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Urban-rural water cycle and environmental health: systemic interrelations and strategies for resilient services in climate change contexts

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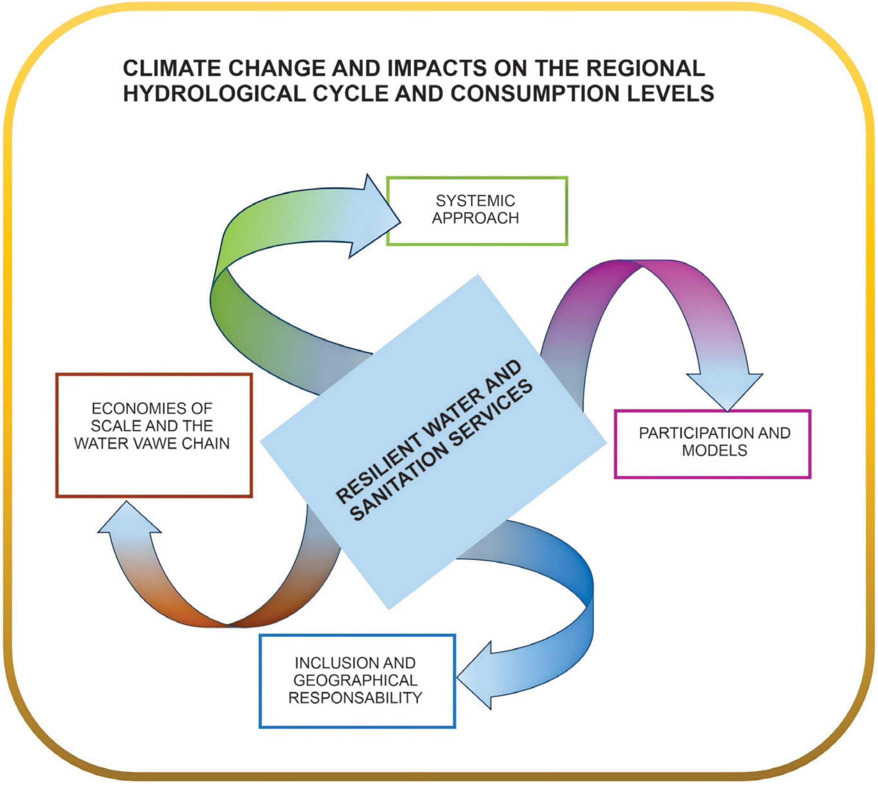
Graphical abstract



Highlights

• *Relational sustainability strengthens the resilience of water services in the face of climate change.*
• *Inclusive and systemic approaches connect urban and rural water challenges. Strategic partnerships and local planning enhance adaptive water governance.*

Abstract

Case study based on observations carried out at CEGELAH over a 16-year period, promoting research, innovation, and technology transfer aimed at strengthening the planning capacities of small- and medium-scale drinking water services in the province of Entre Ríos. There are four levels of interrelations between the internal and external aspects of water supply systems. The objective is to identify areas of intervention in terms of innovations that can counteract the main vulnerabilities detected at this scale of services in a context of climate change. The first level involves understanding the urban/rural water cycle as a complex system, highlighting the scientific approach provided by General Systems Theory as an interdisciplinary language that enables the parts to be addressed not in isolation, but in interrelation. A second relational level is the expansion of the knowledge base through the participation not only of specialists, but also of key social actors in formulating this systemic understanding of the issues and in grounding the design of consensus-based action strategies. A third level consists of inclusive possibilities for rural sectors as beneficiaries with equal rights to urban users of the water supply. And a fourth relational level concerns the formation of public-private partnerships that progressively shape the water value chain, fostering synergies among the public water service, local governments, the scientific-technological system, suppliers of materials, equipment and services, professionals in the sector, laboratories, etc.

Keywords: Water Supply. Climate Change. Human Rights. Equipment and Supplies. Systems Theory. Water Value.

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INTRODUCTION

This work arises under the impetus of the objectives of the International Congress on Relational Sustainability (Alta Gracia, Córdoba, Argentina, October 2024). It aims to contribute to Luca Fioriani's proposal for a transition toward a paradigm of relational sustainability, the central theme of this Congress. Such contributions are made from the perspective of research, development, and technology transfer praxis in the field of the Urban-Rural Water Cycle, in a province in northeastern Argentina.

The article is structured as a Case Report, based on the authors' observations within the institutional environment of the Center for Sustainable Local Management of Water and Human Habitat (CEGELAH), part of the Faculty of Science and Technology at the Universidad Autónoma de Entre Ríos, Argentina. The initial objective is to highlight the relevance of considering relational aspects around a category that has been widely used since the renowned Brundtland Report, in which the term "sustainable development" was coined. This relevance is supported from a strategic planning perspective: climate change is imposing conditions that compromise the continuity of drinking water sourcing in vast regions of the planet.

The hypothesis supporting the relevance of relational sustainability in this field is the following: "The conditions for resilience in the face of changes in the hydrological cycle caused by climate change are strengthened by the robustness of the links (relational capacity) between water supply services and their multi-actor context." Four relational levels of interest are presented. This article will be limited to the "Urban/Rural Water Cycle." Figure 3 will provide the reader with an overview of the scope of this Cycle.

METHODOLOGICAL ASPECTS BROKEN DOWN BY RELATIONAL LEVEL

First Relational Level. The systemic approach of the doctoral dissertation by the Director of CEGELAH proved to be a positive process for applying General Systems Theory to the Center's object of study: the sustainability of the urban water cycle in small- and medium-sized municipalities. From this experience, relevant aspects were drawn, such as the treatment of complexity and the formulation of operational models that mainly allow for representing the interrelations among the components of a given situation under analysis.

Second Relational Level. Linked to the previous one, a case presented in the background of the aforementioned dissertation was selected, referred to as Liwa, in which the multi-actor participation in defining the components of the system under study stands out as a response to criticisms regarding the biases of technological instruments that underpin decision-making processes.

Third Relational Level. Observations made during the training processes of the Specialization in Sustainable Management of Drinking Water Services, in which the recommendations of the baseline international standard, ISO 24512, specifically its section concerning the geographical responsibility of drinking water services, are contrasted with the praxis of the services participating in this training program.

Fourth Relational Level. Observations drawn from the same source as the previous level, documenting deep shortages in human resources and support services for local water management in small and medium-sized localities. In addition, there is a low level of institutionalized cooperation among the services in these localities.

As a synthesis of the four relational levels, they can be visualized in the following conceptual map as inputs oriented toward strengthening local planning capacities in the drinking water sector and enhancing adaptive responses to climate change.

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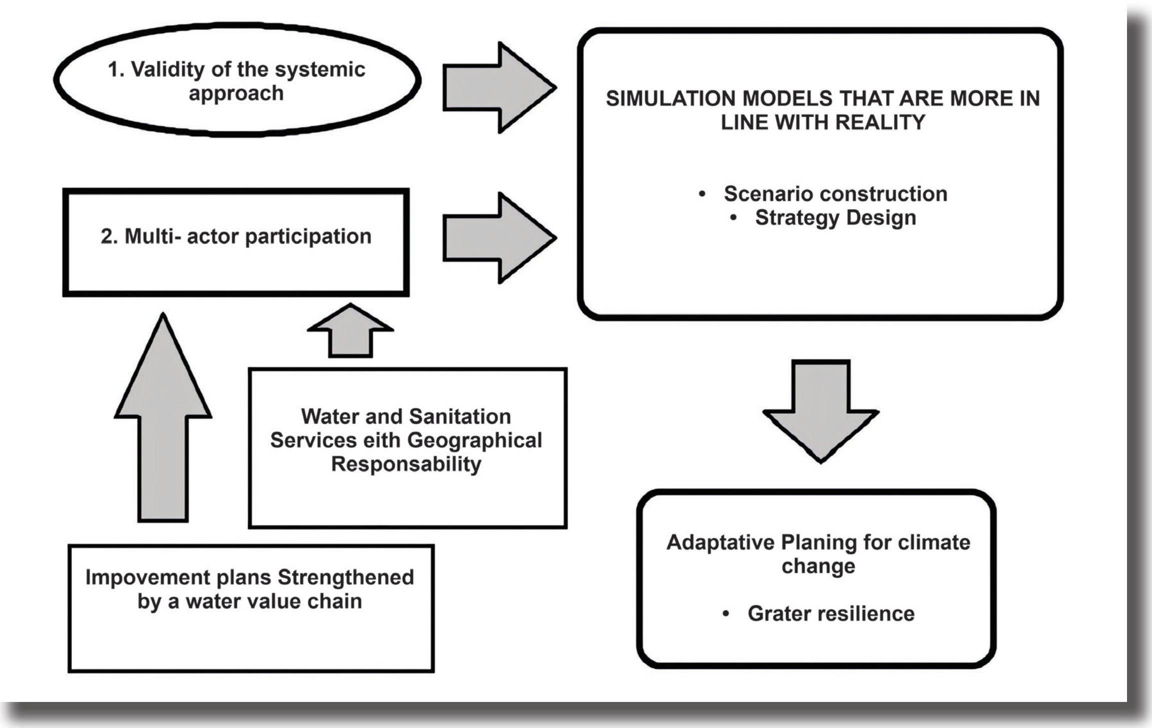


Figure 1 - Conceptual map: four relational levels for local drinking water planning oriented toward resilience in the face of climate change

RESULTS OF THE OBSERVATIONS CONDUCTED

A. Brief overview of climate change and its impact in Entre Ríos

To contextualize relational sustainability in the field of drinking water services, certain points are highlighted that have been directly impacting not only empirical aspects but also the collective imaginary of the Province of Entre Ríos. Regarding the latter, thanks to CEGELAH's participation in the *Cultura del Agua en Entre Ríos program*[1], it was possible to assess, alongside those experiencing the impacts of these transformations firsthand, the shift in their perception of the environment.

Water management in the province was, until this decade, strongly influenced by the notion that water is abundant in Entre Ríos and would always be available. Although historically there have been cycles of excess (intense rainfall and overflow of watercourses) and of scarcity due to droughts, underground aquifers have always served as a guarantee of access to drinking water for all services in the province.

What new things did climate change bring to the province? According to CIMA[2] (*Centro de Investigaciones del Mar y la Atmósfera*), this can be summarized as follows: in scenarios where global decarbonization policies fail to meet their targets (RCP 8.5 Scenario), there will be an increase in heatwaves and so-called tropical nights. Precipitation, in turn, would maintain a stable annual average but would become concentrated in periods of extreme rainfall followed by severe droughts.

What is the impact on the hydrological cycle and the main water sources of the province?

Below is a dimensionless graph representing this.

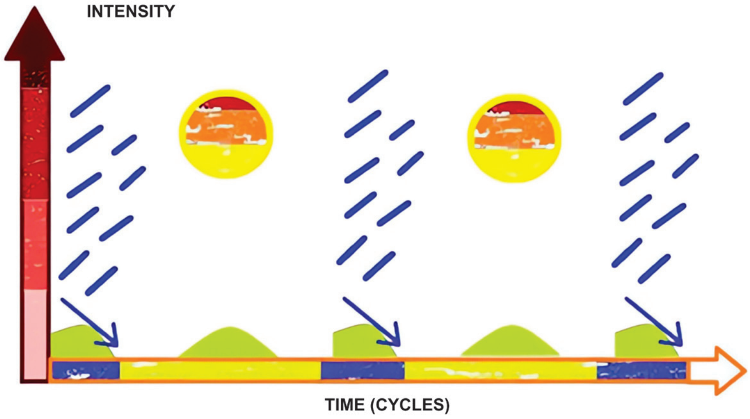


Figure 2 - Diagram of the estimated impact of the alternation of cycles with droughts – heatwaves – extreme rainfall in Entre Ríos

In unequivocal terms, this impact would consist of the following interrelated effects:

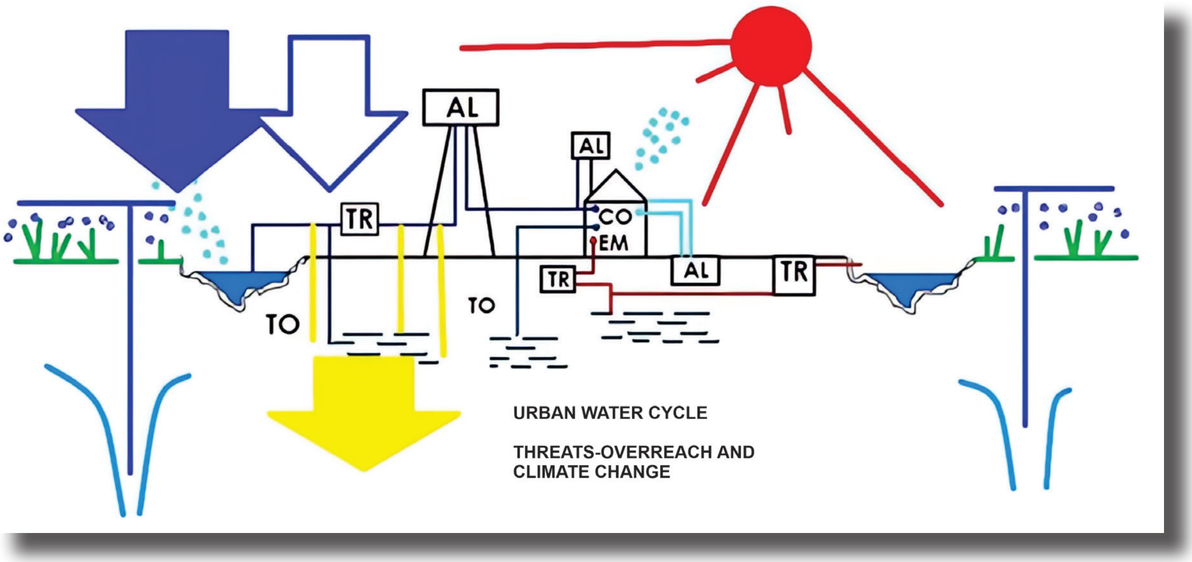
• The concentration of rainfall in shorter periods, characterized by extreme precipitation events and increased frequency, will result in strong flash floods and changes in aquifer recharge processes.

• On the other hand, heatwaves and the rise in tropical nights will impact water demand, increasing it.

• Extraordinary droughts at the sources of the major rivers in the coastal region have caused significant decreases in their flow rates. A phenomenon observed in various localities in the interior of Entre Ríos was the substantial drop in the water table level of underground wells in use, leading to their deactivation.

• The combination of heatwaves and prolonged droughts will negatively affect crop yields and viability. As a consequence, producers with greater financial capacity will opt to expand areas with complementary artificial irrigation, primarily using groundwater.

• The convergence of these factors reveals a scenario of increased vulnerability of both underground and surface water sources, with highly probable risks of changes in resource availability due to both altered aquifer recharge and situations of overexploitation.



Caption: TO: Groundwater and/or surface water intakes; TR (blue): Potabilization treatment; AL: Storage – Gravity pressure; CO: Water consumption; EM: Wastewater discharge; TR (red): Wastewater treatment prior to disposal (in situ, underground, or into a receiving body).

Figure 3 - The Urban Water Cycle and its rural surroundings – synthesis of the threats brought by climate change to the region.

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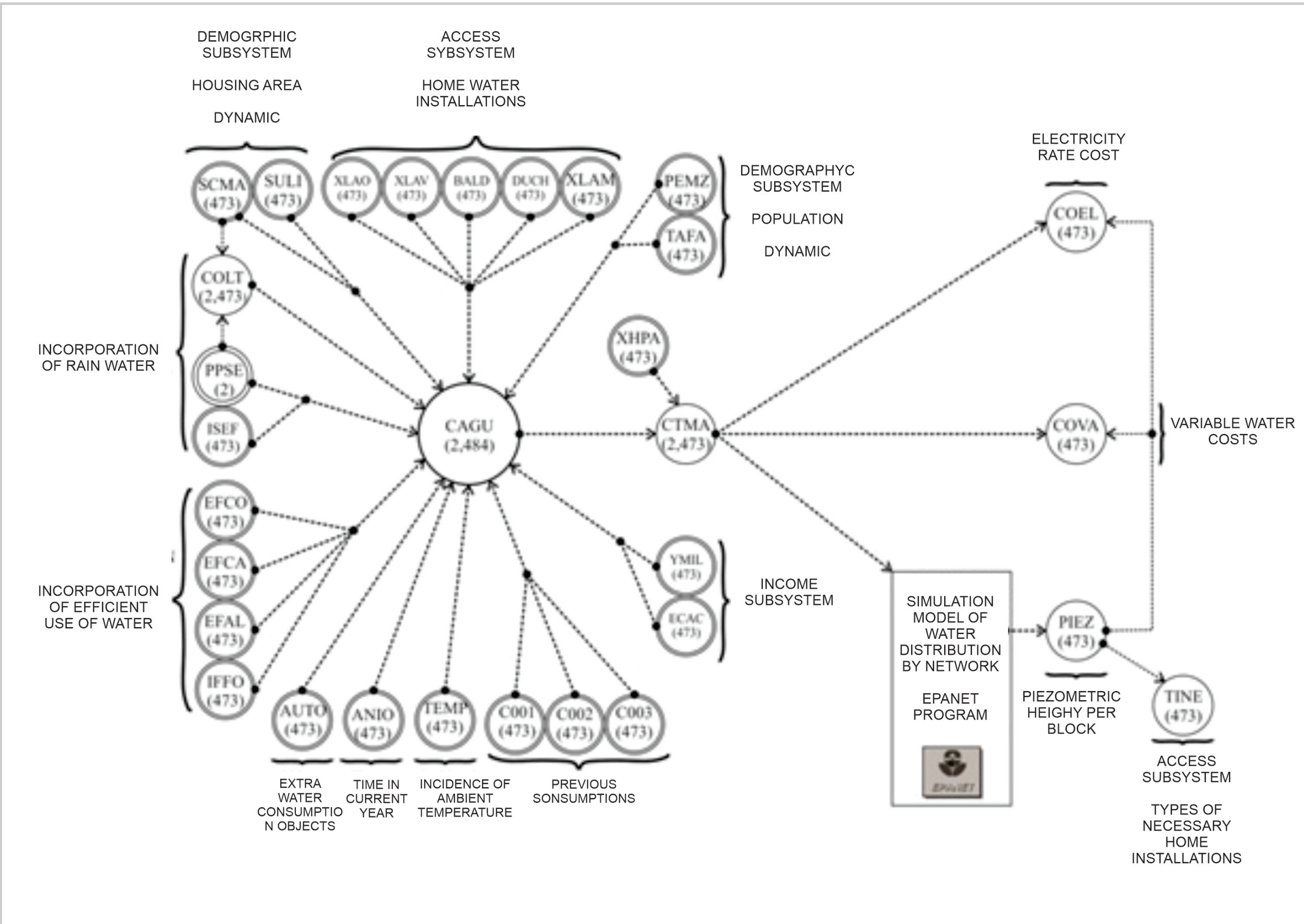
These initial data place the reader within a context of profound transformations in the living conditions of localities across the province. The adaptation policies proposed by the IPCC (Intergovernmental Panel on Climate Change) to minimize negative impacts on local vulnerabilities follow an iterative framework based on knowledge derived from the evaluation of adaptive actions[3]. To this end, it is crucial to understand the complex network of factors that affect the desirable goal of sustainability, applied in this case to ensuring continued access to water, both in quality and quantity, for the entire population. What follows will demonstrate how, based on the proposal of four relational levels applied to the urban-rural water cycle, it is possible to approach this complexity in a way that supports the relevance of relational sustainability as a tool for understanding and strategically addressing it in sector planning.

B. First Relational Level: Complexity Through a Systemic Approach

Von Bertalanffy and the scholars who contributed to systems thinking developed an approach that allows not only for understanding the components of reality individually and in isolation, but also for defining the interrelations among those components[4]. This set, within clearly defined boundaries and with specific objectives, is referred to as a system.

To demonstrate the relevance of this approach, a subsystem developed in the doctoral dissertation of the Director of CEGELAH is presented: water demand in a medium-sized municipality located in a developing region of Argentina. The guiding question was: what does water demand depend on? This is not a trivial question. If the factors on which demand depends are understood, it becomes possible to intervene in them to achieve outcomes of water savings and efficient use within the supply system.



Source: Nudelman, 2016[5].

Figure 4 - Forrester Diagram – Water Consumption Subsystem.

From the presented diagram, on the one hand, the main variables influencing water demand can be identified, depending on the location within the urban grid. On the other hand, the diagram includes the mathematical functions that explain the interrelation between these variables and water consumption. Both aspects are detailed in the tables below.

Table 1 - Selection of Relevant Variables in the "Water Consumption Subsystem" for Determining Demand.

Code	Variable Name	Unit	Remarks
BALD	Average number of bucket shower bathrooms per block	No.	Indicates the absence of showerheads in the water facilities
XLAV	Average number of automatic washing machines per block	No.	Availability of washing machines in the block
XLAO	Average number of washbasins per block	No.	Availability of washbasins in the block's bathrooms
DUCH	Average number of personal hygiene activities using showers per block	No.	Availability of showers in the block's bathrooms
XLAM	Average number of manual laundry activities per block	No.	Average number of units in the block where laundry is done by hand
YMIL	Average income per block, over the total population	Pesos	∑ Block income / Total population (divided by 1000 for calculation)
ECAC	Average income per block, over the economically active population	Pesos	∑ Block income / E.A. population (divided by 1000 for calculation)
PEMZ	Number of people per block	No. People	Resident population in the block (divided by 1000 for calculation)
TAFA	Average family size in the block	No. People	Average number of household members per block (divided by 1000)
SULI	Average free surface area per lot in the block	m^2	Average unbuilt area per lot in the block (divided by 1000)
SCMA	Average built surface area per lot in the block	m^2	Average built area per lot in the block (divided by 1000)
AUTO	Average number of private cars per block	No.	Estimate of water use for vehicle washing
CO01	Average water consumption per block per semester – 2001	m^3	2001 consumption pattern as an independent variable (divided by 1000)
CO02	Average water consumption per block per semester – 2002	m^3	2002 consumption pattern as an independent variable (divided by 1000)
CO03	Average water consumption per block per semester – 2003	m^3	2003 consumption pattern as an independent variable (divided by 1000)
TEMP	Average temperature per semester and year	°C	Data obtained from the nearest weather station (divided by 1000)
CAGU	Water consumption per lot and block	m^3	Differentially calculated consumption according to block location

Table 2 - Example of a Representative Function of the Interrelations Between CAGU (Water Consumption) and Independent Variables of the Block and Semester Under Study
Source: Nudelman, 2016.

Block 46	1st semester ("warm")	Determination Coefficient R^2 = 0.738

Implicated Variables

TAFA: Average family size per block (divided by 1000)

XLAV Número medio de lavadoras automáticas por manzana

YMIL: Average income per block over the total population (divided by 1000)

XLAO: Average number of washbasins per block

DUCH: Average number of people using showers per block

Equation (13)

```
h=9.405179270909800e+000+1.303531075121132e+002*(TAFA(i1)*XLAV(i1))+1.703939375930131e+001*(YMIL(i1)*XLAO(i1)) -2.822452265058277e+001*(1/DUCH(i1))+2.611987434590440e+001*(1/XLAO(i1))
    AA=1146.707781135041*((TAFA(i1)*XLAV(i1))-0.006684)^2+14.940235040672*((YMIL(i1)*XLAO(i1))-0.093307)^2+4.919812943306*((1/DUCH(i1))-3.580403)^2+4.191338569795*((1/XLAO(i1))-3.864641)^2
    AB=-2*29.480554636427*((TAFA(i1)*XLAV(i1))-0.006684)*((YMIL(i1)*XLAO(i1))-0.093307)
    AC=-2*26.630879895221*((TAFA(i1)*XLAV(i1))-0.006684)*((1/DUCH(i1))-3.580403)
    AD=2*24.617962245698 *((TAFA(i1)*XLAV(i1))-0.006684)*((1/XLAO(i1))-3.864641)
    AE=-2*1.992911372906*((YMIL(i1)*XLAO(i1))-0.093307)*((1/DUCH(i1))-3.580403)
    AF=2*1.853071703269*((YMIL(i1)*XLAO(i1))-0.093307)*((1/XLAO(i1))-3.864641)
    AG=-2*4.540915169092*((1/DUCH(i1))-3.580403)*((1/XLAO(i1))-3.864641)
    s=1.398164*sqr(1+1/35+AA+AB+AC+AD+AE+AF+AG)
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Antonio Caselles, from the University of Valencia, developed decades ago a methodology and supporting computer programs that enable a systemic approach to any type of reality and the construction of a computer simulator (application) capable of representing the behavior of a target variable based on the projection of its dependent variables[6]. In this way, what is conceptually identified as "complex" can be translated into an application that, with its limits and margins of error clearly stated, provides specialized knowledge about the variable in focus—in this case, water demand in different sectors of a locality—by integrating the fields of knowledge that contribute to the definition of the independent variables involved and the types of interrelations known or identified in the case study. Moreover, the construction of future scenarios based on the environmental variables involved allows for estimating the trajectory of this demand in the face of, for example, the climate change conditions projected within a given time horizon.

C. Second Relational Level: Participation for More Realistic Models

Models have rightly been criticized as incomplete and even biased lenses for understanding reality. As early as the 1970s, Erich Fromm focused his critique on the prevailing trend of using computer programs and their models detached from reality and from the people upon whom their results and subsequent actions would have an impact. Technically, this is known as "bias" and corresponds, in Fromm's terminology, to the "logic of facts"[7]. The core of this critique was: who decides which variable is relevant for understanding a given reality and, therefore, should be incorporated as part of the explanatory model of that reality?

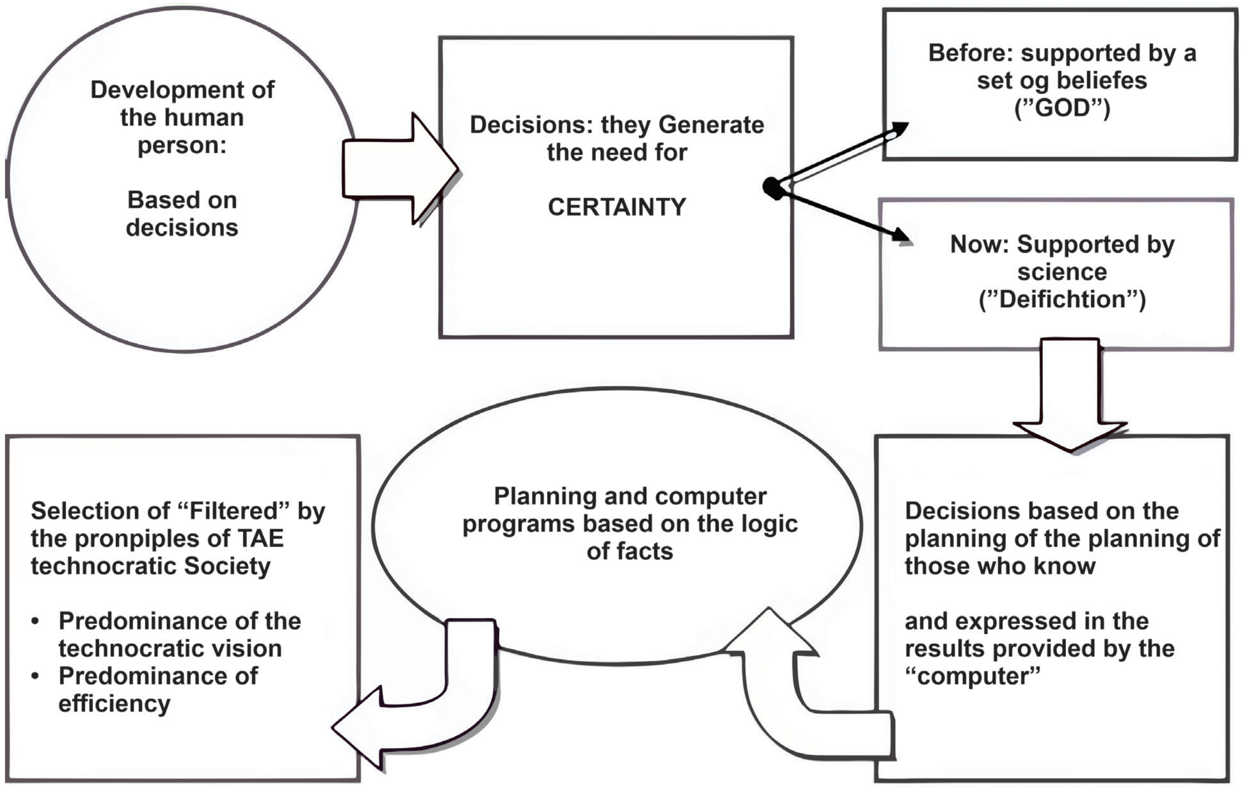

Figure 5 - Conceptual Map of Erich Fromm's Critique of the Selection of Significant Variables According to the Logic of Facts. Source: Nudelman, 2016

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There are very interesting experiences in which, through group techniques and participatory methods, it is possible to incorporate the perspectives of those who are part of the problem being analyzed—perspectives that can prove fundamental to achieving results more aligned with reality. As an example, the Liwa Project[8] illustrates, in the following diagram, how a model with multilateral participation is incorporated as a tool that supports participatory planning based on reliable evidence provided by the participants themselves.

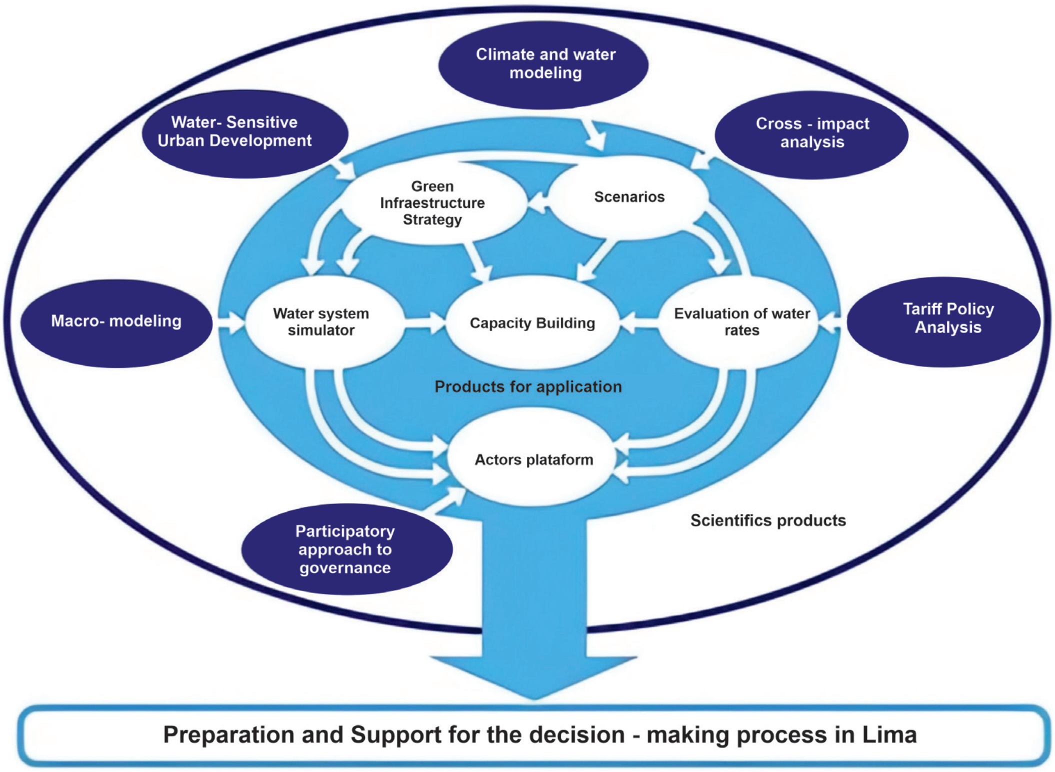

Figure 6 - Overview of the LiWa Project Methodology and Its Outputs
Source: Liwa, 2015.

Undoubtedly, this is a relational level that has been very little addressed. On one hand, in certain sectors, there is a visceral rejection of quantitative methodologies for explaining phenomena, especially in the social field. No one is idolizing such methodologies, as any scientist or technologist committed to objectivity and honesty clearly states the criteria, scope, and limitations with which a model has been developed. However, their construction and refinement constitute a virtuous process that enables a kind of knowledge which, otherwise, would remain fragmented in voluminous studies that contribute little when it comes to field decision-making. On the other hand, the systemic approach provides a language that fosters interdisciplinarity.

Regarding these benefits, advancing in the opening of these processes to those who possess experiential knowledge of the reality (under study or intervention) undoubtedly represents a valuing of the contributions made by citizens, industrialists, managers, and producers. These actors can contribute to building a more accurate model that enables the establishment of a sustainable relationship with the natural environment, with respect to the ecosystem services it provides locally or regionally, and also to a more equitable distribution of water.

Finally, it is noteworthy how Erich Fromm's thinking converges at this point with that of Romano Guardini, who is frequently cited by Pope Francis in *Laudato Si'*[9], in his discussion of the need to offer humanizing alternatives to the "technocratic paradigm." That technology, specifically the rapidly advancing technology of computing and simulation, might become a tool in service of the majority, helping to explain the phenomena that affect them and enabling strategic collective efforts to overcome them, is undoubtedly a horizon that must not be abandoned.

D. Third relational level: Water Supply Services and Their Users

When shifting from the more technical aspects of understanding the urban/rural water cycle to management practices, a clear situation of disadvantage in water access becomes evident. In the province of Entre Ríos, each municipality is responsible for supplying water to its inhabitants. Jurisdictionally, there exists what is referred to as the *ejido municipal*, that is, the portion of territory under its administration, within which a water supply system is established that may be publicly managed (mu-

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nicipal water service) or cooperatively managed (water and sanitation service cooperatives).

The problem arises in the processes of territorial occupation around these *ejidos municipales*, where there is a dispersed population or small settlements known as "colonies," which may be connected to a network focused on urbanized localities.

Inequality becomes evident when it is found that legal equality does not translate into equal access to water. A practical example: residents of the urban center have access to the water supply network, and regardless of the service's management efficiency, there is an entity responsible for ensuring a certain standard of water quality and quantity. Outside the ejido municipal, however, there is no responsible entity, the entire burden of securing access to water falls on the resident or the colony itself. Evidently, this is a situation of neglect and lack of protection that generates significant social inequity.

Although there have been rural water supply programs, such initiatives have always suffered from a lack of continuity and, above all, from the fact that the ultimate responsibility for operating the implemented system ends up falling on the user.

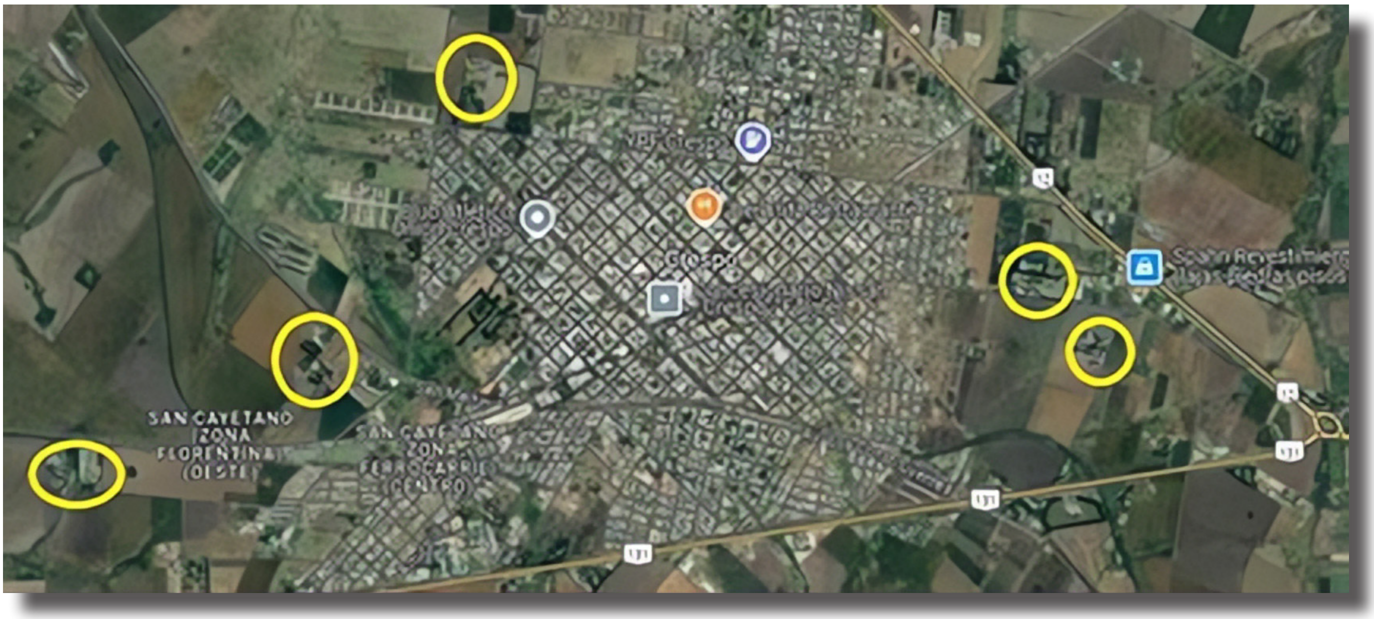

Figure 7 - Example of the City of Crespo, Residents Outside the Ejido Municipal.
Source: Google Earth, 2024 – Prepared by the authors, 2024.

However, the international standard ISO 24500 for water and sanitation services proposes an advancement that represents a starting point with great relational potential at this third level. It introduces the concept of "geographic responsibility" in water supply, going beyond the administrative boundaries of a *ejido municipal*[10]. In short, the standard broadens the scope of listening: what matters is the water consumed by every individual, family, or group located near a locality.

Currently, advances in communication and information systems allow for precise monitoring of the supply conditions of dispersed populations within the geographic responsibility area of a municipal or cooperative water service. For instance, the periodic verification of potability conditions would already serve as a form of support for the health of these populations. Even more so, vulnerability to impacts caused by poor pesticide management is significantly higher in these contexts, requiring regular monitoring of water quality parameters related to such substances.

All of this can be assessed and guided by specialized technical staff from municipal drinking water services, acting as extensions of those services. Relational sustainability creates room for new challenges and invites the development of creative solutions, harnessing the capacities of all stakeholders involved.

E. Fourth Relational Level: Economies of Scale and the Water Value Chain

As early as 2010, the Economic Commission for Latin America and the Caribbean (ECLAC) studied the economic vulnerability faced by small- and medium-scale water supply systems. The concept of "economy of scale" in these systems, presented by Lentini and Ferro[11], addresses relevant operational aspects of this challenge. It became evident in Argentina how the wave of privatization of drinking water services in the 1990s focused almost exclusively on the large systems of provincial capitals. The reason was clear: there was no "commercial interest" on the part of large consortia to operate in less profitable localities.

This observation offers a diagnosis of the low economic profitability of these services. However, where there is threat, there can also be opportunity. The links between localities whether related to transportation, production, watersheds, political affiliation, or cooperative networks already exist informally in emergency situations. One example occurred when, after the burning of a groundwater intake pump in a city, a simple phone call to the mayor of a neighboring municipality was enough to obtain a spare pump and restore the service within a few hours.

In the context of a proposal for sectoral planning based on clusters of localities, with agreements on the best technologies to be adopted, joint procurement would be feasible, increasing scale and securing better prices from suppliers. Another sensitive point is the growing scarcity of skilled operators. The idea of specialized human resources working across municipal networks is not utopian. In Spain, for example, there have been for decades mancomunidades of small localities that share watersheds, such as the Mancomunidad del Alto Palancia[12], which managed, among other things, waste collection services for all associated communities.

Without a doubt, the creation of trust-based relationships and the ability to formulate joint development plans - even modest ones - can be crucial steps toward overcoming structural vulnerabilities and strengthening the resilience of water supply services.

Figure 8 - Example of Potential Economies of Scale in Water and Sanitation: Crespo (Entre Ríos), Its Colonies, Villages (Yellow), and Nearby Localities (Orange). Source: Google Earth – Prepared by the authors, 2024.

Finally, another aspect within this same level is the "water value chain." Mapping the components of the entire process that makes up the Urban-Rural Water Cycle - and, within each component, identifying the involved actors - reveals the complexity and breadth of this chain. As a preliminary sketch of the value chain, Table 3 has been developed. It would be necessary to expand upon it and, of course, to classify these actors and assess their availability, quality, and roles within the chain. However, reality shows that this chain is nonexistent as such. And the fundamental reason is that there are no clearly defined service goals or commitments to water resource stewardship on the part of those who should be governing the local water supply system.

One example clearly illustrates the issue: a recurring headache in every local drinking water service is the seasonal overload caused by the filling of private or communal swimming pools during the summer. The main problem lies in the lack of maintenance of these pools; when the water is no longer in good condition, consumers prefer to drain and refill them. A missing link in this chain is the presence of one or more well-trained entrepreneurs equipped to provide pool maintenance services. There are dozens of such disconnections in small and medium-sized localities.

Another example: the IDB (Inter-American Development Bank) estimates that approximately 40% of the water extracted and treated by drinking water services is lost through leaks (non-revenue water). This represents a waste of both water resources and electricity, as each leaked liter was previously pumped. Finding technology-based entrepreneurs specialized in leak detection (in networks or households) is like looking for a needle in a haystack. A highly subsidized public service such as water provision leads to the economic inviability of efforts to detect and repair leaks.

Some degree of interest in reducing energy costs does exist among water services, as demonstrated by the intervention carried out in the city of Nogoyá by CEGELAH, through a Hydro-Energy Efficiency Diagnosis of its drinking water service[13].

The following table presents a visualization of potential components of the water value chain, organized according to the stages of the Urban-Rural Water Cycle.

Table 3 - Potential Links in a Water Value Chain.

Potential Components of a Water Value Chain				
Source	**Storage**	**Treatment and distribution**	**Consumption**	**Discharge**
Professionals and Technicians: • Hydrogeologists • Well drillers • Certified water quality laboratories • Specialized services for aquifer exploitation condition studies **Suppliers:** • Subsurface pumping equipment • Measurement instruments • Filters and materials	**Profesionales y Técnicos:** * constructores **Proveedores:** * de almacenamientos de grandes volumenes * de equipos de bombeo para impulsión * de instrumentos de medición. * de servicios de mantenimiento de equipos e instalaciones	**Professionals and Technicians:** • Professional water sampling • Water quality supervision • Certified water quality laboratories • Specialized services for disinfection system calibration • Network installation companies • Network design and optimization consultants • Leak detection services **Suppliers:** • Chlorinators for raw water • Inputs and materials	**Consumption Organizations representing water demand:** • Neighborhood commissions • Commercial and industrial chambers • User-members (cooperatives) **Urban demand formulators:** • Real estate developers • Designers and builders of residential, institutional, and industrial structures **Suppliers:** • Devices and installations • Maintenance services for equipment, devices, and installations	**Professionals and Technicians:** • Specialized services for studies on discharge conditions into receiving water bodies • Specialized services for sewage treatment plant design and maintenance • Services for monitoring discharged water quality and receiving water bodies • In situ maintenance services
Common to all stages of the Urban-Rural Water Cycle: • Credit institutions • Development cooperation agencies • Technical and vocational training institutions • Entities responsible for inspection, verification, operation, maintenance, and service management.				

DISCUSSION

The following discussion seeks to reflect on possible questions the reader may ask.

In what way is a relational approach superior to a traditional approach?

The relational approach to sustainability proves to be relevant due to the notion of complexity. A recent example from Argentina's economic context illustrates this well. The prevailing economic model has imposed more or less homogeneous lifestyles, based on comfort, status, and consumption. When thinking about doing laundry, no one fails to picture an automatic washing machine. However, environmental care measures have led to the development of "eco-efficient" appliances—in this case, automatic washing machines that offer low water consumption functions.

Nonetheless, correlation studies on the factors influencing water demand (see Tables 1 and 2 above) showed a positive association between the use of such washing machines and household water consumption. This apparent contradiction can be explained by lifestyle: since these machines are very easy to use and water tariffs are very low, consumers tend to wash clothes more frequently, even after minimal use. This would explain how, although an "eco" machine consumes less water per cycle than older models, its more frequent use throughout the day results in greater total water consumption.

If we add to this the economic reactivation measures already implemented in the country (such as civil construction and increased access to home appliances), it is possible to see how such policies may negatively impact water resource conservation by driving water consumption. This example highlights how social factors (lifestyles and advertising that promotes them), economic factors (tariffs, wages, credit), technological factors ("eco" certifications), and other possible conditions converge. This complex network of interrelations is the one that, with academic support, must cease to be a "black box" and become a "transparent box" in order to be incorporated into local planning processes and the effective resolution of water demand management policies that are more efficient.

What is the relationship between climate change resilience and the use of simulation models that incorporate the participation of the involved actors?

The main strength of a model lies in its ability to represent reality as faithfully as possible. This means that its outcomes (target variables) must be reliable. When the individuals involved in building a model represent a broad spectrum of social actors familiar with the system whether through academic training or empirical knowledge biases that distort the represented reality are avoided.

When projecting the impact of climate change on specific factors within a local or regional reality, such reliability becomes essential, so that the investments and efforts undertaken can effectively contribute to successful adaptation to climate change or, in other words, enhance the resilience of the system in question.

The case presented was geographically centered on an Argentine province, Entre Ríos, the area of action of CEGELAH. But which elements of this case could be extrapolated to other geographic contexts?

Climate change in Entre Ríos, with visible signs for the entire society, such as the extraordinary low water level of the Paraná River and the prolonged droughts between 2022 and 2024, has posed a culturally unprecedented question for the region: Can Entre Ríos run out of water? This represents a major shift, since the prevailing social imagination always regarded such a scenario as impossible. In the face of a transformation of this magnitude, much work remains, as water management in the territory has long been characterized by a lack of verifiable objectives for resource stewardship and by a disorganized pattern of distribution.

In this regard, the case of Entre Ríos may be comparable to other regions where water, particularly groundwater, has historically been abundant, and therefore no more rigorous, evidence-based management practices were developed. Another extrapolable aspect, due to its international standardization, is the emphasis on training human resources and decision-makers with the aim of advancing, among other areas, the local production of Performance Indicators (PIs), in accordance with the standards established by the ISO 24500 series.

It is well known that a solid planning foundation depends on relevant, reliable, and regularly updated information. The design and implementation of the Specialization in Drinking Water Service Management, referenced in various parts of this paper, was the executive strategy chosen to introduce changes in the territory. This strategy also promotes, indirectly, the adoption of systemic methodologies that make it possible to build, through participatory processes, reliable foundations for action in the sector.

How would the geographic responsibility of water supply services proposed by the ISO 24500 standard contribute to public policies in the sector?

If we consider the logic of politics, it tends to respond to users' "demands" (needs) only when these are formally expressed. What is desirable, however, is a shift in local regulations that not only broadens geographic coverage but also redefines the very concept of drinking water service understood as a heterogeneous system that ensures an equitable standard of service for all.

CEGELAH has made progress in this direction by building communication channels through improvement plans developed within the scope of the Specialization program[14], along with the development of indicators that make it possible to visualize the relationship between service providers and users. Specifically, the ISO-IRAM 24510 standard addresses these relationships.

To implement this geographic responsibility, one possible path would be through State action (at the municipal or local level), proposing alternative technological solutions: for example, smaller-scale drilling (even if costly), the use of alternative sources such as rainwater, or the installation of electronic systems for remote monitoring of water quality, among other possibilities.

Using the Liwa example, an important gap is highlighted regarding the construction of models in which the main actors involved in the studied system participate. How could this be applied to the reality of small and medium-sized localities, for example, in Argentina?

In this context, there is no consolidated technical culture of territorial planning in general nor in the water sector specifically that incorporates the formulation of local simulation models capable of generating reliable forecasts and, based on them, constructing scenarios and strategies grounded in verifiable evidence. The main lesson from the LIWA example is that this is indeed possible: not only the use of such models but also their co-construction through appropriate social methodologies that incorporate empirical knowledge, observation, and the wisdom of social groups capable of making meaningful contributions in this field.

To achieve this, it will also be necessary to abandon the prejudices that fragment and isolate different forms of knowledge. Academia plays a fundamental role in this process. A modest contribution from CEGELAH, for instance, is represented by the course ICTs Oriented Toward Strategic Local Planning, offered as part of the Bachelor's Degree in Systems at the Faculty of Science and Technology. This course provides a space where students seek to connect their technical and computational knowledge with the real needs of localities in the province especially regarding the production of information for sustainable water management.

The previous point highlights how heterogeneous it would be to work with knowledge from such diverse sources. How can one reconcile the rigor of scientific knowledge with that which stems from trustworthiness and practical experience?

Undoubtedly, this is a significant bottleneck: reconciling, within a single model, knowledge derived from different disciplines. The systemic methodology in this case, the one proposed by Antonio Caselles Moncho from the University of Valencia, an authority in the use of General Systems Theory (GST) as a scientific methodology is an example that such reconciliation is possible. Likewise, the previously mentioned Liwa example shows the extent to which it is feasible to converge knowledge from different sources.

Moreover, there is a common element shared by both modeling processes. Antonio Caselles proposes not only the incorporation of mathematical functions as explanatory components of the interrelations between variables, but also the inclusion of simple logical expressions, which can very well translate empirical observations provided by trustworthy individuals as contributions to the model's construction.

An artificial example applicable to the case: in localities lacking data on a local watershed, one might affirm that "if 'n' millimeters of rain fall in the wetlands region, the stream that flows through our community will reach point 'p'." Arriving at this kind of expression requires the support of a participatory process, involving representative social actors who belong to the system in question, speaking a shared language and using methodologies that enable the identification of reliable components and the achievement of properly tested results.

The concept of a "value chain," originating from the field of economic development, when applied to the water sector, is indeed innovative. Are there institutional frameworks that support its construction?

The shortage of specialized human resources for the various functions of the Urban-Rural Water Cycle is a severe deficit in the province. This problem, shared by many localities, suggests that its solution could emerge through permanent mechanisms for communication and resolution.

A favorable space for building this value chain lies in the microrregions. In the area presented in Figure 8, the MiCra (Microregión Crespo y Aldeas), was recently established, obtaining its legal status at the end of August 2023. This offers all territorial actors a platform to identify problems and define common goals related to the UR-WC (Urban-Rural Water Cycle), as well as to share technical and organizational capacities to achieve them.

Could another example of missing links in the water value chain be presented?

An additional critical link is the absence of services capable of addressing water contingency situations. This becomes particularly evident during the summer in small villages. Crespo is the center of a poultry production zone, and many of the villages that are part of MiCra depend on water supplied by the municipality.

However, during the summer season, a conflict of interest emerges: how much of the available water should be allocated to human consumption and how much to animal consumption? In this context, one can envision, for example, the role of private companies capable of constructing specific wells dedicated to supplying water for animal consumption.

Was CEGELAH able to empirically verify the effectiveness of measures aimed at the sustainability of the URWC?

As empirical evidence, the cases of the cities of Crespo and Nogoyá are presented. At the time the diagnostic studies were conducted, the main complaints from residents concerned service intermittency and lack of pressure in the network in specific areas. Internally, however, the top priority for both municipal governments was the frequent breakdown of electric pumps and the high and rising energy costs associated with their operation.

A controllable hydro-energy efficiency measure was implemented by the municipal water services: the automation and strengthening of pumping systems. Following the implementation of improvements in the municipality of Crespo, an 8% reduction in energy consumption was recorded during July and August between the periods of 2011 and 2012; the same effect was observed in Nogoyá during September of the same years.

As for pump breakdowns in Nogoyá, an evaluation of repair costs was proposed. The result showed an estimated expense of $70,000 in 2009, with a significant reduction to less than $20,000 in 2011. With this level of confidence in the results, it becomes possible to move forward for example, in leak management, thus paving the way to develop a demand management policy that involves a broader range of social actors[15].

Was it possible to record the impact of simulation models applied to local water management?

Not for models of the scale presented here, as the most advanced one, outlined in specific parts of this article, still requires validation. However, CEGELAH has participated in and locally promoted the use of simulation models, although these have been limited to the use of the water distribution network behavior simulator, EPANET, widely known in the field of urban hydraulics (Third-Party Service Experiences, Nogoyá).

A particularly illustrative example is the routine practice in local water distribution services of granting access permits to new users. The capacity of distribution systems to admit new users is a dynamic factor that, without simulation, would require costly studies and the involvement of specialized professionals.

The availability of a simulator such as EPANET - properly calibrated and equipped with data input points that allow for periodic model updates - would provide the opportunity to access, in real time, reliable and free information to supply new users with accurate service conditions. This would in turn enable the issuance of technical recommendations for the design of hydraulic installations that ensure reliable water consumption.

From the two international experiences (LIWA and the Mancomunidades in Spain), what lessons could be applied to the Province of Entre Ríos?

Both are replicable, provided they originate from concrete initiatives and leadership. Specifically, through the actions of the Center, the implementation of the first two cohorts of the Specialization in Sustainable Management of Water Services, with the participation of seven municipalities[16], represented an initial step toward establishing a common language based on evidence, such as the development of Performance Indicators (PIs) following the standardized logic of the ISO 24500 standard. The construction of reliable indicators forms the foundation for future participatory modeling initiatives.

On another front, the recent alliance formed by CEGELAH with the Provincial Water Sources Regulatory Council (CORUFA) seeks to create consensus-building spaces based on local evidence and the involvement of major productive water users, with the aim of operationalizing existing legislation (Water Law) regarding integrated watershed management.

When it comes time to effectively regulate the territory through consensus, this will enable the inclusion of both urban and rural water actors in efficient use practices and in collaborative strategies that help reduce the costs of priority technologies to be implemented.

To introduce this proposed vision, it was acknowledged that leadership is lacking. Who would be the key actors to drive these changes?

The well-known strategy "Think globally, act locally" is particularly relevant here. Therefore, field-level actions (local level) cannot remain isolated from higher-level coordination namely, the provincial level. Municipalities and cooperatives responsible for water services are indispensable actors. In the Province of Entre Ríos, the provincial level is represented by Obras Sanitarias de Entre Ríos and the Dirección de Hidráulica. At the watershed scale, CORUFA is another key player.

Thanks to the alliance previously mentioned, sustainability-oriented approaches are also beginning to be developed with large-scale users, starting with the agricultural sector - though this remains in an early stage.

Finally, academia plays a crucial role, offering a broad range of expertise. Within it, CEGELAH stands out as a center of the Universidad Autónoma de Entre Ríos, with a presence throughout the provincial territory—an ad-

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vantage not yet fully leveraged.

As for other institutions, recent years have seen progress in research and development (R&D) efforts in collaboration with other universities, such as the Universidad Nacional de Entre Ríos, and R&D agencies like the Instituto Nacional de Tecnología Industrial (INTI). In practice, this represents the current view on the matter.

Given the relevance of political decision-makers in the implementation of actions, what type of language is considered appropriate to engage them in the proposed approach?

CEGELAH has tested three strategies that proved effective in engaging political decision-makers in sustainable water management. The first strategy is based on the language of economic and political "convenience", focusing on the saving of public resources, especially through the reduction of energy costs associated with water pumping (as demonstrated by hydro-energy efficiency measures). The second strategy emphasizes the reduction of social conflict caused by poor service quality. This includes the implementation of early warning systems for monitoring the operational status of wells and the adoption of IRAM standards for drinking water quality. The third strategy involves the development of "ad hoc" pedagogical models, creating learning spaces aimed at training technical, professional, political, and community leaders, using the university's educational platform. In this line, in addition to the aforementioned Specialization in Sustainable Management, a Specialization in Citizen Water Management (currently under approval) has been designed. This program presents the principles of ISO 24512 in a practical way, focusing on improving services for users of drinking water systems. Short training courses on water quality management have also been offered.

The most recent initiative - still under development - consists of a self-learning strategy, offering autonomous courses open to diverse user profiles (water services, slaughterhouses, schools, agricultural producers, etc.) for the installation of water quality monitoring tools. These are integrated into a virtual network of remote technical assistance operating at the provincial level.

Did the simulation model of urban water cycle sustainability and its set of equations, presented at the first relational level, serve for local action planning?

The doctoral thesis reached the stage of model construction, but it has not yet completed its validation phase, a stage in which it still remains. This is due to the fact that the Center's priority has been the implementation, through the aforementioned strategies, of information systems capable of generating data and indicators compatible with models such as the one proposed for the sustainability of the urban water cycle.

Would it be possible to concretely apply the four relational levels presented?

The formulation of these four relational levels was primarily intended to present a possible horizon. Possible because the Center is actively working in that direction and, through the strategies outlined and alliances established, has defined priorities that were presented in this article as lines of action either implemented or underway. It was not possible to present conclusive data, mainly because CEGELAH is a small center operating within a context of many limitations.

The main contribution lies in sharing, with the various fields of knowledge that the issue of water engages, the relevance and pertinence of the interrelations among these four levels, if the goal is to contribute to adaptive policies in the face of climate change that ensure access to water for all actors involved, not only in terms of quantity and quality, but also with equity.

Overcoming institutional inertia is costly. Are there any guidelines for addressing it?

To break such inertia, and from the perspective of this R&D&I Center, a number of possible lines of action have been identified as illustrative:

- Amendments to current legislation, in order to strengthen the capacity of a central authority with regulatory power over the territory, responsible for measuring service/water provision standards and providing technical assistance to all water-demanding actors (urban, industrial, and agricultural), with a focus on efficient use and the reduction of contaminants discharged into surface and groundwater bodies.
- Funding for improvement actions, through the activation of resources already provided for in Provincial Water Law No. 9172, which, in Chapter XX, establishes the creation of the Provincial Water Fund, largely intended to finance R&D&I activities in this field.
- Training of regional technical and professional personnel, capable of providing technical assistance to all water-demanding actors across the territory for sustainable water management.
- Incubation initiatives for technology-based enterprises, aimed at supporting key water-demanding actors in their sustainable management practices.
- Capacity-building for local decision-makers and their government teams, to plan the water and sanitation sector with a participatory approach, involving all water-demanding sectors and service providers, based on evidence.
- Development of accessible and participatory digital platforms (publicly available), aimed at water service operators and large-scale users, to facilitate the integration of climate change impacts on the hydrological cycle and to support the design of water resource preservation goals.

CONCLUSIONS

First, the descriptive presentation of these four relational levels constitutes, as previously noted, a contribution to Luca Fiorani's proposal for building a new paradigm of sustainable development that of *Relational Sustainability*[17]. The authors agree with the general outlines of this proposal and complement it with greater specificity by applying the four relational levels to the urban-rural water cycle.

The first two levels present methodological aspects for addressing complexity, a defining characteristic of sustainable development. The authors concur with Fiorani's emphasis on the "relational," that is, the understanding that complexity cannot be grasped through its components in isolation, but rather through their interrelations. This had already been timely proposed by systems thinking, which underscores the contemporary relevance of this scientific approach. Although Fiorani also advocates for "transdisciplinarity," the systemic approach presented here proposes, first and foremost, a common language among the various disciplines involved in the understanding of a given reality conceived as a system with clearly defined boundaries and influencing factors. The authors believe that the field of interdisciplinarity when not merely declarative but operational, grounded in a shared language still has much to contribute in Latin America.

Focusing on the initial hypothesis, as anticipated in the discussion section, it cannot yet be confirmed or refuted due to a lack of conclusive results. However, honest indications have been presented that justify further, in-depth study, given the relevance that the relational approach may have for the sustainability of the urban-rural water cycle.

Looking to the future, it would be highly beneficial to link these contributions to the field of Technical Cooperation. In this field, the logical framework approach prevails in project formulation, representing the final expression of sector-specific policies. In the logical framework process (which is essentially participatory), one of the diagnostic stages is the construction of "problem trees," which, from the perspective of General Systems Theory (GST), correspond to initial causal diagrams the logical basis of Forrester diagrams.

A potentially very positive line of R&D work would be the case-based study of projects that systematically validate such causal diagrams or problem trees, as a way to model realities more closely and consistently with real-world conditions. Applying this strategy to the other relational levels also appears relevant for advancing the verification of the initial hypothesis.

Finally, implementing a relational approach such as the one proposed requires leadership that, within the province, has not yet clearly emerged. The weight of decades of inertia in the water sector with substantial inefficiencies across every point of the Urban-Rural Water Cycle (URWC) poses a challenge to all involved sectors. Breaking this inertia and maintaining a clear path toward transformation is urgent, so that the social suffering caused by water scarcity, crop failure, reduced productive capacity, and diminished tourism potential does not lead communities into conflict over a natural, public, and increasingly scarce resource conflicts in which the most vulnerable are always those who lose the most[18].

As a hopeful closing, affirming that change in this field is indeed possible, the following testimony is worth recording:

"I remember when we were implementing the improvement plan in the Crespo municipal government back in 2011. Mr. Martínez, the long-standing head of the municipal waterworks department, was always resistant to innovation: Digitizing the drinking water network! Replacing the electric panels! From star-delta to smart starters (soft starters)! Substituting metal pipes with hoses for submersible pumps! Installing phase sensors! Solar pressure switches on the lines Telemetry!

— What for? — he would say. — It's always worked fine the way it is... — he declared.

Until, two years later, he came to our office and said, in just a few words, the unthinkable:

— What you did here... this really works.

A true good omen for the future.

CRediT author statement

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Declaration of competing 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.

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