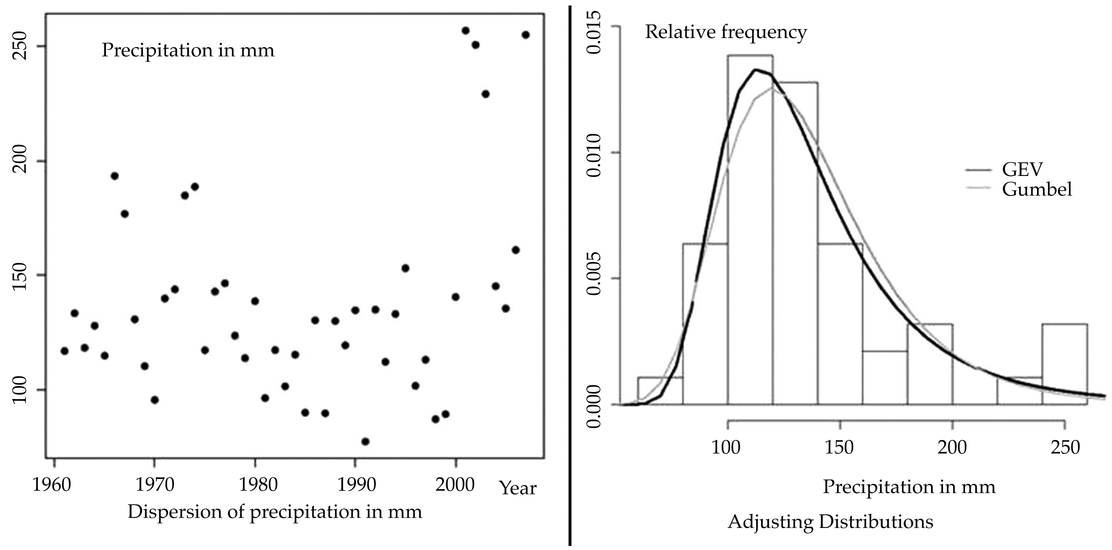

Figure 1. Graph of the estimation for the Balancan municipality.

Table 8. Return periods per municipality.

Municipality	Return period			
	100 mm	150 mm	200 mm	250 mm
Balancán	1.174	3.513	12.860	41.492
Cárdenas	1.206	3.370	14.765	72.082
Centla	1.094	2.674	8.852	27.072
Centro	1.019	1.862	7.249	35.443
Comalcalco	1.437	4.150	13.180	38.315
Cunduacán	1.241	2.954	10.099	38.515
E. Zapata	1.038	2.077	6.397	19.303
Huimanguillo	1.035	1.359	2.460	5.405
Jalapa	1.018	1.745	6.122	27.262
Jalpa	1.109	2.328	7.870	30.891
Jonuta	1.112	3.104	11.265	36.163
Macuspana	1.205	3.364	12.205	41.889
Nacajuca	1.112	2.303	7.594	29.071
Paraíso	1.049	2.843	16.789	115.446
Tacotalpa	1.065	1.410	2.518	5.785
Teapa	1.054	1.434	2.623	5.702
Tenosique	1.295	2.191	13.073	27.014

mm, since experience suggests that flooding problems have occurred as of this value. These results are shown in Table 9 and Figure 2 presents the flood risk map.

Discussion of Results

The bootstrap goodness-of-fit test proposed conserved the nominal values of the size of

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Table 9. Proposed Flood Risk Index.

No.	Municipalities	*C*	*V*	P150	RI	Category
1	Balancán	2.514	0.221	0.285	0.158	Low
2	Cárdenas	2.955	0.556	0.290	0.487	Medium
3	Centla	2.624	0.664	0.374	0.652	High
4	Centro	3.403	0.526	0.345	0.962	Very high
5	Comalcalco	2.866	0.366	0.241	0.253	Medium
6	Cunduacán	2.757	0.632	0.316	0.590	High
7	E. Zapata	2.571	0.065	0.481	0.080	Low
8	Huimanguillo	2.770	0.526	0.718	1.000	Very high
9	Jalapa	2.577	0.405	0.555	0.580	High
10	Jalpa	2.734	0.373	0.421	0.438	Medium
11	Jonuta	2.313	0.138	0.322	0.103	Low
12	Macuspana	2.806	0.564	0.297	0.470	Medium
13	Nacajuca	2.901	0.166	0.425	0.210	Low
14	Paraíso	2.820	0.467	0.241	0.463	Medium
15	Tacotalpa	2.333	0.220	0.682	0.364	Medium
16	Teapa	2.564	0.124	0.680	0.221	Low
17	Tenosique	2.596	0.218	0.481	0.258	Medium

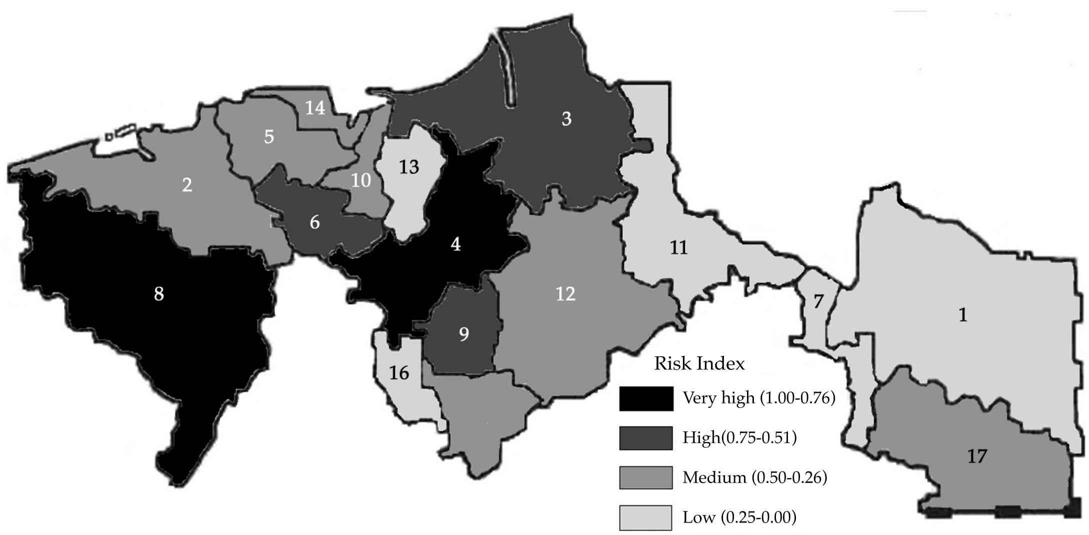

Figure 2. Proposed Risk Index Map.

the test and the powers remained quite high, which makes it a better test for the GEVD than that by Campos-Aranda (2001). Only historical values were included in previous investigations of rainfall (González-Camacho, Pérez-Rodríguez, & Ruelle, 2011), (Coronel-Brizio & Llanos-Arias, 1996; Díaz-Delgado, Bâ, & Trujillo-Flores, 1999). Likewise, in terms of vulnerability there are works that are related with this factor (Green et al., 1994)

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and the same is true for residential coastal zones (Baró-Suárez, Díaz-Delgado, Calderón-Aragón, Esteller-Alberich, & Cadena- Vargas, 2011). In the investigation of flood risks, the index proposed is based on a PCA and includes all the variables for which there was information, grouped into the three factors mentioned (Ordaz, 1996). This is a more reliable method to monitor flood risks in the 17 municipalities in the state of Tabasco.

Conclusions

The risk map obtained was compared to historical results related to disasters from floods in the 17 municipalities in Tabasco. The results obtained were in agreement with the floods recorded in the years 1982, 1989, 1995, 1998, 2002, 2003, and from 2005 to 2009. Table 10 shows the comparison between the proposed risk index (PRI) and the historical (HI) flood records from the years mentioned.

Some municipalities were not in agreement, which may be due to not having found records from all the municipalities that had problems with flooding or not having considered other factors that could increase the degree of vulnerability or the cost.

Lastly, it can be concluded that, in general, the factors included in the construction of the index were correct, as was the use of the principal components to obtain the appropriate weights of each one of the factors considered.

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Table 10. Comparison of proposed risk index with historical records..

Mun.	**Balancán**	**Cárdenas**	**Centla**	**Centro**	**Comalcalco**	**Cunduacán**	**E. Zapata**	**Huimanguillo**	**Jalapa**
HI	Low	High	High	Very high	High	High	Low	High	High
PRI	Low	Medium	High	High	Medium	High	Low	Very high	High
Mun.	**Jalpa**	**Jonuta**	**Macuspana**	**Nacajuca**	**Paraíso**	**Tacotalpa**	**Teapa**	**Tenosique**	
HI	Medium	Low	Medium	Medium	Medium	Low	Low	Medium	
PRI	Medium	Low	Medium	Low	Medium	Medium	Low	Medium	

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Relation between the Parameters of the Kostiakov and Lewis-Kostiakov Infiltration Models, Cordoba, Argentina

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Abstract

Weber, J. F., & Apestegui, L. (March-April, 2016). Relation between the Parameters of the Kostiakov and Lewis-Kostiakov Infiltration Models, Cordoba, Argentina. *Water Technology and Sciences* (in Spanish), 7(2), 115-132.

Certain relationships between the parameters of the Lewis-Kostiakov infiltration model were found, calibrated based on the results obtained from a field measurement campaign in the city of Cordoba, Argentina. A portable rainfall micro-simulator was used as an instrument, designed and built by this workgroup as a better alternative to the double-ring infiltrometer. This equipment, which can be completely disassembled, defines a 1 m^2 test plot, making it possible to generate rainfall intensities between 65 and 120 mm/h. The test sites were selected based on soil type and use. Different initial moisture conditions were considered. The measuring campaign was conducted over six months with between two and three tests per week. The values measured were digitalized and processed and accumulated infiltration curves and infiltration rates over time were generated. Based on these values, the parameters of the Kostiakov and the Lewis-Kostiakov (Mecenzev) infiltration models were fitted, which in themselves represent an original contribution to knowledge about the urban hydrology in this city. The graphing of the different relationships between the parameters indicated the existence of an empirical function which would enable reducing the number of parameters of the Mecenzev model to two, with an acceptable loss in the quality of the predictions. This relationship will improve the selection of infiltration parameters for the design of the urban hydrology in Cordoba, Argentina.

Keywords: Rainfall simulator, hydrologic measures, urban hydrology, Lewis-Kostiakov model, infiltration.

Resumen

Weber, J. F., & Apestegui, L. (marzo-abril, 2016). Relaciones entre parámetros de los modelos de infiltración de Kostiakov y Lewis-Kostiakov - Córdoba, Argentina. Tecnología y Ciencias del Agua, *7(2), 115-132.*

Se presentan ciertas relaciones halladas entre los parámetros del modelo de infiltración de Lewis-Kostiakov, calibrados a partir de los resultados obtenidos en una campaña de medición in situ en la ciudad de Córdoba, Argentina. Como instrumento se utilizó un microsimulador de lluvia portátil diseñado y construido por este grupo de trabajo, como alternativa superadora al infiltrómetro de doble anillo. Este equipo, que es completamente desarmable y define una parcela de ensayo de 1 m^2, permite generar lluvias de intensidades comprendidas entre los 65 y 120 mm/h. La selección de los sitios de ensayo respondió al tipo y uso del suelo. A su vez, se consideraron distintas condiciones de humedad inicial. La campaña de medición se extendió durante siete meses, realizando entre dos y tres ensayos por semana. Los valores medidos fueron digitalizados y procesados, construyéndose las curvas de infiltración acumulada y tasa de infiltración en función del tiempo. A partir de estos valores, se ajustaron los parámetros del modelo de infiltración de Kostiakov y de Lewis-Kostiakov (Mecenzev), que en sí mismos representan un aporte original al conocimiento de la hidrología urbana en esta ciudad. Al graficar diversas relaciones entre parámetros, se evidencia la existencia de una función empírica, que permitiría disminuir a dos el número de parámetros del modelo de Mecenzev, con una aceptable pérdida de calidad en las predicciones. Se considera que esta relación permitirá mejorar la elección de parámetros de infiltración en tareas de diseño hidrológico urbano en Córdoba, Argentina.

***Palabras clave**: simulador de lluvia, mediciones hidrológicas, hidrología urbana, modelo de Lewis-Kostiakov, infiltración.*

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Introduction

For engineering works involving the design and calculation of urban rainwater drainage systems, the project manager must consider two types of surfaces which are present in basins in order to quantify supply flows —impermeable and permeable. Impermeable surfaces undoubtedly have a large effect on flood volumes and decrease a basin's response time (Tucci, 2001). In terms of permeable surfaces, several different formulations can be used to quantify the fraction of precipitation that is direct runoff and the fraction infiltrated. These include the Rational Method (Chow, Maidment, & Mays, 1994), the method known as CN-SCS (SCS, 1972) which has been widely used through its application with popular HEC-1 computer programs (USACE, 1981) and the most recent HEC-HMS (USACE, 2001), and the Horton method (1939) used in the field of hydrological computing with a model called SWMM (among others) (USEPA, 1977). As with many other conceptual models of the infiltration process (Ravi & Williams, 1998), these attempt to simplify the rigorous approach to solving the Richards equations (Chow *et al*., 1994) and thus are more widely used in the practice of hydrology.

One of the primary difficulties with modeling when applying these infiltration models is the estimation of their parameters in order to obtain an adequate representation of reality. Unfortunately, it is very difficult to obtain infiltration data measurements for permeable urban areas in Argentina. For example, systematic work has recently begun in the city of Cordoba to produce experimental information related to infiltration based on work by Weber, Urbano, Stuyck, Azelart and Martínez (2005), by the Hydrualic Laboratory (LH-UTN, Spanish acronym) of the Civil Engineering School of the National Technological University. This work involves a campaign to obtain experimental infiltration data from soil in the city of Cordoba using a double-ring infiltrometer technique. This test procedure, also known as the Muntz method (Custodio & Llamas, 1976), can be used to obtain direct infiltration measurements in small areas (point measurements). Determining measurements in this way is known to have serious limitations, particularly with respect to the test's lack of representativeness of the rainfall process, on the one hand, and the large alteration of the land surface due to the sinking of the rings, on the other. These limitations produce experimental errors that are difficult to quantify.

In order obtain an experimental characterization that more closely resembles the hydrological infiltration process, the use of a portable rainfall simulator developed by the LH-UTN was proposed as a test instrument. The immediate benefits expected are improved simulation of the rainfall-infiltration process and less alteration of the test plot. That is, it attempts to compensate for the limitations of the double-ring infiltrometer used previously.

Objectives

The overall objective of this line of work is to characterize infiltration processes in permeable areas in the city of Cordoba, Argentina.

In particular, as a specific objective this work proposes the determination of the parameters of the Kostiakov and Lewis-Kostiakov models (Mecenzev) (Ravi & Williams, 1998) for these areas, taking into account characteristics such as land use and type of soil and based on experimental observations obtained from a rainfall simulator. It is also aimed at exploring possible relationships between these values in order to reduce the number of parameters, thereby making their selection easier for work related to urban hydrological design. It is worth mentioning that the work group has determined the

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parameters of other infiltration models with these same experimental data, including Horton (Weber, 2014a), Green-Ampt (Weber & Apestegui, 2013), Philip (Weber, 2015a) and CN-SCS (Weber, 2014b), which are not part of the scope of this present study.

Methodology

Rainfall Simulator Device

The general characteristics of the equipment used to conduct the measuring campaign are described next (Weber, Paoli, & Apestegui, 2009, 2010).

The advantage of the rainfall micro-simulator is its ability to more accurately reproduce precipitation. Many authors ((Marelli, 1989) have demonstrated the importance of how drops on the top micro-layer of soil affect the water balance, as well as their obvious effect on surface erosion. Meanwhile, this type of device makes it possible to simulate precipitation with intensities that vary over time, and even discontinuous precipitation. In response to the need to reproduce the effects of precipitation under controlled conditions, different mechanisms and instruments have been developed over the years to simulate natural rainfall, and particularly the impact of raindrops on the physical properties of the soil's surface and its consequences on infiltration, runoff and erosion (Pla-Sentis, 1981; Rostagno & Garayzar, 1995). The largest of these problems is reproducing drops that resemble natural rainfall.

The drop generator is composed of a 2-inch long hypodermic needle with a 0.8 mm internal diameter which is placed inside a rigid tube by cutting it at the edge of the needle. It was decided to include a total of 289 drop generators distributed in 17 rows by 17 columns and separated by a distance of 5.30 cm between the axes. Each drop generator thereby covers an area of approximately 28.10 cm^2 above the base of a tray measuring 96 x 96 cm per side.

The equipment (Figure 1) basically consists of metal steel piping structure with a square section, forming a square prism 2 m high x 1 m per side. This prism is created by four columns and enclosed with a windbreaker curtain. The columns support the water feed system which is composed of two tanks —one only to feed the water and the other to feed the water and also regulate its intensity with a floater (Achutegui, Abreu, & Páez, 1996). A tray containing the 298 drop generators which produce the simulated rainfall is located under the water feed system. The base of this prism is composed of a square iron frame measuring 1 m per side and 0.10 m high, with drains at the four sides and tubes to transport the water runoff. This frame is pounded into the ground and walls off the boundaries of

Figure 1. Rainfall simulator in the field.

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the measurement plot. The total weight of the assembled equipment is 110.6 kg and the fluid can weigh up to 100 kg.

This equipment has an empirical calibration curve (which was determined through an experimental process in this laboratory) which determines the relationship between the available hydraulic head at the end of the needles that generate the drops and the intensity of the rainfall generated. The regression equation between these two variables, with a coefficient of determination of $R^2 = 0.997$ is:

$$i = 15.15\, h^{0.63} \tag{1}$$

In this equation, i is the intensity of the rainfall produced (in mm/h) and h is the head (in cm) on the generators. Figure 2 graphically presents the relation obtained.

From the statistical analysis of the calibration data, it can be concluded that the intensity values obtained with equation (1) have an uncertainty of 3 mm/h, which reflect an error in the intensity produced of 3 to 5%.

Site Selection

As in previous works (Weber *et al*., 2005), the test sites were determined based on the two variables with the most *a priori* influence on the results to be obtained —the type of soil and land. With respect to type, rather than a geotechnical classification, regional characteristics were considered to provide the most representative hydrological results. To this end, the classification of geomorphological environments developed by Quintana-Salvat and Barbeito (1994) was used as the criterion. This work detected primarily two different environments in the area of the city of Cordoba. One is a loess plains with sandy silt soil, good cohesion and low moisture levels. The other is a flood terrace from the old Suquía River channel (first) which was classified by the authors cited as having three sub-environments —lower, medium and upper— according to their nearness to the current river channel that runs through the city.

In terms of land use, three basic types were differentiated: patios and gardens in

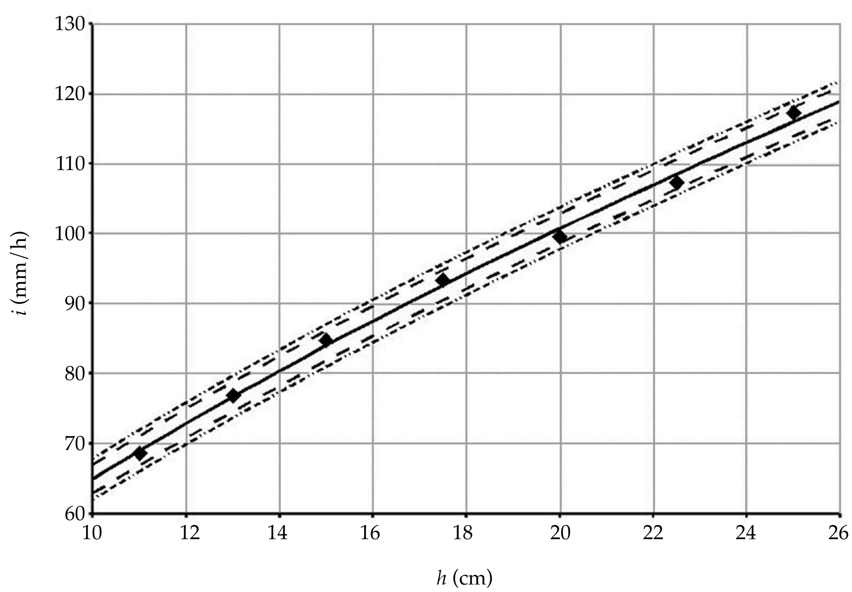

Figure 2. Calibration Curve of the Rainfall Simulator.

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residential housing (green areas with little traffic); plazas, parks and public walkways (green areas with medium traffic); and unpaved roads (dirt streets). The primary selection criterion was based on the intensity of both pedestrian and vehicular traffic due to their direct impact on the infiltration capacity of the soil. In addition, the bed of a retention lagoon in the northern part of the city was added as a particular point of interest.

Figure 3 shows the geomorphological layout of the city of Cordoba and the sites selected (classified according to land use) as well as the different geomorphological environments described (Weber, Apestegui, & Baldazar, 2011). The study region's broad geography can be seen. Table 1 shows the test sites selected according to land use and the geomorphological environment. As can be seen, it was not possible to access land to test low-traffic green spaces in the middle Suquía River terrace because this environment covers a relatively small and highly urbanized region of the city. A total of 12 sites throughout the urban area of the city were tested.

Application of the Rainfall Simulator

Three tests were performed at each of the sites selected using the rainfall simulator with relatively constant low intensities (on the order of 70 mm/h) and different initial moisture conditions from the prevailing weather conditions or from having previously watered the land under dry conditions. In addition, the classical infiltration test with a double-ring infiltrometer was performed simultaneously at the majority of the sites, as a control and to compare measurements. The measurement campaign lasted for seven months and involved the simultaneous work

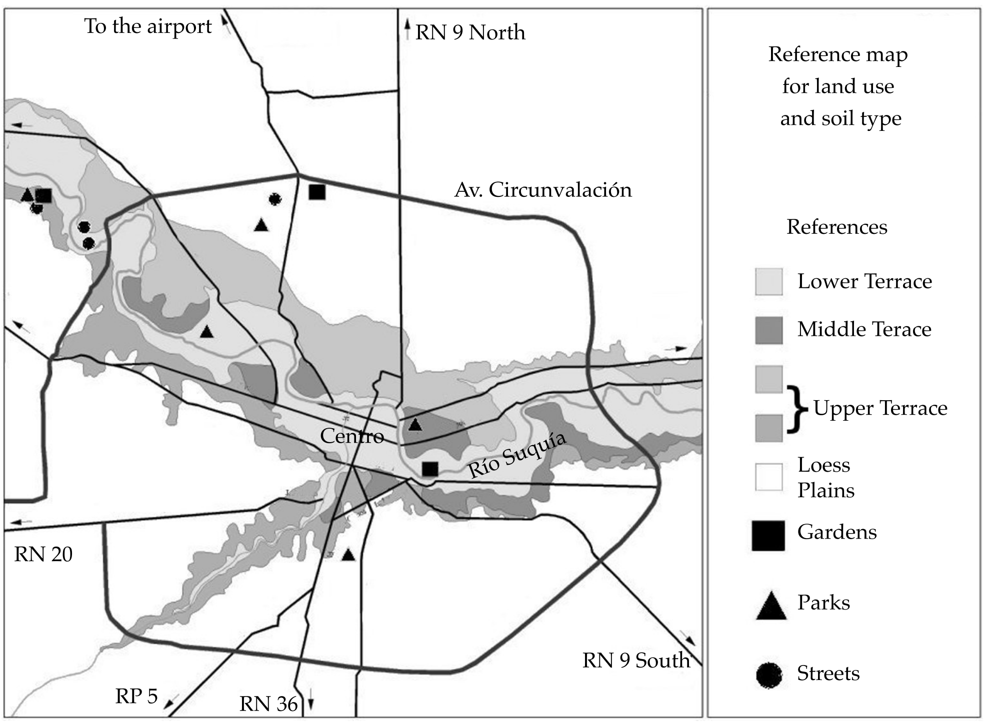

Figure 3. Location of the test sites.

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Table 1. Test Sites.

Type of soil (geomorphological environment)	Land use		
	Green Spaces (low traffic)	**Green Spaces (Medium Traffic)**	**Unpaved Streets (High Traffic)**
Upper Terrace	ITS Villada	ITS Villada	ITS Villada
Middle Terrace	------	General Paz Park	Justo Liebig 5940-Bº Villa Belgrano
Lower Terrace	Torres de Bº Junior	Park of the Nations	Carlos Gauss 4619-Bº Villa Belgrano
Loess Plains	L. Suárez de Figueroa-Bº M. de Sobremonte	UTN Park Retention Lagoon	Hugo Miatello 4600-Bº Poeta Lugones

of three people who performed two to three tests per week.

The tests generally lasted between 1.5 and 2 h, depending on the infiltration behavior observed *in situ*, in terms of the speed at which the regime condition was reached. The number and frequency of the observations also depended on local conditions. Simulator measurements were taken less frequently than infiltrometer measurements for soils with a higher infiltration capacity. To facilitate taking the measurements, a measurement volume ranging from 50 to 500 cm^3 was selected for each case.

Laboratory Determination of Moisture Contents

Before beginning each test, soil samples were extracted to determine the antecedent moisture content. This was performed gravimetrically by extracting soil samples from a depth of 10 cm, drying them at 100°C in a stove and then weighing the dried samples. The gravimetric moisture ω was determined based on expression (2):

$$\omega = \frac{m_a}{m_s} \tag{2}$$

where m_a is the water mass in the soil sample resulting from the differences between the mass of the moist sample minus the mass of the dry sample and m_s is the mass of the dry sample. Expression (3) was used for the relationship between the gravimetric moisture ω (primarily used in geotechnics) and the volumetric moisture θ (more often used for underground hydrology):

$$\theta = \omega \frac{d_a}{d_s} \tag{3}$$

In this expression, d_a is the water density (assuming 1 g/cm^3) and d_s is the density (unit weight) of the soil. This value was estimated based on *in situ* observations performed previously at each of the geomorphological environments described (Weber *et al*., 2005).

Digitalization and Data Processing

The data obtained in the field were digitalized and processed using a calculation spreadsheet and then exported in plain text format to process the codes developed specifically for this work. It is important to note that the processing also involves the sum of the partial runoff over time at each one of the collector reservoirs in order to obtain a single record of surface runoff per test. In terms of the amount of experimental information generated, 34 tests were performed which produced 6 259 pairs of time-infiltration values (an average of 184 observations per test).

Theoretical Framework

Kostiakov Model

Kostiakov proposed the following empirical equations in 1932 (Ravi & Williams, 1998) to estimate the infiltration rate and accumulated infiltration:

$$F(t) = Kt^a \quad (4)$$

$$f(t) = Kat^{a-1} \quad (5)$$

where K and a are the parameters of the model, which meet the restrictions $K > 0$ and $0 < a < 1$. It is important to note that equation (5) tends toward 0 as t approaches infinity, and therefore the model usually does not provide good results for extended periods of time. In addition, with the restrictions mentioned, expression (5) is indeterminate for $t = 0$, that is, the initial infiltration rate cannot be defined.

Modifications of the Kostiakov Model

Considering what was mentioned above, different modifications of the Kostiakov have been proposed, particularly the modified Kostiakov method (Al-Azawi, 1985) and the Lewis-Kostiakov method (Ahuja, Kozak, Andales, & Ma, 2007) or the Mecenzev (Ravi & Williams, 1998) method, which includes the base infiltration rate f_b as an additional parameter:

$$F(t) = f_b t + Kt^a \quad (6)$$

$$f(t) = f_b + Kat^{a-1} \quad (7)$$

In this formulation, the infiltration rate tends towards the base rate f_b as t approaches infinity. Meanwhile the value of $f(0)$ continues to be undefined, which could be significant to the representation of processes having very short durations and low intensities, which generally do not have a practical application in the design of urban hydrology.

Other models

Other authors have presented improved versions of the model mentioned. Clemens (1981, cited by Ahuja *et al*., 2007) discusses an improvement of the Lewis-Kostiakov model by introducing a step function without increasing the number of parameters of the model. This has been shown to substantially improve the long-term prediction of infiltration capacity.

Analysis and Definition of the Model to be Used

In spite of the advantages of the modified versions, it is still common to find applications of the original Kostiakov equations (4), (5) primarily because of their mathematical simplicity which result in a linear relation on double logarithmic paper, when applying logarithms to both sides of expression (4):

$$\ln F(t) = \ln K + a \ln t \quad (8)$$

which makes it possible to find the parameters of the model graphically or through a simple linear regression tool, since $\ln K$ is the ordinate at the origin and a is the slope of the regression line on log-log paper.

Unlike other methods, such as Horton, where the parameters have a direct correlation with some property of the function $f(t)$, the parameters K and a of the Kostiakov model affect both the value of the initial infiltration rate (understood as the value of f for a sufficiently small positive time) and the base infiltration (understood as the minimum value reached by $f(t)$ during a finite time interval). Figure 4 shows various curves of the function $f(t)$ for different values of the parameters K and a. As can be seen with K, as a increases

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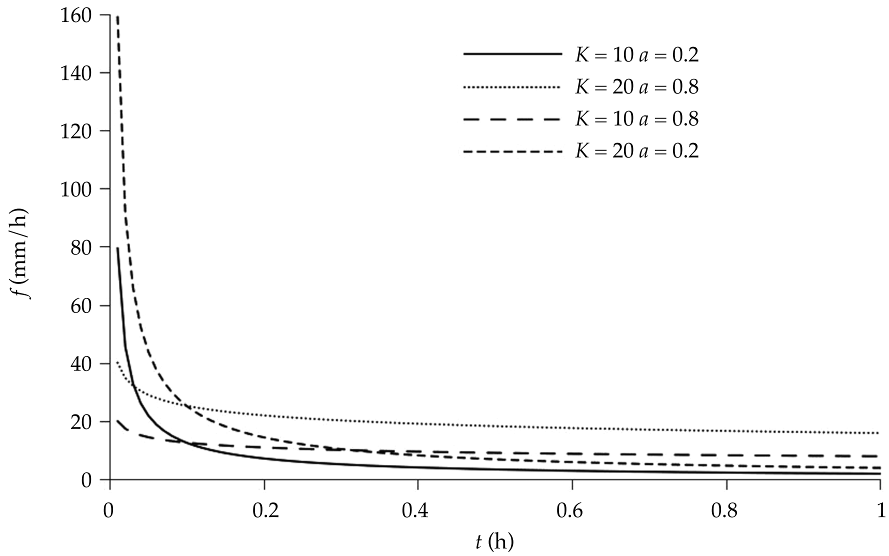

Figure 4. Infiltration rate according to the Kostiakov model for different parameter values.

the initial infiltration rate decreases and the base infiltration rate increases. And as with a, when K increases both the initial and the final infiltration rates increase (K represents a scale factor). The behavior is similar with the Lewis-Kostiakov model, but when adding the constant f_b this value is established as the absolute minimum rate.

Results

The experimental information described was expressed for the variables accumulated surface runoff, accumulated infiltration and the infiltration rate. As way of example, Figures 5 and 6 present the surface runoff rate and the accumulated infiltration for a test of one of the particular sites (L. Suárez de Figueroa-B^{o} M. de Sobremonte) with a rainfall intensity of 66.6 mm/h.

Accumulated infiltration was the variable used to fit the parameters since, given its nature, it presents better dispersion than its derivative (rate).

Fitting of Parameters

The parameters of the models described were fitted based on the information compiled by the rainfall simulator campaign, minimizing the objective function (OF) represented by the sum of the quadratic deviations between the n observed (F_i) and calculated (F^c_i) accumulated infiltration values, for each test site and each initial moisture condition:

$$F.O. = \sum_{i=1}^{n}\left(F_i - F_i^c\right)^2 \qquad (9)$$

The process was automated using an *ad hoc* code developed with GNU Octave (Eaton, Bateman, & Hauberg, 2007). For the Kostiakov model, this consisted of applying the linear regression to the set of data linearized by expression (8). The same procedure was applied to the Lewis-Kostiakov model but for the reduced variable F^0 defined as:

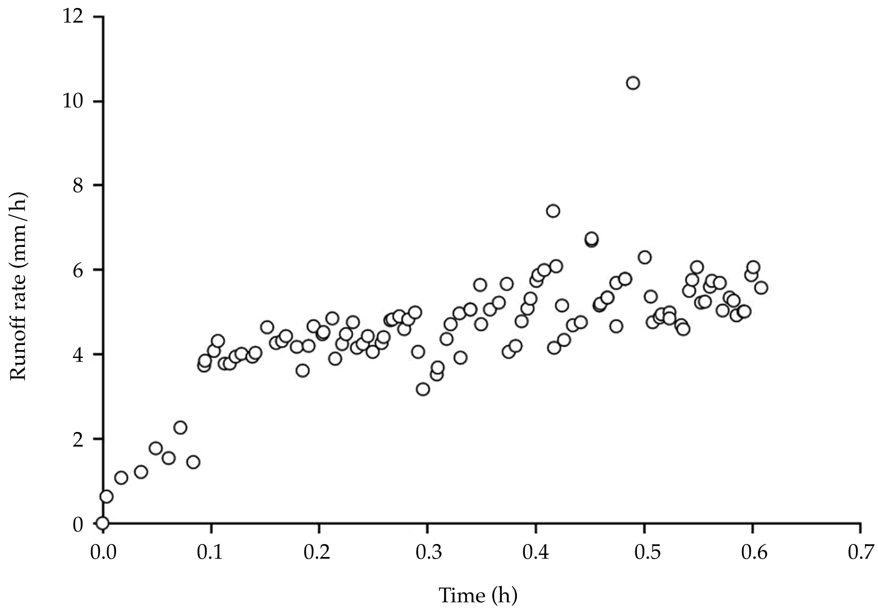

Figure 5. Surface Runoff Rate-Marques de Sobremonte.

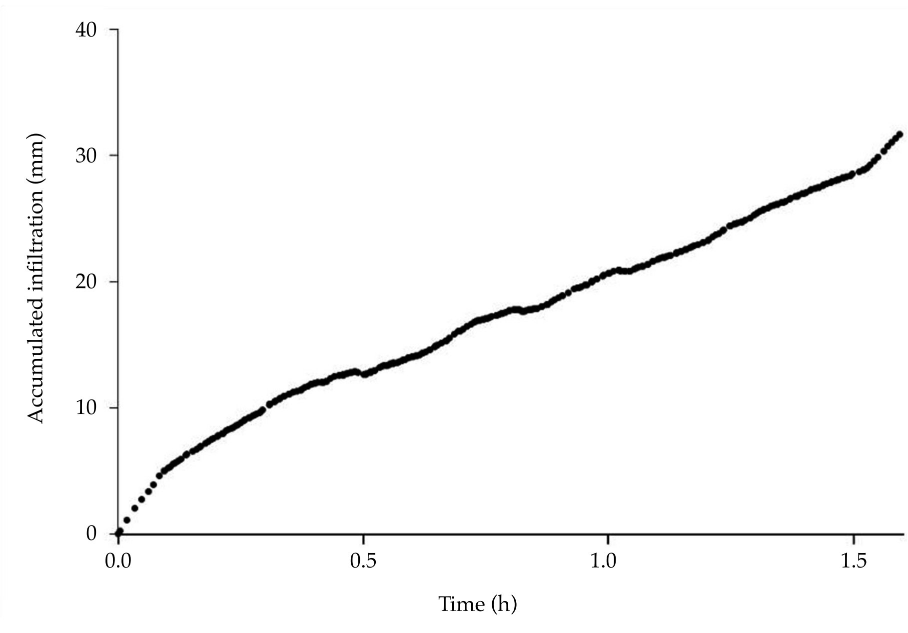

Figure 6. Accumulated infiltration-Marques de Sobremonte.

$$F^0 = F(t) - f_b t \qquad (10)$$

such that the problem of fitting is reduced to optimizing the variable f_b, which was done using the brute force method, or direct search (Chapra & Canale, 2006), with an accuracy of one decimal place. This method consists of discretizing the search domain with a fixed step and evaluating the function on the resulting grid, thereby detecting the minimum that is sought. The precision and accuracy of this method are clearly and directly related to the step or interval selected.

Thus, 24 sets of parameters were obtained for each model (since two measurements were not considered valid), along with the value of the objective function itself which is a measure of the goodness-of-fit obtained.

Table 2. Parameters of the Kostiakov model.

Use	Site	1st measurement	2nd measurement	3rd measurement
Dirt streets	Gauss 4619	K = 23.01	K = 28.05	K = 15.70
		a = 0.55	a = 0.64	a = 0.87
		R^2 = 0.995	R^2 = 0.993	R^2 = 0.997
	Miatello 4600	K = 31.68	K = 26.50	K = 20.80
		a = 0.76	a = 0.76	a = 0.82
		R^2 = 0.997	R^2 = 0.997	R^2 = 0.996
	Liebig 5940	K = 40.06	K = 30.78	K = 25.82
		a = 0.87	a = 0.95	a = 0.73
		R^2 = 0.999	R^2 = 0.999	R^2 = 0.999
	ITS Villada	K = 20.06	-----	K = 31.05
		a = 0.51		a = 0.75
		R^2 = 0.994		R^2 = 0.996
Parks	Gral. Paz Park	K = 50.60	K = 28.97	K = 45.76
		a = 0.87	a = 0.72	a = 0.85
		R^2 = 0.998	R^2 = 0.986	R^2 = 0.996
	ITS Villada Park	K = 31.13	K = 30.68	K = 31.77
		a = 0.79	a = 0.89	a = 0.76
		R^2 = 0.999	R^2 = 0.998	R^2 = 0.999
	Retention lagoon	K = 19.42	K = 29.16	K = 33.44
		a = 0.71	a = 0.74	a = 0.75
		R^2 = 0.997	R^2 = 0.995	R^2 = 0.995
	Park of the Nations	K = 48.02	-----	K = 33.55
		a = 0.86		a = 0.76
		R^2 = 1.000		R^2 = 0.992
	UTN	K = 33.10	K = 32.45	K = 37.27
		a = 0.79	a = 0.76	a = 0.84
		R^2 = 1.000	R^2 = 0.999	R^2 = 0.996
Residences	Marques de Sobremonte House	K = 43.66	K = 27.55	K = 35.67
		a = 0.82	a = 0.79	a = 0.72
		R^2 = 1.000	R^2 = 0.998	R^2 = 0.997
	ITS Villada Garden	K = 26.89	K = 34.22	K = 40.45
		a = 0.81	a = 0.71	a = 0.76
		R^2 = 0.996	R^2 = 0.995	R^2 = 1.000
	Torres de Junior	K = 24.20	K = 16.65	K = 23.91
		a = 0.55	a = 0.63	a = 0.70
		R^2 = 0.998	R^2 = 0.979	R^2 = 0.992

Table 2. Parameters of the Mecenzev or Lewis-Kostiakov.

Use	Site	1st measurement	2nd measurement	3rd measurement
Calles de tierra	Gauss 4619	$K = 12.80$	$K = 7.52$	$K = 1.23$
		$a = 0.34$	$a = 0.13$	$a = 0.36$
		$f_b = 10.2$	$f_b = 20.4$	$f_b = 14.7$
		$R^2 = 0.999$	$R^2 = 1.000$	$R^2 = 0.998$
	Miatello 4600	$K = 5.25$	$K = 4.86$	$K = 1.28$
		$a = 0.19$	$a = 0.26$	$a = 0.05$
		$f_b = 26.5$	$f_b = 21.7$	$f_b = 20.1$
		$R^2 = 1.000$	$R^2 = 1.000$	$R^2 = 1.000$
	Liebig 5940	$K = 5.64$	$K = 2.25$	$K = 11.20$
		$a = 0.42$	$a = 0.81$	$a = 0.50$
		$f_b = 34.4$	$f_b = 28.7$	$f_b = 14.6$
		$R^2 = 1.000$	$R^2 = 0.999$	$R^2 = 1.000$
	ITS Villada	$K = 11.41$	---	$K = 5.39$
		$a = 0.29$		$a = 0.19$
		$f_b = 8.6$		$f_b = 25.7$
		$R^2 = 0.999$		$R^2 = 1.000$
Parques	Gral. Paz Park	$K = 3.22$	$K = 2.49$	$K = 2.00$
		$a = 0.05$	$a = -0.20$	$a = -0.09$
		$f_b = 47.6$	$f_b = 26.7$	$f_b = 44.2$
		$R^2 = 1.000$	$R^2 = 0.999$	$R^2 = 0.999$
	ITS Villada Park	$K = 8.01$	$K = 0.47$	$K = 10.95$
		$a = 0.42$	$a = -0.39$	$a = 0.47$
		$f_b = 23.1$	$f_b = 30.5$	$f_b = 20.8$
		$R^2 = 1.000$	$R^2 = 1.000$	$R^2 = 0.999$
	Retention lagoon	$K = 6.93$	$K = 5.92$	$K = 5.16$
		$a = 0.39$	$a = 0.24$	$a = 0.10$
		$f_b = 12.4$	$f_b = 23.4$	$f_b = 28.3$
		$R^2 = 0.998$	$R^2 = 1.000$	$R^2 = 1.000$
	Park of the Nations	$K = 14.81$	---	$K = 2.75$
		$a = 0.63$		$a = -0.10$
		$f_b = 33.2$		$f_b = 31.1$
		$R^2 = 1.000$		$R^2 = 1.000$
	UTN	$K = 18.46$	$K = 32.45$	$K = 2.31$
		$a = 0.66$	$a = 0.76$	$a = -0.18$
		$f_b = 14.6$	$f_b = 0.0$	$f_b = 34.8$
		$R^2 = 1.000$	$R^2 = 0.999$	$R^2 = 0.999$
Residencias	Marques de Sobremonte House	$K = 27.91$	$K = 8.24$	$K = 9.66$
		$a = 0.74$	$a = 0.49$	$a = 0.27$
		$f_b = 15.7$	$f_b = 19.3$	$f_b = 25.9$
		$R^2 = 1.000$	$R^2 = 0.999$	$R^2 = 1.000$
	ITS Villada Garden	$K = 26.89$	$K = 9.67$	$K = 40.45$
		$a = 0.81$	$a = 0.30$	$a = 0.76$
		$f_b = 0.0$	$f_b = 24.5$	$f_b = 0.0$
		$R^2 = 0.996$	$R^2 = 0.998$	$R^2 = 1.000$
	Torres de Junior	$K = 23.80$	$K = 2.53$	$K = 4.52$
		$a = 0.54$	$a = -0.07$	$a = 0.11$
		$f_b = 0.4$	$f_b = 14.3$	$f_b = 19.4$
		$R^2 = 0.998$	$R^2 = 0.998$	$R^2 = 0.999$

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Table 2 presents the fitted values of these parameters for the Kostiakov model, per test site and measurement. Table 3 presents this same information for the Mecenzev or Lewis-Kostiakov model.

As can be seen, the values of R^2 are high, ranging from 0.9301 to 0.9998 for the Kostiakov model and 0.9575 to 0.9999 for the Lewis-Kostiakov. In fact, the best fits were obtained with the Lewis Kostiakov model, as expected. This is shown in Figure 7 which presents the R^2 values obtained with the Lewis Kostiakov model versus those obtained with the Kostiakov model. It can be seen that the set of points are located above the identity line.

It is worth mentioning that for some of the measurements, parameter *a* of the Lewis-Kostiakov model was negative. This is explained by the slight increase in the infiltration capacity during the test, which may have been due to a slight decrease in the intensity of the rainfall generated or the particularities of the test site.

As way of example, Figures 8 and 9 present the accumulated infiltration corresponding to a particular measurement (first measurement on Gauss Street), along with the fit obtained with the Kostiakov and Lewis-Kostiakov models, respectively. Tables 4 and 5 present the mean values (and range of variation) of the parameters of the Kostiakov and Lewis-Kostiakov models, respectively, according to land use.

In all the cases, the inclusion of the term *fb.t* in the Lewis-Kostiakov expression for accumulated infiltration (6) translated into a decrease in the values of parameters *K* and *a*, as seen in Figures 10 and 11.

A possible dependency between the parameters of both models was analyzed by graphing *K* versus *a* for the Kostiakov model and *K* versus *a*, *K* versus *fb*, *fb* versus *a* for the Lewis-Kostiakov model, indicating a possible relationship in the case of *K* versus *a* with the Lewis-Kostiakov (Figure 12). The points of agreement with land use were also classified by these graphs, based on which no grouping according to land use could be identified, although with the Lewis-Kostiakov model the range of the values of parameter *K* was lower

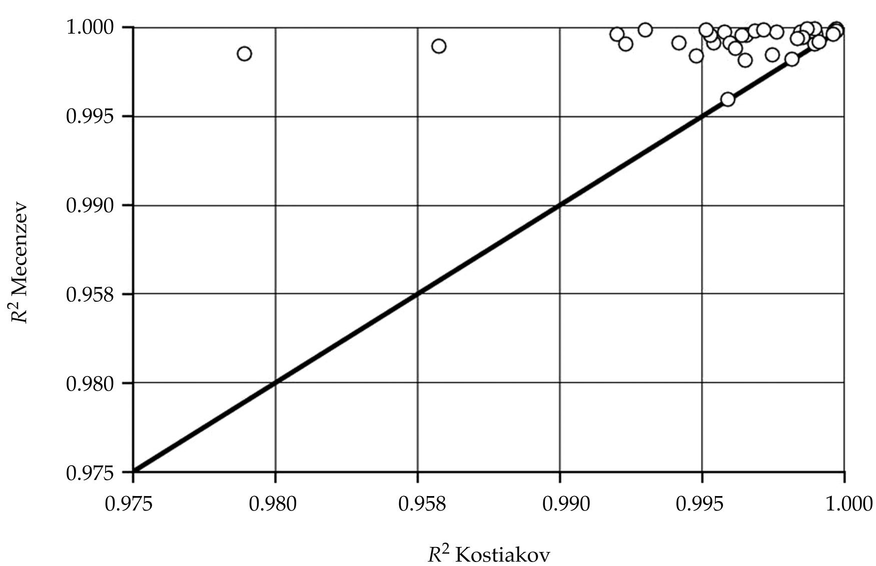

Figure 7. Coefficient of Determination R^2 obtained by fitting the Mecenzev model in function of the R^2 obtained with the fitting of the Kostiakov model.

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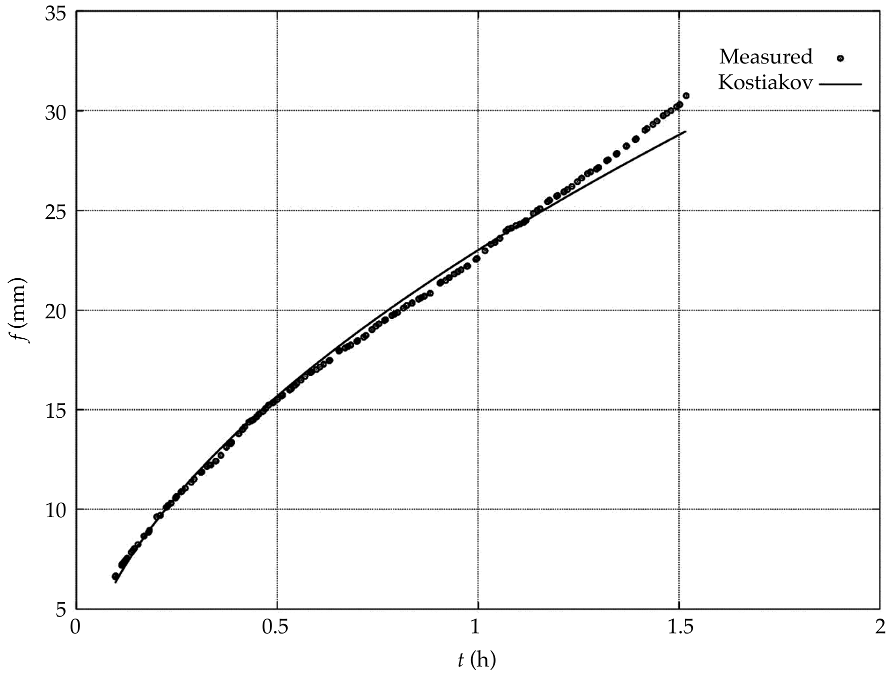

Figure 8. Measured accumulated infiltration and values obtained with the Kostiakov model-first measurement, Gauss Stree.

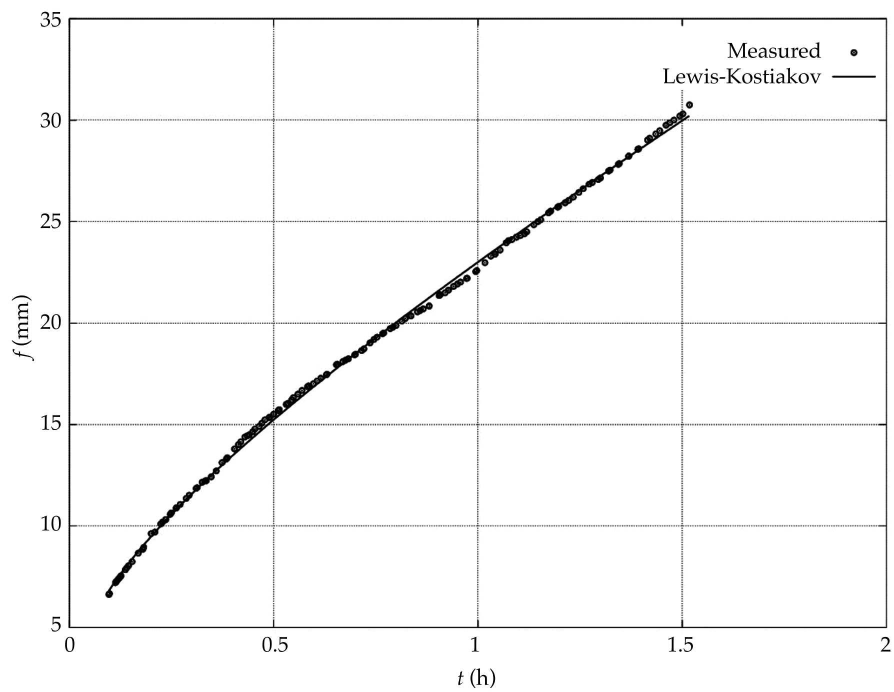

Figure 9. Measured accumulated infiltration and values obtained with the Lewis-Kostiakov (Mecenzev) model-first measurement, Gauss Stree.

Table 4. Mean parameters of the Kostiakov model acocrding to land use. Range of variation in parenthesis.

Use	*K*	*a*
Streets	26.68 (15.70-40.06)	0.75 (0.51-0.95)
Parks	34.67 (19.42-50.60)	0.79 (0.71-0.89)
Housing	30.35 (16.65-43.66)	0.72 (0.55-0.82)

Table 5. Mean parameters of the Lewis-Kostiakov model acocrding to land use. Range of variation in parenthesis.

Use	*K*	*a*	f_b (mm/h)
Streets	6.26 (1.23-12.80)	0.32 (0.05-0.81)	20.51 (8.60-34.40)
Parks	8.28 (0.47-32.45)	0.20 (-0.39-0.76)	26.48 (0.00-47.60)
Housing	17.07 (2.53-40.45)	0.44 (-0.07-0.81)	13.28 (0.00-25.90)

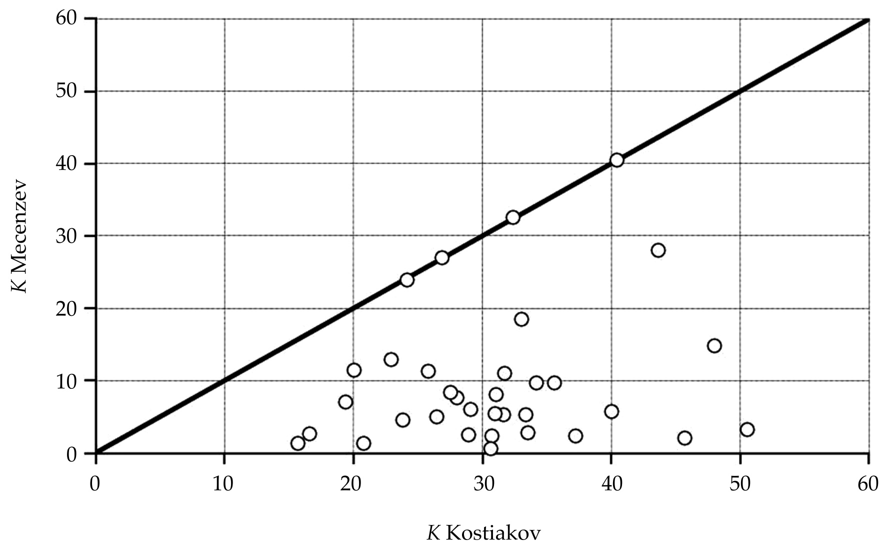

Figure 10. Relation between parameters K of the Kostiakov and Lewis-Kostiakov (Mecenzev) models. The solid line corresponds to the identity function.

and smaller for unpaved streets than for other land uses (Figure 12).

Figure 12 shows outlier values of K = 2.2488 and a = 0.8125. The following expression could be fitted by extracting this value from the series:

$$a = \alpha \ln K - \beta \tag{11}$$

with α = 0.261145, β = 0.203251 and R^2 = 0.76586. Based on this result, the possibility of a modification of the Lewis-Kostiakov model was proposed, which was named LK-2p (two-parameter Lewis-Kostiakov):

$$F(t) = f_b t + K t^{\alpha K - \beta} \tag{12}$$

where f_b and K must be fitted for each measurement and α and β would be constant at the regional level. To explore this hypothesis, an *ad hoc* code was developed with Octave to globally fit (that is, all of the 34 measure-

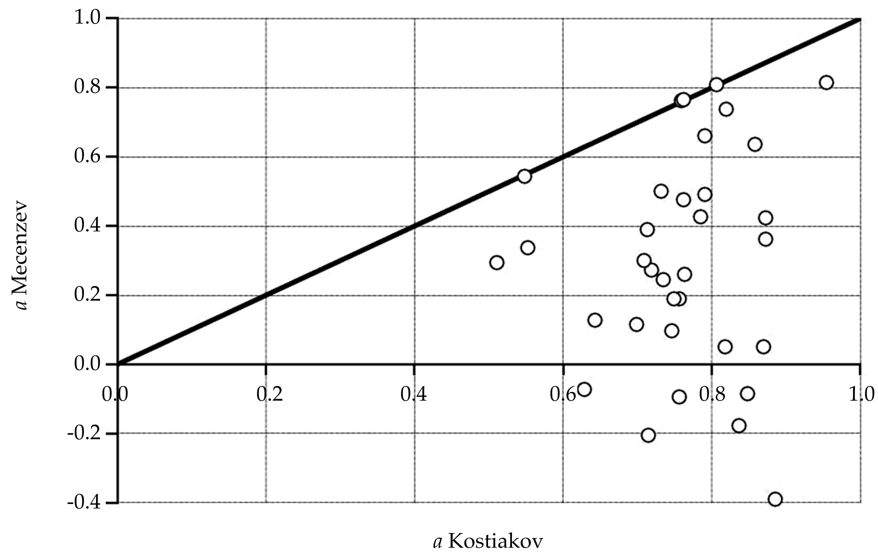

Figure 11. Relationship between parameters a of the Kostiakov and Lewis-Kostiakov (Mecenzev) models. The solid line corresponds to the identity function.

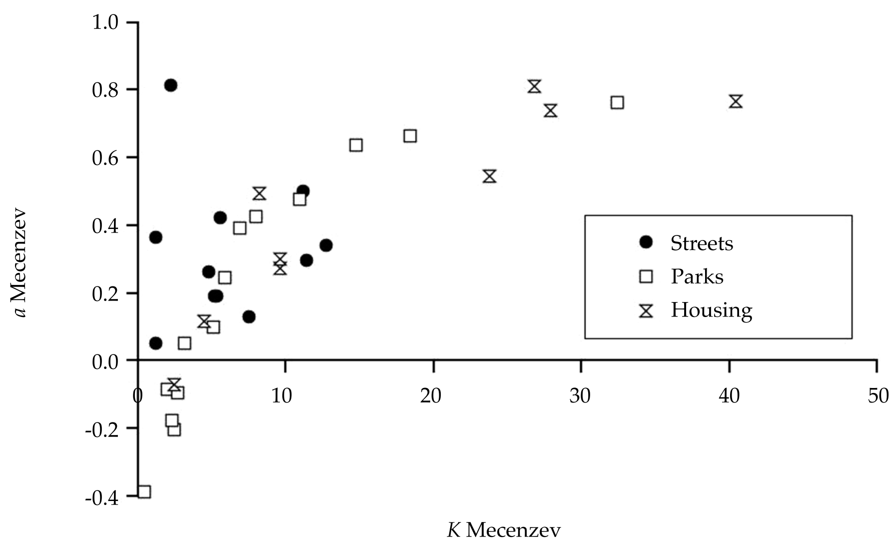

Figure 12. Relation between parameters *a* and *K* of the Lewis-Kostiakov (Mecenzev) model.

ments) the optimal values of α and β and locally fit (that is, for each of the 34 measurements) the optimal values of f_b and *K*. The global optimization of α and β was obtained using a simple cellular automata, minimizing the sum of the quadratic residuals (equation (9)). In this procedure, a pointer traverses a uniform two-dimensional grid in the eight possible directions, beginning with an approximate central solution. It identifies the position of the minimum, repositions the grid, and repeats the process until the position of the minimum does not change. The local values of f_b and K were optimized by applying the Nelder-Mead method (Mathews & Fink, 2004), applying an unrestricted optimization for both cases. Optimal values of $\alpha = 0.2560$ and $\beta = 0.2040$ were obtained, which were relatively close to the original values. The local values of the f_b and K parameters can be

Cuadro 6. Parámetros del modelo LK-2p.

Use	Site	1st measurement	2nd measurement	3rd measurement
Dirt Streets	Gauss 4619	$K = 22.78$	$K = 14.42$	$K = -0.90$
		$f_b = 0.40$	$f_b = 13.73$	$f_b = 17.29$
		$R^2 = 0.997$	$R^2 = 0.998$	$R^2 = 0.981$
	Miatello 4600	$K = 5.81$	$K = 4.07$	$K = 1.00$
		$f_b = 25.98$	$f_b = 22.45$	$f_b = 20.00$
		$R^2 = 0.999$	$R^2 = 1.000$	$R^2 = 0.999$
	Liebig 5940	$K = 3.27$	$K = 2.06$	$K = 7.73$
		$f_b = 36.66$	$f_b = 29.30$	$f_b = 17.99$
		$R^2 = 0.999$	$R^2 = 0.999$	$R^2 = 1.000$
	ITS Villada	$K = 20.29$	-----	$K = 6.15$
		$f_b = -0.08$		$f_b = 25.00$
		$R^2 = 0.996$		$R^2 = 1.000$
Parks	Gral. Paz Park	$K = 3.75$	$K = 4.55$	$K = 2.40$
		$f_b = 47.11$	$f_b = 24.80$	$f_b = 43.91$
		$R^2 = 1.000$	$R^2 = 0.998$	$R^2 = 0.999$
	ITS Villada Park	$K = 5.57$	$K = 28.97$	$K = 7.79$
		$f_b = 25.44$	$f_b = 0.89$	$f_b = 23.90$
		$R^2 = 1.000$	$R^2 = 1.000$	$R^2 = 0.999$
	Retention lagoon	$K = 4.84$	$K = 6.15$	$K = 7.54$
		$f_b = 14.42$	$f_b = 23.19$	$f_b = 26.01$
		$R^2 = 0.998$	$R^2 = 1.000$	$R^2 = 1.000$
	Park of the Nations	$K = 5.95$	-----	$K = 4.36$
		$f_b = 41.85$		$f_b = 29.59$
		$R^2 = 1.000$		$R^2 = 0.999$
	UTN	$K = 8.53$	$K = 18.99$	$K = 3.59$
		$f_b = 24.38$	$f_b = 13.12$	$f_b = 33.66$
		$R^2 = 0.999$	$R^2 = 0.999$	$R^2 = 0.999$
Residences	Marques de Sobremonte house	$K = 12.86$	$K = 5.18$	$K = 15.07$
		$f_b = 30.52$	$f_b = 22.18$	$f_b = 20.64$
		$R^2 = 1.000$	$R^2 = 0.999$	$R^2 = 1.000$
	ITS Villada garden	$K = 4.29$	$K = 13.64$	$K = 54.31$
		$f_b = 22.58$	$f_b = 20.61$	$f_b = -13.80$
		$R^2 = 0.993$	$R^2 = 0.998$	$R^2 = 1.000$
	Torres de Junior	$K = 35.04$	$K = 3.38$	$K = 5.57$
		$f_b = -10.76$	$f_b = 13.51$	$f_b = 18.40$
		$R^2 = 0.998$	$R^2 = 0.998$	$R^2 = 0.999$

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seen in Table 6. The overall results from fitting the parameters in this way were acceptable, although some inconsistencies (negative values) were observed in certain cases, in one K and three f_b values. As expected, the values of R^2 with the LK-2p model were generally slightly lower than with Lewis-Kostiakov (higher with LK-2p only in 3 of the 34 tests). The slightly decreased precision could be explained by having reduced the free local parameters from three to two.

Conclusions and Recommendations

By using the information collected *in situ* during the campaign performed at several sites in the city of Cordoba, it was possible to fit the parameters of the Kostiakov and Lewis-Kostiakov (Mecenzev) infiltration models. The Lewis-Kostiakov model performed better in the majority of cases. A tendency towards a logarithmic relationship was shown by the analysis of the relations between the parameters a and K of this model. Globally and simultaneously fitting the constants with local parameters f_b and K resulted in a two-parameter model named LK-2p. This presented some inconsistencies due to not imposing restrictions on the fit, but the results obtained were generally acceptable, with higher R^2 values than the Kostiakov model and slightly lower than the Lewis-Kostiakov.

Although the Kostiakov and Lewis-Kostiakov models do not use more sophisticated algebraic formulations to represent the infiltration process, they have been demonstrated to provide a good fit to the experimental data collected, and even better than other widely-used methods such as the CN-SCS (Weber, 2015b). And the idea of increasing the parsimony with an empirical relation such as the one resulting in the LK-2p model is attractive.

RIt is still necessary to investigate whether the logarithmic relation (12) corresponds only to the local information obtained from the measurements taken in the city of Cordoba or if it has a more generalized character.

In any case, fitting the set of parameters in this way is considered of interest to project managers involved in the management of urban runoff of rainfall in the city.

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Water Supplied by Truck in the Valley of Texcoco, Mexico

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Abstract

Gómez-Valdez, M. I., & Palerm-Viqueira, J. (March-April, 2016). Water Supplied by Truck in the Valley of Texcoco, Mexico. *Water Technology and Sciences* (in Spanish), 7(2), 133-148.

This study included five municipalities in the Valley of Texcoco —Chiautla, Chiconcuac, Papalotla, Tepetlaoxtoc and Texcoco— in which the users of water supplied by truck (water tank cars, delivery cars and cistern trucks) were characterized and the number of users was calculated. Water supplied by trucks is crucial to a portion of the population, nevertheless knowledge is greatly lacking about this type of supply and the characteristics of the users. As will be described, the coverage of water by the supply network in the Valley of Texcoco is significantly deficient due to the increase in settlements. It is therefore common for many zones in the area to receive water from trucks. Nevertheless, the supply network's lack of coverage is not the only reason why water is supplied by trucks.

Keywords: Water trucks, supply, water, neighborhoods, informal settlements.

Resumen

Gómez-Valdez, M. I., & Palerm-Viqueira, J. (marzo-abril, 2016). El abasto de agua por pipa en el valle de Texcoco, México. Tecnología y Ciencias del Agua, *7(2), 133-148.*

El estudio de caso centrado en cinco municipios del valle de Texcoco: Chiautla, Chiconcuac, Papalotla, Tepetlaoxtoc y Texcoco aborda la caracterización de los usuarios de agua de pipa (carros tanque, carros aguateros, camión cisterna) y establece un estimado del número de usuarios. El abasto de agua por pipa es esencial para un sector de la población, sin embargo hay un gran desconocimiento sobre este tipo de abasto y las características de los usuarios. Como se verá, en efecto la cobertura de agua por medio de red en el Valle de Texcoco presenta importantes rezagos debido al incremento de diversos asentamientos, por ello es común que en muchas zonas del área, el suministro de agua se proporcione por pipas; pero no sólo es por ausencia de cobertura de red que se recurre al abasto de agua por pipa.

Palabras clave: *pipas, abasto, agua, colonias, irregulares.*

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Introduction

In 2000, the United Nations (UN) established the Millennium Development Goals (MDG) in order to reduce extreme poverty by 2015. Goal number seven to "ensure environmental sustainability" includes target 7.C related to drinking water and sanitation, which establishes halving the proportion of people without sustainable access to improved drinking water supplies between the reference year (1990) and 2015. Access to drinking water means having a water supply source at least 1 km from the place where it is used and the ability to reliably obtain at least 20 liters per day for each family member for domestic and personal hygiene purposes as well as for drinking and cooking (WHO, 2015). It is worth mentioning that this definition does not include drinking water supplied by trucks (cistern trucks, tank cars or delivery cars).

In late 2008, Mexico announced that it had already achieved target 7.C when indicating that, "According to the definitions by the MDG, by 2008 Mexico had a drinking water coverage of 90% nationally" (Domínguez-Serrano, 2010). In a different text, the National Water Commission (Conagua, Spanish acronym) (Conagua, 2012) reported that 90.9% of the population had drinking water coverage according to data from the 2010 Population and Housing Census (Table 1).

The definition by the INEGI describes the population without "safe and sustainable access" to water according to a set of situations characterized in the census as "no access to a network," and in which case it is possible to indicate "source of water: truck" or "source of water: stream, river, lake, well." The census shows that 8.59% of the total population of the country "does not have access to a network" and that 1.92% does not have access to a network and its source of water is trucks. Another 1.47% was reported by the census as "unspecified" (INEGI, 2010) (Table 2).

Case Study: Valley of Texcoco

The study was conducted in five municipalities in the Valley of Texcoco: Chiautla, Chiconcuac, Papalotla, Tepetlaoxtoc and Texcoco.

Table 1. Composition of the national drinking water coverage, 1990-2010 census series (percentage).

Date	Have piped water inside or outside the home, but on the property (%)	Water obtained from a vehicle, public faucet or other house (%)	Total (%)
1990	75.4	3.0	78.4
1995	83.0	1.6	84.6
2000	83.3	4.5	87.8
2005	87.1	2.1	89.2
2010	87.6	3.3	90.9

Source: Conagua (2012).

Table 2. Consumers of water supplied by trucks in the country.

States	Total Population	Piped water not available	
		From trucks	From a well, river, lake, stream or other
Aguascalientes	1 177 687	5 511	6 074
Baja California	3 074 323	88 269	20 577
Baja California Sur	620 566	34 161	9 649
Campeche	813 983	10 029	68 993
Coahuila de Zaragoza	2 704 498	16 824	20 681
Colima	638 872	581	6 878
Chiapas	4 730 208	104 890	948 837
Chihuahua	3 291 665	32 247	129 930
Distrito Federal	8 588 972	136 366	16 257
Durango	1 600 143	3 954	87 325
Guanajuato	5 444 741	145 407	145 885
Guerrero	3 363 541	188 481	808 214
Hidalgo	2 639 465	45 360	194 263

Table 2 (continuation). Consumers of water supplied by trucks in the country.

States	Total Population	Piped water not available	
		From trucks	From a well, river, lake, stream or other
Jalisco	7 230 012	95 068	182 575
México	14 953 514	373 405	470 756
Michoacán de Ocampo	4 288 330	77 191	267 321
Morelos	1 743 741	71 998	71 341
Nayarit	1 070 295	5 151	74 715
Nuevo León	4 582 448	36 385	63 596
Oaxaca	3 771 663	143 104	746 018
Puebla	5 710 227	199 441	505 860
Querétaro	1 809 908	47 225	41 649
Quintana Roo	1 302 257	20 238	58 980
San Luis Potosí	2 556 679	47 254	313 760
Sinaloa	2 747 428	11 654	116 966
Sonora	2 615 993	56 605	23 653
Tabasco	2 208 377	7 365	399 800
Tamaulipas	3 157 698	33 390	57 230
Tlaxcala	1 163 055	6 875	10 211
Veracruz de Ignacio de la Llave	7 533 923	67 933	1 397 909
Yucatán	1 938 190	1 214	40 693
Zacatecas	1 475 182	12 957	66 937
Total nacional	**110 547 584**	**2 126 533**	**7 373 533**
Porcentaje	**100**	**1.92**	**6.67**

Source: INEGI (2010).

The INEGI has reported that 7.55% of the population in these municipalities receive their water from trucks. Nevertheless, the data from the case study which we report herein show that the problem with the coverage of the public water network is greater than that indicated by the INEGI census (2010).

Based on the results, consumers in the study area who regularly receive water supplied by trucks can be characterized as follows (Table 3):

a) Consumers in "irregular" neighborhoods or localities without a drinking water network. The residents themselves call these localities "irregular" and are connected with civil organizations (CO), primarily Antorcha Campesina. This category includes 39 130 consumers, that is, 12.79% of the total population of the study area.

b) Consumers in "regular" localities without a drinking water network. The residences themselves call the localities "regular" and are not connected with COs. Some cases obtained the status of new growth of pre-existing localities. Communities are excluded that have access to other sources of water such as springs, even when they do not have a network, for example, San Jerónimo Amanalco. This category includes 5 977 consumers, that is, 1.95% of the total population of the study area.

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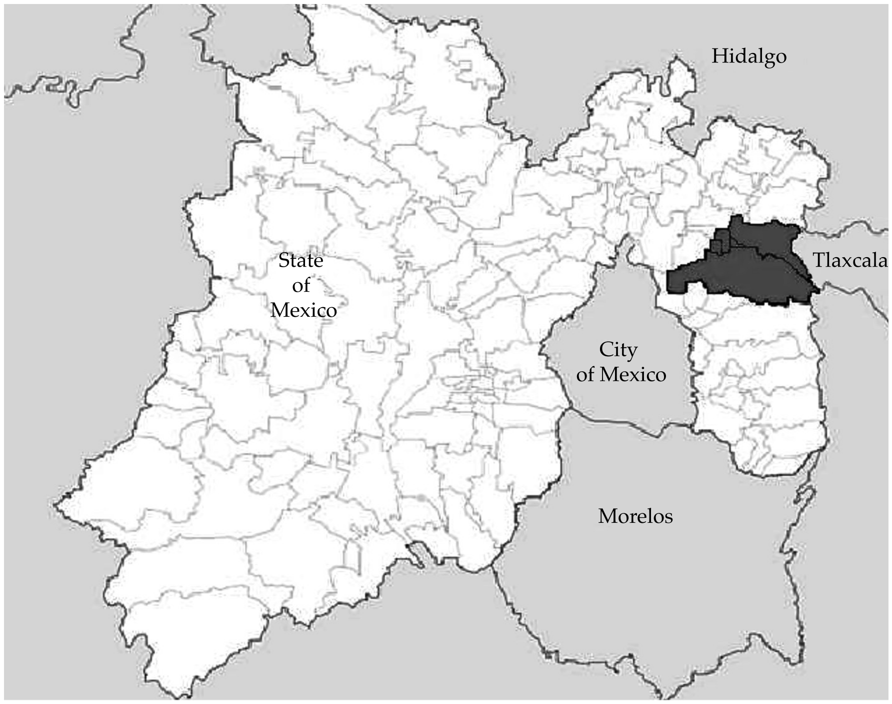

Figure 1. Study Area.

c) Permanent network failure. These are consumers in localities where portions of the drinking water network have problems with low pressure, being at the end of the network and inadequate distribution schedules. Two situations can be considered: consumers who systematically and continually get their water from trucks and cases in which trucks supply their water sporadically due to service failures. The systematic and continuous supply of water by trucks involves three situations:
   - When the network to which they are connect has an inadequate distribution schedule, that is, the number of hours they receive water does not meet their needs, for example, the well operates from 6am to 11am and again from 6pm to 9pm.
   - When the network to which they are connected has a "scheduled distribution" or days during which there is not enough water. Scheduled distribution occurs when the neighborhood is divided into sections, and valves in the network open and close the service to the different sections. In the two previous cases, the consumers of trucked water service do not coincide with the hours of the distribution schedule and constantly lack water, and therefore they rely on trucks to ensure that they have water.
   - Cases in which the network to which they are connected has low pressure and/or are located at the end of the network and therefore very little water reaches them and does not fill their storage. This category has 1 213 consumers, that is, 0.40% of the total population of the study area.

d) Consumers due to water quality. These are residents in the localities who rely on water trucks because of their perception of the quality of the water. This is the case of residents of San Pablito, in the municipality of Chiconcuac, who receive their water from trucks because the water from the well is "hard" or the residents in La Magdalena Panoayac, who prefer trucked water because the water from the well is "salty." This category has 2 107 consumers, that is, 0.69% of the total population of the study area.

e) Consumers in localities that have a drinking water network but are not connected. These are consumers who decide to use trucked water because of the costs of connecting to the network, network fees and corresponding commitments to the community. These cases were identified based on interviews with those in charge of the Drinking Water Committees (DWC) along with residents in La Purificación Tepetitla in the municipality of Texcoc, San Andrés Chiautla in the municipality of Chiautla, and the Barrio San Pablo, in Tepetlaoxtoc. This group of consumers includes users who consider: a) the cost of connection to be very high, in one case 30 000 pesos; b) that a large family on the same property should not have to pay to get connected; c) that it is burdensome to have to participate in the *faenas* (unpaid work by users) and other community fees, such as school. It is worth mentioning that the first case includes residents with a water intake on their land which contains apartment buildings and they want to pay the annual fee for only one intake. These cases include 3 182 consumers, that is, 1.04% of the total population of the study area.

The results obtained by this study indicate that the population without access to a network and which depends on trucks is larger than that reported by INEGI: 45 107 inhabitants, that is, 14.75% of the population. In addition, the criteria for trucked water supply in the INEGI census do not include cases that have a connection to the network but consume trucked water due to several reasons, such as low pressure, a network's insufficient distribution schedule, water quality and residents who refuse to connect to the network, corresponding to a population of 6 502 residents, that is, 2.13%. Thus, the total number of residents in the study are who regularly consume water supplied by trucks is 51 609, that is, 16.87% of the total population of the municipalities studied. This does not include cases of sporadic failure in the networks' services or regular truck supply to the service sectors (schools, businesses, health centers, etc.) which are also important.

Methodology

The methodology used to locate the regular users of trucked water services is described next.

Table 3. Consumers of water supplied by trucks in the municipalities studied.

	2010 INEGI Data		Data reported by the study					
	Total population in the five municipalities studied	Population supplied by water trucks	"Irregular" without networks	"Regular" with networks	Permanent network failure (insufficient distribution schedule, end of network, low pressure)	Water quality	With network access but not connected	Total calculated
Number	305 855	23 099	39 130	5 977	1 213	2 107	3 182	51 609
Percentage	100	7.55	12.79	1.95	0.40	0.69	1.04	16.87

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1. Interviews with Administrators of the Piped Water System

To identify the zones in the study area with network supply problems and would use trucked water services, interviews were conducted with public municipal officials in the five municipalities making up the study area. This was based on the supposition that the municipalities are committed to supplying piped water service (Galindo-Escamilla & Palerm-Viqueira, 2007a and b). The municipal officials in Papalotla and in one of the systems that supply the Chiautla municipal capital and some of its localities indicated the existence of Drinking Water Committees (DWC) that are responsible for the administration of the piped water systems. The DWC are composed of a president, secretary and treasurer who are elected at a community assembly. The positions are unpaid and have a term of three years.

The DWC were interviewed because of the lack of municipal information. A list of the

Table 4. Localities and types of water administration, per municipality.

Municipality	Locality	Administrators	Source administered	Interviewed
Chiautla	Santa Catarina	Local government, public services	La Mediania Well	✓
	Colonia Guadalupe			
	Jalapango			
	Ampliación San Francisco			
	Fraccionamiento San Antonio		San Antonio Well	
	Arboledas			
	San Alberto			
	San Alberto II			
	San Luis			
	Real los Cedros			
	Pueblo San Lucas Huitzilhuacán	Drinking Water Committee (DWC)	Wells 1, 2 and 3	✓
	Barrio San Francisco			
	Pueblo San Juan			
	Pueblo San Sebastián			
	Pueblo Atenguillo			
	Barrio Santa Catarina			
	Pueblo Nonoalco	Drinking Water Committee (DWC)	Well	
	Pueblo Chimalpa			
	Barrio Amajac			
	Atenguillo			
	Pueblo Huitznáhuac			
	Barrio Ixquitán			
	Barrio de San Bartolo			
	Pueblo Tepetitlán			
	Pueblo Ocopulco			
	Pueblo Tlaltecahuacán			
	Colonia La Concepción			
	Colonia Xalapango			
Chiconcuac	San Miguel			✓
	San Pablito Calmimilolco			✓
	Santa María			
	San Pedro			
	La Joyas			
	El Xolache y Xala			

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Table 4 (continuation). Localities and types of water administration, per municipality.

Municipality	Locality	Administrators	Source administered	Interviewed
Papalotla	Barrio Belém	Local Papalotla government, through the Department of Public Works and Urban Development	Belen Well	✓
	Barrio Chimalpa			
	Barrio Coxotla		Los Morales Well	
	Barrio Ixayoc			
	Barrio Mazatla			
Tepetaoxtoc	Tepetlaoxtoc de Hidalgo	Drinking Water Committee (DWC)	Well	✓
	San Juan Totolapan			
	Sto. Tomás Apilpilhuasco			
	San Pedro Chiautzingo			
	San Bernardo Tlalmimilolpan			
	San Andrés de las Peras			
	La Loma			
	Los Reyes Nopala			✓
	La Concepción Jolalpan			✓
	La Candelaria Jolalpan			
	San Pablo Jolalpan			✓
	San Francisco Jolalpan			
	Colonia Tulteca Teopan			
	Barrio Tulteca Teopan			✓
Texcoco	Barrio San Pedro	Local Texcoco government through the Drinking Water and Sewers Department	Well	✓
	El Xolache I			
	El Xolache II			
	Joyas de San Mateo			
	San Juanito			
	Santa Úrsula			
	Niños Héroes			
	Valle de Santa Cruz			
	El Centro			
	Las Salinas			
	Las Américas			
	San Lorenzo			
	El Carmen			
	San Mateo			
	San Martín			
	La Conchita			
	Joyas de Santa Ana			
	Zaragoza-San Pablo			
	Unidad Habitacional Las Vegas			
	Colonia Guadalupe Victoria			
	Los Sauces			
	Salitrería			
	Lomas de Cristo			
	Unidad Habitacional ISSSTE			
	Lomas de San Esteban			
	Colonia Villas de Tolimpa			
	San Sebastián			

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Table 4 (continuation). Localities and types of water administration, per municipality.

Municipality	Locality	Administrators	Source administered	Interviewed
Texcoco	San Felipe	Drinking Water Committee (DWC)	Well	
	San Miguel Tocuila			
	Santa Cruz de Abajo			
	Vicente Riva Palacio			
	La Magdalena Panoaya			✓
	Boyeros			✓
	Santiaguito			
	Santa María Tulantongo			
	San Simón			✓
	Pentecostés			
	La Resurrección			✓
	San José Texopa			
	Los Reyes San Salvador			✓
	San Bernardino			
	Montecillos			✓
	El Cooperativo			✓
	Fraccionamiento El Tejocote			
	San Luis Huexotla			
	San Mateo Huexotla			
	San Nicolás Huexotla			
	Villa Santiago Cuautlalpan			
	San Miguel Coatlinchán			✓
	Colonia Bellavista			
	Colonia Sector Popular			✓
	Colonia Lázaro Cárdenas			
	Colonia Leyes de Reforma			✓
	Colonia El Trabajo			
	Unidad Habitacional Embotelladores			✓
	La Trinidad			
	San Diego			
	Santa Cruz de Arriba			
	Xocotlán			
	Santa Inés			✓
	Santa Cruz Mexicapa			✓
	San Dieguito Xochimanca			
	San Juan Tezontla			
	San Pablo Ixayoc			
	San Nicolás Tlaminca			
	San Joaquín Coapango			
	La Purificación Tepetitla			
	Santa María Nativitas			
	Tequexquinahuac		Well and spring	
	San Miguel Tlaixpan			
	Santa Catarina del Monte		Spring	
	Santa María Tecuanulco			
	San Jerónimo Amanalco			
	Colonia Guadalupe Amanalco			

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DWC in each of the municipalities was generated. There is a total of 80 DWC and three local governments that manage the systems in four municipalities (Table 4). Public officials from all the local governments that manage systems were interviewed and a non-random sampling of the DWC was performed. The DWC were contacted by visiting the localities. In each case, the members of the DWC who were contacted were explained the type of study being conducted and a date for the interview was agreed upon. An interview guide was used which focused on the question of whether there were homes **that used water supplied by trucks** and the reason, as well as their location. A total of 25 system administrators were interviewed —22 from the DWC and 3 municipalities — of a total of 83 administrators (80 DWC and 3 municipalities).

The regions indicated by the DWC as having homes supplied by trucks were then visited and the residents were interviewed. The number of houses affected and their geopositioning were determined. The information obtained was used to create a descriptive file for each case with. The reasons for the regular supply of water by trucks were low pressure, insufficient distribution schedule, water quality and homes with access to the network that decided not to connect.

It is worth mentioning that a discussion is currently being presented about the evaluation of the capacity of municipalities and DWC to effectively manage small systems. In general, studies indicate that the DWC are more effective (Ennis-McMillan, 2001; Galindo-Escamilla & Palerm-Viqueira, 2007a, 2007b, 2009, 2012; Guerrero *et al*., 2010; Lopez, Martínez-Saldaña, T., & Palerm-Viqueira, 2013; Salcido, Peter, & Martínez, 2010).

The users in the localities mentioned that resources were directly invested through the DWC to improve the water system in the locality. In addition, connection requests are quickly addressed and there is transparency in the use of the resources. Actions are also taken before the municipality to improve the local drinking water system. Through assemblies, the users are able to establish a system of fines for failure to comply with the regulations and have the right to demand the accountability of the DWC. In the case of poor management of resources, the fines for those who are part of the DWC are established by their families and neighbors. The possibility of being exposed to the community makes the members of the DWC committed to clearer management and administration.

2. Location of the Wells that Supply the Trucks

Nine wells that supply the trucks were located. One was located with information provided by the Texcoco Drinking Water and Sewers Sub-Department, four through field surveys and four were indicated by the truck operators. Each truck operator provided information about the operating schedule of the well and the cost of the truck's load.

The wells were visited to request an interview with the person in charge. No positive response to conducting interviews was received. Access to the wells is restricted, all of which are surrounded by walls or fences and have a gate that opens and closes when a truck enters and exits.

The wells were geopositioned and a database was created in Google Earth. A general search of each municipality was then performed using the Public Water Rights Registry (REPDA, Spanish acronym) to identify consistencies between each well with the coordinates registered in the system, in order to obtain more information about each well. When entering the coordinates of one of the wells indicated by the REPDA database, identified by the name of the owner, Google Earth showed its location in the state

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of Puebla. Therefore, the data obtained from the field was used to mark its position in the database of points. Three types of wells were identified: municipal drinking water well for public urban use; private drinking water well for multiple uses; and a private well for farming use. A descriptive file was created for each well located.

3. Interviews with Truck Operators

The truck operators were contacted at the wells where they load the water and the locations where they deliver it. They were generally difficult to interview because they were working and because of their high reluctance to talking about how they are organized, who are their representatives in the organizations, the relationships with those in charge of the wells, etc. A total of 12 interviews were conducted with the truck operators. They were asked about where they deliver the water and the reasons why the trucked water service is requested, the number of homes and/or families they supply.

The localities identified by the truck operators were written on a list and they were asked for some landmarks in order to locate them. A field survey was later conducted to confirm the absence of the network on the land and the supply of trucked water. In the irregular housing areas (locally called colonies), the representative of each one and the residents were interviewed.

Most of the trucks have a telephone number written on the tank and some have a sticker or emblem of a civil organization (CO) on the doors. Some of those which could be seen were the Mexico Confederation of Workers (CTM, Spanish acronym), the Workers and Farmers Revolutionary Confederation (CROS, Spanish acronym), the Drinking Water Drivers Union of the Valley of Texcoco (UTRAP, Spanish acronym) and the Single Truck Operators Union (Sindicato Único de Piperos). Private suppliers do not display emblems and only have the telephone number written on the truck to place orders. All are marked with the words "drinking water transportation" in some part of the truck.

4. Database Review

The information from the truck operators was important to locate the neighborhoods without a network which were affiliated with the CO and those not affiliated, since the municipal officials and the DWC do not have this information. The data from the interviews with the truck operators were supplemented with a search in the Degree of Marginalization Catalogue of the National Population Council (Conapo, Spanish acronym), (Conapo, 2012) and in the Program for the Development of Priority Zones Catalogue (PDZP, Spanish acronym) of the Ministry of Social Development. Interestingly, the information from these two catalogues do not include all the localities identified through the interviews with the truck operators.

The procedure to locate the neighborhoods in the catalogues is described next.

In the case of localities in the database with high and very high marginalization (Conapo, 2012), the Conapo website (http://www.conapo.gob.mx/es/CONAPO/Indice_de_Marginacion_por_Localidad_2010) was accessed and the "complete database by entity" was downloaded in Excel, version 2007. Once downloaded, the database was opened and the information for the State of Mexico was located. A search was conducted of the municipalities in the study: Chiautla, Chiconcuac, Papalotla, Tepetlaoxtoc and Texcoco.

The data corresponding to the municipalities in the study were copied and pasted into a new Excel spreadsheet. This contained data for the total population, total number of private occupied households, percentage of the population 15 years or older that was illiterate and those without complete elementary education, percentage of private occupied housing without a toilet, percentage without

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electricity, percentage without piped water, average occupants per room, percentage of occupied private housing with dirt floor, percentage without a refrigerator, marginalization index on a scale of 0 to 100, placement nationally, placement on the state level.

The columns of information that were not of interest were deleted from the spreadsheet, leaving columns corresponding to locality, percentage of private housing without water available and degree of marginalization. Localities with a very low, low and medium degree of marginalization were deleted, which coincided with 0 to 15% of private occupied housing without piped water. A table with 35 localities was obtained.

In the case of the database Catalogue of Localities in the Program for the Priority Development Zone, the Ministry of Social Development's website was accessed (http://www.microrregiones.gob.mx/catloc/LocdeMun.aspx) and the information in the database corresponding to the municipalities in the study (Chiautla,Chiconcuac, Papalotla, Tepetlaoxtoc and Texcoco) was downloaded in Excel. The information from the housing deficiency indicator was reviewed, placing particular attention on the indicator of housing without piped water for each locality.

The data corresponding to the municipalities in the study were copied and pasted into a new Excel spreadsheet. The database contained the data: state code, state name, municipality code, municipality name, type of coverage, National Crusade Against Hunger (CNH, Spanish acronym) municipality, locality code, locality name, total population, occupied private housing without piped water, without drainage, without electricity, with a dirt floor and without a bathroom or toilet, marginalization of the locality, main results per locality (Estatus Iter 2010), creation after 2010, priority attention zone (ZAP, Spanish acronym), coverage by the Priority Development Zone Program (PDZP, Spanish acronym) and area.

The columns of information that were not of interest were deleted from the spreadsheet, leaving columns corresponding to locality, percentage of private housing without water available and degree of marginalization. Localities with a very low, low and medium degree of marginalization were deleted. A table with 35 localities was obtained (Table 5) which coincided with the localities obtained through Conapo.

5. Verification through Field Surveys

Using the information from the interviews with truck operators, representatives of the colonies, the DWC and municipal departments, a list was created which was the basis for the field surveys conducted to verify the localities, neighborhoods and colonies that had been identified by the interviewees, and from the databases of water supplied by trucks. Visits and interviews were conducted to confirm the type of supply. Each colony identified as being supplied by water trucks was geopositioned and a file was created for each of the 54 colonies located.

After the field surveys and the visits to the colonies, neighborhoods and towns, it was found that some cases now have water service from the network, and localities supplied by spring water from the community were eliminated, such as Tequexquinahuac, San Miguel Tlaixpan, Santa Catarina del Monte, Santa María-Río Verde Hydrographic System María Tecuanulco, San Jerónimo Amanalco y Colonia Guadalupe Amanalco, belonging to the municipality of Texcoco.

To plan the field surveys, a list was first created of localities whose locations were identified by knowledge of the zone. Then, localities mentioned by the truck operators were added along with their instructions about how to reach them. All the localities were grouped by municipality and the route for conducting the field survey was developed (for example, municipality of Texcoco-

Table 5. Localities and Type of Water Administration, by Municipality.

Municipality	Locality	Without "irregular" network	Without "regular" network	Permanent network failure (insufficient distribution schedule, end of network, low pressure)	Water quality	With network but not connected	
Chiautla	Colonia La Concepción	1 634					
	Chiautla			215		903	
	Ejidos Chiautla	1 290					
Chiconcuac	Barrio de San Pablito Calmimilolco				1 720		
	Ejidos Chiconcuac	1 075					
Papalotla	Orillas de la red			761			
Tepetlaoxtoc	Colonia Progreso	1 634					
	Barrio de San Pablo					516	
	Barrio de La Concepción					258	
	Colonia Víctor Puebla	8 600					
	Colonia Guadalupe Victoria	1 290					
	Colonia Fray Servando	2 150					
	Colonia Lázaro Cárdenas	860					
	Colonia Elsa Córdova	5 375					
	Colonia Wenceslao Victoria Soto	4 300					
	Colonia Valle de Tláloc	3 655					
	Colonia Los Tepetates	989					
	Colonia Las Torres	430					
	Colonia Guadalupe	108					
	Colonia Ampliación Sector	258					
	Ejido Montecillos	430					
	Colonia Salitrería	344					
	Ejido Huexotla	602				430	
	Ejido Boyeros	430					
	La Purificación					1 075	
	Colonia El Gavilán	258					
	Colonia El Jardín	86					
	La Magdalena Panoayac				387		
	Santa Cruz Mexicapa		26				
	Unidad Habitacional Embotelladores			237			
	Colonia Humberto Vidal	2 150					
	Santa Cruz de la Constancia		43				

Table 5 (continuation). Localities and Type of Water Administration, by Municipality

Municipality	Locality	Without "irregular" network	Without "regular" network	Permanent network failure (insufficient distribution schedule, end of network, low pressure)	Water quality	With network but not connected	
	Rancho Xalapango		112				
	Colonia La Presa		69				
	Colonia El Paraíso		99				
	Santa Irene		103				
	Rancho Santa Martha		2 430				
	Rancho Santa Rosa		95				
	Colonia Ex-hacienda Tepetitlán		138				
	Colonia El Barco		43				
	Ejido San Juan Tezontla		112				
	Colonia Pozo el Milagro		34				
	San Agustín		120				
	Colonia Los Sauces		133				
	Rancho La Castilla		138				
	Colonia Las Tijeras		503				
	La Nopalera		125				
	Praderas de Tecuac		241				
	Ejidos de Beltrán Cuautlalpan		520				
	Colonia Puente Quebrado		262				
	Santa María Hidalgo y Carrizo		271				
	Colonia Paraíso 300 (Profesores)	1 075					
	Colonia San Isidro	108					
	Ejido los Reyes San Salvador		361				
Total		**39 130**	**5 977**	**1 213**	**2 107**	**3 182**	**51 609**
Percentage of the total population in the study area		**12.79**	**1.95**	**0.40**	**0.69**	**1.04**	**16.87**

Coatlinchán: colony Las Tijeras-Praderas de Tecuac-Valle de Tlaloc-Las Torres-ex Hacienda Tepetitlán-Paraíso 300).

In the localities visited, residents were asked about the location of those on the list corresponding to the municipality visited, and when known they gave directions for how to get there. These were included on the list of the colonies to be visited or were visited if they were nearby.

The field survey verified a total of 54 localities without water networks.

6. Representatives and Residents of Colonies with Water Supplied by Trucks

Another source of information was the interviews with representatives of the colonies supplied by trucks, who provided information about lots, houses, families and total population of the colony, as well as the number of trucks that supply the colony and the days on which water is supplied. They were also asked about the reason why they did not have a drinking water network and whether they belonged to a civil organization. In addition, when performing the field surveys and interviews, they provided information about colonies that were supplied by trucked water service which we did not have registered, such as the Guadalupe Colony located on the Candelapa ranch, and the San Isidro Colony.

Summary of Information about Localities

Table 5 shows a summary of the users of trucked water:

a) Consumers in "irregular" neighborhoods or colonies without drinking water network. Neighborhoods that call themselves "irregular" and belong to civil organizations, primarily Antorcha Campesina.
b) Consumers in "regular" neighborhoods without a drinking water network. The residences themselves call these "regular" and are not connected with COs. Some cases obtained status as new growth of pre-existing localities.
c) Consumers in localities with a drinking water network where portions of the network have low pressure, are at the end of the network or there the distribution schedule is inadequate.
d) Consumers because of water quality.
e) Consumers in localities with a water network but are not connected.

Analysis

Of the total number of consumers located in the study area, 75.82% corresponds to the self-named "irregular" neighborhoods affiliated with CO, the majority of which belong to Antorcha Campesina. This CO has a large presence in the region. Worldwide, these neighborhoods are typically peri-urban and grow rapidly. "Irregular" neighborhoods (slums, lost cities, shanty towns) proliferate when there are no or limited government policies to provide inexpensive housing. In fact, their informality or irregularity means that they are not included among those who are to receive public services (Allen, Dávila, & Hofmann, 2005; Navarro-Garza, 2005; Saavedra, Bain, & Pardo, 2011).

Next are the cases of consumers in localities without networks which are self-named "regular," with 11.58%. These are distinguished by the others as not being affiliated with a CO and rather seem to correspond to the growth of pre-existing neighborhoods. Several of these cases (five of a total of 22 localities) succeeded in establishing that the DWC in the original community of residents initiate a planning process to expand the network to the new neighborhoods. This inclusion was not attained in all the cases because of the controversy caused by the proposal for a new water law that year (2015), which generated large concerns among the members of the governing committees of the DWC.

It is notable that the percentage of users who refuse to connect to the network is greater (6.17%) than the percentage supplied by trucks due to permanent failures in the network (insufficient distribution schedule, low pressure and being at the end of the network (2.35%). This group that refuses to connect to the network is actually evading the regulations imposed by the local water authority.

A considerable amount (4.08%) of residents are supplied by trucks because of their perception of the water quality. These cases

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occur in the Barrio San Pablo and Barrio La Magdalena Panoayac.

A total of 51 609 persons in the region are supplied by water trucks. With a base mean of 100 liters per capita per day to supply this group, it would require 883 729 m^3 yearly to meet the needs of this population.

It is important to mention that no planning exists at the municipal and state levels to support the supply of water, adding to the two local solutions (well networks and trucks). There are no programs related to recharge, water treatment plants for reuse, roof water catchment or others to support the supply and recovery of the aquifer — reported to have an overexploitation of 43 million m^2 (Conagua, 2009). In addition, the use of well networks as a solution in the region is not possible in all cases because of the water quality or the lack of an aquifer. This is the situation in the upper portions of La Purificación and Coatlinchan, which are forced to re-pump water from lower areas, resulting in high energy costs and in reaching agreements with the communities located in that area. The water quality of the wells in some areas also limits the use of this technological alternative.

For the aquifer that supplies Texcoco (larger than the municipalities in the case study), there is little possibility of transferring water allocations from the agricultural to the urban sector since agriculture accounts for only 9.3% of total allocations, and corresponds to a volume equal to the aquifer's deficit. The situation of overexploitation is even more serious when taking into account data from the 1990 census performed by Gravamex, which indicates an extraction of 465 367 701 cubic meters as compared to the 92 546 817 reported in 2009 by REPDA (Conagua, 2009: 25 and 29).

Lastly, no programs exist to improve the trucked water supply or reduce its cost, such as community basins with distribution networks connected to storage that is filled by trucks, which have solved the domestic storage problem (Lima Drinking Water and Sewer Service and the World Bank Water and Sanitation Program, 2006).

Conclusions

The methodology to locate the population that depends on trucked water made it possible to estimate the number of users and their characteristics. The category corresponding to permanent network failure may be underestimated since not all of the DWC in the study area were interviewed. Using the methodology, it was possible to detect a group of users who choose not to connect to the network. The estimations show that the population supplied by trucks is higher than that reported by the population and housing census (INEGI, 2010).

Given the overexploitation of the aquifer, the problem with access to drinking water networks cannot depend on drilling more wells. Other regional public policies are needed.

The limited access to public services does not limit the purchase of land and/or housing in areas with non-urban land use.

In light of the excessive growth in "irregular" colonies, public policies are needed that enable housing or land near populated centers to gain access to services, where there are not only water, electricity and drainage services but also education, businesses and health centers.

As administrators of water, the DWC have responded as much as possible to the challenging increase in demand. It is notable that unpaid committees are able to meet the water needs of 277 879 residents with very limited government help.

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Irrigation Management for Potato Crops Based on Climate Variability: Application in Irrigation District 075, Fuerte River, Sinaloa, Mexico

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Abstract

Sifuentes, E., Macías, J., Ojeda, W., González, V. M., Salinas, D. A., & Quintana, J. G. (March-April, 2016). Irrigation Management for Potato Crops Based on Climate Variability: Application in Irrigation District 075, Fuerte River, Sinaloa, Mexico. *Water Technology and Sciences* (in Spanish), 7(2), 149-168.

A computer platform was developed for integrated irrigation scheduling and management of potato crops based on information and communications technology using the internet. This technology adjusted the water demands of the potato crop according to the climate variability observed over recent years in the Valle del Fuerte, Sinaloa, Mexico. The basis of the technology was an integrated irrigation scheduling model based on increasing degree-days, with the integration of Irrimodel software operated over the internet. The system has the following capabilities: a) generates irrigation plans based on different scenarios related to climate, water availability and water management; b) produces a highly accurate irrigation prognosis according to the development of the crop and the accumulation of degree-days, and c) generates and sends irrigation requests to the service providers. The technology was transferred to producers over three months and covered over 3 000 ha. Two levels of use were identified —a high application level by 56% of the area (1 738 ha) and a medium level by the remaining area. The area with a high application level was composed of 396 ha which used gravity irrigation and 1 334 ha which used sprinkler irrigation. In both areas, with gravity irrigation as well as sprinkler irrigation, there was an increase in application efficiency (18%), yield (7 t) and water productivity (1.5 kg·m^{-3}). The increase was greater with gravity than with traditional management. This work presents an analysis of the use of this technology on a large scale, as an option to adapt irrigation scheduling to the effects of climate change.

Keywords: Precision irrigation, degree days, climate change, irrigation areas.

Resumen

Sifuentes, E., Macías, J., Ojeda, W., González, V. M., Salinas, D. A., & Quintana, J. G. (marzo-abril, 2016). Gestión del riego enfocada a variabilidad climática en el cultivo de papa: aplicación al Distrito de Riego 075, Río Fuerte, Sinaloa, México. Tecnología y Ciencias del Agua*, 7(2), 149-168.*

Se desarrolló una plataforma computacional basada en tecnologías de información y comunicación (TIC´s) para la programación integral y gestión de riego por Internet en el cultivo de papa, la cual ajusta las demandas hídricas del cultivo de papa a la variabilidad climática observada en los últimos años en el Valle del Fuerte, Sinaloa, México. El fundamento de la tecnología fue un modelo de programación integral del riego basado en grados-día crecimiento (GD), integrándose a un software (Irrimodel) operado a través de Internet. El sistema cuenta con las siguientes capacidades: a) elabora planes de riego bajo diferentes escenarios climáticos, disponibilidad de agua y manejo; b) pronostica el riego con alta precisión de acuerdo con el desarrollo del cultivo y acumulación de GD; y c) genera y envía solicitudes de riego al módulo prestador del servicio. La transferencia a productores se hizo en tres meses en más de 3 000 ha, donde se presentaron dos niveles de uso. En 56% (1 738 ha), su aplicación fue con nivel alto, mientras que el resto con nivel medio. La superficie con nivel alto se conformó de 396 ha bajo riego por gravedad y 1 334 ha bajo riego por aspersión. Tanto en parcelas con riego por gravedad como de aspersión se incrementó la eficiencia de aplicación (Ea) (18%), rendimiento (7 t) y productividad del agua (1.5 kg·m^{-3}), siendo mayor en las de gravedad contra manejo tradicional. En este trabajo se presenta un análisis de esta tecnología a gran escala como alternativa para la adaptación de la programación del riego ante los efectos del cambio climático.

***Palabras clave**: riego de precisión, grados-día, cambio climático, zonas de riego.*

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Introduction

Given their high water content (80%) in relation to weight, potatoes are among the crops which are most sensitive to irrigation. The quality and quantity of the yields essentially depend on irrigation management. This is the fourth largest crop in northern Sinaloa, Mexico, with 12 000 to 14 000 hectares planted each year, 75% of which uses gravity irrigation, 22% sprinkler systems and 3% drip irrigation. The average production is 26 t/ha. This is also a crop which requires large investments, roughly $80 000/ha in production costs (Sagarpa, 2010) due to the very high application of inputs.

An increase in climate variability has been seen in northern Sinaloa over recent years, which has caused considerable changes in the phenological cycles of crops and increased the occurrence of extreme events such as droughts, freezes and floods. Given this situation, the traditional management of crops is becoming less precise, particularly in terms of irrigation and fertilization. Technologies are required that can adapt the management of crops to new climate scenarios (Ojeda, Martínez & Hernández, 2008). With the development of communications (internet) and informatics, agro-climate models can now be used to generate practical farming applications for producers to manage irrigation, infestations, diseases and for other purposes. Using the internet, climate data can be accessed in real-time from anywhere in the world, computing systems can be developed to be operated through the internet and various types of users can interact simultaneously (Ojeda, Sifuentes, & Unland, 2006).

Considering these factors, the INIFAP's Campo Experimental Valle del Fuerte (Cevaf) computing platform was developed for the 2008-2009 autumn-winter agricultural cycle using the Programa de Investigación Uso y Manejo del Agua (Water Research, Use and Management Program). This consists of communications technology and the *Irrimodel* software (Sifuentes, Quintana, Macías, & González, 2013) for real-time integral scheduling and management of irrigation using the internet, generating the conditions to use this technology on a large scale beginning with the 2009-2010 cycle. This system has the following capabilities (among others): 1) develop irrigation plans for different climate, water availability and management scenarios, 2) project irrigation with a high level of accuracy according to the crop's development, determined by the accumulation of growing degree-days (GDD) and 3) generate and send irrigation requests to the module that provides the hydraulic services.

The advantage of this tool over the traditional method is that the producer applies integral scheduling and irrigation models in real-time over the internet, in a simple manner. Thus irrigation can be pre-scheduled from any place where a person may be located. Another advantage is more efficient use of irrigation and fertilizers since optimal moisture levels can be maintained, along with the possibility of reducing the amount of nitrogenated fertilizers. These conditions also lower the risk of diseases such as *Rhizoctonia solani, Streptomyces scabies* (Thaxt) and *Phytophthora infestans*, which helps to significantly increase the quality of production (Avery, 1983).

This work presents the results from the use of this technology with a potato crop in Valle del Fuerte, in the northern portion of the state of Sinaloa, Mexico, during the 2009-2010 autumn-winter agricultural cycle. It reflects challenges involved in the first application of these models using the internet. Given the latent threat of extreme events such as droughts and freezes, this type of tool is crucial to address and reduce their effects. This technology is currently being adapted not only for potato crops but also for other crops and other regions in the state.

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Theoretical Background

Importance of Precision in Potato Crop Irrigation

The quality and quantity of tubers are related to correct irrigation schedules. Generally, poor scheduling is counteracted by increasing the application depth and frequency of irrigation, or agrochemicals are applied to prevent significant reductions in conventional yields. This practice is beginning to be questioned given uncertainty in the availability and amount of water, climate variability and pollution problems attributable to intensive agricultural practices.

Water is the largest component of the potato plant, up to 95% of green tissue and 85% of tubers. Under optimal growth and moisture conditions, a potato plant can replace its moisture contents through transpiration up to four times per day. The potato is more sensitive to water deficits in the soil than wheat, soy and beans, and its most sensitive phenological stages are the formation of stolons and tubers.

The FAO (1986) has reported that stressing potato crops by 50% of the potential evapotranspiration requirements will reduce the yield by 35% during the tuber formation stage, by 10% during the ripening stage and 22% during the vegetative stage. Drastic changes in the soil moisture from late and heavy irrigation can result in cracking or the formation of black hearts (internal necrosis) in the tubers. It can also contribute to the presence of other diseases including *Fusarium*, white mold and *Rhizoctonia* (UCLA, 2006).

An analysis by Dudek, Gerald and Marshall (1981) concluded that the scheduling of irrigation was worthwhile and beneficial if producers could apply irrigation with sufficient precision. Parker, Cohen-Vogel, Osgood and Zilberman (2000) determined that the program California Irrigation Management Information System (CIMIS) operated by the Water and Resources Department, at a cost of $850 000 dollars per year, conserves water and has other benefits that far outweigh the operating costs. Thus, irrigation scheduling has become known for its benefits (Marek *et al*., 2010).

Effect of Temperature on the Phenology of the Crop

The physiological age of a tuber is the product of the chronological age and environmental conditions. Physiological age is often measured by the growing degree-days (GDD) related to the appearance of each development stage, which is different for each variety (Jefferies & Lawson, 1991). That is, the development stages almost always occur when the same GDD value is accumulated regardless of the planting date and year, whereas calendar days vary widely (Table 1). Their daily estimation requires knowledge about the daily mean air temperature (T_a), according to the following equations (Ojeda *et al*., 2006):

$$DD = T_a - T_{c\text{-min}},\ \text{if } T_a < T_{c\text{-max}} \quad (1)$$

$$DD = T_{c\text{-max}} T_{c\text{-min}},\ \text{if } T_a \geq T_{c\text{-max}} \quad (2)$$

$$DD = 0,\ \text{if } T_a \leq T_{c\text{-min}} \quad (3)$$

where $T_{c\text{-}min}$ and $T_{c\text{-}max}$ are the critical minimum and maximum temperatures of the crop, which in the case of potatoes are 2 and 29°C, respectively.

In northern Sinaloa, the cycles of the crops planted in October and in December differ by nearly one month, which calls for changes in the scheduling of crop management practices. In addition to the effect of the planting date, climate variability and climate change also cause variations.

Climate Change Projections for Mexico and the State of Sinaloa

Climate change is a phenomenon that has recurred over the history of the planet, but

Table 1. Days to reach various accumulated degree-day (GDD) values for potato, alpha variety, for different planting dates, in the Valle del Fuerte, Sinaloa (Sifuentes, Macías, Apodaca, & Cortez, 2009).

	Planting date								
GDD	**01 oct.**	**10 oct.**	**20 oct.**	**30 oct.**	**10 nov.**	**20 nov.**	**30 nov.**	**10 dec.**	**20 dec.**
	Días								
800	33	35	38	42	47	50	53	54	54
900	37	40	43	48	53	57	60	61	60
950	40	42	46	51	57	60	63	64	63
1 000	42	45	49	55	60	64	66	67	66
1 100	47	50	56	62	66	70	73	73	72
1 150	49	53	59	65	70	74	76	76	75
1 500	69	76	83	89	93	96	97	97	96
1 600	76	83	90	95	100	102	103	103	101
1 700	82	90	97	102	106	108	109	109	107
1 750	86	93	100	105	109	110	112	111	109
1 800	90	96	103	108	102	113	115	114	112
1 850	93	100	106	111	115	117	117	116	114
1 900	96	103	110	114	118	120	120	119	117
2 000	103	110	116	121	124	126	126	124	122

at a slower pace than what is currently observed. The Intergovernmental Panel on Climate Change (IPCC) (2007) defines this as a statistically significant variation in the global state of the climate or in its variability over an extended time period.

The IPCC has developed four possible greenhouse gas emissions scenarios up to the year 2100, known as SRES or IEEE scenarios. These take into account possible changes in the global population, the degree of globalization, technological changes and the degree to which alternative energy sources are used (Nakicenovic & Swart, 2000). The four future emissions scenarios are B1 (low), B2 (medium), A1 (medium to high) and A2 (high).

Emissions projections are often used to speculate about future climate change. Their basic projections of socioeconomic, demographic and technological changes serve as a basis for many studies about vulnerability to climate change and evaluations of its impact on society (IPCC, 2007). Scenario A1B is a particular case belonging to scenario A1, representing a moderate, medium emissions scenario based on society having a balanced use of energy sources and fossil fuels.

For Mexico, most of the models project decreased precipitation throughout most of the country, although an increase is expected in other regions of the world. Seager *et al.* (2007) have shown that northwestern Mexico is in the process of becoming increasingly dry due to less precipitation and more evaporation.

Based on scenario A1B for the state of Sinaloa, Table 2 shows the mean temperatures that could be reached for the different climate change scenarios for periods P0 (1961-1990), P1 (2011-2040), P2 (2041-2070) and P3 (2071-2098).

With respect to precipitation, Table 3 shows the variability in precipitation for three projection periods: P1 (2011-2040), P2 (2041-2070) and P3 (2071-2098), and the base period P0 (1961-90), for the state of Sinaloa.

Agriculture is one of the activities most affected by this phenomenon since the development of crops depends on the climate (mainly

Table 2. Mean temperatures reached for the different climate change scenarios in the state of Sinaloa, Mexico (IMTA-INIFAP, 2011).

Variable	Period	*P*0	*P*1	*P*2	*P*3
Mean temperature	Annual	24.1	25.2	26.3	27.2
	June-October	27.9	29.1	30.2	31.1
	October-March	21.0	22.1	23.1	24.0
Mean maximum temperature	Annual	31.6	32.2	33.4	34.5
	June-October	33.9	34.4	35.7	36.8
	October-March	29.2	29.8	31.0	32.0
	Mes más caliente	35.6	36.1	37.3	38.2
Mean minimum temperature	Anual	16.8	17.0	18.1	18.9
	Junio-June-October	21.7	22.2	23.2	24.0
	October-March	12.7	13.4	14.5	15.3
	Coldest Month	10.1	10.8	12.0	12.8

Table 3. Variability in precipitation for three projection periods and the base period for the state of Sinaloa, Mexico (IMTA-INIFAP, 2011).

Variable	*P*0	*P*1	*P*2	*P*3
Annual precipitation	755.8	677.2	663.7	619.8
Precipitation October-March	176.9	122.6	113.0	96.4
Precipitation June-October	629.5	602.8	598.9	568.6
Precipitation, rainiest month	196.7	193.2	190.3	184.6

temperature). Failing to take adaptation and mitigation actions for Sinaloa, a predominantly agricultural state, could have catastrophic consequences for the state's economy.

Potential Impacts of Climate Change on Agriculture

In terms of agricultural processes, climate change should be seen as a current problem for which decision-makers require information to develop planning processes and public policies to reduce the sector's socioeconomic vulnerability to the impact of climate variability and climate change. Both positive and negative impacts are possible, as follows:

Positive Impacts

- Possibility of new crops.
- Longer period for crop development.
- Increased production from more $CO_2\uparrow$.
- Accelerated ripening.
- Reduction in the severity and duration of freezes.
- More harvests per year.

Negative impacts

- Higher incidence of infestation and diseases.
- Less crop diversity.
- Crop damage due to extreme heat.
- More intense cyclones and floods.
- Less effective herbicides and insecticides.
- Less reliable predictions (planning difficulties).
- Less production due to shortening of the cycle.
- More water and thermal stress.

- Problems with sufficient cold hours.
- Increased peak irrigation demand.
- Need for new varieties.

Given this situation, adaptation and mitigation strategies need to be developed to respond to the impact of climate change on agricultural systems in a timely manner.

Management of Irrigation Zones

Irrigation zones, such as irrigation districts, have primarily been operated based on empirical rules obtained through the accumulated experience of operations personnel. Its application has not permitted optimizing the use of water, land, capital and human resources available in the nation's districts. Although efficient water management in the irrigation districts is conceptually simple, in practice many different types of secondary problems are involved (cultural, social, economic and technological). The combined result is low water use efficiency. One of the factors that most affects efficiency is the procedure to determine the volumes of water needed for operations. The main factors that affect their estimation are:

- In many cases, irrigation services are scheduled by giving priority to the ease in hydraulically managing the distribution network rather than the needs of the crops.
- When the crops are taken into account, planning is based on general estimates of the water consumption needs of crops (water requirements) and not on essential factors such as the soil, spatial variability and weather conditions.
- In many cases, when scheduling according to user demand, this is based on traditional factors or only on empirical and subjective judgments about the need for irrigation.
- Although the nature of the problem is known, there is concern that the causes have been accepted as "necessary evils," and application efficiencies are below 60%, indicating serious problems rather than efficiency.

While there has been interest over recent years about improving the efficient use of water for plot irrigation, efforts are inconclusive when adequate methods are not used and are not combined with current technological levels, such as the development of informatics and electronics and scientific advances in soil physics, vegetable physiology and agro-climatology (Exebio, Palacios, Mejía, & Carmona, 2005).

The Role of Information and Communications Technologies (ICT) in Modern Agriculture

Globally, agriculture has been influenced by the new technological paradigm and has thereby benefited from enormous advances in informatics. The use of information and communication technologies (ICT) has considerably improved the work of producers, researchers and all those working in the agricultural sector (Pérez, Milla, & Mesa, 2006). According to the interests expressed by agriculturalists, Gonzalez (2003) reported that the agricultural tasks to which informatics could be applied are:

- Technical advice about crops: the use of software to answer concrete questions about crop practices, including soil preparation, irrigation systems, determination of infestation and diseases.
- Accounting, market prices, investment calculations, inventories and transactions, calculation of agricultural inputs, etcetera.
- Financial information and management.
- Crop planning and management: selection of cultivation areas, projection of planting dates.

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- Calculation of insecticide doses: per unit area, application recommendations
- Local weather: maintaining daily, monthly and annual records of rainfall, precipitation, relative humidity, radiation and other meteorological variables that are highly important to agricultural production.

Many ICT projections have been applied to agriculture, such as those presented in the Jornadas de Agroinformática (INTA, 2008), the first and second Argentine Conference on Agro-informatics (Congreso Argentino de Agroinformática) in 2009 and 2010. For example:

- Simulation environment, monitoring and remote control of a drip irrigation system.
- Determination of management zones using soil surveys and informatics tools.
- Digital processing of multispectral aerial images to quantify fallen sugar cane.
- Simulation of the carbon dynamic in soil subject to direct planting and traditional tillage.
- *Informe de estado hídrico de suelos* information system (report of water status of soil).
- Model to simulate the phenology of soy.

Simulation programs greatly help to estimate the water needs of crops and, thus, to calculate irrigation scheduling. They also make it possible to generate criteria for irrigation planning and management, which improves the use of water resources (Arteaga, Ángeles, & Vázquez, 2011).

The internet is a useful tool for rural and agricultural development, providing new sources of information, opening new communication channels for the rural sector and agricultural organizations. This network offers a way to bridge the gap between development professionals, the rural population and agricultural producers through dialogue and interaction. It also supports alliances and interpersonal networks as well as transverse and parallel connections among organizations. The main benefits also include more efficient use of resources for development, less duplication of activities and lower communication costs, as well as access to information and human resources worldwide.

Methodology

Generation of the Integral Irrigation Scheduling Model

The scheduling model used was created by Ojeda, Sifuentes, Slack and Carrillo (2004) for the Valle del Fuerte, which was validated for the study area. The model is composed of the parameters crop coefficient (K_c), root depth (D_r) and the abatement factor (F), expressed as non-linear functions with GDD as the independent variable (x). These self-adjust to the climatic variability present over the long planting season in this region (September to January) and to the effects of climate change (Table 4). These conditions create problems for adaptation when using parameters expressed in calendar days, as traditionally used.

The variable K_{co} is the crop coefficient for the first phenological stage, which mainly depends on evaporation from the soil; K_{max} is the maximum value of K_c during development; x_{Kmax} corresponds to an auxiliary variable defined by the GDD when the crop coefficient is at its maximum; α_1 is a regression parameter obtained by fitting the experimental data; *erfc* is the complementary error function and x is an auxiliary variable calculated with the following expression:

$$x = \frac{GDD}{\alpha_o}$$

where GDD are the growing degree-days from planting or emergence until a determined

Table 4. Scheduling parameters used for integral scheduling of potato irrigation for northern Sinaloa, Mexico (Ojeda, Sifuentes, Slack, & Carrillo, 2004).

Variable	Model	Parameter
Crop coefficient	$K_c = K_{max}\, erfc((\frac{x - x_{Kmax}}{\alpha_1})^2)$ If $Kc < K_{co}$, then $K_c = K_{co}$	$K_{max} = 1.3$ $XK_{max} = 0.6$ $\alpha_1 = 0.45$ $Kc_o = 0.2$
Root depth	$D_r = D_{ro} + (D_{rmax} - D_{ro})\left\{1 - \exp\left[-\frac{(GDD_n)^2}{\alpha_2^2}\right]\right\}$	$D_{ro} = 0.15$ m $D_{rmax} = 0.7$ m $\alpha_2 = 600$
Abatement factor	$F = \alpha_3 - \alpha_4 K_c$	$\alpha_3 = 0.68$ (gravity), 0.45 (sprinkler) $\alpha_4 = 0.1$

time and α_o are the GDD required to reach maturity, calculated as already explained.

D_{ro} and D_{rmax} represent the planting depth and maximum root depth, respectively. The value α_2 of the model was empirically adjusted from an approximate value to $^2/_3$ the GDD, at which point the crop reaches its maximum root depth. The values of parameters α_3 and α_4 for the abatement factor *F* were calibrated empirically, taking into account the crop's sensitivity to water stress and the gravity and sprinkler irrigation practices used in the area.

The experimental values of K_c, *F* and D_r were obtained from two plots on which the *alpha* variety was planted. Both were located under 1 200 m from an automated weather station. Their characteristics are shown in Table 5.

The baseline values of K_c used in the previous plots were proposed by Martin, Slack and Pegelow (1996). The parameter D_r was obtained from the SCS-Scheduler v. 2.0 program developed by the University of Michigan, United States and the Soil Conservation Service (Shayya, Bralts, & Olmstead, 1990; Shayya & Bralts, 1991).

Development of the Computing Platform

The computing platform contained three elements: 1) real-time climate link to the agro-climate network in the agricultural zones, 2) a virtual server managed by the Cevaf and 3) the *Irrimodel* software (Sifuentes *et al*., 2013).

To obtain the climate data in real-time from the agro-climate stations, the *Addvantage Pro software* was used, connected to an A840 Telemetry Gateway device which uses Radio Telemetry Units (RTU). These data were obtained from the internet, as shown in Figure 1. To establish the connection, the *Addvantage Pro* server, username and password were configured to replicate the climate data from the stations connected to the RTU.

The *Irrimodel* program was downloaded from the virtual server (http://cevaf.redirectme.net) and its user databases were stored. After downloading, a username and password are required to operate it. The program was developed with a multi-layer architecture using Datasnap technology from Delphi, which enables separating the business logic in an applications server and the presentation with the VCL components that can be connected through the internet using *DBEXPESS*.

The system is designed for three types of users: 1) the system administrator, 2) producers and technicians and 3) irrigation module operators. Each user can have access to a specific configuration of the system according to their operating needs, which is defined

Table 5. General characteristics of the experimental plots to generate the scheduling parameters K_c, F and D_r in function of GDD (Ojeda et al., 2004).

Name	Area (ha)	Clay (%)	Sand (%)	Usable moisture (mm)	Irrigation System
GRAV	50	57.8	22.8	14.7	Gravity (furrows)
ASP	50	51.8	26.8	14.5	Sprinkler (center pivot)

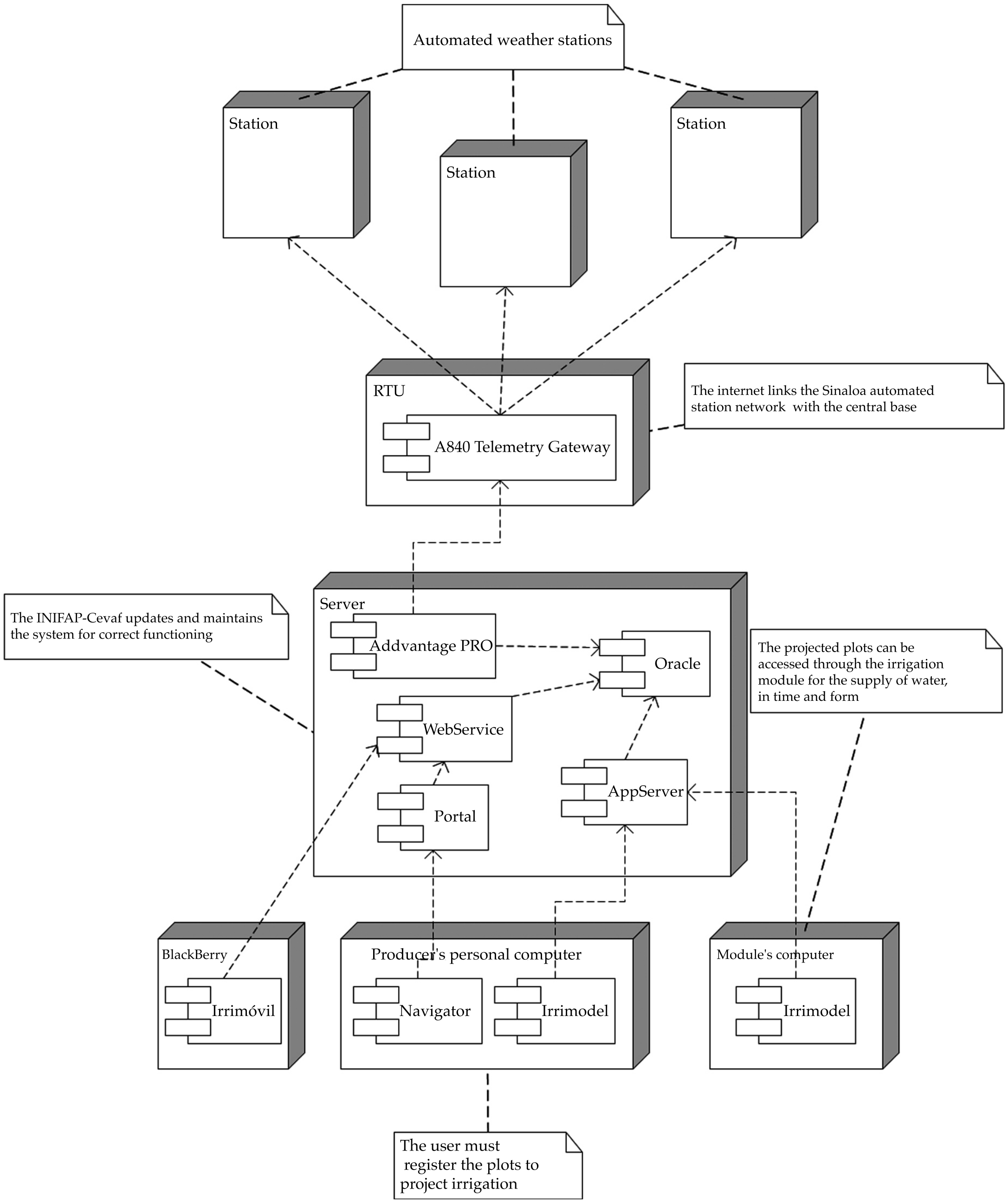

Figure 1. Flow diagram of the processing of climate information for real-time scheduling.

in coordination with the administrator, as shown in Figure 2.

The main benefits from using the *Irrimodel* program are:

- Develop irrigation plans for a complete biological cycle under different scenarios for climate, water availability, soil and irrigation systems.
- Adjust the water demand of the crop daily from the time of planting and considering climate variability.
- Project irrigation with a high level of accuracy according to crop development, determined by growing degree days (GDD), or thermal temperature.
- Propose indicators to aid monitoring and the efficient application of irrigation.
- Present and predict the phenological stages of the crop.
- Helps to evaluate irrigation management for one or a group of plots at the end of a growing cycle.
- Access to real-time and historic climate and soil moisture databases.
- The program also has the advantage of improving the amount of fertilizers used, mainly nitrogenated, and reducing the risk of diseases since optimal moisture levels can be maintained throughout the crop's growing cycle. This helps to significantly increase the quality of production.

Adoption of the Technology

Training and Technical Support

In September 2009 technicians and producers began to be trained in the operations of the system and its applications. The potato producers in northern Sinaloa participated through the local Potato Product System (Sistema Producto Papa), also in the Santa Rosa irrigation module, in irrigation district 075, where roughly 4 000 ha of potato are grown. The users who participated in the training program received technical support (agronomic and informatics) throughout the crop cycle through the webpage or direct visits.

Establishment of Plots

Two types of plots were established during the project: 1) pilot plots with better control over the application of the technology and 2) adoption plots where the technology was applied directly by the users. There were four pilot plots (Table 6) in the municipalities of Ahome, Guasave and El Fuerte.

The adoption plots were entirely managed by the uses who received training in the courses that were held as well as users who requested to participate during the growing cycle. Most of these parcels were located in the municipalities of Ahome and Guasave, although some were also established in the municipality of El Fuerte (Figure 3).

Results and Discussion

Degree of Use of the Technology

The degree to which the technology was used in the plots in the system varied due to different circumstances, particularly the internal operations of each producer. To quantify these differences, two categories of parcels were defined: 1) high level, with 90 to 100% application of the technology; 2) medium level with 40 to 70% application. A total of 56 plots were included covering 3 067.4 ha, of which 1 738.4 were high and the rest (1 329 ha) were medium (Table 7).

Analysis of Pilot Plots

Cevaf Plot

This plot was established with gravity irrigation using the fianna variety. It was planted

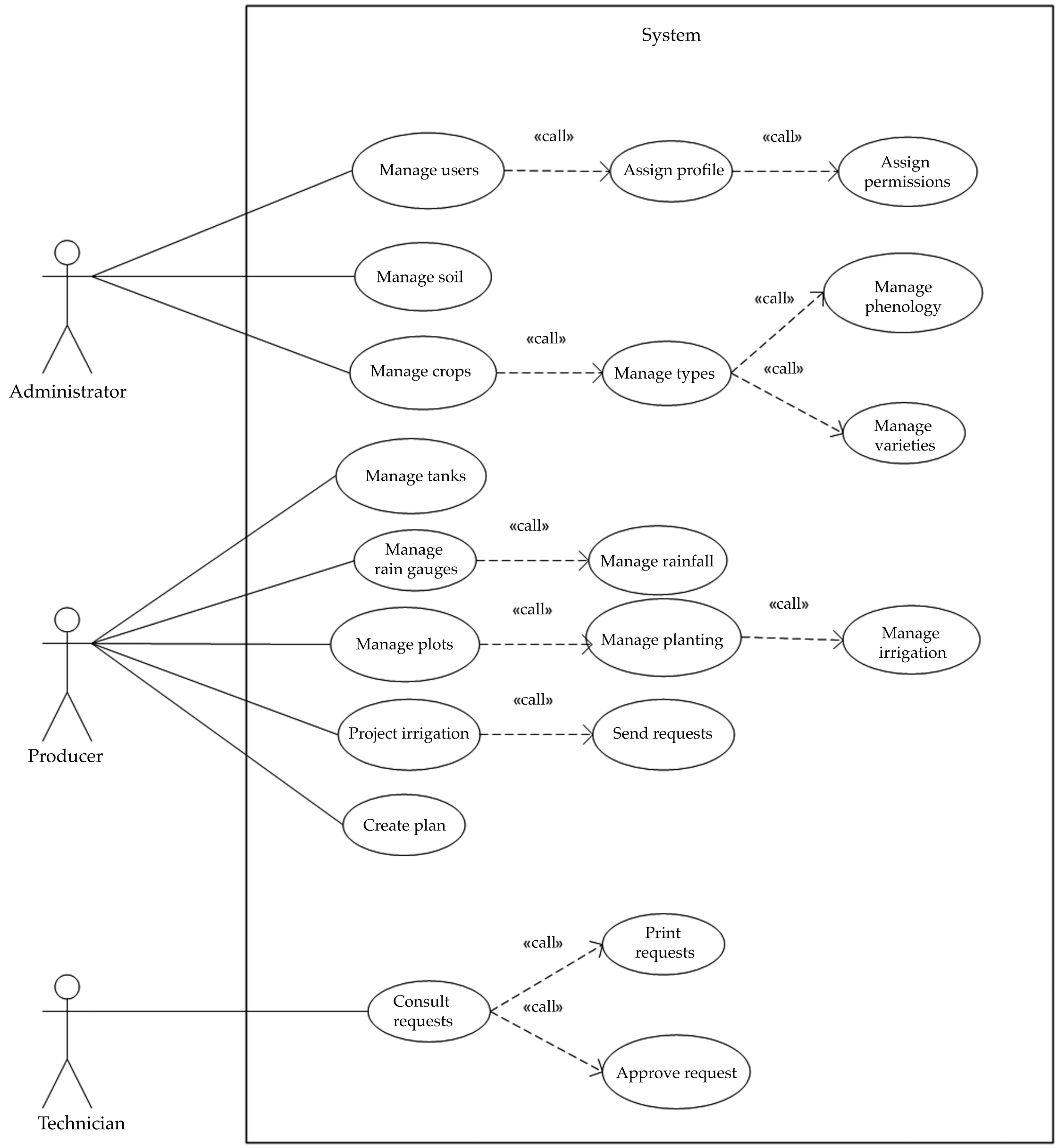

Figure 2. Diagram of cases of using the *Irrimodel* system..

11/11/09 with a density of 4 seeds·m^{-1}. The dry planting method was used (with immediate germination irrigation), with 80 meter-long furrows separated by 80 cm. Six irrigations were applied, with a total water requirement (net total application depth) of 36.39 cm and net depths of 5.61 to 6.3 cm for the auxiliary irrigations. The total gross application depth was 57.74 cm, with an average efficiency of 63.02%.

Lot "9 de Diciembre" was used as the witness plot, with 9 hectares having similar soil conditions, varieties, planting dates and irrigation systems. This plot was located in the municipality of Ahome, next to the town of Benito Juarez, in the Santa Rosa irrigation

Table 6. General characteristics of the pilot plot.

No.	Name	Area (ha)	Soil	Irrigation system	Planting date	Variety	Location
1	Cevaf	0.2	Clay	Gravity	11/11/09	Fianna	Cevaf (Guasave)
2	Hugo Gómez	20	Silty clay	Sprinkler	29/10/09	Ágata	Km 24, canal valle del Fuerte (El Fuerte)
3	Lote B-41	105.4	Clay loam	Sprinkler	28/12/09	Atlantic	Ejido Luisiana (Ahome)
4	Lote B-73	60	Clay loam	Sprinkler	19/11/09	FL-1867	Ejido 1º de Mayo (Ahome)
Total		**185.6**					

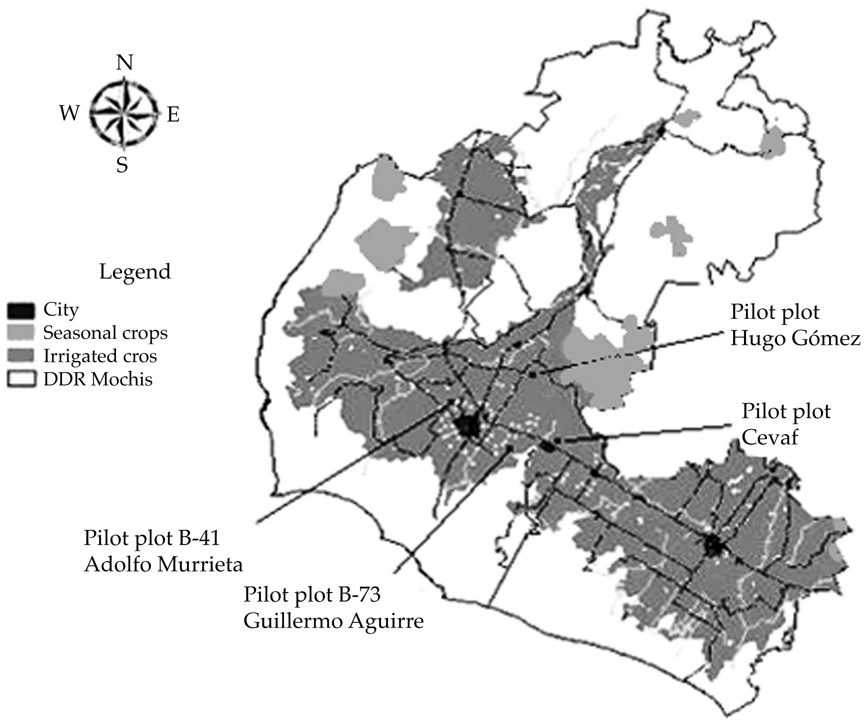

Figure 3. Potato plots (light grey) where integral irrigation scheduling and management technology is used through the internet in the Valle del Fuerte.

Table 7. Degree to which the irrigation management technology is used through the internet, in two types of potato users in the Valle del Fuerte, 2009-2010 autumn-winter cycle.

Degree of use	Area		Number of producers	Number of plots	Average area (ha)	Number of owners
	ha	%				
High	1 738.4	56.67	9	41	42.4	174
Medium	1 329.00	43.33	8	15	88.60	130
Total	**3 067.40**	**100.00**	**17**	**56**	**54.77**	**304**

module. Six irrigations were applied, including pre-planting, with an irrigation application depth of 78 cm and an average efficiency of 51% (12% less than the Cevaf plot).

Figure 4 compares these plots based on seven variables: yield, net application depth, applied irrigation, gross application depth, efficiency, volume and water productivity. A yield of 43.06 t·ha^{-1} was obtained with the Cevaf plot and 38 t·ha^{-1} with the witness plot. The applied water depth was 20 cm (2 000 m^{3}·ha^{-1}) less than the witness. Water productivity of 7.33 kg·m^{-3} and 4.87 kg·m^{-3} was estimated for the Cevaf and witness plots, respectively.

In addition, the quality of the tuber improved significantly. The plot managed by the project's technology resulted in 20% more first-class tubers than the witness plot and a lower number of third-class tubers (3.5 cm smaller diameter) (Figure 5).

Hugo Gomez Arroyo Plot

This plot was established with sprinkler irrigation (center pivot) and 90 cm of separation between furrows. The agata variety was used, planting date 29/11/09 and a density of 4 seeds·m^{-1}. The first irrigation was applied before planting on 11/10/09. A total of 9 irrigations were applied, including pre-planting, with a total water requirement of 39.39 cm and net application depths for each irrigation of 4.18 to 6.11 cm. The total gross application depth was 46.96 cm, with an average efficiency of 83.87% (Table 8).

Lot B-41

Sprinkler irrigation was used in this plot (front advance). The atlantic variety was established with planting date 08/12/09 and a density of 4 seeds·m^{-1}. Seven irrigations were applied (including pre-planting), with a total irrigation requirement (net total application depth) of 35.59 cm and required application depths for each auxiliary irrigation of 3.8 to 5.12 cm. The total gross application depth was 41.07 cm, with an average efficiency of 86.65% (Table 9).

Lot B-73

The FL-1867 variety was established on this plot, with planting date 19/11/09 and a density of 4 seeds·m^{-1}. Eight irrigations were

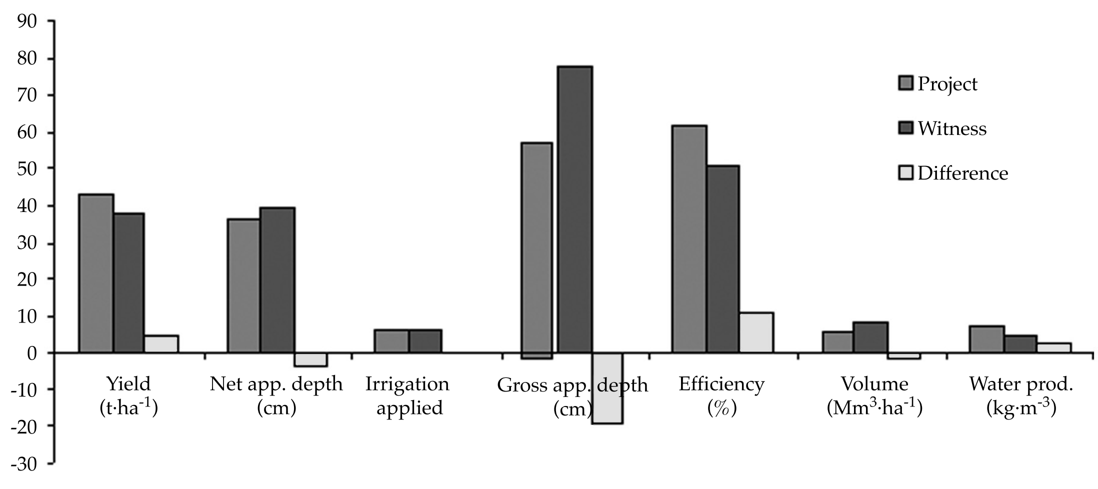

Figure 4. Results obtained from the potato plot managed with the project's technology compared to a witness plot in the Valle de Fuerte, SInaloa, 2009-2010 cycle.

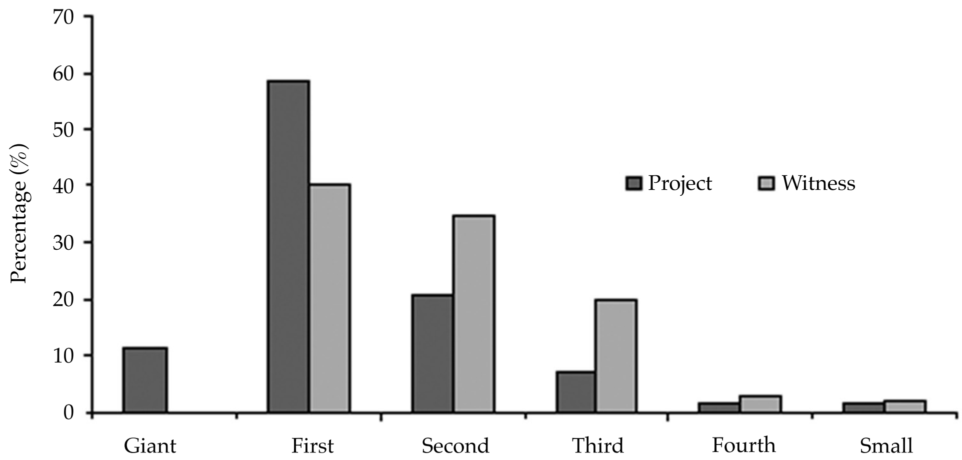

Figure 5. Distribution of the Quality of the crop in the Cevaf plot compared with the witness (lot 9 de Diciembre).

Table 8. Irrigations applied in the Hugo Gomez Arroyo pilot plot, scheduled according to climate variability, in Irrigation District 075, Río Fuerte, Sinaloa, 2009-2010 autumn-winter cycle.

Irrigation No.	Irrigation date	Irrigation days	Intervalo (días)	Net app. depth (cm)	Gross app. depth (cm)	Efficiency (%)	Stages
1	11/10/2009	-	-	8.81	10.15	86.80	Pre-planting irrigation
2	16/11/2009	17	17	3.31	4.65	71.18	Budding
3	25/11/2009	28	11	3.62	4.53	79.91	Stolonization initiation
4	04/12/2009	37	9	3.84	4.16	92.30	Stolonization initiation
5	14/12/2009	47	10	4.01	4.16	96.39	Stolonization initiation
6	23/12/2009	56	9	4.90	4.96	98.79	Stolonization initiation
7	04/01/2010	67	11	3.85	4.91	78.41	Tuber initiation (diam: > 1 cm)
8	14/01/2010	77	10	3.81	4.54	83.92	Tuber initiation (diam: > 1 cm)
9	23/01/2010	86	9	3.24	4.91	65.98	Tuber development (diam: 3-5 cm)
				39.39	**46.97**	**83.87**	

applied with sprinkler systems (center pivot). The total water requirement was 30.47 cm and the required application depths for each irrigation were 3.8 to 5.11 cm. The total gross application depth was 41.88 cm, with an average efficiency of 72.75%.

Overall Analysis

This analysis was performed based on the results obtained from the plots with a high use of the technology to estimate the commercial capacity of this technology. This group of plots was compared to another group with traditional management, chosen randomly, and located in Santa Rosa irrigation model, ID-075, with 4 000 ha of potato. The plots with gravity (396 ha) and sprinkler irrigation (1 334 ha) were analyzed separately. The variables analyzed were efficient water use, yield, water productivity and water requirements by planting date.

Efficient Water Use

With gravity irrigation, the application efficiency of all the plots evaluated was greater than the average efficiency in the region,

Table 9. Irrigations applied in lot B-41 scheduled while taking into account climate variability, in Irrigation District 075, Río Fuerte, Sinaloa, 2009-2010 autumn-winter cycle.

Irrigation no.	Irrigation date	Irrigation days	Interval (days)	Net app. depth (cm)	Gross app. depth (cm)	Efficiency (%)	Stage
1	07/11/2009	-	-	10.45	11.80	88.52	Germination irrigation
2	02/12/2009	-	-	3.86	3.89	99.22	Germination irrigation
3	15/01/2010	38	38	3.49	4.84	72.10	Emergence
4	28/01/2010	51	13	3.62	4.96	72.98	Stolonization initiation
5	10/02/2010	63	12	4.53	5.00	90.68	Tuber initiation (diam: > 1 cm)
6	22/02/2010	75	12	4.78	5.70	83.94	Tuber initiation (diam :> 1 cm)
7	06/03/2010	88	13	4.85	4.88	99.48	Tuber development (diam: 3-5 cm)
				35.59	**41.07**	**86.65**	

which is 51%. An increase of 5 to 30% was observed, that is, application efficiencies of up to 80% are possible with the support of this technology (Figure 6).

The behavior of the irrigation application efficiencies with sprinkler systems was similar to that of gravity. The average efficiency in the region was 78% while the efficiency obtained with 10 of the 12 plots evaluated ranged from 81 to 97%. The two others were under the mean for the region. That is, with scientific management, a maximum increase of up to 19% is possible (Figure 7).

Analysis of Yield

The average yield in the study area was 27 $t \cdot ha^{-1}$. It is worth mentioning that the mean yield in the state is 26 $t \cdot ha^{-1}$. Only one of the 13 plots using gravity irrigation and managed with the system did not exceed the mean (cane seedlings), as observed in Figure 8. In terms of this variable, the Cevaf, Remolacha and Viuda plots are notable, with 43, 40 and 33 $t \cdot ha^{-1}$, respectively. That is, an increase of 16, 13 and 6 $t \cdot ha^{-1}$, respectively.

With sprinkler irrigation, the average yield in the region was 35 $t \cdot ha^{-1}$, and therefore most of the plots had this same value, with the exception of three (Figure 9) which had a yield of roughly 44 $t \cdot ha^{-1}$. It is worth mentioning that one of these three plots was a pilot plot.

Water Productivity

This is one of the most important variables from an environmental and economic perspective since it is an indicator of the production systems' efficiency in transforming water input into products, which in turn translates into benefits for the society, such as food and material goods. Only 2 of the 13 plots managed with gravity irrigation did not exceed the mean productivity, which was 4.2 $kg \cdot m^{-3}$, the rest ranged between 4.7 and 7.3 $kg \cdot m^{-3}$. The maximum value was obtained with the Cevaf plot where the proper application of the technology was best controlled.

The increase in water productivity with sprinkler irrigation was more significant, compared to the yield. This indicates the ability of these systems to apply lower water depths and maintain optimal soil moisture with the help of the integral irrigation scheduling technology. The water productivity ranged from 6.5 to 11 $kg \cdot m^{-3}$, with a mean of 6.1 $kg \cdot m^{-3}$.

Potential Impacts of the Technology

Environmental Impacts

Better management of the scheduling of irrigation translates into better control over

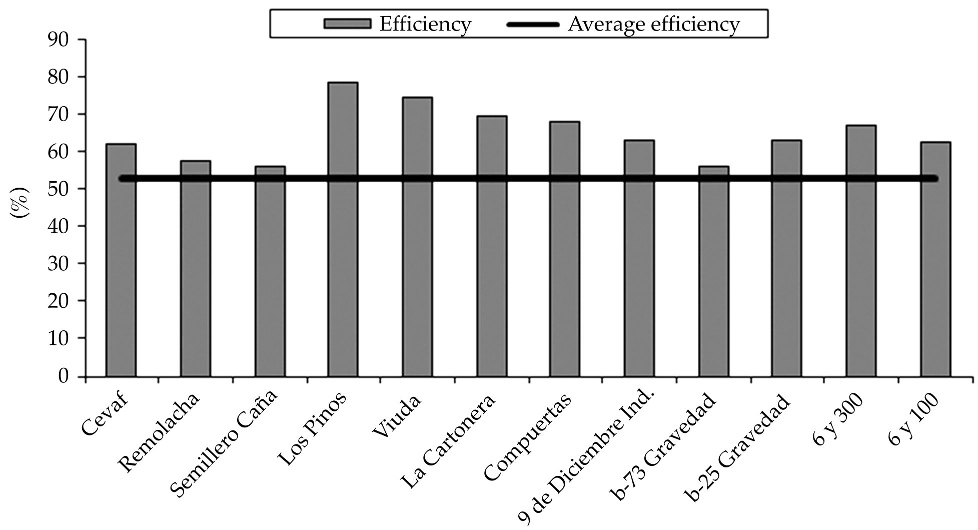

Figure 6. Irrigation efficiency in potato plots managed with the technology and using gravity irrigation, compared with average efficiency.

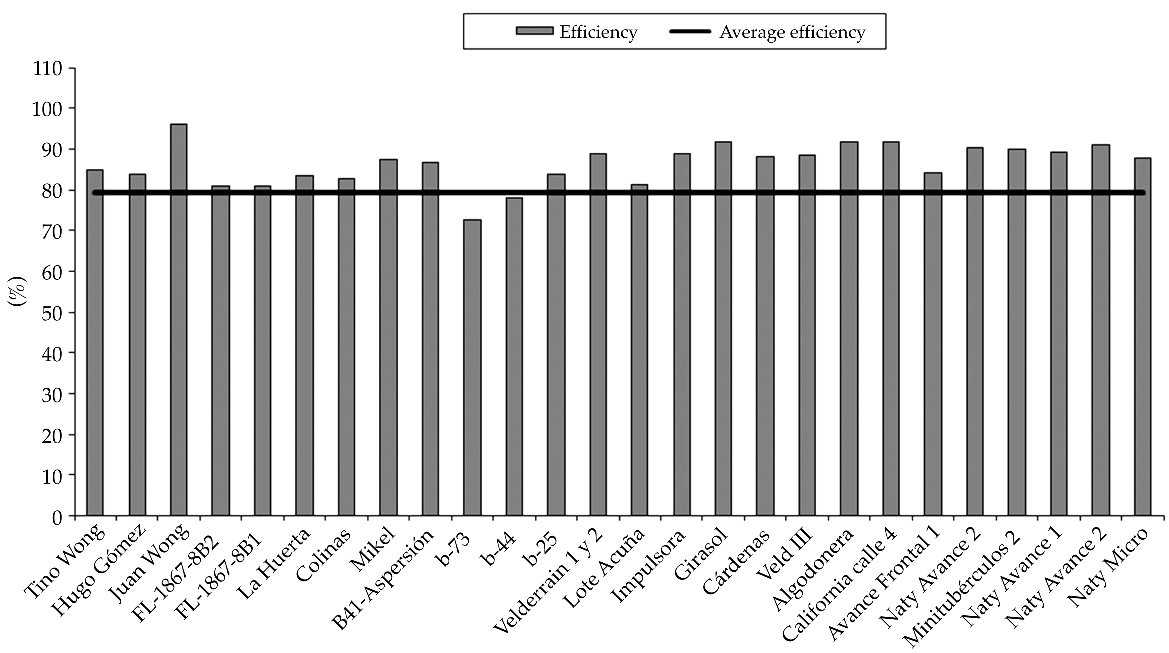

Figure 7. Irrigation efficiency in plots with sprinkler irrigation and managed with integral scheduling, compared with average efficiency.

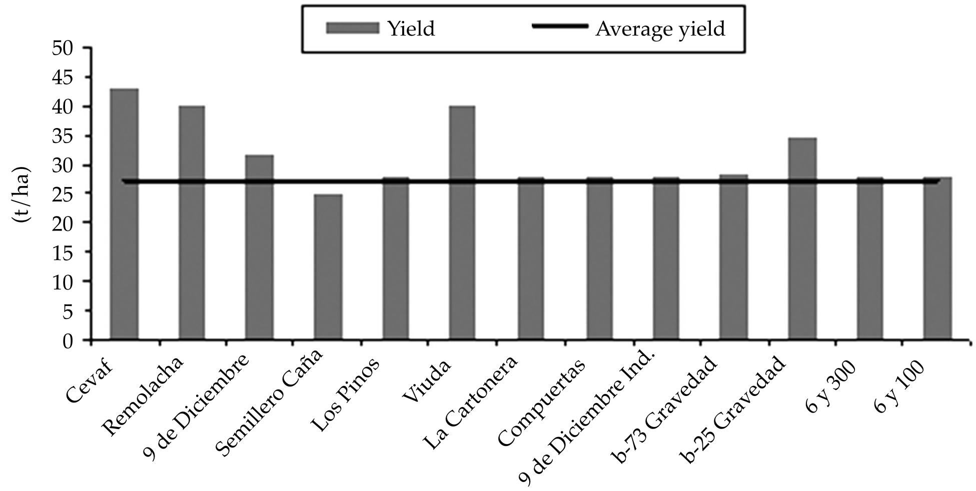

Figure 8. Yield obtained in plots with gravity irrigation and managed by the technology, compared to the average of a representative region.

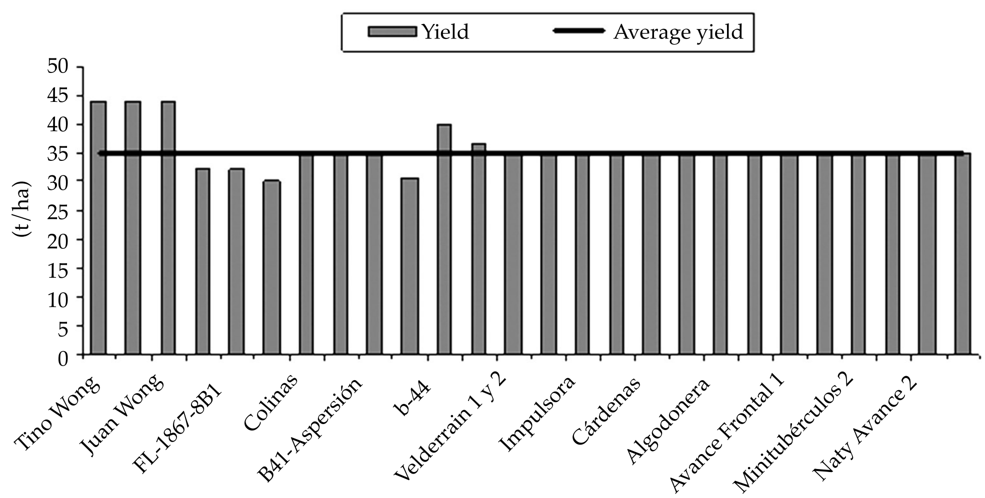

Figure 9. Yield obtained in plots with sprinkler irrigation and managed by the technology, compared to the average of a representative region.

salinity and environmental pollution. Using the system to accurately apply irrigation will increase the certainty and confidence of agriculturists when scheduling irrigation. This technology is expected to help to reduce conventional application depths for potato crops by 20% without negatively affecting yields. This will enable reducing the amount of nitrogen applied, which currently is 200 units per hectare.

Economic Impacts

The potato crop in northern Sinaloa contributes roughly 20% of the total economic revenue, equal to around $1 400 million Mexican pesos. The use and management of this technology not only decreases the irrigation volume but also ensures potential yields by taking into account both the crop's water requirement and climate conditions.

Technological Impacts

Given a lack of easily accessible and usable scientific tools, agriculturists apply inputs empirically. Therefore, management of irrigation using the internet is an indispensable tool to initiate a technological change in how irrigation is scheduled and applied. The present technology serves as a basis to reduce the uncertainty in potato production systems caused by the climate, among other factors, in keeping with current technological advances and the growing competition among agriculturists.

Social Impacts

Increasingly more agriculturists have access to the internet. The computing platform will undoubtedly initiate a new phase in agriculture in Sinaloa by providing a new way to present and transfer the available knowledge to agriculturists and the society. This tool will help to rapidly promote a water culture and reduce social problems generated by disputes over this resource. According to Massieu (2004), potato generates 90 daily wages·ha^{-1}, which in Sinaloa represents roughly 1 260 000.

Conclusions

- A robust computing platform is available to manage irrigation through the internet, with a focus on climate variability and climate change, and is prepared to include other crops and agro-meteorological applications.
- Using the internet to manage irrigation with the *Irrimodel* program enables the involvement of a large number of producers.
- Efficiencies of 60 to 80% in the use of water can be achieved with gravity irrigation, 85 to 90% with sprinkler systems and 95% with drip irrigation, in addition to improving the quality and quantity of yields. This tool also optimizes the use of other inputs such as fertilizers by reducing periods of water stress and the water depths applied by excessive irrigation.
- The system will also contribute to improving irrigation service for the users in the modules, since the supervisor can monitor, in nearly real-time, irrigation requests generated by the producer through the internet and improve the operation of the canals.
- This is an excellent tool to reduce the negative effects of extreme events such as extended droughts and freezes, and also serves as an option for adaptation to climate change.

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Conventional gravity irrigation in potato cultivation in northern Sinaloa, Mexico.

Photo: Fredy González Hernández.

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