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Research

Application of a Multi-Method Approach to the Study of Entropy-Recycling Cycles in Sustainable Hydrological Systems

Aplicación del enfoque multi-método al estudio de ciclos entropía-reciclaje en sistemas de agua sostenibles

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Abstract

Context: Anthropogenic pressures have intensified entropy in urban hydrological systems, affecting water availability, quality, and long-term sustainability. However, entropy remains underutilized as an operational variable in water management studies.
Methodology: This study applies a multi-method approach integrating documentary analysis, fieldwork (n = 179), and geospatial modeling. Quantitative and qualitative indicators, including extraction/recharge ratios, contamination levels, and social perception, were systematically linked to the Entropy-Homeostasis-Negentropy (EHN) conceptual model.
Results: The findings reveal that the principal water sources of the Guadalajara Metropolitan Area (GMA) span entropy states from subcritical to hypercritical. Groundwater systems exhibit structural deficits, while social data indicate low adoption of water recycling practices due to infrastructural and institutional barriers.
Conclusions: This study operationalizes entropy as a measurable variable and demonstrates its direct relationship with water sustainability and security. The Entropy-Hydrological-Network (EHN) model constitutes a novel analytical framework for diagnosing system states and guiding policy-oriented interventions under circular economy principles.

Keywords: entropy, water sustainability, hydrological systems, circular economy

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Resumen

Contexto: Las presiones antropogénicas han intensificado la entropía en los sistemas hidrológicos urbanos, afectando la disponibilidad, calidad y sostenibilidad del agua a largo plazo. Sin embargo, la entropía sigue estando subutilizada como variable operativa en los estudios de gestión del agua.

Metodología: Este estudio aplica un enfoque multimétodo que integra análisis documental, trabajo de campo (n = 179) y modelado geoespacial. Los indicadores cuantitativos y cualitativos, incluyendo las relaciones extracción/recarga, los niveles de contaminación y la percepción social, se vincularon sistemáticamente con el modelo conceptual Entropía-Homeostasis-Negentropía (EHN).

Resultados: Los hallazgos revelan que las principales fuentes de agua en el Área Metropolitana de Guadalajara (AMG) abarcan estados de entropía desde subcríticos hasta hipercríticos. Los sistemas de aguas subterráneas exhiben déficits estructurales, mientras que los datos sociales indican una baja adopción de prácticas de reciclaje de agua, debido a barreras infraestructurales e institucionales.

Conclusiones: Este estudio operacionaliza la entropía como una variable medible y demuestra su relación directa con la sostenibilidad y seguridad hídricas. El modelo EHN proporciona un marco analítico novedoso para diagnosticar los estados del sistema y guiar intervenciones orientadas a políticas públicas bajo los principios de la economía circular.

***Palabras clave*:** economía circular, entropía, sostenibilidad hídrica, sistemas hidrológicos

Contents

1. Introduction 3

1.1. Feasibility and relevance of the entropy concept 4
1.2. Sustainability of Water Resources 5
1.3. Water Recycling as a Strategy for a Circular Economy 7
1.4. Cause-effect models in urban water systems 8
1.5. Water sources in the Guadalajara Metropolitan Area, Mexico 9

2. Methodology 10

2.1. Document Analysis and Revision 11
2.2. Fieldwork 11
2.3. Geospatial Schematization 12
2.4. Application of the EHN conceptual model: 12

3. Results 14

4. Discussion 17

5. Conclusions 19

6. Acknowledgements 20

7. Author contributions 20

8. Funding 20

9. Data availability 20

10. Conflict of interest 20

11. Use of artificial intelligence 21

References 21

Authors and biographies 24

1. Introduction

Water resources constitute a public good and are fundamental to the fulfillment of human rights; therefore, they are of great importance for the sustainable development of communities. "Water is a unique element, fundamental and present in all living species that inhabit the planet, which makes it the support for the existence of flora, fauna and ecosystems" [1]. However, rapid urbanization in contemporary cities has disrupted the natural water cycle by increasing runoff and reducing infiltration. This imbalance has been described as a form of systemic entropy.

This organizational disorder represents a critical imbalance between natural cycles and human demands, manifesting through intra- and inter-systemic entropic forces. Specifically, it has been estimated that more than 20% of aquifers are overexploited, which entails serious consequences such as ground subsidence and saltwater intrusion [2]. In the drainage basins, the process of groundwater recharge, resulting from the infiltration, precipitation, surface runoff, and river flows, is of great hydrological importance [3].

According to the Food and Agriculture Organization of the United Nations (FAO) [4], forested areas have a greater water-harvesting capacity due to evapotranspiration processes. These processes maintain a higher atmospheric humidity index in forested soils, whose thin, porous layers facilitate infiltration and water retention.

This mechanism enhances the hydrological connectivity, seamlessly linking water flows, ecosystems, and basins. However, recharge areas are affected by precipitation variability and land-use changes. In other words, when tree canopy cover increases, water erosion decreases and infiltration increases; conversely, when vegetation cover decreases, surface sealing is favored and infiltration is reduced, with a consequent decrease in groundwater recharge.

Based on the above, land-use changes in basin areas directly affect water infiltration and runoff capacity, thereby altering the balance of the hydrological cycle. Infiltration capacity is largely controlled by the resistance of the surface soil layer to rainwater infiltration.

However, direct measurement of infiltration is challenging because of the multiple factors involved [5]. These factors, which include surface sealing, waterproofing, particle migration or fissures, soil preparation, organic matter and crop rotation, soil and water salts, sediments in irrigation water, and soil profile, alter infiltration rates [6]. Not all these factors have an anthropogenic cause; however, those of this type are the ones that cause the greatest entropy in the system.

1.1. Feasibility and relevance of the entropy concept

Entropy is a concept originating in thermodynamics and was formalized by Rudolf Clausius in 1865. Later, the physicist Ludwig Boltzmann formulated its statistical interpretation through his famous equation

$$S = k_B \ln W \tag{1}$$

where S represents entropy, k_B is the Boltzmann constant that relates statistical mechanics and classical thermodynamics, and W is the number of possible microstates. Since then, the term has been applied in natural sciences, such as chemistry, physics, or biology [7]-[13], as well as in those disciplines concerned with human and societal phenomena, such as architecture, sociology, economics, psychology, among others [14]-[20].

From a thermodynamic conceptualization, a system is subject to the interaction of internal and external forces and imports matter and energy from its environment in order to function. Likewise, this system expels a certain amount of unused matter and energy within its intra-systemic processes, which generates entropy. In this sense, adjacent systems and raw material suppliers (natural systems) experience a dual affectation; on the one hand, they lose significant amounts of matter and energy due to overextraction; on the other, they receive substantial residual loads from anthropogenic processes that ultimately damage, transform, and contaminate other subsystems and their functioning.

As reported in [21], entropy originates from the overconsumption of natural inputs, "therefore the increase in the entropy of a system automatically increases the disorder of that system" [22]. In this analysis, water entropy manifests as a loss of order in water availability, quality, and accessibility, which directly affects water security indicators; that is, the concept of entropy explicitly integrates degradation, decreased availability, and water risk.

The aforementioned argument is supported by the direct and indissoluble link between increased entropy and the degradation of water security in urban socio-ecological systems. Whereas water security implies safeguarding sustainable access to water of acceptable quality for well-being and development, the entropic forces derived from uncontrolled urbanization act in the opposite direction. That is, massive over-extraction of groundwater volumes and the continuous contamination in surface flows (S) imply anthropogenic pressures that exponentially increase (log) the number of disordered microstates of the water system (W).

This thermodynamic and functional disorder disrupts natural synergies, transforming stable sources into critical and highly vulnerable zones. Therefore, the loss of water security can be formally understood as a macroscopic manifestation of the accumulated entropic disorder and degradation, in which the ecosystem's inability to self-regulate directly compromises the future availability of the resource."

1.2. Sustainability of Water Resources

The ecosystem approach is a proactive strategy for integrated management of land, water, and living resources that promotes conservation and sustainable equitable use. Its principles seek that people change people's perceptions and culture regarding natural resource management, in order to ensure water provision and maintain quality of life on earth.

As institutional initiatives demonstrate [23], the basic principles of the ecosystem approach to water emphasizes adaptive management, account for all usable goods and services, and optimize the mix of their benefits; they also incorporate other forms of knowledge, including indigenous and local. This is a people-centered approach grounded in society and culture; it is oriented toward the preservation of the environment and society, operates top-down and bottom-up, takes a long-term view and considers goods and services as the product of a healthy ecosystem and not as an end in itself.

Furthermore, guaranteeing water availability in the short and long term requires an integrated approach that recognizes the complexity of the problem and considers its social, economic, environmental, and cultural dimensions; within this approach, the participation of society in the application of ecosystemic principles in water is paramount. Accordingly, it is necessary to delimit the scope of conceptual categories such as sustainability and water sustainability.

Based on the foregoing, transitioning from water security to multidimensional water sustainability requires a negentropic perspective. That is, sustainability cannot be limited to static volumetric balances but instead requires actively mitigating the thermodynamic disorder of the urban water cycle. In particular, when a metropolis manages resources under a linear model, importing significant amounts of energy (high-quality water) and exporting highly degraded effluents (high entropy), it ultimately disrupts environmental homeostasis. In this sense, long-term resilience necessitates structural and governance interventions that function as entropy sinks, restoring order to the water system through recirculation and ecological preservation, as shown in Table I.

Table I. Comparison between water security and water sustainability

Water security	Water sustainability
Prioritizes the long-term conservation of water resources	Seeks a balance between water accessibility and socio-environmental welfare
Aims at the rational use and protection of available water sources	Seeks equity in access to water, thus considering the ecological impact of water management
Seeks to maintain availability for productive sectors, focusing on hydrological planning, ecological flows, and extraction control	Analyzes long-term economic impacts, integrating environmental, social, and participatory-governance costs
Prioritizes resource supply	Prioritizes integrated resource management
Is technical-environmental in nature	It is multidimensional in nature
May exclude social factors from planning when focused solely on ecological aspects	Integrates environment, economy, and social considerations in water planning

Source: authors' own elaboration, based on information from [24]-[30].

Water sustainability provides a broader referential framework, without compromising environmental, economic, and social interrelations. In other words, whereas water security would be confined to the purely environmental aspect and the recovery of supply sources (surface and underground), water sustainability would seek this recovery without affecting economic processes or social benefits.

The water crisis is experienced in different urban and non-urban territories; however, urban areas have aggravated the problem in terms of collection, storage, treatment, transport, disposal, and reuse. Moreover, studies by [31]-[37], among other organizations, indicate that many countries have a water deficit compared to those with a surplus or a balance between water inputs and outputs as shown in Table II.

Table II. Status of countries with water deficit

Nº	Country	Water Status	Deficit/Surplus	Causes
1	India	Extreme stress	Deficit	High agricultural and urban demand
2	Mexico	High stress	Deficit	Aquifer overexploitation; prolonged droughts
3	Chile	High stress	Deficit	Megadrought lasting more than 10 years
4	Egypt	Extreme stress	Deficit	High dependence on the Nile
5	Saudi Arabia	Extreme stress	Deficit	Use of desalination; aquifers nearly depleted
6	South Africa	High stress	Deficit	Poor infrastructure, frequent droughts
7	Jordan	Extreme stress	Deficit	One of the driest countries in the world
8	Iran	Extreme stress	Deficit	Intensive agriculture; depleted aquifers
9	Spain	Medium-high stress	Deficit	Increasing droughts; agricultural overuse
10	Australia	Variable status	Regional surplus	Surplus in the north; recurrent deficit in the south
11	China	Mixed status	Deficit	Dry north, wet south; intensive water use
12	United States	Mixed status	Regional deficit	West with high water stress; east with surplus
13	Brazil	Water surplus	Surplus	High availability but uneven distribution
14	Canada	Water surplus	Surplus	High freshwater availability
15	Colombia	Water surplus	Surplus	Megadiverse country with abundant water resources
16	Peru	Mixed status	Regional deficit	Dry coast vs. Amazon rainforest with abundance
17	Bolivia	Variable status	Regional surplus	Andes with stress, Amazon rainforest with surplus

18	Argentina	Mixed status	Regional deficit	Dry north, wetter south
19	Venezuela	Water surplus	Surplus	High availability, although with infrastructure problems
20	Russia	Water surplus	Surplus	Large number of rivers and lakes
21	Germany	Adequate status	Balanced	Good water management, though under pressure due to recent droughts
22	France	Adequate status	Balanced	Good access, though affected by heat waves
23	United Kingdom	Adequate status	Balanced	Regular rainfall, but with urban pressure
24	Italy	Medium stress	Deficit	South with shortage; more stable north
25	Indonesia	Adequate status	Surplus	Abundant rainfall but quality and access problems
26	Japan	Adequate status	Balanced	Good management and availability
27	Turkey	High stress	Deficit	Intensive agricultural use
28	United Arab Emirates	Extreme stress	Deficit	High per capita consumption; use of desalination
29	Ethiopia	Medium stress	Deficit	Climate variability and lack of infrastructure
30	Norway	Water surplus	Surplus	High availability due to abundant rainfall

Source: authors' own elaboration, based on data from [31]-[37].

1.3. Water Recycling as a Strategy for a Circular Economy

The circular economy is a sustainability-oriented model whose objective is to retain the value of used resources, products, and materials and keep them in use for as long as possible. One of the main objectives of the circular economy is to improve the efficiency in the use of water by 10%. In the water sector, this implies using water repeatedly as occurs in the natural cycle.

Reusing water reduces consumption by assigning it to a second use in another process, such as irrigation or cleaning [38]. Under this logic, water is kept in the system as long as possible before disposal, which minimizes the use of this resource and reduces waste. This circular economy also seeks to redefine growth by generating social, economic, business, and environmental benefits [39].

Recycling reduces primary extraction and ecosystemic pressure, as it makes use of "the solid waste that is generated to obtain from it a raw material that can be directly incorporated into a production or consumption cycle" [40]. In the water sector, recycling has been incorporated into various production processes and treatment technologies have advanced significantly and can meet environmental regulatory frameworks. Nevertheless, the practice has not been fully standardized.

Historically, "efforts to meet the growth in demand consisted mainly of increasing the supply of resources, which were abundant and relatively cheap" [41]. This approach is no longer viable because

those conditions no longer exist. Consequently, it is a priority to optimize and make supply more efficient, as well as to manage demand and raise awareness of it.

Linear water management leads to an inefficient use of water resources because it increases the use of matter and energy, degrades ecosystems, and heightens vulnerability and social inequality. These effects create a need for new management and technological alternatives. In the circular economy model, water is established as a solution that uses the application of socio-technical tools that address problems in an integrated manner, and it is used as an alternative to linear water management.

Hence, because water is an essential resource to ensure the well-being of ecosystems and the population, its use is the basis for economic growth. The circular economy favors the sustainable use of natural resources and has been adopted in various sectors as an alternative to the linear consumption or production model. Several companies have already implemented circular economy initiatives to make a better use of resources [42].

1.4. Cause-effect models in urban water systems

Urban- hydrological systems, both surface water (rivers, lakes, and natural and artificial ponds) and groundwater (aquifers), have experienced unprecedented anthropogenic pressure in recent years. As mentioned above, in several territorial contexts these systems show water deficit and overextraction, which has created uncertain scenarios for sustainability.

In this context, a stress-response framework for environmental statistics was presented in Canada in 1979 [43], laying the conceptual foundations of what would later become the Pressure-State-Response (PSR) model.

This cause-effect (action-reaction) model has inspired conceptual developments that describe degrees of interaction between social and environmental subsystems. According to the OECD, these indicators are classified according to the PSR model as follows: i) direct and indirect pressure indicators on the environment; ii) environmental condition indicators; and iii) societal response indicators [44].

Models derived from PSR include Driving Forces-Pressure-State-Impact-Response (DPSIR), Driving Forces-State-Response (DSR), Pressure–State/Impact–Response (PS/IR), Pressure-State-Impact/Effect-Response-Management (PSI/ERM), and Entropy-Homeostasis-Negentropy (EHN) models [20],[45],[46].

The EHN model comprises a series of phases that classify the anthropogenic impact on ecosystems. From this impact, it identifies the state of the system (homeostasis) and the possible response to minimize entropy (negentropy), as shown in Table III.

Table III. Phases of th EHN model

Term	Phases
1. Entropy	1.1. Subcritical 1.2. Critical 1.3. Supercritical
2. Homeostasis	2.1. Reversible 2.2. Quasi-reversible 2.3. Irreversible
3. Negentropy	3.1. No existence 3.2. Sporadic or specific actions with short-term effects 3.3. Strong actions with a systemic approach and long-term effects

Source: authors' own elaboration, based on [20].

The EHN subclassifications are conceptual generalizations that can be adapted to specific contexts. Each phase can be delimited qualitatively, quantitatively, or both, in relation to the structure of the rest of the cause-effect conceptual models.

1.5. Water sources in the Guadalajara Metropolitan Area, Mexico

In Mexico, water supply shortages, land subsidence, overexploitation of water sources, and infrastructure deficiencies make it necessary to integrate the principles of water sustainability [47]. In the state of Jalisco, the Santiago River is one of the bodies of water that has generated the most negative effects on the environment and society. More than 250 industries and companies discharge into this river, generating major problems of contamination of the river and health problems for the city.

Companies located near the river generate toxic waste, especially leachates formed during the fermentation and decomposition of organic matter. Rainwater filtering through the waste carries chemical compounds and biological materials, contaminating the body of water and directly and indirectly affecting people, animals, and the ecosystems around it [48].

This water crisis has left 60% of Mexico's water bodies with an alarming degree of contamination, and 157 aquifers are overexploited. According to the technical coordinator of the Universidad Nacional Autónoma de México (UNAM) water network, under the support of the Education, Science and Culture Units (UNESCO), 71% of the national territory is under high or very high water stress, meaning that these areas can no longer meet new demands [49]. Mexico City, for example, faces severe water stress driven by a population of more than 20 million inhabitants.

The center of Mexico lies at approximately 2,400 meters above sea level, so water must be pumped water from rivers to supply its population. Without careful action, water stress will increase in Mexico, and society will become more vulnerable to drought, floods, and severe storms. Ensuring water availability rests on four aspects: providing sufficient water for human consumption, supplying economic activities, ensuring water for the environment, and guaranteeing water reserves for future droughts [50].

The Guadalajara Metropolitan Area (GMA), one of the largest in Mexico, faces a particularly concerning scenario. According to [51], its population exceeds 5.2 million, which places daily pressure on surface and groundwater sources as illustrated in Fig. 1. The main objective of this research is to identify entropy levels and evaluate the feasibility of water recycling as a strategy for long-term sustainability. To this end, three scenarios were analyzed: the Tesistán-Toluquilla aquifer, Lake Chapala, and Calderón Dam were analyzed.

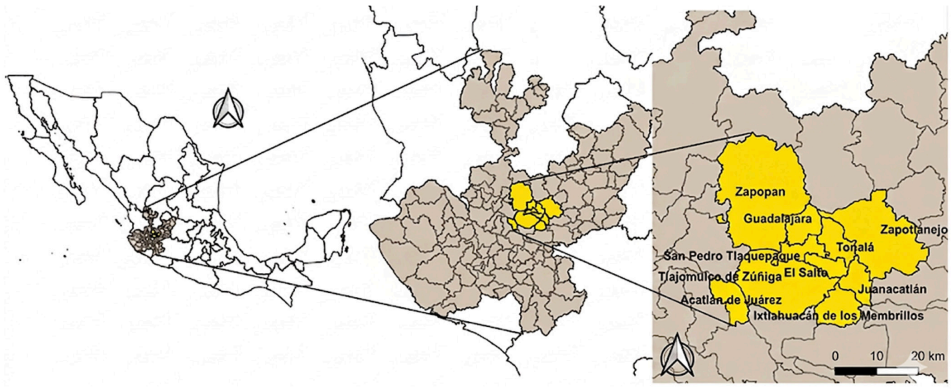


Figure 1. Guadalajara Metropolitan Area (GMA), Mexico.

2. Methodology

The research followed a multi-method, exploratory-analytical design that addressed the systemic complexity of the main water sources supplying the GMA. The design was grounded in the foundational principles of systems theory and the second law of thermodynamics.

Key concepts strategically guided the literature review and the structure of the model, as shown in Fig. 2. The design integrated qualitative, quantitative, and geospatial components to identify entropy states and to explore the feasibility of implementing negentropic strategies, such as water recycling, under increasing anthropogenic pressure.



Figure 2. Key concepts for the documentary analysis

To ensure the replicability and objectivity of the documentary analysis and fieldwork, the research was organized into four phases.

2.1. Document Analysis and Revision

A systematic search was conducted for theses, books, book chapters, journal articles, and press articles. Regulatory frameworks, government datasets, and technical reports from national and international organizations were also reviewed. For journal articles, priority was given to publications indexed in SCImago, Scopus, Web of Science, SciELO, and other repositories. National government information was obtained from the Comisión Nacional del Agua (CONAGUA), the Instituto Nacional de Estadística y Geografía (INEGI), the Instituto de Información Estadística y Geográfica de Jalisco (IIEG), the Secretaría de Medio Ambiente y Recursos Naturales (SEMARNAT), and UNAM. International sources included studies by the United Nations (UN), UNESCO, FAO, the OECD, and the World Bank, among others.

The review covered just over three decades, from 1990 to 2023. This criterion was based on the fact that during this period there were significant empirical contributions on water sustainability, system complexity, cause-effect models. The search strategy combined three sets of keywords using Boolean operators, as shown in Table IV.

Table IV. Boolean Operators

Entropy	**OR**	**Anthropogenic Pressure**	**AND**	**Surface-water sources**	**OR**	**Groundwater sources**
Water security	OR	Sustainability	AND	Recycling	OR	Reuse
Urban water thermodynamics	OR	Cause-Effect Models	AND	Mexico	OR	Guadalajara

Source: authors' own elaboration, 2025

2.2. Fieldwork

Direct inspections were carried out at water collection and distribution locations, specifically at Lake Chapala and the Calderón Dam as surface water bodies. A structured questionnaire was designed and administered to household users (n = 179). It collected data on water use, recycling practices, trust in the authorities, and water-related supply and quality issues.

a) Sampling strategy: A probabilistic cluster sampling design was implemented, accounting for socioeconomic status across the central municipalities of the GMA (Guadalajara, Zapopan, San Pedro Tlaquepaque, and Tonalá). The sample size was set at n = 179, assuming a 95% confidence level and a

5% margin of error. Housing units were selected by systematic random-route sampling, starting from predetermined geographic nodes within the municipal seats.

b) Evaluation process and validation criteria: The collection instrument (questionnaire) underwent content validation through expert judgment by a committee composed of three researchers in socio-ecological and hydraulic sciences. A pilot test was conducted with 10% of the sample (18 individuals) was then conducted to verify the clarity of the items. The internal consistency of the scale, measured with Cronbach's alpha coefficient, was 0.81, which demonstrates reliability and stability in the social perception measurements of entropy and recycling practices.

c) Spatial calibration procedure: Institutional cartographic layers (aquifers and sub-basins) were processed at a vector scale of 1:50,000, and socio-demographic data from the 2020 census (SINCE 2020) were integrated at the urban basic geostatistical area (AGEB) level.

d) Informed consent, anonymity, and data protection: This study complied with international ethical standards and with Mexico's General Law on the Protection of Personal Data Held by Obligated Parties, all participants were informed of the research objectives, scope, and academic purpose, and oral informed consent was obtained from each respondent. Responses were anonymized by dissociating identity data, omitting names, exact addresses, or telephone numbers. In line with the data minimization principle, only the sociodemographic and perception variables directly indispensable to feed the dimensions of the EHN model were collected and processed, discarding any sensitive or superfluous information.

2.3. Geospatial Schematization

Maps of aquifer conditions were produced in QGIS to show the correlation between environmental variables and anthropogenic entropy. To model the spatial distribution of the 179 fieldwork points, Inverse Distance Weighting (IDW) interpolation was applied in QGIS 3.x with a power parameter p = 2, and an output resolution of 30 meters per pixel, matching the local digital elevation models.

2.4. Application of the EHN conceptual model:

Urban water systems in the GMA were subclassified using the conceptualization of the EHN model. To this end, pollution levels, input/output ratios (extraction/recharge), and anthropogenic intervention were considered under the following criteria as shown in Table V.

Table V. Criteria for applying the EHN model

Key Variable	Entropy Phase	Homeostatic State and Hydrological Limits	Pollution Level and Anthropogenic Load	Social Perception Logic and Intervention (Negentropy)
Extraction / Supply	Subcritical	Extraction Volume < Recharge Volume. Positive balance or surplus.	None or low. Presence of contaminants within strict regulatory limits.	High public awareness. Coordinated governance, stable preventive actions.
Contamination / Quality	Critical	Extraction Volume = Recharge Volume. Availability compromised at the limit (0).	Moderate. Seasonal presence of leachates and partially treated discharges.	Alert perception among the population. Sporadic short-term remediation actions.
Perception / Entropy	Hypercritical	Extraction Volume > Recharge Volume. Severe and continuous hydrological deficit.	Critical and systemic. Massive dumping of heavy metals and industrial leachates.	Generalized institutional distrust. Low recycling rate due to lack of infrastructure.

Source: authors' own elaboration, 2026.

To quantify the behavior of the the EHN model, a set of indicators was defined based on the hydrological balance and anthropogenic pressure: the water balance (W_b), the entropy index (EI), the anthropogenic pressure index (API), and the recycling index (RI). Together, these metrics allow for the identification of transitions among subcritical, critical, and hypercritical phases, as shown in Table VI.

Table VI. Quantitative metrics

Systemic Indicator	Mathematical Formula	Physical and Thermodynamic Interpretation
Water Balance (W_b)	$W_b = R-E$	Evaluates the mass balance of the system. Negative values indicate direct over-extraction.
Entropy Index (EI)	$EI = E/R$	Measures hydrological entropy. If EI>1, the system's disorder increases exponentially.
Anthropogenic Pressure (API)	$API = E/(R+R_e)$	Measures the total urban pressure mitigated by recycled water flows (R_e).
Recycling Index (RI)	$RI = R_e/E$	Quantifies the installed capacity for urban entropy reduction (negentropic action).

Source: authors' own elaboration, 2026.

The variables used correspond to hydrological and socio-ecological parameters that characterize the dynamics of the aquifer system. Recharge (R) is the natural replenishment of groundwater, and extraction (E) is the anthropogenic demand from urban and productive activities. Recycling water (R_e) is the volume of water reused within the system and represents the negentropic dynamics capable of partially restoring hydrological homeostasis.

3. Results

The document review, surveys, and geospatial analysis provided a preliminary assessment of the status of water sources in the study area. The data reveal critical areas of overexploitation, as well as areas of potential recharge, which gives an initial assessment of water availability. The resulting maps made it possible to identify patterns of use and social perception of water.

Applying the EHN model supports the interpretation of the institutional, territorial, and sociocultural dynamics that influence the integrated management of water supplies. This section summarizes the main hydrogeological and socio-environmental characteristics of the aquifers that supply the GMA municipalities, articulating empirical evidence and conceptual analysis to inform strategies for sustainable water resource management.

According to the Intermunicipal Drinking Water and Sewerage System (SIAPA), urban supply in 2024 came mainly from surface water sources (Lake Chapala and Calderón Dam), which contributed approximately 89% of the total. Groundwater sources (springs and aquifers) supplied the remainder, as shown in Table VII.

Table VII. Distribution of water supply sources in the GMA

Water supply source	Average flow rate (m^3/s)	Annual availability (hm^3)
Lake Chapala	6,844	215,83
Calderón Dam (Elías González Chávez)	2,350	74,11
Groundwater (wells)	0,961	30,31
Springs	0,135	4,26
Total SIAPA	10,29	324,51

Source: authors' own elaboration, based on data from [52].

However, according to [53], [54], the average annual recharge, both naturally and induced, in the Atemajac and Toluquilla aquifers is 147,3 hm^3/year and 49,1 hm^3/year, respectively. After deducting the committed natural discharge, both aquifers show a groundwater deficit, as shown in Table VIII.

Table VIII. Atemajac and Toluquilla aquifers at the GMA

Aquifer	Total annual recharge (hm^3)	Compromised natural Discharge (hm^3)	Annual extraction (hm^3)	Annual availability (hm^3)
Atemajac	147,3	25,7	134,279	-12,679
Toluquilla	49,1 (39,3 natural and 9,8 induced)	2,4	122,314	-75,614

Source: authors' own elaboration, based on data from [53]-[55].

The survey of GMA residents provided information on perceptions, practices, and limitations regarding efficient use of water and recycling. The responses identify institutional barriers, lack of incentives and technological weaknesses as factors that hinder the adoption of circular strategies in water resource management.

The results presented below summarize the main hydrogeological and socio-environmental characteristics of the aquifers that supply the municipalities that make up the Guadalajara Metropolitan Area, articulating empirical evidence and conceptual analysis to inform strategies for sustainable water resource management. The quantitative instrument administered to heads of households in the GMA (n = 179) was processed statistically to characterize the sociodemographic profile of the sample, which is summarized in Table IX.

Table IX. Interpretive restructuring of perception data

Gender Distribution	Age Segmentation	Educational Attainment
Within the sample, 58,6% corresponded to women and 41,4% to men. This sample characteristic reflects the reality of urban households, where women predominantly assume the direct management of domestic water. Consequently, they express a more sensitive and detailed perception regarding seasonal scarcity and qualitative supply deficiencies.	The age spectrum was predominantly concentrated among adults aged 35 to 54 (48,2%) and older adults over 55 (31,5%), while the youth segment aged 18 to 34 accounted for 20,3%. The adult and elderly population evidenced a long-term perception of historical water availability, explicitly contrasting the abundant water availability of previous decades with the current critical scenario of intermittent supply and service disruptions, directly correlating rapid urban expansion with the loss of homeostasis in the water system.	The educational profile reported 34,6% with basic education (primary/ lower secondary), 42,8% with upper secondary education (high school), and 22,6% with higher education or postgraduate studies. A direct statistical correlation was detected between higher educational attainment and a greater conceptual understanding of water recycling (negentropy). However, regardless of schooling, 89% of respondents stated that the primary constraint for reusing effluents is not cultural disinterest, but rather the limited availability of secondary greywater infrastructure and decentralized treatment infrastructure at the household or neighborhood level.

Source: authors' own elaboration, 2026.

Tables X, XI, and XII present the population's qualitative perceptions of the various dimensions of the urban water service.

Table X. Social perception of daily supplied water

Continuous Availability (24 hours)	Intermittent Supply (Weekly Rationing)	Critical Scarcity (Dependence on Water Tankers)
18,4% of the respondents reside in high-income residential sectors with robust storage infrastructure. In these areas, the situation falls within the subcritical phase.	54,2% of the respondents experience restricted water-distribution schedules, with households receiving water only during certain hours of day or on specific days of week. In these areas, the situation falls within the critical phase.	27,4% of the respondents reside in peripheral neighborhoods or settlements experiencing prolonged outages lasting several weeks, forcing households to purchase water from external sources. In these areas, the situation falls within the hypercritical phase.

Source: authors' own elaboration, 2026.

Table XI. Physicochemical and organoleptic quality of distributed water

Optimal Quality (Clear)	Fair Quality (Turbid)	Poor Quality (Fouled)
12,3% of the respondents perceive water suitable for routine domestic use, with no visible signs of pollution.	46,9% of the respondents perceive the water as having a whitish coloration due to excess chlorine or light sandy sedimentation that may damage internal pipes.	40,8% of the respondents recurrently perceive water as having a brownish, amber, or yellowish hues, unpleasant odors, and sediment accumulation and mineral scaling

Source: authors' own elaboration, 2026.

Table XII. Primary entropies and failures of the urban system

Lack of catchment and treatment infrastructure	Lack of citizen awareness regarding waste	Government inaction and institutional distrust
38,5% of the respondents consider that the root of the problem lies in the massive waste of stormwater and undertreated wastewater, without corresponding treatment or opportunities for reuse.	32,1% of the respondents recognize that the problem stems from linear domestic consumption habits and severe waste in agricultural irrigation.	29,4% of the respondents perceive administrative inefficiency within the operating agency, together with a lack of economic incentives or subsidies for the adoption of water-related ecotechnologies.

Source: authors' own elaboration, 2026.

4. Discussion

Data from the document and bibliometric analyses, field observations, and household surveys were triangulated. Their integration produced a water sustainability matrix, in which variables such as the characterization of water quality, energy consumption per unit of recycled water, and level of resource recovery are weighted.

The matrix was used to classify subsystems according to their ecological recovery capacity. Additionally, the cartographic data generated in the geospatial component of the study revealed the correlation between the distribution of recycling infrastructure and anthropogenic pressure indicators on local bodies of water. All datasets were subsequently integrated into the EHN model, which enabled a systemic diagnosis of the study area and the design of interventions that are preventive and regenerative rather than merely corrective, as shown in Table XIII.

Table XIII. Hydrological systems scenario in the GMA from the ehn model

Water source	Inflow vs. outflow dynamics	Availability state / deficit	Entropy phase	Homeostatic state	Priority negentropic strategies (intervention)
Lake Chapala	Outflows < Inflows	Temporary relative surplus	Subcritical	Reversible	a) Interstate coordination of flow rates b) Domestic water-saving programs
Calderón Dam	Outflows < Inflows	Transitory surplus	Subcritical	Reversible	a) Scheduled temporary rationing b) Physical reduction of network leaks
Deep wells (general)	Outflows > Inflows	Continuous systemic deficit	Hypercritical	Irreversible	a) Strict regulation and closure of clandestine wells b) Intensive awareness campaigns
Urban springs	Outflows approx. Inflows	Equilibrium under pressure	Critical	Quasi-reversible	a) Delimitation of ecological protection polygons b) Strict control of extractions
Atemajac aquifer	Outflows (134,27 hm^3) > Inflows (47,3 hm^3)	Negative availability (12,68 hm^3); -8,6% deficit	Hypercritical	Quasi-reversible	a) Strict ban on new real estate concessions. b) Repair of distribution networks
Toluquilla aquifer	Outflows (122,31 hm^3) > Inflows (49,1 hm^3)	Accumulated critical deficit (75,61 hm^3); -154% deficit	Hypercritical	Irreversible	a) Massive and systematic artificial recharge b) Real-time industrial telemetric monitoring

Source: authors' own elaboration, 2026

These results indicate that hydrological conditions in the GMA demand urgent action that combines immediate interventions with long-term negentropic strategies. This inference follows from the analysis of the variables and the interpretation of the model phases. In this context, recycling emerges as an alternative that would significantly reduce the volumes required for consumption.

In this regard, 40,8% of the 179 respondents identify water quality as a priority. The main barriers to recycling include a lack of infrastructure, insufficient incentives, and limited institutional trust. Hence, the perception of inefficiency predominates in the responses. Overall, the findings detailed the scenario of four pending agendas:

(a) the entropy-homeostasis relationship in surface and groundwater water systems;

(b) the qualitative feasibility of water recycling

(c) the relation between water sustainability and entropy reduction; and

(d) the territorial and public policy implications in urban contexts of high water pressure

According to the EHN model, 50% of the water sources analyzed in the GMA are in a hypercritical entropy state. This situation requires urgent action by government institutions and collective governance by communities to reduce the anthropogenic pressure that has driven these sources toward quasi-reversible and irreversible homeostatic states.

Implementing the model also clarified the role of water recycling processes as a negentropic action capable of reducing entropy within the system. Consequently, the reuse of adequately treated wastewater, rainwater harvesting, and the modernization of urban recycling infrastructure, are key strategies for transitioning toward circular water management systems.

From this perspective, urban planning should aim to facilitate a closed-loop water cycle in which water flows are retained within the urban system through reuse and advanced treatment. These strategies not only reduce anthropogenic pressure on aquifers but also decrease energy costs associated with water pumping and transport.

A significant implication of the model is the need to integrate green infrastructure and nature-based solutions into urban water management policies. Such measures include sustainable urban drainage systems, restoration of infiltration zones and aquifer recharge areas, designation of ecological corridors, and urban parks with hydrological functions, all of which contribute to increasing aquifer recharge capacity and reducing the entropy of the urban hydrological system.

Accordingly, the model transcends the purely technical and reaches the design of public policies oriented toward urban water resilience. In particular, it posits that urban water systems must be managed as complex socio-ecological systems, where sustainability depends on the interaction between natural processes, hydraulic infrastructure, and social consumption practices. Water policy should therefore be oriented toward strengthening water governance, promoting water recycling technologies, implementing incentives for consumption efficiency, and integrating water sustainability criteria into urban planning. In this sense, the model lays the groundwork for consolidating the resilience of water systems.

5. Conclusions

More than seven decades after the original formulation of General Systems Theory, this study consolidates the methodological relevance of its fundamental principles for addressing the global water crisis from a thermodynamic and socio-ecological perspective.

Efforts to understand complex phenomena have spurred critical analysis of contemporary challenges. Global climate change, persistent drought in many regions, and increasing anthropogenic pressures on ecosystems underscore the need for new approaches to studying socio-environmental dynamics.

The findings are consistent with the proposition that water sustainability is unattainable under traditional linear economic models and that a paradigm shift toward the circular economy of water is required. The study identified entropy levels ranging from subcritical to hypercritical in the main water sources of the metropolitan area: Lake Chapala, the Calderon Dam, urban springs, and the Atemajac and Toluquilla aquifers.

Consequently, we propose that sustainability, as an epistemological category, is closely linked to the postulates of circular economy. In this framework, water recycling is a fundamental strategy for long-term sustainability, given the high dependence of economic processes on water resources. Therefore, the hypotheses proposed in this study suggest that neither water sustainability nor water security can be achieved in linear economic models, which calls for a transition toward circular-economy frameworks with a smaller entropic footprint.

The methodological triangulation based on the Entropy–Homeostasis–Negentropy (EHN) model made it possible to identify the current scenario (homeostasis) of water systems according to the degree of entropy observed. In general, higher the entropy implies greater irreversibility, whereas lower entropy implies greater reversibility and a higher likelihood of recovery. This approach facilitated the identification of phase transitions induced by anthropogenic disturbances. The homeostasis of water systems can fluctuate between irreversible and quasi-reversible states. However, the urban stretch of the Santiago River, adjacent to the GMA, has remained unresolved for decades, since the negentropic

interventions carried out have proven ineffective. This suggests that the problem is rooted structurally and requires a systemic, large-scale approach.

Although new water sources, such as the El Zapotillo Dam, have produced temporary negentropic effects, these have not been sufficient to address the underlying problem. Technical, social, and political constraints have limited the operation of this infrastructure and prevented it from supplying the originally planned volume. A supplementary dam system is being built, with the El Purgatorio Diversion Dam standing out as a partial solution. This suggests the need for a substantial shift in the prevailing water-management paradigm and a comprehensive reassessment of the metropolis's future.

Finally, this study contributes a methodological framework that integrates entropy into water system analysis, empirical evidence linking entropy and sustainability, and decision-support model for policy design. The findings suggest that urban water systems are unlikely to be managed sustainably without addressing the structural drivers of entropy. The transition toward circular economy models is therefore necessary for long-term resilience.

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7. Author contributions

Mario Guadalupe González Pérez: conceptualization, methodology, writing (original draft). Mirna Aidee Avilés Mis: visualization, investigation, writing (review and editing). Yefer Asprilla Lara: data curation, writing (review and editing).

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9. Data availability

The data supporting the findings of this study are available from the corresponding author upon request.

10. Conflict of interest

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.

11. Use of artificial intelligence

During this work, the authors did not employ any technologies associated with artificial intelligence.

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