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UN ENFOQUE INTEGRADO PARA LA GESTIÓN DE LAS AGUAS SUBTERRÁNEAS

POR:

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RESUMEN GENERAL

UN ENFOQUE INTEGRADO PARA LA GESTIÓN DE LAS AGUAS SUBTERRÁNEAS

POR:

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El agua es un recurso vital para el desarrollo de los ecosistemas, el crecimiento económico y la sostenibilidad. Alteraciones como el cambio climático y la falta de gestión del suministro de agua en la planificación urbana, generan un detrimento en la disponibilidad provocando un estado insostenible. Una de las condicionantes que se han considerado en el análisis y propuestas de la gestión del agua subterránea, es enfocar esta evaluación a su disponibilidad y uso; en concreto a la gestión de su oferta y demanda. El objetivo de este trabajo es desarrollar una metodología específica para establecer un Enfoque Integrado para la Gestión Urbana del Agua Subterránea. El trabajo consta de cuatro estudios. El primer estudio utiliza datos meteorológicos y de agua subterránea para diseñar una metodología que evalúe los factores influyentes en el sistema de agua subterránea en la ciudad de Chihuahua, lo cual es parte de la gestión de la oferta. El segundo estudio diseñó una metodología (gestión de la demanda) basada en el control del caudal/presión para lograr una transformación eficiente de un sector con suministro de agua intermitente (IWS) a suministro constante (CWS). El tercer estudio aplicó la metodología del segundo estudio para transformar varios sectores a CWS, cuantificando el impacto en el ahorro de agua, es decir integrar e interrelacionar la gestión de la oferta/demanda. El último estudio evaluó el riesgo de utilizar agua residual tratada como fuente de recarga en un tratamiento de suelo-acuífero, como parte integradora de un ciclo de gestión hidráulico urbano. El resultado de las cuatro fases permite contribuir a un análisis extenso e intensivo del estado actual del uso del agua subterránea en un sitio urbano, revisando y mejorando las metodologías utilizadas con el propósito de avanzar hacia un uso sostenible de este recurso.

ABSTRACT

INTEGRATED APPROACH TO GROUNDWATER MANAGEMENT OF THE CITY OF CHIHUAHUA

BY:

DAVID HUMBERTO SÁNCHEZ NAVARRO

Water is a vital resource for the development of ecosystems, economic growth, and the sustainability of society. The challenges cities face to achieve sustainable water use are increasingly complex. Alterations as climate change, deterioration of water sources, lack of consideration of the drinking water supply capacity in urban planning generate a detriment to water availability causing an unsustainable state. The objective of this work is to develop a specific methodology to set an Integrated Approach to Urban Groundwater Management (IAUGM). This framework evaluates the general situation of the use of groundwater in urban areas; seeking to improve methodologies depending on the current state. Groundwater management mainly focuses on the availability and use of the resource, summarized in supply management. However, it is essential for IAUGM to consider demand management. The work consisted of four case studies. In the first study, meteorological and groundwater data were used to design a multi-step approach to assess the influential factors on the groundwater system in the City of Chihuahua, Mexico. In the second study, a methodology-based on flow/pressure control was designed to accomplish an efficient transformation from an intermittent water supply (IWS) sector to a constant water supply (CWS), in the City of Chihuahua. In the third study, the previous methodology was used to transform several sectors to CWS, quantifying the impact in water savings in the entire City. The last study, evaluated the risk of using treated wastewater as a source of water recharge in a soil aquifer treatment. The result of the four studies can contribute to an extensive and intensive analysis of the current state of groundwater use in an urban site, reviewing and improving the methodologies used to move towards a sustainable use of this resource.

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GENERAL INTRODUCTION

Water is a vital resource for the development of ecosystems, economic growth, and the sustainability of society. The challenges urban orbs face to achieve sustainable water use are increasingly complex. The population growth coupled with the need for industrial development has generated an uncontrolled increase in water demand. Alterations as climate change and the deterioration of water sources, generate a detriment to water availability causing an unsustainable state (Cosgrove and Loucks, 2015).

Six billion inhabitants have settled in areas with low or very scarce water availability, generating an imbalance between water capacity and human needs. This imbalance can cause aquifers to be overexploited or polluted. In turn, population density produces low water availability in cities and collaterally in rural areas, through agricultural harvest.

Water availability in Mexico is determined by the NOM-011-CNA-2000 norm, which defines the availability of surface and underground water. These two concepts include the amount of water that is present in the basins, however, to be able to use it is necessary to extract it. To determine the real availability of water, four aspects must be considered: i) the cost-benefit ratio that guarantees its profitability; ii) the spatial and temporal variability of the runoff that determines where and when it can be used; iii) the water quality; iv) the volumes and minimum qualities that must be present in water bodies to guarantee the sustainability of ecosystems (CTMMA, 2003). Therefore, the actual availability of water in Mexico differs from what is established by official figures, in regions such as the center and north of the country there are severe problems regarding the availability of the resource. This situation has been aggravated due to the fact that before the current National Water Law, no reference was made to usable volumes. This caused problems of allocation, management, and indiscriminate use of the resource, and concessions were granted for quantities greater than those available (Vega and Rolland, 2010).

Cities in Mexico are developed focusing on urbanization master plans based on land use destined according to population load or densification. Specific plans in the city of Chihuahua are carried out by the Municipal Urban Planning Institute (IMPLAN). These plans do not consider the transversality of water resources in the activities and the construction authorization of the master plans; making even more complicated the provision of services related to water and its eviction when used. This lack of criteria causes a difficulty that affects the null or ineffective decision-making by the authorities resulting in the deterioration of environmental resources, in particular, water resources, which must be the support for a social-technical and economically feasible development.

There are currently matrices and methods of evaluating several environmental factors, however, the evolution of existing indicators is necessary to set a continuous analysis of the sustainability of the water resource. The development of a specific methodology will allow the water operating agency to make decisions and analyze the results of the proposed public policies.

The application case that is proposed to develop and apply this monitor is the city of Chihuahua. In the city of Chihuahua, the relationship between water resources and economic development has begun to deteriorate, due to the limited capacity of the aquifers. It is vitally important to articulate a sustainable water resources management model. Establishing an Integrated Approach to Urban Groundwater Management (IAUGM) sets the criteria that determine the hydrological exploitation capacity of a system, satisfying two basic functions: water supply and demand management. A series of indexes are necessary to determine this criterion to assess the sustainability of water (Menció *et al.*, 2010; Charnay, 2011).

The general objective was to develop a framework that allows the establishment of an IAUGM to evaluate the general situation of the use of groundwater in urban areas; seeking to determine improvements on methodologies depending on the current state.

The particular objectives of this thesis were: 1) Determine the response of groundwater levels to meteorological and anthropogenic factors in the City of Chihuahua; as part of the availability or decrease in groundwater supply; 2) Establishing a methodology based on flow/pressure control to accomplish an efficient transformation from an intermittent water supply (IWS) to a constant water supply (CWS); as part of the impact in groundwater demand 3) Evaluate water savings by transforming a city from IWS to CWS; this objective combines the reduction or requirement to integrate new sources (supply management) and the effects of a better operation based on demand management; 4) Evaluate the risk of use of treated wastewater as a source of water recharge in a soil aquifer treatment recharge; as part of the impact on the possibility of increasing the availability or management of the supply.

This will allow setting a methodology that, according to the results of the monitor and the applied indexes, can be used to recover volumes of water. This water volume can be used to satisfy basic human needs and preserve the ecosystem.

LITERATURE REVIEW

Given projected rates of urbanization and the subsequent pressures on water resources, cities are increasingly becoming important units of integrated water resource management. Although cities occupy less than 1% of the territory of most countries (Angel *et al.*, 2011), they consume between 5% and 20% of the water (IANAS and UNESCO, 2015). By 2025, water consumption in urban areas is likely to double as urban areas grow.

Water management has usually been seen in parts, which has led to fragmented views and insufficient actions on the part of the different entities that participate in the use and administration of water. The development of a framework that allows for analysis of the current state and determining actions for the management appears as an opportunity to change the model used by Water Operating Agencies (WOA).

There are various frames of reference and methodologies used for the management of water and related resources. In general, these frameworks attempt to decentralize system functions so that water management actions can be considered globally from an administrative perspective by breaking down these elements. The frameworks explained below are considered most relevant to establishing comprehensive water management, in this particular case of groundwater.

Frameworks

The frame of reference or monitor in which the different variables of water use are analyzed is an important consideration in the selection of indicators. Many frameworks have been proposed and used by different organizations around the world. These include the concept of the three pillars:

1) DPSIR (drivers, pressures, state, impact, and response model of intervention) is a causal framework for describing the interactions between society and the environment (Labianca *et al.*, 2020). This framework is an extension of the PSR model developed by the OCED.
2) An alternative to the DPSIR framework is the driving force-pressure-state-exposure-effect-action (DPSEEA) framework. DPSEEA has been widely used in European and international health assessments (Gentry-Shields and Bartram, 2014). By emphasizing the link between environmental degradation and human health, DPSEEA de-emphasized elements of the DPSIR framework, such as natural capital provided by ecosystems (impact) which is a core concept of sustainability.
3) The “Daly Triangle” which relates natural wealth to ultimate human purpose through technology, economy, politics, and ethics, provides a simple integrating framework. Extending the definition of capital to natural, human, and social capital could provide an easily understood base for calculating and integrating the Daly triangle (Meadows, 1998).

The choice or development of an appropriate reference framework depends mainly on the purpose, on the indicators chosen for each domain, and their relative importance in a decision-making process for the specific sustainable development that is intended to be implemented. It is necessary to implement a dynamic model that allows an active process of information accumulation and performs data analysis. This model, originates a summary which provides iterative learning allowing improvement and adaptation towards a state of sustainability (EPA, 2012).

Methodologies for Sustainable Use of Water

There are several analysis methods and techniques to measure the evolution towards sustainable development, which can be highlight in the following studies:

a) Hajkowicz *et al.* (2007) used a multiple criterion analysis (MCA) to multiple evaluation matrices, finding a relationship between the various MCA techniques used to manage water resources. MCA's proven methods include assigned value, value range, PROMTHEE II, Evamix, and commitment programs. In conclusion, the selection of the MCA technique is important, it is necessary to emphasize on the initial structure of the problem, which includes decision criteria and decision-making possibilities.

b) Hajkowicz *et al.* (2008) analyzed 113 water resource management through the MCA framework of 34 countries, in which the performance of decision-making is classified and evaluated against multiple objectives. The MCA in the management of water resources uses formal axioms of decision making. It concludes that the use of Index of Watershed Indicators (IWI) on the MCA theory will improve the status and rigor of this index.

c) Chaolun *et al.* (2008) developed a groundwater management model with a multiobjective distributed quadratic parameter, using a matrix that considers distributed parameters and boundary conditions. This model allows to determine the best alternative for planning and pumping operation, establishing which values will respond better to the fluctuation of the water level. This method is relevant in the management of water resources to evaluate the overexploitation of aquifers and environmental degradation.

d) European Regional Development Fund (2010) generated a methodology to develop a reference framework to define indicators to monitor sustainable water management. Developing a strategic water management plan using indicators and implementing a SWOT analysis.

e) Calizaya *et al.* (2010) the IWRM (Integrated Water Resources Management) paradigm has been recognized as the only feasible option to ensure the planning and management of water systems from a sustainable perspective. Calizaya *et al.* developed a Multi-criteria Decision Analysis (MCDA) based on: economic, social, and environmental criteria through an analytical hierarchy process (AHP) to solve the MCDA and identify the alternatives with the highest expectation of utility.

f) UC Davis (2014) developed the framework for water sustainability in California. This framework includes water sustainability indicators and the water system's relationship with the social, economic, and ecosystem conditions. The use of the sustainability indicators was developed to evaluate how the sustainable state of water evolves according to the actions taken. The water indicators evaluated in this framework are the availability, renewable sources, environment, sustainability, quality, water uses, indices for the ecosystem's productivity, and infrastructure and institutions for the sustainable development of water resources, capacity, and reliability of the infrastructure and effectiveness of the institutions.

g) United Nations Department of Economic and Social Affairs (2015), determines the need for a frame of reference that unites water with sustainable development. A monitor will allow systematic decision-making for water resource management.

Establishing an Integrated Approach to Urban Groundwater Management

In Mexico, the management model of drinking water, sewerage, and public sanitation services limits development and the capacity to respond to the growing needs of cities. Unless a modification to the development of urbanization and resource depletion is applied, efforts to achieve and maintain water security will be undermined; availability and access to water will be eroded and conflicts over its use will intensify. These trends exacerbate the need for a more systematic and comprehensive view of urban water management.

To solve this situation, several approaches have emerged to improve how cities carry out urban water management. These approaches deal with managing different elements of the urban water cycle (water supply, sanitation, stormwater, and urban water management) while minimizing the disturbance of natural systems.

Currently, there are some relevant but limited models such as, Management of water through networks of policies (Rhodes, 2000), Integrated water management (Carabias and Landa, 2005; Guhl, 2008), Water management by intermunicipality (Ventura, 2010), City Water Resilience Approach (CWRA)

(Saika *et al.*, 2020), City Blue Approach (CBA) (Kim *et al.*, 2018). The models explained below are considered relevant for carrying out urban water management. They are very general models, which give guidelines to deepen and use them by adapting their elements to a specific context.

- Hooper's model of integral management of water resources in hydrographic basins (Hooper, 2006). This model formulated dimensions and general performance indicators for the water sector. There were obtained 115 indicators for the management of hydrographic basins and the following categories: objectives, change and fulfillment of the objectives, coordinated decision-making, response in decision-making, organizational design, financial sustainability, training and development, responsibility and monitoring, information and research, the role of law and functions of the public and private sector. Hooper (2006) also developed an instrument for measuring water management using a Likert-type scale.
- Water management model in the cities of Mexico of the water consulting council. This model was designed for the context of Mexico in 2010 by experts in the subject of water, who defined five essential dimensions for the management of drinking water and sanitation systems: efficiency, public finances, quality of service, environment, and institutional framework (water advisory council, 2011).
- Efficient management model in water and sanitation operators of the American Association of Public Works *et al.* (2012). In this model, leaders from Mexico's WOA came together to identify and address the most urgent

needs. They identified 10 important dimensions for efficient water resource management: water quality, technical development, operational optimization, customer satisfaction, financial viability, adequate water resources, infrastructure stability, sustainability, understanding and support of the members involved, and operational resilience (Flores *et al.*, 2012).

- The CBA has been developed to assess the sustainability of IWRM in a municipality (Van Leeuwen *et al.* 2012; Koop and Van Leeuwen, 2017). The CBA consists of three assessment frameworks: (1) the Trends and Pressures Framework, which summarizes the principal social, environmental and financial pressures that impede water management, (2) the City Blueprint Framework (CBF), which provides an overview of the performances of IWRM, and (3) the water governance capacity framework, which identifies key barriers and opportunities in urban water governance (Makropoulos *et al.*, 2018). The CBF has been used extensively since its development for rapid baseline assessments in about 70 cities around the globe. This allows for a comparison with other cities and facilitates city-to-city learning on strategic planning, exchange of knowledge, experiences, and best practices.
- The CWRA is a methodology that emerges as a new urban water management model that will help cities collaboratively build resilience actions to local water challenges through improved water governance (Saika *et al.*, 2020). Through step-by-step guidance combined with tools and resources, CWRA enables cities to make better urban water planning

and investment decisions. It defines five steps: identifying and engaging with key stakeholders; conducting a baseline assessment of the city's current water resilience capacity through multi-stakeholder consultation; collaboratively defining, prioritizing, and water resilience action plans; step 4, implementing previous actions; and finally, monitoring and evaluating results to reassess the priorities and inform future programs and planning (Arup Global Water Leader, 2019).

- The IWRM is a process that promotes the coordinated development and management of water, land, and related resources, to maximize the economic results and social welfare in an equitable manner, without harming the sustainability of vital ecosystems (GWP, 2000). An IWRM-oriented planning process has, in contrast to urbanization master plans, a more flexible and dynamic approach to development planning and management of water resources. The planning process acquires a special role in strengthening effective governance within the strategic framework of policies and actions to achieve the goals of IWRM (Silva, 2014).

Integrated Approach to Urban Groundwater Management (IAUGM)

The development of an IAUGM was done by adapting the different frameworks, methodologies, and models to modify its elements to a specific context.

The purpose of IAUGM is to handle the entire urban water resource system as part of a coherent structure. IAUGM considers the different water sources found within an urban catchment area and establishes plans to protect, conserve and use this vital resource. It also analyzes the process of water distribution, storage, and discharge as part of a cycle instead of considering them as separate activities and plans the infrastructure according to this vision. IAUGM examines the effectiveness and function of the WOA's and the regulations that govern water in the city. It also considers the quality of different water sources (including reused water) and seeks to allocate it according to the quality required for different needs. IAUGM tries to balance economic efficiency, social equity, and environmental sustainability.

The IAUGM seeks to link the plans and management processes in a broad context which allows aligning the urban water sector. Thus, the IAUGM is not an end, but rather, it is a means to monitor a subsystem in search of water security. This security is achieved by setting access to water, better availability, and the reduction of conflicts over the use of this resource and the risks related to it. Implementation of the IAUGM requires coordinated action at all decision-making levels to ensure availability and access to water. Those who manage water resources and those who make decisions in cities must act to:

- Develop specific strategies and policies to prioritize, share and manage available water resources. These strategies consider: the climatic variables, the source and use of water, the level of extraction, population growth, the inherent characteristics of the place, the service model, and the water quality.
- Keep the subsectors that make use of water engaged in the analysis, the definition of options, and the decision-making related to the sustainable management of resources. This engagement seeks to set a service:

equitable, with the least possible loss of water, with optimal pressure, and that extends the system’s life.

- Ensure that options for new water sources do not negatively affect the city's future needs, social equity, or economic development goals.
- Promote a culture of long-term planning that, based on proven methodologies, allows establishing a specific design for the population's consumption pattern.
- Implement monitoring systems in which quality data can be collected through reliable sources of information for regulation and policy guidance.

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STUDY I. EVOLUTION OF THE GROUNDWATER SYSTEM IN THE CHIHUAHUA-SACRAMENTO AQUIFER DUE TO CLIMATIC AND ANTHROPOGENIC FACTORS

BY:

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ABSTRACT

EVOLUTION OF THE GROUNDWATER SYSTEM IN THE CHIHUAHUA-SACRAMENTO AQUIFER DUE TO CLIMATIC AND ANTHROPOGENIC FACTORS

BY:

M.I. DAVID HUMBERTO SÁNCHEZ NAVARRO

Groundwater is the main source of water in arid cities where precipitations are low and not evenly distributed. The combined impact of climate variability and intensive human activities has caused a substantial decline in groundwater levels. Understanding the response of groundwater levels to meteorological and anthropogenic factors is a key step to propose water management alternatives. Meteorological and groundwater data were used to design a multi-step approach to assess the influential factors on the groundwater system in the City of Chihuahua, Mexico. The analysis of historical groundwater levels and climate showed a clear increase in meteorological drought, as well as a groundwater abstraction trend since 1986. Rainfall, groundwater recharge, and groundwater level displayed a significant decrease. Overall, the groundwater depth is continuously increasing with a strong correlation with groundwater abstraction. Despite having a significant trend, the change in land-cover, groundwater recharge, and meteorological drought, were not the main factors inducing the decrease level of water in the aquifer. The continuous abstraction of groundwater from 1986 to 2010 has led to a depletion of groundwater levels from 32m to 92m. The findings of this study lay a foundation for future water-resource management in the study area.

Keywords: static level decline; meteorological drought; sustainability;

On behalf of all authors, the corresponding author states that there is no conflict of interest.

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

RESUMEN

EVOLUTION OF THE GROUNDWATER SYSTEM IN THE CHIHUAHUA-SACRAMENTO AQUIFER DUE TO CLIMATIC AND ANTHROPOGENIC FACTORS

POR:

M.I. DAVID HUMBERTO SÁNCHEZ NAVARRO

El agua subterránea es la principal fuente de agua en las ciudades áridas donde las precipitaciones son bajas y no se distribuyen uniformemente. El impacto combinado de la variabilidad climática y las actividades humanas intensivas ha causado una disminución sustancial en los niveles de agua subterránea. Comprender la respuesta de los niveles freáticos a factores meteorológicos y antropogénicos es un paso clave para proponer alternativas de gestión del agua. Datos meteorológicos y de aguas subterráneas fueron utilizados para diseñar una metodología de múltiples pasos para evaluar los factores influyentes en el sistema de aguas subterránea de la ciudad de Chihuahua, México. El análisis de los niveles históricos de agua subterránea y el clima mostró un claro aumento en la sequía meteorológica, así como una tendencia de extracción de agua subterránea desde 1986. Las precipitaciones, la recarga de agua subterránea y el nivel estático mostraron una disminución significativa. En general, la profundidad del agua subterránea aumenta continuamente en correlación con la extracción de agua subterránea. A pesar de tener una tendencia significativa, el cambio en la cobertura del suelo, la recarga de aguas subterráneas y la sequía meteorológica, no fueron los principales factores que indujeron la disminución del nivel de agua en el acuífero. La extracción continua de agua subterránea desde 1986 hasta 2010 ha llevado a un descenso de los niveles de agua subterránea de 32 a 92 m en promedio. Los hallazgos de este estudio sientan las bases para desarrollar la futura gestión de los recursos hídricos en el área de estudio.

Palabras clave: descenso del nivel estático; sequía meteorológica; sostenibilidad;

INTRODUCTION

Groundwater is the main source of water in arid cities, where precipitations are low and not evenly distributed. The continuous groundwater pumping causes a long-term water-level decline defined as groundwater depletion. The effects of groundwater depletion are complex and dependent on the combinations of aquifer characteristics, climate variability, human demand, land use, among others (Aeschbach-Hertig and Gleeson, 2012). The water-level decline produces an increase in the costs of pumping or drying wells (Campana, 2007; Fishman *et al.*, 2011); reduced groundwater discharge, quantity, and quality, to streams and springs affecting ecosystems (Sophocleous, 2000). Anthropogenic contamination can be generated by salt mobilization in irrigated regions or widespread of pesticides (Fogg and LaBolle, 2006). There may also be problems produced by natural origin, related to aquifer geology most notably high levels of arsenic and fluoride (Fendorf *et al.*, 2010; Giordano, 2010).

In cities under arid conditions, groundwater depletion may cause water shortage during the dry season (Hoque *et al.*, 2007; Táany *et al.*, 2009; Garamhegyi *et al.*, 2018). The sustainability of groundwater resources in many basins or plains in the world is threatened, as a result of continuous groundwater depletion through human activities and climatic stress (Wang *et al.*, 2013). Likewise, the overpumping and population growth (linked to urbanization) are causing groundwater levels to decline around the world (Schwartz and Ibaraki, 2011). Human activities, such as groundwater pumping near streams, irrigation, and the construction of reservoirs, etc., also impact groundwater dynamics and results in some side effects on the eco-environment (Hanson *et al.*, 2004; Brekke *et al.*, 2009; Famiglietti, 2014; Yang *et al.*, 2017). Likewise, authors have reported that in certain regions, the groundwater level decline is related to substantial aquifer dewatering (Garamhegyi *et al.*, 2018), while the increase in annual mean temperature (due to climate change) has been a significant driving effect on the decrease in shallow groundwater levels (Chen *et al.*, 2004). Overall, climate change and variability combined with increased anthropogenic demands on water resources are the two major stressors on reliable and sustainable water resources all over the world (Hanson and Dettinger, 2005).

In a recent study focused on identifying the influencing factors on groundwater drought and depletion in north-western Bangladesh, it was shown that there is a vital need of including human-induced effects for drought analysis, and a latent urgency for new research and methods to identify the human influence on groundwater depletion (Mustafa *et al.*, 2017). Several studies have improved the general understanding of how a groundwater system may respond to human influences, as well as on the potential impacts on groundwater drought (Parkinson *et al.*, 2016; Jakóbczyk-Karpierz *et al.*, 2017; Thomas *et al.*, 2017; Han *et al.*, 2019; Escriva-Bou *et al.*, 2020; Persaud *et al.*, 2020; Kavianpour *et al.*, 2020).

Groundwater in Chihuahua, Mexico, is the most important source of drinking water and plays a vital role in the region, however, a few studies have been carried out about human influence on groundwater detriment in Chihuahua (Reyes *et al.*, 2017; CONAGUA, 2018; Sánchez-Navarro *et al.*, 2019; Mendieta-Mendoza *et al.*, 2020). Moreover, it is essential to identify which indicators of climate variability and human activities affect groundwater depletion and sustainability. This paper presents an adapted methodology that can be replicated in places with similar conditions and characteristics where fully integrated databases are non-existent. This manuscript allows a preliminary evaluation of the influential factors on the groundwater depletion in the Chihuahua-Sacramento (CHS) aquifer, which is a typical semi-arid area with a majority of urban use of groundwater. It is expected that the outcome of this study can provide a better understanding of the anthropogenic and climate impact on the groundwater system in the CHS aquifer, and thus contribute to groundwater management by the concerned authorities to ensure sustainability in the study area.

Site description

The study area is located in the north-western part of Mexico as shown in Fig. 1. The CHS aquifer is located in the Sacramento-Chihuahua Valley where the Chihuahua, Aldama, and Aquiles Serdan municipalities and agriculture occur between 28º 24' 19.7" and 28º 56' 46" to the North, 105º 57 '41.8" and 106º 32' 48.5" to the West and has an area of 1889 km2 with an average altitude of 1,415 m above sea level (CONAGUA, 2018). The CHS aquifer is unconfined and is filled with quaternary alluvial, fluvial, and loess deposits with a thickness that goes from 350 to 700 m (CONAGUA, 2009; CONAGUA 2018). In addition, this aquifer system is comprised of several stratigraphic units, such as: rhyolite, basalts, sandstones, limestone rocks, conglomerates, and andesites. The climate in the study area is dry, similar to a desertic type, the mean annual temperature is 16.1 ºC and the mean precipitation is 441.2 mm yr-1 for the years range 1950-2010

(Sánchez-Navarro *et al.*, 2019). Regarding the annual distribution of precipitation, almost 70% of rainfall occurs in July, August, and September.

This aquifer is located in Hydrological Region 24 called Bravo-Conchos basin (Fig. 1), (CONAGUA, 2009). The Sacramento and Chuviscar rivers, which flow from the south to north through the valley, are considered as the main surface-water sources in the study area. The inflow of surface water to the Sacramento River is from northwest to southeast while to Chuviscar River is from southwest to southeast. In the aquifer area, there are placed four dams, two of them on the Chuviscar River (Chihuahua and Chuviscar dams), one on the Sacramento River (San Marcos dam), and the last one on the San Pedro River (El Rejon dam). From those dams, only the water from the Chihuahua dam is used for human use and consumption while the others are for recreational uses and flood control. Fig. 2 shows the geology and the distribution of the surface-water network in the study area. The CHS aquifer also underlies most of the urban area of Chihuahua City. The water from this aquifer has several purposes, being the main use of the water supply for urban demand, and to a minor degree the use for agricultural, livestock, industrial, services, and mixed activities. The city of Chihuahua is the state capital with a population of 878,000 as of 2019 and is a growing urban area within a drought-prone region (David *et al.*, 2020).

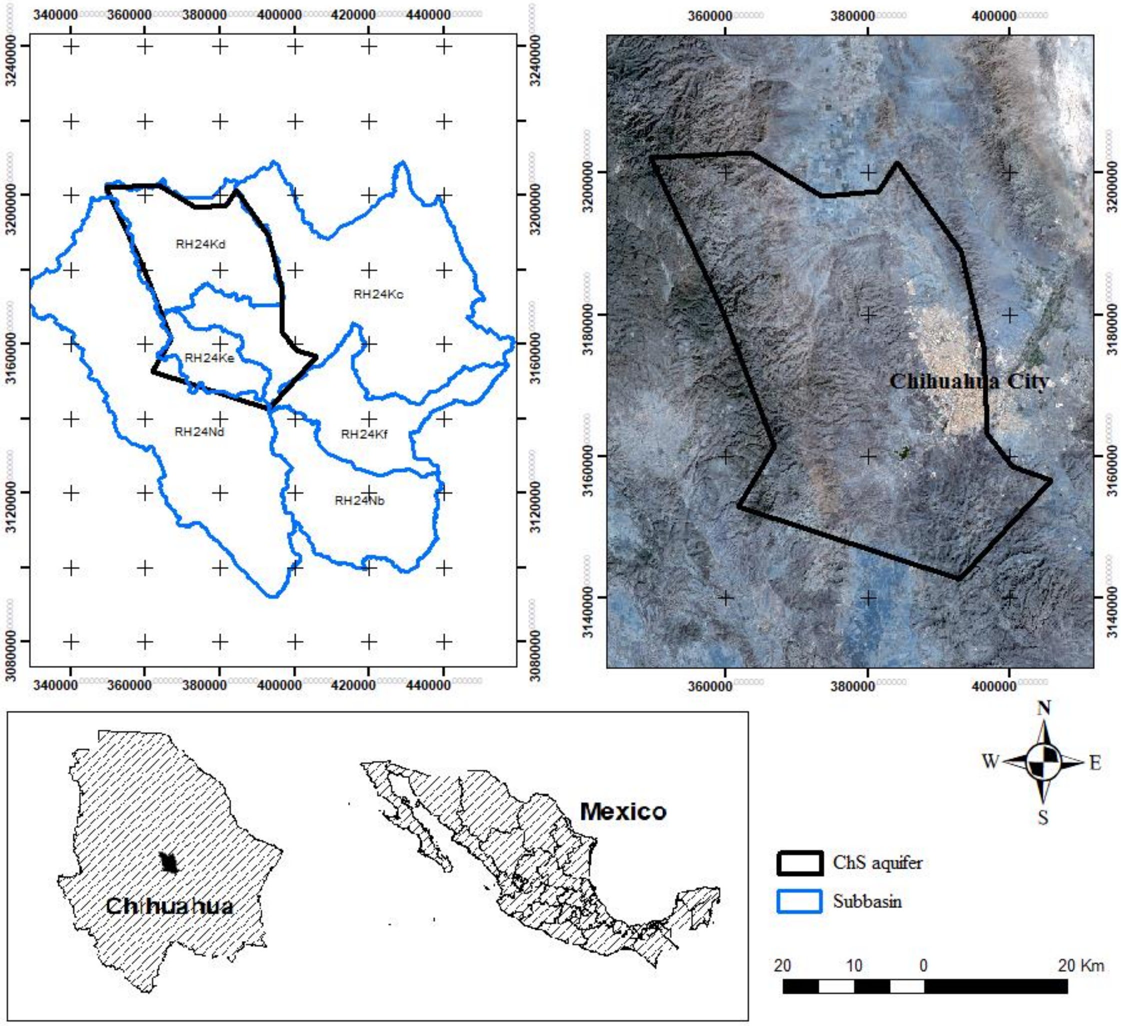


Fig. 1 Geographical localization of the Chihuahua Sacramento aquifer.

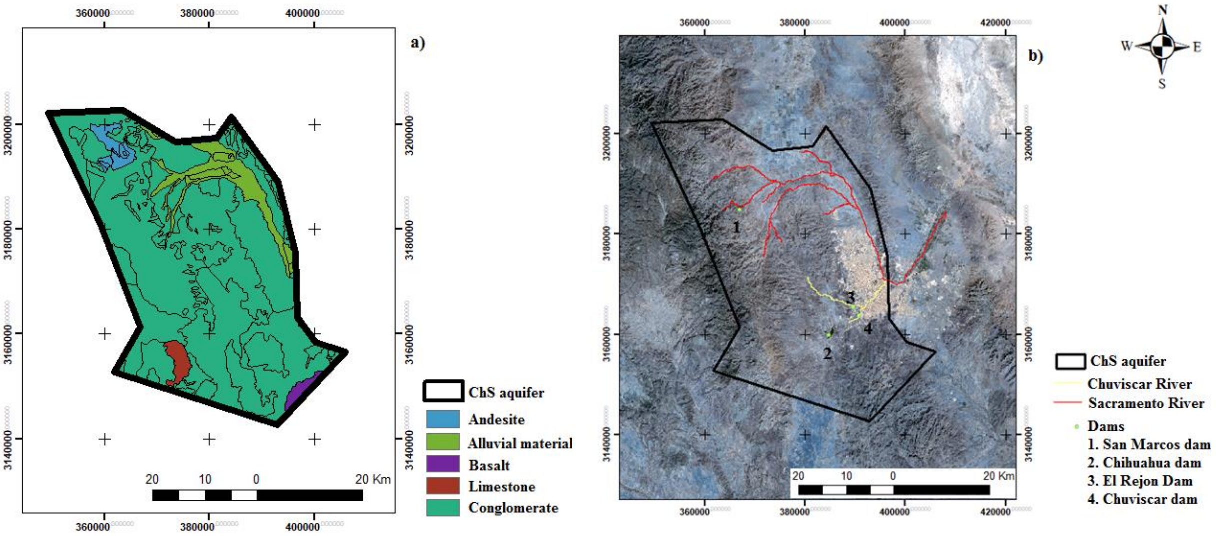


Fig. 2 Geology and surface-water distribution in the Chihuahua Sacramento aquifer.

MATERIAL AND METHODS

A semi-integrated layered approach with passive connections between separate estimates was employed for this study. The methodology by Mustafa *et al.* (2017) was used as a framework to adapt the methods, in order to achieve the objectives of the study. The methodological procedure examined step by step the effects of a) meteorological variables, b) land cover change, and c) water abstraction on groundwater level (groundwater depletion) over a recent historical period, 1986 - 2010.The meteorological drought was assessed using the Multivariate Drought Monitor in Mexico (known in Spanish as MoSeMM) (Rangel, 2017). The monthly groundwater recharge was calculated using the land-cover changes evaluated through the groundwater model previously developed for the study: feasibility of alternative sources and a preliminary draft of necessary hydraulic infrastructure, made by the State Water and Sanitation Board (known in Spanish as JCAS). The groundwater demand was assessed using data obtained by the Municipal Water and Sanitation Board (known in Spanish as JMAS). Figure 3 shows the conceptual model applied to identify the main factors that influence groundwater in the study zone. This approach provides an initial view of the potential drivers of supply and demand that can affect groundwater depletion and sustainability.

Meteorological Analysis

The meteorological drought was analyzed using the MoSeMM (Rangel, 2017). The MoSeMM uses data obtained from Modern-Era Retrospective analysis for Research and Application 2.0 (MERRA-2) (Gelaro *et al.*, 2017).

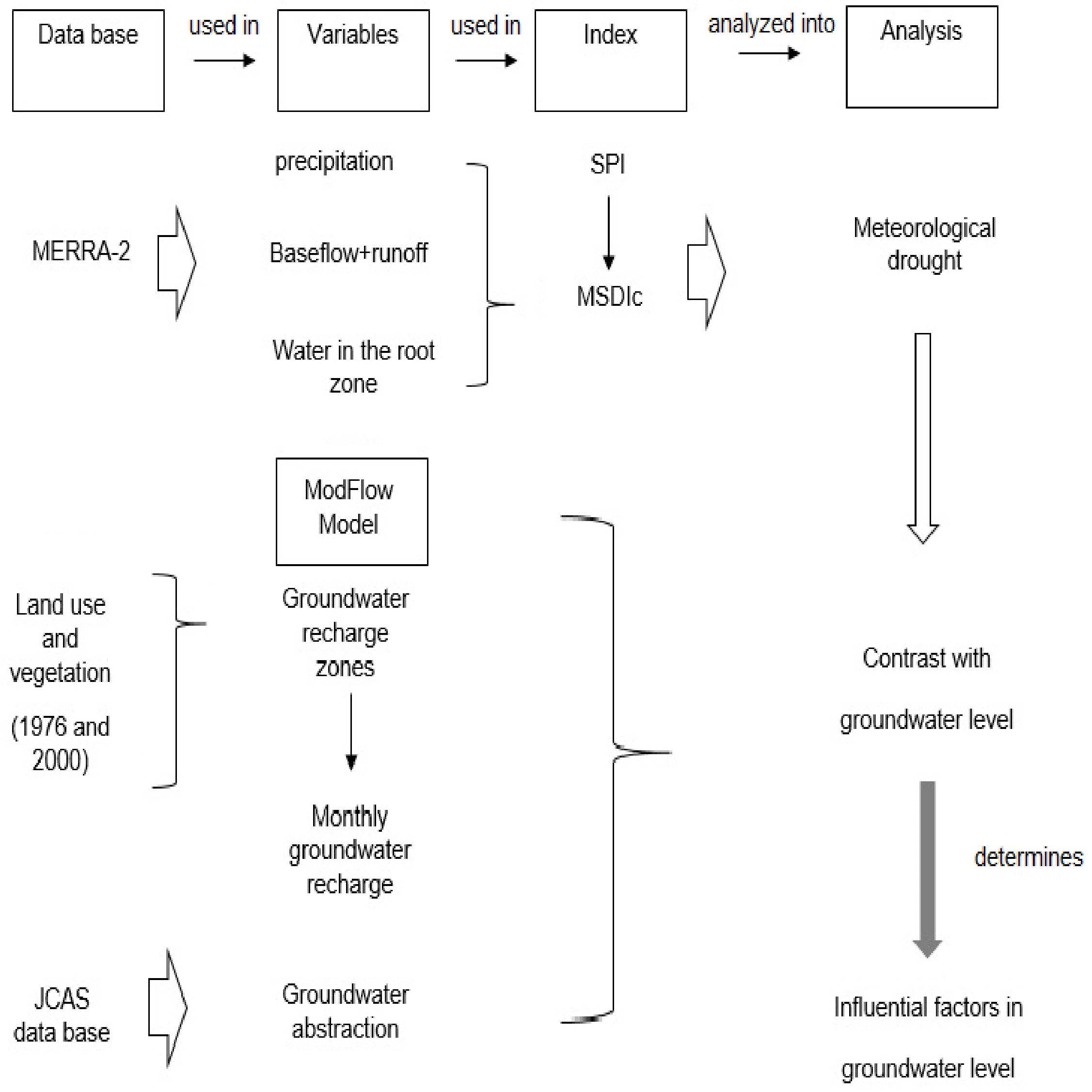


Fig. 3 General methodology diagram. The meteorological drought was assessed through the Multivariate Drought Monitor in Mexico (MoSeMM). MoSeMM uses the data set of the Modern-Era Retrospective analysis for Research and Applications version 2 (MERRA-2). Multivariate standardized drought index (MSDIc). Standardized precipitation index (SPI).

This program implements a multivariate standardized drought index (MSDIc) which considers the use of standardized indexes for pairs or thirds of hydrological variables. The standardized precipitation index (SPI) evaluated the difference between the values of the analyzed variable and the condition considered as "normal" in a normalized sample (Rangel, 2017). For this case, the univariate indexes used for the study area were taken from MERRA-2 data collection: 1) the standardized precipitation index (SPI) (McKee *et al.*, 1993) which quantifies the conditions of deficit or excess of precipitation; 2) standardized soil moisture index, that estimates soil moisture using a hydrological model of one layer; and 3) the standardized rate of runoff. All of these indexes are determined monthly for the entire country and using different time scales (1, 3, 6, 9, and 12 months). The value of MSDIc is calculated using the following equation (Hao *et al.*, 2014):

$$MSDIc = \varphi^{-1}(P)$$

where φ is the standard normal distribution function and P is computed using the following equation:

$$P(X \leq x_i, Y \leq y_i) = \frac{\sum_{m=1}^{i} \sum_{l=1}^{j} n_{ml} - 0.44}{n + 0.12}$$

Where $\sum_{m=1}^{i} \sum_{l=1}^{j} n_{ml}$ represent the pairs of variables associated with drought X and Y from the i-th year in the corresponding time basis of m or l (months), and n represents the number of years of the available time series. The MSDIc classification of drought categories is presented in Table 1.

Table. 1. North American Drought Categories (North American Drought Portal 2002)

Range	Code	Category
$-0.8 < SI < -0.5$	D0	Abnormally dry
$-1.3 < SI < -0.8$	D1	Moderate drought
$-1.6 < SI < -1.3$	D2	Severe drought
$-2.0 < SI < -1.6$	D3	Extreme drought
$SI \leq -2.0$	D4	Exceptional drought

*SI stands for standardized index.

Land-cover Change

The land-cover change was assessed to determine the impact on groundwater recharge and actual evapotranspiration from natural, riparian, urban, and agricultural subregions. The main crops in the study area are: a) for fall-winter season forage: oats, grain oats, prairie, ryegrass, wheat, and triticale, b) for the spring-summer season: forage oats, grain oats, green chili, beans, fodder corn, grain corn, potatoes, sorghum, and red tomato, and c) the permanent crops are alfalfa, peach, apple, and walnut. The land cover analyses were carried out for the years 1986, 1996, and 2011. Multispectral Landsat 5 Thematic Mapper (TM) and Landsat 7 ETM composite images of 1996 to 2011 were used to determine the location, area, and crop type. Landsat images were collected from USGS Global Visualization Viewer (GLOVIS). The Landsat 5 images are composed of 7 different bands with a resolution of 30m. The Landsat 7 ETM dataset is composed of 8 bands with a 30 m resolution. The image analysis was conducted by ENVI 4.7, in which, through the combination of spectral bands, zones were discriminated. Also, Google Earth was used to obtain a resolution from one to ten meters in each image. Cultivated areas, water storage, bare soil, and lacustrine zones were the main zones obtained. For the identification of crops, the spectral signature was carried out by six bands from Landsat 5, based on the ratio of the amount of radiation reflected by a surface to the length of the electromagnetic wave. Knowing the spectral signature of the cover, allowed to classify the crop by pixel. Finally, a land-cover map with 8 different classes was derived considering two years 1976 and 2000; one of those classes is the crops class having different values for the time series.

Fig. 4 shows the classes of land cover for analyzed years. Cultivated areas were found bordering the city of Chihuahua and the Chihuahua dam, having a greater presence in the extreme north of the aquifer, with an area of 143.95 km2, equivalent to 7.62% of total coverage.

Groundwater Abstraction

Based on the data provided by the JMAS and the information obtained by the JCAS report (2013), it was approximated the total water withdrawal from the CHS aquifer for the years 1986 to 2010. This aquifer has 564 units (deep and shallow wells) of water abstraction with volumes of 72 hm^3 yr^{-1} (1986), 71 hm^3 yr^{-1} (1996), and 78 hm^3 yr^{-1} (2011) (JCAS, 2013). Likewise, groundwater abstractions for agricultural use were estimated using the well-crop allocation process by satellite images, where the active crop areas are related to the corresponding well according to its location, hydraulic infrastructure, as well as the type and crop area. Thus, the water abstraction volumes for agriculture reported by JMAS are 12 hm^3 yr^{-1}, 12 hm^3 yr^{-1}, and 13 hm^3 yr^{-1} to 1986, 1996, and 2011, respectively. In the study area, ninety-one observation wells are the ones that have complete information over time to perform data analysis. Fig. 5 shows the location of wells under study.

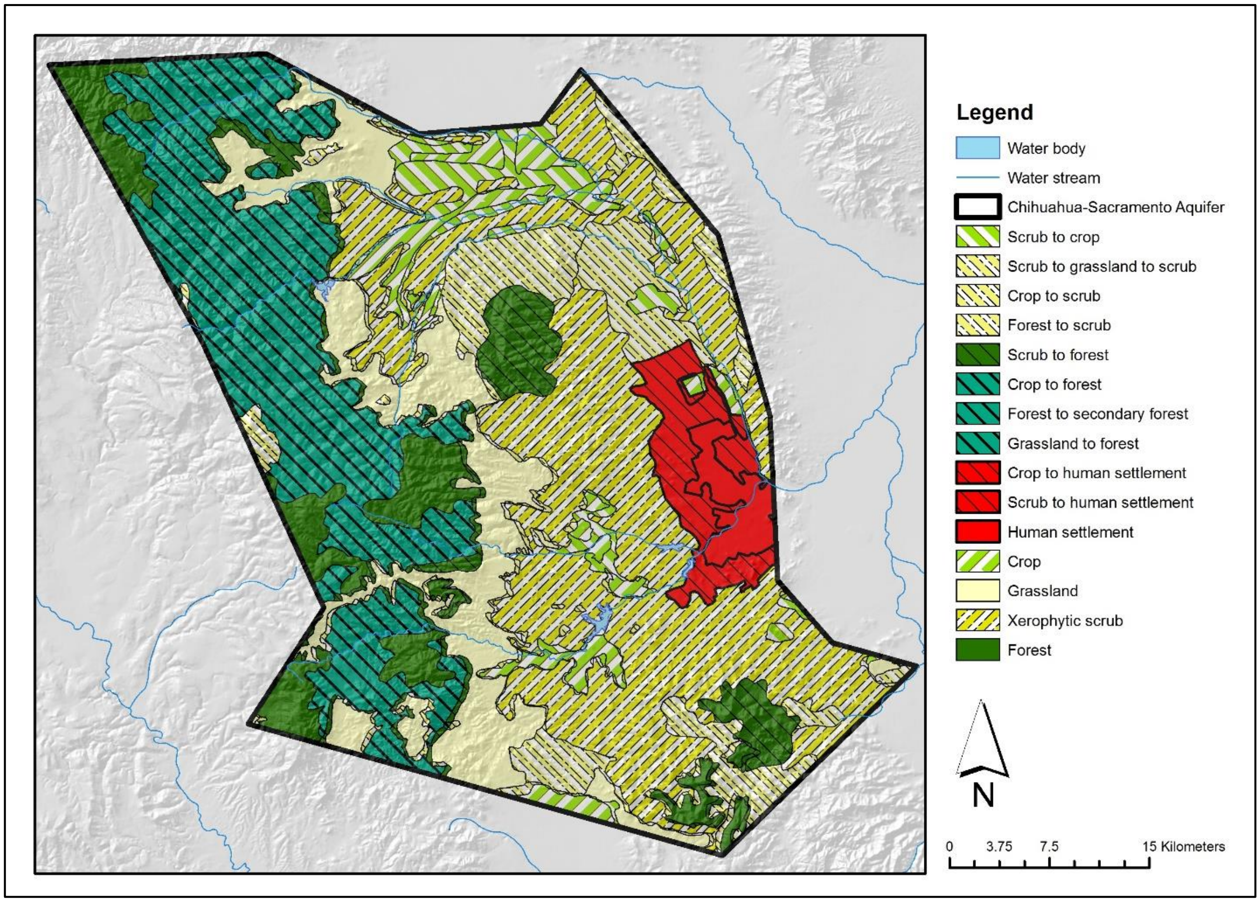


Fig. 4 Land cover change 1976 and 2000 (JCAS, 2013). The land-cover change was assessed to determine the impact on groundwater recharge.

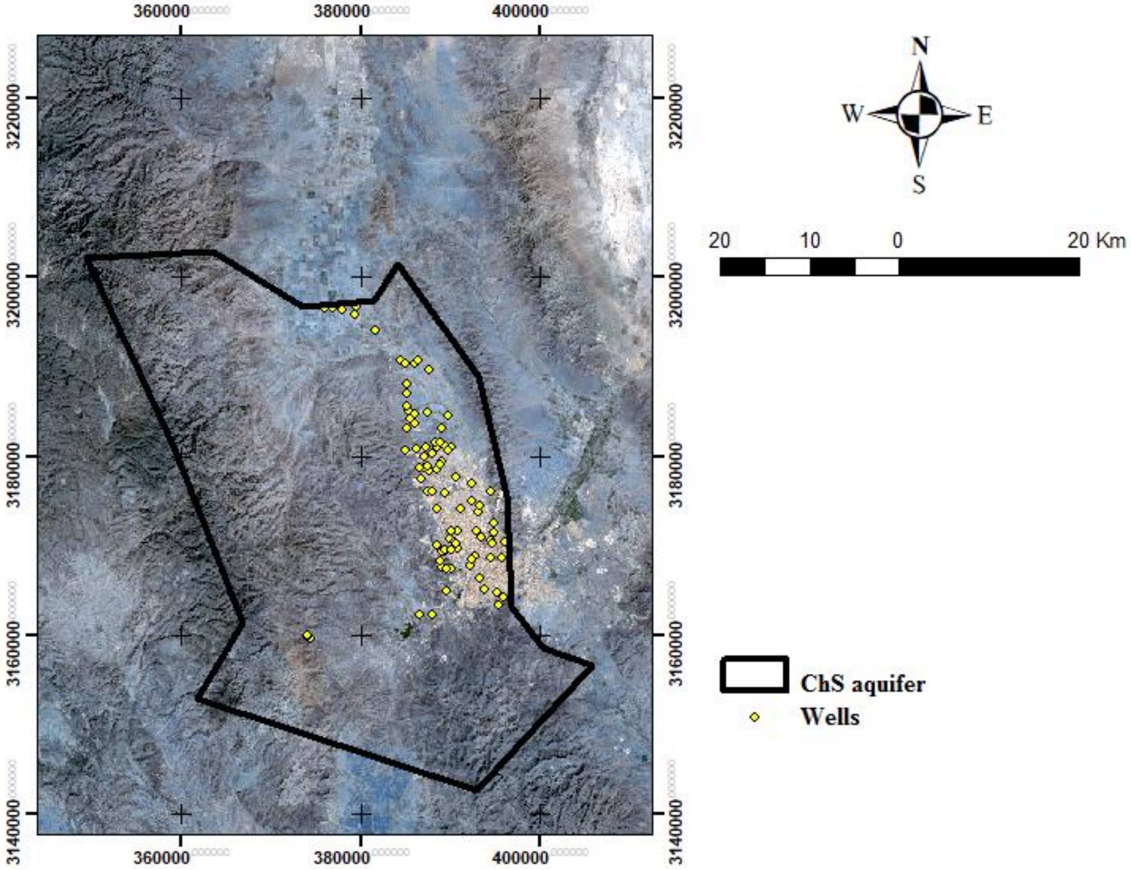
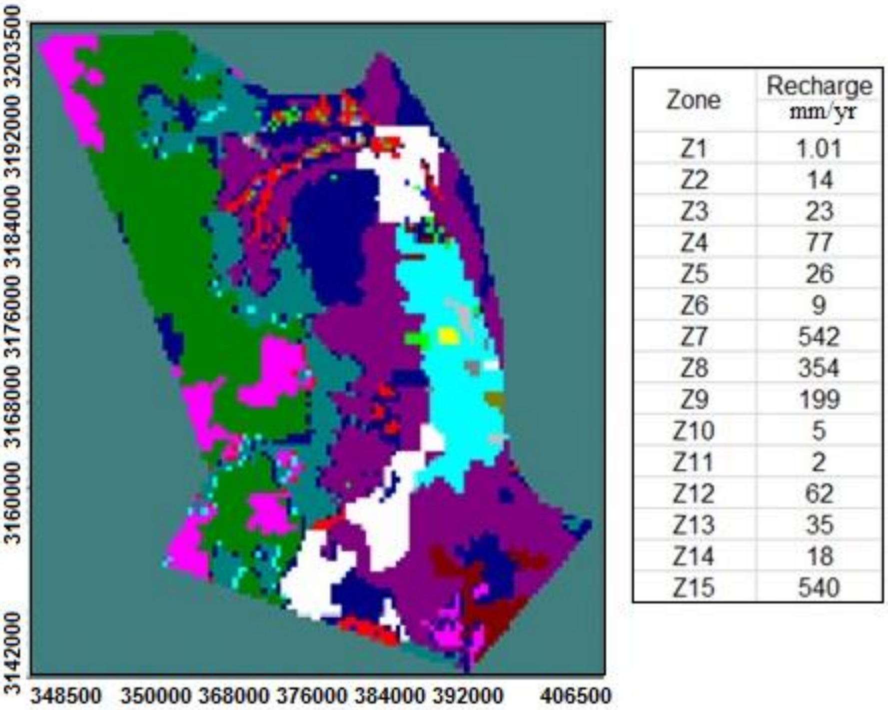


Fig. 5 Wells location in Chihuahua-Sacramento aquifer.

The agricultural irrigation return was estimated from the crops identified in the area establishing the return volume of the range 20 to 40%, in the case of this model the lower limit was taken based on climatology and geology, reaching values from 2 to 2.41 hm^3 yr^{-1}. The induced recharge from leaks in the distribution network was determined from the percentage of area that the city occupies in the CHS aquifer and from the leakage percentages estimated according to the diagnostic study, modeling, and planning of sectors in the drinking water distribution network (JMAS-IMTA, 2008), reaching recharge values from 1986 to 1996 of 4.53 hm^3 yr^{-1}; 1996 to 2009 from 5.20 hm^3 yr^{-1}; 2009 to 2011 from 5.35 hm^3 yr^{-1}.

It was found that 7 of the 15 zones within the model belong to agricultural zones. The spatially distributed recharge was calculated a priori based on water and land-cover use, specifying 15 zones for the groundwater model (Fig. 6). The groundwater recharge was a boundary condition applied to the top layer of the groundwater model.

The groundwater recharge zones were analyzed by the simulation results from the groundwater model using the postprocessor Zonebudget and the zonation file that groups model cells into the five zones were used as an input for a spatially distributed map of the groundwater budget for the years 1997, 2009, and 2011.



Zone	Recharge mm/yr
Z1	1.01
Z2	14
Z3	23
Z4	77
Z5	26
Z6	9
Z7	542
Z8	354
Z9	199
Z10	5
Z11	2
Z12	62
Z13	35
Z14	18
Z15	540

Fig. 6 Modeling of groundwater recharge zones (JCAS, 2013).

Groundwater Flow Model

The JCAS (2013) developed a groundwater flow model of the CHS aquifer for the historical period 1986 to 2011 using VISUAL MODFLOW 2011.1 v.4.6.0.160. The model uses three layers to represent the current understanding of the geological environment. The hydraulic properties of the materials within these hydrostratigraphic units used to represent groundwater flow and selected boundary conditions were assigned to all three model layers that included groundwater pumpage, natural and artificial recharge, river gains and losses, and evapotranspiration. The initial conditions of groundwater flow and hydraulic loads were model in transient time.

Groundwater Model Framework

The CHS model shows an area of 3,567 km2 by the spatial discretization of the aquifer, with a finite-difference grid with three layers, 124 rows, and 119 lines, with a grid size of 0.5 km x 0.5 km. The stratigraphic model was determined based on: geological sections reported in the geological mining cross-sections derived from electrical resistivity modeling and well logs, lithological cuts provided by the National Water Commission (known as CONAGUA in Spanish), and the geophysical surveys provided by JMAS and JCAS. However, the lithological units bordering the aquifer were deactivated, leaving 7,556 active cells per layer, equivalent to an equal areal extent in all three model layers of 1,889 km2 (Fig. 7).

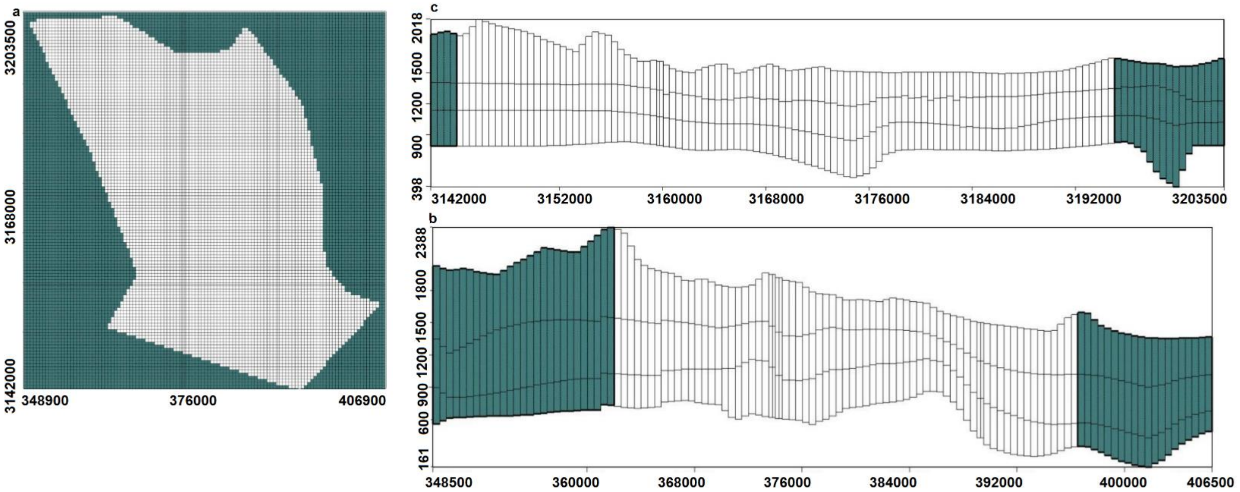


Fig. 7 Chihuahua-Sacramento (CHS) finite-difference grid: a. Discretization of the model mesh (active white cells and inactive green cells) b. Profile of a column of the model mesh c. Profile of a row of the model mesh.

This model was designed with three layers: the first layer represents a combination of alluvial deposits representing the alluvial plain and part of the mountain range composed of the fractured rocks; the second layer is also a combination of the older alluvial deposits and fractured volcanic rocks; the third layer corresponds to the same material as the second, but with more volcanic fractured rocks.

From the temporal point of view, the CHS model simulated the historical period from 1986 to 2011, assigning as the initial flow conditions, those of the year 1986, because it is the oldest date with extraction volumes reported within the aquifer. The temporal discretization was mostly annual stress periods with additional temporal refinement for 1996 and 2010 with 5 to 10 amplified time steps per stress period.

Aquifer Parameters

The CHS aquifer system is heterogeneous and anisotropic on a regional scale; it is mostly composed of alluvial filling with water flow direction from north to south. The relevant parameters of this aquifer system: hydraulic conductivity, specific yield, and storage coefficient, were assigned using zones with uniform properties. The initial parameter values of each zone were specified based on: parameters estimated from the stratigraphic lithology, geomorphic unit, and sedimentary type of the aquifer. 60 pumping tests were reinterpreted using the programs Visual Two-Zone Model and Aquifer Test, as well as, the traditional methods of Logan and Eden-Hazel to determine the hydraulic conductivity, giving values from 0.08 to 16.53 m d^{-1}. Both, the hydraulic conductivity and storage coefficient were adjusted in the calibration of the transient flow model.

Statistical Analysis

Analysis of trend is necessary to determine if conditions in a waterway, aquifer, or watershed are improving or deteriorating (Hirsch *et al.*, 1982). Distribution-free trend analysis is ideal due to the unknown nature of the data, making non-parametric methods better suited for these data. The widely used non-parametric Mann-Kendall is considered one of the strongest correlation trend tests (Berryman *et al.*, 1988). It is appropriate for data that are not normally distributed, tolerates missing values, and is relatively unaffected by extreme values or skewed data. The nonparametric Sen's method (Gilbert, 2006) was performed to determine the slope of the trend for all variables (SPI, MSDIc, groundwater recharge, groundwater abstraction, and groundwater level) (Mustafa *et al.*, 2017).

Related to the Mann-Kendall test, the Seasonal-Trend decomposition procedure based on Loess (STL) (Cleveland *et al.*, 1990) was performed to determine whether or not significant changes have occurred over time while considering the variation due to seasonal effects (Hirsch *et al.*, 1982). Average monthly time series of recharge and meteorological drought were decomposed by the STL method using the statistical software R. Groundwater abstraction and depth were not decomposed, as monthly data were not available.

Multiple linear regression was performed for each variable (abstraction, recharge, SPI, and MSDIc) to evaluate the relative contribution in increasing groundwater depth. Annual time series of 1986 - 2010 were used in the regression analysis to ensure the same length for all data. The partial coefficient of determination (R2) was estimated for each of the influencing factors.

To determine the most influencing factors, stepwise multiple linear regression analysis was conducted (Mustafa *et al.*, 2017) according to Draper and Smith (1998).

RESULTS AND DISCUSSION

Variability in the Meteorological Factors

The monthly time series of MSDIc and SPI (Fig. 8) both shows a negative trend. Exceptional meteorological drought occurs in 1994-1995 and 1999-2000, but in some years severe to extreme drought occurs mainly from 1995-1996 and 2000-2003. The patterns of the SPI cycle generally agree with those of MSDIc, displaying that SPI derived from rain gauges can detect severe drought episodes (De Jesús *et al.*, 2016; Kavianpour *et al.*, 2020).

Fig. 8 represents the spatial distribution of MSDIc over the study area. MSDIc drought categories are varying from exceptional to abnormal or no drought within the study area. There are no clear spatial trends observed in MSDIc in the study area when analyzed on an annual basis, suggesting that a seasonal analysis may yield a more meaningful result. The relation between the average groundwater depth with the annual MSDIc can be evaluated qualitatively, which shows that the groundwater depth is continuously increasing with little correlation to MSDIc or SPI. It is observed that although there is a negative trend in MSDIc and SPI values, both indexes do not have a continuous decrease in value, unlike groundwater depth which is continuously increasing. In 1986, the average groundwater depth was about 32m from the surface. After 25 years, in 2010, the average groundwater depth had increased to about 92m from the surface. On average, the difference increased monotonically with time, which can indicate a slight constant decrease in storage due to abstraction as stated in the study made by Van Loon and Van Lanen (2013).

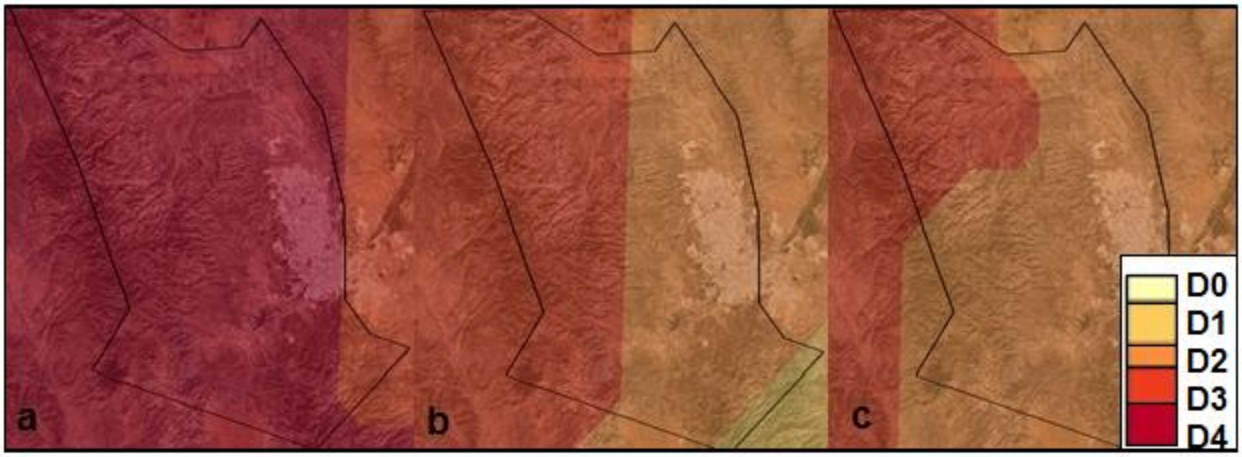


Fig. 8 Spatial distribution of MSDIc a. August 1994 Exceptional drought, b. February 1999 Extreme drought and c. September 1995 Severe drought.

It seems that in some years there is a relation between MSDIc/SPI and groundwater depth in the study area (Fig. 9) (Kavianpour *et al.*, 2020). The exceptional meteorological drought in 1994 corresponds to an increase in groundwater depth in the consequent year of 1995. Between the years 2000-2003, an extreme long-term meteorological drought occurred, which can be related to a high increase in the depth of groundwater in 2003. In 2004, the MSDIc level was positive, which can be related to a moderate stabilization of the depth of the groundwater. The year 2007 had an abnormally wet MSDIc probably contributed to a recovery of the groundwater depth in the year 2008. The same behavior is observed in the whole period of study.

The meteorological drought and groundwater depth reflect a similar behavior throughout the whole period of study (Breña-Naranjo *et al.*, 2015). This means that the meteorological drought seems to have some effect, leading to groundwater level fluctuations, as Mustafa *et al.* (2017) reported in their study using SPI. Only a couple of studies present a conclusive relationship between drought and the water level behavior, e.g. (Edossa *et al.*, 2016), or (Garamhegyi *et al.*, 2018) which establish the level fluctuations with periodic behavior of drought, just as can be observed in this study.

Groundwater Recharge

Monthly groundwater recharge (Fig. 10) shows that there has been a significant long-term trend in groundwater recharge over the last 30 years period.

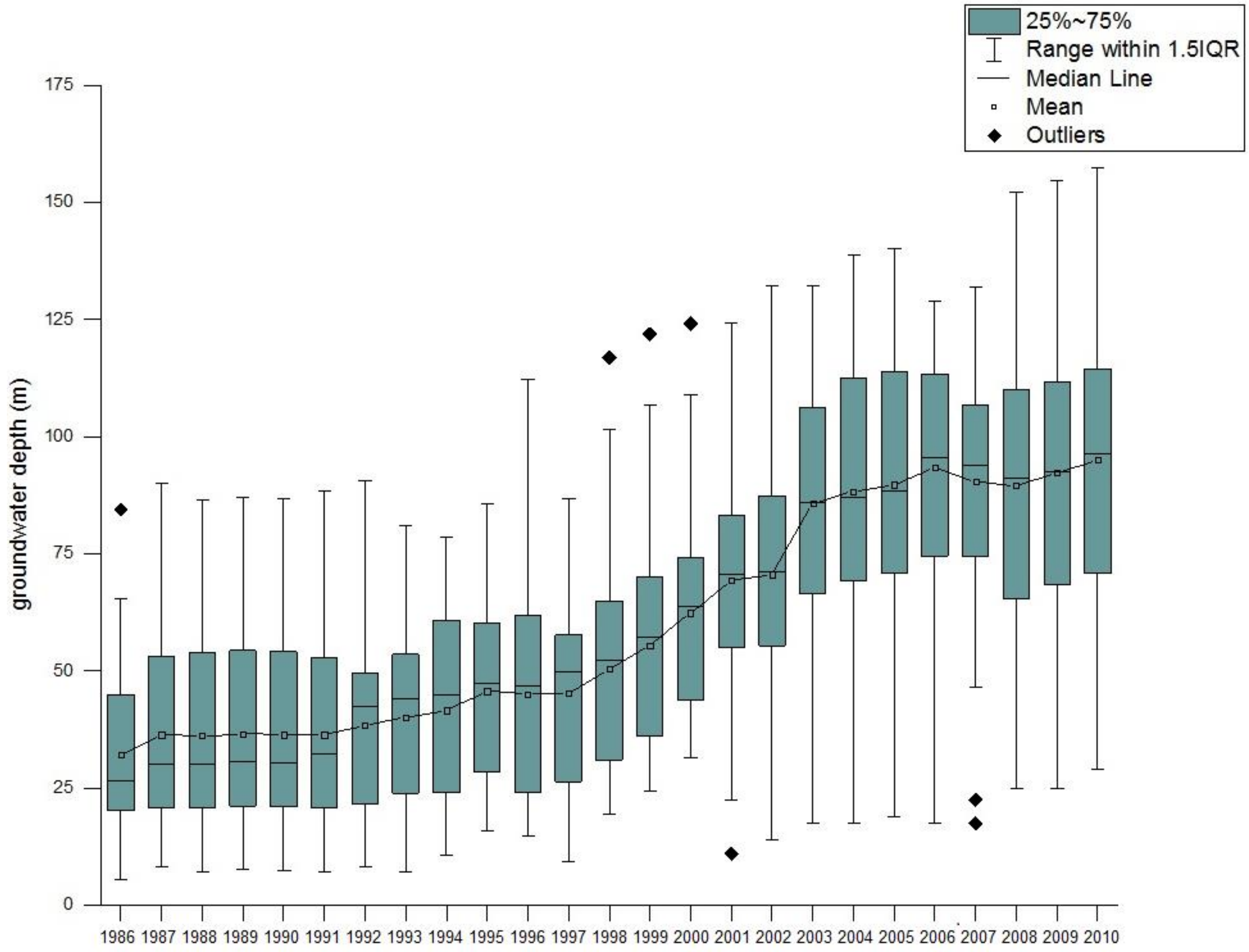


Fig. 9 Average annual groundwater depth in CHS aquifer. Average groundwater depth increased monotonically.

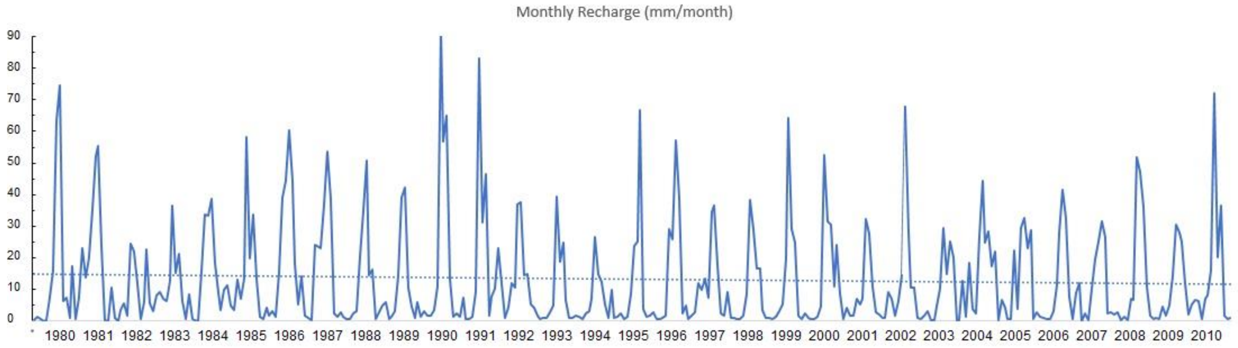


Fig. 10 Monthly groundwater recharge in the study area. The dotted line is the linear trend for the data.

Groundwater recharge is not uniformly distributed over the year; however, it shows that groundwater recharge is very low during the dry season (November to April) and very high in July, August, and September, in accordance with the wet season.

Yearly groundwater recharge in the study area has varied between 72 and 253 mm yr-1 over the last 30 years with a yearly average groundwater recharge value of 150 mm. Some parts of the study area were characterized by null or very low recharge, due to impermeable soil, mainly in the urban area. The area of greatest recharge occurs in the outcrop areas determined in Fig. 4, as well as in the forested area located in the Sierra el Mogote and Azul. For the year 1986, a surface of 1,104.73 ha was planted, with the extraction of groundwater of 12.04 hm3 yr-1, for the year of 1996 an area of 914.98 ha was planted, with the extraction of groundwater of 11.9 hm3 yr-1 and finally for 2011, an area of 705.08 ha was planted with the extraction of 13.23 hm3 yr-1, for the year 2009, there is only the volume of groundwater extracted, which is equivalent to 10.0 hm^3 yr^{-1}. Concerning the previous data, there was a recharge for return of irrigation for the year 1986 of 2.41 hm^3 yr^{-1}, for 1996 of 2.38 hm^3 yr^{-1}, for the year of 2009 of 2.0 hm^3 $yr^{-1,}$ and the year of 2011 of 2.65 hm^3 yr^{-1}.

Fig. 11 represents the comparison of the deviation of groundwater recharge from the long-term average with the annual MSDIc. Here the long-term average was calculated for each year.

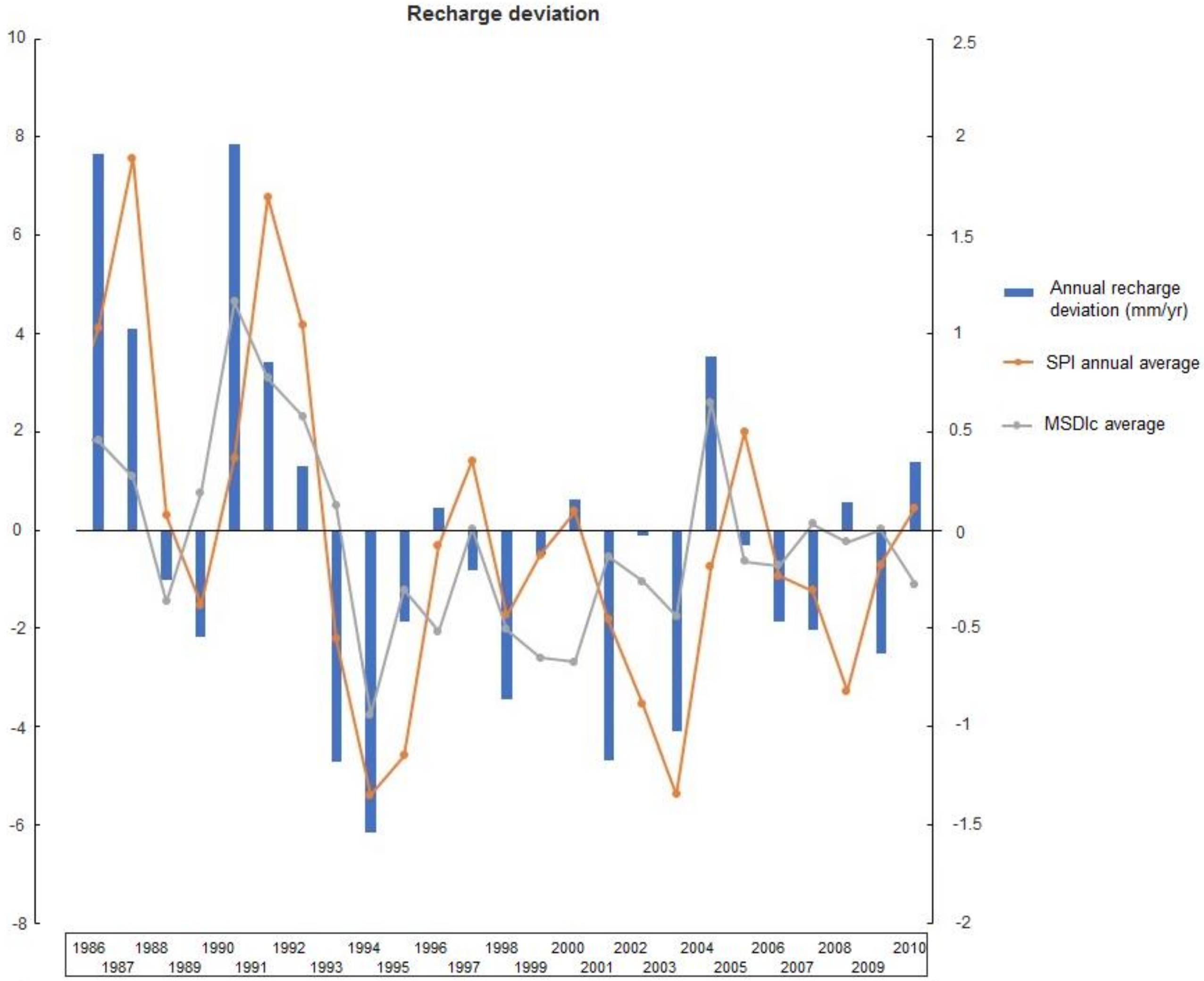


Fig. 11 Comparison of the deviation of annual groundwater recharge (blue bars) from long-term average with annual SPI (orange line) and MSDIc (gray line).

Negative values of the deviation mean that the recharge is less than the long-term average value (negative anomalies). Positive values of the deviation mean, that the recharge is higher than the long-term average value (positive anomalies).

Fig. 11 shows that MSDIc has a direct relation with the groundwater recharge deviation (recharge anomalies), inferring that the variables that compose the MSDIc (rainfall, runoff, and soil moisture) are a very sensitive input for the recharge estimation (Van Loon and Van Lanen, 2013). Both MSDIc and groundwater recharge deviation (recharge anomalies) show almost the same temporal pattern and dynamics. Based on the results, if the periodic behavior of water levels in the wells changes, it is expected that recharge from precipitation will decrease as well (Garamhegyi *et al.*, 2018). The irrigation areas in the study area seem to be the most vulnerable to the detriment of groundwater recharge.

Groundwater Abstraction

The public water use of the city and the exploitation of the CHS aquifer (Fig. 12) present opposite trends, public use tends to increase over time due to various factors such as: population growth rate, economic and industrial growth. The public use is satisfied through: CHS aquifer, Sauz-Encinillas (SE) aquifer, Tabalaopa-Aldama (TA) aquifer, and superficial water. In contrast, the CHS aquifer presented a variability in the abstraction with a negative trend.

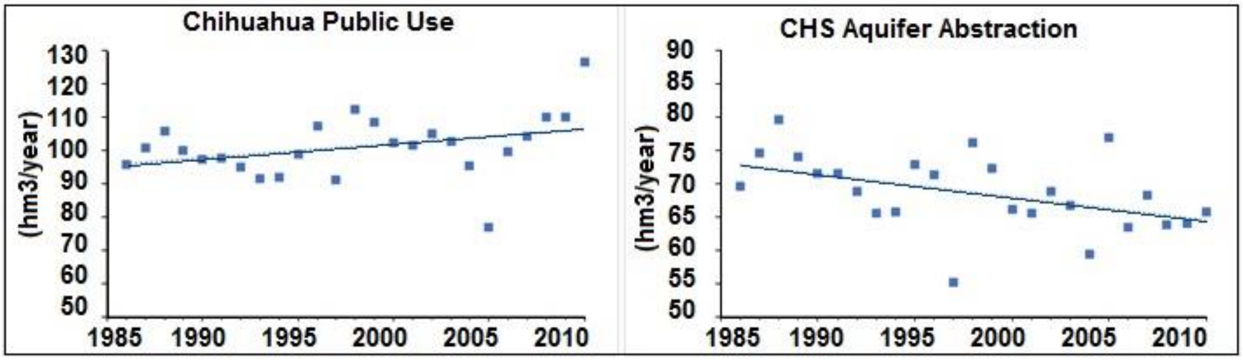


Fig. 12 Water use to satisfy the public demand of the city and the annual groundwater abstraction of the CHS aquifer.

From 1988 to 1993 there was a constant decrease in the abstraction of the CHS aquifer (Fig. 12), this period presented mostly wet years that were combined with the implementation of intermittent water supply (IWS) (David *et al.*, 2020) to satisfy the growing demand of the population.

From 1993 to 1997 a constant increase in the abstraction of CHS aquifer can be appreciated along with the boost of water supply from the SE and TA aquifers. From 1998 to 2000 there is a decrease in the abstraction of the CHS aquifer despite being a dry season, in consequence, JMAS reduced the hours of water supply. The year 2004 is the one with the highest MSDIc value and coincides with the highest precipitation value with 577.7 mm, showing a decrease in the extraction of water in that year.

From 2005 to 2010, has a decline in water extraction reaching the lowest values observed for the year 2008. As is seen in many other agricultural areas, extraction as groundwater pumping varies inversely with precipitation and directly with acres of production. The exploitation of the Chihuahua-Sacramento aquifer, in general, is variable throughout the study period due to diverse factors, such as: population growth rate, economic and industrial growth, agricultural use, precipitation, and the exploitation of other sources of groundwater (JCAS, 2013).

The influence of groundwater abstraction on average groundwater depth can be evaluated qualitatively. Between 1988 to 1993 there is a stability of the groundwater depth that can be related to the decrease in abstraction that exists in the same range of years. From 1995 to 1997 there is a minor recovery of the static level that adjusts with the considerable decrease in groundwater exploitation in the same range of years. The trend of the average groundwater depth displays a monotonically increase in the deepening of the groundwater.

Table 2 shows the annual and monthly trend values from the Mann-Kendall trend test and Sen’s method. A positive (negative) value of ZMK indicates that the data tend to increase (decrease) with time. It is observed that groundwater depth had a significant increasing trend, in contrast, groundwater abstraction, SPI, and MSDIc had a significant decreasing trend meaning that meteorological drought worsens (Hao *et al.*, 2014). The Sen’s slope value shows the average groundwater depth at a rate of 2.97 m year^{-1} even though the groundwater abstraction is been reduced at a rate of 0.41 hm^{3} yr^{-1}. Groundwater recharge demonstrates a significant decreasing trend, resulting from a complex approximation from induced recharge and natural recharge, the amount of natural recharge from precipitation is reduced as proven by the variables of SPI and MSDIc on the contrary the induced recharge increases due to various factors such as: the need to use groundwater for irrigation (irrigation return), possible leaks in the drinking water network and the increase of losses due to the setting of IWS.

The STL test was used to determine whether or not significant changes have occurred over time while taking into account variation due to seasonal effects. Fig. 13 provides the details about decomposed time series of monthly average rainfall, groundwater recharge, SPI, and MSDIc. The patterns of meteorological index present a similar seasonal component emulating the results obtained by Rangel (2017). These findings are concordant with (Teng *et al.*, 2018), where precipitation decreased over the past five decades, varying from year to year.

Table.2. Trend values from the Mann-Kendall trend test and Sen’s method.

Time series	Z_{MK}	P-value	Sen's value
Annual Groundwater abstraction (hm^3)	-3.10	0.0009	-0.4152
Annual Groundwater depth (m)	6.46	0.0001	2.9760
Monthly SPI	-4.96	0.00001	-0.0003
Monthly MSDIc	-3.02	0.0012	-0.0017
Monthly Groundwater recharge (mm)	-4.71	0.00001	-0.0103

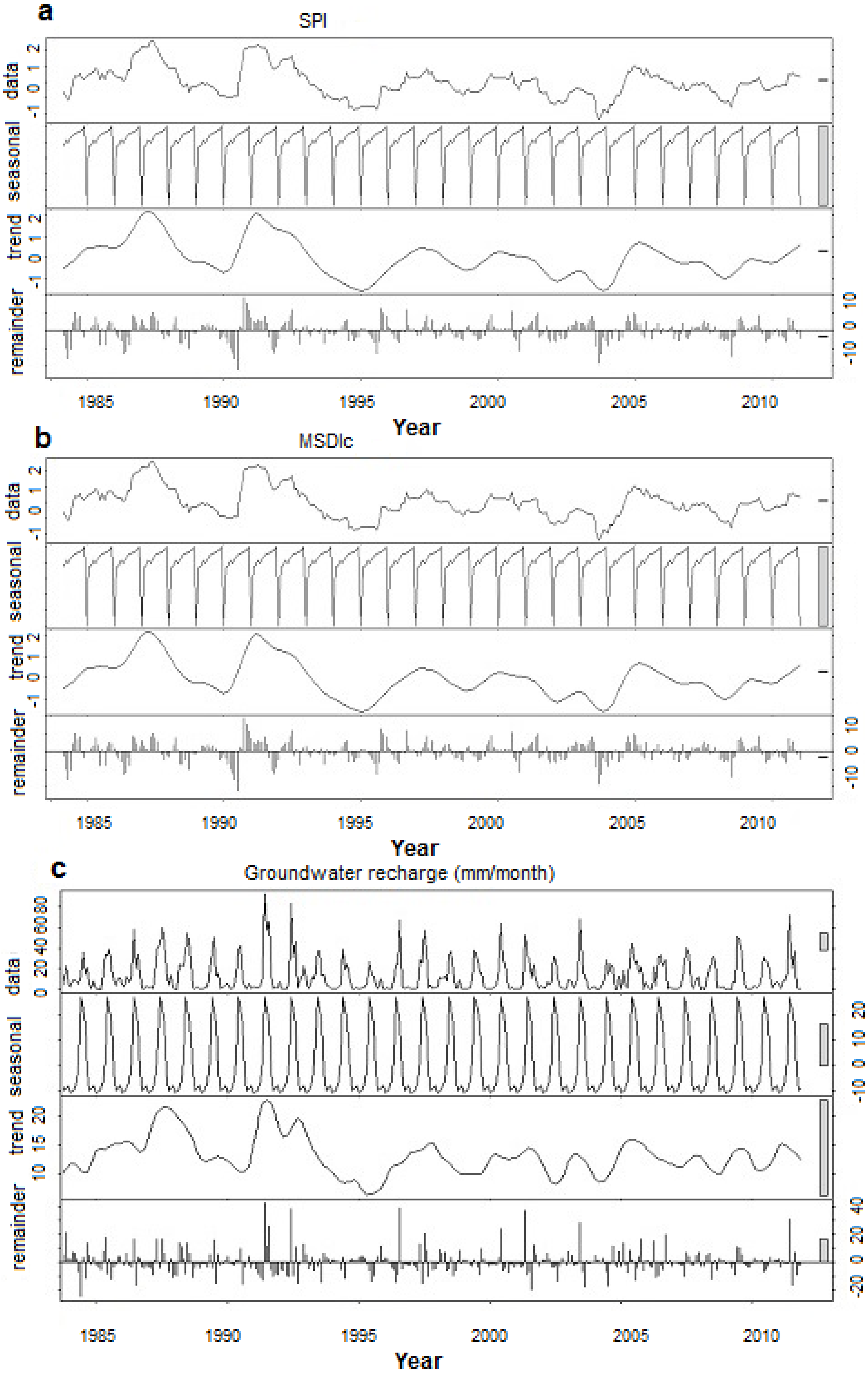


Fig. 13 Decomposed time series of the monthly average of the original data of: a. SPI, b. MSDIc, and c. Groundwater recharge (mm); the seasonal and trend component of time series after STL decomposition, and the residual component of the time series. The bars on the right show the comparison of vertical scales.

MSDIc decreased with a slope of .0017 from 1986 to 2010, this value unambiguously represents a drought trend. As Rangel (2017) stated, the use of MSDIc has managed to capture the persistence of drought through its propagation process based on specific information. These meteorological trends accord with the global climate change warming trend (Lin *et al.*, 2018; Meehl and Stocker, 2007).

Regression Analysis

Table 3 shows the T-value and P-value of the different variables in predicting groundwater depth by multiple linear regression. In this study, only the groundwater abstraction contributes significantly to predict groundwater depth. These findings are in accordance with Bui *et al.* (2012) and Lu *et al.* (2014), who mentions that groundwater abstraction is the main influence factor in the changes of the groundwater level. The model obtained in this study differs from the findings of other researchers, where a larger percentage of the total variation in the groundwater level can be explained by the different models proposed by Li *et al.* (2017) and Mustafa *et al.* (2017). The distribution of the data showed obvious peaks, fat tails, or heteroscedasticity; making the robustness of the multiple regression model to be poor. The low model R2 value (39.62%) indicates that the multiple linear regression assumptions could not be achieved, causing errors in the case of looking to produce a precise prediction. The detriment of the groundwater level despite the decrease in the abstraction of the aquifer is related to the overcoming of the balance.

Table.3. T-value and P-value of different variables in predicting groundwater depth by multiple linear regression.

Term	[a]Coef	T-value	P-value
Constant	202.1	3.69	0.001
Groundwater abstraction	-2.265	-2.99	0.007
SPI	-7.92	-1.13	0.271
MSDIc	-7.3	-0.63	0.538
Groundwater recharge	0.86	0.47	0.642

[a]Coef stands for the regression coefficient.

The balance of the aquifer is estimated by quantifying the inputs, outputs, and the change of storage in a period, according to the JCAS (2013), the CHS aquifer presents for the years 1996 and 2009 inputs of 50.23 and 50.93 $hm^3\ yr^{-1}$ and outputs of 72.06 and 65.67 $hm^3\ yr^{-1}$, so there is a storage change of -21.83 and -11.73 $hm^3\ yr^{-1}$ respectively, exemplifying that despite the decrease in the exploitation of the aquifer, there is a constant negative evolution of the groundwater level because the recharge capacity (natural and induced) in the aquifer is constantly exceeded.

It is well established that groundwater pumping affects surface-water availability by intercepting water that would otherwise discharge to streams, conversely, surface-water management affects groundwater availability by altering the timing, location, and quantity of groundwater recharge and pumping. A lack of modeling tools capable of simulating interactions between surface-water and groundwater affect the analyses of climate change impacts on water resources (Hanson *et al.*, 2004) it is essential to create a model that shed light on this interaction and is capable of baring the importance of interdecadal-climate cycles as controls on rates and mechanisms of climate-varying recharge and support the conclusion that understanding natural climate variability is a necessary step toward predicting ground-water response under climate change. Such understanding may help managers to better plan for the long-term sustainability of groundwater resources (Hanson *et al.*, 2012).

CONCLUSIONS AND RECOMMENDATIONS

This study develops a methodology for the analysis of influential factors in groundwater in a study area in which there is no complete and comprehensive database. This proposed methodology allows a primary evaluation of the state of groundwater use. This study comprehensively analyzes the influential factors on groundwater depletion in CHS aquifer in Chihuahua México. It was found that there are serious impacts of human activities on the groundwater system. This study area experienced a trend towards an increase in the intensity of the climatic drought from 1986 to 2010. The univariate standardized indexes (SPI) and the multivariate standardized index (MSDIc) allowed weighing the intensity of the main influential meteorological variables in climatic drought. The combined impacts of the change in land cover and the trend of increase in climatic drought have caused impacts in the reduction of groundwater recharge. According to the model obtained, it can be determined that the decrease that exists at the static level is significantly correlated with the increase in the amount of groundwater abstraction. The average groundwater level was 32m for the year 1986, increasing to 92m in 2010.

From the multiple linear regression model, it can be observed that the only significant variable that produces an effect on the groundwater level is the groundwater abstraction. The detriment of the groundwater level despite the decrease in the abstraction of the aquifer is related to the overcoming of the balance. Meteorological variables and groundwater recharge, despite maintaining a diminishing trend as the static level does, do not prove to be significant to the detriment of groundwater level. Due to various factors such as: low model robustness, the need for a greater number of observations (years analyzed), and the inaccuracy of the calculation of water withdrawal volumes, causes the model to have a low R2. This low percentage of the response variable variation explained by the model does not allow to establish accurate predictions regarding the evolution of groundwater levels. An invariable monthly measurement of the static level in the different piezometers that the JCAS has, is indispensable to be able to evaluate the variability of the evolution of the static level according to the seasonality of the year.

The study area will face unprecedented challenges concerning the management of the groundwater resources to meet the increasing water demand of a growing population. The findings of this study could be beneficial to decision-makers and could help ensure adequate preparations of effective climate variability and change adaptions plans at a national and local level. Strengthening meteorological, hydrological, and groundwater monitoring is vital to ensure the data that can allow researchers to continue to elaborate knowledge that will shed light to endure water usage sustainability. Seasonal monitoring data would allow improving this model, making it possible to predict the behavior of the aquifer under different conditions. Additionally, the changes generated to the detriment of the groundwater level can cause changes in native water quality. Thus, a study to provide comprehensive data on groundwater quality to evaluate the sustainability to protect the groundwater source should be further explored.

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STUDY II. PRACTICAL PRESSURE MANAGEMENT FOR A GRADUAL TRANSITION FROM INTERMITTENT TO CONTINUOUS WATER SUPPLY

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ABSTRACT

PRACTICAL PRESSURE MANAGEMENT FOR A GRADUAL TRANSITION FROM INTERMITTENT TO CONTINUOUS WATER SUPPLY

BY:

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Cities in developing countries that do not consider water resources as the basis for sustainable growth usually accept intermittent water supply (IWS) as the alternative to satisfy the demand of the population. Networks designed as constant water supply (CWS) operated as IWS hinder a safe and reliable water supply, thus, feasible alternatives to return the operation to CWS are required. This paper presents a methodology-based flow/pressure control to accomplish an efficient transformation from an IWS sector to a CWS, in the City of Chihuahua, Mexico. The management of pressure at sector entrance and critical supply points leads to successful improvement of service, ensuring water availability with adequate pressure at the peak of demand, as well as reducing the supply of water volume by 58% compared to the sector operated in IWS. The methodology allowed the improvement of decision-making and operating policy for the water operating agency (WOA), fixing service deficiency, avoiding the loss of water volumes, and maintaining competent management control. Nonetheless, resistance to the transition of using automation and setting the volume/pressure consumption based on reliable data persists. The change process will be successful to the extent that the WOA efficiently channels the participation of the personnel.

Keywords: CWS; DMA; Hydraulic efficiency; IWS; Pressure management.

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RESUMEN

PRACTICAL PRESSURE MANAGEMENT FOR A GRADUAL TRANSITION FROM INTERMITTENT TO CONTINUOUS WATER SUPPLY

POR:

M.I. DAVID HUMBERTO SÁNCHEZ NAVARRO

Las ciudades de los países en vías de desarrollo que no consideran los recursos hídricos como la base del crecimiento sostenible suelen aceptar el suministro intermitente de agua (IWS) como la alternativa para satisfacer la demanda de la población. Las redes diseñadas para suministro de agua constante (CWS) operadas como IWS dificultan un suministro de agua seguro y confiable, por lo que se requieren alternativas factibles para devolver la operación de estas redes a CWS. Este artículo presenta una metodología de gestión de flujo/presión para lograr una transformación eficiente de un sector con IWS a CWS, en la ciudad de Chihuahua, México. La gestión de la presión en la entrada del sector y en los puntos críticos de suministro conduce a una mejora exitosa del servicio, asegurando la disponibilidad de agua con presión adecuada en el pico de la demanda, así como la reducción del volumen suministrado de agua en un 58% en comparación con el mismo sector operado en IWS. La metodología permitió la toma de decisiones y mejorar la política operativa del organismo operador de agua, subsanando la deficiencia del servicio, así como, evitando la pérdida de volúmenes de agua y manteniendo un control de gestión competente. No obstante, persistió la resistencia a la transición a utilizar la automatización y datos confiables generados sobre el consumo de volumen o presión. El proceso de cambio será exitoso en la medida que el organismo operador canalice eficientemente la participación del personal.

Palabras claves: CWS; DMA; eficiencia hidráulica; IWS; Gestión de presiones.

INTRODUCTION

Piped water supply for a few hours a day or intermittent water supply (IWS), is a common form of access to water in developing cities with 500,000 or more inhabitants (Ilaya-Ayza *et al.*, 2018). IWS has been growing as an alternative to public policy in communities where continuous water supply (CWS) is complex to achieve (Tsegaye *et al.*, 2011). Totsuka *et al.* (2004) stated that IWS exists due to poor technical management, economic scarcity, or insufficient water supply. The absence of consideration of the infrastructure or water resources as a baseline for the sustainable growth of a city causes the lack of the ability to provide water service in sufficient quantity and quality. It is the case of the city of Chihuahua where the operation of several districts is "forged" day by day through the experience and criteria of the Municipal Water and Sanitation Board (known in Spanish as JMAS). The JMAS decides to maintain a "more or less" service to existing zones, alternatively in new zones, a need for extraction of higher volumes is arisen to satisfy the new demand. It should be noted that the increase in supply is not equated with effective demand coverage, because of the lack of effective conduction and distribution (Klingel, 2012; Galaitsi *et al.*, 2016). Several studies have shown that network deficiencies caused by IWS, may not guarantee the safe and reliable provision of water (Hunter *et al.*, 2009; Herrera *et al.*, 2012; Kumpel and Nelson, 2013; Ilaya-Ayza *et al.*, 2017). One of the best ways to assure water quality in the network and to reduce deficiencies for users is maintaining a positive and continuous pressure level throughout the network (Kumpel and Nelson, 2014; Ilaya-Ayza *et al.*, 2018). Thus, transforming a network operating in IWS to a CWS is the main challenge in developing countries (Vairavamoorthy *et al.*, 2008). The first step in the transition process is the division of the network into district metered areas (DMAs) (De Paola *et al.,* 2014). DMAs splits an interconnected and intricate network into smaller, virtually independent sub-networks (districts) that can be better managed; each district proposes a maximum demand value, seeking to maintain homogeneity in the pressure distribution. A substantial benefit of DMAs implementation is the ease to detect any abnormality within the district (Morrison *et al.*, 2007; Herrera *et al.*, 2012). For a Water Operating Agency (WOA) as JMAS, detecting abnormalities allows the recovery of water volume losses in network leaks and makes it possible to identify clandestine connections or malfunctions of the flowmeter.

The traditional design of DMAs has been based on empirical suggestions (limits on the number of properties, length of pipes, etc.) (Nardo *et al.*, 2013), in the case of Chihuahua, the number of user accounts was the criteria to elaborate the physical delimitation of the sectors, giving priority to zones with greatest service deficiency. JMAS put into operation the delimitated sectors with constant water supply (CWS), causing leaks in the surrounding areas because of the uncertainty in the cadaster, therefore, there was no impact on the perception of improvement of the service by the population. JMAS concluded that the unacceptable results were due to the quality and quantity of data generated from the delimitated sectors. The data generated through the supply and distribution of drinking water by the WOA can be “dark data”, presenting uncertainty in the flow or pressure values making them unreliable, causing the WOA to view the “dark data” skeptically. Digitization, intelligent learning systems, information and communication technologies (ICT), and automated machine learning, are methods that led to the rebirth of water data. Nevertheless, no specific reference for the use of reliable data to improve the transition of IWS sectors to CWS may be found in the literature. WOA seeks for alternatives to solve the transition from IWS to CWS, where water companies are not able to make large investments to achieve transition processes in a single and large project (World Bank 2013; Patil *et al.*, 2017). As Ilaya-Ayza *et al.* (2018) stated, the gradual transition based on improvement stages is deemed to be a good option, as the first transitioned sectors to CWS serve as guidance for the next sectors. This paper presents a methodology based on reliable data (obtained by ICT) to accomplish an efficient transformation from the IWS sector to CWS. The process will allow to improve service deficiency, avoid the loss of water volumes, and maintain competent management control. New methodologies exist to gradually increase the capacity of guaranteeing water supply equity in an intermittent and continuous coexistence network, such as the one of the group Ilaya-Ayza *et al.* (2018) that lead to improving the hydraulic behavior of the network, driving to new scenarios with increased capacity that allow higher pressure level in all sectors. However, this study addresses the use of ICT data to analyze the pressure in a sectorized network to optimize the transformation from IWS to a CWS sector. It is expected that the results will contribute to the efficient management of water resources, providing WOA with a greater understanding of the water supply and distribution making it able to ensure water equity and stable pressure for the consumers.

MATERIAL AND METHODS

Description of the Case Study System

The city of Chihuahua is located in the northern part of Mexico between 28°500 to 28°300 North latitude and 106°120 to 105°500 West longitude. Chihuahua is the capital of the Chihuahua state (Sánchez-Navarro *et al.*, 2019), and the second most populated city of the region with a population of 929 739 in 2018. The city has a land area of 224.85 km^2 and uses 3 300 km of the water distribution network to serve 327,000 customers. The distribution network is a complex system, because of the extension and the topography of the supplied area (with elevations ranging between 1348 and 1500 a.s.l.). The length of the mains in the network is 829.6 km, which is only for the mains of the network that are bigger than 100 mm, the remaining of the network have a length of 2,527.1 km used for service connections. The volume of non-revenue water in Chihuahua changes every year, but the average non-revenue water volume is 49 Mm^3 per year (38% of supplied water).

There are several methods for portioning the network into DMA's (Morrison, Tooms and Rogers, 2007; Herrera *et al.*, 2012; Di Nardo *et al.*, 2013), recently the JMAS in collaboration with the Mexican Institute of water technology (IMTA) designed a methodology to restructure the DMA's in the city of Chihuahua. This research, however, does not design the DMA in the Chihuahua network but focuses on integrating pressure management to evolve the DMA from IWS to CWS.

The DMA is part of a zone composed of 8 sectors that supply water to an estimated population of 35,994, the study sector has a population of 3850 and an average volume consumption prior to pressure management of 450,900 m^3/yr. The studied DMA has 1100 customers connected to the network, of which 99.5% are households and the rest commercial services. The mains length in the DMA is 1.63 km (0.20 and 0.45 m diameter), and the length of sub mains and service connection is 7.4 km (diameters less than 0.20 m). The DMA has an area of 0.356 km^2, with elevations ranging between 1486 and 1474 a.s.l. in a length of 606 m (Fig. 1). The DMA before the application of the methodology had an IWS with two schedules, from 4:00-9:00 and 16:00-20:00. The IMTA and JMAS carried out a pressure survey to record the pressure within the sector. With the network pressurized, pressure gauges were installed in 55 households outlets. The results were a minimum pressure of 0.7 kg/cm^2, maximum pressure of 2.50 kg/cm^2, and an average pressure of 1.56 kg/cm^2. The pressure distribution within the sector allowed to validate the behavior predicted in the hydraulic model made by the JMAS using INFOWORKS PRO program.

Measuring instruments, real-time network monitoring, and control equipment were included to enable real-time knowledge (Maiolo *et al.*, 2019).

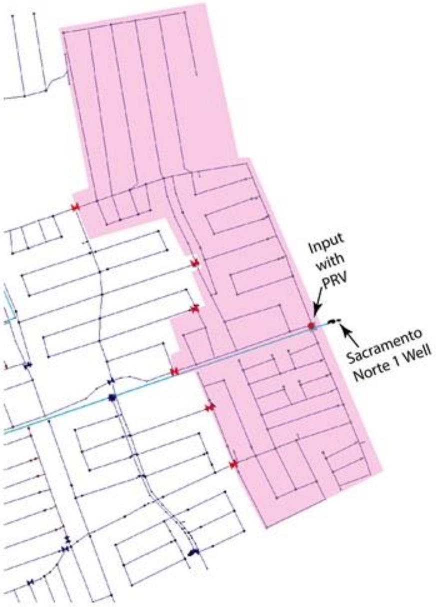

Fig. 1 The Sacramento 1, Study DMA.

The entrance to the sector was instrumented with: Arkon electromagnetic flowmeter with pulse output, starting flow of 0.5 m^3/h maximum flow of 200 m^3/h and ±2% accuracy; a Bermad pressure regulating valve (PRV) and Pegasus+ pressure control system developed by HWM-Water Ltd. (Cwmbran, UK) were installed to control upstream and downstream pressure/flow; two data loggers Multilog LX with two pressure and one flow channel developed by HWM-Water Ltd. (Cwmbran, UK) were set in the most unfavorable points (high and low) within the sector to record the pressure/flow (Fig. 2).

Fig. 3 shows the behavior at the DMA entrance and at the critical points, this data was taken while operating as IWS. A peak can be observed at the beginning of the flow service hours (black line) which serves only to displace air in the pipe network (saturate the sector), this volume of water does not turn into consumption by the user. It took an hour between the opening of the PRV and the gauging of the operating pressure at the critical points, as it is appreciated in the displacement between the pressure downstream of the PRV and the pressure in the critical points (highest and lowest point respectively). This displacement can only be observed through in situ measurement, since all simulation models are based on the assumption that, once in operation, the network remains loaded. Knowing the flow/pressure behavior in the DMA allowed establishing a multi-step methodology to achieve an efficient transformation from IWS to CWS.

Fig. 2 Real-time instrumentation for pressure management in the city of Chihuahua, México. 1. Electromagnetic flowmeter. 2. Pressure regulating valve (PRV). 3. PRV controller with GPRS communication. 4. Multilog, advanced data logger with integral GPRS telemetry. 5. Multilog, advanced data logger with integral GPRS telemetry at a critical point.

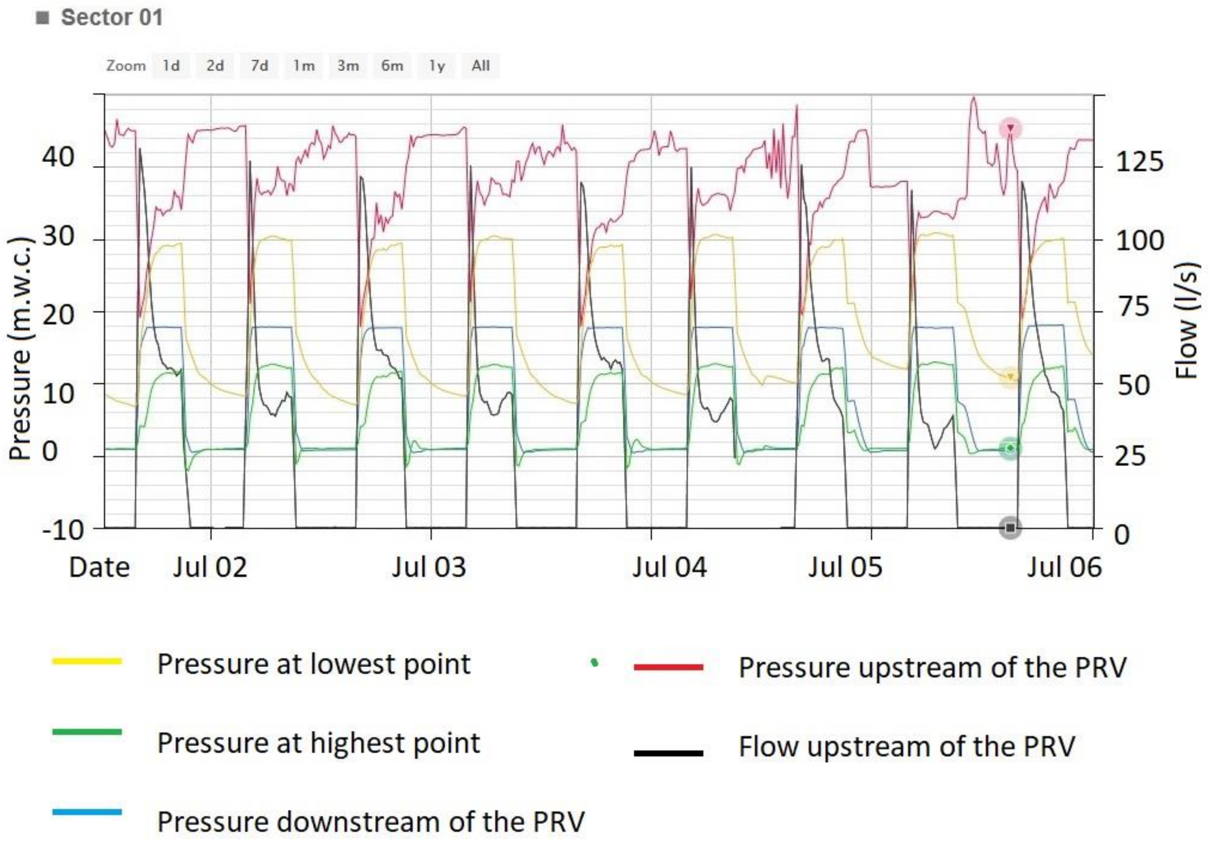

Fig. 3 Flow/pressure data at PRV and critical points within sector 01. This data register was taken in an intermittent water supply (IWS).

Methodology of transition from IWS to CWS

In the first step, the command was to establish the schedule to have sufficient pressure and flow at the time of greatest demand in the sector (Nyende-Byakika, 2018; Taylor, Slocum and Whittle, 2019; David, García and Navarro Góme, 2020). The second step included a supply modulation considering a critical point or the most unfavorable point within the sector, in this stage, there is a constant pressure supply schedule in the PRV. Equitable distribution of pressure was sought by contemplating the loss due to topography, which supports the uniformity of available service time (Ameyaw, Memon and Bicik, 2013). The last step included the regulation of the flow, to determine the minimum night flow (MNF). MNF analysis is the most common method for leakage assessment at the scale of the DMA (AL-Washali *et al.*, 2018). The MNF is the lowest inflow in the DMA over 24 h of the day. MNF occurs depending on the consumption pattern of the DMA when most of the customers are probably inactive and the flow at this time is predominantly leakage (Farley and Trow, 2003; Farley and Liemberger, 2005; Puust *et al.*, 2010).

RESULTS AND DISCUSSION

In the first step, the timing instruction was given to set the pressure and water flow in higher demand. The service schedule was determined by the day-night cycle on a weekday of July 2018 (hot season) operating in CWS. As can be appreciated in Fig. 4 when high demand the pressure in the network decreases and vice-versa. The highest demand occurs between 07:00-11:00, reaching max. flow values of 55 l/s and pressure of 18 m; while the lowest demand occurs between 22:00-06:00 reducing the consumption up to 10 l/s with a max. pressure of 60 m, these values were measured downstream of the PRV.

The behavioral pattern identified in Fig. 4 was used to establish the service hours in the sector. This schedule was based on the flow displacement and minimum required pressure, seeking to avoid negative pressures and peak flows at the beginning of the water supply.

Fig. 5 shows the DMA as it was adapted to the water demand based on the behavior. In this stage, because there is an equalization of the water supply with the demand, the peak of filling of cisterns or water tanks is no longer so pronounced decreasing the max. flow to 106 l/s compared to 130 l/s operating as IWS. The water pressure and flow were aligned, offering water availability with pressure downstream of the PRV. The change in pressures within the sector can be recognized; displaying values of 17 to 13 m at the lowest topographic point, having water availability during the 24 h service. Alternately in the highest topographical point, minimal essential pressures are shown, without reaching suction ranging values from 10.5 to 2.5 m.

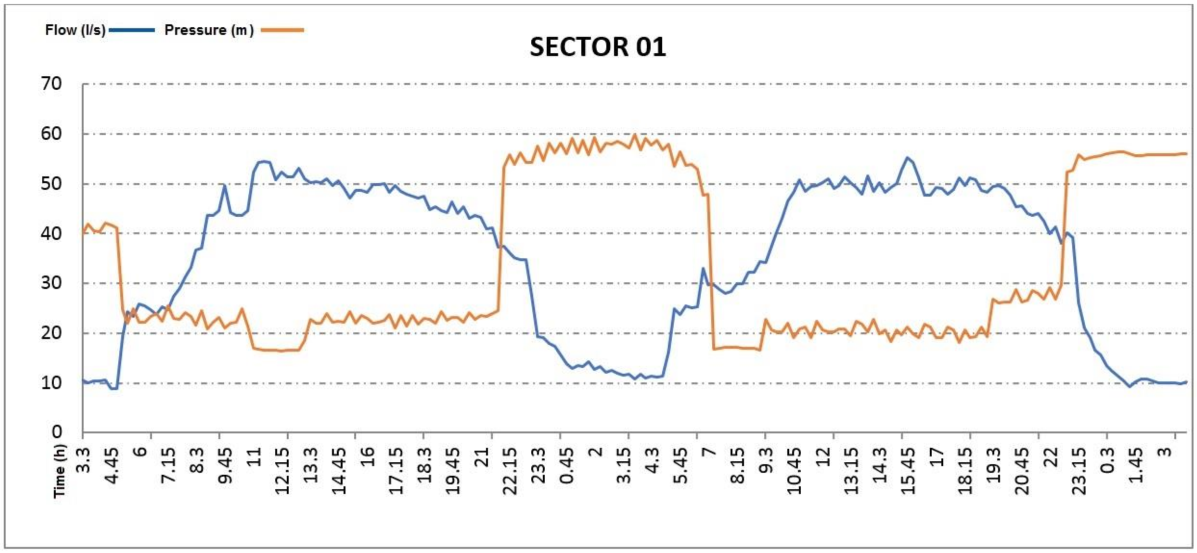

Fig. 4 Pressure and water flow pattern downstream of the PRV in sector 01.

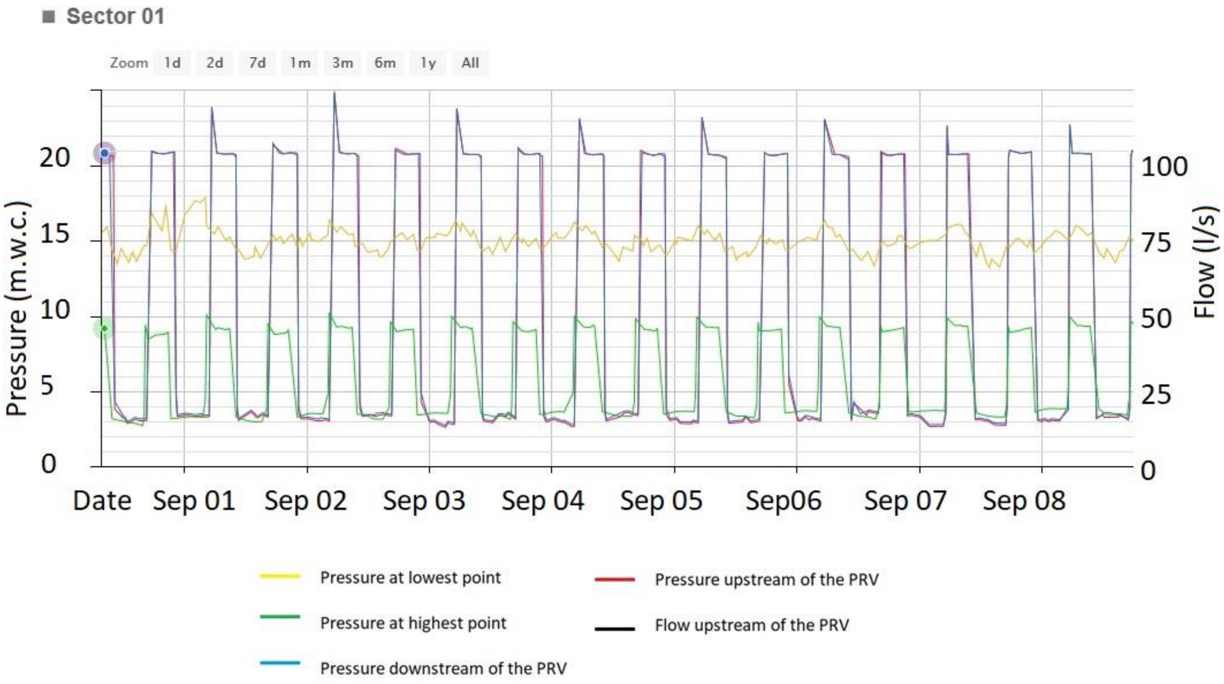

Fig. 5 Pressure/flow adapted according to the behavior of the DMA.

The second step addressed the modulation through critical points within the sector to set a homogeneity of the water supply. This was accomplished by controlling the differential of pressure downstream of the PRV, to pair the flow with the required demand. As illustrated in Fig. 6, the pressure lines downstream of the PRV and at the critical points show similar behavior presenting water availability with adequate pressure at the peak of demand. The flow values were decreased in the DMA to 75 l/s with a min. of 30 l/s stating a reduction of 43% with respect to the use of IWS and 30% compared to the first step. The downstream pressure of the PRV was modified to a range of 16 to 6.5 m. The lowest critical point increased its pressure range to 20.5 - 29 m, staying within the acceptable limit to avoid generating overpressures in the network. The highest topographic point also increased its pressure range to 3.5 - 12.2 m, obtaining enough pressure to supply water even in households with the highest elevation during the 24 hours.

The third step consisted of reducing the flow to a minimum using legitimate night consumption (AL-Washali *et al.,* 2018), the use of MNF will allow identifying the leak volume. The downstream PRV instruction was to reduce the flow to 16 l/s between 23:00-05:00, maintaining a minimum pressure of 0.6 m to prevent void in the network (Fig. 7). This methodology started after the JMAS finished the proper delimitation of the sector and operated the DMA as CWS to establish the behavior of the sector (Fig 4) during July 2018. The sector when operating in IWS required a daily supply of 1509 m^3, 1.37 m^3 per household (hh) per day.

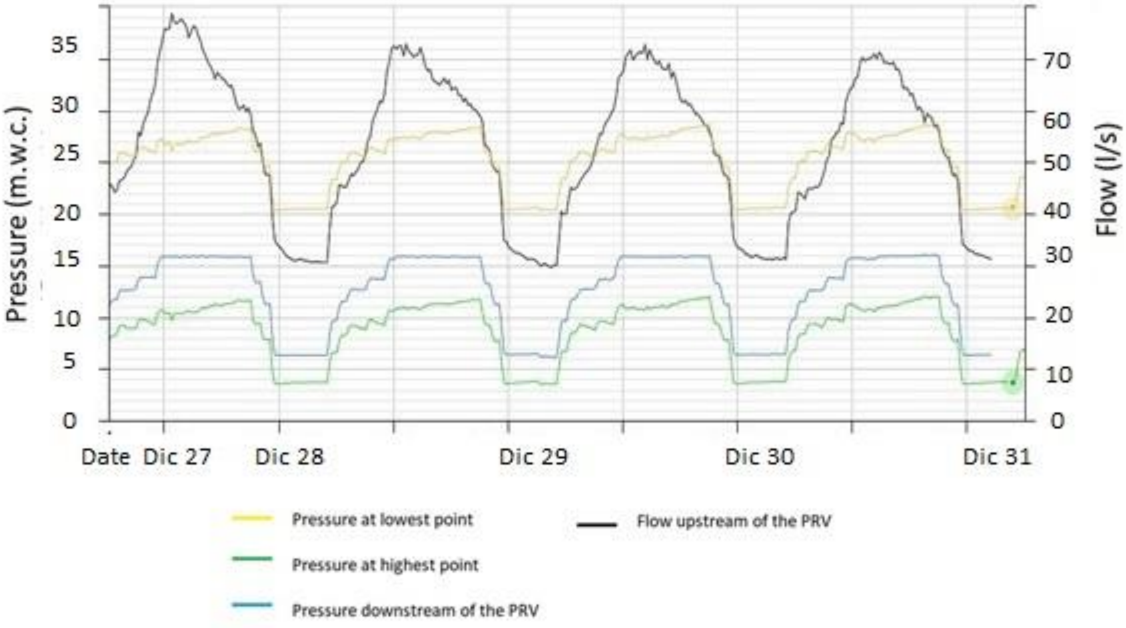

Fig. 6 Pressure/flow aligned according to the critical topographic points of the DMA.

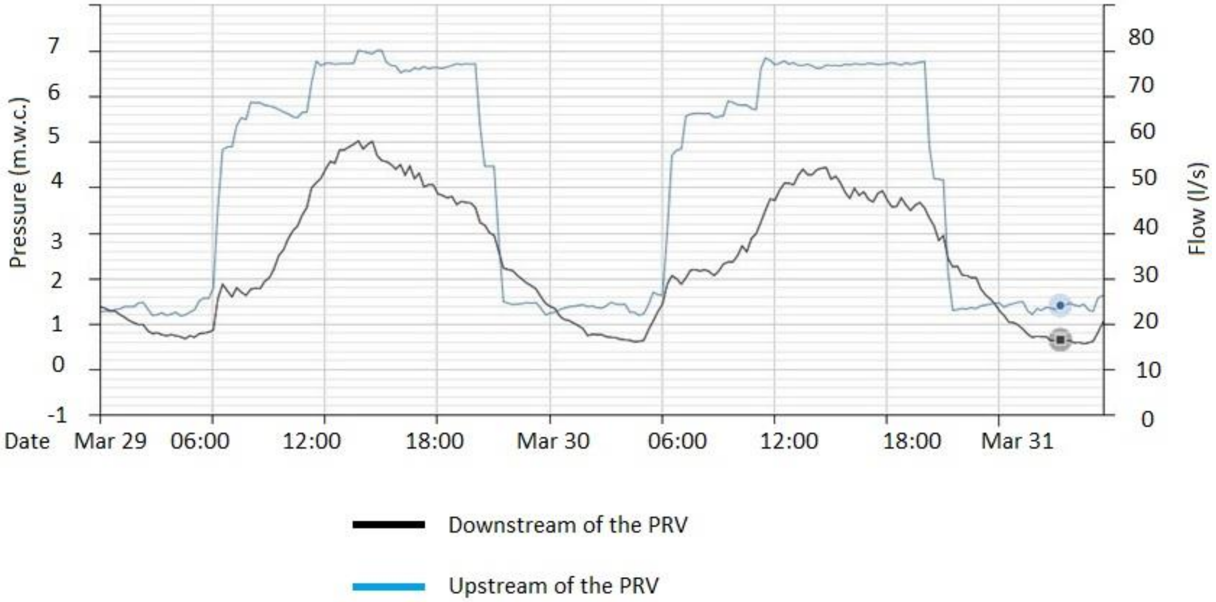

Fig. 7 Regulation of flow by setting the minimum night flow.

The first step of this study began in August 2018 (Fig. 5), in which 770 m^3 per day were supplied to the sector (0.7 m^3/hh/day) reducing the consumption compared to the IWS operation in 49%.

The second step was set up from November 2018, in which the daily consumption increased to 1013 m^3 (0.92 m^3/hh/day) compared to the first stage, however, this step provided water volume with sufficient pressure to the entire sector during 24 h. The last step began in January 2020, managing to reduce daily consumption to 636.8 m^3 per day (0.58 m^3/hh/day) leading to a 58% reduction in consumption compared to the operation of the sector in IWS. The estimation of the water savings by April 2020 is 477,280 m3, in 21 months from the origin of the study.

CONCLUSIONS AND RECOMMENDATIONS

In this paper, the results of practical pressure management were given, to evaluate the transition from intermittent to continuous supply using reliable data (obtained by ICT). Data were collected by monitoring a district of the Chihuahua (Mexico) water distribution network. The district serves around 1,100 properties with a total population of about 3,850. Pressure and Flux were measured upstream/downstream of the PRV and at the topographic critical points (highest and lowest), in order to establish the water consumption behavior of the DMA. The methodology set in the study improves the decision-making and operating policy for the JMAS. However, it should be noted that the operators and users are skeptical because they have become accustomed to a water supply routine and they consider that lowering the pressure is to lower the quality of the service. Furthermore, leaks come into sight because keeping the network charged at a minimum pressure makes them visible instead of having the leaks disappear in the discharge of the line, therefore, rehabilitation and leak detection is a priority. It should be noted that the volume supplied in the DMA operating in IWS is more than double, opposite to the water consumption using this gradual transition with restricted pressures. Nonetheless, resistance to the transition of using automation and setting the volume/pressure consumption curve based on reliable data measurement persists, because the perception of the operator is that the data is not registered or measured correctly. The change process will be successful to the extent that the WOA efficiently channels the participation of the personnel involved in the improvement of the processes. The management approach is directly related to institutional strengthening, and specifically to the direction and support actions required by the technical aspect.

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STUDY III. METHODOLOGY FOR SAVING WATER BY GRADUALLY RETURNING A CITY TO CONSTANT WATER SUPPLY; CASE STUDY, CHIHUAHUA

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ABSTRACT

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M.I. DAVID HUMBERTO SÁNCHEZ NAVARRO

A sustainable drinking water system is essential to ensure the availability of water, efficient management is developed by maintaining a positive and continuous pressure level. However, in developing countries, the conception is that constant water supply (CWS) is unsustainable and the preferred alternative is to modify to an intermittent water supply (IWS). In this paper, a methodology for gradually transform several sectors to CWS to decrease the quantity of water supplied is developed. Network sectorization and pressure management were achieved, indicating that the operation of 19% of the households under this methodology generates 24% of the water-saving of the city.

Keywords: dma; mnf; pressure management; real-time monitoring;

RESUMEN

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POR:

M.I. DAVID HUMBERTO SÁNCHEZ NAVARRO

Un sistema de agua potable sostenible es fundamental para asegurar la disponibilidad del recurso hídrico, la gestión eficiente se desarrolla manteniendo un nivel operativo de presión positivo y continuo. Sin embargo, en los países en desarrollo, la concepción es que el suministro de agua constante (CWS) es insostenible y la alternativa preferida es modificar a un suministro de agua intermitente (IWS). En este artículo, se desarrolla una metodología para transformar gradualmente varios sectores de IWS a CWS para disminuir el volumen de agua suministrado. A través de la sectorización de la red y la gestión de presiones se obtuvo que la operación del 19% de las viviendas bajo esta metodología genera un ahorro del 24% del agua de la ciudad.

Palabras clave: dma; mnf; gestion de presiones; monitoreo en tiempo real;

INTRODUCTION

A sustainable drinking water system (DWS) is essential to achieve the goal of ensuring availability and sustainable management of water, as stated in the development goals of the UN for 2030. The ability to set a sustainable DWS is linked to resource monitoring, quantifying use, and identifying management operations (Maiolo et al. 2019). According to several authors (Kumpel and Nelson, 2014; Ilaya-Ayza et al. 2018), one of the best ways to ensure efficient management of DWS is by maintaining a positive and continuous pressure level throughout the network. Sustaining a continuous water supply (CWS) provides water at required pressures and flows (Nyende-Byakika 2018), reducing health risks for users (Ilaya-Ayza et al. 2018).

In developing countries, the reduction of available water resources, climate change, urban population growth, and management deficiencies (Ilaya-Ayza *et al.* 2017) generates the conception that CWS becomes unsustainable and the preferred alternative is to opt for an intermittent water supply (IWS). However, operating as IWS a system designed for CWS can cause complex problems because the system does not foresee an eviction or emptying of the pipes after the filling for the supply. The possible drawbacks associated with the operation of the system as IWS includes: unreliable provision of water; inability to practice effective supply and demand management; operational inadequacies; customer inconvenience and coping costs; water quality problems; inequitable water distribution; network deficiencies provoke by the transient phenomena causing suction and possible failures in the pipes (Ameyaw, Memon, and Bicik 2013). Therefore, returning to a CWS should be the optimal operation option of the system but water companies are not able to make large investments to achieve a 24-hour supply. Thus, a gradual transition based on improvement stages is an efficient strategy (Ilaya-Ayza *et al.* 2018).

In the literature, very few models have been proposed to establish an effective transition from an IWS to CWS, with scarce practical cases (Gupta and Kulat 2018; Ray *et al.* 2018; Varu and Shah 2018) that return to CWS a DWS operating in IWS. However, if the DWS is not sectorized, sectorization must be a first step before the transition process (Ilaya-Ayza *et al.* 2018). In this paper, an approach based on a process of gradually transforming several district-metered areas (DMA's) to CWS, is developed to decrease the quantity of water supplied in these sectors. This case study is operated by the Municipal Water and Sanitation Board (known in Spanish as JMAS), the water operating agency (WOA) of the City of Chihuahua, Mexico. The results of this study look to improve the hydraulic behavior of the network and enhance user satisfaction by maintaining stable pressures and constant supply.

Site Description

The city of Chihuahua is located in the northern part of Mexico between 28°50' to 28°30' North latitude and 106°12' to 105°50' West longitude (Fig. 1) (Sánchez-Navarro *et al.* 2019). Chihuahua is the capital of the Chihuahua state, and the second most populated city of the region with a population of 929 739 in 2018, the city has a land area of 224.85 km^2. For the year 1970, the city had a population of 257 000 with CWS, but the exponential growth leads JMAS to implement IWS.

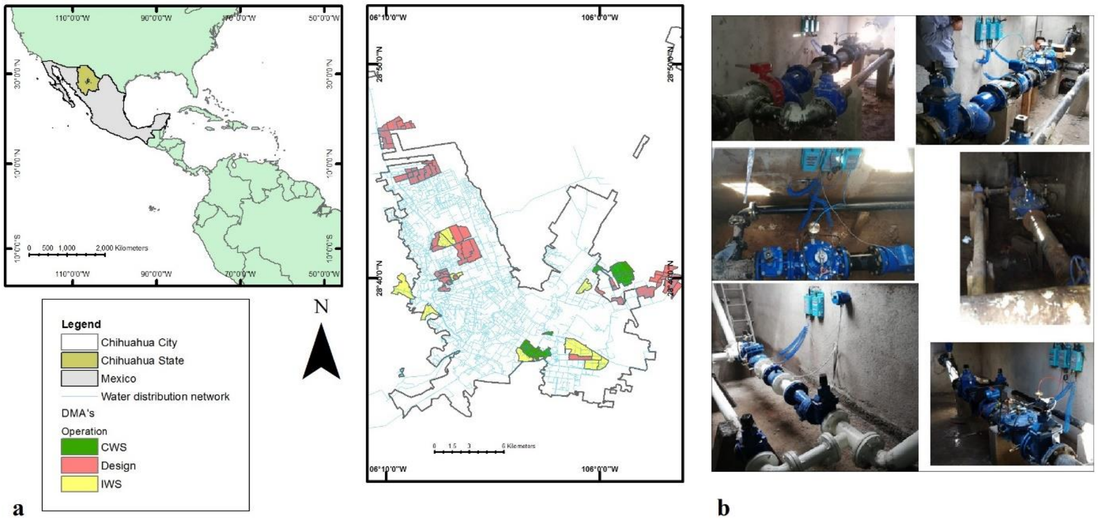

Fig. 1 (a) Map of the City of Chihuahua showing the water distribution network and the location of the DMA's. (b) Sample of generally installed instrumentation for pressure management in the city of Chihuahua, México.

The impact of the IWS policy generated endless operational, administrative, and financial problems, motivating JMAS to search for alternatives considering that there are no other water sources.

The Chihuahua DWS serves 327,000 customers (as of 2018) which accounts for 929,739 consumers, 93.3% of these customers belong to households (hh), 5.6% to commercial accounts, 0.3% to industrial accounts, and public buildings/schools represent the remaining 0.6%

The water demand is covered almost entirely by groundwater through 167 wells located in three different aquifers: the Sauz-Encinillas aquifer provides 910 l/s through 26 wells; the Tabalaopa-Aldama aquifer 1420 l/s using 53 wells, and the Chihuahua-Sacramento aquifer is exploited for 2,233 l/s over 88 wells. The city needs to exploit 128.52 Mm3 annually to "satisfy" the population demands.

The DWS serving the city of Chihuahua is a rather complex system, because of the extension (around 224.85 km^2) and the topography of the supplied area (with elevations ranging between 1348 and 1500 a.s.l.). The length of the mains in the network is 829.6 km, which is only for the mains of the network that are bigger than 100 mm, the remaining of the network have a length of 2,527.1 km used for service connections.

The volume of non-revenue water in Chihuahua changes every year, but the average non-revenue water volume is 49 Mm^3 per year (38% of supplied water).

MATERIAL AND METHODS

Returning the water system of Chihuahua to CWS is based on two goals: achieve network sectorization; and the management of pressure at DMA's. DMAs splits an interconnected and intricate network into smaller, virtually independent sub-networks (districts) that can be better managed. Each district proposes a maximum demand value, seeking to maintain homogeneity in the pressure distribution. Managing the pressure in the DMA allowed to establish a multi-step methodology to achieve an efficient transformation from IWS to CWS.

Network Sectorization

Network reduction into connected sectors, or DMAs, is a useful strategy to control the water flow and consumption and ease the possibility to identify leakage. There are several methods for DMAs design (Di Nardo *et al.* 2013; De Paola *et al.* 2014), based on criteria including topology, connectivity, reachability, redundancy, and vulnerability of the network (AL-Washali *et al.* 2018). The complexity of DMAs construction in a practical case resides in setting an accurate hydraulic analysis with a DWS cadastre that does not reflect the reality. However, instituting the DMAs implementing criteria allows to create a hybrid model between the physical knowledge and the technical model obtained from the hydraulic analysis.

The following procedures were used to set the DMAs:

(1) Information was obtained to establish the inlet volume for every DMA proposed.

(2) The DWS cadaster was used as the main reference to reconstruct the conditions of the hydraulic network.

(3) Field trips were made to recognize the need to be able to completely isolate the DMAs from the distribution network to set a single flow entrance, as well as, to diagnosticate the real state of the infrastructure.

(4) The number of users per DMA was obtained from the commercial area of the JMAS.

(5) It was proposed that sectorization design be carried out from the outer ends of the network to the interior, due to the complexity of distribution in the city center.

The criteria for DMA selection were:

- Use the existing network configuration, so that the proposed changes do not generate additional costs.
- The number of population to be served, considering a water supply of 176 l/day per inhabit plus physical losses.
- Homogeneous topography, a minimum pressure of 10 m.w.c. (meters of water column) and max. pressure of 20 m.w.c. must be maintained in the DMA.
- Single flow entrance, for adequate control of each DMA.

Using the obtained information from the field trips and DWS plans, a simulation model was created with the program Infoworks. This simulation model allowed to present a sectorization proposal to implement and manage the pressure in several DMA’s. Additionally, the hourly variation of water consumption was considered in the model using data obtained from a sector with CWS and pressure control at the entrance of the DMA. This allows representing the behavior of water demand in the city of Chihuahua.

For each DMA, specific modifications and actions were made to guarantee that there are no other flow inlets or outlets. Part of these actions was the installing of isolating valves, reinforcement pipes, control valves, and measurement sites. Measuring instruments, real-time network monitoring and control equipment enable real-time interventions for malfunctions or hydrodynamic imbalance (Maiolo *et al.* 2019). Real-time network monitoring generated the consumption indicators at the entrance for each DMA. Electromagnetic water meters were used to quantify the flow/volume and pressure regulating valve (PRV) to measure the pressure upstream and downstream from the entrance (Fig. 1).

After the DMAs construction, field tests were carried out to evaluate the operation of each sector. The test results and the data generated by the measuring instruments allowed the calibration of the simulation model. Once the analysis of the DMAs was carried out through mathematical modeling. The next step was the DMAs isolation test, which consists of verifying nonexistent flow communication between districts. To corroborate the isolation, a pressure inspection was made within and outside the district boundary, confirming the existence of a single supply inlet.

Management of Pressure at DMAs

From the isolation and pressure inspection it was possible to establish: the pressure behavior in each DMA, knowing the pressure at critical points (lower and higher topographical position); flow consumption at the inlet, which responds to user demand; the pressure requirement downstream from the PRV to satisfy the sector demand. In addition, for the adjustment of the simulation model, an hourly variation curve was generated to represent the pressure behavior. This curve sheds light on the exact policy of operation in each DMA. In the simulation model, the lower flow was presented during the nighttime, attributed to physical losses in the network. Minimum Night Flow (MNF) analysis is the most common method for leakage assessment at the scale of the DMA (AL-Washali *et al.* 2018). The MNF is the lowest inflow in the DMA over 24 h of the day, which occurs depending on the consumption pattern of the DMA when most of the customers are probably inactive and the flow at this time is predominantly leakage (Puust *et al.* 2010). The management of pressure at DMAs was set in three steps (Fig. 2). In the first step, the purpose was to set a schedule with sufficient pressure and flow at the time of greatest demand in the sector. In the second step, a supply modulation was included considering a critical point or the most unfavorable point within the sector. In this stage, there is already a time homogeneity of the pressure in the sector. Equitable pressure distribution was obtained by contemplating the loss due to topography, which supports the uniformity of available service time. The last step was to include the regulation of the flow to determine the minimum night flow. As well as, defining the flow demand during peak hours, thereby, increasing both physical and commercial efficiency in the sector.

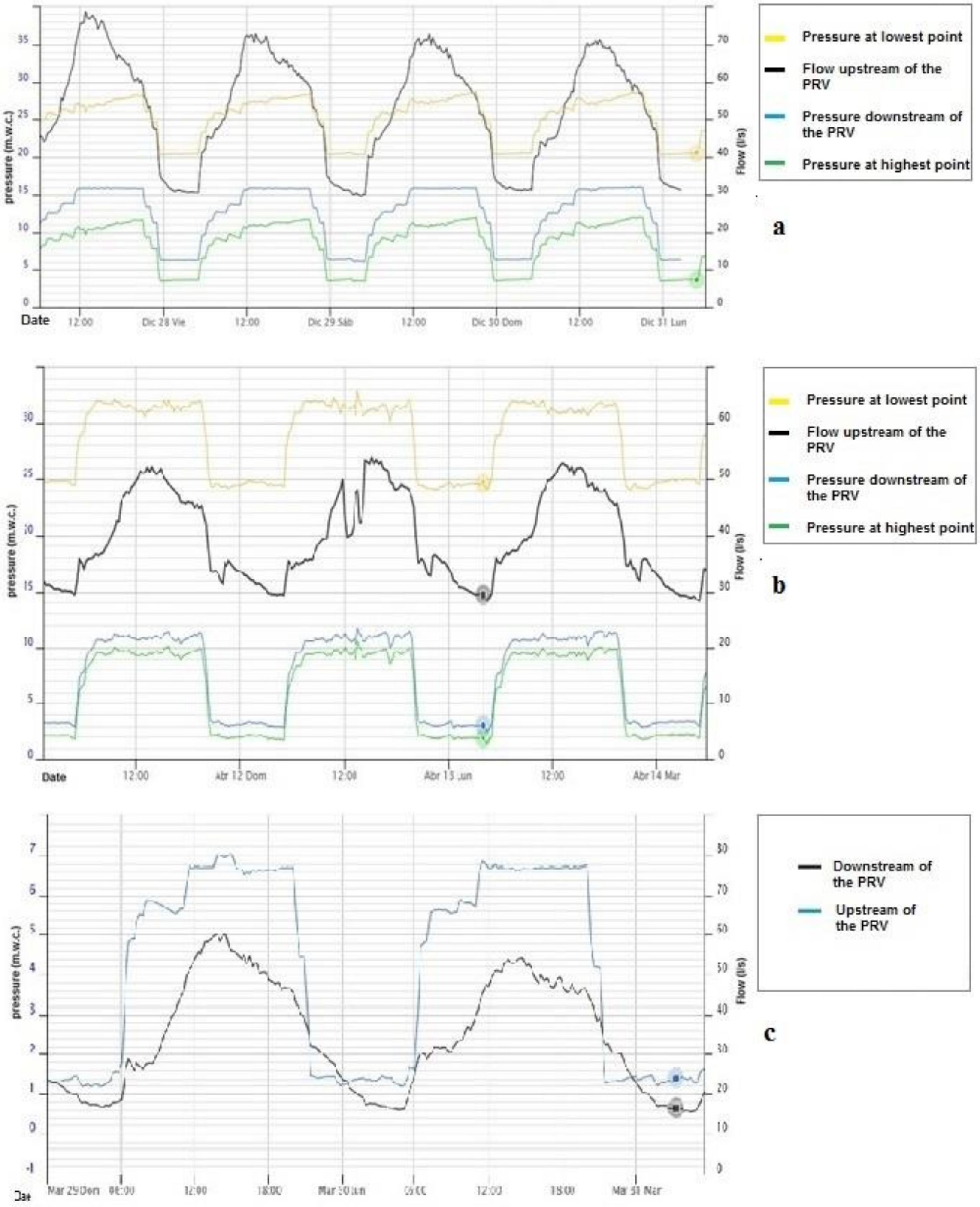

Fig. 2 Example of the management of pressure at DMAs in three steps. The first step (a), establish the schedule to have sufficient pressure and flow at the time of greatest demand in the sector. The second step (b) sets a supply modulation considering a critical point or the most unfavorable point within the sector. The third step regulates (c) the flow according to the minimum night flow.

RESULTS AND DISCUSSION

JMAS with the support of IMTA (Mexican institute of water technology) began the process of obtaining knowledge about the network to implement the sectorization in the year 2008. The DMA’s delimitation was carried out, giving priority to where there was the greatest service deficiency. By putting these sectors into operation with CWS, collateral impacts were difficult to predict due to the uncertainty in the cadastre. Therefore, the DMA’s that shared the same supply source generated a greater water volume wasted by leaks. These complex problems produce a lack of impact on the perception of service improvement by the population and the JMAS. Therefrom, in the year 2018, the JMAS decided to start with the redesign of the DMA’s using the methodology reported in this study.

As of June 2020, the JMAS endures 19 sectors in operation according to the presented methodology, of which eight DMAs are operated in CWS serving 24,388 hh, and the remaining still performed in IWS serving 38,961 hh. Besides, eight sectors are currently undergoing redesign (10,209 hh) and 24 DMA’s (108,452 hh) are in design and construction.

The results presented correspond to the 19 DMA’s operated by the methodology of this study (Fig. 1). The results are separated according to whether the sectors were operated in CWS or IWS with the proper sectorization. Data of the sectors were obtained from July 2018 to June 2020 (24 months), unfortunately, JMAS was able to collect information only for one month (June 2018) prior to the implementation of the methodology.

Fig. 3 shows the total daily average supply of the sectors. In the sectors with CWS, all the months reflect a decrease in the volume supplied reaching up to 25% (February 2020), except for March 2019, in which there was a considerable leakage of water in sector 1, leading to a consumption of twice the average. It is important to state that pressure management lowers the failure frequencies but limits the potential of leakage detection surveys, as leaks will become harder to detect (AL-Washali *et al.* 2018). To keep it in the perspective of the climatic variables, in comparison with the prior month (June 2018), June 2019 presented a decrease of 13% of the volume supplied and June 2020 a 19%. The total saving of daily supplied volume in the sectors with CWS was 67,715.4 m3, estimating a saving of 49.4 Mm3 in two years. The DMA's operated in IWS presented a decrease in supplied volumes of up to 32%, there were three months (December 2018, January 2019, and March 2019) in which there was an increase in the supplied volumes (29 %, 1%, and 9% respectively). Based on the comparison with the prior month (June 2018), June 2019 presented a decrease of 11% of the volume supplied and June 2020 a 19%. The total saving of daily supplied volume in the sectorized DMAs was 124,109.554 m3, estimating a saving of 90.5 Mm3 in two years. The application of the methodology in the 19 DMA's translates to 1,100 l/s saving, which is 24% of the water supply for the entire city. The savings obtained in this analysis is similar to the percentages presented by AL-Washali *et al.* (2018) which determined the leakage volume based on the MNF. Noticeably, more work is required to improve the reliability of the volume analysis due to the lack of previous information.

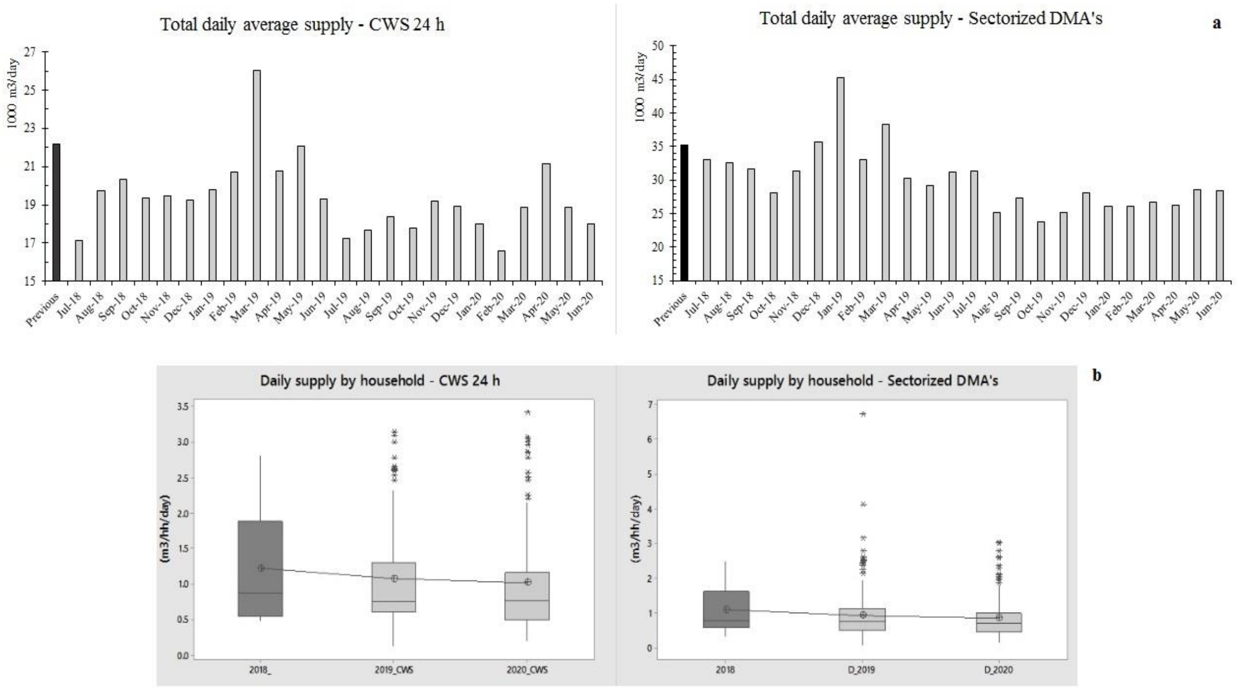

Fig. 3 (a) Total daily average supply of the study sectors. (b) Average yearly daily supply per household for the study period.

When comparing the sectors with IWS and CWS, it can be seen that the average monthly supply per hh is 27.52 versus 32.22 m3/month/hh, providing a 24-hour service for 15% more water, these results differ from those obtained by Criminisi *et al.* (2009) and Andey & Kelkar (2009), who stated that water consumption does not change appreciably under IWS compared with that of CWS.

This can be analyzed accurately until the historical data on leak repairs in both types of sectors is available, since it can be assumed that in the sectors with CWS the repairs and leaks that occur are lower (Ilaya-Ayza *et al.* 2016), so the trend of the decrease in supply is stable in comparison with the sectors with IWS which have not yet stabilized due to the different losses that this type of operation may generate. Several studies declare that during the period of implementation of IWS and right after that, there is a significant increase in the number of water loss incidents and a deterioration of the network condition. This indicates that IWS operations negatively impact the vulnerability of DWS (Christodoulou and Agathokleous 2012; Agathokleous, Christodoulou, and Christodoulou 2017).

Fig. 3 shows the daily supply per hh. The average of the sectors prior to the CWS was 1.22 m3/hh/day measured for June 2018 (the only measure available before the application of the methodology), comparing the sectors with CWS for the year 2019 (counting the year from July 2018 to June 2019) was 1.08 m3/hh/day, decreasing the supply per household per day by 12%. In contrast, the year 2019 with the average in 2020 (counting the year from July 2019 to June 2020) daily supply per household was reduced by 5%.

The average of the sectors prior to the correct setup of the DMA’s was 1.09 m3/hh/day measured for June 2018 (the only measure available prior to the application of the methodology), comparing the sectors with CWS for the year 2019 (counting the year from July 2018 to June 2019) was 0.94 m3/hh/day, decreasing the supply per household per day by 14%. Contrasting the year 2019 with the average in 2020 (counting the year from July 2019 to June 2020) daily supply per household was reduced by 6%.

This paper shows that designed DMA’s using maximum demand (or flow) that can be met while maintaining suitable pressures throughout the network, and strictly ensuring the minimum pressure required at the node with the lowest pressure. The application of the design methodology to return the DWS to CWS shows that this approach can be used to initiate continuous monitoring and assessment of the water losses, the actions taken allowed to increase and maintain physical efficiency and developing mechanisms to distribute drinking water according to the consumption analysis of each sector. The gradual transformation from IWS to CWS will eventually present the need to increase and improve the capacity of the system as several studies agree (Ilaya-Ayza *et al.* 2016; Gupta and Kulat 2018; Ray *et al.* 2018; Varu and Shah 2018).

CONCLUSIONS AND RECOMMENDATIONS

The work presented in this paper describes a methodology to gradually return a city to CWS, through the real knowledge of the DWS, a pre-process of data, input validation, and the physical determination of the DMA's. The approach using network sectorization and pressure management at DMA’s enables a hybrid model between the physical knowledge and the technical model obtained from the hydraulic analysis.

The analyses show that during the period of implementation of the DMA’s operating in CWS and IWS, both showed a significant decrease of the water volume supplied, increasing the service hours (in the CWS DMA’s). The operation of 19% of the households of the city under this methodology results in a 24% of water saving of the entire city. Thus, this study contributes to improve intermittent supply systems, stating that well-designed and administered sectors contribute to saving water and gradually achieve CWS.

There is a gap in the literature in the process to return a city to CWS due to the methodologies that are proposed, as well as the DMA designs according to the characteristics of the city. The use of CWS and DMA's is proposed as an ideal and sustainable solution. However, when it is applied no longer on a pilot scale but with the purpose to modify the entire operation of a city, constant failures and disappointments are generated. These setbacks provoke scepticism in the WOA perpetuating the operation of IWS and rooting of the problems derived from it. Thus, this paper seeks a gradual evolution based on a specific design for the conditions of the city and each sector, being in constant assessment to continue its operation, improving the state of sustainability of the drinking water service.

Future research would focus on the analysis of the potential water savings and the leakages while adding the inter-dependency relationship between pressure management and active leakage control. It is of great importance to establish a real-time micro-measurement in the households to maintain control and an evaluation of the types of leaks and to be able to determine a real loss combined indicator. Updating the user registry and the micro-measurement will make it possible to carry out a commercial analysis and establish real balances for WOA to determine physical and commercial efficiencies.

Declaration of interest statement:

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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STUDY IV. TREATED WASTEWATER VIABILITY OF USE IN GREEN AREAS ACCORDING TO NITROGEN COMPOUNDS CONCENTRATION

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ABSTRACT

TREATED WASTEWATER VIABILITY OF USE IN GREEN AREAS ACCORDING TO NITROGEN COMPOUNDS CONCENTRATION

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Treated wastewater is commonly used for park irrigation in arid zones of Mexico without considering groundwater contamination. The objective was to investigate the possibility of nitrogen compounds leaching into the groundwater and their reaction occurring throughout the main types of soils. Lysimeters samples were taken to scrutinize the soil characteristics of the green areas irrigated with treated wastewater from the Northern Wastewater Treatment Plant in the city of Chihuahua. Testing samples were setup to recreate treated wastewater irrigation conditions. Nitrogen-based compounds were identified and measured before and after percolation through the soil columns. Based on the results, one meter of sand column was sufficient to remove 68 to 100% of nitrogen compounds present in the residual water. The removal of all nitrogen-based compounds as they percolate through one meter of clay soil column was not enough, due to the biochemical reactions that occur through the percolation process. Results indicate minimal risk of nitrate and nitrite leach into the aquifer, since the average static level depth is 20 m which provide broad filtration. This demonstrates an opportunity for *in-situ* investigations to reevaluate the standards for soil aquifer treatment recharge, based on the soil type and water quality of the area.

Key words: Artificial recharge, nitrate, wastewater treatment.

RESUMEN

TREATED WASTEWATER VIABILITY OF USE IN GREEN AREAS ACCORDING TO NITROGEN COMPOUNDS CONCENTRATION

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Las aguas residuales tratadas se utilizan comúnmente para el riego de parques en zonas áridas de México sin tomar en consideración la posible contaminación de las aguas subterráneas. El objetivo de este estudio es investigar la posibilidad de que los compuestos nitrogenados se infiltren en las aguas subterráneas y como reaccionarían estos compuestos conforme a los principales tipos de suelos. Se tomaron muestras del suelo de las áreas verdes de la Planta Norte de Tratamiento de Aguas Residuales de la ciudad de Chihuahua para formar lisímetros. Los lisímetros se configuraron para recrear las condiciones de riego con agua residual tratada. Se identificaron y midieron los compuestos nitrogenados antes y después de la percolación a través de las columnas de suelo. Se pudo observar que un metro de columna de arena fue suficiente para remover del 68 al 100% de los compuestos nitrogenados presentes en el agua residual tratada. La eliminación de los compuestos nitrogenados a medida que se infiltran a través de un metro de columna de suelo arcilloso no fue suficiente, debido a las reacciones bioquímicas que ocurren durante el proceso de percolación. Los resultados indican un riesgo mínimo de lixiviación de nitratos y nitritos al acuífero, ya que la profundidad promedio del nivel estático es de 20 m, lo que proporciona un amplio rango de filtración. Esto demuestra una oportunidad para que las investigaciones in situ reevalúen los estándares de recarga del tratamiento suelo-acuífero, según el tipo de suelo y la calidad del agua a infiltrar.

Palabras clave: Recarga artificial; nitratos; agua tratada.

INTRODUCTION

There is a constant need around the world to meet the increasing water demand. The reutilization of non-potable water is an effective solution for sparing drinkable water, especially in regions with water scarcity like the northern part of Mexico (Bixio *et al.*, 2005). The benefit is derived from the use of treated wastewater (TW) in activities where potable water quality is not required, allowing drinkable water to be spared, and satisfy the population's growing demand. Additionally, use of TW for agriculture and gardening can lead to a reduction or elimination of fertilizer applications (Heinze *et al.*, 2014). Excessive infiltration of irrigation water can introduce contaminants (e.g. nitrate) to shallow groundwater (Böhlke, 2002; Brown *et al.*, 2011). Ammonia (NH_3) is one of this contaminants that might produce numerous adverse effects on the environment (Jana, 1994),, it is recycled naturally in the environment as one of the steps of the Nitrogen cycle. Because of its reactivity, NH_3 does not last long in its pure form (Agency for Toxic Substances and Disease Registry 2015). In the transformations of NH_3 to nitrate (NO_3), the quality of stored water can be affected (Power *et al.*, 2000). NO_3 is currently known as the main source of diffuse contamination of surface and groundwater in some environments (Majumdar and Gupta, 2000; Laftouhi *et al.*, 2003;Almasri and Kaluarachchi, 2004; Widory *et al.*, 2004; Moore *et al.*, 2006; Murgulet and Tick, 2009; Ako *et al.*, 2014). NO_3 itself is relatively nontoxic, its toxicity is determined by its reduction to NO_2 in the human body, which in high concentration can lead to methemoglobinemia (Camargo and Alonso, 2006).

The possible percolation of nitrogen compounds to groundwater is produced due to the induced recharge from the non-visible leaks of hydro-sanitary networks and the irrigation of green areas with TW. Several studies have correlated land use/cover and environmental variables in the soil’s capture zone with variations in water quality in sampling stations, using different statistical modelling approaches (Nkotagu, 1996; McLay *et al.*, 2001; Spruill *et al.*, 2002; Gardner and Vogel, 2005; Kaown *et al.*, 2007; Stigter *et al.*, 2008; Mfumu *et al.*, 2016). Teng *et al.* (2018) for instance, applied a multivariate analysis of the hydraulic connection between the superficial and groundwater, analyzing the hydrogeochemistry and pollutant data, to evaluate their interaction, they were able to prove that the degree of hydrogeochemical response depends on the different types of hydraulic connection; and therefore interaction process, dilution, adsorption, redox reactions, nitrification, denitrification, and biodegradation contributed to the concentration of pollutants. The water quality degradation has become more urgent due to the close hydraulic relationship between irrigated water and groundwater (Teng *et al.*, 2018). However, to date, the effects of TW interaction on percolated water quality have not been evaluated in the city of Chihuahua. The objective of this study was to assess the possibility of nitrogen compounds leaching through the main types of soils on the green areas irrigated with TW in Chihuahua. The use of multivariate methods in this study is based on the fact that the groundwater nitrogen compounds concentration can be influenced by several independent environmental variables, considering mainly the type of soil. Multivariate statistical models allow an understanding of which terms have different response (Mfumu *et al.*, 2016). The results will shed light to perform a proper a MAR (Managed Aquifer Recharge) in Chihuahua-Sacramento aquifer (CHSA).

MATERIAL AND METHODS

The city of Chihuahua is located in the northern part of Mexico between 28°50’ to 28°30’ North latitude and 106°12’ to 105°50’ West longitude, it is the capital of the Chihuahua state, and the second most populated city of the region. The climate is arid to semiarid, averaging a 415 mm annual rainfall. Due to high evapotranspiration and low infiltration, aquifer recharge is not promoted. The city relays almost 100 percent in groundwater to satisfy the drinking water demand, resulting on severe water stress in the different aquifers. Chihuahua city depends mainly from the aquifers: CHSA, Tabalaopa-Aldama and Sauz-Encinillas. The continuous pumping has caused declines in the water table of CHSA from 2 to 3 meters annually (National Water Commission, 2010). Green areas above CHSA have been irrigated with TW from the North Treatment Plant (NTP) for more than 20 years according to the municipal water and sanitation board. The NTP gardens were chosen as a representative area of the green areas irrigated with TW, where the TW irrigation began (Fig. 1).

Lysimeters were used as the experimental units (EU) for this study (Heinze *et al.*, 2014). Lysimeters were designed to directly measure a drainage flux, leading to a representation of the recharge process (Allen *et al.*, 1991; Pakrou and Dillon, 2000; Walker *et al.*, 2002). Water, vegetation, soil and rock material were characterized to establish the EU representativeness of the experimental site (ES). Besides the parameters previously mentioned, meteorological variables (temperature, wind, humidity) were evaluated in a climatological station installed by the Center for Advanced Materials Research (CIMAV) (Fig. 2).

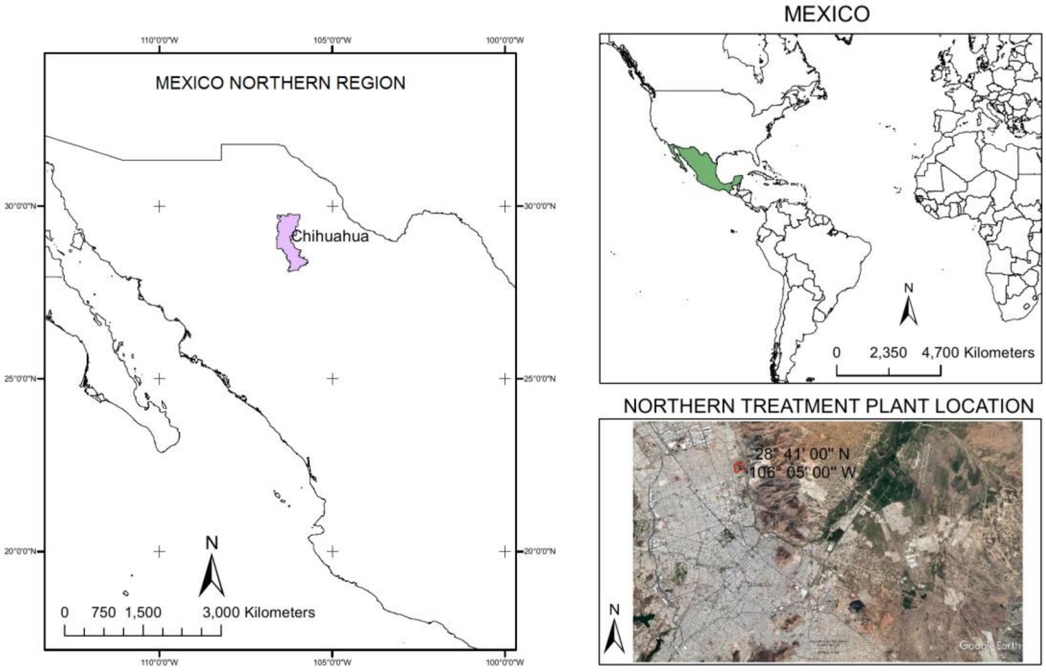

Fig. 1 Green areas irrigated with TW in Chihuahua city

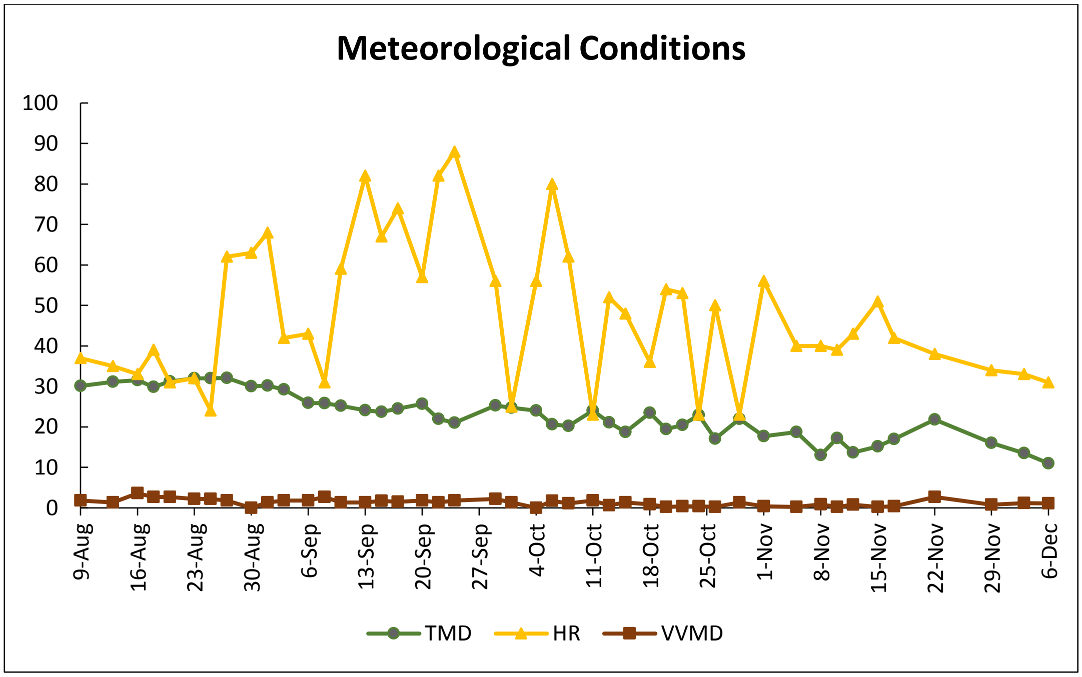

Fig. 2 Meteorogical conditions in the climatological station. TMD stands for daily mean temperature in ºC, HR stands for daily mean relative humidity in %, as VVMD stands for daily mean wind velocity in km/hr.

Precipitation was not allowed to interfere with the different types of irrigation water in the experiment.

Soil characterization was first made by vertical electric sounding (VES). The VES readings were correlated with existing lithological cuts from nearby wells, delivering geological interpretation of the NTP subsoil. The subsoil, composed of a series of granular units, corresponds to an old bed of the Sacramento River. Four points samplings of the ES were characterized by the Agricultural Union of Fruit Growers of the State of Chihuahua (UNIFRUT) laboratory, in order to comply with NOM-014-CONAGUA-2003 regulation. NOM-014 establish the requirements to evaluate a site for MAR in Mexico.

The lysimeters were packed with representative soil of the ES, in which unaltered samples up to 2 m depth were taken. Each sample was analyzed to in order to obtain their granulometric components, orientation, compaction, and moisture content. The presence of nitrogenous components was also analyzed in the soil matrix.

Based on the results from the laboratory analyses, two soil horizon sets were classified: the first set of horizons of 15 and 40 cm depth and the second set correspond to: 80, 100 and 130 cm depth (Table 1).

The soil hydraulic conductivity was also measured, which is an intrinsic property of the soil matrix and the fluid (Scanlon *et al.*, 2002). The infiltration capacity was also obtained, in order to evaluate the volume of water that can be infiltrated (Scanlon *et al.*, 2002).

Table 1. Physicochemical properties of the NTP soil.

Physicochemical properties	Soil horizon (15 – 40 cm)	Soil horizon (80 - 100 - 130 cm)
Electric conductivity (mm/cm)	2.16	0.76
NO_3 (Kg/Ha)	267.3	23.4
Phosphorus (ppm)	54.53	11.15
Organic matter (%)	15.93	1.174
$CaCO_3$ (%)	0.0	0.0
Moisture (%)	17.17	13.23
pH	7.4	8.69
Na (ppm)	464	440
K (ppm)	1452	208
Fe (ppm)	7.96	9.36
Total N (ppm)	0.679	0.058
Sand (%)	64.44	42.44
Silt (%)	25.84	29.84
Clay (%)	9.72	27.72
Hydraulic Conductivity (cm/hr)	13.42	1.25
Texture	Sandy loam	Sandy loam

The infiltration capacity was obtained in the ES through infiltrometers, allowing the identification of hydraulic conductivity to be done through the excavation of soil horizons, in which exhaustion and recovery tests are carried out (Walker *et al.*, 2002). Similar values were obtained for the horizons of 15 and 40 cm of 2.1 and 2.2 cm/h respectively. The horizons of 80, 100 and 130 cm delivered values of: 2.8, 2.0 and 0.8 cm/h respectively. This all defined a sandy behavior, according to infiltration rates established by the Environmental Protection Agency (EPA). The vegetation samples used as representation were obtained by doing a set of 4 individual pieces, collected in a single composite sample from the ES, in accordance to the method described by Brady and Weil (2002). This composite sample was sent to the laboratory specialized in edaphology from UNIFRUT.

Experiment Design

The drinking water quality was used as the control, to compare it with the TW. Drinking water and TW infiltrated in two types of packing and filling material in lysimeters. Lysimeters one and two were the basis for the integrated approach; the experiment design resulted in the construction of 4 EU. Each lysimeter was identified by a number (L1 or L2) corresponding to the water quality of irrigation, L1 corresponding to drinking water and L2 to TW. Letters S and C (sand and clay) were used to identify the type of soil in the packaging. This experiment was based on the transformations of nitrogen in the soil-water interaction. The process sought to quantify the transformation of the main inorganic nitrogenous components, as well as defining if the climate factor has an impact in these transformations. This was raised with the conceptual model in Figure 3.

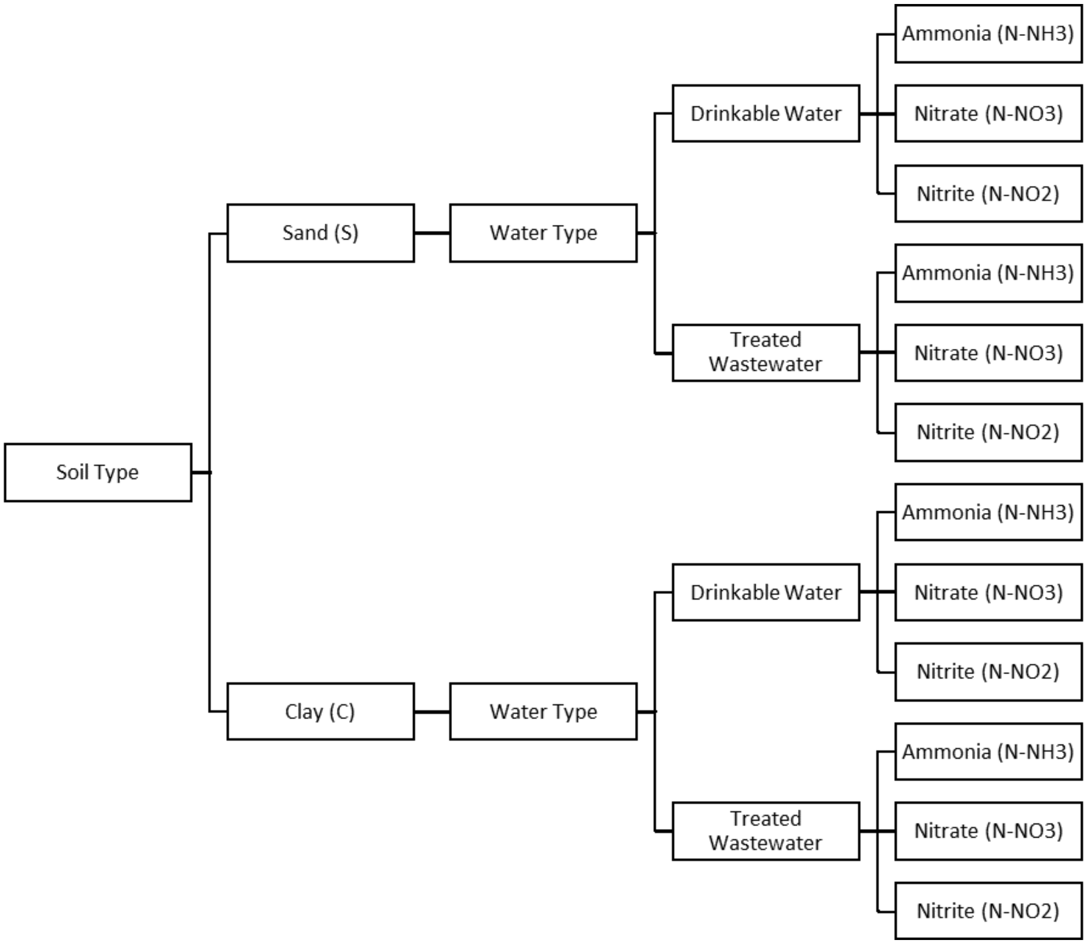

Fig. 3 General Diagram of Process.

The lysimeter’s geometric design was the same used by Bojorquez *et al.* (2018). Each lysimeter measured 50 cm × 50 cm × 100 cm, it was made of acrylic, and had a thickness of 10 mm. They were comprised of a steel structure with three stirrups to prevent thrust during experimentation. Each lysimeter was connected to a supply water tank (drinking water or TW). They also featured an irrigation simulator, which had a valve to control the irrigation rate. In addition to this, the lysimeters had acrylic covers on top of them, to prevent the infiltration of rainfall during the rainy season.

The techniques and equipment used to evaluate the water samples at the entrance and exit of the lysimeters are shown in Table 2.

Nitrogen compounds were measured 46 times over half a year for each EU, with a repeatability of five times per observation. The leaching analysis of the columns was fulfilled, starting from the natural humidity of the soil with a continuous flow of water. The irrigation in the EU was carried out as it is done in the green areas of the NTP. The irrigation sheet had a maximum of 10 cm, because most of the cover was grass. The type of irrigation was by sprinkling.

Table 2. Analyzed parameters entering and evacuating the lysimeters.

Parameter	Technique	Norm
Turbidity	Nephelometric colorimeter method	NMX-AA-038-SCFI-2001.
pH	Portable potentiometer Corning no. 180225	NMX-AA-008-SCFI-2000
Temperature	Mercury thermometer	NMX-AA-007-SCFI-2000
Electric conductivity	Electrometric conductivity meter	NMX-AA-093-SCFI-2000
Total Dissolved Solids, TDS	Gravimetric.SM-2540-C-1998	NMX-AA-034-SCFI-2001
Nitrate N-NO_3	Colorimetric method in Hach spectrophotometer with specific reagents. model 890,	NMX-AA-079-SCFI-2001
Nitrites, N-NO_2	Colorimetric method in Hach spectrophotometer with specific reagents. model 890,	NMX-AA-026-SCFI-2001.
Ammoniacal nitrogen, N-NH_3;	Colorimetric method in Hach spectrophotometer with specific reagents. model 890,	NMX-AA-026-SCFI-2001
Chemical Oxygen Demand, COD	Spectrophotometric method	NMX-AA-030-SCFI-2001

RESULTS AND DISCUSSION

Nitrogen Compounds Transformation

$N\text{-}NH_3$ was not present at the potable water input, for that reason the L1 sample had a $N\text{-}NH_3$ minimum concentration increase throughout the experiment, produced by organic nitrogen mineralization (Schulten and Schnitzer, 1997) (Figure 4).

The L2 sample showed a total removal of $N\text{-}NH_3$. This parameter had continuous variations in the TW input and was completely removed by the nitrification process, probably coupled with $N\text{-}NH_3$ volatilization (Müller *et al.*, 2002) (Figure 5). In both L1 and L2 systems, sands and clays soils had a 100% $N\text{-}NH_3$ removal efficiency.

The experimental system L1S, presented an increase of $N\text{-}NO_3$ after passing through the soil column, due to the presence of total N and $N\text{-}NO_3$ in the sand. On average from 0.6 mg/l at the entrance of the soil column to 5 mg/l at the exit. Leachate $N\text{-}NO_3$ content is associated with $N\text{-}NO_3$ solubilization in the soil and the ammonification reactions of organic nitrogen in the soil and subsequent $N\text{-}NH_3$ oxidation to $N\text{-}NO_3$ (Bernat *et al.*, 2011) (Figure 6). L1 irrigated with drinking water presented an increment of $N\text{-}NO_3$ content by soil column washing, higher for clay soil type (Ye *et al.*, 2012), however, this tends to stabilize and gets removed. The L2S experimental system presented $N\text{-}NO_3$ detriment after soil column washing, even in the presence of total nitrogen and $N\text{-}NO_3$ in the sand. On average from 19 mg/l at the input to 5.8 mg/l at the exit, which represented a consistent and similar removal with the behavior of COD.

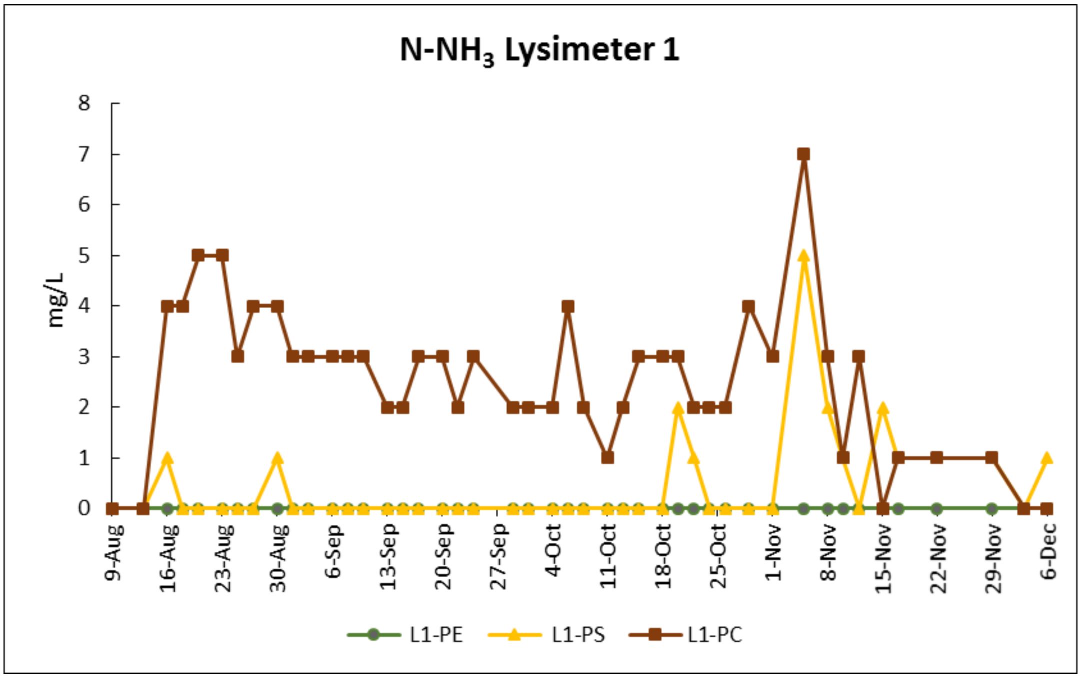

Fig. 4 N-NH$_3$ content in Lysimeter 1 irrigated with drinking water. PE stands for concentration level at lysimeter input, PS stands for concentration level at L1S (with sandy soil) output and PC stands for concentration level at L1C (with clay soil) output.

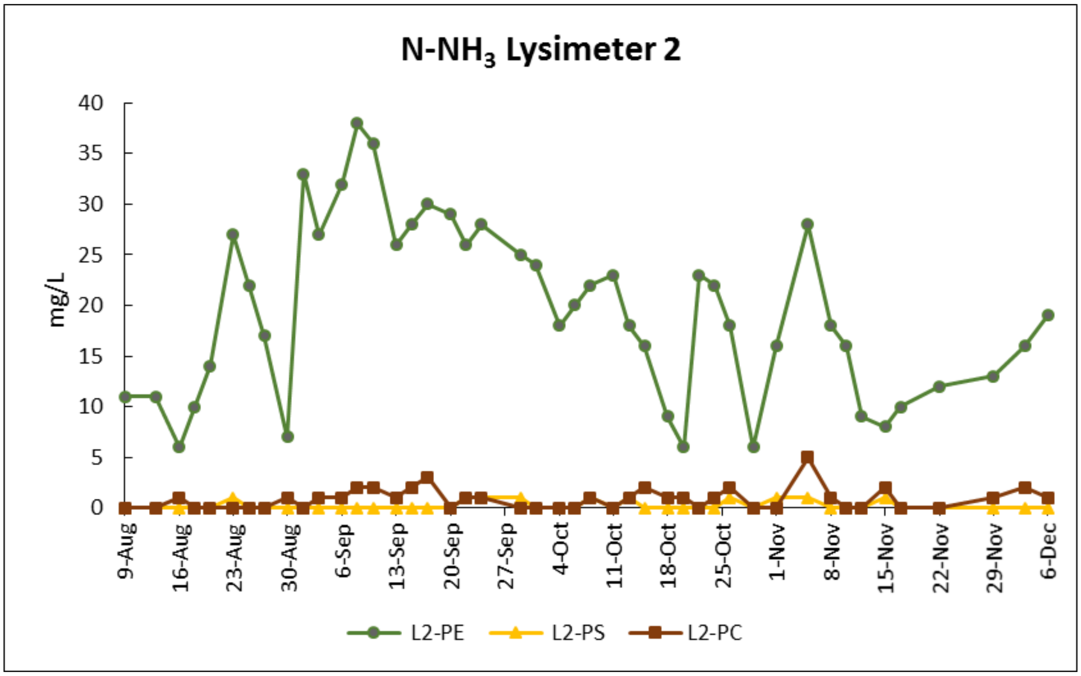

Fig. 5 N-NH$_3$ content in Lysimeter 2 irrigated with treated waste water. PE stands for concentration level at lysimeter input, PS stands for concentration level at L2S (with sandy soil) output and PC stands for concentration level at L2C (with clay soil) output.

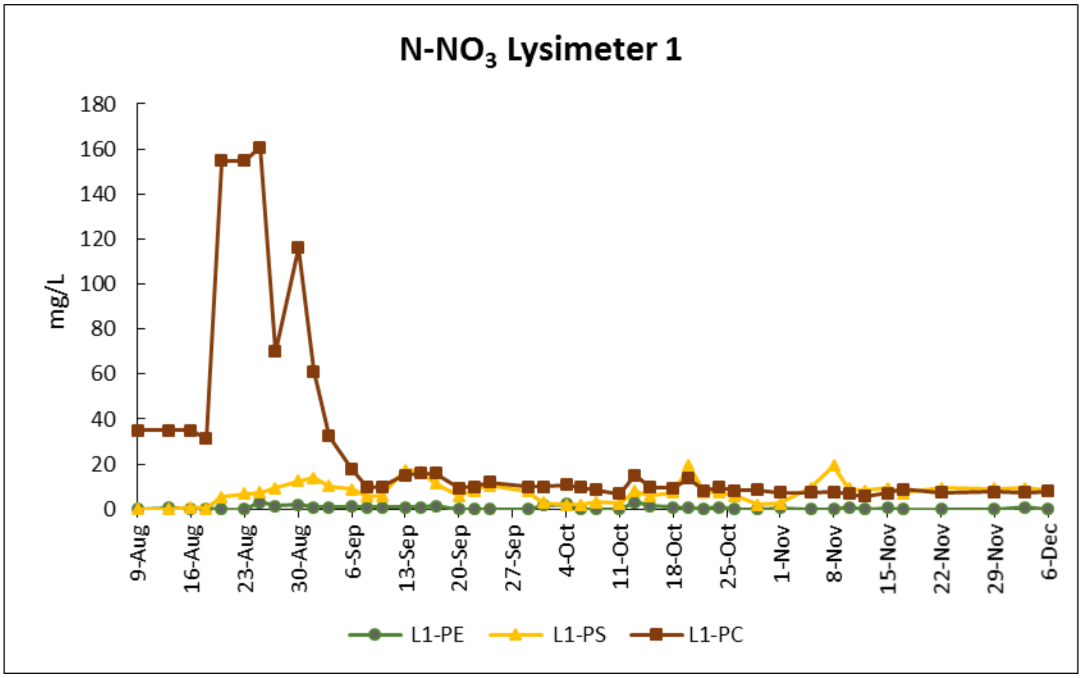

Fig. 6 N-NO$_3$ content in lysimeter 1 irrigated with drinking water. PE stands for concentration level at lysimeter input, PS stands for concentration level at L1S (with sandy soil) output and PC stands for concentration level at L1C (with clay soil) output.

L2C presented an average increase of 19 mg/l at the entrance to 31 mg/l at the output, as a consequence of N-NO_3 compound transformations and percolation rate, allowing longer permanence in the soil (Figure 7). The N-NO_3 behavior showed periods of increase and decrease over time, this is attributed to the soil column washing and the TW N-NH_3 transformation to N-NO_3. This phenomenon occurs mainly in clay soil because of the slow vertical velocity of water, when N-NO_3 is converted to N-NO_2 (Welch *et al.*, 2011). The sand oscillates in their N-NO_3 removal efficiency in this period from 60 to 90% and in the case of clay up to 50%.

L1S and L1C showed an increase of N-NO_2 after soil washing from 0.3 mg/l to 2.5 mg/l, in the same N-NO_3 increase ratio; subsequently having a tendency to stabilize and present greater removal (Figure 8). Otherwise L2S and L2C presented a N-NO_2 removal from 3.8 mg/l to 0.8 mg/l and 4 mg/l to 2 mg/l on average, respectively (Figure 9). The sand oscillated in their N-NO_3 removal efficiency in this period from 90 to 100% and the clay samples up to 80%.

Sandy soil columns provided further efficiency and effectiveness in terms of inorganic nitrogen compounds concentration removal in the TW; N-NO_2 and N-NO_3 were eliminated almost entirely. From October onwards, the denitrification phenomenon could be identified in the system as a consequence of the organic matter consumption, in the way of a carbon source for denitrifying heterotrophic organism. The nitrification-denitrification process could be verified even with the drastic decrease in temperature observed during the last month of the experiment.

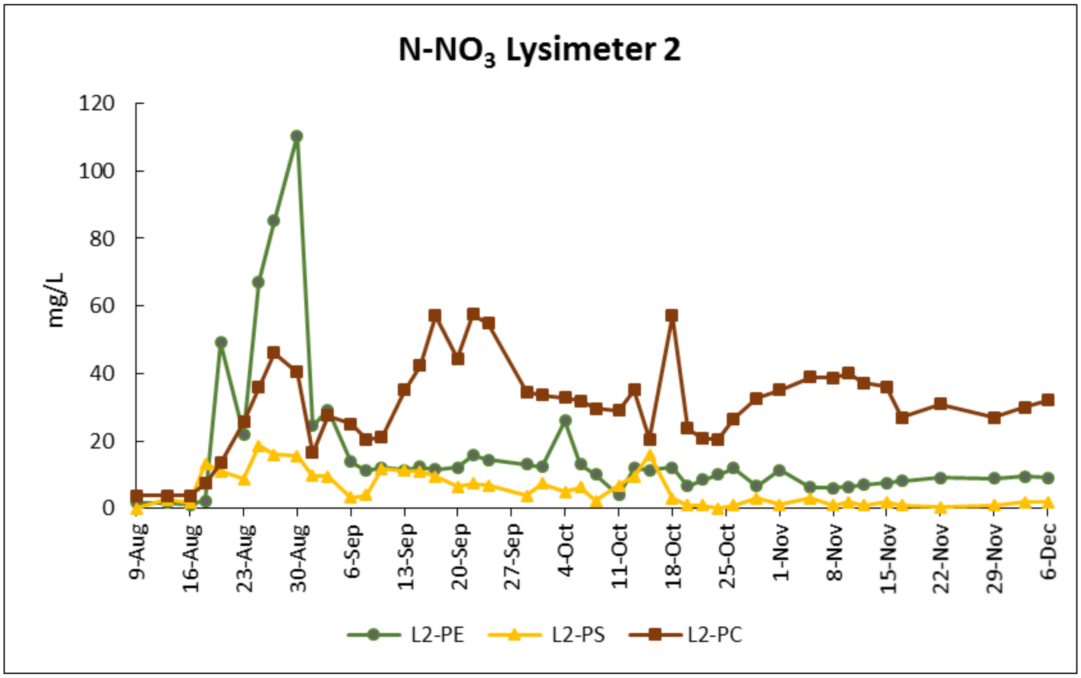

Fig. 7 N-NO_3 content in lysimeter 2 irrigated with treated waste water. PE stands for concentration level at lysimeter input, PS stands for concentration level at L2S (with sandy soil) output and PC stands for concentration level at L2C (with clay soil) output.

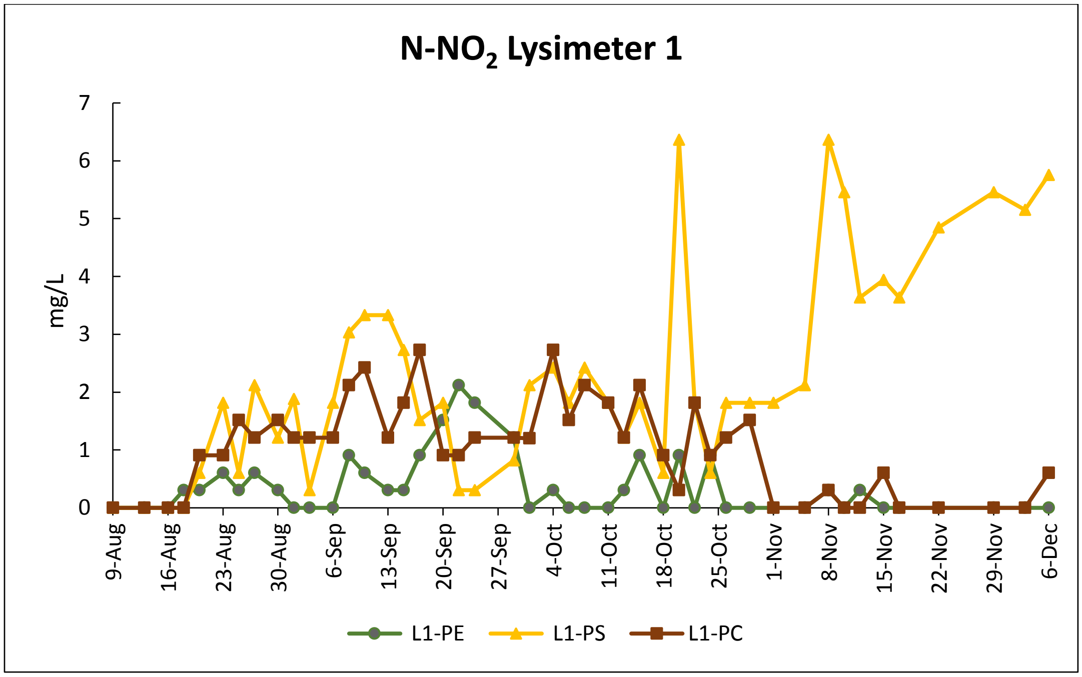

Fig. 8 N-NO_2 content in lysimeter 1 irrigated with drinking water. PE stands for concentration level at lysimeter input, PS stands for concentration level at L1S (with sandy soil) output and PC stands for concentration level at L1C (with clay soil) output.

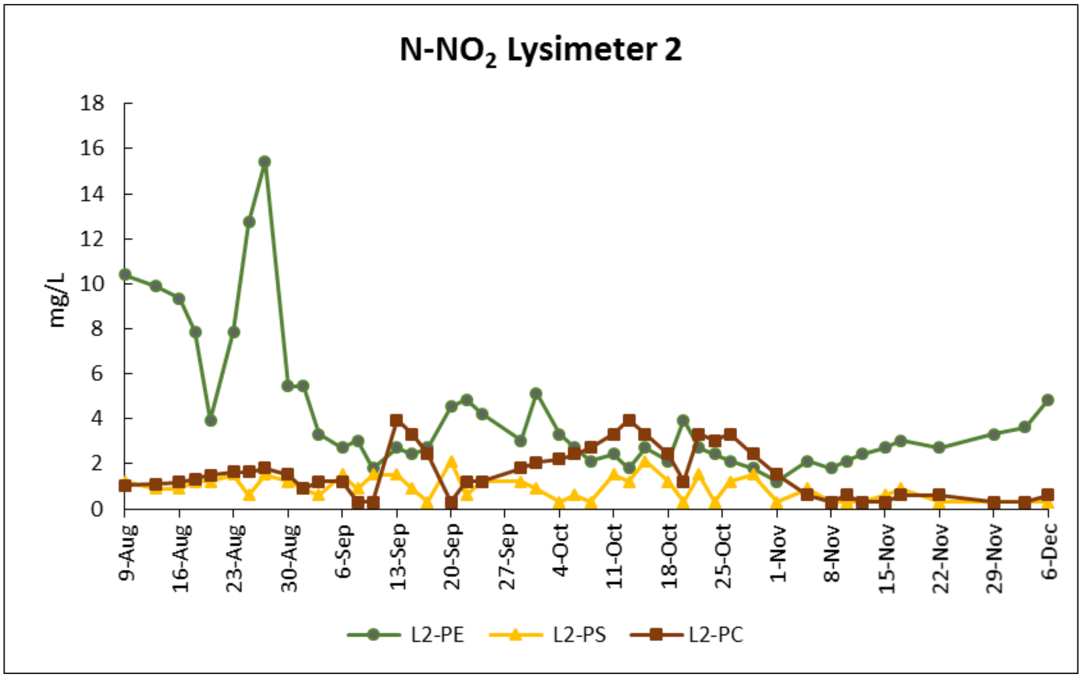

Fig. 9 N-NO2 content in lysimeter 2 irrigated with treated waste water. PE stands for concentration level at lysimeter input, PS stands for concentration level at L2S (with sandy soil) output and PC stands for concentration level at L2C (with clay soil) output.

The nitrogenous component losses found could be associated to adsorption processes in the soil itself or to microbiological transformations (denitrification, dissimilative reduction) (Teng *et al.*, 2018).

The results obtained allowed to distinguish different concentration magnitudes, according to water quality drained from both columns (Table 3). To determine the statistical difference in the results, the experimental values were contrasted with the model's results. To consider a significant contrast, the probability must be less than $P = 0.05$. A uni-factorial ANOVA between groups was performed (TWO WAY option), this procedure provides a regression analysis and an ANOVA for a dependent variable ($N\text{-}NO_2$ and $N\text{-}NO_3$ in this case) by one or more factors (soil type and type of water). The effects of the variables were compared on the means of several pairings of a single dependent variable also giving information on the interactions between the factors. In this case by the reduction of $N\text{-}NO_3$ to $N\text{-}NO_2$, the analysis was applied for both variables separately. In the study, a balanced model is presented. To carry out this analysis, the Minitab 15 software was used. After the ANOVA analysis was performed, the model regression value observed for the data (R-Sq = 4.35%) and the adjusted value (R-Sq (adj) = 2.75%) were low and similar, although with high reliability because of its low dispersion. It was observed that both models (observed and adjusted) have a normal distribution behavior, stating certainty that the experimental and adjusted regression values are reliable. Table 4 shows an example of the standard deviation for the standard and adjusted method in L2S for the variable $N\text{-}NO_3$. Figure 10 shows an example of control in the repeatability and quantification of the measurements in $N\text{-}NO_3$.

Table 3. Summary values of the nitrogenous components.

	Lysimeter 2= water type (TW)					
	Soil type					
	Sand (S)			Clay (C)		
Water Quality Entry (mg/L)	N-NO_3	N-NO_2	N-NH_3	N-NO_3	N-NO_2	N-NH_3
Max.	38	15	110	38	15	110
Mean	19	4	17	19	4	17
Min	6	1	1	6	1	1
Water Quality Exit (mg/L)	N-NO_3	N-NO_2	N-NH_3	N-NO_3	N-NO_2	N-NH_3
Max.	19	2	1	58	4	5
Mean	6	1	0	31	2	1
Min	0	0	0	4	0	0
	Lysimeter 1= water type (Potable Water)					
	Soil type					
	Sand (S)			Clay (C)		
Water Quality Entry (mg/L)	N-NO_3	N-NO_2	N-NH_3	N-NO_3	N-NO_2	N-NH_3
Max.	3	2	0	3	2	0
Mean	1	0	0	1	0	0
Min	0	0	0	0	0	0
Water Quality Exit (mg/L)	N-NO_3	N-NO_2	N-NH_3	N-NO_3	N-NO_2	N-NH_3
Max.	19	6	5	161	3	7
Mean	5	1	0	27	1	3
Min	0	0	0	6	0	0

Table 4. Test and CI for one standard deviation in L2S: N-NO_3 mean, min. and max.

Sampling moment	Variable	N	St Dev [a]	Variance	Method	CI for St Dev [b] 95%	CI for Variance [b] 95%
Input	N-NO_3 mean	46	21.0	441	standard	(17.4, 26.4)	(303, 699)
					adjusted	(13.9, 42.2)	(194, 1779)
	N-NO_3 min	46	20.9	436	standard	(17.4, 26.4)	(303, 699)
					adjusted	(13.9, 42.2)	(194, 1779)
	N-NO_3 max	46	21.1	446	standard	(17.4, 26.4)	(303, 699)
					adjusted	(13.9, 42.2)	(194, 1779)
Output	N-NO_3 mean	46	5.10	26.1	standard	(4.23, 6.43)	(17.9, 41.3)
					adjusted	(4.28, 6.32)	(18.4, 39.9)
	N-NO_3 min	46	5.07	25.7	standard	(4.20, 6.38)	(17.7, 40.7)
					adjusted	(4.25, 6.28)	(18.0, 39.4)
	N-NO_3 max	46	5.15	26.5	standard	(4.27, 6.48)	(18.2, 42.0)
					adjusted	(4.32, 6.36)	(18.7, 40.4)

[a] St Dev stands for standard deviation.

[b] CI stands for confidence interval.

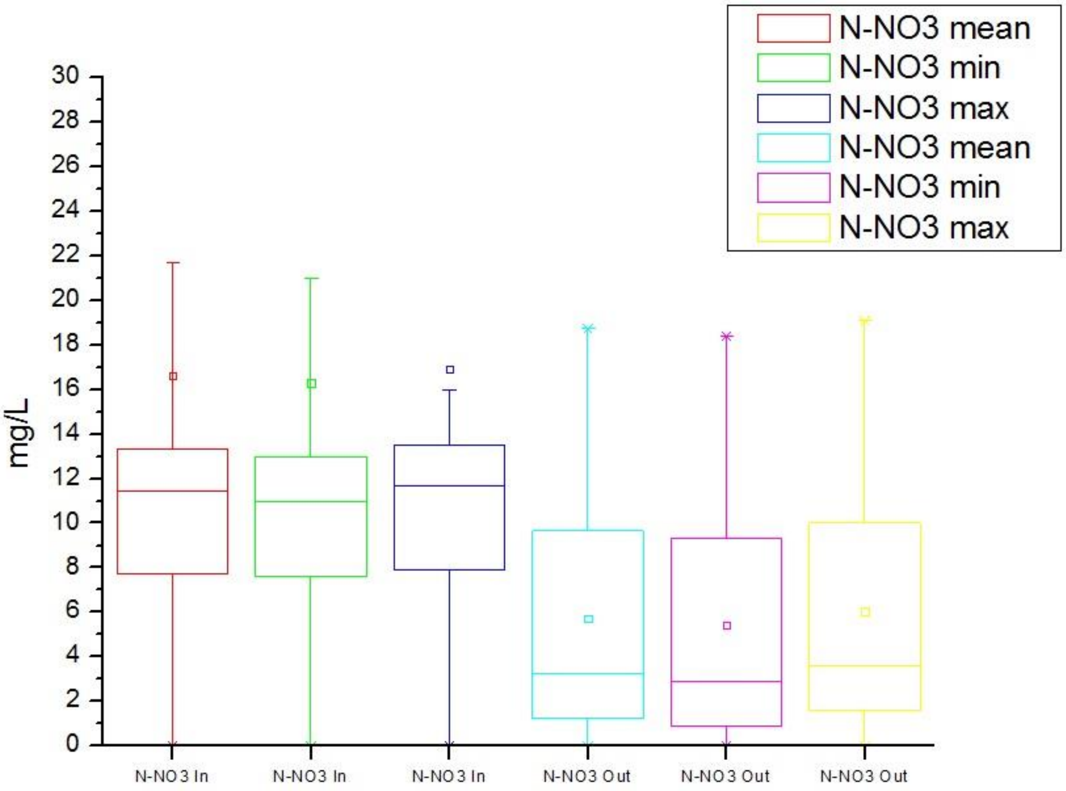

Fig. 10 Box plot for N-NO_3 content in lysimeter L2S.

Fisher tests are presented for means and variance comparison of the Gaussian samples, the variance analyses for the concentrations of N-NO_2 are shown the Table 5. The water type was the factor that most influenced the presence of N-NO_2. The difference between the means of the sampled groups with respect to the N-NO_2 is significant, in regards to the type of water. Alternately, the soil type did not present significant differences.

For the N-NO_3 concentration, the results obtained are shown in the Table 6, significant differences were obtained concerning type of soil and water quality. Although similar tests have been carried out, it is necessary to particularize for the specific TW quality and native soil type; the TW use viability depends deeply on the removal of existing compounds in the TW quality (Paradis *et al.* 2017). The obtained results demonstrated that groundwater N-NO_3 contamination can vary depending on the native soil type. Using a statistical model can be a powerful tool to identify and classify major variables explaining groundwater pollution, thus aid the groundwater quality management. Groundwater N-NO_3 pollution is however not only a spatial, but also a temporal process; and N-NO_3 is not a conservative tracer, since its concentration can be affected by complex biogeochemical processes, redox chemistry in particular (Mfumu *et al.*, 2016).

The lysimeter 2 was analyzed against the existing regulations for inorganic nitrogen compounds with recharge possibility (NOM-014-CONAGUA-2003; NOM-127-SSA1-1994). The sand columns had the greatest efficiency in terms of removal of inorganic nitrogenous compounds existing in the TW; even with the intense decrease in temperature during December, the phenomenon of nitrification-denitrification could be verified.

Table 5. N-NO_2 ANOVA results for output water.

Source [a]	DF [b]	Seq SS [c]	Adj MS [d]	F-value	P-value
TS	1	1.073	1.07284	1.78	0.184
TA	1	2.601	2.060134	4.31	0.009
TS*TA	1	1.261	1.26128	2.09	0.150

[a] TA stands for variation of water and TS stands for soil type

[b] DF total degree of freedom, amount of information in data.

[c] Seq SS, sequential sums of squares are measures of variation for model components.

[d] Adj MS, adjusted mean squares.

Table 6. $N\text{-}NO_3$ ANOVA results for output water.

Source [a]	DF [b]	Seq SS [c]	Adj MS [d]	F-value	P-value
TS	1	4194	4194.36	8.34	0.004
TA	1	7473	7472.78	14.85	0.000
TS*TA	1	4060	4059.86	8.07	0.005

[a] TA stands for variation of water and TS stands for soil type

[b] DF total degree of freedom, amount of information in data.

[c] Seq SS, sequential sums of squares are measures of variation for model components.

[d] Adj MS, adjusted mean squares.

$N\text{-}NH_3$ adsorption could be seen in both the clay and sand columns (Müller *et al.*, 2002). The greater presence of $N\text{-}NO_3$ in leached water denoted the possible nitrification reactions of the $N\text{-}NH_3$.

Highly permeable soils such as sand and gravel, infiltrate water faster than clay, transporting dissolved substances such as $N\text{-}NO_3$. Sandy soils are generally well aerated, providing favorable conditions for the conversion processes to produce $N\text{-}NO_3$. Clay soils have instead slower vertical downward flow due to smaller pores. Establishing anaerobic conditions nitrogen can be obtained as a gas that will escape to the atmosphere by means of the denitrification process (Bojorquez *et al.*, 2018).

The lysimeter percolate analysis provides the most direct measurements of vertical flux through time at the depth of installation (Heppner *et al.*, 2007). Lysimeters give a first estimate of the water quality leached variability in response to type of soil (Walker *et al.*, 2002). However deep-drainage representation generates some difficulties, as is the case of the ES (Scanlon *et al.*, 2002; Walker *et al.*, 2002). The unsaturated zone of the ES corresponds to an old channel of the Sacramento River, made of granular units deposited by the river, or in connection with abandoned meanders. The presence of intercalated clay materials slows the infiltration rate. When the average depth of the water table in CHSA is 100m, piezometric monitoring and groundwater analysis are required before assessing $N\text{-}NO_3$ contamination in the aquifer (Scanlon *et al.*, 2002).

CONCLUSIONS AND RECOMMENDATIONS

The present study concluded that in the area of NTP irrigated with TW, the risk of nitrogen compounds leaching into the aquifer is minimal. The environmental conditions favor N-NO_3 removal from the subsoil. One meter of sand column is sufficient for the total removal of inorganic nitrogenous components present in TW of the NTP of Chihuahua, following the criteria of Mexican norms NOM-014-CONAGUA-2003; NOM-127-SSA1 (Official journal of the Federation, 1994). In clays, the removal of N-NO_2 and N-NO_3, produced by one meter of soil column is not enough, the smaller pores and lower permeability produce a slower vertical downward flow. It must be considered that in clay soils there may be slightly anaerobic conditions, so by means of the denitrification process, nitrogen will be obtained as a gas that will escape to the atmosphere (Bojorquez *et al.*, 2018). In soils with clay presence, it is necessary to confirm the existence of sand layers that are at least one meter thick. The presented results are important in the context of using TW in the development of MAR structures. It is feasible to make a prototype of artificial recharge in the CHSA with TW quality, obtained with a secondary water treatment. The NTP gardens provide an ideal sub-superficial process for artificial recharge. Methods for mapping of MAR opportunities remain poorly founded in the absence of comparative information and in relation to practical experience (Dillon *et al.*, 2018).

This research lays down a latent need to evaluate *in-situ* protocols that allow to improve recharge criteria based on soil type and water quality. The lack of values limits the adequate classification and adoption of efficient criteria, according to the MAR technique or device to be used.

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GENERAL DISCUSSION

It was possible to develop a framework that integrates an urban groundwater management approach through the use of specific indicators and methodologies for the study area. This framework allowed to evaluate the situation of groundwater use in the city of Chihuahua. The development of the groundwater monitor based on existing indices and indicators determined which are the factors with the greatest impact on the detriment of groundwater level. Based on the variables with the highest incidence, methodologies were designed to comprehensively evaluate the urban management of the use of groundwater. The first step to know the state of sustainability of the water resource is the measurement by a monitor.

The first study comprehensively analyzes the influential factors on groundwater depletion in CHS aquifer in Chihuahua México. It was found that there are serious impacts of human activities on the groundwater system. This study area experienced a trend towards an increase in the intensity of the climatic drought from 1986 to 2010. The univariate standardized indexes (SPI) and the multivariate standardized index (MSDIc) allowed weighing the intensity of the main influential meteorological variables in climatic drought. The combined impacts of the change in land cover and the trend of increase in climatic drought have caused impacts in the reduction of groundwater recharge. According to the model obtained, it can be determined that the decrease that exists at the static level is significantly correlated with the increase in the amount of groundwater abstraction. The average groundwater level was 32m for the year 1986, increasing to 92m in 2010.

The second study implemented the management of pressure in the distribution network of drinking water to evaluate how the management and/or operation influences the availability of supply or volumes to be extracted.

It is important to mention that the operation of a system, whether continuous or intermittent, set the standard for defining the magnitudes of water volumes that enter the system for user satisfaction. Also, other factors such as pipe diameter and material, topography, domestic storage, uses and customs of the community might influence determining how much pressure the pipe requires and for how long. Likewise, this continuous or intermittent operation largely determines the volumes of water loss and collateral problems causing the user's demand to not be satisfied and is often supplied by larger volumes of water to the network without sufficient outcomes. Data were collected by monitoring a district of the Chihuahua (Mexico) water distribution network. The district serves around 1,100 properties with a total population of about 3,850. Pressure and Flux were measured upstream/downstream of the PRV and at the topographic critical points (highest and lowest), in order to establish the water consumption behavior of the DMA. Furthermore, leaks come into sight because keeping the network charged at a minimum pressure makes them visible instead of having the leaks disappear in the discharge of the line, therefore, rehabilitation and leak detection is a priority. It should be noted that the volume supplied in the DMA operating in IWS is more than double, opposite to the water consumption using this gradual transition with restricted pressures. The management approach is directly related to institutional strengthening, and specifically to the direction and support actions required by the technical aspect. In conclusion, demand management directly affects the need (or not) to require a greater supply to be abstracted, therefore affecting groundwater levels.

Given the complexity of making an immediate change from intermittent to continuous supply, in the third study a methodology was proposed to gradually return the DWS of a city to CWS, through a real knowledge. The approach using network sectorization and pressure management at DMA's enables a hybrid model between the physical knowledge and the technical model obtained from the hydraulic analysis. The analyses show that during the period of implementation of the DMA's operating in CWS and IWS, both showed a significant decrease of the water volume supplied, increasing the service hours (in the CWS DMA's). The operation of 19% of the households of the city under this methodology results in a 24% of water saving of the entire city. Thus, this study contributes to improve intermittent supply systems, stating that well-designed and administered sectors contribute to saving water and gradually achieve CWS. There is a gap in the literature in the process to return a city to CWS due to the methodologies that are proposed, as well as the DMA designs according to the characteristics of the city. The use of CWS and DMA's is proposed as an ideal and sustainable solution.

However, when evaluating this proposed methodology, it allows defining the amount of volume that is required and reduces the volume of water lost due to visible and non-visible leaks. Therefore, saving or recovering volumes of water reduces the need to resort to new groundwater sources and optimize the operation of supply networks and satisfy the demand of the end-user.

Thus, this paper seeks a gradual evolution based on a specific design for the conditions of the city and each sector, being in constant assessment to continue its operation, improving the state of sustainability of the drinking water service.

The last study establishes that it is possible to recharge water from a treated wastewater source and that it self-purifies under particular conditions without negatively impacting the quality of the native water of the aquifer. Therefore, it offers an alternative that must be evaluated in a technical and rigorous way to obtain results that affect the stabilization of groundwater levels. This study concluded that in the area of NTP irrigated with TW, the risk of nitrogen compounds leaching into the aquifer is minimal. The environmental conditions favor N-NO3 removal from the subsoil. One meter of sand column is sufficient for the total removal of inorganic nitrogenous components present in TW of the NTP of Chihuahua, following the criteria of Mexican norms NOM-014-CONAGUA-2003; NOM-127-SSA1 (Official journal of the Federation, 1994). In clays, the removal of N-NO2 and N-NO3, produced by one meter of soil column is not enough, the smaller pores and lower permeability produce a slower vertical downward flow. It must be considered that in clay soils there may be slightly anaerobic conditions, so by means of the denitrification process, nitrogen will be obtained as a gas that will escape to the atmosphere. In soils with clay presence, it is necessary to confirm the existence of sand layers that are at least one meter thick. The presented results are important in the context of using TW in the development of MAR structures.

GENERAL CONCLUSIONS AND IMPLICATIONS

The framework developed by an Integrated Approach to Urban Groundwater Management, it is determined by the connection and correlation of the variables that affect the exploitation of groundwater. Groundwater variables must go accordingly with the demand management so it won’t require more water volumes due to the poor operation or lack of knowledge of the operation of the drinking water system.

A balance must be found between the need to satisfy the user's demand in terms of quantity and pressure of water with the time in which it is available through the system, therefore reducing the flows and pressures in the network to maintain only the saturation of the network. This operational modification allows to avoid (air pockets due to voids, blockages, etc.) failures and breakages, therefore reducing the waste of volumes of water that are not visible and that infiltrate without recharging the aquifer due to the return by evaporation to the atmosphere. This prevents the extraction of an additional volume of groundwater than required, which causes the levels to deepen with the consequence of a decrease in recharge due to the transit of water precipitated from the surface. The reuse of treated wastewater as recharge would help reduce this deepening. However, it is not possible in all cases, it must be done with an exhaustive knowledge of the selected site and the chosen method to obtain the expected results in an acceptable time horizon (5 to 10 years).

In this work, the foundations are laid to determine which variables or factors should be included in the framework with an integrative approach. As a future line, it is proposed that these variables be defined and classified into two groups:

physical framework: precipitation, static level, lithology, time period

urban infrastructure using groundwater: flow, pressure, and time evaluated mathematically or with a multi-criteria approach.

Below and as a result of the analysis of the thesis, some possible actions are proposed that can be adapted and adopted by the water operating agency:

The use of a specific methodology makes it possible to determine which are the factors that mainly affect the detriment of groundwater, but it is necessary to have reliable data that allow establishing statistically valid correlations and predictions in order to have more useful conclusions for the WOA. For this reason, it is recommended that the static level be measured in piezometers in the study area over time (including measurements in different seasons of the year) to assess the variability of the evolution of the static level according to its seasonality.

For the IAUGM evaluation to be beneficial in responding to the unprecedented challenges concerning the management of the groundwater resources to meet the increasing water demand of a growing population, it is vital to ensure data that can allow researchers to continue to elaborate knowledge.

There are several methodologies and actions that can be taken to guide a city to a sustainable use of groundwater, making a change from the use of a system in IWS to CWS is proven to generate a large number of benefits. The difficulty results when applying the theory to a practical case, because problems and disappointments occur. These setbacks provoke skepticism in the WOA perpetuating the operation of IWS and rooting of the problems derived from it. Resistance to the transition of using automation and setting the volume/pressure consumption curve based on reliable data measurement persists, because the perception of the operator is that the data is not registered or measured correctly. The change process will be successful to the extent that the WOA efficiently channels the participation of the personnel involved in the improvement of the processes. It is vital for the development of this type of action to establish an institutional management that allows strengthening decision-making and directing the institution based on the technical aspect. It is convenient to develop studies that allow evaluating the analysis of the potential water savings and the leakages while adding the inter-dependency relationship between pressure management and active leakage control.

Another action that allows moving towards a sustainable use of water resources is the substitution of drinking water for treated wastewater. It is possible to set uses for the treated wastewater or devices to make an artificial recharge that allows recovering the groundwater levels, but it is important to establish and modify protocols and methodologies so they are adapted to the specific conditions of the site.