Using stakeholders network analysis to enhance groundwater and landscape governance: A case from arid areas in Tunisia

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Abstract

This paper examines groundwater and landscape governance in irrigated areas of central Tunisia, (North Africa). A stakeholders' network analysis was employed to characterize the landscape and assess governance dynamics. The results highlight the necessity of developing inclusive and effective groundwater management policies in Tunisia, which may also be applicable to other North African and Middle Eastern countries facing similar water-related challenges. Key points include addressing the irregular distribution of network influence in groundwater governance, fostering more inclusive and collaborative governance approaches, intentionally engaging less connected actors, and leveraging the centrality of network hubs.

Keywords*: Groundwater, Landscape governance, Irrigated areas, Network analysis, Inclusive, Collaborative, Tunisia.*

1. Introduction

Sustainable agricultural development is essential for addressing global challenges such as food security, rural livelihoods, and environmental conservation (FAO, 2017). Yet, in many developing regions, water scarcity poses a major constraint on the productivity and viability of agricultural activities. Groundwater (GW) serves as the primary source of irrigation water supporting the viability of the agricultural sector and the livelihoods of local populations in several countries (Giordano, 2009). Accordingly, effective groundwater governance is imperative for ensuring the equitable and sustainable water resources use, particularly in areas where surface water supplies are limited (Knieper *et al.*, 2010).

The study of water governance requires landscape governance, which recognizes the complex relationships between water resources, land use, and socioeconomic issues within a landscape (Ghiotti, 2016). The integration of water management into landscape governance is essential for fostering development, needing a muli-stakeholder approach involving governments, local communities, private entities, and

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civil society organizations. A landscape is a socio-ecological system comprising both natural and human ecosystems (Scherr *et al.*, 2013). Landscape and water governance (WG) are interconnected and mutually influential components of environmental management and sustainable development. Landscape governance embraces decision-making processes, resource management strategies, and actions that shape landscape use, conservation, and management. Within this broader context, WG focuses specifically on the management, allocation, and preservation of water resources (Zagt *et al.*, 2017).

Effective landscape governance requires the development of transparent and inclusive decision-making processes, the enforcement of policies and regulations which protect natural resources, the provision of incentives for sustainable resources use practices and the recognition of rights and needs of local communities (Kusters *et al.*, 2020). However, the dissimilar values and interests of multiple stakeholders, at different scales, present challenges for landscape governance (Kozar *et al.*, 2014). At the same time, efficiently managing and harmonizing water resources use with food production needs an obvious examination of the roles played by local water management institutions and related development areas (Nabiafjadi *et al.*, 2021). As highlighted by Knieper *et al.* (2010), a greater understanding of governance systems is critical for effective natural resource management. However, despite some limited success stories (Naustdalslid, 2014), the diversity of physical, legal, institutional and cultural contexts makes it difficult to derive universal lessons or recommendations (López-Gunn, 2003; Jia and Li, 2021; Shiferaw *et al.*, 2023).

The landscape governance in rural areas of Tunisia is marked by a decentralized management approach. This strategy aims to enhance sustainable development and improve resource management throughout participatory water management. Water decentralization in Tunisia has progressed through legislative reforms aimed at transferring management responsibilities from the central public institutions to local user associations. These associations, created to oversee irrigation districts, serve as intermediate structures that promote participative and autonomous management of water resources. Despite their supportive role, their effectiveness is often limited by financial, technical, and organizational constraints, reflecting an ongoing shift away from centralized control towards more localized, shared management systems (Al Atiri, 2005; Bachta and Zaibet, 2006). After decades of decentralization and transfer of water resource management to users' associations (GDAs), the limitations of this participative approach – integrating users into irrigation resource management – have become evident and face significant challenges (Ben Nasr and Bachta, 2018). The main issue with the (GDAs) lies in their limited capacity to effectively manage water resources, largely due to insufficient financial, technical, and organizational resources. Their performance remains poor, partly because of stakeholders' capacities to collective management, water shortages, irrigation quotas, and non-compliance with governance regulations (MAHRF, 2021, 2023). The problem of regulation enforcement is a critical challenge facing policymakers, managers, and academics across the world. This lack of effective governance and institutional frameworks to manage and regulate groundwater use can make it challenging to implement sustainable resource management strategies (Molle and Berkoff, 2007). Weak governance systems often lead to landscape-level problems such as conflicts over water resources and social inequities. In fact, effective governance with commitment from key stakeholders is essential for broader water security (Ahopelto *et al.*, 2023). Besides, lack of coordination between stakeholders often leads to unsustainable water management practices (Jariego, 2024), intensifying issues such as rural-urban migration, social problems, and poverty (Houdret, 2012).

The success of sustainable water management strategies often depends on the ability to navigate complex relations among a wide range of actors, both within and beyond the water sector (Santos *et al.*, 2023). Therefore, the proposed study applies a governance approach that considers all the issues in the landscape with the potential to inform the development of more inclusive and effective groundwater management policies in Tunisia.

This research paper aims to investigate the challenges of landscape governance related to water problems. The fieldwork involves a water stakeholders network analysis to identify key actors and examine collaboration patterns among these actors. Furthermore, the study area represents a transboundary region with deep-rooted social and local development challenges. The insights from this work can be replicated in similar regions across North Africa and the Middle East, where climatic and socio-economic conditions are similar to those found in Tunisia.

The remainder of this paper is structured as follows: it begins with a brief overview of landscape governance and water governance, followed by a detailed methodology section that outlines the methods used in the study. Next, the results section presents the key findings derived from the analysis, culminating in a conclusion that summarizes the main insights and discusses their implications for future research.

1.2. *Landscape governance and water governance concepts overview*

Landscape is an object of both social and natural-spatial conditions, with the benefit of targeting potential societal and environmental dimensions (Görg, 2007). The importance of a landscape approach is increasingly recognized (Reed *et al*., 2015). It can be defined also as an area identified by an actor for a given range of goals (Gignoux *et al*., 2011). The landscape is described in broader conceptual terms instead of just defining it as physical space (Farina, 2000), in fact, landscapes are multi-actors, multi-purposes, and multiscaled.

Landscape governance is a significant aspect of the landscape approach that refers to the multi-sector, multi-actors, and multi-level connection and spatial decision-making process at the landscape level (Van Oosten *et al*. 2014; Ros-Tonen *et al*. 2014). In fact, landscape governance is concerned with the institutional arrangements, decision-making processes, policy instruments, and underlying values by which multiple actors pursue their interests in sustainable food production, biodiversity, ecosystem service conservation, cultural and heritage preservation, and livelihood security, resulting in multifunctional landscapes (Kusters *et al*., 2020; Kozar *et al*., 2014). The nature of governance systems, their functioning, and effectiveness depend upon the interaction of institutions, organizations, and networks including across scales and levels (Kofinas, 2009). The purpose is to bring spatial decision-making relatively close to actors directly impacted by the spatial decisions made; and presuming that landscapes allow stakeholders negotiation and working on collective decisions about their space arrangement (Van Oosten *et al*., 2014). Another fundamental governance question is about who decides, based on what principles, and who is involved and exempted from activities and incentives related to various features within the complex landscape management (Kozar *et al*., 2014). Water governance varies depending on the organizational governance system (Harlin and Kjellén, 2015). In fact, Water resources are embedded in social systems that are characterized by multi-stakeholders' management based on different values, perceptions and timeframes (Pahl-Wostl and Hare, 2004; Roux *et al*., 2010) Improved WG is path-dependent and needs to be linked to development goals in society (Harlin and Kjellén, 2015).

2. Material and method

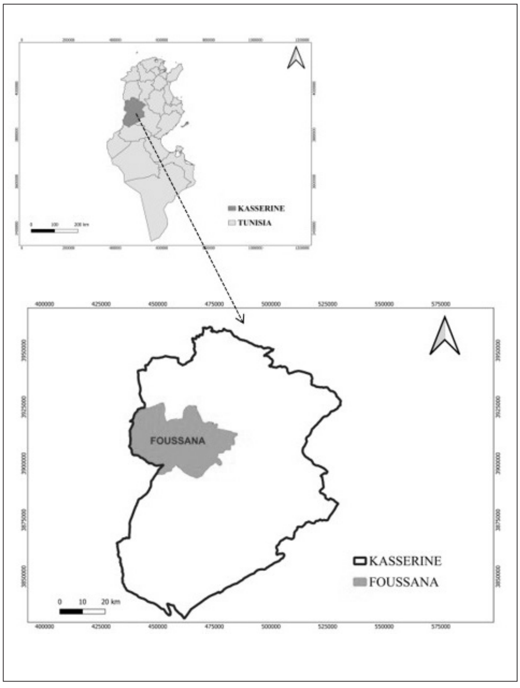
The study employed a landscape governance approach to examine the complexities of groundwater management in the study area. This methodology aims to capture the different interactions between all relevant stakeholders within the broader landscape. Combining causal analysis and social network assessment allows a deep understanding of the complex groundwater management challenges within the studied landscape.

2.1. *Study area*

The data collection was conducted within the Kasserine governorate (Tunisia), with a specific focus on the Foussena delegation. The Kasserine governorate is strategically located in the central-western part of Tunisia (Figure 1), covering 8,260 Km². Within this area, there are 360,000 hectares of farmland, 80,000 hectares of rangeland, and 304,046 hectares of forests and alfa grasslands (ODCO, 2017). The agricultural land covers 360,000 hectares of farmland, which has expanded significantly due to transformative changes in rural areas, resulting in notable advancements in the production of crops such as apples, tomatoes, and pistachios. This geographical region falls within the arid bioclimatic zone, characterized by an average annual precipitation of approximately 300 millimeters (M'Hamed *et al.*, 2008).

This region is characterized by economic struggles and marginalization, and critical reliance on groundwater resources for irrigation and local social and economic development (ITCEQ, 2018). The agricultural sector holds a key role in the economy of the region. Public and private irrigated areas are estimated at 39,788 hectares (CTV Foussena, 2018). The number of GDAs in the Foussena region (Tunisia) is estimated at 18 irrigation GDAs and two mixed GDAs (irrigation and drinking water).

Figure 1 - Geographical localization of the study area.



The number of operators in the public irrigated areas is estimated to be 394 farmers, covering a total area of 747 hectares, of which 526 hectares are irrigated (CTV Foussena, 2018).

The exploitation rate of the deep sandstone aquifer in Foussena is estimated at 356.15%, while the Plio-Quaternary aquifer in the region has a rate of 353.75% (CRDA Kasserine, 2015). This assessment includes a total of 789 wells. As natural resources in Kasserine are depleted at an alarming rate, the agricultural sector faces a significant threat to the viability of small-holder farming and a substantial risk of job loss.

2.2. *System thinking Causal Loop Diagram (CLD)*

The analysis began with the creation of a causal loop diagram for this purpose. This tool was used to systematically map out water-related problems and challenges associated with the irrigated agricultural practices in the region. Causal relationships allow the identification of an initial set of stakeholders directly involved in groundwater management and utilization.

The CLD provides a system-level perspective on the key variables and feedback mechanisms that influence groundwater governance in the studied landscape (Bouchet *et al.*, 2022; Van Lap *et al.*, 2023). This conceptual model was used to identify water-related issues at the landscape level and identify all stakeholders, both directly and indirectly, involved in the management and decision-making processes within the landscape. The landscape under consideration is limited to the rural areas and the irrigated agricultural zone. Building upon this foundation, the subsequent governance network analysis was able to investigate deeper into the degrees of each actor's position, interests, and capacity to affect change. This multi-layered analysis, combining the system-level perspective of the CLD with the detailed stakeholder network analysis, provides a robust understanding of the groundwater governance challenges in the landscape. This approach sets the stage for the development of more effective and targeted interventions for sustainable groundwater management.

Table 1 - Importance of Social Network Analysis in Participatory Water Management and Good Governance.

Aspect	*Importance of SNA*
Stakeholder Identification	- SNA helps in identifying key stakeholders involved in water management, ensuring no group is marginalized (Prell, 2006).
Understanding Relationships	- Reveals patterns of relationships among stakeholders, which is critical for effective communication and collaboration (Wasserman and Faust, 1994).
Measuring Participation	- SNA provides insights into the level of stakeholder participation, allowing for a more inclusive decision-making process (Yang *et al*., 2011; Gatt, 2016).
Enhancing Inclusiveness	- Throughout connections' visualizing, SNA can identify underrepresented groups and promote strategies to include them in governance (Bulkely, 2005).
Facilitating Communication	- Improves channels for stakeholders to express opinions and constraints, fostering a higher level of societal inclusiveness (Biermann, 2007).
Supporting Decision Making	- Helps decision-makers understand specific community problems and perspectives, leading to more informed and equitable decisions (Allan and Rieu-Clark, 2010).
Securing Ownership	- Encourages stakeholder buy-in and ownership of decisions by recognizing their contributions and roles (Rouse, 2007).
Evaluating Influence	- Assesses the influence of different stakeholders on decision-making processes, helping to identify power dynamics (Yang *et al*., 2011).

2.3. *The analysis of water governance networks*

The study conducted a detailed Social Network Analysis (SNA) to examine the relationships, interactions, and power dynamics between all the identified stakeholders.

SNA is an empirical approach that allows for mapping and analyzing the connections and interactions between different actors, it provides a means to translate the conceptual idea of mutual connections into tangible, measurable terms (Table 2). This enables a deeper understanding of the collaborative dynamics at play within water governance frameworks (Jariego, 2024). Stakeholders network analysis helps to clarify the social factors that lead to governance outcomes (Nabiafjadi *et al*., 2021; Jariego, 2024). Visualization of social networks can be used to portray these networks concisely and easily (Arif, 2015). In this context, Rhodes defines governance as the fact of governing with and through networks (Rhodes, 2007). Network arrangements and relationships can boost the probability of social change and cooperation throughout natural resources governance (Prell *et al*., 2009). Moreover, using SNA offers a strong lens for viewing the WG socio-political process (Horning *et al*., 2016). Stein *et al*. (2011) demonstrated by analyzing WG in the Mkindo catchment in Tanzania, that the SNA is useful to objectively map collaborative SNs between actors affecting water flows directly or indirectly in the catchment (Stein *et al*., 2011). Environmental governance networks could be defined as a series of constant communication relationships between actors or stakeholders involved in resource management, and based on degrees of shared values, mutuality, and collaboration (Chaffin *et al*., 2016).

Table 1 highlights how SNA is helpful in promoting participatory management and good governance in water resource management, emphasizing its role in inclusiveness and effective decision-making.

To address the limitations of SNA in discerning the motivations behind the formation, functioning, and governance of networks over time, this research supplemented the SNA with qualitative methods (Rowley, 1997; Sørensen and Torfing, 2016). SNA alone is unable to fully capture the individual behaviors, attitudes, and beliefs that drive the evolution of networks, or provide answers to important questions about how and why networks are formed, institutionalized, and contribute to effective policy (Sørensen and Torfing, 2016) Therefore, this study combined interviews, documentation analysis, system thinking, and causal diagrams to triangulate the data and gain deeper insights into the network structure (Coviello, 2005).

Table 2 - Social Network Analysis Metrics and Interpretations.

SNA Metric	*Interpretation*	*References*
Density	Indicates how closely actors within a network are connected, reflecting overall group cohesion. It's calculated as the ratio of observed connections to the maximum possible connections. Useful for comparing the interconnectedness of different networks.	Wasserman and Faust, 1994
Degree Centrality	Measures the number of direct connections a stakeholder has to others. High degree centrality identifies active players good at mobilizing the network and bringing others together, often by diffusing information. While they have many ties, these ties can be weak, meaning they can spread information but might not exert significant influence over those they are tied to. It identifies actors extensively involved in direct relationships.	Freeman, 1979; Scott, 2017; Stein *et al*., 2011
Closeness Centrality	Measures how close a stakeholder is to all other stakeholders in the network, representing the average path length to all other actors. A high closeness centrality indicates an actor with fast access to all other nodes within the network, capable of quickly reaching others and disseminating information.	Rodrigues *et al*., 2006
Betweenness Centrality	Measures the extent to which a stakeholder lies on the shortest paths between other pairs of stakeholders. Actors with high betweenness centrality act as «brokers» or «gatekeepers,» controlling the flow of information and resources between different parts of the network. They are crucial for long-term planning by connecting disconnected segments, bringing diversity and new ideas. However, they may feel torn between different network elements.	Freeman, 1979; Wasserman and Faust, 1994; Prell *et al*., 2009; Stein *et al*., 2011; Kim and Hastak, 2018; Huang *et al*., 2019; Pérez *et al*., 2021
Authority	A measure of a user's influence and capacity to disseminate information within a social or professional network, based on their position and interactions within the network structure.	Pérez *et al*., 2021

2.4. *Data collection*

Fieldwork was conducted during the agricultural campaign 2019-2020 and updated in 2023, essentially through structured and semi-structured interviews. The selection process of stakeholders employed snowball sampling techniques (Pasikowski, 2024) which is a method of sampling that involves identifying new participants through referrals from existing participants after the initial research has begun. This research began with initial interviews with key informants from public agriculture agencies, specifically the CRDA and CTV. These informants provided a first list of actors involved in water management and identified potential relationships among them. This iterative process continued with subsequent interviews featuring stakeholders recommended by earlier participants. After employing the snowball sampling technique, we compiled an extensive list of actors. Subsequently, by identifying challenges and issues related to water management in the studied landscape, we refined our focus to include only those stakeholders who are directly or indirectly linked to water management. Simultaneously, a list of potential relationships and connections among the actors was developed.

The territorial extension unit (CTV) of Foussena directed its efforts towards engaging with GDAs, initiating the study with a pilot survey involving 30 farmers. This survey served to test the field research work and to complete the identification of relationships or links that farmers have with the stakeholders identified

Table 3 - Matrix of actor interactions.

		Actor 1	*Actor 2*	*Actor 3*	.....	*Actor n*
Actor 1		-	L*1	L4		
Actor 2			-	L6/L2/L1		
Actor 3			L1/ L4	-		L6/L3/L1
.....						
Actor n						-

in the landscape. Two types of structured interviews were conducted with the farmers. The first type consisted of five modules and took an average of 45 to 60 minutes per farmer. This interview covered five sections: demographic data, information related to the farm, management of water resources, the institutional framework, production costs, and the value of water. Additionally, interviews related to collecting social network analysis (SNA) data averaged about 15 minutes with each farmer. In total, 159 farmers in public irrigated areas managed by GDAs and 100 farmers in private irrigated areas were interviewed. Furthermore, 12 GDAs were consulted to identify existing challenges within the system.

Following the identification of stakeholders, a matrix of actor interactions (Table 3) was employed during each interview to examine the relationships and linkages among participants. Actor-linkage matrices are a widely used method for describing stakeholder interrelations (Biggs and Matsaert, 1999; Reed *et al*., 2015). In this approach, stakeholders are listed in the rows and columns of a table, creating a grid that allows for the description of interrelations using key terms.

2.4.1. *Data analysis and visualization: the Force Atlas 2 Model*

To visualize the network, we adapted the Force Atlas 2 algorithm. It is an improved version of the original Force Atlas algorithm, which is a force-directed layout algorithm used for graph visualization (Jacomy *et al*., 2014). The main goal of the Force Atlas 2 algorithm is to enhance the structure and readability of graph visualization. The algorithm works by simulating the physical forces acting on the nodes in the network, such as attraction and repulsion, to determine the optimal arrangement of the nodes. The attraction forces draw connected nodes closer together, while the repulsion forces push unconnected nodes apart, creating a more organized and readable graph layout. The model's algorithm uses the following equations to calculate the position and movement of nodes in the graph:

Repulsive force:

The repulsive force between two nodes i and j is calculated as:

$F\_rep = k\_rep / d\_ij^2$

Where:

F_rep is the repulsive force.

k_rep is the repulsive force constant.

d_ij is the distance between nodes i and j.

Attractive force:

The attractive force between two connected nodes i and j is calculated as:

$F\_att = k\_att * d\_ij$

Where:

F_att is the attractive force.

k_att is the attractive force constant.

d_ij is the distance between nodes i and j.

Gravity force:

The gravity force acting on a node i is calculated as:

$F\_grav = k\_grav * m\_i$

Where:

F_grav is the gravity force

k_grav is the gravity force constant

m_i is the mass of node i

Displacement:

The displacement of a node i in the current iteration is calculated as:

d_x = F_x / (m_i + 1)
d_y = F_y / (m_i + 1)

Where:

d_x and d_y are the displacements in the x and y directions, respectively
F_x and F_y are the total forces acting on the node in the x and y directions, respectively
m_i is the mass of node i

The total force acting on a node i is the sum of the repulsive, attractive, and gravity forces:

F_x = Σ F_rep_x + Σ F_att_x + F_grav_x
F_y = Σ F_rep_y + Σ F_att_y + F_grav_y

The new position of the node i after the current iteration is calculated as:

x_new = x_old + d_x
y_new = y_old + d_y

These equations are applied iteratively until the graph layout converges or a certain number of iterations is reached.

3. Results and discussion

3.1. *The Causal Loop Diagram (CLD)*

3.1.1. *GDA-managed perimeters (public irrigated areas)*

CLD has helped identify the key actors involved, both directly and indirectly, in groundwater governance in the studied landscape. The CLD (Figure 2) represents in a systemic way the key issues related to water management in public irrigated perimeters in Tunisia, managed by the Agricultural Development Groups (GDA). It highlights the feedback loops that amplify or mitigate the problems of groundwater overexploitation in these perimeters.

The central loop shows how an "Insufficient supply of groundwater" in the irrigated perimeters leads to "Longer irrigation programs", thus generating "Dissatisfaction of farmers" which results in the digging of "Illegal private wells". This then aggravates the "Overexploitation of groundwater", closing the loop.

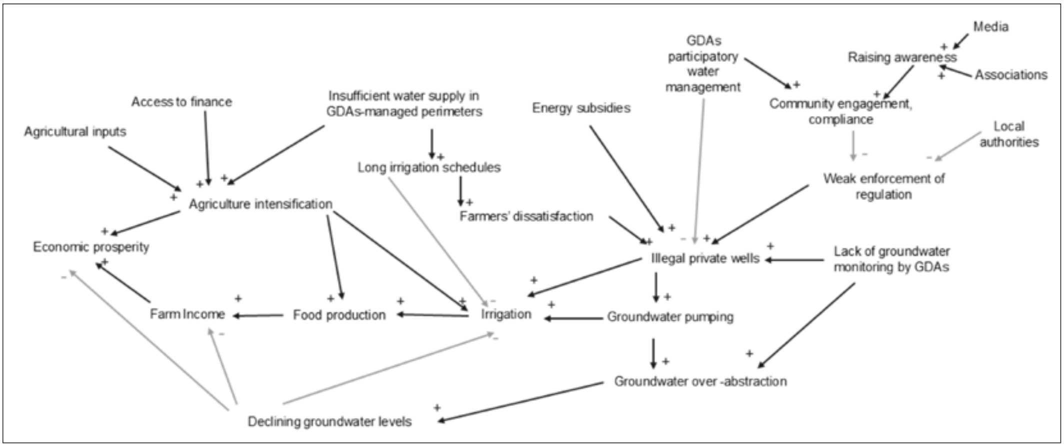
Other loops illustrate the impact of agricultural expansion, supported by subsidies and financial incentives, on the increase in "Demand for agricultural water", thus exacerbating the problem of insufficient water supply. However, it is important to note that the number of farmers who have benefited from financial incentives is not large, and most farmers have problems accessing financing, which hinders their access to technology and modernization of their farms.

The diagram also highlights the role of the media, local associations, and local authorities in raising awareness among farmers about the need to protect water resources, as well as the GDAs' ability to enforce regulations. These stakeholders can therefore play a significant role in breaking some of these negative feedback loops. The model emphasizes the importance of more efficient irrigation management, groundwater monitoring, and enforcement of regulations by the GDAs to reduce groundwater overexploitation in these public irrigation perimeters.

3.1.2. *Private irrigated areas*

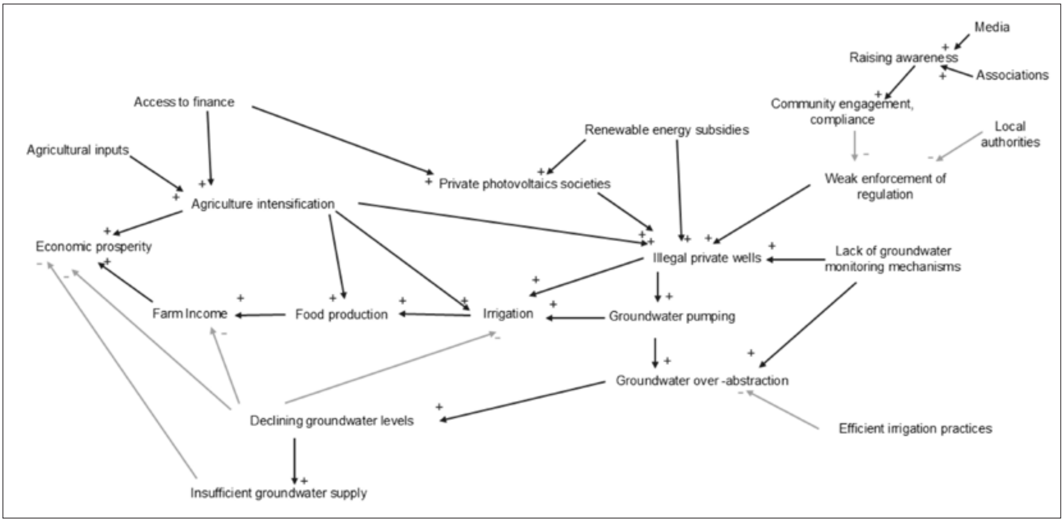
In the case of private irrigated areas in Tunisia, there are strict regulations in place that manage groundwater's use. Farmers are required to obtain authorization from the Ministry of Agriculture (MARHP) to dig wells deeper than 50 meters. However, the CLD (Figure 3) highlights the problem of "Illegal Private Wells" in these private irrigated perimeters, despite the regulatory framework. The CLD illustrates the complex interactions between distinct factors related to groundwater overexploitation in the studied landscape. The nodes represent the different elements of the system, while the arrows indicate the cause-and-effect relationships between these elements. At the core of the diagram is the problem of "Groundwater Overexploitation," which leads to a "Groundwater Level Decline". This decline in groundwater levels drives farmers to drill new wells, increasing their "Groundwater Pumping Capacity." This increased pumping capacity, in turn, fuels the overexploitation of groundwater, creating a positive feedback loop. The agricultural water demand and the expansion of agricultural land also contribute to the overexploitation of groundwater. Crop irrigation supports food production, which in turn contributes to economic prosperity and farmers' incomes.

Figure 2 - Causal loop diagram (CLD) of water governance in public irrigated areas (GDA-Managed Perimeters).



Source: the Authors, 2024.

Figure 3 - Causal loop diagram of water governance in private irrigated areas.



Source: the Authors, 2024.

Factors such as inefficient irrigation practices (Leghrissi *et al*., 2023), lack of groundwater monitoring, and weak enforcement of regulations, also contribute to the overexploitation of groundwater.

Farmers who have illegal, unauthorized wells are not eligible to receive public subsidies from the Agricultural Investment Promotion Agency nor can they access funding from national banks. Crucially, these farmers are also unable to obtain the necessary permits for the electrification of their wells. As a result, some of them have resorted to installing private photovoltaic energy systems to power their unauthorized groundwater extraction, rather than connecting to the electrical grid. Thus, the installation of photovoltaic systems is indirectly linked to the illegal installation of wells, which further aggravates the groundwater overexploitation problem. The prevalence of these illegal wells, coupled with the "Weak Enforcement of Regulations" by local authorities, exacerbates the issue of "Groundwater Overexploitation" in the private irrigated perimeters.

This CLD highlights the complex and interconnected nature of the factors contributing to

Table 4 - Stakeholders description.

Stakeholders	*Description/ Roles*
Regional Commissariat for agricultural Development (CRDA)	• Agricultural planning, implementation, monitoring and evaluation, water resources management.
Territorial Extension Unit (CTV)	• Support farmers, Farmers extension, conduct field visits; coordinate with the boroughs of the CRDA and technical services.
Farmers (F)	• They are the main users of groundwater for irrigation in the perimeters. • Their dissatisfaction with water shortages leads them to dig illegal private wells, exacerbating groundwater overexploitation.
Agricultural Development Groupings (GDA)	• Community based organizations (CBO). • They manage the irrigation water supply in the public irrigated perimeters. • Their ability to enforce regulations and monitor groundwater use is essential to address the overexploitation issue.
Farm Input Providers (FIP)	• They supply farmers with agricultural inputs like seeds, fertilizers, and equipment. • Their pricing and availability of inputs can influence farmers' decisions and water use.
Local authorities	• They play a key role in enforcing regulations and supporting the GDAs in their water management efforts. • Their involvement can help break the negative feedback loops related to illegal well-digging and overexploitation.
Local Associations (ASSO) *Media*	• They can raise awareness among farmers about the importance of sustainable groundwater management. • Their engagement can influence farmers' behavior and support the GDAs' efforts.
Local People's Representatives (PR)	• The Assembly of People's Representatives is where laws are discussed and approved through voting. • Elected representatives in each governorate relay local issues and challenges, ensuring that the concerns of their constituents are addressed. • These representatives act as intermediaries between the population and government institutions, promoting citizen participation and enhancing governance.
Electricity Utility (STEG)	• The Tunisian Company for Electricity and Gas is the exclusive electricity provider in the country. • To submit a request for electrification of a well, an authorization for drilling from the CRDA is required, along with a tax declaration, indicating that the farmer is following tax regulations.
Public Banks (BNA, BTS)	• Agricultural financing

groundwater overexploitation. It highlights the importance of a systemic approach to addressing this complex environmental issue.

3.2. *The analysis of water governance networks*

3.2.1. *Public irrigated areas (GDA-managed irrigated perimeters)*

**) Graph level index: Network statistical description*

The network has a total degree of 14,556, indicating a prominent level of overall connectivity among the stakeholders. The weighted degree of 14,556 suggests that the strength of the connections between actors is also substantial. The network diameter of 5 implies a relatively short path length between the most distant nodes, reflecting a well-connected and compact network structure.

The network density of 0.078, interpreted as a directed network, suggests a moderate level of overall connectedness within the system. This indicates that while there are many linkages between stakeholders, there is still potential for greater integration and collaboration.

The modularity score of 0.247 reveals the presence of distinct subgroups or communities

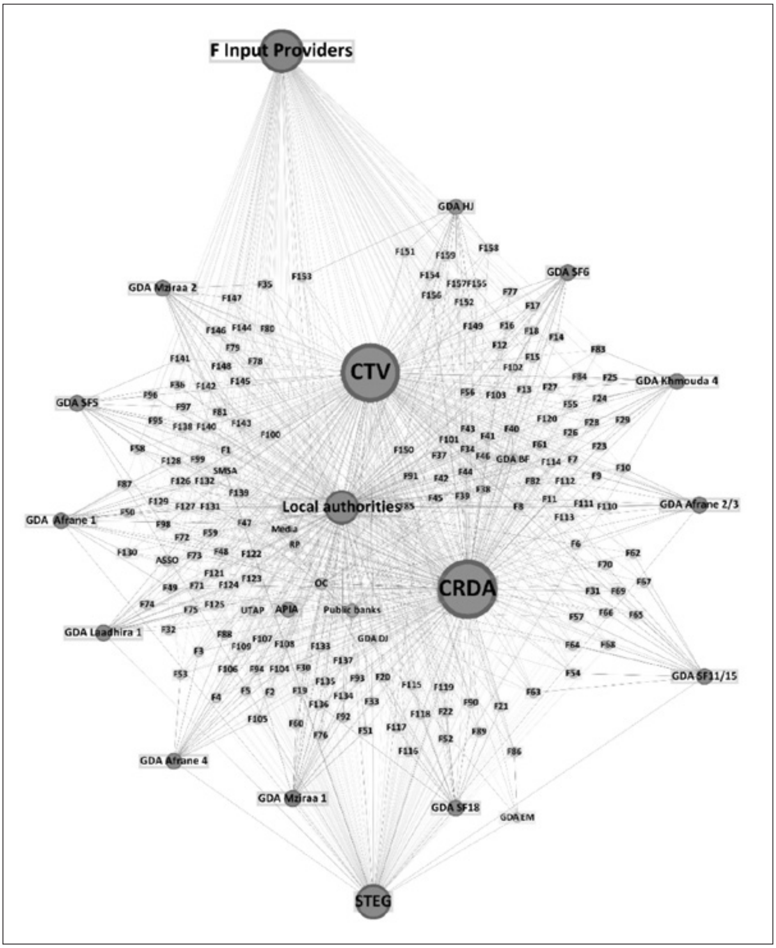


Figure 4 - Stakeholders mapping in public irrigated areas in the study zone.

within the network. This suggests that there are clusters of stakeholders with stronger internal ties compared to their connections with other parts of the network. These modular structures may reflect differences in interests, priorities, or organizational affiliations among the actors.

The high statistical value of 3959.574 suggests an important level of statistical significance in the network structure, indicating that the observed patterns are unlikely to have arisen by chance. This provides confidence in the validity and robustness of the network analysis findings.

**) Stakeholders' positions*

The network analysis (Figure 4) reveals stark differences in the degree centrality of the different stakeholders, highlighting their disparate levels of influence and involvement. The Territorial Extension Unit (CTV) and the Regional Commissariat for Agricultural Development (CRDA) emerge as the most central and well-connected actors, with degree values exceeding 500. These highly influential stakeholders play a crucial role in information sharing, coordination, and decision-making processes within the network. Local authorities also exhibit a high degree of 344, positioning them as another core group of stakeholders with substantial connectivity and potential to drive collective action. In contrast, the involvement of Agricultural development Groupings (GDA) is more nuanced. The active GDAs have a medium-range degree, between 32 and 72, suggesting they are moderately well-connected and play an important, but not necessarily central, role in the network. However, the non-active GDAs have significantly lower degree values, ranging from 9 to 11, indicating a peripheral position and limited integration with the other stakeholders. This disparity in the degree of GDA involvement highlights the need to better understand the factors influencing the varying levels of participation and influence of these community-based organizations in groundwater governance. The Farmers' Union, media, and local people's representatives have low degree values, suggesting they occupy more peripheral positions and may be less integrated into the broader network.

The centrality of the CTV and CRDA is highlighted also by their closeness centrality values of 522 and 521, respectively. This indicates that they have the shortest path lengths to all other stakeholders in the network, suggesting they are in a prime position to access and disseminate information, coordinate activities, and exert major influence over the total governance processes. The local authorities, with a closeness centrality (CC) of 344, also have a highly central position in the network. This highlights their strategic importance as intermediaries and potential facilitators of collaboration among identified stakeholders.

The farm input providers (CC=246), Electricity utility (CC=184), and public banks (CC=65) demonstrate moderately central roles, while the APIA (CC=47), farmers' union (UTAP) (CC=26) exhibit lower closeness centrality. This suggests these stakeholders may have more limited direct access to the broader network and may need to rely on the more central actors to effectively participate in and influence groundwater governance. The civil society stakeholders (Asso) (CC=7) and local people's representatives (RP) (CC=7) have the lowest closeness centrality scores, indicating their peripheral position in the network and potential challenges in directly shaping the overall governance dynamics. Regarding the GDAs, the active GDAs have closeness centrality values ranging from 32 to 57, suggesting a moderate level of centrality and integration. However, the non-active GDAs have significantly lower scores, between 9 and 11, highlighting their more isolated and marginalized status within the network.

The centrality values of the active and non-active GDAs suggest challenges in maintaining their active engagement and community-level representation in the water governance system, underscoring the need to address this imbalance by empowering the peripheral actors, fostering inclusive multi-stakeholder engagement, aligning incentives, and promoting transparency and accountability to enhance collective action and improve the overall water governance.

The interpretation of the authority values reveals a groundwater governance network characterized by a significant power imbalance, where the Territorial Extension Unit (0.983), the Regional Commissariat for Agricultural Development (0.983), and the Electricity Utility (1.0) wield substantial power and influence as central decision-makers, while the local authorities (0.980) and farm input providers (0.931) also hold considerable sway, but the public banks (0.488), agriculture investment promotion agency (0.621), associations (0.380), farmers' union (0.385), media (0.519), and people's representatives (0.512) possess relatively lower authority values, suggesting that their participation and influence in the governance system may be limited; moreover, the authority values of the groundwater development associations (GDAs), ranging from 0.35 to 0.391, indicate that these community-based organizations are not fully empowered or integrated into the decision-making processes, underscoring the need to address this power imbalance by empowering the less influential stakeholders, fostering more inclusive and collaborative decision-making, and ensuring that the concerns and needs of all affected communities are adequately represented and considered to enhance collective action and improve the overall water governance.

The key points highlighting the marginalization of the GDA include their low centrality metrics, minimal authority and power, and limited brokerage and gatekeeping role within the overall governance network. Specifically, the GDA had low degree centrality, closeness centrality, and eccentricity compared to the highly central actors like the CTV, CRDA, and Local Authorities. This suggests that the GDA are not well-connected and integrated within the overall network, limiting their ability to access and disseminate information, as well as to quickly coordinate with other stakeholders.

This lack of meaningful participation and influence of the GDAs, which represent the water users and community-level stakeholders, is a significant barrier to achieving true collective action and participatory water management. The findings suggest that the groundwater governance system is not adequately inclusive and responsive to the needs and perspectives of the end-users. To address this gap, the governance framework should be reformed to foster greater integration and empowerment of the GDA and other marginalized stakeholders. This could involve establishing formal mechanisms for shared decision-making, building the capacity of the GDA, and redistributing power and authority more equitably among the diverse set of actors. Only then can the groundwater governance system truly become participatory and effective in managing this critical resource.

The hierarchical network structure and uneven distribution of power may inhibit the development of truly collaborative and inclusive governance approaches, as the peripheral actors, such as the media, local people's representatives, and non-active GDAs, may have limited opportunities to participate in and shape the governance processes, undermining the legitimacy and effectiveness of the overall governance system. Feiock (2013) explored the impact of fragmented authority and externalities on collective action in governance, and he sheds light on the cooperation dynamics among stakeholders and emphasizes the challenges arising from fragmented governance.

The groundwater governance system should adopt an approach that leverages the key role of GDAs to enhance collective action and water governance. Empowering the GDAs, which are peripheral yet crucial actors, can help address the challenges posed by the hierarchical structure and irregular distribution of power by facilitating meaningful participation, decentralizing decision-making, and fostering collaborative governance. A study conducted in a similar context, in Spain, demonstrates that Water User Associations play a critical role in fostering cooperation among stakeholders, thereby enhancing the effectiveness of groundwater management practices (López-Gunn, 2003). This finding aligns with the importance of collective action in sustainable water management, reinforcing the need for collaborative governance models. In fact, better groundwater management requires multi-stakeholder approaches that involve local actors to develop shared visions and improve governance frameworks (Mekki *et al*., 2022).

Strengthening the synergy between public agencies, such as the CRDA, CTV and the GDAs can further strengthen the adaptive capacity and resilience of the groundwater governance system, this finding aligns with previous research indicating that structural and institutional arrangements significantly influence collective action effectiveness in water user associations (Bassi *et al*., 2010; Indranil De *et al*., 2022). Moreover, engaging the media as a central actor can increase public awareness, share critical information, and reduce information asymmetries, thereby enhancing the legitimacy and accountability of the governance processes and promoting more inclusive and equitable groundwater management.

The groundwater governance system must adopt an integrated approach that leverages the influential roles of specific stakeholders, including the central private sector actors such as the farm input providers. Informed by the SNA, this strategy recognizes the critical position of the farm input providers and the need to regulate their input pricing and industry norms to align with sustainable groundwater management. Aligning the incentives of all stakeholders, including the farm input providers, to promote sustainable practices is key to enhancing the overall adaptive capacity and resilience of the groundwater governance system.

4. Conclusions

The study on groundwater governance stakeholder networks reveals a hierarchical structure characterized by an uneven distribution of power and influence. Key actors occupy central positions, while civil society representatives, local community members, and some inactive groundwater associations remain on the periphery. This concentration of power poses significant challenges to the effectiveness and resilience of the groundwater governance system, limiting the diversity of perspectives necessary for addressing emerging challenges. A key limitation of the applied method is that using organizations as nodes may overlook the influence of individual actors within these entities, potentially missing important nuances in collaboration dynamics. Additionally, this approach might oversimplify the social complexity by focusing solely on organizational structures, thereby ignoring informal or less structured relationships that also impact water governance.

To enhance the governance of groundwater resources, several key actions are essential. First, developing more inclusive and collaborative governance approaches is crucial to actively engaging a broader range of stakeholders, particularly those currently marginalized within the network. Second, strategies must be implemented to redistribute influence and power more equitably, ensuring diverse viewpoints are integrated into decision-making processes. Third, intentional engagement of less connected actors, such as civil society organizations and local representatives, can harness their unique insights and experiences. Finally, leveraging the existing network structure to facilitate information flow and knowledge sharing among all stakeholders will help bridge the gap between central and peripheral actors.

Creating a more inclusive governance framework can significantly improve groundwater management policies. This approach is relevant not only for Tunisia but also for other North African and Middle Eastern countries facing similar water-related challenges.

References

Ahopelto L., Sojamo S., Belinskij A., Soininen N., Keskinen M., 2023. Water governance for water security: analysing institutional strengths and challenges in Finland. *International Journal of Water Resources Development*, 40(2): 153-173. https://doi.org/10.1080/07900627.2023.2266733.

Al Atiri R., 2005. Analyse des politiques hydrauliques. Cas de la Tunisie. In: *Actes du séminaire Euro éditerranéen «Les instruments économiques et la modernisation des périmètres irrigués»*, 21-22 novembre 2005, Sousse, Tunisie.

Allan A., Rieu-Clarke A., 2010. Good governance and IWRM – a legal perspective. *Irrig. Drainage Syst.*, 24(13): 239.

Arif T., 2015. The Mathematics of Social Network Analysis: Metrics for Academic Social Networks. *International Journal of Computer Applications Technology and Research*, 4: 889-893. 10.7753/IJCATR0412.1003.

Bachta M.S., Zaibet L., 2006. Les innovations institutionnelles comme adaptations à l'évolution du contexte des périmètres irrigué : cas de la Tunisie. In : *L'avenir de l'agriculture irriguée en Méditerranée. Nouveaux arrangements institutionnels pour une gestion de la demande en eau*. Actes du séminaire *Wademed*, 6-7 novembre 2006, Cahors, France.

Bassi N., Rishi P., Choudhury N., 2010. Institutional organizers and collective action: the case of water users' associations in Gujarat, India. *Water International*, 35: 18-33.

Ben Nasr J., Bachta M.S., 2018. Conflicts and water governance challenge in irrigated areas of semi-arid regions. *Arabian Journal of Geosciences*, 11: 753.

Biermann F., 2007. Earth system governance as a crosscutting theme of global change research. *Global Environmental Change*, 17(3): 326.

Biggs S., Matsaert H., 1999. An actor-orientated approach for strengtheningcresearch and development capabilities in natural resource systems. *Public Administration and Development*, 19: 231-262.

Bouchet L., Thoms M.C., Parsons M., 2022. Using causal loop diagrams to conceptualize groundwater as a Social-Ecological system. *Frontiers in Environmental Science*, 10. https://doi.org/10.3389/fenvs.2022.836206.

Bulkely H., 2005. Reconfiguring environmental governance: towards a politics of scales and networks. *Political Geography*, 24(8): 875.

Chaffin B.C., Garmestani A.S., Gosnell H., Craig R.K., 2016. Institutional networks and adaptive water governance in the Klamath River Basin, USA. *Environmental Science and Policy*, 57: 112-121. DOI: 10.1016/j.envsci.2015.11.008.

Coviello N.E., 2005. Integrating qualitative and quantitative techniques in network analysis. *Qualitative Market Research*, 8(1): 39-60. https://doi.org/10.1108/13522750510575435.

CRDA Kasserine, 2015. *Exploitation assessment of the aquifers in Kasserine (Tunisia)*.

CTV Foussena (Territorial Extension Unit), 2018.

Technical reports for irrigated areas in Foussena (Kasserine, Tunisia).

FAO, 2017. W*ater for Sustainable Food and Agriculture A report produced for the G20 Presidency of Germany*. Rome: FAO.

Farina A., 2000. The cultural landscape as a model for the integration of ecology and economics. *Bioscience*, 50(4): 313-320.

Feiock R., 2013. The Institutional Collective Action Framework. *Policy Studies Journal*, 41: 397-425.

Freeman L.C., 1978. Centrality in social networks conceptual clarification. *Social Networks*, 1(3): 215-239. https://doi.org/10.1016/0378-8733(78)90021-7.

Gatt K., 2016. Social network analysis as a tool for improved water governance in Malta. *International Journal of Society Systems Science*, 8(2): 131. https://doi.org/10.1504/ijsss.2016.077013.

Ghiotti S., 2006. Les Territoires de l'eau et la décentralisation. La gouvernance de bassin versant ou les limites d'une évidence. *Développement Durable et Territoires*, Dossier 6. https://doi.org/10.4000/developpementdurable.1742.

Gignoux J., Davies I., Flint S., Zucker J-D., 2011. The ecosystem in practice: Interest and problems of an old definition for constructing ecological models. *Ecosystems*, 14(7): 1039-1054.

Giordano M., 2009. Global groundwater Issues and solutions. *Annual review of Environment and Resources*, 34: 153-178. DOI: https://doi.org/10.1146/annurev. environ.030308.100251.

Görg C., 2007. Landscape governance: the 'politics of scale' and the 'natural conditions' of places. *Geoforum*, 38(5): 954-966.

Harlin J., Kjellén M., 2015. Water and Development: From MDGs towards SDGs. *Content*, 8.

Horning D., Bauer B.O., Cohen S.J., 2016. Missing bridges: Social network (dis)connectivity in water governance. *Utilities Policy*, 43: 59-70. DOI: 10.1016/j.jup.2016.06.006.

Houdret A., 2012. The water connection: Irrigation and politics in southern Morocco. *Water Alternatives*, 5(2): 284-303.

Huang M., Wang Z., Chen T., 2019. Analysis on the theory and practice of industrial

symbiosis based on bibliometrics and social network analysis. *Journal of cleaner production*, 213: 956-967. https://doi.org/10.1016/j.jclepro.2018.12.131.

Indranil De I., Chattopadhyay S., Nathan H.S., Mishra P., Parey A., Dutta S., 2022. Structural and institutional arrangements impacting collective actions in WUAs of West Bengal, India. *International Journal of Water Resources Development*, 39: 433-458.

ITCEQ (Tunisian Institute of Competitiveness and Quantitative Studies), 2018. *Indicateur de Développement Régional : Méthodologie et resultats*.

Jacomy M., Venturini T., Heymann S., Bastian M., 2014. ForceAtlas2, a continuous graph layout algorithm for handy network visualization designed for the GEPHI software. *PLoS ONE*, 9(6): e98679. https://doi.org/10.1371/journal.pone.0098679.

Jariego I.M., 2024. Using stakeholder network analysis to enhance the impact of participation in water governance. *Humanities and Social Sciences Communications*, 11(1). https://doi.org/10.1057/s41599-024-02958-x.

Jia S., Li D., 2021. Evolution of water governance in China. *Journal of Water Resources Planning and Management*, 147(8). https://doi.org/10.1061/(asce)wr.1943-5452.0001420.

Kim J., Hastak M., 2018. Social network analysis: Characteristics of online social networks after a disaster. *International Journal of Information Management*, 38(1): 86-96. https://doi.org/10.1016/j.ijinfomgt.2017.08.003.

Knieper C., Holtz G., Kastens B., Pahl-Wostl C., 2010. Analysing water governance in heterogeneous case studies—Experiences with a database approach. *Environmental Science and Policy*, 13(7): 592-603. DOI: 10.1016/j.envsci.2010.09.002.

Kofinas G.P., 2009. Adaptive co-management in social-ecological governance. In: Chapin III F.S., Kofinas G.P., Folke C. (eds), *Principles of ecosystem stewardship: resilience-based natural resource management in a changing world*, pp. 77-101. New York: Springer. http://dx.doi.org/10.1007/978-0-387-73033-2_4.

Kozar R., Buck L., Barrow E., Sunderland T., Catacutan D., Planicka C., Hart A., Willemen L., 2014, *Toward Viable Landscape Governance Systems: What Works?* Washington, DC: Eco Agriculture Partners, on behalf of the Landscapes for People, Food, and Nature Initiative.

Kusters K., De Graaf M., Buck L., Galido K., Maindo A., Mendoza H., Nghi T.H., Purwanto E., Zagt R., 2020. Inclusive Landscape Governance for Sustainable Development: Assessment Methodology and Lessons for Civil Society Organizations. *Land*, 9: 128.

Leghrissi H., Chebil A., Mellah T., Frija A., 2023. Optimizing water use efficiency in Arid Tunisia: An economic evaluation of public irrigated schemes for agricultural development. *Zenodo (CERN European Organization for Nuclear Research)*. https://doi.org/10.5281/zenodo.7956272.

López-Gunn E., 2003. The role of collective action in water governance: A comparative study of groundwater user associations in La Mancha Aquifers in

Spain. *Water International*, 28(3): 367-378. https://doi.org/10.1080/02508060308691711.

MAHRF (Ministry of Agriculture Hydraulic Resources and Fisheries), 2023. *Annual report on the water sector 2023*.

MAHRF (Ministry of Agriculture Hydraulic Resources and Fisheries), 2021. *Annual report on the water sector 2021*.

Mekki I., Ferchichi I., Taouajouti N., Faysse N., Zairi, A., 2022. Oasis extension trajectories in Kebili territory, southern Tunisia: drivers of development and actors' discourse. *New Medit*, 21(5). https://doi.org/10.30682/nm2205f.

M'Hamed H.C., Abdellaoui R., Kadri K., Naceur M.B., Hadj S.B., 2008. Assessment of genetic diversity of local rice accessions cultivated in Guinea revealed by SNPs markers, and identification of markers associated with tolerance to iron toxicity. *Biotechnologies*, 28: 30-37.

Molle F., Berkoff J., 2007. Water Pricing in Irrigation: The Lifetime of an Idea. In: Molle F., Berkoff J. (eds), *Irrigation Water Pricing: The Gap between Theory and Practice*, pp. 1-20. Wallingford: CABI.

Nabiafjadi S., Sharifzadeh M., Ahmadvand M., 2021. Social network analysis for identifying actors engaged in water governance: An endorheic basin case in the Middle East. *Journal of Environmental Management*, 288: 112376. DOI: 10.1016/j.jenvman.2021.112376.

Naustdalslid J., 2014. Multi-level water governance – the case of the Morsa River Basin in Norway. *Journal of Environmental Planning and Management*, 58(5) : 913-931. https://doi.org/10.1080/09640568.2014.899895.

ODCO (Office du Développement du Centre Ouest), 2017. *Gouvernorat de Kasserine en Chiffre*, ISNN 773-9857.

Pahl-Wostl C., Hare M., 2004. Processes of social learning in integrated resources management. *Journal of Community and Applied Social Psychology*, 14: 193-206.

Pasikowski S., 2024. Snowball Sampling and its Non-Trivial nature. *Przegląd Badań Edukacyjnych*, 2(43): 105-120. https://doi.org/10.12775/pbe.2023.030.

Pérez J.F.R., Del Castillo D.C.L., Valdés M.M., 2021. Algorithm for measurement and analysis of authority and influence of users in social and professional networks. *PAAKAT Revista De Tecnología Y Sociedad*, 11(21): 1-27. https://doi.org/10.32870/pk.a11n21.598.

Prell C., Hubacek K., Reed M., 2009. Stakeholder analysis and social network analysis in natural resource management. *Society and Natural Resources*, 22(6): 501-518. https://doi.org/10.1080/08941920802199202.

Reed J., Deakin L., Sunderland T., 2015. What are 'Integrated Landscape Approaches' and how effectively have they been implemented in the tropics: a systematic map protocol. *Environmental Evidence*, 4(1): 2. https://doi.org/10.1186/2047-2382-4-2.

Rhodes R.A.W., 2007. Understanding Governance: Ten Years On. *Organization Studies*, 28(8): 1243-1264. DOI: 10.1177/0170840607076586.

Rodrigues L., Machado C.R., Lourenço N., 2006. Social networks and the management of water resources for agriculture in Rio Caia Catchment (Portugal). *Italian Journal of Agronomy*, 1(4): 741. https://doi.org/10.4081/ija.2006.741.

Ros-Tonen M.A.F., Derkyi M., Insaidoo T.F.G., 2014. From Co-Management to Landscape Governance: Whither Ghana's Modified Taungya System? *Forests*, 5: 2996-3021.

Rouse M., 2007. *Institutional Governance and Regulation of Water Services: The Essential Elements*. London: IWA Publishing.

Roux D.J., Stirzaker R. J., Breen C. M., Lefro E. C., Cresswell H. P., 2010. Framework for participative reflection on the accomplishment of transdisciplinary research programs. *Environmental Science and Policy*, 13(8): 733-741. DOI: 10.1016/j.envsci.2010.08.002.

Rowley T.J., 1997. Moving beyond Dyadic Ties: A Network Theory of Stakeholder Influences. *Academy of Management Review*, 22: 206-221.

Santos E., Carvalho M., Martins S., 2023. Sustainable Water Management: Understanding the socioeconomic and cultural dimensions. *Sustainability*, 15(17): 13074. https://doi.org/10.3390/su151713074

Scherr S.J., Shames S., Friedman R., 2013. Defining Integrated Landscape Management for Policy Makers. *EcoAgriculture Policy Focus*, n. 10.

Scott J., 2017. *Social network analysis*. https://doi.org/10.4135/9781529716597.

Shiferaw B.A., Reddy V.R., Sharma B., 2023. Groundwater governance under climate change in India: lessons based on evaluation of World Bank interventions. *International Journal of Water Resources Development*, 40(3): 401-424. https://doi.org/10.1080/07900627.2023.2207694.

Sørensen E., Torfing J., 2016. Metagoverning collaborative innovation in governance networks. *The American Review of Public Administration*, 47(7): 826-839. https://doi.org/10.1177/0275074016643181.

Stein C., Ernstson H., Barron J., 2011. A social network approach to analyzing water governance: The case of the Mkindo catchment, Tanzania. *Physics and Chemistry of the Earth*, Parts a/B/C, 36(14-15): 1085-1092. https://doi.org/10.1016/j.pce.2011.07.083.

Van Lap N., Oanh T.T.K., Phuong L.K., Lan N.T.M., Quyen V.T.H., 2023. Assessing the potential of shallow groundwater for agriculture adapting to drought and saltwater intrusion, Ben Tre Province, Mekong River Delta, Vietnam. *Earth Sciences*. https://doi.org/10.11648/j.earth.20231201.12.

Van Oosten C., Gunarso P., Koesoetjahjo I. Wiersum F., 2014. Governing Forest Landscape Restoration: Cases from Indonesia. *Forests*, 5: 1143-1162. DOI: 10.3390/f5061143.

Wasserman S., Faust K., 1994. *Social network analysis: Methods and applications*. Cambridge: Cambridge University Press.

Yang J., Shena G.Q., Hoa M., Drewa D.S., Xueb X., 2011. Stakeholder management in construction: an empirical study to address research gaps in previous studies. *International Journal of Project Management*, 29(7): 900.

Zagt R., de Graaf M., Shames S., Buck L., 2017. *Assessing landscape governance – a participatory approach*. Wageningen: Tropenbos International and EcoAgriculture Partners. DOI: 10.13140/RG.2.2.35850.36808.