Insights and participatory actions driven by a socio-hydrogeological approach for groundwater management. The Grombalia Basin case study (Tunisia)

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Abstract: Sustainable groundwater management in water-scarce countries is a pragmatic example of the necessity to guide future decision-making processes by simultaneously considering local needs, environmental problems and economic development. For these reasons the new socio-hydrogeological approach, Bir Al-Nas, proposed by Re (2015), has been tested in the Grombalia region (Cap Bon Peninsula, Tunisia), to evaluate the effectiveness of `complementing hydrogeochemical and hydrogeological investigations by considering the social dimension of the issue at stake. Within this approach the social appraisal, performed through Social Network Analysis and public engagement of water end-users, allowed hydrogeologists to get acquainted with the institutional dimension of local groundwater management, identifying issues, potential gaps, such as weak knowledge transfer among concerned stakeholders, and the key actors likely to support the implementation of new science-based management practices resulting from the ongoing hydrogeological investigation. Results hence go beyond the specific relevance for the Grombaila basin, showing the effectiveness of the proposed approach and the importance to include social assessment in any given hydrogeological research aimed at supporting local development through groundwater protection measures.

Keywords: Socio-economic aspects, groundwater protection, public engagement, social network analysis, Bir Al-Nas

1. INTRODUCTION

Groundwater constitutes 30% of world's freshwater storage and it corresponds to 97% of global freshwater potentially available for human uses (UN-Water 2014). However, due to the recent increase in groundwater withdrawal, driven by the shift towards more water-dependent economies, many aquifers worldwide are being depleted at alarming rates (Richey et al. 2015). Indeed, the most stressed ones are often located in arid/semi-arid regions, where, due to scarce precipitation and recurrent droughts, groundwater represents the main freshwater source for local population (Re and Zuppi 2011), or in poor and densely populated regions, where alternatives to water supply are limited and water shortages can easily become a driver to social and economic instability (Richey et al. 2015). Consequently, not only groundwater has to be used and managed in a more sustainable way (and this strongly depends on the behaviour of both decision makers and water end-users), but also its quantity and quality issues have to be tackled using multidisciplinary approaches, balancing the difficulties raised by both limited access to the resource and the lack of appropriate knowledge on aquifer dynamics (Shah et al. 2003; Moench 2007).

Despite the growing awareness on the need to promote participatory processes to support sound environmental management, the latter are seldom implemented in investigations dealing with the identification of groundwater pollution sources. In fact, looking at the recent literature on groundwater management, only few studies combine stakeholder analysis and engagement with hydrogeological assessments to find both criticalities and possible pathways for the implementation of more sustainable practices (e.g. Foster et al. 2004; Bekkar et al. 2009; Villholth et al. 2013; Re 2015 and references therein). In addition, although increasing attention is paid to groundwater governance (e.g. Shah 2010; van der Gun et al. 2012; Varady et al. 2013), groundwater withdrawal and pumping management (e.g. Bekkar et al. 2009; Fofack et al. 2015), and to proposing alternative points of view to groundwater knowledge (e.g. Birkenholtz 2008; Budds 2009; Aubriot 2011), new measures are often not associated with a general improvement of groundwater quality (Shah et al. 2003). Therefore, notwithstanding the advances in scientific knowledge and the increasing regulations for groundwater protection, the lack of a robust connection between science and society, associated with scarce involvement of water end-users (and polluters), seems to hamper the achievement of sustainable groundwater management. Indeed, a stronger engagement by hydrogeologists (and by groundwater scientists in general) in bridging this gap could contribute to the implementation of new science-based strategies that can take into account both the needs of groundwater users and the necessity to protect this already vulnerable resource from further contamination.

In this context, socio-hydrogeology has been introduced by Re (2015) as a way to go beyond the state of the art of hydrogeological investigations and contributing to effectively bridging the gap between science and society. To this end the application of the new Bir Al-Nas approach, combining hydrogeological assessments and social analysis to provide advices and to support integrated management practices in areas highly affected by aquifer pollution and over-exploitation, was proposed. Within this approach the hydrogeological assessment, targeted to understanding the general aquifer characteristics and identifying the different pollution sources, is associated to a public engagement activity aimed at ascertaining the needs and issues of water end-users while also retrieving information on local groundwater use patterns. Moreover, a stakeholder analysis is proposed to comprehend how different actors are involved in the decision making process related to groundwater management. The two main objectives of these analyses are to cross boundaries between social and natural sciences (in order to consider both the socio-political and the environmental dynamics of groundwater issues), and moving the scientific community closer to the "field realities", hence making hydrogeologists and local stakeholders collaborating to find sustainable solutions for groundwater use and protection.

This paper presents the preliminary results of the application of the Bir Al-Nas approach in the Grombalia basin, one of the main agricultural regions of Tunisia, affected by different issues shared by most of the coastal aquifers in the Mediterranean Basin (i.e. aquifer pollution and salinization, water overexploitation and saline-water intrusion), hence requiring adequate management plans for the long-term protection of its water resources. In particular it focuses on the discussion of the social analysis outcomes and of the benefits derived by combining hydrogeological and social assessments. Together they can help fostering the role of hydrogeologists as advocates of new bottom-up actions for groundwater contamination reduction that does not compromise end-users needs. In fact, understanding the complex web of relationships between actors at local and central level, as well as their engagement in the decision making process, is fundamental for the implementation of effective science-based groundwater management strategies.

2. CONCEPTUAL FRAMEWORK AND METHODOLOGY

2.1 The Bir Al-Nas approach

Bir Al-Nas (Bottom-up IntegRated Approach for sustainabLe groudNwater mAnagement in rural areaS) proposes the integration of hydrogeochemical and socio-economic analyses to support groundwater management in rural areas, as reinforced by the translation of the Arabic *bir al-nas*, meaning “the people’s well”. (Re, 2015). This new socio-hydrogeological approach is centred on the role of hydrogeologists as advocates for groundwater management and protection, being able to promote and implement actions that embed local know-how into water management strategies. All this can be achieved by creating a network of mutual trust between hydrogeologists and end-users (and polluters), eventually bridging the gap between scientists and citizens.

In practical terms, Bir Al-Nas features the integration of specific social analysis to hydrogeochemical and hydrogeological assessment aimed at defining the baseline characteristics of the studied groundwater system and to evaluate deviations from natural conditions due to human activities:

- A stakeholder analysis, targeted to the identification of the relevant actors in the issue being studied;
- Direct engagement and discussion with well owners and farmers to i) tackle the research project more effectively, ii) retrieve reliable information about water and land use, and iii) disseminate the results while performing knowledge exchange on groundwater status and protection strategies.

2.2 Case study

The Grombalia coastal plain (720 km^2; NE Tunisia) is one of the country's most important rural districts, providing 16% of the total agricultural production. The region is characterized by a semi-arid to sub-humid Mediterranean climate, with low and irregular rainfall of about 512 mm/year, and with a mean annual temperature of 18°C. The region is particularly suitable for arboriculture (mainly citrus – representing 82% of the national production, grapes – 80% of Tunisian vineyards, and olives), and horticulture (mainly tomatoes, strawberries and legumes). Most of the agricultural production is sold on both the national and international markets (Gafsi and Ben Hadj 2007). The agro-industrial sector is also rapidly expanding with more than 1250 factories located in the surrounding areas of the cities of Nabeul and Grombalia.

The main source of water supply for both agricultural and industrial purposes is groundwater from the Grombalia coastal aquifer. This is a multi-layer aquifer system comprised of a shallow phreatic aquifer, with an average thickness of about 50 m (hosted in the Quaternary continental sand, clayey sand and sandstones deposits), and different confined aquifers reaching 200 m of depth. The different layers are connected through discontinuities between the different marl layers (Castany 1948; Ennabli 1980). The recharge in the shallow unconfined aquifer mainly occurs in the pediments of the surrounding mountains and converges to the central part of the basin. There, a general southeast–northwest flow carries groundwater to the Gulf of Tunis, as the aquifer discharge area (Ben Moussa 2007; Gaaloul et al. 2014). Due to the growing water demand the aquifer is constantly exposed to increasing pressure (with annual exploitation rates of about 250 Mm^3/year) resulting in a severe piezometric level decrease (about 10 m in the last 50 years) (Charfi et al. 2013a; Gaaloul et al. 2014). Therefore, the rising groundwater use has led to severe water exploitation, especially in the dry season, due to abstraction rates exceeding natural aquifer replenishment from rainfall infiltration through permeable layers in the north-eastern part of the plain (Charfi et al. 2013b). In addition, the aquifer is facing severe groundwater issues related to salinization, salt water intrusion near the sea shore and nitrate pollution (Ben Moussa et al. 2010; Ben Moussa and Zouari 2011), due to both natural processes and anthropogenic activities. In fact, water-rock interaction processes (e.g. dissolution of halite and gypsum) are one of the main causes of the high natural salinity of the aquifer, while agricultural practices (namely uncontrolled use of fertilizers and agricultural return flow) combined with industrial effluent discharge and the lack of adequate sanitation facilities in some rural neighbourhoods are the main drivers of high nitrate concentrations (Ben Moussa and Zouari 2011).

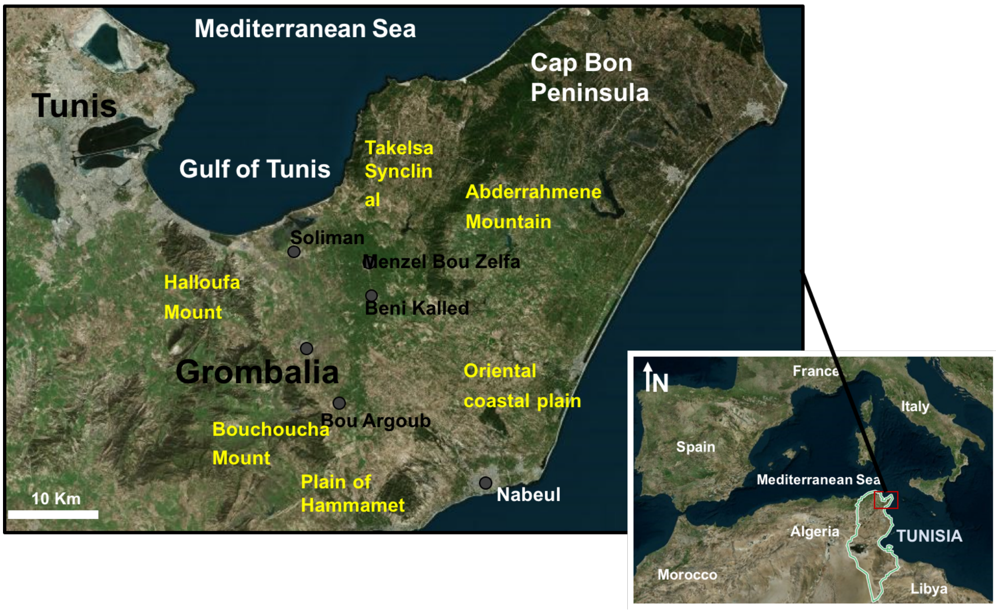

***Fig. 1 The Grombalia Basin (Tunisia). Background satellite image from Microsoft® Bing™ Maps").**

2.3 Stakeholder identification and Social Network Analysis

Stakeholder Analysis (SA) provides a complete picture of all the actors involved in a particular problem, highlighting their relationships and possible conflicts, their power relations and their roles in the issue concerned (Reed et al. 2009). With regard to water management the direct engagement of all the stakeholders dealing with water resources (e.g. consumers, polluters and managers) is fundamental for the achievement of sustainability goals and for the implementation of new long-term water management practices.

For the application of the Bir Al-Nas approach a preliminary SA was performed through a review of the main documents and legislation on water management in Tunisia (e.g. Tunisian Water Code 1975; Chkir et al. 2005; Al Atiri 2007; Canesse 2011). This permitted an initial appraisal of all the actors involved in groundwater consumption and management, considering both institutional actors and end-users. A Stakeholder Network Analysis (SNA) was then carried out to gain a better understanding of the formal and informal interactions between the different actors (Wasserman and Faust 1994). SNA permits the identification of the most influential stakeholders within a specific network, the analysis of formal and informal interactions among them (Scott 1991; Schiffer and Hauck 2010; Marshall and Staeheli 2015) and it is considered a particularly powerful tool in natural resource management initiatives seeking to influence stakeholders' behaviour through key influential individuals (Reed et al. 2009, Bellarby et al., 2016). For the purpose of the proposed investigation the SNA was performed using the Net-Map toolbox (Schiffer and Waale 2008). Net-Map is an interview-based mapping tool, facilitating the identification of all the actors involved in a given issue while also highlighting their power relations, their influence and their main goals (Schiffer et al. 2007), by means of the so-called Influence Network Map (INM). Between February and March 2014, Net-Map discussion meetings and qualitative interviews were conducted with three key target groups with specific knowledge of groundwater-related issues in the Grombalia basin (Tringali, 2014): i) a group of hydrogeologists from the National Engineering School of Sfax (Tunisia) working on the hydrogeochemical characterization of the Grombalia aquifer's recharge and pollution sources; ii) a decision-support system (DSS) and public participation in the water sector expert from the University of Sfax (Tunisia); iii) a local agent of the Tunisian Ministry of Agriculture working at the Regional Commissariat for Agricultural Development (CRDA) of Nabeul (i.e. the institution responsible for water resource management and control in the Grombalia region). The point of view of the hydrogeologists was useful to capture the vision of academics related to the social implications of scientific researches. The DSS expert was involved to assess the perception of the studied issue by an informant more familiar with holistic approaches to water resources management and with specific knowledge of the problems in the Grombalia region. The last key-informant provided insights on the position of local authorities. Since it was not possible at the moment of the investigation to perform a INM with local farmers, their point of view was captured during the public engagement phase, through questionnaires administration (cfr. Section 2.4).

For the realization of the SNA it was decided to ask each group to build an individual map during a separate interview (Figure 2). Not only did this permitted to clearly outline the way each group of key informants perceived the issue being analysed, but it also prevented the limitations caused by power differences between the various interviewees (i.e. possible biases due to intimidation effect).

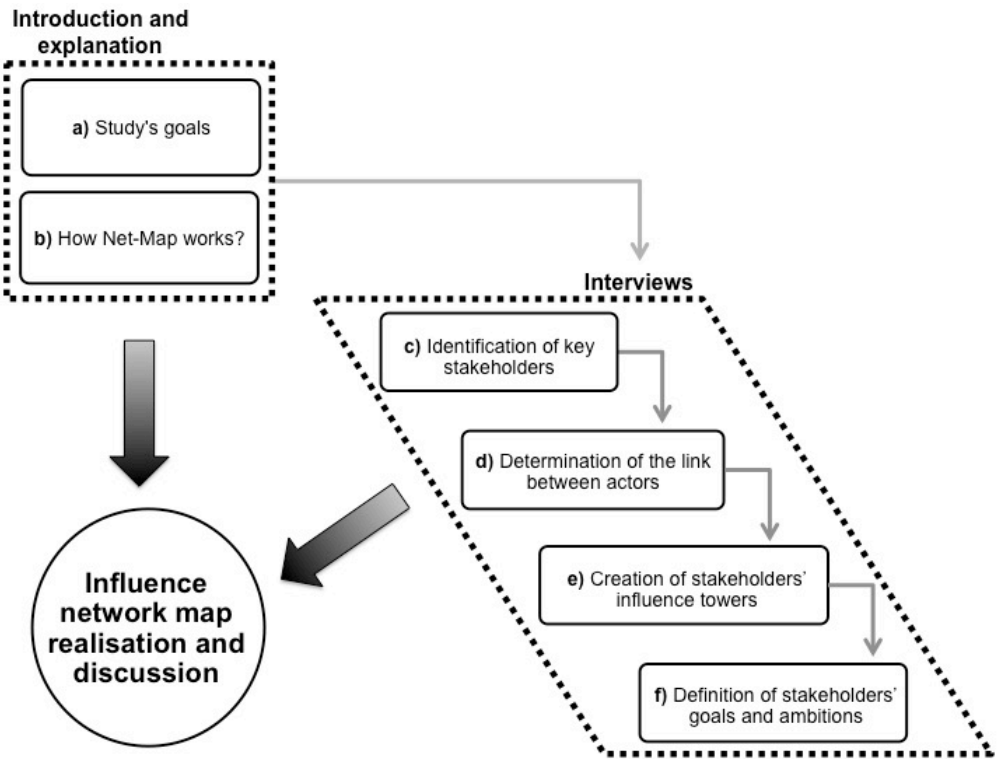

***Fig. 2 Phases of the Influence Network Map (INM) creation**

The guiding questions for the creation of the INM maps were: "Who can influence groundwater pollution reduction in the rural areas of the Grombalia basin?" and "Who can influence the implementation of new groundwater protection actions based on the outcomes of the hydrogeochemical investigation?". With the help of these questions key informants identified and listed all the stakeholders involved in groundwater use, management and protection in the Grombalia region, with a special focus on the agricultural and rural sectors. Subsequently it was asked them to highlight the relationship among the different stakeholders according to the following links: i) exchange of technical information about groundwater status; ii) control and authorisations; iii) advices and best practices exchange; iv) money flow; and v) conflicts.

Key informants were then asked to highlight the relative power of each actor/group of actors (i.e. how strongly they could influence the issue being studied and the behaviour of other actors; Sander et al. 2013). The influence degree of each stakeholder was calculated as the average value assigned by the different key informants in each map, where the influence degree ranges between 0 (no influence) and 5 (high influence). The final step was to assign each stakeholder a specific goal with respect to the topic under investigation, choosing between environmental protection and economic development. The three individual maps so obtained were subsequently merged to create an overall INM showing the interactions among the actors identified (Schiffer and Waale 2008). The latter was created also taking into account the information retrieved with the SA and those obtained during the public engagement of local farmers and well owners phase.

Network data of the common influence map were displayed and analysed using Visualyzer software (Visualyzer 2.0; Medical Decision Logic, Inc. 2007), and the final structure was studied using network centralization and degree centrality analyses. The first one measures the extent to which the network is centred on one (or more) key actor, showing how power and influence are distributed. Node centrality analyses the number of relationships (i.e. ties) an actor has within the network and it is a measure of the importance/influence of the stakeholders within the network. Three different centrality investigations were performed: *degree centrality*, representing the total number of links between a given actor and the others; *in-degree* and *out-degree*, which are the number of inward and outward links to other actors, respectively.

2.4 Public Engagement

As previously mentioned Bir Al-Nas promotes a structured approach to public engagement and communication with local farmers/well holders that may eventually become a compulsory component of hydrogeological and hydrogeochemical investigations targeted at rural development (Re 2015). To this end, during the hydrogeological field campaign to investigate groundwater pollution sources in the Grombalia Basin (February-March 2014) farmers and well owners of the 51 sampled sites were asked to respond to structured interviews on water and agricultural practices (Tringali 2014). The spatial distribution of the interviewed farmers and well owners hence corresponds to the location of the sampling network of the hydrogeochemical investigation, and extends over the whole Grombalia plain. The participation to the interviews was on volunteer base only and no direct incentives (e.g. reimbursements, gifts) was given to participants. In addition, to ensure that privacy is respected, an informed consent form was signed prior each questionnaire administration. The form clearly explained the purpose of the investigation and the use of the information retrieved, explicitly mentioning that data would only be used in disaggregated form, and asked for permission to take pictures (or record videos) during the sampling phase (Re, 2015). The main goal of the public engagement activity was to create momentum for dialogue on local groundwater protection and capacity building, while also collecting relevant information on groundwater use and farmers' perceptions of pollution issues. Each interview started with a full explanation of the project's objectives and goals, and concluded with an overview of groundwater resources status and issues in the region, according to the scheme provided by Re, 2015. The last part of the interviews was intended to evaluate the potential for the implementation of participatory water monitoring and management initiatives by assessing the interviewees' perceived role in groundwater protection, and their awareness of the role of scientists and policy makers in local groundwater management (Re, 2015). In particular, in line with the SNA objectives, interviewees were asked to indicate the most powerful stakeholders involved in groundwater protection actions.

Structured interviews were administered directly by the research team during *in situ* hydrogeological measurements and sampling collection activities in order to i) start a dialogue with groundwater users as the basis for participatory management approaches and ii) obtain direct and reliable information to support hydrogeochemical data interpretation.

3. RESULTS AND DISCUSSION

3.1 Main stakeholders involved in the Tunisian water management framework

Results of the SA (Tab. S1of the electronic supplementary material (ESM)) were used to preliminary characterize the stakeholders and to group them into three general categories:

- Decision makers (with legislative power);
- Groups and commissions with executive power;
- Water users.

The national decision-making level includes the Ministries and the National Water Committee. With respect to the studied issue, their functions are to: i) define water policies, ii) coordinate activities related to water development and iii) give advice on water distribution plans. The groups and commissions with executive power include actors that support the implementation of national policies and legislation on water distribution, rural development and water sanitation at regional level. The third category is composed by the groups of actors corresponding to water user associations, namely, the Groups of Hydraulic Interest (GHIs), and the Associations of Collective Interest (AICs), subsequently replaced by the Groups of Agricultural Development (GDAs). The latter, composed by landowners, farmers and water users sharing water resources in each irrigated area, and coordinated by a board of democratically elected local members, have played (and plays) an important role in Tunisian agricultural development. The GDAs, are mainly responsible for water management at local level, and in particular are in charge of the i) organization of the irrigated areas, ii) implementation and maintenance of the hydraulic infrastructures within the irrigated area of competence, iii) coordination of water distribution among farmers, iv) safeguarding and protection of natural resources, and v) promotion of agricultural techniques (Al Atiri 2004; Mouri and Marlet 2007; Canesse 2010). GDAs are therefore quite important at the local level, representing a "connecting point in the triangle of administration/farmers/natural resources" (Canesse 2010). In fact, on the one hand, farmers pay for natural resources utilization, and on the other, they elect the GDA committee, which identifies problems, proposes solutions, and manages agricultural areas. The constitution of the GDA is based on a transfer of competences from the central to the local level, representing the first step of the reconstruction of rural institutions in Tunisia (Canesse 2010).

3.2 Social Network Analysis: Net-Map results for the Grombalia basin

Figure 3 shows the final INM where each stakeholder, or group of stakeholders, is represented by a node (different coloured shapes in the network visualised in Figure 3), and nodes are connected using different links (coloured arrows in the network visualised in Figure 3). The stakeholders' influence degree is depicted by the size of each node in the INM. Moreover, for mapping purposes, the local and national actors were grouped into seven main categories, as indicated in Tab.1.

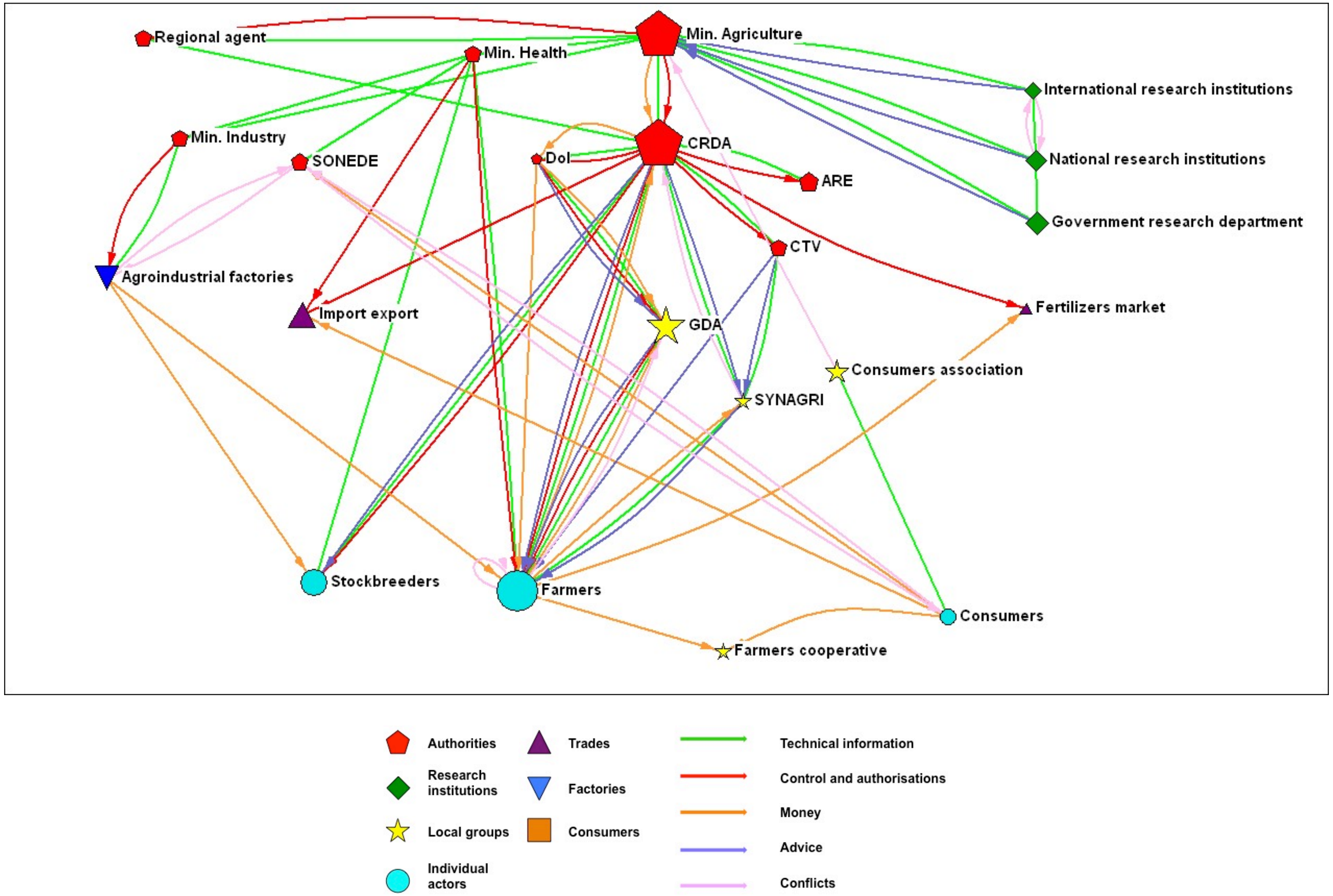

*****Fig. 3 Common INM for stakeholders involved in groundwater management and protection in the Grombalia basin. List of acronyms used in the map: SONEDE: National Society for Water Exploitation and Distribution; CRDA: Regional Commissariat for Agricultural Development; DoI: Department of Irrigation; ARE: Water Resources Office; CTV: Local Divulgation Centre; GDA: Groups of Agricultural Development; SYNAGRI: farmers' trade union.**

***** Table 1 Comparison between the stakeholders identified during the SA included in the maps, and the stakeholders identified during the SNA. Blue: Decision-making level; Grey: Executive level; Magenta: Users level; Black: Others.**

Groups	Stakeholders identified with SA	Stakeholders identified with SNA
Authorities	• Ministry of Agriculture • Regional Commissariat for Agricultural Development (CRDA), • National Society for Water Exploitation and Distribution (SONEDE)	• Ministry of Health • Ministry of Industry • Water Resources Office (ARE) • Department of Irrigation of the CRDA (DoI) • Crop Production Office • Local Divulgation Centre (CTV) • Regional Agent • Local and National Police
Research institutions		• Universities • National Research Institutions • International Research Institutions • Consultants • Government Research Department • Non-Governmental Organizations (NGOs)
Local groups	• Groups of Agricultural Development (GDA)	• Consumers association • Farmers cooperative • Farmers trade union (SYNAGRI)
Individual actors		• Farmers • Stockbreeders • Landowners
Factories		• Factories • Agro-industrial factories
Trades		• Import-export agricultural products, • Fertilizers market
Consumers		• Local Communities • Citizens/Consumers

Results show that in addition to the actors identified with the SA (Tab. S1of the electronic supplementary material (ESM)), other stakeholders playing an important role in the Grombalia groundwater system management were identified by key informants during the SNA elaborations (Tab. 1). These are:

• Institutional actors at national and regional level, whose competences also partially span in the water domain, and that may influence the implementation of new groundwater management actions in the region (e.g. the Regional Agent receiving and implementing ministerial directives at regional level, the Department of Irrigation of the CRDA – DoI – in charge of managing the irrigated areas; the Crop Production Office in charge of quality control of agricultural production; and the Local Divulgation Centre depending on CRDA – *Cellule Territoriale de Vulgarisation*, CTV– which organizes outreach campaigns sharing good practices regarding agriculture and water use in rural areas).

- Research institutions, identified as relevant actors due to the presence of a significant number of investigations (both national and international level) carried out to assess groundwater status in the region.
- Business and trade companies, especially in the agro-industrial sector, as potentially influencing the import-export of agricultural products and the fertilizers market.
- Local rural actors, such as the local community (i.e. citizens, consumers, farmers, stockbreeders and landowners), and agricultural associations (i.e. consumers' association, farmers' cooperative, farmers' trade union – *Syndicat des agriculteurs de Tunisie*, SYNAGRI), recognized to potentially affect decision-making processes related to water resources as far as agricultural production is at stake.

All the information obtained trough the SA and SNA where taken into account while creating the common influence network map, therefore stakeholders identified in one of these phases, but that do not actually play a significant role related to the studied issue, were not included in the final IWM. These are the Crop Production Office, local and national police, and private consultants. As far as factories are concerned, it was decided to pay particular attention to agro-industrial plants (the most numerous in the study area). Some actors, identified with different names by interviewees, have been unified using a common label, such as universities (grouped with national research companies) landowners (unified with farmers), local community and citizens (grouped as consumers), and NGO (included in international research companies since key-informants compared their work with the technical cooperation performed by foreign research groups).

As a result, a more complete picture of the social dynamics related to groundwater use and management in the region have been obtained. Indeed, without the SNA, relevant information not present in the literature would have been missed.

3.2.1 Analysis of the actors' links

The analysis of the relationships identified by the key informants (Figure 3) demonstrated that:

i) All the actors are involved in a technical information exchange, mainly referred to groundwater quality and wells' status. This type of flow occurs between Ministries and research institutions responsible for environmental quality assessments and control prior to new wells' drilling. Technical information also moves from ministerial central offices to local offices (CRDA), and from local groups and associations to water end-users. Private research companies are also involved, generally providing evaluation on crop's quality.

ii) Control and authorisation is mainly exerted by the Ministries through the local government authority (CRDA), responsible for checking fertilizers quality and application rates, crop's quality, and borehole maintenance. Furthermore, is responsible for authorizing researches in the region, and for regulating groundwater exploitation and well construction activities (new drilling can be carried out without prior authorization only if the well depth does not exceed fifty meters and if the well is not located within a "perimeter of interdiction" or "safeguard"; Tunisian Water Code, 1975).

iii) Money exchange flows involve not only consumers, public water distributors, and the actors within the crops market, but also the Ministry of Agriculture (through the CRDA) giving GDA subsidies for the maintenance and construction of new wells, with the overall goal of discouraging the construction of illegal wells. As an additional connection, the use of international research funds to perform investigations in the region was highlighted.

iv) As concerns the advices flow, it emerged that local authorities usually task research institutions with carrying out environmental studies, both concerning well drilling feasibility and groundwater quality assessments. Results of these investigations are also declared to be shared to give advices to water end-users regarding optimal fertilizers and groundwater use. Thus, the advice flow usually moves from the Ministry of Agriculture to the CRDA, CTV, GDA and, finally, to farmers. Advice flow from research institutions to water end-users was also mentioned sporadically occur.

v) All the key informants confirmed that conflicts are usually due to water scarcity and groundwater pollution problems. Farmers who participated to local surveys have reported conflicts, due to water distribution, with local administrations, such as the CRDA. During the dry season (and especially between June and September), local authorities impose water use restrictions upon farmers, who in turn organize protests against these measures. It interesting to underline that representative of local authorities involved in the INM construction did not recognize the latst conflict flow, while stressed the existence of disagreements among farmers due to competing interest in water use (also exacerbated by abovementioned restrictions in the dry season).

3.2.2 Influence degree and centrality analyses

In the influence degree analysis stakeholders are classified according to interviewees' perception of the ability to affect the implementation of new groundwater management practices, either directly or by inspiring/persuading the behaviour of other actors. Results (Figure 4) indicate that the most influential stakeholders in the studied area are:

i) Ministries and CRDA, given their administrative, decisional and control functions on groundwater activities, and their legislative power on water resources management;

ii) Farmers and stockbreeders, as concerned water users and potential polluters, given the impacts of rural activities on groundwater quality and quantity;

iii) Local groups working on rural development issues (i.e. GDAs), due to their potential role as mediators between the local and national authorities and the water end-users.

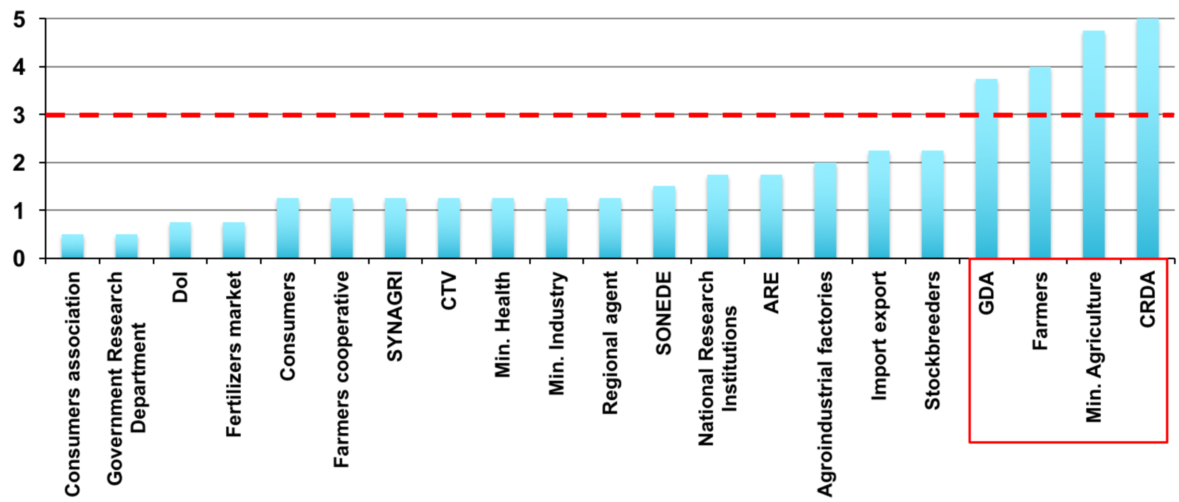

*****Fig. 4 Stakeholders' influence degree, as indicated in the common INM. The red area indicates the most influential stakeholders, according to the interviewees INM**

Figure 5 shows the results of the node centrality analysis for the common INM. According to this analysis the most central stakeholders in the network are:

i) The farmers, involved in 66.6% of network connections; and

ii) CRDA together with the Ministry of Agriculture and Environment, accounting for 57.1% and 52.3% of network connections, respectively.

Farmers are also the most central actors according to *in-degree* analyses, with 38% of incoming links regarding mainly money, control and authorization and advice. They receive money from agro-industrial factories by selling crops to them and subsidies from the CRDA to support agricultural production as specified earlier. As far as the control and authorization link is concerned, farmers are subject to the Ministry of Agriculture's control and require its authorization for all activities linked to groundwater exploitation, well construction and fertilizer use through the CRDA monitoring activities. Finally, they receive advice from the CRDA, GDA, CTV and trade union for the application of good water management practices to improve groundwater quality and availability.

The *out-degree* analyses show the CRDA to be involved in 42.8% of outward links reflecting its important role in providing advices, technical information on groundwater management, and control on rural activities.

The outcome of the centrality analysis shows that the stakeholders centrality within the network does not necessarily correspond to the key informants' perception of stakeholders' influence. In fact, some actors, such as the GDA, identified as influential for the Grombalia water management (Figure 4), are not actually central in the network. This is an important result since it shows that some actors, although being perceived as relevant by the interviewees are not so well connected in the network, thus highlighting potential gaps that can hamper knowledge exchange between the actors and therefore the successful implementation of new groundwater management actions. In the case of GDAs, for instance, the lack of a strong connection within the network (with a degree centrality of only 14.28% - Figure 5) can undermine their abilities to mediate between authorities and groundwater end-users, essential for the local implementation of resource management strategies dictated at government level. In this case improving GDA's connections in the network can be beneficial for a more effective management of the water resources in the basin. These results also highlight the importance of including a SNA in any hydrogeological investigation targeted to local development. Not only it permits to identify all the relevant stakeholders involved in the studied issue since the early stage of the project, but also, it will give hydrogeologists inputs for discussing how the actors, links, influence and goals mapped out on the INM could affect specific groundwater reforms resulting from their investigation. In addition, based on the SNA outcomes, they would know who (and how) to engage to support the design and implementation of such reforms.

Degree Centrality:			
Nodes	Degree	InDegree	OutDegree normalized
Farmers	66.66%	38.09%	28.57%
CRDA	57.14%	14.28%	42.85%
Min. Agriculture	52.38%	19.05%	33.33%
Min. Health	28.57%	9.52%	19.05%
National research institutions	23.81%	9.52%	14.28%
SYNAGRI	23.81%	14.28%	9.52%
SONEDE	23.81%	9.52%	14.28%
Agroindustrial factories	23.81%	9.52%	14.28%
Consumers	23.81%	4.75%	19.05%
International research institutions	19.05%	9.52%	9.52%
Min. Industry	14.28%	9.52%	4.76%
Government research department	14.28%	9.52%	4.76%
CTV	14.28%	4.76%	9.52%
DoI	14.28%	4.76%	9.52%
Stockbreeders	14.28%	14.28%	0
GDA	14.28%	9.52%	4.76%
Import export	14.28%	14.28%	0
Regional agent	9.52%	9.52%	0
Consumers association	9.52%	4.76%	4.76%
Fertilizers market	9.52%	9.52%	0
Farmers cooperative	9.52%	9.52%	0
ARE	4.76%	4.76%	0

AVG:	22.08%	11.04%	11.04%
STD:	15.89%	6.94%	11.43%
MIN:	4.76%	4.76%	0
MAX:	66.66%	38.09%	42.86%

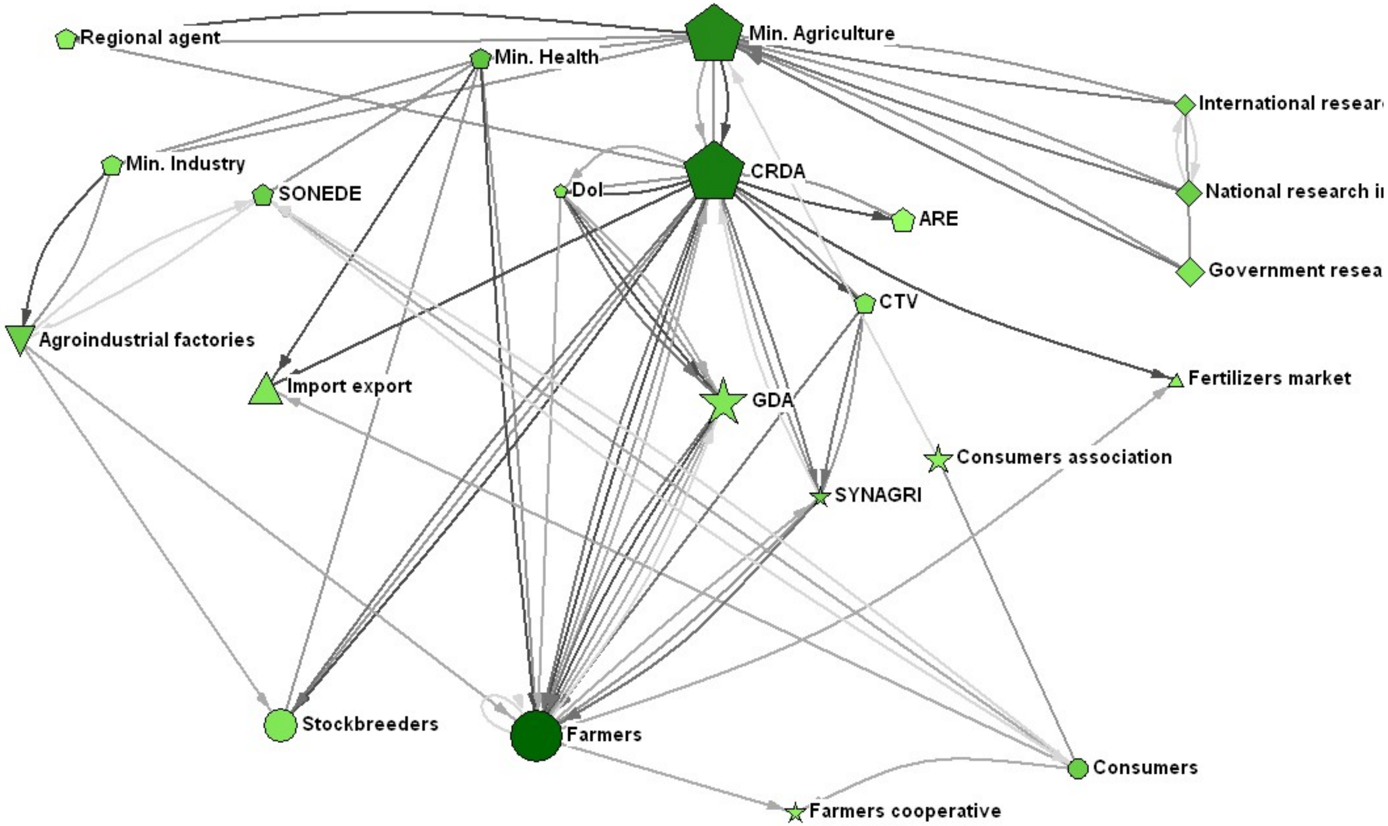

*****Fig. 5 Node Centrality analysis map. Light green indicates marginal stakeholders, while dark green indicates more central stakeholders (multiple links between two nodes are counted as a single link). The table in the figure shows the results of the centrality degree analyses (degree, in-degree and out-degree) in percentage values. Percentage indicates a ratio of the degree (out or in-degree) to the number of actors in the network minus one and allows comparison of degree centrality scores across other networks of different sizes. List of acronyms used in the map: SONEDE: National Society for Water Exploitation and Distribution; CRDA: Regional Commissariat for Agricultural Development; DoI: Department of Irrigation; ARE: Water Resources Office; CTV: Local Divulgation Centre; GDA: Groups of Agricultural Development; SYNAGRI: farmers' trade union.**

3.3 Public Engagement results

The structured interviews administered during the hydrogeological field campaign provided useful information to supporting SNA results, and favouring the identification of priorities, gaps and challenges to be addressed. This activity also permitted to include in the analysis the point of view of the farmers and well owners involved in the monitoring assessment, hence providing the basis for the implementation of a bottom-up approach tailored to their real needs and perceptions. Forty-four farmers, landowners and well owners answered questions about groundwater uses and impacts on water resources, and regarding their personal knowledge/perception of groundwater problems in the region (Figure S1 of the electronic supplementary material (ESM)). The interviewees' average age was 44 (with the youngest aged 20 and the oldest 67), while 14 people preferred not to state their age. Seventy-seven percent of the interviewees showed considerable interest in the research project and agreed to be involved in the monitoring network for the on-going hydrogeological assessment of groundwater quality in the Grombalia basin. The questionnaires showed that local people are aware of the existence of groundwater issues in the region, and that they consider as the most crucial problems: i) the general salinity increase; ii) the decrease in the piezometric level due to groundwater overexploitation; and iii) a clearly perceived degradation of water quality over the years. All of the interviewed farmers and well owners adopt the following strategies to deal with these issues: i) in case of significant piezometric level decrease, they suspend groundwater pumping and resort to alternative water sources (e.g. surface water) for irrigation. Alternatively, when this option is not possible (due to both economic or technical limitations), they dig deeper into the wells in order to reach a new water table depth; ii) where aquifer salinization can seriously hamper crop productivity, they mix groundwater with the irrigation channel water (i.e. Medjerda River waters, with salinity lower than 1.5 g/L, distributed in the region of Cap Bon by SECADENORD; Tlili-Zrelli, 2013) in order to obtain water suitable for irrigation.

Despite the common perception of the overall decline in groundwater quality over the years, none of the interviewees made reference to nitrate (NO_3^-) contamination, which is one of the main problems affecting the region, and thus a great challenge for current water management plans (Zouari et al. 2015). The differing views between farmers and academics regarding the nitrate issue are the main consequence of scarce or ineffective knowledge transfer of scientific findings. This highlights the need for hydrogeologists and groundwater scientists to play a more active in raising awareness about the link between agricultural practices (especially the widespread use of fertilizers) and the lack of adequate sanitation systems with nitrate pollution in aquifers, on the one hand, and about the effects of high nitrate concentrations in both irrigation and drinking water, on the other. In fact, nitrate concentrations exceeding the WHO statutory limit for drinking water (50 mg/L; WHO 2011), as in the case of the Grombalia aquifer (Zouari et al. 2015) can cause a variety of health problems, especially in children who can contract methemoglobinemia, also known as the blue-baby syndrome (Fan and Steinberg 1996), and gastric cancer (Feast et al. 1998). Indeed, during the hydrogeological investigations (and associated field works), special attention should be paid to specific capacity building on nitrate contamination in groundwater, sharing the analytical results of the sampled waters throughout the region, as often requested by interviewed well's owners. Moreover, collaborations with the sanitation sector could be strengthened. In fact, the INM showed that the Ministry of Health was not recognized to have an important role (degree of influence <2), compared to other stakeholders involved in the studied issues (i.e. "Who can influence groundwater pollution reduction in the rural areas of the Grombalia basin?" and "Who can influence the implementation of new groundwater protection actions based on the outcomes of the hydrogeochemical investigation?"). In fact, this ministry, being responsible to undertake drinking water quality monitoring, is mainly linked to the other stakeholders through the technical information flow (Figure 3), and through the control and authorization one (in this case it only linked to farmers and the import-export sector). This highlights the potential for strengthening its role within the network in order to raise awareness on nitrate-driven issues in drinking water. Indeed, the Ministry of Health could play a fundamental role in promoting public health advocacy strategies related to water quality needs for domestic, drinking and agricultural uses, and in collaborating with other non-governmental and community-based organizations involved in water, sanitation and hygiene (WASH) actions.

In addition, given that groundwater is mainly used for irrigation and domestic purposes (often including drinking use; Figure S2a of the electronic supplementary material (ESM)) it will be crucial to collaborate with local agronomists in order to provide advice on fertilizer optimization rates, enabling farmers to obtain the maximum returns from crops while reducing environmental impacts on soil and water (and of course fertilizer cost). Well-informed farmers might therefore be willing to engage personally in fighting nitrate contamination in the region (for example, by reducing fertilizer loads and calling upon the ministries for more support in actions targeted at groundwater quality protection) without compromising their profits. In the same way, it is necessary to explore alternatives that would reduce vulnerability to climate uncertainties and effect of droughts (in case of rainfed agriculture and the increasing use of surface waters for dominant drop-by-drop irrigation; Figure S2b of the electronic supplementary material (ESM)), and increase the implementation of dryland farming.

Most of the participants to the surveys indicated local and governmental authorities (in particular the Ministry of Agriculture and the State – 47.7% and the CRDA – 4.5%), as being responsible for the management and control of water and agriculture, although they also highlighted the perceived lack of practical support from state actors to local farmers. For example, only three participants stated that they used the type of fertilizers recommended by the CRDA, whereas the remaining interviewees stated that the CRDA had never contacted them to provide any kind of advice or guidelines on irrigation or agricultural practices. This is in disagreement with the information provided by the key informants involved in the SNA, highlighting a potential gap between theory and practice, i.e. the formal duties of some stakeholders and their effective application. As previously mentioned a stronger involvement of GDAs could contribute to bridging this gap and favour a more effective communication among the stakeholders (especially in terms of exchange of advices on good practices), and facilitate farmer's voice to be captured in decision-making processes. Moreover, none of interviewees declared to have ever been in contact with scientists and hydrogeologists prior to this meeting with the research group, even though the Grombalia basin (together with the Cap Bon Peninsula) is one of the most studied regions in the country, especially as far as groundwater is concerned. Clearly there is a pressing need for a closer links between the scientific community and water end-users to make optimum use of the outcomes of their investigations and ensure that scientific activities lead to real benefits for local populations. In addition, none of the interviewees was aware of Integrated Water Resources Management and Climate Change issues even though these are the main topics currently under discussion in the international hydrological community, again highlighting the need for improved dissemination activities that will increase the know-how exchange from within the scientific arena to households, citizens and local authorities.

3.4. Lessons learned and management recommendations

The application of the Bir Al-NAs approach in the region of Grombalia (Tunisia) permitted to highlight some actions to be taken to improve the management and protection of local groundwater resources:

- The Group of Agricultural Development (GDA) involvement must be fostered to fully benefit of its potential role as mediators between local/national authorities and the water end-users, and to ensure that farmer's voice and needs are adequately considered in the groundwater-related decision making processes.
- The scientific community should collaborate in a more efficient way with the other stakeholders involved in the network with the overall goal of finding adequate strategies to engage farmers in groundwater protection. This might imply improving advocacy actions together with the Ministry of Health and the sanitation sector, as well as collaborating with local NGOs and consumers' associations. Clearly engaging scientists in sound outreach activities and results presentations to end-users and local authorities would be an asset.
- Bottom-up driven strategies to groundwater protection that take into account farmers need and science-based management decisions should be prioritized in order to achieve environmental protection and conflicts reduction.

Moreover, besides its relevance for regional development, this study has some broader implications, especially related to the need to go beyond the state of the art of hydrogeological assessments and to bridge the gap between science and society through sound integrated approaches. In particular, this socio-hydrogeological application demonstrated:

- The importance of identifying the key stakeholders involved in the studied issues since the early stages of the hydrogeological assessment, in order to understand who is affected (directly or indirectly) by the groundwater system in question and whether the project/investigation likely to raise conflicts. Results highlighted that the SA performed through the literature review was not sufficient to gain a complete understanding of the social dynamics related to local/regional groundwater use and management. Indeed, performing a full SNA permitted not missing some relevant information related to the socio-economical system. This outcome is particularly relevant for investigations performed in different regional contexts (i.e. where hydrogeologists are nor fully acquainted with local issues) or when different cultural sensitivities are at stake.

- The need to perform integrated investigations more coherent with the complex network of interactions between the environmental and social sphere. Going beyond the classical hydrogeological assessment approach implies considering the cause-effect relationship between humans and groundwater, hence analysing not only how a given groundwater system is affected by human activities, but also how human activities and wellbeing are hampered by scarce or polluted groundwater resources.
- The importance of including local knowledge in hydrogeological assessment and to foster capacity building and information sharing with end users. Indeed, knowing their point of view related to the studied issue would permit not only to better address any investigation targeted to the improvement of local groundwater resources, but also to be aware of possible gaps to be bridged. In fact, as previously mentioned in the Grombalia application, differing views between farmers and academics regarding groundwater pollution issues and emergencies are mainly associated to the lack of adequate knowledge transfer. This problem can be effectively tackled with a stronger engagement of hydrogeologists in capacity development.
- The urgency to make scientists and local stakeholders working together to identify shared sustainable solutions for long-term groundwater protection.

4. Conclusions

A novel socio-hydrogeological approach, Bir Al-Nas, has been tested in the Grombalia basin (Tunisia) to evaluate the effectiveness of combining hydrogeological and social analysis (namely Social Network Analysis and public engagement) in investigation targeted to rural development. Results of the SNA, performed using the Net-Map toolbox, permitted obtaining a preliminary appraisal of the institutional setting in terms of groundwater management relative to the groundwater issues in Grombalia basin, also highlighting the most influential and central stakeholders able to support the implementation of new groundwater pollution reduction strategies. It emerged from the study that the stakeholders perceived as most influential in the Grombalia water management are not necessarily the most well connected ones. In particular, GDAs although covering an important role regarding the studied issue, are not central (i.e. well connected) with the other stakeholders, highlighting a potential knowledge exchange and communication gap within the network. Hence it will be necessary to create a new 'meeting point' for these influential actors, where GDAs, could partly compensate for the lack of support reported by farmers during the public engagement activities. They could also act as delegates representing farmers' needs at governmental level, as well as supporting end-users in applying groundwater best practices (e.g. optimizing groundwater and fertilizers use) developed by the state in collaboration with research institutions.

Not only was the public engagement activity carried out by using structured questionnaires – the first experimentation of public engagement practices in Grombalia– but it has also helped supporting the Social Network Analysis outcomes with useful information on farmers' perception of water pollution in the studied area. Although researchers and scientists could potentially cover an important role related to sustainable groundwater management, the public engagement results show that households rarely interact with them and have little confidence in the outcome of their work. For example, none of the interviewees had either a precise perception of local groundwater issues or a strong awareness of living in a water-scarce area. The Grombalia case study clearly reveals the importance of engaging farmers and groundwater end-users, as they can play a key role in implementing successful management practices and effective local actions. In this regard more attention should be paid to scientific outreach targeted at information sharing and promotion of advice to the general public. Moreover, improved communication between scientists and concerned stakeholders would contribute to building trust for a more reliable and sound management of groundwater resources. In this context, the Bir Al-Nas approach can represent a preliminary attempt to bridge the gap between science and society by i) making end users more aware of both the water issues and of the power they have to reduce groundwater pollution (Re, 2015), and ii) making scientists and decision makers more aware of end-users challenges and needs. Results of the social analysis are also currently being used to support hydrogeochemical data interpretation to assess nitrate pollution origin in the region and will be shared with concerned stakeholders identified through the SNA to discuss the implementation of new actions for groundwater protection in the region, without compromising farmer's wellbeing and productivity. Future perspective also include involving GDA's representatives to participate in the SNA in order to adequately capture their point of view and to assess their perceived role within the network and with respect to the analysed issues. Additionally, the proposed approach will be tested in other regional and hydrogeological contexts to evaluate its overall validity in contributing bridging the gap between science and societies as long and groundwater management is at stake.

To conclude, considering hydrogeologists' perspective and the overall relevance of the application, the incorporation of social analysis into hydrogeological investigation proved to be effective in identifying and presenting explanations for otherwise unexplained social and political dynamics governing the groundwater sector. Understanding these drivers, through Social Network Analysis and public engagement activities, can provide important insights for a more complete assessment of local groundwater issues, improve their understanding of local processes and power relations, and create the basis for more effective implementation of new management strategies. Such an approach can hence ensure an optimal use of scientific knowledge, permitting hydrogeologists to contribute solving groundwater issues through effective communication and a better engagement with water end-users. Being interested in generating insights that matter to people, through socio-hydrogeology hydrogeologists can engage for the implementation of knowledge-oriented management that embeds both sound scientific information and the real needs of local populations. Indeed, this approach can represent the basis for a complete and multidisciplinary assessment of groundwater issues and its status in different contexts worldwide.

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Fig. 5 Node Centrality analysis map. Light green indicates marginal stakeholders, while dark green indicates more central stakeholders (multiple links between two nodes are counted as a single link). The table in the figure shows the results of the centrality degree analyses (degree, in-degree and out-degree) in percentage values. Percentage indicates a ratio of the degree (out or in-degree) to the number of actors in the network minus one and allows comparison of degree centrality scores across other networks of different sizes. List of acronyms used in the map: SONEDE: National Society for Water Exploitation and Distribution; CRDA: Regional Commissariat for Agricultural Development; DoI: Department of Irrigation; ARE: Water Resources Office; CTV: Local Divulgation Centre; GDA: Groups of Agricultural Development; SYNAGRI: farmers' trade union.

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