Received: 24 July 2024 | Revised: 9 April 2025 | Accepted: 24 April 2025
DOI: 10.1111/wej.12986

RESEARCH ARTICLE

Water and Environment Journal
Promoting Sustainable Solutions
CIWEM WILEY

Identifying solutions to face groundwater overexploitation and degradation: A policy design experiment in Tunisia

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Funding information
Centre National de la Recherche Scientifique

Abstract

Groundwater plays an important role in achieving sustainable development goals, particularly in the Maghreb. There, groundwater management policies have been unable to stop groundwater degradation and overexploitation. In this context, it is urgent to propose concrete methodologies allowing local stakeholders to identify solutions that (1) take into account water issues but also energy and food production (i.e. solutions that are "bundled"); (2) are innovative; and (3) create a sense of collective belonging among participants. This article analyses to what extent the P-KCP method, derived from policy design, can tackle this challenge. P-KCP was used in the Lymaoua area in Tunisia. The article analyses the 39 solutions identified by Lymaoua participants and discusses the limitations and lessons learnt from this experiment. These concern the choice of the geographical area, farmers' engagement, gender representation and the use of models. The conclusion includes recommendations for coupling P-KCP with participatory planning to detail how the solutions can be concretely implemented and monitored, as well as the governance arrangements needed. Another recommendation is to expand the scope of collective groundwater organizations to encompass energy, agricultural production, land use, social equity and ecosystem preservation issues. Finally, avenues for future research are suggested.

KEYWORDS
aquifer, bundles of solutions, energy, innovation, nexus, participation, P-KCP, SDGs

Highlights

- P-KCP helped identifying bundled and innovative solutions
- Linkages of solutions to SDGs highlighted interconnections (water-energy-equity-etc.)
- Participatory planning can support reflection on solutions' contradictory impacts
- The process created a sense of collective belonging despite remaining tensions

- It laid the foundations for the newly created groundwater comanagement organization

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1 | INTRODUCTION

In 2022, the United Nations called for “making the invisible visible” regarding groundwater (United Nations, 2022). In fact, as mentioned in the precited report, “groundwater accounts for 99% of liquid freshwater on Earth […] [it] provides half of the volume of water withdrawn for domestic use by the global population, including the drinking water for the vast majority of the rural population who do not get their water delivered to them via public or private supply systems and around 25% of all water withdrawn for irrigation”. Yet, despite the significant role played by groundwater in ecosystems and societies, the 17 Sustainable Development Goals (SDGs) adopted by world leaders in 2015 do not explicitly account for groundwater (Guppy et al., 2018). Only one SDG target explicitly mentions groundwater (target 6.6): “By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes” (United Nations, 2015). Yet, groundwater is linked to 53 other SDG targets out of 169 (Guppy et al., 2018). Indeed, groundwater plays a key role in food security, resilience towards droughts and water scarcity, fighting poverty and resilience to climate change. However, groundwater is often used unsustainably. The rate of global aggregated groundwater storage depletion for the beginning of the present century is estimated between 100 and 200 km^3/year (Bierkens & Wada, 2019). Groundwater is also subject to various sources of pollution which are often irreversible, notably anthropogenic (agricultural, industrial, domestic) and geogenic (arsenic, fluoride in the subsoil).

The Arab region is one of the most water-scarce areas globally and is heavily dependent on groundwater. Thirteen Arab states are situated below the absolute water scarcity threshold[1] (Aquastat, n.d.; UNDESA, 2020) and groundwater is the most relied-upon water source in at least 11 of the 22 Arab states (United Nations, 2022). Tunisia belongs to both categories. Regionally, arid to semi-arid climates, high evaporation rates and low, variable precipitation reduce surface water availability and groundwater recharge in the Arab states. Groundwater, which is the primary water source for many vulnerable groups, is being over-extracted, leading to declines in groundwater tables, particularly in densely populated and agricultural areas. Most groundwater resources are non-renewable, and unsustainable agricultural practices, urbanization and pollution are damaging both the quality and availability of these resources. Climate change, population growth and political conflicts also exacerbate the situation. Although new technologies have emerged, groundwater extraction is still difficult to monitor, and cooperation on the 42 transboundary aquifer systems remains limited (UNESCWA, 2022).

It is therefore crucial to reverse these trends in order to sustain the critical role of groundwater in sustainable development in the Arab region and globally. Improved governance, better management strategies, policy reforms and regional cooperation are crucial for addressing the region's socio-economic and ecological challenges and achieving sustainable development goals.

Over the years, researchers and practitioners have come up with various solutions to face issues of groundwater degradation and over-exploitation (Amarasinghe, Shah, & Mccornick, 2008; Faysse et al., 2011; Mukherjee et al., 2024). They encompass increasing water supply by managing aquifer recharge or resorting to alternative resources (e.g. wastewater reuse), decreasing water demand (e.g. switching to crops that are less water consuming), better knowing and managing groundwater uses (e.g. water meters) as well as supporting effective governance (e.g. ensuring equal access to capital) (Dumont et al., 2021; Singh et al., 2022). But in the Middle East and North Africa, these solutions have rarely been successfully implemented (Closas & Villholth, 2019). This is partly because water users are reluctant to provide information on their wells for fear of being taxed, of having their use restricted or because they contest state ownership and intrusion. In parallel, States often lack the capacity to enforce rules and sanctions on the ground (Closas & Molle, 2016) and the implementation of licences and permits for wells often leads to petty corruption. In many places, groundwater governance responsibilities have been delegated to local levels of administration and water user associations without a genuine devolution of power, necessary resources and capacity development (Ghazouani, Molle, & Rap, 2012). This prevented governance and management solutions from achieving sustainable, resilient and equitable groundwater use. Finally, in these countries, the provision of additional resources has in several places led to expanded use and increased depletion (e.g. Al Naber & Molle, 2017; Molle, 2017).

These contrasted effects are due, among other things, to the interconnected and invisible nature of groundwater. Groundwater is connected with surface water, energy and agriculture, meaning that solutions to one issue may aggravate another one (Bhaduri et al., 2015). For instance, the increasing use of solar panels, which is considered as one option to achieve SDG7, has been shown to increase groundwater overpumping (Shah et al., 2018). Moreover, the specificities of groundwater, including “invisibility”, overlapping of aquifers, interdependencies between actors, and less easily available data (Zwarteveen

[1]Ranking from 2020. The absolute water scarcity threshold is of 500 m3/capita/year, based on the Falkenmark water scarcity index for total annual renewable water resources per capita for the year (Falkenmark, 1989). The other two thresholds are water stress for values below 1700 m3 per person per year and water scarcity for values below 1000 m3 per person per year.

et al., 2021) mean that local actors: (1) are not necessarily aware of the problems, (2) do not know how to respond collectively, 3) do not always have the necessary data to make informed decisions.

As a result, the number of illicit boreholes continues to increase in many places and will prevent the achievement of SDG target 6.6. In this context, it is urgent to propose concrete approaches allowing to identify solutions that (1) take into account not only water issues but also energy and food production (i.e. solutions that are "bundled"); (2) are innovative since current solutions fail at addressing groundwater overexploitation and degradation; and (3) create a sense of collective belonging among participants. It is increasingly emphasized in the literature that building a collective and finding common ground between stakeholders must be a prerequisite for finding solutions (Dumont et al., 2021). Indeed, stakeholders concerned by groundwater issues often have contrasting visions and partial knowledge of these problems. Yet their beliefs and norms are key in decision-making (Salehi & Bijani, 2023). As a result, they may propose solutions that are partial, ineffective, ill-suited to the context or contradictory or refuse to accept solutions proposed by other stakeholders. Additionally, identifying solutions without building relationships of trust between stakeholders or a sense of collective belonging increases the risk that the solutions identified will not be accompanied by sound governance and therefore will not be implemented (Closas & Villholth, 2019). This needs to move from a "command-and-control" approach to a greater consideration of care and forms of community solidarity and collective action for aquifers is increasingly emphasized by researchers (Kulkarni, Shah, & Vijay Shankar, 2015; Zwarteveen et al., 2021). Some examples of how to implement these new approaches exist (Wester, Hoogesteger, & Vincent, 2009), but they are few and more feedback is needed from other case studies around the world.

The experiment presented in this paper aims at filling these gaps, with a focus on the situation in the Maghreb and Tunisia in particular. It presents and analyses a policy-design experiment that was led in the Lymaoua area in Southern Tunisia in 2021 and 2022 to support the participatory identification of solutions to face groundwater overexploitation and degradation in the area.

2 | MATERIAL AND METHODS

2.1 | The Lymaoua area

The Lymaoua area is located in the Gabes governorate in South Tunisia (Figure 1). The area belongs to the Jeffara aquifer system,

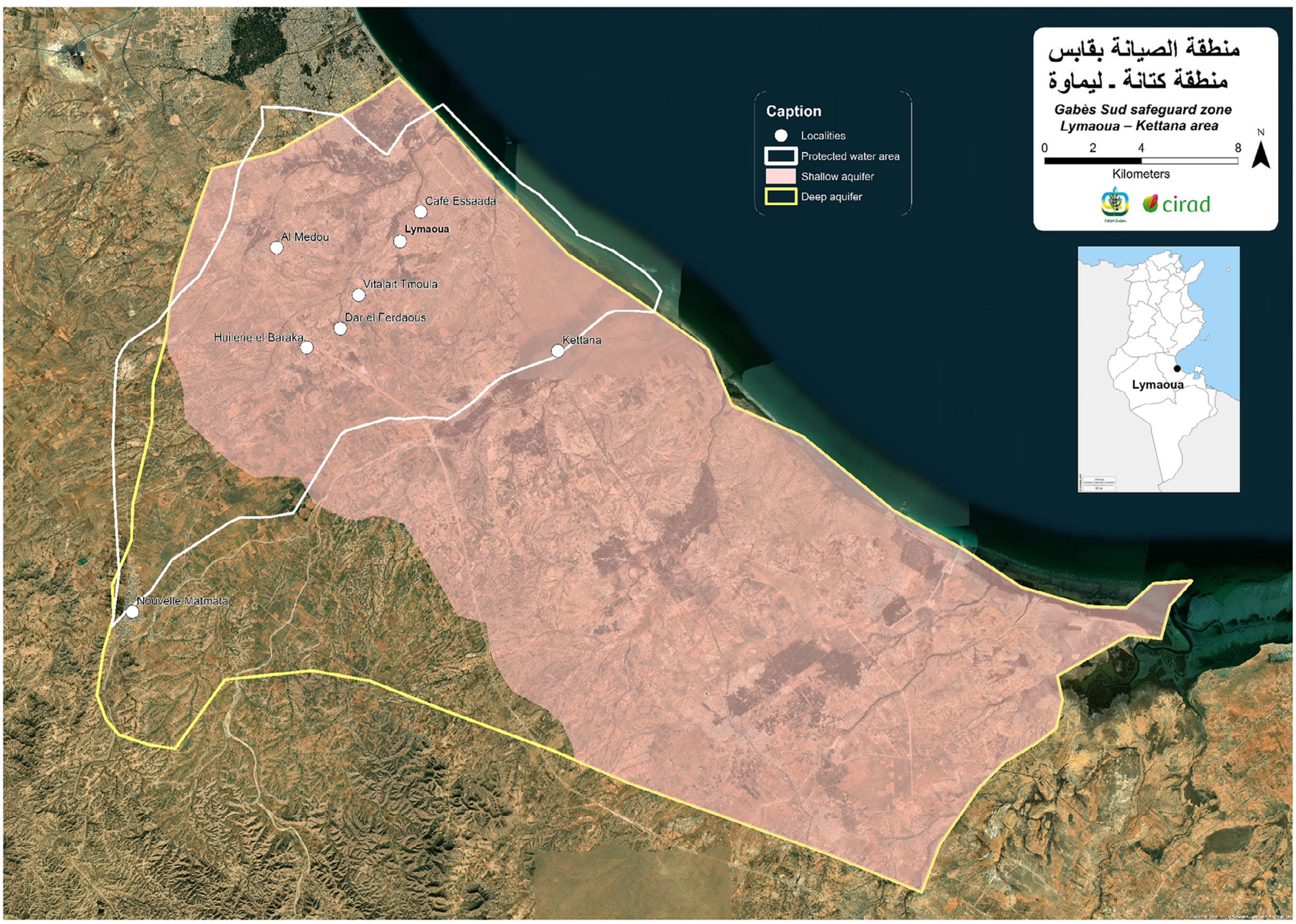

FIGURE 1 **Location of the Lymaoua area and its groundwater resources** (CRDA, elaborated by J. Bourgoin, 2022).

which is composed of three aquifers: Gabes North, Gabes South and El Hamma Henchou (Vernoux & Horriche, 2019). The main water resources used in the area come from the lower senonian carbonate aquifer, which is part of the Gabes South aquifer and is located at a depth of 60–250 m. The case study area corresponds to the "safeguard zone", which is an area established in 2017 by the administration to limit the number of drillings. Since then, no more permits are issued for drilling over 50 m, but surface wells shallower than 50 m can still receive permits.

The water resources of the Gabes South aquifer are estimated at 36 million cubic meters per year. The exploitation is estimated at 47 million cubic meters per year (CRDA, 2016). The average rainfall is 180 mm per year. Several streams cross the area and flow into the sea, but their flow is limited. Exploitation of the Jeffara's deep aquifers has doubled over the last 50 years (Vernoux & Horriche, 2019). This over-exploitation has led to a quasi-drying up of the springs supplying the oases and a fall in piezometric levels.

An inventory of water-extracting points conducted in 2021 identified 1597 water points within the Gabes South aquifer, including 89 public wells, 558 private wells, 887 simple wells and 196 illicit water points. About 60% of the water points are equipped, mainly with electric motor pumps (77% of equipped water points), diesel motor pumps (10%) or photovoltaic motor pumps (3%). The number of water points within the Gabes South aquifer has considerably increased, especially since the Revolution in 2011 and the creation of the safeguard zone in 2017, which marked the beginning of several drought years.

Water in the Lymaoua area is mainly used for agricultural purposes, especially arboriculture, including olive, pomegranate, almond, citrus and vineyards. The area currently includes about 630 farmers. Most of them are large farmers owning plots from 10 to 300 ha, but the area also has six public irrigated perimeters managed by water users' associations which are called "agricultural development groups" (GDAs) in Tunisia.

The area benefits from the good quality of the soil, access to grid energy and road infrastructures allowing easy access from the city of Gabes. These advantages have attracted many new arrivals over the last fifteen years, especially wealthy populations who have acquired land. Most of these installations have been accompanied by the creation of boreholes and surface wells, licit or illicit, leading to overexploitation of the aquifer. The annual drop in the aquifer level is between 0.4 and 1 m, leading to farmers' concerns about the decreasing of water resources availability. The creation of the safeguard zone created tensions between farmers and the administration, and the number of boreholes, particularly illicit ones, continued to increase. This situation could worsen in the coming years with the risk of saltwater intrusion from the coast and the passage of the area into a "prohibited area", which would mean stronger sanctions than at present.

In Tunisia, most GDAs are associations of irrigators managing irrigated areas with water from public boreholes or public surface water networks. Under these conditions, the administration can control the volume of water used (Frija et al., 2014). But in private irrigated perimeters, each farmer has his own well or borehole and assumes the costs of water extraction and maintenance of his irrigation network. Monitoring access to the aquifer is difficult and the local administration is not in a position to enforce the law in practice. Only one case in Tunisia has implemented collective management of private irrigated perimeters through a GDA. This is the irrigated perimeter of Bsissi Oued El Akarit created in 2001 and located a few kilometres north of the Lymaoua area. Strengthened by this experience, the actors of the regional administration in charge of agricultural development (CRDA of Gabes) wanted to duplicate this experience in Lymaoua.

2.2 | The P-KCP methodology

Within this context, French and Tunisian researchers met with the Gabes regional administration in 2021 and they decided to implement a participatory process for co-designing solutions to face groundwater overexploitation and degradation in the area. The participatory process started in 2021. It relied on the P-KCP tool for collaboratively structuring problems and for the innovative generation of policy alternatives (Pluchinotta et al., 2019). P stands for policy, K for knowledge, C for concepts and P for proposals. The P-KCP tool is based on the C-K theory (Hatchuel & Weil, 2009). It has been developed and used within the policy design and decision science research fields. P-KCP appeared as a relevant tool for identifying innovative solutions, bundled solutions and creating a sense of collective belonging among participants, as it formalizes and supports the creative process and knowledge co-production in multi-stakeholder settings. Specifically, C–K theory explains that the design process happens through the co-evolution of two expandable spaces: the Knowledge space (K-space) and the Concept space (C-space). This interaction helps understand how learning (K-space) and the creation of new ideas (C-space) work together. The K-space represents all the existing knowledge relevant to a particular design or problem-solving process. The C-space, or C-tree, is a visual representation of the different concepts or ideas generated during the design process. It starts with an initial concept and branches out into various sub-concepts and alternatives. Each branch represents a different direction or possibility that can be explored. The C-tree helps in organizing and structuring the creative process, making it easier to see how different ideas are connected and how they evolve over time.

According to Pluchinotta et al. (2019, 2020), C–K theory provides a framework for the design process that applies to any field. It emphasizes that creative thinking, learning, organizing knowledge, sharing knowledge and innovation are central to the theory. Therefore, C–K theory helps identify the limitations of traditional methods of group creative design (Hatchuel et al., 2015).

From an operational perspective, the P-KCP participatory tool consists of three key phases:

1. Policy–Definition Phase: This phase focuses on identifying key topics and relevant expertise to support the development of policy alternatives. It includes data collection and scoping interviews.

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2. Policy–Knowledge Phase: The goal of this phase is to reach a collective problem formulation agreed upon by all participants. It involves gathering missing information, creating a comprehensive summary of current knowledge about the policy issue, and conducting workshops 1 and 2.
3. Policy–Concepts Generation Phase: This phase aims to generate policy alternatives using the C–K theoretical framework. It includes a one-day generative workshop (workshop 3).

Finally, the Policy–Project Phase uses the K-space and the C-space generated in the previous steps to build actionable policy projects and strategies. For further details, the reader should refer to Pluchinotta et al. (2019).

Concretely, these three phases were implemented in Lymaoua through a multi-step participatory process (Figure 2). The first step was to start building the knowledge space on the issue and the case study through a literature review. Afterwards, the research team elicited and analysed the different knowledge and values hold by various actors attached to the issues and to the area. Seventeen semi-structured interviews were made by a member of the research team (Table 1). The sample size was limited by the impact of the COVID-19 pandemic on research activities, which restricted fieldwork and face-to-face interviews. Despite these challenges, broad representation was ensured by categorizing stakeholders into eight distinct groups based on expertise, land size and institutional role (Table 1). Farmers were grouped according to the size of their agricultural land, while administrative representatives and researchers were classified separately. This categorization ensured that diverse perspectives and understanding on the problem under consideration (namely, groundwater management) were represented effectively (see (Pluchinotta, Salvia, & Zimmermann, 2022). Language barriers, particularly between Arabic- and French-speaking participants, added to the logistical difficulties. While no strict quantitative threshold was applied, stakeholder selection ensured diversity and inclusivity, in line with similar studies where cognitive maps are constructed from interviews. In addition, during the interview, participants were given the opportunity to suggest other stakeholders for snowball sampling. A detailed table of stakeholder groups was provided to increase transparency. Thus, although the sample may appear small, it provides a well-representative cross-section of relevant perspectives within the given constraints.

TABLE 1 Stakeholders and interviews.

Stakeholder group	Number of interviews	Description
State and Administration	3	Representatives from territorial extension unit (*Cellule Territoriale de Vulgarisation*, CTV), CRDA-1 and CRDA-2, responsible for water resource management and policy implementation.
Agricultural Development Groups (GDA)	4	Representatives from four GDAs (GDA-A, GDA-B, GDA-C, GDA-D) involved in agricultural development and irrigation management.
Tunisian Union of Agriculture and Fisheries (UTAP)	2	Two members from UTAP (UTAP-1, UTAP-2), representing agricultural and fisheries stakeholders.
Local Researchers	2	Two researchers (Researcher-1, Researcher-2) providing academic and technical insights on groundwater management.
AGRI-1 (Large Farmers: >50 ha)	2	Two large-scale farmers (A-1, A-2) managing agricultural land over 50 ha.
AGRI-2 (Medium Farmers: 10–49 ha)	2	Two medium-scale farmers (A-3, A-4) managing agricultural land between 10 and 49 ha.
AGRI-3 (Small Farmers: <10 ha)	2	Two small-scale farmers (A-5, A-6) managing agricultural land under 10 ha.
AGRI-4 (External Investors)	2	Two farmers (A-7, A-8) investing in agricultural land in the region but originally from outside.

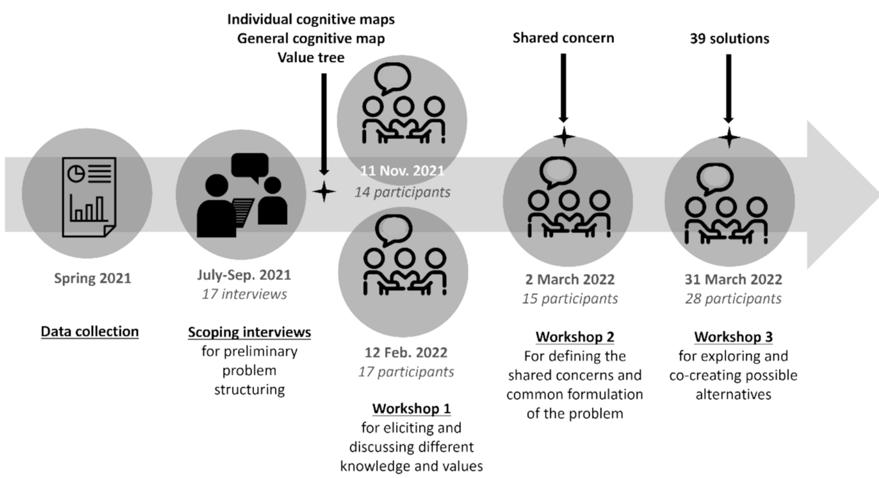

FIGURE 2 Overview of the participatory process in Lymaoua using the P-KCP methodology.

Stakeholders from each group participated in a semi-structured interview guided by a carefully designed interview protocol, that included follow-up questions to clarify and validate responses. The interviews included questions about interviewees' roles and objectives, their fundamental value (What do you want to achieve? Why?), their vision of the problems, their causes, consequences and the interrelations among those, as well as about main strategies available and initial ideas for resolution actions (Appendix 1). By structuring the discussions around key concerns and policy-related issues, both the specific priorities of each group and their broader understanding of groundwater management were captured.

Interviews were transcribed and they formed the basis for the development of a cognitive map for each stakeholder group. Cognitive maps are models representing how reality is perceived by an individual (Eden, 2004). They take the form of graphs, illustrating groundwater problems, their causes and consequences (i.e. concepts) as well as the links among them. For instance, in Figure 3, the fact that public boreholes are insufficient (concept 1) leads to the creation of illicit wells (concept 2), which in turn leads to the overexploitation of groundwater (concept 3), etc. Once the group-level maps were constructed, the research team aggregated them into a comprehensive cognitive map (Figure 3). This process required careful synthesis to preserve unique perspectives while identifying common elements. The fundamental value of agricultural production emerged consistently across all groups and provided a central reference point for integration. Using responses from the interview guide, the team identified key sub-nodes and structured the aggregated map to reflect both shared concerns and distinct perspectives. If conflicting fundamental values had emerged, separate maps would have been necessary, but the consensus around agricultural production allowed for a unified cognitive structure.

Researchers also elaborated a value tree based on the interviews and cognitive maps (Tosunlu et al., n.d.). A value tree is a simplified diagram with a tree structure representing hierarchically the main shared or conflicting values among various stakeholders when faced with a given problem (based on Pitz & Riedel, 1984). The value tree can help raising creativity and generating unknown solutions. For example, if a group wants to design a house, and if mobility is their value, they can think of a house with wheels, which they might not have thought of without the value tree. In the Lymaoua case, "Agricultural production" was the fundamental value shared by most interviewees, along with securing electricity and water availability.

Two initial workshops were organized to present the participatory process and share available knowledge. The choice to separate large

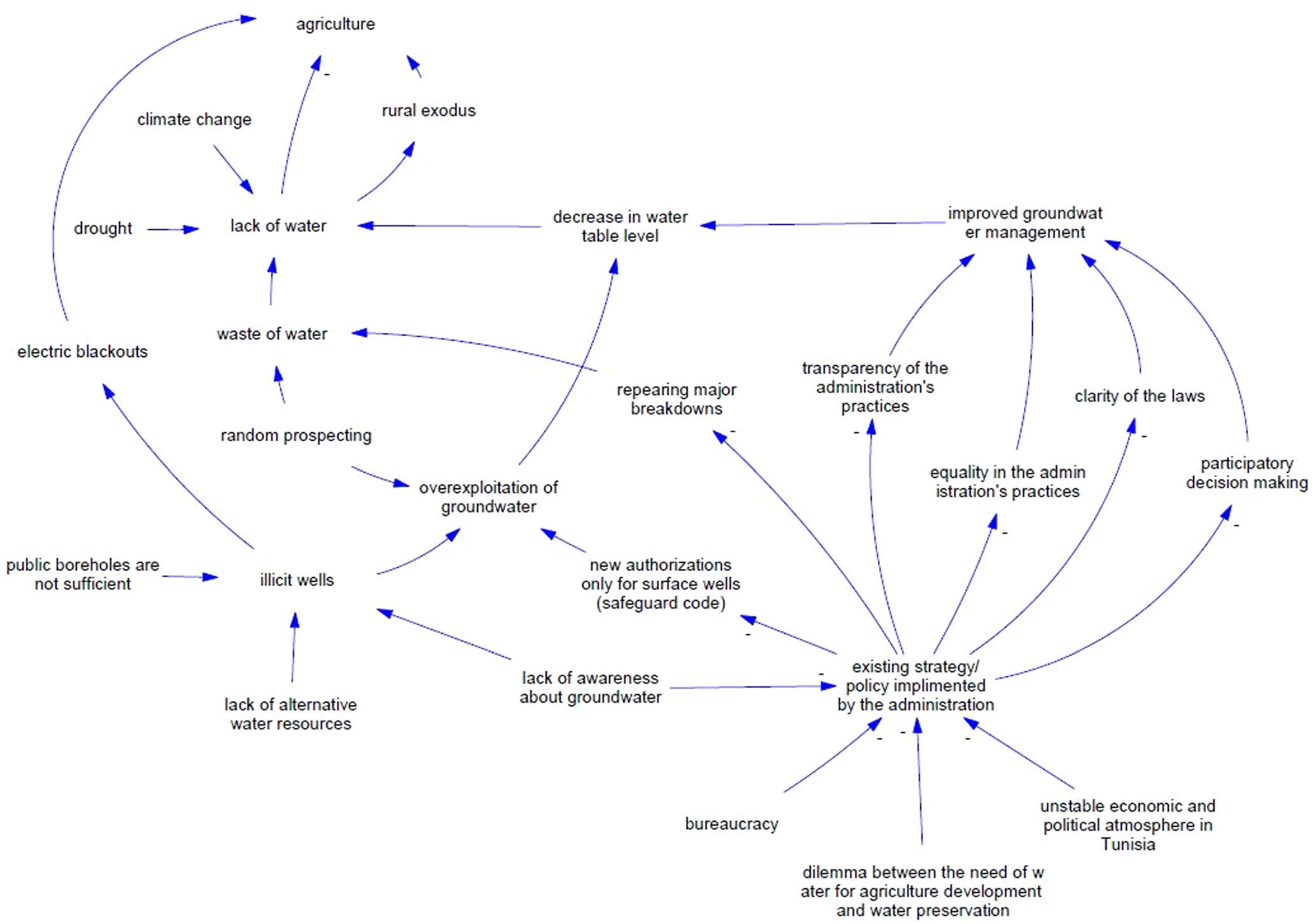

FIGURE 3 The general cognitive map.

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and medium-sized holder farmers from small-holder farmers aimed at reducing unbalances, allowing participants to speak more freely of their issues. The two workshops gathered 31 participants[2] Representatives of the administration and researchers participated in both workshops.

The consequent step involved the identification of shared concerns among the different actors and the common formulation of the problem during a second workshop. The general cognitive map was presented and discussed with participants. Differences and similarities in the participants' problem understanding were underlined during the discussion. Participants then agreed on a common formulation of their shared concern: "Our objective is to find solutions for a good participatory water governance guaranteeing a sustainable agriculture and an increase in farmers' income through the creation of an organization".

The last step consisted of the participatory exploration of possible alternatives and solutions to address the shared concern and thus, how to collectively manage Lymaoua groundwater (workshop 3). Participants were divided into two heterogenous groups and they identified and then shared solutions. A dedicated facilitation supported the application of the P-KCP principles, namely primarily identifying solutions already known by stakeholders, and then formulating innovative solutions by exploring alternative paths of the concepts space (as described in Agogué et al., 2014). Participants were then asked to identify and vote what they considered were the most innovative solutions using sticky-dot stickers. The workshop ended with a self-facilitated discussion among participants regarding the next steps.

Sixty-two individuals were involved in the process (Table 2): administration (8), researchers (2), association (1) and farmers (51). All farmers in the area were invited.

The participatory process was engineered by researchers and the regional administration in charge of the agricultural development of Gabes, all co-authors of this paper. All workshops were held in the Tunisian dialect. Detailed reports of each workshop were produced.

The participatory process described in this paper is only the beginning of a longer-term participatory process aiming at supporting the sustainability of groundwater resources, supply, use and governance in Lymaoua. Following the three workshops, the participants created a collective organization to manage groundwater in Lymaoua. The next steps involve, among other aspects: (i) engaging other farmers; (ii) build an integrated groundwater management plan; (iii) experimenting and testing the integrated plan thanks to a dedicated tool (serious game). These steps fall out of the scope of this paper and are described elsewhere (Boulay, 2023; Kekli, 2023; Hassenforder et al., n.d.).

3 | RESULTS

Before the implementation of the participatory process, several groundwater management instruments were implemented in the Lymaoua area. These include the "safeguard zone" mentioned above, sanctions against illicit boreholes (fines, blocking, uprooting) and subsidies (for drip irrigation, olive tree planting, agricultural equipment, etc.).

TABLE 2 Number of participants in the process.

Number of participants who ...	
Were only interviewed	12
Attended one workshop	33
Attended two workshops	11
Attended three workshops	4
Attended four workshops[3]	2
TOTAL number of participants	**62**

[3]Two participants attended both workshops 1.

The last workshop resulted in the identification of 39 different solutions (Table 3). Some solutions are very broad (e.g. #1 Prioritize agriculture), while others are very specific (e.g. #26 To have a department within the GDA in charge of water resources). The breadth of the alternatives is primarily due to the fact that the P-KCP methodology aims at widening the space of solutions rather than at specifying the proposals made.

3.1 | Bundles of solutions

In this article, the term 'bundles' is borrowed from Barrett et al. (2020). Following these authors, it can be argued that contextualized combinations of solutions, coupling technological advances with sociocultural and policy changes and encompassing water, energy, land and food production, are needed to address pressing groundwater degradation and overexploitation issues.

Almost all of the 39 solutions in Table 3 are linked to agricultural production. Some are directly linked to agriculture (e.g. #2 Use of crops that require less water, #10 Training for farmers in several areas related to agriculture), but most are indirectly linked to agriculture, e.g., through water or social structures (e.g. #37 Use water-saving irrigation techniques or #17 Create an organization to organize farmers in the area). This is due in part to the initial framing of the participatory process, which focused on the use of groundwater for irrigation. It also reflects the fact that "agricultural production" was identified as the fundamental value for most participants.

Energy is only mentioned directly in two solutions (#8 Encourage people to use free solar energy and #33 Subsidize farmers using electric or solar energy with 40% of the costs of the electrical installation). The small number of energy-related solutions is probably due to the fact that electric grid power is available in most of the area. In the interviews, however, concerns were particularly raised about black-outs affecting, and affected by, groundwater pumping. Those who have solar energy do so either to reduce their bill or to feed illicit boreholes as solar energy has lower ongoing costs than grid energy.

[2]The number of participants mentioned in the paper do not include the engineering and facilitating team.

TABLE 3 The 39 solutions identified.

#	Solutions	Innovations (number of votes)
1	Prioritize agriculture	
2	Use of crops that require less water	
3	Have more available phytosanitary products	
4	Give new authorizations	
5	Non-corruption: equality	6
6	Regulate the situation of illicit drilling and legalize it + give new authorizations	2
7	Collective authorizations for small farmers	1
8	Encourage people to use free solar energy	
9	Help farmers to pay back their debts	1
10	Training for farmers in several areas related to agriculture	2
11	Support and awareness-raising for farmers	
12	Awareness-raising workshops for farmers on the importance of groundwater preservation	
13	Create new laws to limit the number of illicit drillings	
14	Revise existing laws concerning the functioning of GDAs	1
15	Monitoring and control by the administration	
16	Control of illicit drilling	
17	Create an organization to organize the farmers in the area	
18	Form the executive board of the organization on the basis of elections	
19	This organization must sensitize the farmers	
20	To know the sources of financing for the activities of this GDA	1
21	Establish a relationship of trust between the different members	
22	The GDA must be managed through regulations; the executive office must be controlled and monitored by farmers	
23	Participation and membership of different farmers in the organization (GDA)	
24	Make regular and simple evaluations of the work of the GDA	
25	Special membership fees for farmers	
26	To have a department within the GDA in charge of water resources	
27	Involve qualified people in the management of the GDA	
28	Hold meetings at the national and international level with other farmers who have had experience in creating this type of organization	
29	Involve more the agricultural development groups in the decision-making process	
30	Help and support the GDAs by maintaining public wells and installing water-saving irrigation systems	
31	Organize the agricultural development groups of the public irrigated perimeters	
32	Make regular meetings with the CRDA, APIA and the various stakeholders	
33	Subsidize farmers using electrical or solar energy with 40% of the costs	
34	Administrating subsidies' demands more rapidly	
35	Maintenance of public wells	
36	Desalination of sea water	
37	Use water saving irrigation techniques	
38	Use variable speed drives for boreholes	
39	Have more water for irrigation	

Note: GDA = agricultural development group, CRDA = regional administration in charge of agricultural development, APIA = Agency for the Promotion of Agricultural Investments. "Innovations" refers to the number of people who considered the solution to be innovative. The fact that 12 solutions (#17 to #28) out of 39 relate to the creation of a collective farmers' organization was influenced by the fact that the administration encouraged farmers to create such an organization, especially in the invitation letter for attending the workshop.

The case of Lymaoua is really illustrative of the "conflicting SDG targets" mentioned by Guppy et al. (2018) among them target 6.6 "By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes", 2.1 End hunger, 2.3 Double agricultural productivity and 7.1 Access to energy. The crux of the issue also involves target 6.4, with the challenge of ensuring sustainable water withdrawals and supply. In Lymaoua, the increase in illicit drilling, and therefore overexploitation of groundwater, is enabled by the increase in solar energy use, as has been shown elsewhere in the world (Shah et al., 2018). In the solutions mentioned by participants, encouraging farmers to use free solar energy will most likely decrease their costs and thus increase their income, but also increase their production as they can pump more and longer. But it may also have adverse effects on groundwater depletion. In parallel, State programs relating to agricultural intensification since the 1980s have led to a race to irrigation, to an extension of irrigated perimeters and ultimately to the creation of illicit wells (Gana, 2008). Lymaoua is no exception. If the 2016 investment law seems to take more into account these environmental effects, it nevertheless encourages investment in renewable energy that can have an adverse impact on groundwater. Similarly, the National Agency for Energy Management subsidizes renewable energy for all drilling.

In Lymaoua, access to grid and solar energy has mainly attracted large farmers and investors to the detriment of small farmers who do not have the financial resources to invest in solar panels or in water storage. Thus, the development of energy alone may also have a detrimental effect on equity, and therefore on the achievement of SDG 16 regarding just, peaceful and inclusive societies.

In conclusion, identifying solutions to groundwater problems alone is not enough. It is also necessary to take into account energy and agricultural production, not to mention land, equity and ecosystems' preservation aspects. The analysis of the 39 solutions in terms of their linkage to the SDGs highlights these interconnections, and shows that the future organization targeted by Lymaoua participants cannot be limited to groundwater management alone, but must also take these other aspects into account. The silo structure of the Tunisian administration makes this integration difficult. The creation of a co-management body, including both the administration and users, is, therefore, all the more relevant, provided that it encompasses responsibilities regarding groundwater, but also energy, agricultural production, land, equity and ecosystems' preservation. From a methodological point of view, this also means that the P-KCP process needs to be followed by a participatory planning step allowing Lymaoua participants to design an integrated plan and to select which solutions can help reach the expected impacts (P-proposal phase). Such participatory planning will support a reflection on the potentially contradictory impacts of the various solutions identified and will help organizing the implementation of the solutions in space and time (where and when).

3.2 | Innovative solutions

Innovations are defined in this article as "novel solutions for problems" based on Sartas et al. (2020). Solutions are considered as "innovative" when they have never been implemented in the intervention area, even if they are not intrinsically new.

Table 3 shows that only 14 participants out of 30 voted for the solutions that they considered innovative. A short interview with voters after workshop 3 revealed that some voted for solutions they considered priorities rather than for solutions they considered innovative. The results presented here should therefore be taken with caution. It however gives an indication of which solutions are considered innovative by local actors.

Of the seven solutions that received votes, five are solutions that exist elsewhere but are not currently in effect in Lymaoua (#5 Non-corruption/equality, #6 Regulate the situation of illicit drilling and legalize it + give new authorizations, #9 Help farmers to pay back their debts, # Training for farmers, #20 To know the sources of financing for the activities of this GDA).

Two on the other hand are solutions which, to the authors' knowledge, are not implemented elsewhere in Tunisia: #7 Collective authorizations for small farmers and #14 Revise existing laws concerning the functioning of GDAs. Collective authorizations relate to the possibility for farmers to get together to ask collectively the administration to have authorization for a new well. Usually, these requests are on an individual basis. Solution #14 is linked to the possibility to pay the people managing the GDAs, including the president and treasurer. Currently, these functions are unpaid. This creates difficulties in mobilizing qualified people to take part in decisions concerning the development of the area and to manage the GDA over the long term. The president of the GDA of Bsissi had testified to these difficulties when he came to attend the first workshop in Lymaoua. This meeting allowed Lymaoua participants to reflect on the potential and the limits of the application of the Bsissi governance model on their territory, and to come up with innovative solutions to supersede Bsissi's limits.

In conclusion, the participatory process did allow the identification of seven solutions that are novel for the Lymaoua territory and for local actors, even if few intrinsically innovative solutions were raised. Known or obvious solutions received substantial attention, perhaps indicating that overcoming implementation challenges is more important than identifying innovative solutions.

3.3 | Creation of a sense of collective belonging

Following Dudwick et al. (2006), "sense of collective belonging" is defined in this article as one dimension of social capital which focuses on "the tenacity of social bonds and their dual potential to include or exclude members of community. [It] can be demonstrated through community events, […], or through activities that increase solidarity, strengthen social cohesion, improve communication, provide learning for coordinated activities, promote civic-mindedness and altruistic behaviour, and develop a sense of collective consciousness.".

At the beginning of the participatory process, there were many tensions, especially between small and large farmers and between farmers and the administration over drilling permits. Notably, some groups of farmers were less likely to mention overexploitation as an issue, blame was commonly assigned to other parties, and there was varying existing knowledge about the state of the groundwater resource. One of the successes of this process was to create a dialogue between small and large farmers and to agree on a common understanding of the problem, a common objective, solutions to be implemented and the will to create a collective organization.

One of the main limitations of the process, however, was the lack of inclusion of women. Despite the team's repeated efforts to mobilize them, few women came to participate in the workshops. One should also note that the process only included 51 farmers out of 630 owning plots in the safeguard zone (8%). Farmers using groundwater from the same aquifer but owning plots outside of the safeguard zone were also missing.

At the end of workshop 3, participants discussed ways of mobilizing and engaging stakeholders who had not participated in the process so far so that they could be part of the future collective organization. From this, it can be deduced that the process created a sense of collective belonging among participants. One large farmer testified: "Water management and production cannot be in the hands of the farmer alone. It must be cooperative. It must be managed by the region or by the State. But it also needs investment in infrastructure and a clear legal framework for everyone to work together towards the same goal."

Nevertheless, some farmers doubt the ability of a co-management organization to solve problems that the State cannot, as evidenced by this tense dialogue during Workshop 3 (translated by the authors):

- (Man 1, CRDA)" I totally agree that the State should disengage and give the responsibility to the GDA and to the SMSA (mutual company of agricultural services). In return, the State is the only one responsible for everything related to subsidies. And you all know that there are farmers with illicit wells so they can't take aid and subsidies. Can this GDA inspired by Bssisi solve this problem by settling the situation of these farmers? We have to work together, the State is no longer represented by the administrations but rather it wants to involve all organizations.
- (Farmer): The administration with its executives is not able to do its role and it wants a simple GDA to do all this
- (Man 1, CRDA): The State wants to train responsible and autonomous farmers, the farmer is the engineer of his plot, the State no longer has the means: it lacks staff, cars …

[…]

- (Man 2, CRDA): "We want to preserve the resources. We have two choices: either apply the laws, give punishments and bury illicit drillings. This option will create conflicts. Or to manage in a participatory way the water resources because at the end water is a common good."

This tension between the desire for co-management as an actual sharing of responsibilities between users and the State, and the fact that this co-management could also be a way for the State to devolve its responsibilities underpinned the discussions throughout the participatory process. Some participants feared that the creation of a collective organization would mark a disengagement of the State, while others saw it as an opportunity to become more involved in decision-making concerning groundwater resources. These aspects were discussed on several occasions with members of Bsissi GDA, who reassured participants that the CRDA had not disengaged in Bsissi, and warned them about the steps to be taken to ensure an equitable sharing of responsibilities. At the end of the third workshop, Lymaoua participants decided to set up a collective organization based on the by-laws of Bsissi GDA, modulating them to ensure an equitable sharing of responsibilities. These debates have long been underlined in the literature (e.g. Romagny & Riaux, 2007), and various works exist highlighting the factors and conditions for achieving successful collective action in groundwater management (e.g. Shalsi et al., 2022). These researches fed the next stage of the participatory approach and the construction of the collective organization.

Another tension that underpinned the process was between the injunction to move forward quickly and to create an organization as soon as possible on the one hand and the desire, on the other hand, to take the time, through the workshops and the P-KCP methodology, to create a "sense of collective belonging". The first was promoted by certain members of the CRDA and certain farmers while the latter was promoted in particular by researchers and by another group of farmers. The engineering of the participatory process needs to take these tensions into account by providing time for the creation of a "sense of collective belonging" while moving forward quickly enough to avoid participation fatigue. Arguably, examples like the dialogue above suggest that the sense of collective belonging was not yet fully achieved, especially between farmers and the State.

4 | DISCUSSION: LIMITATIONS AND LESSONS LEARNT

Results from this study are in line with existing literature on the interaction between SDGs (e.g., Guppy et al., 2018), in particular between water and energy and between food production and water preservation. For groundwater, trade-offs arise between increased access to solar energy and sustainable supply of groundwater (Shah et al., 2018) and between agricultural production and limits to resource use (Rodríguez-Flores et al., 2023). In this Tunisian case study, however, it is clear that progress towards the SDGs depends not just on the identification and understanding of these trade-offs, but also on deeper issues. These issues include creating a sense of collective ownership, creating the institutions needed to develop bundles of solutions that cross existing institutional responsibility boundaries, and creating the conditions for effective collective action. The latter is particularly important in a disrupted post-revolutionary context in which the role of the State is contested. The participatory process reported here appears to have made progress towards these objectives but leaves a number of questions open, that are discussed below, with opportunities for improvement before scaling up to other regions in the Maghreb.

Some choices made regarding the participatory process limited its scope. The first aspect concerns the geographical area chosen, which influences the participants who were invited. In Lymaoua, researchers and the administration chose to focus initially on the safeguard zone, which corresponds to only part of the aquifer (Figure 1). This choice was made to limit the number of targeted participants and to start with an area where users felt concerned with the issue of degradation and overexploitation of the aquifer and were therefore easier to mobilize. From a hydrogeological point of view, a more logical delimitation would have been the aquifer as a whole. But should the delimitation be the shallow unconfined or the deep confined aquifer? And in the case of a system combining groundwater and surface water (which is not the case in Lymaoua), should the delimitation be the extent of the aquifer or of the watershed? Moreover, in Tunisia, water is managed at the governorate level, so a relevant delimitation could have been this administrative delimitation. Finally, insofar as the Lymaoua case has highlighted the need to take into account energy and agricultural production, land, equity and ecosystems' preservation aspects, other delimitations still could have been considered (power grid, agricultural value chain, etc.). Expanding the geographical scope of the current experiment could certainly have had an impact on the findings: one can assume that the involvement of other stakeholders could have led to the identification of other solutions, or even had an impact on the fundamental value. For example, the rest of the area located on the deep aquifer is more oriented towards tourism, which could have influenced the fundamental value, the common objective and the proposed solutions. Nevertheless, regarding the engineering and facilitation of the participatory process, starting with a small and motivated group seems a simpler and more operational idea than starting with a very large area and a wide range of stakeholders. It is then possible to extend the process to other stakeholders. This selection of geographical area naturally constrains the transferability of the findings. In theory, they apply to regions with comparable characteristics: a relatively small aquifer, primarily used for agriculture, where water users are directly impacted by the lowering of the water table. Another key aspect of this work was to identify 15 preconditions for successful multi-stakeholder dialogue on the sustainable and equitable co-management of groundwater resources (Hassenforder et al., 2024). These conditions serve as criteria for the transferability of the results presented in the current paper.

In addition, farmers' engagement was limited. Even though all farmers in the area were invited to the workshops, only 8% participated. This represents a relatively low percentage of users, even though specific efforts were made to ensure that the various categories of stakeholders were represented. Moreover, as mentioned above, gender representation was unbalanced, with less than five women taking part in the process out of the 51 participants. Similarly, landless people did not participate. As participation was voluntary, one can assume that most of the participants are people who feel concerned by the problem of groundwater degradation and overexploitation. The reason why other farmers did not participate was not analysed in detail. One reason given by some participants was the fear of having their access to groundwater restricted, particularly for users with illicit boreholes. This voluntary participation was a choice made by the engineering team in order to involve the most motivated farmers first so that they could then mobilize other stakeholders. The same choice had been made in Bsissi, and all users ended up joining the GDA as a result of social pressure from other members and the constraints associated with non-membership. Participants in Lymaoua are planning a similar strategy to mobilize stakeholders who have not yet taken part in the process. A door-to-door mobilization campaign has already been launched following the last workshop by members of the new collective organization's committee. The GDA is also planning to organize training in apiculture and irrigation management in order to show farmers what they can gain when becoming part of the collective.

Another aspect concerns the P-KCP methodology. Cognitive maps and value tree (Tosunlu, Guillaume, & Tsoukiàs, 2023) development imply a significant amount of modelling work. Interviews were therefore limited to 17. One can question whether such a small number can be truly representative of the different points of view in the territory. Moreover, since these models are relatively complex, the choice was made not to show them to the stakeholders, apart from the general cognitive map (Figure 3), after having been simplified beforehand. Only key learnings from the maps were shared with the stakeholders. Insofar as these models are in the end quite similar to other models (e.g. ARDI, see Etienne, du Toit, & Pollard, 2011), one may wonder whether other forms of modelling, still allowing to elicit different problem understanding but more easily mobilized with participants, would not be more relevant for the first stages of the process. Another possibility could be to use art (painting, theatre, poetry, music or else) to represent and discuss the different points of view in the territory (for a discussion about this, see Cham, 2010).

Finally, the methodology did not include yet the analysis of whether the 39 solutions identified are really relevant and feasible for the area, as it focused on the creative phase of innovation solutions. The last phase of the P-KCP participatory tool (P-Proposals) is key in this respect. This phase allows participants to develop an integrated plan and detail how the identified solutions can be concretely implemented while considering the potentially conflicting impacts of the selected solutions. A methodology such as CoOPLAN (Ferrand et al., 2024) could be particularly relevant to support this phase. It would enable participants to 1/assess the feasibility of the identified solutions and 2/determine whether these solutions may achieve the expected social, economic, environmental or other impacts. The 39 solutions identified using the P-KCP method in Lymaoua (Table 3) are primarily regulatory, financial and capacity-related. An integrated planning approach helps assess whether these solutions cover all aspects of integrated territorial planning. This planning process also includes considering how solutions will be monitored and evaluated in the future, as well as the governance arrangements needed to implement these solutions and adapt to future changes in the area.

As part of the Lymaoua process, the following are planned for 2025–2026:

- To define a "territorial charter" setting out the principles for sharing and accessing the various resources in an equitable and sustainable manner. In particular, this would enable to better include women, landless people and other stakeholders in the process.
- To hold two workshops on the internal and external governance of the GDA. The workshops aim at reflecting on the roles and responsibilities of the various people involved in the GDA, on relationships between the GDA and other players as well as to create adaptive and anticipatory governance capacities.
- To co-design a groundwater management plan using the CoOPLAN approach and based on the 39 solutions identified using the P-KCP approach, but also drawing on solutions implemented elsewhere (Bouzidi et al., 2023). Stakeholders will then be able to test the impact of the bundles of solutions identified using a role-playing game developed for that purpose, Ground-WAG-Er (Hassenforder et al., n.d.).
- To develop a territorial observatory to monitor territorial dynamics and changes, to assess the impact of the solutions that will be implemented, and to support the GDA's decision-making process.
- To use anticipation to develop a vision for Lymaoua at horizon 2035 or 2040, enabling future changes in the area to be better anticipated.

Effective change in Lymaoua can only be achieved through a comprehensive territorial approach such as the one presented above. The P-KCP methodology alone is insufficient. This territorial approach requires that the collective organization established by Lymaoua participants encompasses more than just groundwater management; it must also address energy, agricultural production, land use, social equity and ecosystem preservation. This holistic approach is innovative for Tunisia, as most existing GDAs focus solely on water management. The new Water Code, currently in preparation, aims to expand the scope of these collective organizations. Moreover, a territorial approach necessitates the involvement of diverse stakeholders, including administrators, elected officials, citizens and researchers from various disciplines. These recommendations could be applied to other regions facing similar groundwater challenges.

5 | CONCLUSION

This article aimed at applying a participatory approach for the design of innovative solutions, bundled solutions and creating a sense of collective belonging among participants. The implementation of this approach in the Lymaoua area, in southern Tunisia, allowed us to draw the following conclusions.

Firstly, the P-KCP methodology allowed identifying solutions coupling technological advances (ex. #38 in Table 3) and sociocultural and policy changes (#21, #14) and encompassing both water and energy. It therefore allowed the emergence of bundles of solutions. Analysis of the linkage of the 39 solutions to the SDGs highlighted that certain aspects that are key for groundwater sustainability are not covered by the 39 solutions (e.g. land) or are conflicting (e.g. energy water and equity). Secondly, the P-KCP methodology allowed the identification of seven solutions that are novel for the Lymaoua territory and for local actors in a participatory setting. Even if few of the solutions identified are intrinsically innovative, one can hypothesize that participants will be more inclined to implement this future plan and respect the associated management principles to the extent that they themselves have proposed some of the solutions included in the plan. Beyond the solutions identified, the process has above all helped to create a sense of collective belonging among participants, creating a foundation of trust that should maximize participants' commitment to the rest of the process and to the sustainability of the collective organization they have created. Furthermore, knowledge was shared and also co-created during the participatory process, allowing to reduce the level of conflicts among the stakeholders and differences in problem understanding.

From an operational perspective, these results underscore the importance of focusing on the last phase of the P-KCP participatory tool (P-Proposals), eventually coupling it with a participatory planning tool. They also highlight the need for a comprehensive territorial approach to achieve effective change.

The results suggest several avenues for future research. First, exploring modelling techniques that are more accessible to participants than cognitive maps could be beneficial. Additionally, using art to represent and discuss the system's complexity shows promise. Second, when identifying different solutions, integrating the P-KCP methodology with a framework focusing on SDG interlinkages could diversify the range of solutions and address trade-offs, both in terms of themes (water, energy, food production, etc.) and types of solutions (regulatory, financial, social, etc.). Finally, more feedback and concrete evaluations are needed to assess the effectiveness of integrated territorial approaches, like the one mentioned above, in promoting sustainable and equitable groundwater management and achieving the SDGs.

ACKNOWLEDGEMENTS

The Lymaoua experiment was held with the financial support of the LAMSADE joint laboratory of Université Paris Dauphine and the CNRS. The authors thank the LAMSADE for this support. This work was also made within the ANU-CNRS collaboration program and thanks to the long-lasting partnership between ANU and G-EAU joint research unit. Support and feedback were also provided by the Policy Analytics research group (3720 https://www.lamsade.dauphine.fr/wp/gdr3720) and by members of the Sirma partnership (https://www.rcp-sirma.org). The authors are grateful for the valuable feedback and reviews received. Finally, yet importantly, the authors thank all the people who have contributed to the Lymaoua participatory processes, as participants, organizers, experts, facilitators and observers.

DATA AVAILABILITY STATEMENT

Data available on request from the authors.

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How to cite this article: Hassenforder, E., Chrii, S., Pluchinotta, I., Tosunlu, H.B., Ghoudi, R., Braiki, H. et al. (2025) Identifying solutions to face groundwater overexploitation and degradation: A policy design experiment in Tunisia. *Water and Environment Journal*, 1–15. Available from: https://doi.org/10.1111/wej.12986

Water and Environment Journal
Promoting Sustainable Solutions
CIWEM —WILEY

APPENDIX

KEY QUESTIONS USED FOR THE SCOPING INTERVIEWS

#	Question	Objective
1	What is your name and surname?	Stakeholder identification
2	What is your job title and for what organization do you work?	Stakeholder identification
3	(if relevant) What is the main mission/goal of your organization with regards to the *case study topic?*	Organization's objectives
4	What is your role with regard to the *case study topic?*	Stakeholder's role and objectives
5	What are your interests in the *case study topic?* What do you want to achieve? Why? (prompt: Do you have any target that you would like to reach/achieve? What is your main concern in relation to the case study topic?) *Notes:* **Asking the "why" is key here. For reasoning and logical flow, it would be beneficial to ask 'why/why do you think this?* **Examples: maximize water consumption, minimizing the pollution)*	Stakeholder's fundamental value
6	According to your experience, what are the main problems related to environmental/water faced by the *case study*? (prompt: Could you briefly describe them?) *Notes:* **You should take notes on every problem that they mention, and ask the stakeholder if any of these problems are forgotten or misunderstanded by other stakeholders.* **Listing/numbering the problems will help you with questions 7, 8, 9 when you need to return to them (problem 1, problem 2, etc).* **We will have transcripts, therefore these notes are only for you and for the interview.* **It is very difficult to receive precise answers to questions 7, 8, 9, you should not feel stressed about this, just try to follow their reasoning and lat them talk, without forgetting the problems that they mention.*	Case study problems
7	For each of the above-mentioned problems, what are their causes? (prompt: Why?)	Causes
8	For each of the above-mentioned problems, what are the main consequences? (prompt: Why?)	Consequences
9	Do you think the problems that you mentioned are linked? if yes, how? (prompt: Are there any relations between the problems mentioned above that are worth mentioning?)	Relationships
10	(if relevant, this is not a question for all the stakeholders) According to your best knowledge, what are the existing main strategies/policies/plans or informal agreements that are (or will be soon) implemented in order to deal with the above-mentioned problems?	Identify the main strategies available, K-space building.
11	What could you personally do to contribute to the resolution of these problems? Why do you think this idea will be successful? (if possible) For each mentioned problem what is your idea of possible solutions?	Initial ideas for resolution actions (future scenarios, individual actions) C-space building
12	Given what you have previously said about what you want to achieve, which of the strategies/ actions do you feel are most important? Why? *Notes:* **Asking the "why" is key here. For reasoning and logical flow, it would be beneficial to ask 'why/why do you think this?* **We would like to identify links that reach the fundamental concern that could be related to a fundamental value, here by looking at it from a means-ends perspective. This provides a consistency check against the more direct question 5.* **For example, If my main concern is pollution, an environmental restriction on the firms could be the action that I feel most important. In this situation, we can explicitly see the means-ends relationship*	Eliciting means-ends relationships
13	For each of the above-mentioned problems, who has this problem? And who is responsible for it?	Contribution to stakeholder analysis
14	All in all, what is the fundamental outcome you would like to achieve in relation to the *case study topic?* *Notes:* ** Previous questions focus generally on objectives and means-ends. At the end of the interview, the aim here is to ask them to reflect on everything they've said and pull out their fundamental objective. This may be different from what they have previously said they want to achieve, because they've explored the topic further.* **other prompt questions: What is your fundamental/final goal for resolution of the problems afflicting the case study? Why do you care about the problems afflicting the case study?*	Stakeholder's fundamental value follow-up
15	Is there anyone else you think we could usefully speak to?	Stakeholder snowballing