2020, Instituto Mexicano de Tecnología del Agua

DOI: 10.24850/j-tyca-2020-06-05

Articles

Proposal for an urban water indicators framework for Mexico City 2005-2018

Propuesta de un marco de indicadores de agua urbana para la Ciudad de México 2005-2018

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Abstract

One of the obstacles in the implementation of an integrated urban water management (IUWM) is the absence or non-implementation of tools that help to set goals and evaluate processes and progress. The use of indicators to analyze changes has been widely accepted; however, until now these indicators have been developed mainly on a large scale, omitting to attend to specific local characteristics and problems. Therefore, this paper develops a framework of indicators to be used as a tool in the IUWM, applied to the case study of Mexico City in the period 2005-2018. The conceptual and methodological framework adopted is based on the principles of IUWM and the Pressure-State-Response causality approach. The formulation of the framework was carried out in five stages. As a result, a set of 12 indicators is presented, divided into four subgroups: (1) operational efficiency to meet drinking water and sanitation service needs; (2) pressure on the water resource that affects water availability and quality; (3) the environmental status of the resource; and (4) society's response to reduce pressures and improve water quality and quantity. For each indicator, its basic attributes were delimited and values were calculated, demonstrating its viability as a public policy evaluation tool in the monitoring stage of the IUWM.

Keywords: Urban water management, urban water, water indicators, Mexico City water.

Resumen

Uno de los obstáculos en la implementación de una gestión integrada del agua urbana (GIAU) es la ausencia o no implementación de herramientas que ayuden a establecer metas, y evaluar procesos y avances. El uso de indicadores con el objetivo de analizar los cambios ocurridos es ampliamente aceptado; sin embargo, hasta ahora, tales indicadores se han desarrollado a grandes escalas, omitiendo atender las características y problemáticas específicas locales. Por ello, en el presente trabajo se desarrolla un marco de indicadores para utilizarse como herramienta en la GIAU, aplicado al estudio de caso de la Ciudad de México, en el periodo 2005-2018. El marco conceptual y metodológico adoptado tiene como base los principios de la GIAU y el enfoque de causalidad presión-estado-respuesta. La formulación del marco se llevó a cabo en cinco etapas. Como resultado, se presenta un conjunto de 12 indicadores divididos en cuatro subgrupos: 1) de eficiencia operativa para satisfacer las necesidades del servicio de agua potable y saneamiento; 2) de presión sobre el recurso hídrico que afecta la disponibilidad y calidad del agua; 3) del estado ambiental del recurso, y 4) la respuesta de la sociedad para reducir las presiones, y mejorar la calidad y cantidad de agua. Para cada indicador se delimitaron sus atributos básicos y se calcularon los valores, demostrando la viabilidad como herramienta de evaluación de política pública en la etapa de monitoreo de la gestión integrada del agua urbana.

Palabras clave: gestión integrada del agua urbana, indicadores de gestión, Ciudad de México.

Received: 22/11/2018

Accepted: 23/03/2020

Introduction

The academic literature recommends the adoption of indicators for the evaluation and monitoring of change processes (including public policy) towards sustainable development (Hezri & Dovers, 2006). International organizations have found powerful decision support tools in the indicators (UN-WWAP, 2003; OECD, 1998). On the issue of water, in the last twenty years indicators related to water resource management have proliferated rapidly (Dunn & Bakker, 2011), due to the growing need to develop tools to assess the development process in an integrated manner (UN-WWAP, 2003). In this sense, indicators play an important role in the dissemination of information, transforming scientific and complex data into a simplified and quantified expression (Gleick, Chalecki, & Wong, 2002); that allows to inform decision makers and society about the trends of change and fulfill the commitments acquired internationally (Pintér, Hardi, & Bartelmus, 2005).

Despite this rapid development in the literature on water indicators, their implementation in public policy is still quite limited. Among the reasons are: the non-coincidence between natural boundaries of basins and aquifers, with administrative boundaries; the limited institutional capacity to collect or evaluate data, and the limited interaction between the sectors of society that generate and use the information, among others (Dunn & Bakker, 2011; Hill, Furlong, Bakker, & Cohen, 2008). The formulation of an adequate proposal of indicators that consider both economic and socio-environmental factors and, in particular, that take into account their interdependence, is an arduous task that requires a deep understanding of complex processes and their interaction between various disciplines.

According to Dunn and Bakker (2011) and UN-WWAP (2006), although there are a number of indicators related to water and the need to link scientific assessment with issues of integrated water management, there is little progress achieved in the systematic application of indicator-based evaluation methods. Existing indicators are usually one-dimensional (for example, related to water quality or quantity) and rarely consider other aspects, such as aquatic ecosystems, human health, land use and water management within the same framework (Dunn & Bakker, 2011). In summary, sustainability indicators, indices and information systems have gained popularity in recent years, but their effectiveness in influencing public policy remains limited (Pinter *et al*., 2005). These authors indicate that this gap between the potential and actual influence of indicators on wider adoption suggests that indicators can play a stronger role in articulating and monitoring progress towards sustainability in a wide range of circumstances.

The paradigm of integrated urban water management (IUWM) focuses basically on water management by natural availability, use of alternative water resources and decentralization of the administration process. According to Niemczynowicz (1999), integrated urban water management involves land use policies, urban planning, land use planning, economic development processes, regulation and legislation, education, environmental awareness and integration of society into participatory water management.

Cities in transition and developing countries raise increasing challenges to IUWM where trends and pressures of urbanization, economic growth (UN, 2014), climate change, lack of consciousness and preparation, or government effectiveness and limited financial resources for infrastructure construction and maintenance present enormous barriers to adequate IUWM implementation (OECD, 2015). Climate change amplifies the situation of urban water vulnerability, in the sense of flooding, water stress, water scarcity and water pollution. This occurs mainly in almost all the world's megacities (Ligtvoet *et al*., 2014). Given this complexity of socio-environmental problems and global changes in urban areas, there is a need to design and adapt indicators to the urban context, based on the recognition of the distinctive water challenges of cities and their responses. Within an evidence-based policymaking paradigm, indicators are expected to contribute to many stages of the public policy process, from problem identification, ex-ante evaluation of policy alternatives, to monitoring, evaluation and adjustment of policy alternatives.

In this sense, this paper develops a framework of indicators oriented to the evaluation of progress within the principles of the IUWM for the case study of Mexico City, 2005-2018, under the hypothesis that it is feasible to build a framework of indicators as an instrument to measure progress in public water policy (even with existing official information). The conceptual framework is based on the IUWM and the indicators for this purpose; and methodologically it is supported by the realization of several stages, from the collection and systematization of information, to the consultation and application of a survey to specialists, the analysis of information and, finally, the design of the indicators framework for the IUWM.

Conceptual framework

Integrated urban water management

This research is based on the IUWM paradigm promoted by Mitchell (2006), and Hardy, Kuczera and Coobes (2005), among other authors (Perevochtchikova & Martínez, 2010; Andrade & Navarrete, 2004; Martínez, Escolero, Kralisch, & Wolf, 2007). The conventional model of water management is characterized by drinking water supply and sanitation systems oriented towards satisfying the demand for water without taking into account natural availability and the social and natural processes of the water cycle (Pinkham, 1999; Tucci, 2010). On the other hand, the IUWM seeks the sustainable integration of the water services in a city -drinking water, sanitation and sewerage- into an integrative physical system (Mitchell, 2006); and it is recognized that this system is based on a common organizational scheme within the integral vision of the interconnection with the natural landscape.

The IUWM paradigm is mainly oriented to water management by availability, the use of water resources in an alternative way and encourages the decentralization of the administration process. The IUWM involves planning and territorial ordering, processes of economic development, regulation and legislation, education, citizen awareness and integration of society in participatory water management, according to Niemczynowicz (1999).

Two principles of the IUWM are important: i) planning and decision-making that includes all components of the water service and landscape; and, ii) that this decision-making be oriented towards sustainability in water management by balancing short, medium, and long-term environmental, social, and economic interests (Mitchell, 2006).

Indicators for urban water management

Within IUWM, an important stage is the evaluation and monitoring of action plans both at the basin level and on a local scale (Gangbazo, 2004). This requires appropriate indicator frameworks (Pahl-Wostl *et al*., 2005; Bahduri *et al*., 2016) that describe and communicate current conditions, encourage critical thinking about required remedial measures and facilitate the participation of various stakeholders in decision-making processes (Brugmann, 1997). Ideally, indicators are used to provide essential information on the viability of a system and its rate of change, and on how these contribute to the overall sustainable development of the system (Perevochtchikova & Negrete; 2013; Tiburcio & Perevochtchikova, 2012).

Currently there are multiple and varied approaches and methodologies of indicators oriented to the measurement of sustainability (Bossel, 1999; Meadows, 1998). Among the different methods, UN-WWAP (2003) identifies the cause-effect method, known as Pressure-State-Response, which has other variants, such as Driving Force- Pressure-State-Impact-Resource, or Driving Forces-Pressure-State-Exposure-Effect-Action; and which uses indicators from the causality of the processes.

The Pressure-State-Response (PER) framework was first introduced by the OECD in 1994 and is based on a logic of causality in which human activities are interrelated as sources of *pressure*, and their impact on the environment by changing the quality and quantity of natural resources (state), thus generating (responses) from society to the problem through environmental, economic and sectoral policies (OECD, 1998) (Figure 1).

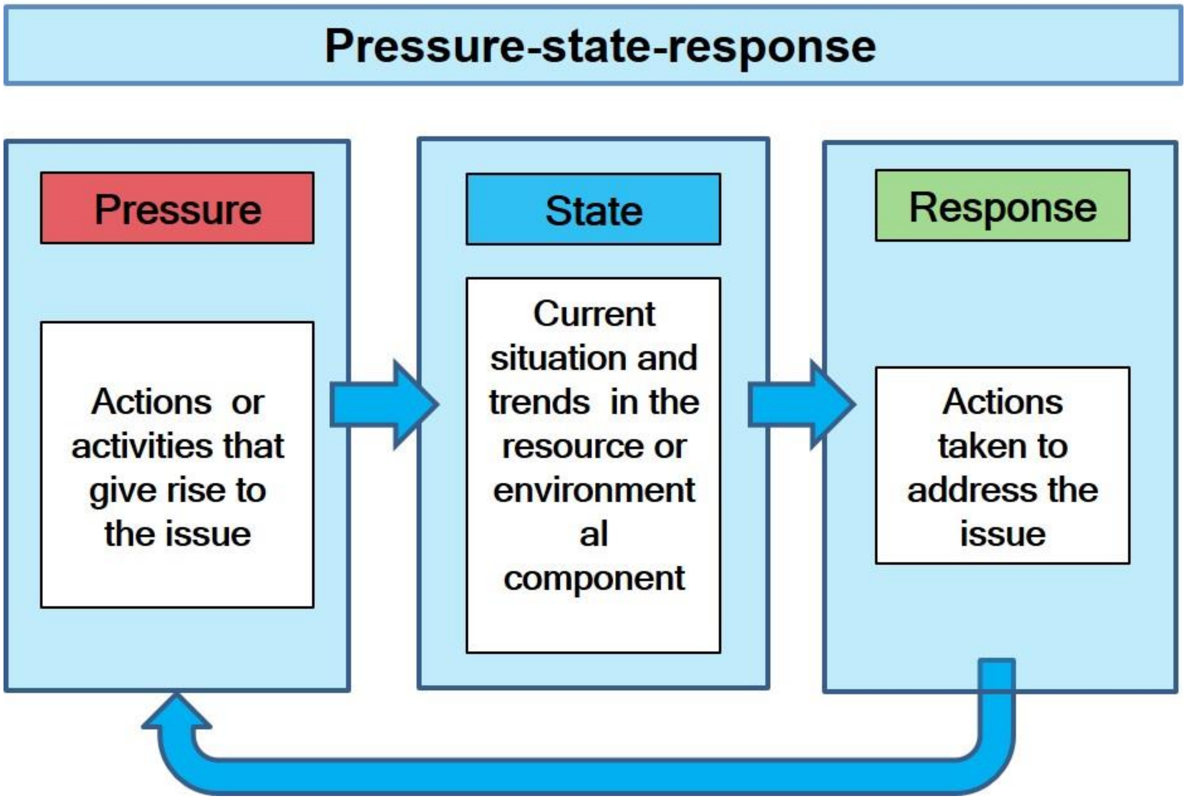

Figure 1. Pressure-state-response Diagram (Source: based on OECD, 1998).

The PER approach represents an adequate framework for the development of indicators with a common problem, since it allows to determine the effectiveness of the actions to improve the environmental status, which helps in the establishment or reorientation of public policies or the criteria for the decision making of the main state sectors (Rodríguez & Flores, 2009).

At the city level, there are two main trends in water management indicators: a) those aimed at measuring the performance of water operators, and b) those aimed at measuring the sustainability of the resource from an ecological perspective (Tiburcio, 2013), which are described below:

a) Operational performance indicators. These indicators measure the efficiency and effectiveness of water supply, sewerage and sanitation systems in meeting the needs of the population. According to Alegre, Melo, and Cabrera (2006), these type of indicators have their origins in the 1990s, when city water services began to be evaluated in Europe.

At present, the widespread use of these indicators is observed, with schemes that are variable depending on their rate of evolution. For example, the CCA (2010) presents a simple structure of indicators, whose parameters have information (CCA, 2010). Other initiatives with a longer design time tend to be indicator systems, which present more precise parameters, with periodic measurements, allowing them to be compared over time and oriented towards the needs of users from a management instrument (NWC, 2010; IMTA, 2014; Danilenko, Van der Berg, Macheve, & Moffitt, 2014).

Although operational performance indicators have become widely accepted in recent years, they focus only on one part of water management, namely water supply and sanitation. Performance Indicators are not sufficient to comprehensively assess the urban water management cycle, nor whether it is guided by principles of sustainability. It is necessary to incorporate elements that determine the long-term environmental viability of a city and its relationship with the resource, taking into account factors such as the state of the water resource and the elements involved in the urban water cycle (Zeman, 2012; Vojnovic, 2013).

b) Environmental indicators. The main objective of this type of indicator is to measure the state of the water resource in terms of quality and quantity. Generally, they focus on the analysis of the state of water bodies or on the environmental impacts generated by human activities. Examples of this orientation are the life cycle assessment method (Lundin & Morrison, 2002), in which environmental impacts on water bodies are measured, such as the Metron Project (Kallis & Coccossis, 2003) and the Canadian Water Sustainability Index (Tiburcio & Perevochtchikova, 2012). The latest one evaluates in a multidimensional way the sustainability of the resource in communities of no more than five thousand inhabitants, considering aspects such as the physical state of the resource, pressures, infrastructure and management capacity (PRI, 2007).

It can be concluded that both groups of indicators are complementary, performance indicators allow knowing whether the needs of the population are being fulfilled and environmental indicators allow knowing the state of the ecosystems that provide water. Therefore, a combination of both could provide a more complete overview for urban water management.

Study area

Mexico City (CDMX in Spanish abbreviation), the country's capital, is located at 2,240 meters above sea level in the southwestern part of the Mexico Basin (a hydrologically closed formation). The city is located in the lower part of the basin on a lake area (Figure 2); which since pre-Hispanic times was sustained by an agricultural system that took advantage of all its natural elements from the ancient lake plain (Legorreta, 2006). The urban growth has been extended and accentuated in the last five decades, until forming the Metropolitan Area (MCMA) that has a surface of 4 925 km^2; with a population of about 21 million inhabitants with an average urban density of 160.1 inhabitants per ha (Conagua, 2018).

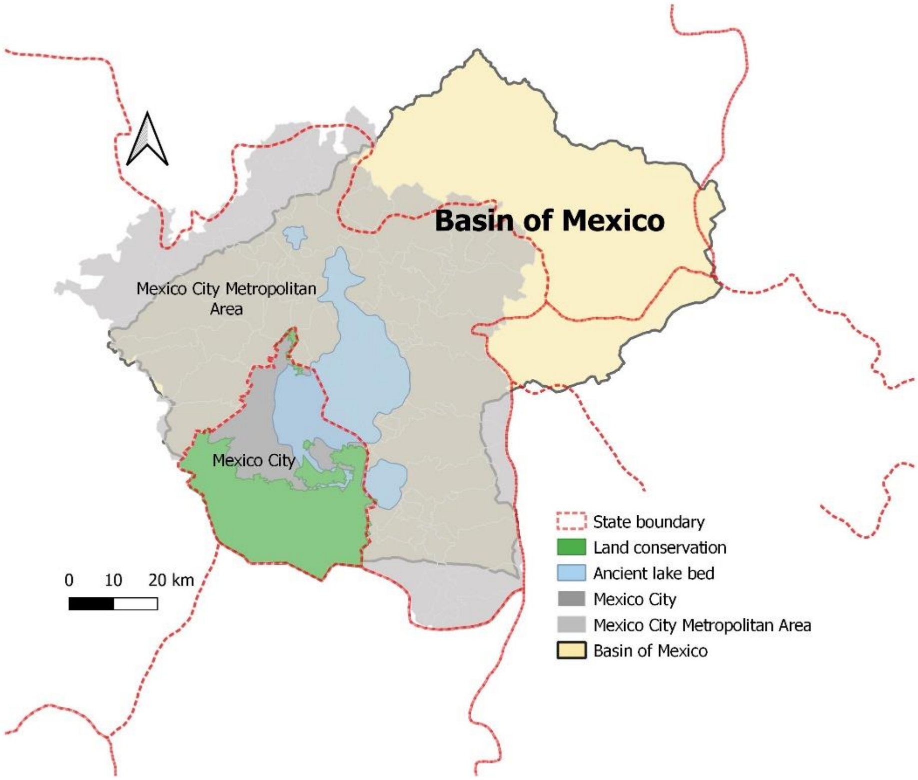

Figure 2. The location of the study area (Source: prepared by authors based on Gutiérrez, González, & Zamorano, 2005).

The federal and state governments and many industries, education, employment and cultural centers are concentrated in the CDMX (Garza, 2000). However, the population's quality of life has declined significantly in recent decades, due to pollution and ecological degradation (Tortajada, 2006; Mazari-Hiriart *et al*., 2018). Particularly, in the Conservation Land, where the land use suitable for agricultural, forestry, agro-industrial activities and rural settlements, which offer multiple ecosystem services for the CDMX, such as water provision and regulation; was changed drastically (Pérez-Campuzano, Perevochtchikova, & Ávila-Foucalt, 2012). Urbanization processes continue their expansion on the Conservation Land (GDF, 2012), modifying the land cover, ecosystem services and productive activities.

Considering the geographical and demographic characteristics of the city, water management in the CDMX presents extraordinary difficulties (Perevochtchikova, 2015). In the course of four centuries a complex physical and institutional infrastructure has been built (Perló & González, 2009), with the aim of making the city viable in two ways: i) to supply it with drinking water and, ii) to prevent it from being flooded. Six large infrastructures and seven tunnels artificially link four hydrological basins under a logic of water import and export (González, 2016), which together result in a water deficit balance with chronic overexploitation of the aquifer. Therefore, the need to import water from distant and expensive sources has been raised by government agencies, in a context of climate change (SACMEX, 2018; Martínez, Kralisch, Escolero, & Perevochtchikova, 2015).

This water management system involves a multiplicity of actors at the federal, state, and municipal levels. For example, the National Water Commission (Conagua), the Secretariat of the Environment of the CDMX, the Water System of the CDMX (SACMEX), the Metropolitan Water and Drainage Commission, the municipal drinking water and sewerage agencies of the municipalities, which make up the MCMA (Tiburcio, 2013). According to González (2016), three levels of management are identified: 1) local, which includes secondary drinking water distribution networks, sewerage and drainage networks; the operation and functioning of this level coincides with the limits of the political-administrative units that make up the MCMA; 2) metropolitan, which includes the infrastructure that is operated by the governments of the MCMA and the State of Mexico, and 3) hydropolitan, which concerns the aqueducts, emitters and tunnels that link the MCMA with other basins. Actions and decisions in this field are predominantly taken by the federation.

Since 2003, CDMX has had a public policy program for water management (SACMEX, 2005), but it was only until 2010 that the first indicators were formulated. In 2016, the indicators were reformulated in the program for Sustainability and Management of Water Services (PSGSH) (Gaceta Oficial de la CDMX, 2016). The topics covered were global efficiency (physical efficiency and commercial efficiency), service coverage, service improvement, water system maintenance, treatment and reuse. In its first edition, the data temporality and its measurement method, were not made explicit. Which evidences the need for a set of systematic indicators for the urban water management system to assess the effectiveness of public policies in this period.

Indicator framework design

The design of the indicators framework was based on the methodologies proposed by Lorenz (1999); Alegre, Cabrera and Merkel (2008); OECD (2003), and Quiroga (2009), for the development of the CDMX case study and the period 2000-2018. They were sought to fulfil the function of being comparable over time and reflecting trends to decision makers. In this way, the following stages were carried out: a) the documentary analysis of the base elements of the indicators framework; b) the search for existing indicators in line with the established conceptual framework; c) the development of the conceptual model of indicators; d) the formulation of possible indicators, and e) the validation of possible indicators based on selection criteria.

Conceptual model

At this stage, the concepts of sustainability were analyzed based on the literature in this topic (Déleage, 2000; Pierri, 2005; CMMAD, 1987), the ecosystem approach (Perevochtchikova & Martínez, 2010) and urban water management (Hardy *et al*., 2005; Pinkham, 1999); specifically, the Australian experience (Mitchell, 2006; Brown, Keath, & Wong, 2009) were analyzed. These approaches helped to define reference attributes to be translated into measurable targets or parameters in the urban management model, in the context of the CDMX, based on available information. Once the conceptual model was established, the search for existing indicators began in order to take advantage of existing experience.

Search for existing indicators

An exhaustive review was made of the specialized literature on indicators related to urban water management: official and academic databases and information systems (Scopus, google academic), as well as websites of scientific journals (Urban Water, Water Resources Management among others), national and international institutions with public information (Conagua, National Water Commission, Australia). All this in order to have a first approach of indicators. A total of twenty-two proposals for indicators related to water management were reviewed and the eight best documented were analyzed in proof (marked with grey in Annex 1). Two main trends of indicators were identified: 1) indicators to measure the operational performance (CCA, 2010; Danilenko *et al*., 2014; NWC, 2010; IMTA, 2014), and 2) indicators to measure the sustainability of the resource from an environmental perspective (Lundin & Morrison, 2002; Kallis & Coccossis, 2003; PRI, 2007)).

Conceptual model of indicators

Based on the classification and analysis of existing indicators, it was observed that the operational performance indicators and sustainability indicators could be complementary; therefore, the indicators were combined within the Pressure-State-Response (PSR) framework (OCDE, 2003). The decision was made due to the possibility of the delimitation of the causal relations of a phenomenon, and to propose, establish or reorient public policies on water management (OCDE, 2003). Figure 3 presents the conceptual model developed, with the proposal of groups of indicators for each block (which are presented in the next stage).

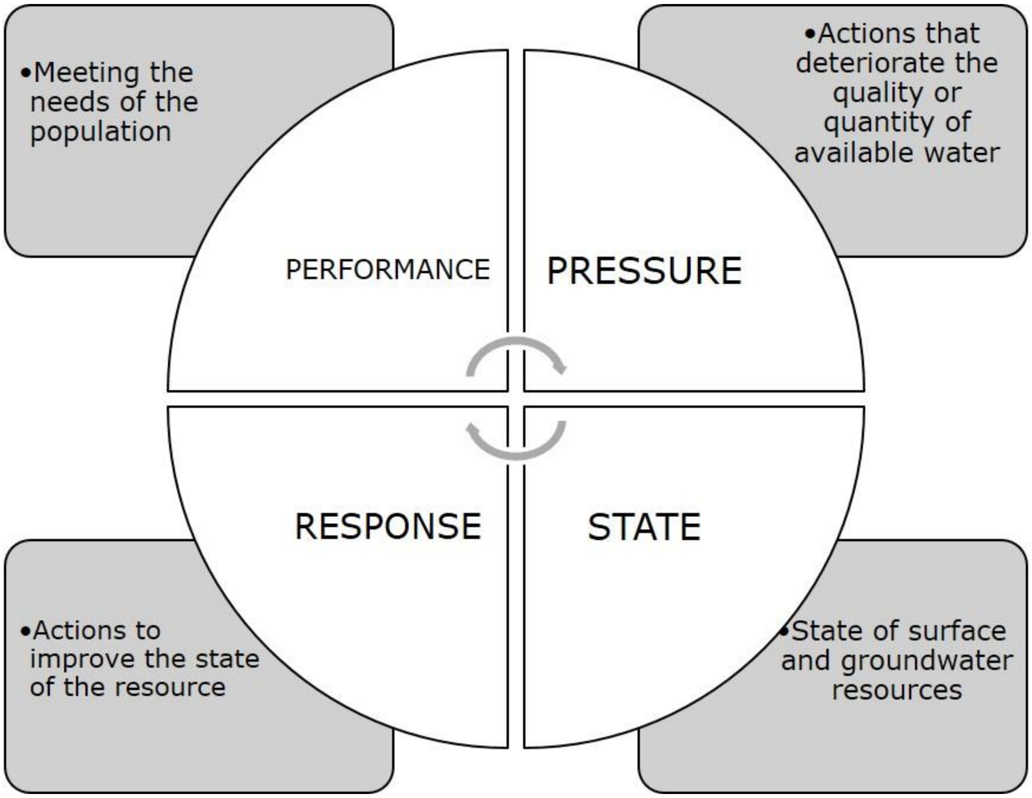

Figure 3. Conceptual model developed for the proposal of IUWM indicators in the CDMX, 2005-2018 (Source: Own elaboration based on OCDE, 2003 and Alegre *et al.*, 2008).

Formulation of possible indicators

For each group of indicators in the conceptual model, five initial indicators were formulated in order to have a margin of selection that would allow the most relevant aspects of the water management process in the CDMX.

It was considered that each indicator should cover the criteria of relevance to reflect the model´s dimensions (performance, pressure, state, response) and be sufficiently clear and understandable. The proposed indicators were also aligned with the CDMX Program on Sustainability and Management of Water Services (Gaceta Oficial de la CDMX, 2016).

These indicators are presented in Table 1. In the formulation of the indicators, the following characteristics were sought: a) integrative, covering the environmental and socioeconomic dimensions of the urban water management paradigm; b) spatially appropriate to the context; c) communicative, expressing the trends and risks in an understandable manner; and, d) forward-looking, with response indicators aimed at improving the urban water management process.

Table 1. Selected indicators and their calculation formula.

	Indicator	**Formula for calculation**	**Bibliographic references**
Performance indicators	Drinking water availability	$\sum_{n=1}^{4} C_{dn} P_{dn} + \sum_{m=0}^{720} C_f P_{fm} \times m$ C_{dn} = Coefficient of access to drinking water (varies from 0.5 to 0 depending on the form of access) P_{dn} = Percentage of households with x form of access to drinking water. C_f = Operating frequency coefficient (varies from 0.5 to 0 depending on operating hours)	Alegre *et al.* (2006); PRI (2007); CCA (2010); IMTA (2014); Jiménez *et al*. (2011)

		P_{fm} = Percentage of dwellings with m hours of service and m = hours of service per month	
	Sewage coverage	$\sum_{n=1}^{4} C_{dn}P_{dn}$ C_{dn} = Sewerage Coverage Coefficient (Varies from 1 to 0 according to the form of wastewater removal) P_{dn} = Percentage of homes with x form of wastewater discharge	CCA (2010); IMTA (2014); Danilenko *et al*. (2014)
	Drinking water quality (Percentage of samples taken that meet health standards)	$({}^{y}/_{x})$ y = Number of samples meeting health standards x = Number of samples taken	Alegre *et al*. (2006); NWC (2010) Salud (1995)
Pressure indicators	Dependence on external sources	$({}^{y}/_{x})$ y = Volume of water imported from other entities. x = Total volume of water produced	OECD (2004)
	Conservation land use change rate	$\frac{x2-x1}{Y}$ $x2$ = Hectares with urban use on conservation land in the final year $x1$ = Hectares with urban use on conservation land in the initial year Y = Conservation land area in year x1	Ulian, Cartes and Lemos (2017)
	Degree of overexploitation of groundwater and surface water	${}^{y}/_{x}$ y = Volume of water concessioned x = Volume of natural water available	Lundin and Morrison (2002); Okeola and Sule (2012)

Status indicators	Natural availability of water in the region	$X - Y$ x = Average annual runoff volume from the downstream basin y = Current annual volume committed downstream	Lundin and Morrison (2002); Kallis and Coccosi (2003); PRI (2007)
	Average natural availability per capita (annual average)	$x - y$ x = Average annual runoff volume of the downstream basin y = Current annual volume committed downstream.	Lundin and Morrison (2002); Kallis and Coccosis (2003); Salud (1995)
	Surface water quality (Chemical Oxygen Demand)	$\frac{1}{n}\sum_{y=1}^{n} PEy$ PE = Chemical Oxygen Demand parameter value n = number of monitored days	Lundin and Morrison (2002); Kallis and Coccosis (2003); Salud (1995)
	Surface water quality (Biochemical Oxygen Demand)	$\frac{1}{n}\sum_{y=1}^{n} PEy$ PE = Biochemical Oxygen Demand parameter value n = number of monitored days	Lundin and Morrison (2002); Kallis and Coccosis (2003); Salud (1995)
	Surface water quality)Total Suspended Solids)	$\frac{1}{n}\sum_{y=1}^{n} PEy$ PE = Total Suspended Solids quantity parameter value n = number of monitored days	Lundin and Morrison (2002); Kallis and Coccosis (2003); Salud (1995)
Response indicators	Percentage of water leaks	Estimation of the percentage of volume of water lost in the network. x = Estimated volume of water lost through leakage.	Lundin and Morrison (2002); SACMEX (2018)

	Percentage of wastewater treated and reused annually in the entity	$({}^{y}/_{x})100$ y = Volume of wastewater treated and reused x = Volume of wastewater produced	Lundin and Morrison (2002)
	Percentage of wastewater treated annually in the entity	$({}^{y}/_{x})100$ y = Volume of treated wastewater x = Volume of wastewater produced	Lundin and Morrison (2002)

Indicator validation

Validation of the indicators consisted in the evaluation of each indicator by a panel of twenty-two experts in the field, to whom a questionnaire was sent (see Appendix 2), and where they rated the indicators on a scale of 0 to 10 in terms of clarity and relevance. Responses were obtained from experts from academia, state water service agencies, international institutions and organizations. Comments were also received about the limitations of the indicators, such as the availability, accessibility, reliability and consistency of the data, as well as its spatiality and temporality. It was suggested to establish a measurement baseline for each indicator, to make comparisons between the initial situation and the current, future or ideal situations.

From an initial list of twenty proposed indicators (based on the reviewed literature (IMTA, 2014; Danilenko *et al*., 2014, Alegre *et al*., 2006; Lundin & Morrison, 2002), twelve indicators were left with the highest scores, as well as those, oriented to public policy, and with available and updateable information (Table 1). For each indicator, a methodological sheet was developed (format presented in Annex 3). It was a fundamental in the construction of each indicator, since it allowed the contents, meaning, scope, methodology and availability of information for the indicators to be objectified (Quiroga, 2009), as well as differentiating those indicators that are susceptible to measurement.

Results

Interpretation of results

In order to compare the indicators and avoid the congregation of different units of measurement, the indicators were standardized to the scale of 0 to 100% (Schuschny & Soto, 2009) (Table 2). This standardization is useful for the subsequent graphical interpretation of the results, where the spiderweb graph was proposed for visual presentation for decision makers (Zeman, 2012).

Table 2. Result of calculation of IUWM indicators for CDMX, 2005-2018.

Name	**Calculation of the indicator**	**Source of Information**	**Ideal Situation**	**Standardization**	**Standard Values**	**Standardised Ideal Target**
Drinking water availability	91 points	Population and housing census. National Household Income Survey www.inegi.org.mx	100 points	0 to 100 %	91%	100%
Sewage coverage	96 points	Population and housing census. National Household Income Survey www.inegi.org.mx	100 points	0 to 100 %	96%	100%
Drinking water quality	87%	Water Quality Report Mexico City Water System. www.SACMEX.cdmx.gob.mx/calidad-agua/analisis-calidad-del-agua	100	%	87%	100%
Dependence on external sources	53%	SACMEX (2012). Integrated Water Resources Management Program, Vision 20 years	0%	%	53%	100%
Conservation land use change	657.62 ha/ year	Conagua. Water statistics in Mexico. Water statistics Hydrological www.region.sina.conagua.gob.mx	0 ha/ year	Land Use Change Rate	99%	100%
Groundwater and surface water overexploitation rate	137%	Conagua. Water statistics in Mexico. Water statistics Hydrological www.region.sina.conagua.gob.mx	0%	%	137%	100%

Natural availability of water in the Region	3 401 million m^3	Conagua. Water statistics in Mexico. Water statistics Hydrological www.region.sina.conagua.gob.mx	Does not apply	Water availability change rate	12%	0%
Average natural availability per capita	142 m^3/ inhabitant	Conagua. Water statistics in Mexico. Water statistics Hydrological www.region.sina.conagua.gob.mx	1 000 m^3/inhabitant	Percentage of availability per capita in relation to international standards	16%	100%
Surface water quality (Chemical Oxygen Demand)	198 mg/l	Obtained data requested to Conagua, Water Quality 2005-2015	Less than or equal to 10 mg/l	Degree of contamination, where 100% is excellent quality and 0 is heavily contaminated	40%	100%
Surface water quality (Biochemical Oxygen Demand)	43 mg/l	Obtained data requested to Conagua, Water Quality 2005-2015	Less than or equal to 3mg/l	Degree of contamination, where 100% is excellent quality and 0 is heavily contaminated	40%	100%
Surface water quality (Total Suspended Solids)	46 mg/l	Obtained data requested to Conagua, Water Quality 2005-2015	25mg/l	Degree of contamination, where 100% is excellent quality and 0 is heavily contaminated	60%	100%

Percentage of water leaks	42%	Diagnóstico, Logros y Desafíos (SACMEX, 2018)	20%	%	42%	20%
Percentage of wastewater treated and reused annually in the entity	36%	Conagua Status of the drinking water, sewerage and sanitation subsector., 2006-2017 https://www.gob.mx/conagua/documentos/situacion-del-subsector-agua-potable-drenaje-y-saneamiento	100%	%	36%	100%
Percentage of wastewater treated annually in the entity	36%	Conagua. Situation of the drinking water, sewerage and sanitation subsector, 2006-2017 https://www.gob.mx/conagua/documentos/situacion-del-subsector-agua-potable-drenaje-y-saneamiento	100%	%	36%	100%

The scale and frequency of measurement for each adopted indicator fluctuated from local to regional scale, and from monthly to years variation, according to the characteristics of the measured parameters. For example, water quality indicators are measured monthly, while drinking water availability and sewerage coverage are updated from population censuses or household surveys conducted by INEGI (INEGI, 2014; INEGI, 2017) on an intermittent period basis. Dependence on sources of drinking water is also an indicator, which value depends on the infrastructure built, which can take years to build, and on the processes of urbanization and population growth, which are gradual and are measured every few years.

Data collection and calculation of indicators

Once the indicators and the formulas for their calculation had been defined, the available information was consulted (Table 2). Data were collected, managed and analyzed from a variety of primary and secondary sources. Data from the Conagua (2015b); monitoring network, population and housing censuses (INEGI, 2000; INEGI, 2010); national surveys (INEGI, 2014; INEGI, 2015; INEGI, 2016; INEGI, 2017), government reports (SACMEX, 2012; Conagua, 2003; Conagua, 2004; Conagua, 2006; Conagua, 2007a; Conagua, 2007b; Conagua, 2008; Conagua, 2009; Conagua, 2010; Conagua, 2011; Conagua, 2012; Conagua, 2013; Conagua, 2014; Conagua, 2015a; Conagua, 2016; Conagua, 2017), and other publications (Jiménez, Gutiérrez, Marañon, & González, 2011; SACMEX, 2018) were used. Quantitative and qualitative data and methods of analysis were employed. For example, quantitative data included information about river flow, water quality, demographic characteristics, were analyzed using geographic information systems. The qualitative part concerned documentary research and consultation of archives and public policy documents (Tiburcio, 2013).

For the 12 proposed indicators, the minimum information was available, verifying their measurability in the future. The results for the case of CDMX illustrate the potential of the developed indicator framework developed to evaluate the IUWM process.

On the other hand, the spiderweb graph was used as a way of visualizing the application of the indicator framework (Figure 4). It allows for prospective evaluations, assessment of changes and trends towards sustainability of public policies, and comparison of actual values between the ideal, hypothetic and current situation.

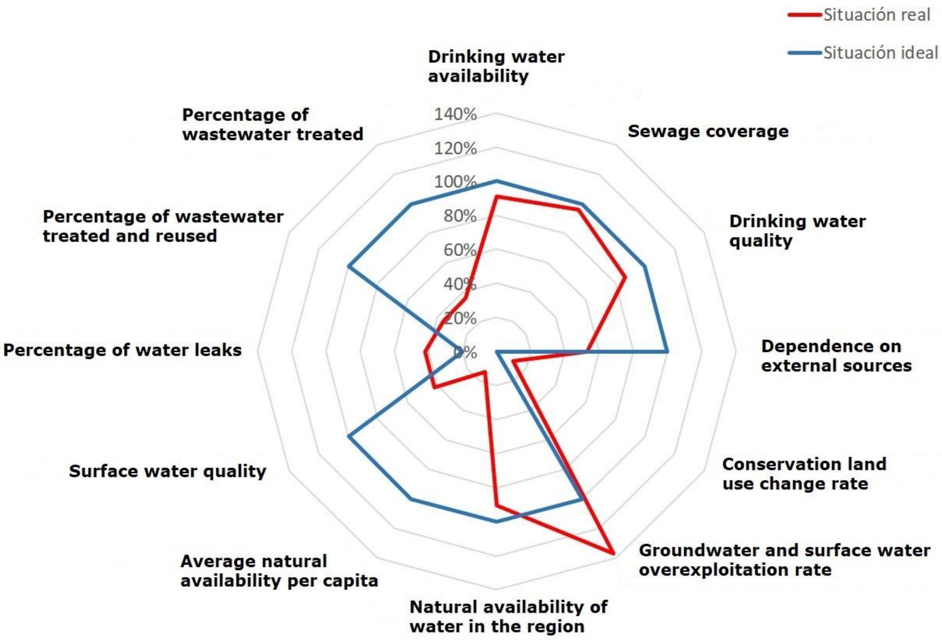

Figure 4. Representation of urban water management indicators in the CDMX, 2005-2018 (on a scale of 0 to 100%).

The results of the indicators for the existing scenario (years 2005-2018) are detailed below.

The group of performance indicators assess the dimensions of access to drinking water and sanitation, with parameters as: the existence of infrastructure for physical water access, the frequency of service, and the quality of water for human consumption. For this group, it was observed high scores with values of 96, 91 and 87% for water availability, sewerage coverage, and drinking water quality, respectively.

On the opposite, for the pressure indicators group the results are not favorable: 50% dependence on external water sources, 130% overexploitation of local sources and 657 ha per year of land use change towards urbanization in the CDMX Conservation Land; which shows that urban water management in the CDMX is in critical condition.

In state indicators, the main attributes were water quality and quantity. Water quantity obtained values of 3,401 Mm^3 of annual natural availability in the region and 141 m^3 per inhabitant. Water quality in surface sources was also poor. The Chemical Oxygen Demand, Biochemical Oxygen Demand and Total Suspended Solids quality indicators obtained values of 198 mg/l, 43mg/l and 46 mg/l, respectively; the values determined as contaminated for Chemical Oxygen Demand and Biochemical Oxygen Demand and acceptable for Total Suspended Solids, according to Conagua criteria (Conagua, 2015b).

The group of Response indicators obtained values of 36.6% both for treatment and for stopping the reuse of wastewater; this indicates that the CDMX has taken actions for the treatment and reuse of wastewater, but it is still partial. For the indicator of water leaks in the service distribution network, a value of 42% was obtained.

The results of these indicators were organized in a format that allows easy communication and unbiased interpretation for different potential users of the information (Table 3). These results, although partial and limited by the deficiency in the quantity and quality of data, represent the baseline from which future comparisons can be made. Therefore, it can become a reference that points out guidelines for action by the actors involved, whether government, academia, industry or civil society.

Table 3. Summary of trends in the proposed IUWM indicators for the CDMX, 2005-2018.

Indicator	Measurement Unit	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Trend
Drinking water availability	Score						91				91			91		Stable
Sewer coverage	Score						97					96				Stable
Drinking water quality	%							88	86	85	85	85	85	89	87	Stable
Dependence on external sources	%		51	50	50	48	48	49		53						Increasing
Conservation land use change rate	ha/year				657											Unbiased
Groundwater and surface	%	119	119	154	155	156	132	133	134	136	136	137				Increasing

water overexploitation rate																
Natural availability of water in the region	Mm^3	3,934	3,934	3,009	3,008	2,885	3,514	3,513	3,515	3,468	3,458	3,442	3,436	3,401		Declining
Average natural availability per capita (annual average)	m^3	186	192	144	143	135	165	164	160	152	150	148	145	142		Declining
Surface water quality (Chemical Oxygen Demand)	mg/l	149	197	244	233	324	180	280	144	173	226	179	195	198		Stable
Surface water quality (Biochemical Oxygen Demand)	mg/l	42	57	65	114	161	98	139	35	45	32	31	56	43		stable
Surface water quality (Total Suspended Solids)	mg/l	60	78	42	54	88	61	103	55	58	44	38	53	46		Stable
Percentage of water leaks	%			36	36	38	39	39	40	42	42	42	42	42		Increasing

Percentage of wastewater treated and reused annually in the entity	%				13		14	15	15			15	41	37		Increasing
Percentage of wastewater treated annually in the entity	%				13		14	15	15			15	41	37		Increasing

Discussion

In general terms, the values of the indicators reveal that CDMX water management is stagnating in the conventional, sanitation-oriented paradigm (Pinkham, 1999). The group of performance indicators is the only one that shows positive values due to the fact that water policy focuses its efforts on a grey infrastructure (Brown *et al.*, 2009).

The indicator of drinking water availability and water quality presents high values, comparable to those of large cities worldwide (SACMEX, 2018). However, it should be noted that there are disparities in the availability of drinking water by municipality; for example, the Milpa Alta municipality is significantly lagging behind the rest of the city (Jiménez *et al*., 2011), where it is observed that having infrastructure does not mean having access to water in sufficient quality and quantity.

The values of the resource pressure indicators confirm that the model of water management in the CDMX is based on the planning, building and centralized management of water supply systems with the objective of satisfying the demand for water, without taking into account the natural limits of availability. The extraction of water from internal and external sources has been increasing, with over-exploitation values rising from 120% to 137% in a period of ten years, and a greater dependence on external supply sources reaching 53% of water. This shows the strong pressure exerted on the resource and implies greater vulnerability in the future. Martínez *et al*. (2015) warn that external sources would be more vulnerable in the context of climate change.

In a similar way, it is observed that the rate of urbanization reaches 1% per year in the Conservation Land, which is related from the conventional paradigm with an increase in water demand that will become more critical in the future (Perló & González 2009). It should be noted that this can be considered low, but that it has accumulative effects (INE, 2006). On the other hand, it is necessary to take into account the land use changes also from a regional perspective (INE, 2006; Cervantes, 2013), that are occurring in the municipalities of the periphery of the CDMX (Delgado, Galindo, & Ricárdez, 2008); therefore, it is important to incorporate regional scale in urban water management of the CDMX.

State indicators have a tendency to decrease the amount of water available to worrying levels. The average annual water availability per capita has reached 141 m^3 per inhabitant, according to the water stress index (Falkenmark, 1989); this indicates that the CDMX is in a situation of absolute stress. Such low levels are precisely related to the urban growth of the city and the management oriented to the demand, and not to the natural availability (Escolero, Kralisch, Martínez, & Perevochtchikova, 2016).

In terms of water quality in surface resources, the values obtained are classified from highly polluted to polluted, according to Conagua (2008). This situation has been promoted by tubing rivers to provide drainage (Legorreta, 2006). The statistics published by the government (Conagua, 2009; Conagua, 2007b) even make a differentiation between the rivers that are used as recipients of wastewater, considering them as drainage infrastructure; and those, which are still part of the ecosystem.

For the response indicators, trends are observed related to the percentage of leaks reported by SACMEX (2018) with an increase from 36 to 42% in ten years. This is 20% more than recommended or expected in response indicators. On the other hand, with a gradual cross-cutting linkage through the creation of infrastructure that could minimize environmental impacts through the recovery and reuse of wastewater, with the construction in 2015 of the wastewater treatment plant in Atotonilco, whose effects are still unknown.

Limitations of the indicator framework

It is important to mention the limitations that were found in the development of this indicators framework. The first arises from the complexity and subjectivity involved in the formulation of an indicator framework (Ioris, Hunter, & Walker, 2008; Jensen & Wu, 2018)**,** particularly when an integrative approach is sought. Another limitation is related to an excessive simplification of reality (Bertrand-Krajewsky, Barraud, & Chocat, 2000); however, it must be understood that a relatively small number of indicators make the evaluation of water management a more manageable issue.

The most critical and challenging problem in this and other works was and is data acquisition (Ioris *et al*., 2008; Shah, 2004; Koop & van Leeuwen, 2015). The availability of reliable, current and potentially future replicable data (Perevochtchikova, 2013) represented a major limitation. Despite the fact that during the course of this research a greater availability of official data through digital platforms was observed in recent years, they are still often deficient or with restricted access. The lack of adequate data affects their credibility through: reliability, which depends on how the information is collected (Dunn & Bakker, 2011); and accuracy, which measures the approximation between the result of the measurement and the value (conventionally) of the variable measured, giving the error associated with the evaluation (Martínez *et al*., 2007). Perevochtchikova (2013) identified in the CDMX environmental monitoring system a lack of updating of data used in official statistics, a low number of monitoring points, lack of continuity in time series, as well as incomplete records in published statistics. This can make the situation of access to information necessary for the construction of indicators more complex.

In this sense, the accuracy and reliability of the values of the proposed framework of indicators could not be assessed, since they were obtained from government databases and reports, which are published without providing information on how these data were calculated. On the other hand, the lack of data and the inconsistency in several parameters make it difficult to project into the future. However, it is thought that the framework developed can be useful to water management decision-makers at the CDMX as first integrative set for evaluate the process and with visual potential of results representation.

Finally, in recent years, urban water management indicators have emerged with a more integrative view, either from a water security perspective (Jensen & Wu, 2018); for resource planning (Satya, Prabhat, Anurag, & Ramesh, 2019); or for assessing the resilience of water systems (van Leeuwen, Frijns, van Wezel, & van de Ven, 2012). Some issues that emerge in the publications are related to governance, water security, and the resilience of water systems in a context of climate change, although no indicator is proposed to measure this effect. The present research does not propose an indicator related to climate change, but the natural water availability indicators can be used as a proxy measure. Some other research mentions that the volume of wastewater treated is a measure of reduction of greenhouse gas emissions (Campos *et al*., 2016). But, in general, it is confirmed that deepening the generation of integrated urban water management IUWM indicators in the context of climate change remains a pending task.

The developed indicators represent a integrate proposal from the PER approach and contribute in the Latin American context with the set of indicators for IUWM; that can be replicated in other regions and projected to different scenario with sufficient data.

Conclusions

This search presents an integrative proposal to facilitate the IUWM process assessment. The framework of developed indicators could serve as a practical tool for decision-makers in order to better understanding of the dimensions of the water management process, their current situation and, finally, to reorient the conventional paradigm towards IUWM.

In this framework applied for the CDMX, 2005-2018, twelve indicators were proposed and measured. The performance indicators were rated positively, while the pressure and state indicators obtained low values; which show that the urban water management paradigm is in a critical point; that calls for urgent public policy actions. For response indicators, a little increase in the trend was observed, although insufficient.

The indicator framework is a proposal that proved being practical, useful and replicable tool, even when the available data or knowledge about the evaluated system is limited. The objective of assessing the current situation was achieved, and it is clear that more effective actions must be adapted. Similarly, information gaps have been identified. The next step is to subject it to stakeholder scrutiny to refine and improve the indicators so that they are accepted and used by decision makers. In the future, there is also a need to make comparisons in other contexts, as well as to integrate more complex indicators such as water security, resilience of water systems in the context of climate change.

Appendix

Appendix 1

List of projects evaluated in the development of proposals for water management evaluation.

	Indicator Name	**Country**	**Conceptual Framework**	**Bibliographic references**
1	Metron Project Water use sustainability indicators	Greece	By topic	Kallis and Coccosis (2000)
2	Canadian Water Sustainability Index	Canada	Thematic index	Policy Research Initiative Canada, (2007)
3	Life Cycle Assessment	Sweden	Life cycle	Lundin and Morrison (2002)
4	International Water Association IWA	Not applicable	Performance Agencies	Alegre *et al*. (2006)
5	Australia's performance indicators	Australia	Performance Agencies	Water Services Association of Australia (WSAA), the National Water Commission and the NWI Parties
6	International Benchmarking Network Association	Not applicable	Performance Agencies	The International Benchmarking Network for Water and Sanitation Utilities (IBNET) (Danilenko *et al*., 2014)
7	Performance Indicators for Operating Agencies in Mexico	Mexico	Performance Agencies	CCA (2010)
8	Management Indicators Program for Operating Agencies	Mexico	Performance Agencies	Instituto Mexicano de Tecnología del Agua (IMTA, 2014)
9	Development of Water Management Indicators	Brazil/ Scotland	By topic	Ioris *et al*. (2008)
10	Hamilton's VISION 2020 Sustainability Indicators	Canadá	By topic	The City of Hamilton Planning & Development Department
11	The Green Plan	Ontario Canada	It does not specify	International Development Research Centre (IDRC)
12	Environmental Justice 2020 Action Agenda	United States of America	By topic	Environmental Protection Agency USA (2016)

13	Jacksonville Quality of Life Progress Report: A Guide for Building a Better Community	United States of America	Pressure Status Response, Capital-Based Approach	Jacksonville Community Council, Inc. (IISD, 2010)
14	Lake Superior Basin Environmental and Socioeconomic Sustainability Indicators Project	United States of America	By topic	GEM Center for Science and Environmental Outreach (IISD, 2010)
15	Community indicators	United States of America	By topic	IISD, 2010
16	Environmental Indicators for Metropolitan Melbourne	Australia	Pressure Status Response, Capital-Based Approach	Steering Committee Members, Wong, Vera
17	Cape Town State of Environment / Sustainability Indicators	South Africa	Driving Forces, Impact Status Response	The City of Cape Town (IISD, 2010)
18	Durban Metro State of the Environment and Development	South Africa	Pressure State Response	Durban Metropolitan Area, and the Department of Environmental Affairs and Tourism (IISD, 2010)
19	Greater Johannesburg State of the Environment Internet Reporting (GJSOE)	South Africa	Pressure State Response	Johannesburg Metropolitan Area, and the Department of Environmental Affairs and Tourism (IISD, 2010)
20	State of the Environment in Tbilisi 2000 ; Core Set of Indicators	Russia	It does not specify	The City of Tbilisi (IISD, 2010)
21	Environmental Indicators of São Paulo City - GEO Cidades de São Paulo	Brazil	PSIR - Pressure Status Impact Response	Ciudad de Sao Paolo, Brazil
22	System of Indicators for the Management of Drinking Water Networks. Aqua-Control Project	Spain	Performance Indicators	Martínez *et al.* (2007)

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Appendix 2

Questionnaire for experts "Environmental indicators for water management":

Questionnaire sent:

Name and surname of the evaluator: ____

Institution you belong to: ______________________

E-mail:_____________________

Area of expertise: ____

Dear participant,

The purpose of this work is to establish a framework of environmental indicators for water management in Mexico City. The aim is to establish parameters that make it possible to know the status of water management in cities, and which include both aspects of efficiency in meeting the population's water needs and elements that have an impact on the quality and quantity of water available to society and ecosystems. This research is expected to be concluded with the contribution of a set of efficiency and effectiveness indicators; and of pressure, water resources *status* and *response* indicators (within the scheme proposed by the OECD, 1998) that will serve as a useful practical tool for the approach of appropriate measures in decision-making.

His assessment as an expert on the subject of water is very important to determine the relevance, measurability and possible limitations of the proposed indicators. We therefore ask for your opinion on the following parameters, as well as your valuable suggestions.

Please rate the proposed indicators on a scale of 1 to 5 (with "1" being the lowest value and "5" the highest value) according to the following:

1. Relevance of the indicator

2. Clarity of the indicator

Indicate, according to your opinion, the possible limitations of the indicator (e.g. measurability, frequency of measurement, and whether they respond to changes in environmental policies).

Thank you for your cooperation!

Operational performance indicators

The purpose of these indicators is to measure the efficiency and effectiveness of the authorities in meeting the population's water needs.

No.	**Indicators**	**Measurement Unit**	**Source**	**Valuation**		**Indicator Limitations**
				Relevance	**Clarity**	
1	Drinking water availability indicator (How access to service and frequency of drinking water service)	Maximum score = 100	INEGI SACMEX			
2	Water supply per inhabitant (Annual average in Mexico City)	l/inhabitant/day	INEGI SACMEX			
3	Sewage Coverage Indicator	Maximum score = 100	INEGI SACMEX			
4	Quality of drinking water for human consumption (Percentage of samples taken that meet health standards)	%	SACMEX			
5	Percentage of water leaks of the total volume of water produced	%	SACMEX			

Observations

The indicator of drinking water availability responds to criticisms of differences in the frequency of drinking water coverage and the frequency of supply. It is based on the variations in access to water in the INEGI population censuses (within the dwelling, within the land of the dwelling, public tap or carried water and the frequency of supply (by hours per month) and the maximum possible score is 100 if the entire population has drinking water within their house without interruption. The following formula is used for its calculation: $\sum_{n=1}^{4} C_{dn} P_{dn} + \sum_{m=0}^{720} C_f P_{fm} * m = Water\ availability\ indicator$ Donde C_{dn}= Coefficient of access to drinking water (varies from 0.5 to 0 depending on the form of access) P_{dn}= Percentage of households with x form of access to drinking water. C_f= Service frequency coefficient (varies from 0.5 to 0, depending on operating hours) P_{fm}= Percentage of homes with m hours of service and m= service hours per month.

INEGI: National Institute of Statistics and Geography.

SACM: Mexico City Water System.

The sewerage coverage indicator. It is a weighting of the population with the different types of forms of wastewater disposal (public network, septic tank, pipe that goes to a river, ravine, lake or to the sea or there is no sewerage at all) Its calculation formula is $\sum_{n=1}^{4} C_{an} P_{an} = Sewerage\ Coverage\ Indicator$ Where C_{dn}= Sewage Coverage Coefficient (Varies from 1 to 0 depending on the form of wastewater) P_{an}= Percentage of the population with x form of wastewater.

Pressure Indicators

The purpose of these indicators is to measure the pressure that human activities exert on the water resource.

Number	**Indicators**	**Measurement Unit**	**Source**	**Valuation**		**Possible Limitations of the Indicator**
				Relevance	**Clarity**	
1	Demand for Drinking Water (Volume of Water Concession)	m^3	Conagua			
2	Volume of water extracted	m^3	SACMEX Conagua			
3	Volume of wastewater discharge produced (by type of discharge: municipal, industrial, etc.)	m^3	SACMEX			

4	Dependence on external sources (percentage of water imported from other basins or aquifers in relation to total volume supplied)	%	SACMEX Conagua			
5	Hectares with changes in land use (e.g. agricultural and/or urban)	ha/year	SMA-GDF			

Conagua: National Water Commission

SACM: Mexico City Water System

Status indicators

The purpose of these indicators is to measure the current situation; in order to establish trends in water resource change.

Number	Indicators	Measurement Unit	Source	Valuation		Possible Limitations of the Indicator
				Relevance	Clarity	
1	Average natural water availability (annual average)	m^3	Conagua SACMEX			
2	Average natural availability per capita (annual average)	m^3/inhabitant	Conagua, SACMEX, INEGI			
3	Average aquifer recharge (annual average)	m^3	Conagua			
4	Volume of water stored in surface water bodies (annual average)	m^3	SACMEX			
5	Water quality (at monitoring stations): Chemical Oxygen Demand, Biochemical Oxygen	mg/l	Conagua/ SACMEX			

	Demand and Total Suspended Solids					

Response Indicators

The purpose of these indicators is to measure the actions carried out, with the aim of mitigating the unfavourable effects of human activity on water.

Number	**Indicators**	**Measurement Unit**	**Source**	**Valuation**		**Possible Limitations of the Indicator**
				Relevance	**Claridad**	
1	Percentage of leaks repaired out of total leaks reported in Mexico City.	%	Conagua SACMEX			
2.	Percentage of wastewater treated annually in Mexico City.	%	Conagua			
3.	Percentage of wastewater reused annually in Mexico City.	%	SACMEX			
4.	Certified constructions under the scheme of sustainable buildings in the area of water in Mexico City.	Number	SMA			
5	Number of environmental facilities per million inhabitants.	Number of facilities per million inhabitants	SMA SEP Conagua			

This indicator was developed by de Esteban-Curiel (2001), as part of a table of indicators for the evaluation of environmental education in Spain. This indicator describes the investment made in aspects of non-formal environmental education. Environmental facilities are considered to be those extra-curricular facilities with sufficient infrastructure and resources to carry out activities that serve the aims and purposes of environmental education, which facilitate the dissemination of environmental concepts, which encourage respect and care for the environment.

SMA: Ministry of the Environment of Mexico City

SEP: Ministry of Public Education

Do you know of any other water management indicator(s) that could be considered for Mexico City? What are they?
Of the proposed sources of information, do you consider them appropriate and reliable?
Do you know of other sources of information for the indicators? What would they be?
Observations and free comments you wish to express

Thank you very much for your contributions

We will soon send you the results of the evaluation

Appendix 3

IUWM Method Sheet Development Format, CDMX, 2005-2018:

Indicator name	
Justification:	
Name:	
Brief definition:	
Measurement unit:	

Objectives and goals:	
Definitions and concepts:	
Measurement method:	
Periodicity:	
Scale:	
Observations:	
Data sources:	
Possible limitations of the Indicator:	

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