Cascading vulnerability scenarios in the management of groundwater depletion and salinization in semi-arid areas

Parisi A.[1*], Monno V.[1a], Fidelibus M.D.[1b]

[1]DICATECh, Dept. of Civil, Environmental, Land, Building Engineering and Chemistry, Polytechnic University of Bari, Via Orabona 4, 70125 Bari, Italy.
*corresponding author, email: alessandro.parisi@poliba.it
[a] valeria.monno@poliba.it
[b] mariadolores.fidelibus@poliba.it

Abstract

Meteorological droughts can have unexpected cascading consequences on social, economic, and environmental systems, which depend on the starting conditions of affected systems, and on natural and human drivers. In coastal areas, droughts propagate their effects to coastal aquifers, causing exacerbation of withdrawals with consequent groundwater quantity and quality. Considering the area of Lecce province (Salento peninsula, Apulia region, Southern Italy), the study outlines the non-linear cascading paths related to groundwater depletion and salinization in an urbanized coastal region depending quite entirely on groundwater resources of a coastal karst aquifer. The outline of cascading events is the outcome of a scenario building process carried out through semi-structured interviews to water management stakeholders. The cascading scenarios relate to different degrees of system resilience and describe chain effects and vulnerabilities. These scenarios can have significant outcomes in improving water management practices and increasing both local manager and end-user awareness about potential and unexpected cascading consequences related to droughts.

Keywords: scenario building, drought, coastal aquifer, water crisis, climate change.

1. Introduction

Nowadays, groundwater resources are more accessible than in the past thanks to technological development. However, negative implications of this improved accessibility outweigh the positive ones. On the one hand, increasing groundwater exploitation provides a wide range of opportunities for human settlements and socio-economic activities in large areas of the world, on the other hand, it triggers new issues about the quantitative and qualitative status of these concealed commons [1].

An even major threat concerns groundwater resources in coastal zones with a climate favourable to human settlement and development of tourism and agriculture. In these areas, the demographic pressure and the consequent high level of urbanization cause high water-demand increasingly met by groundwater. Unfortunately, the favourable climate for the development of human activities is not as effective for the accumulation of surface and groundwater. This, for instance, is the condition of those Mediterranean countries having a semi-arid climate. Therefore, high water-demand has often low possibility to be satisfied due to a low natural availability. Moreover, human activities cause groundwater exploitation and high pollution loads; exploitation, in turn, produces groundwater depletion, triggering seawater intrusion and pollutant dispersion.

In coastal aquifers, fresh groundwater floats on salt water of marine origin, because of the different fluid density, thus groundwater depletion and salinization are concurrent issues. A hydraulic equilibrium defines the coexistence of fresh and salt waters [2–6], which, under natural conditions, are separated by a narrow transition zone of brackish waters. Uncontrolled exploitation triggers increasing fresh groundwater salt content by intrusion of seawater from the coast inland (lateral intrusion) and/or by upward transport (upconing) of salts to fresh groundwater from saltwater at its bottom. As a result, the transition zone expands in time, with the reduction of freshwater thickness and the gradual change of vertical density distribution. The evaluation of the limit of exploitation is extremely difficult in coastal aquifers because many strongly interdependent variables drive the freshwater-saltwater equilibrium, so that they show a non-linear behaviour and feedback loops [7]. The complex effects of human drivers (such as demographic pressure, amount and distribution of exploitation, land use, and policy rules) and natural constraints (such as hydrogeological framework, scale of flow systems, climate, effective recharge, and sea level oscillations) overlaps with the complexity of density driven groundwater flow.

Climate change, including variations in precipitation, total runoff, temperature, and potential evapotranspiration, and increasing frequency and time extension of drought periods, is likely to affect freshwater resources stored in rivers, lakes, and aquifers. M*eteorological drought* propagates its effects on aquifers, causing a corresponding *groundwater drought* (a period with below-normal groundwater levels) [8–11]. The coincident increase of exploitation beyond the usual rates enhances groundwater depletion and salinization.

Droughts develop progressively or cumulatively over a long period as creeping phenomenon [12,13] and the effects on groundwater quality and quantity are normally delayed if compared with the onset of the superficial effects of water depletion [14], depending on the scale of flow systems [15]. These delayed effects on groundwater and those on groundwater-dependent systems (including urban systems) are mostly underestimated because groundwater-monitoring often occurs only in the short term.

If we consider the complex interdependency between groundwater and groundwater-dependent (natural and urban) ecosystems, a worsening in quality and quantity of the former can generate cascading consequences and crises on the latter. To the purpose of water management, such complex and strong interconnections, together with many uncertainties about the functioning of coastal aquifers, raise new issues about the likely resulting emergencies and cascading vulnerabilities on groundwater dependent systems. In this context of announced complexity, we can identify the features of a soft crisis [16] where the chain effects follow a non-linear path, which is, in turn, complex and unpredictable as it depends on the vulnerabilities accumulated in different scales and systemic levels [17]. Within this framework, a mismanagement of water resources can turn the situation in an active crisis, making groundwater-dependent systems vulnerable to unexpected negative consequences.

As droughts have significant economic, social and environmental impacts that persist beyond the end of the drought event, the policy orientations regarding water scarcity and droughts in the European Union include the improvement of drought risk management [18]. The focus on management derives from the observation that drought events have been handled with a simple *crisis management approach*, since there was no preparation to handle extreme events. Current well-established engineering-oriented water management practices seem unable to cope efficiently with the complexity of droughts effects and of the several dependencies between groundwater and urban systems. The above information suggests a change in water management perspective, which should include, according to an integrated approach, a focus on the relationships among droughts, groundwater and vulnerabilities of coastal territories.

Water management could benefit from a strategic approach [19,20] based on the construction of CVSs[1] that describe chain effects figured out by droughts. A focus on cascading effects considering a wide range of visible and invisible outcomes linked to groundwater depletion and salinization should favour the understanding of the non-linear evolutions of a drought, its propagation in coastal aquifers and its relationship with urban systems. The knowledge and the awareness of stakeholders about above problems might configure new insights on the topic.
In the following sections, we describe the first step towards the construction of CVSs concerning GWS[2] caused by meteorological and consequent groundwater drought. The structure of the proposed study deals with: (i) the characteristics of groundwater depletion and salinization in coastal aquifers determined by droughts in the Mediterranean area; (ii) the reasons underlying the need for water management strategies based on scenario building taking into account cascading effects; (iii) the method structured to build CVSs; (iv) the features of water crisis and the hydrogeological background of the study area; (v) the results obtained through semi-structured interviews carried out with experts in the field of both water and spatial planning, and management; (vi) the narratives and the possible actions embedded in three CVSs, which emerged from the analysis of the semi-structured interviews; (vii) the potential improvements in addressing the construction of future CVSs. We applied the method to Salento (the southernmost part of Apulia region, southern Italy), a densely populated area located in the middle of the Mediterranean basin.

1.1 Groundwater drought and salinization in the Mediterranean area

Records show that the average temperature in Europe [21] has risen by 0.95°C over the last century (1901-2001) and that climate change has caused a variation of precipitation and temperature gradients resulting in wetter conditions in northern regions and drier conditions in southern areas. Projections in recent EEA reports (2017) show that droughts will increase in frequency, duration, and severity especially in southern Europe. This is in line with the projections of Kundzewicz et al. [22] who claim that an increased precipitation variability should lead to a worldwide increase of frequency of floods and droughts. Heinrich and Gobiet [23], on the base of Regional Climate Model simulations under the A1B emission scenario [24], examine the variations in the features of wet and dry periods in Europe for 2021–2050 compared to 1961–1990. Their results show significant changes in the characteristics of dry events with a greater risk of longer, severe, more frequent and extensive droughts primarily in France, Italy and Spain. Hiscock et al. [25] show that until the end of 21st century, as opposed to the 1961–1990 control period, the frequency and severity of wet and dry periods will increase: northern regions of Europe will be more affected by flooding events, while droughts are expected to be more common in southern regions. The most recent projections [26] (medium confidence) show an increase in duration and intensity of droughts in Central and Southern Europe and the Mediterranean.
In the southern rim of the Mediterranean sea, because of the rising of frequency and severity of droughts, projections show a dramatic decrease in groundwater recharge alongside with the increase of the areas affected by droughts [27]. A further projection [25] for groundwater recharge in Europe until the end of the 21st century, compared to the 1961–1990 control period, shows a decrease in annual potential groundwater recharge for northern Italy (22%) and southern Spain (78%), with a severe impact on the availability of freshwater resources

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[1] Cascading Vulnerability Scenarios
[2] Groundwater Salinization

for drinking and irrigation uses. In coastal areas with flat and low topography the consequences of such decrease will be even more important than those of sea level rise [28]. Under the A2 emissions scenario of IPPC [24], projections show that Italy will go through significant drying and that precipitation will decrease by about −10% to over −40% in summer [29]. IPCC 2014 [30] confirms (with high confidence) a significant reduction in water availability from groundwater resources, combined with increased water demand and with reduced water drainage and runoff particularly in southern Europe. Moreover, IPCC 2014 claim an overall precipitation increase in northern Europe and decrease in southern Europe (medium confidence). Already twenty years ago groundwater monitoring data and climatic scenarios related to the densely populated coastal territories in the Mediterranean Basin [31], issued a warn about a high drought risk figured out by groundwater depletion and salt-water intrusion, with consequent progressive salinization of groundwater. As support to the previous alarming information, in the light of the succession of major droughts that affected the Mediterranean Basin in the last decades [32], researchers report a series of issues about groundwater depletion and progressive worsening of groundwater quality in Mediterranean coastal aquifers [33]. In the Mediterranean Basin most of the aquifers are coastal: among them, coastal karstic aquifers, present in large areas, are of extreme importance, because fresh ground waters are of very good quality and, in most cases, groundwater stands for the unique resource of water supply for drinking, agricultural and industrial uses. In the Mediterranean countries, groundwater withdrawal is about 60 billion m^3/y (1990-2000) of which the highest quote (59%) is for irrigation and 29% for drinking purposes. Italy, France, and Turkey are the richest in groundwater resources among the Mediterranean countries but have also the highest rate of exploitation [34].

During droughts, groundwater exploitation and saltwater intrusion increase, accompanied by decreasing water levels, groundwater droughts and concurrent GWS. In the Mediterranean countries, droughts can only worsen the situation, which is already threatened by the current exploitation rates.

Droughts expected in the future will make more difficult to comply the targets of the EC Water Framework Directives about the qualitative and quantitative status of ground waters, to such an extent that Directives introduce exceptions in the compliance for “prolonged droughts” as major force events. However, the River Basin Districts are asked to prepare Master Plans for drought to face the related issues and implement specific measures [34].

2. Cascading vulnerability scenarios in the management of groundwater salinization

In order to effectively cope with drought and recursive GWS, local communities and governments have more and more often experimented and adopted new approaches to water management [35]. Many of them purpose to reorient existing water management practices toward integrated, flexible, and adaptive processes that embody the complex and invisible networks of relationships connecting anthropic pressures to natural world. From our point of view, to effectively cope with drought and salinization in highly urbanised coastal areas, water management approaches should be based on social-ecological perspectives and collaborative strategic approaches.

A social-ecological perspective [36,37], with its focus on resilience and vulnerability, offers a crucial opportunity to take into account the complex interdependences between social and ecological systems, at the same time reconsidering the crucial role of groundwater systems in water management. As a matter of fact, groundwater has only been considered by reference to the safeguard of its quantitative and qualitative status. Consequently, drought problems have been managed by ignoring the existing complex relationships among urban assets and infrastructures, and groundwater. In fact, recurrent frightening shortages of water caused by the propagation of drought periods from the surface to the subsurface highlight the crucial role of groundwater in shaping the possibilities of sustainable usage of water resources.

Vulnerability, which stands for the susceptibility of a systems to a stress or harm [38], can particularly be used to represent the complex relationships connecting groundwater systems and urbanisation assets, as well as to manage water crises determined by drought and salinization. Vulnerability *speaks about* a system capacity to adapt and be resilient. Furthermore, as changes in vulnerability in a system also change its relationships with other systems, these variations represent the quality and the direction of the change of a system and its relationships with other systems. However, vulnerability of the groundwater system cannot be used alone to explore and understand the complex effects caused by unsustainable groundwater exploitation on human settlements and the groundwater system itself.

As modern societies become more vulnerable in the risk society [39] the development of water management capabilities, which respond effectively to the unknown new landscape of crises, becomes indispensable [40]. In particular, the management of crises, such as droughts, needs a kind of preparedness to emergencies and disasters, which, if exclusively anchored to the usual “wait 'til it rains" approach [41], can lead to dramatic failures.

C*ascading effects*, which are the dynamics characterizing crisis and disasters [42], can help to maintain such a complex and integrated perspective. The idea behind cascading effects is that primary phenomena can trigger a chain of effects that can, in turn, cause secondary consequences amplifying the magnitude of primary phenomena. As the matter of fact, cascading effects are non-linear, complex, and multi-dimensional and evolve constantly over time. In case of disasters, the impact of physical events or the development of a principal technological or human failure generate an escalation of secondary effects in other human or non-human systems that result in physical, social, or economic disruption. This escalation is more problematic than primary calamities because of their impacts on critical infrastructures, which represent vital elements to the preservation of social functions [43,44]. Thinking about water management by using cascading effects can induce local populations and decision-makers to explore droughts and their consequences on groundwater and urbanized systems beyond contingency. Cascading effects force to explore risks, crises and disasters linked to seawater intrusion in coastal aquifers because of tight interdependencies among social and ecological systems. Further, they generate the opportunity to think of innovative and effective management actions aimed at contrasting and reducing groundwater vulnerability.

Due to their long-term perspective enabling short-term actions, collaborative strategic approaches seem to be specifically suitable to explore cascading effects and manage crisis or disasters produced by droughts in coastal areas, which are still poorly understood. Moving beyond the logic of control, strategic collaborative approaches based on scenario building are considered crucial to activating social learning processes that allow involved actors reformulating the problem or *re-bounding* the *system of concern* [45–48]. In particular, strategic approaches focused on cascading scenarios following changes in vulnerability of groundwater system can force people involved in water management practices to navigate the unknown and be part of a continuous process of review and adaption, which redirects society from control to resilience [20]. Such an approach can help different actors to see unknown complex relationships between groundwater system and urbanisation processes.

It can change existing mental models, current cultural frames, awareness and perceptions as well as enlarge our knowledge on complex problems, such as groundwater drought and salinization, and produce more effective shared management strategies.

Through building scenarios focused on cascading effects, involved actors could explore unknown aspects underlying a crisis, recognise the relevance of its embedded but weak hazards and warning signals, develop appropriate understandings concerning their evolving and changing character and dynamics, and hopefully change inappropriate governance structures and identify strategies that can link useful knowledge to effective actions [45].

2.1 A method to build cascading vulnerability scenarios

Scenarios are stories about the way the world might turn out tomorrow and therefore they embed a plausible description of what might happen [49]. As defined in future studies, scenarios represent a future state and for this reason they can help local population and decision-makers to explore and frame a complex problem and find innovative and creative. They can be quantitative, qualitative or hybrid, be built in several different ways and be developed through groups and/or individual activities[50]. They can be drawn by experts in the field or by people with the help of a facilitator who synthesises different but individual points of views developed on a specific topic. Scenario building is a multi-step process. Both the design of the scenario building process and the methods to be used within it depend on the context, the goals to be pursued and the topic that is going to be dealt with. Whatever the kind of scenario that we want to construct and the method used, the resulting scenarios have to be effective, plausible and surprising at the same time [51] as their credibility is based on their ability to stimulate the imagination rather than on making predictions.

CVSs could benefit from an imaginative process necessary to frame the groundwater drought and consequent GWS problems in all its complexity and they can identify effective water management practices to tackle them. Because the definition of the cascading effects in the case of GWS is characterised by structural uncertainties, fragmented knowledge and conflicting points of view, scenarios are built by using suggestions from the Delphi method [52]. This method allows to build a deep knowledge on an unstructured issue by involving a group of experts. The experts work separately, although directed and coordinated by a facilitator who helps develop their creative and innovative interpretations and solutions to the problem. The process of scenario building develops through iterative phases of individual elicitation of their own knowledge -through filling out surveys- and revisions of surveys filled by other participants. Such process favours the progressive convergence of the different and conflicting points of view towards a shared and satisfactory solution.

From our point of view, the choice of experts should be true to the idea that the value of any scenario lies in its capacity of embodying the plural character of the society. Therefore, the selection of experts in our method promotes the idea of inclusion and representativeness of multiple points of views that are involved in water management process. As it occurs in the Delphi method, anybody can play the role of experts in water management process independently from their social status. Our research, as the Delphi method, consider CVSs only as the first step within a more complex strategic and collaborative water management approach: the process starts with an individual work but, the following iterative phases are collaborative. The knowledge gained through the individual work of experts is used to produce a few scenarios, which are intended to give a useful support to start a collaborative process aimed at selecting one shared water management scenario.

As far as the contents of the cascading scenarios are concerned, the literature on water scarcity and water crisis suggests that they should be based on the perceptions of problems, the envisioned impacts on territorial systems, innovative actions and practices and barriers to change. Perceptions and impacts are crucial elements in a story on the future of water management practices: while perceptions embed social constructions of the problem and hopes concerning how to deal with it, impacts are key means to identify cascading effects linking social and ecological systems. Perceptions and impacts allow differentiating scenarios regarding both cascading effects and innovative water management practices; criticalities are less relevant to this aim since they are obstacles to be removed to define and implement solutions. Innovative water management practices emerge from the interactions among these parameters.

Instead of using surveys as usual in the Delphi method, our scenario building process uses semi-structured interviews, a well-established procedure for gathering information on a specific set of topics [53]. Since open to discovery, a semi-structured interview is a more suitable tool than a survey to acquire the tacit and explicit knowledge. It always gives the possibility to explore a topic in an unexpected way, to discover something invisible, as cascading effects could be, and to envisage narratives and practices water management that influence their evolution.

Following these guidelines, we tested this method considering the Lecce province (Salento area, Apulia region, southern Italy) as study-area.

3. Water crisis and groundwater management approach in Salento

Salento is a peninsula covering the south-eastern part of Apulia (southern Italy) (Figure 1). Its geographical border slightly exceeds the administrative territory of the Lecce province, for which the statistical data are available. The Lecce province is densely populated (about 800,000 inhabitants in 2,759 km^2), with an urban structure characterised by a network of small municipalities (Figures 1a and 4b). Apart from the Lecce Municipality, with about 95,000 inhabitants, the province includes indeed 96 small rural municipalities, most of them with a population between 1,000 and 10,000 inhabitants. Since the 90s of the past century, the whole Salento area has undergone a process of intensification and slow diversification of its economy, favoured by its urban structure, the beautiful and unique rural and coastal landscape, and the rise of the industrial district economy. Starting from an economy based on a typically Mediterranean agriculture (tobacco and vegetable crops, vineyards, and olive trees), Salento has gradually developed family-run small-sized-manufacturing industrial activities, which in the 90s were prevalently in the textile and clothing industries. Over the last two decades, with globalisation and the following crisis of industrial district economy, tourism has become one of the most important activities in this area [54]. Currently, Lecce is the most touristic province of Apulia region, with 4.7 million tourists per year prevalently arriving (85% of the total amount of tourists) between June and September. Forecasts show that this trend will grow in the future [55].

However, a series of drawbacks that are becoming more and more apparent have manifested hand in hand with the positive economic effects of tourism. On the one hand, local agriculture intensified to satisfy the increasing touristic demand with a concurrent increase of water consumption for irrigation because of climate change; on the other hand, the touristic development has strengthened an aggressive process of urbanisation, especially in the coastal areas. This process has prevalently led to the construction of vacation facilities structures along the coast. Land consumption in the Lecce province (Figure 1b) affects 399 km^2, corresponding to a percentage of 14.5% of province territory: this percentage is twice the regional (8.33%) and national (7.64%) percentages [56]. In the

Apulia region, the land consumption affects about the 30% of coastal areas within 300 m from the coastline [56]. However, the urbanisation process is also diffused in the countryside because of networked settlement pattern in the Lecce province. This has a high impact on the exploitation and fragmentation of the local ecosystems and, in particular, the groundwater system. In fact, the Lecce province and Salento as a whole are also characterised by a high landscape fragmentation [56].

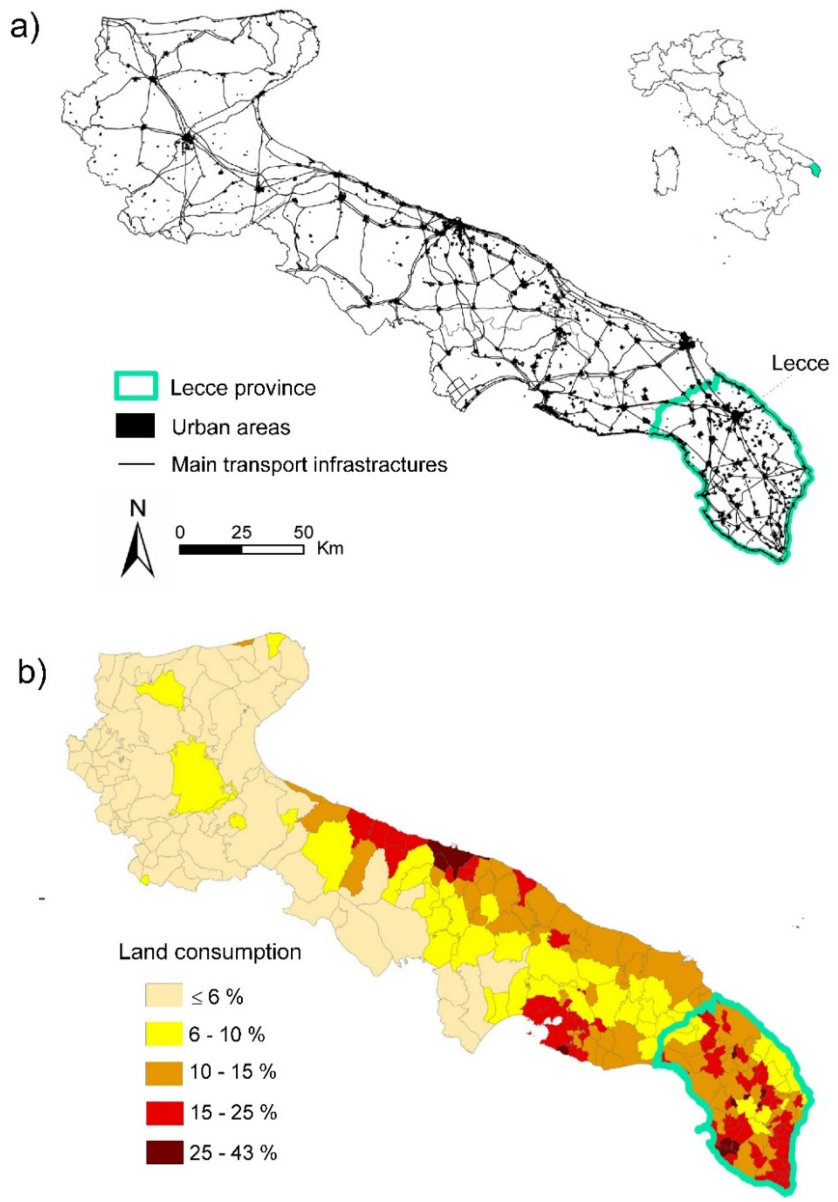

Figure 1 – Apulia region and Lecce province: a) the settlement pattern; b) dynamic of land consumption (data from [56]*).*

In this context characterised by increasing anthropization, pressure on local ecosystems as well as increasing water demand (for drinking water, irrigation, industrial and other uses), which becomes critical during summer because of the combining effects of climate change, urbanisation and tourism, water supply of Lecce province depends quite entirely on the karst coastal aquifer [57]. As a result, water shortage and GWS have become a widespread and worrying problem in the area.

The coastal karst aquifer has a higher extension than that of Lecce province: its borders coincide with the geographical limits of Salento region. Salento belongs to the Apulia carbonate platform (a succession of Jurassic–Cretaceous carbonate rocks from about 3 to 5 km thick), the upper part of the Apulia foreland emerged at the end of Cretaceous [58,59]. Cretaceous limestone and dolomitic limestone form the geological basement, which outcrops in large areas with patchy covers of clay, sand and calcarenite of Miocene to Pleistocene [60]. The basement shows structural highs and lows separated by major faults, as well as minor and major folds. Moreover, subsurface karst forms develop both along the vertical discontinuities and in near-horizontal planes according to the palaeo-geographic history. The karst surface shows karst plains, fracture zones, dolines, sinkholes and hundreds of endorheic basins. The whole of subsurface features causes high anisotropy of the hydraulic conductivity, which is high at regional scale (hydraulic gradient about 0.02 ‰). Freshwater floats on saltwater as a lens, and discharges to the sea through brackish coastal and submarine springs. The scale of the flow system is regional and the piezometric surface reaches max values of 4 m AMSL in the NW and SE sectors of the Peninsula. Precipitation is 638 mm/year, while the yearly average (over 50 years, [61] of effective infiltration is 132 mm/year. Freshwater salt content varies between 0.2 and 0.5 g/L.

The GWS problem emerged in Salento, and with more evidence in the Lecce province, in the 1960s, when the exploitation of groundwater for agricultural purposes started to grow ([62].Thereafter the GWS has relentlessly advanced because of the continuous increase of groundwater exploitation for agriculture, but also for the urban growth. Despite the continuous worsening of groundwater quality, the Regional Government does not perform a regular groundwater monitoring. Nevertheless, even taking into account only limited and unsystematic data, many studies, and technical reports [6,63–67] show the impact on the vulnerability of the groundwater system.

More recent studies [7] tried to investigate the relationships between droughts and GWS. Figure 2 shows the trends of yearly precipitation, irrigation, effective infiltration, and groundwater stress index (i.e. the ratio between irrigation and effective infiltration) for the period 1970-2015 (data from [61]) compared to the trend of chloride concentrations measured in ground waters of wells used for drinking purposes. During the first period of groundwater stress (around 1990), which coincide with a meteorological drought and a recharge decrease, groundwater withdrawals for irrigation notably increase. Chloride concentrations start increasing with a certain lag since the onset of this drought period. When the superficial effects of 1990 drought cease, i.e. the recharge increases, and irrigation decreases (low groundwater stress index), the chloride concentrations are not restored to their previous values, also because of the presence of another drought period between 2000 and 2004. Detailed elaboration of monitoring data not shown here [7] demonstrate that groundwater has been subject to a *critical transition* and an irreversible worsening of groundwater quality as early as after the first serious drought period crossing the 1990.

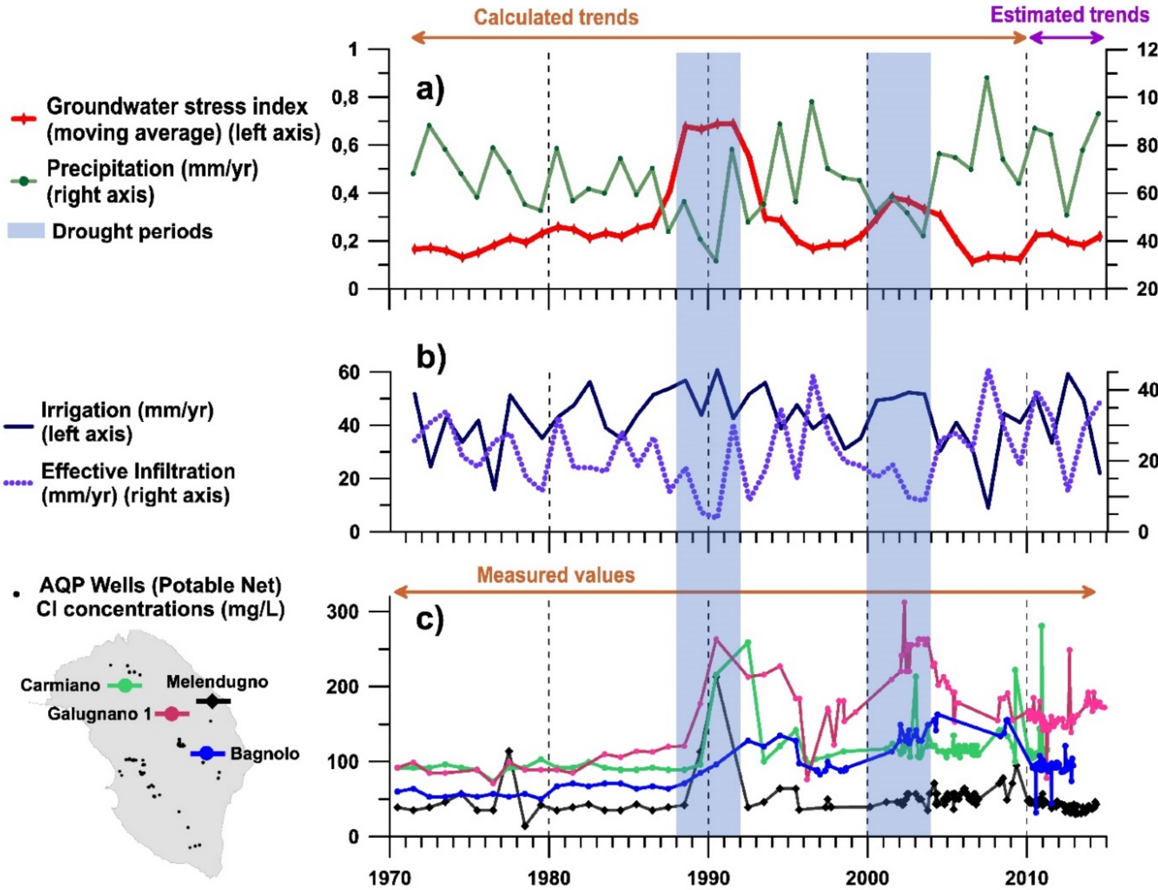

Figure 2 –Timeline plots referred to period 1970-2015: (a) moving average of groundwater stress index and annual heights of precipitation, and (b) effective infiltration and irrigation (calculated from 1970 to 2010 and estimated from 2011 to 2015) (data from [61]*); (c) chloride (Cl) concentrations in ground waters pumped from wells of regional agency for potable water supply (AQP wells).*

The most important risks related to GWS in Salento are desertification, loss of crops, and conflicts between agriculture and other economic activities. These are some of the recurrent problems characterising coastal areas affected by over-exploitation of coastal aquifers and consequent GWS. In different areas of the five continents with tropical wet, humid sub-tropical, tropical wet and dry, Mediterranean, semi-arid and arid climate, the main impacts of water crisis because of GWS regard health problems, wetland deterioration, loss of crops, and soil salinity, aridity, and desertification (Table I). The conflict of uses among end-users is the most frequent amid the discussed impacts.

The above studies allow to outline a general framework, valid for Salento as well, describing the processes involved in water crises consequent to droughts (Figure 3). The primary effect of a drought, linked to the increase of mean temperatures and variation of amount and pattern of precipitation, is the *meteorological* and *soil moisture drought*: the effects are *visible* and are included in the *emergency period*. Meanwhile, the *hydrological drought* starts: it includes the *groundwater drought*. The latter develops in a *concealed* way even after the termination of the *visible* drought and the emergency period because of the start of a new *visible* precipitation period. At the same time *critical transitions* affect groundwater quality and quantity: the effects of the worsening of groundwater quantity and quality cause a sort of *socio-economic drought*, since the impacts of water crisis consequent to droughts also depend on unsustainable interferences between groundwater and territorial systems. The phenomena develop on different time scales, depending on many factors, which characterize both the natural environment and human systems.

Table I – Main impacts of water crisis from studies on coastal areas affected by GWS.

Country/Region	Main Impacts of water crisis	References
Bali, Indonesia	Conflict of uses	[68]
Louisiana, U.S.A.	Wetland deterioration	[69]
Mallorca, Spain	Conflict of uses	[70]
Africa	Loss of crops	[71]
	Soil salinity, aridity and desertification	
Zanzibar, Tanzania	Conflict of uses	[72]
Dacope, Bangladesh	Health problems	[73]
Mekong Delta, Vietnam	Loss of crops	[74]
Bay Islands, Honduras	Health problems	[75]
	Conflict of uses	

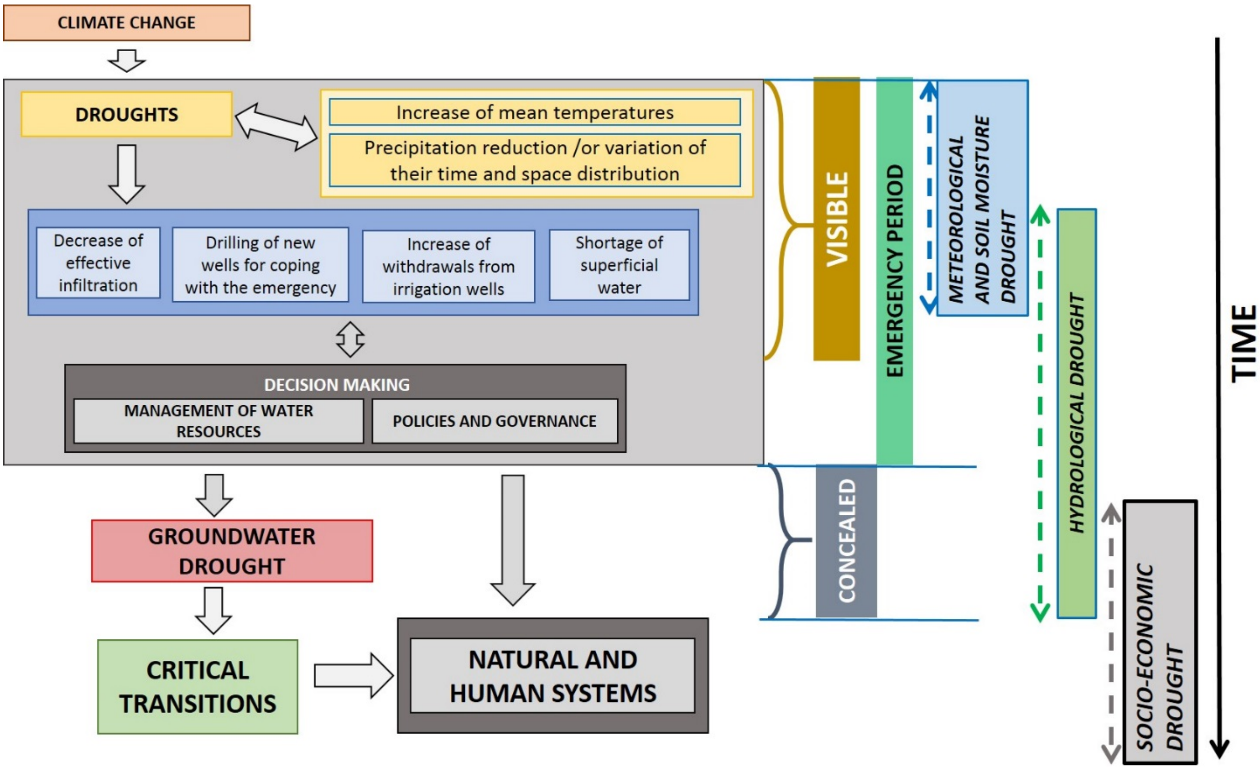

Figure 3 – Framework of the processes involved in water crisis consequent to droughts.

Missing water management practices that consider water crisis as a problem to be urgently dealt with, also depend on the lack of consciousness about the complexity of the problem and the nature of its associated impacts. Despite the worrying signals, current groundwater management practices for the Salento aquifer do not consider groundwater droughts, to such an extent that, at present, under a clear superficial drought, there is no systematic monitoring of groundwater in place. Brunetti [76], indeed, shows that total precipitation of 2017 in Italy are 30% less than the average of the period 1971-2000; moreover, 2017 was the driest year since the 1800. The latest indications about groundwater management go back to 2009: the Water Protection Plan [57] outlines the areas vulnerable to GWS, with indications of the related mitigation actions, such as the delimitation of areas of prohibition of exploitation and/or drilling of new wells.

Figure 4a shows, within the Lecce province, areas vulnerable to GWS, those where groundwater is stressed because exploitation overcomes the recharge and the density of exploitation wells. The latter information addresses the only granted license wells (public and private) and underestimates the real situation. Drawing on the fragmented knowledge, the ratio between illegal and granted licence wells results 10/1 for all Apulia region. Despite the indication of the Water Protection Plan[57], the regional government has continued to apply lenient policies for such abusive wells. The comparison of figure 4a and figure 4b, which shows urban areas, allows grasping the extend of pressures exerted on groundwater.

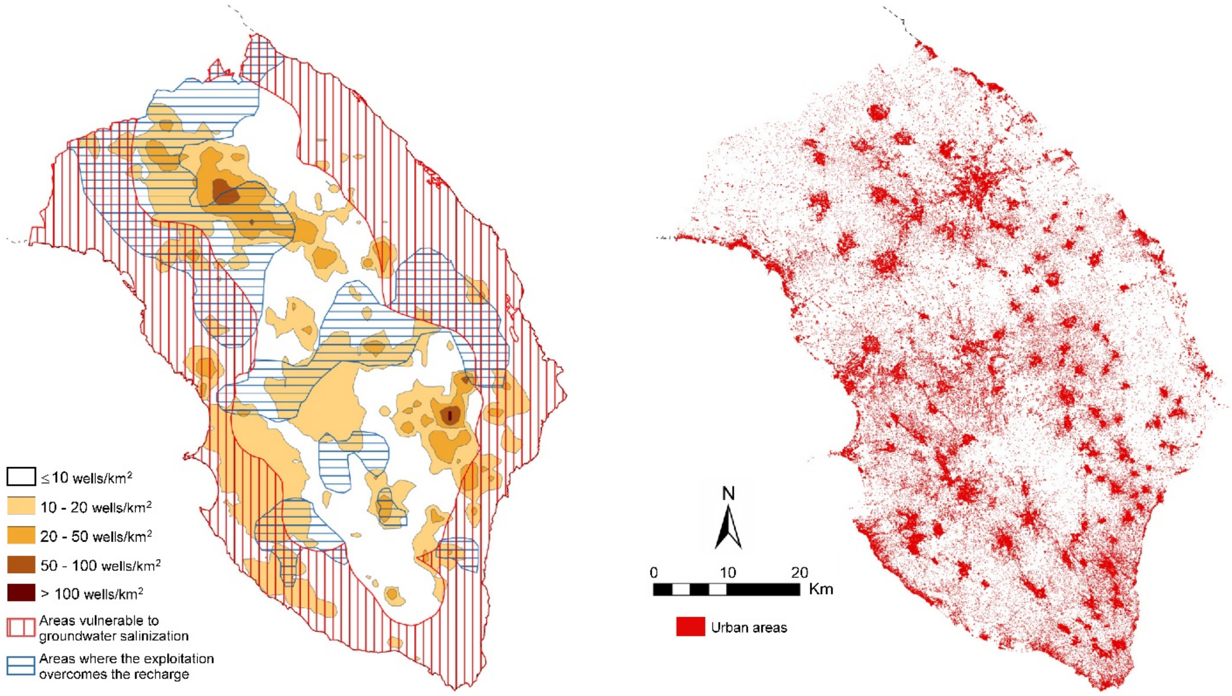

Figure 4 – Lecce province: a) areas vulnerable to GWS, areas where exploitation exceeds the recharge and density of granted licence wells (data from [57]*); b) urban areas of Lecce province.*

4. Building of cascading vulnerability scenarios

The CVSs are the result of the interpretation of semi-structured interviews focusing on expert visions.

4.1 Interviews

We have chosen the twelve experts (Table II) to be interviewed on the base of their formal or informal prominent role in the dominant top-down discourses on water management and decision-making processes. They have also been selected considering that their knowledge represents diverse points of view of regional and local water management processes. More

in detail, from October 2015 to January 2016, we interviewed: (i) decision makers working in the Apulian regional government and other public agencies responsible for water supply, hydrological risks and spatial planning; (ii) consultants with technical competences in hydrology, hydrogeology and hydraulics who often provide technical support to regional agencies; (iii) other experts with an acknowledged reputation, be it academic or not, in the wider field of water management and whose point of view strongly influences local policies; (iv) representatives of farmers and civil society.
The semi-structured interviews were based on a few questions to gather the experts' tacit and explicit knowledge, awareness, and points of view on the cascading effects. The latter were explored by linking to the changes in vulnerability related to GWS of the Salento and possible innovative solutions to water crisis (Table III). These questions, following the main characteristics of water crisis (Figure 3), focus on experts' points of view on the structure of the problem, the impacts of GWS and the influence of management practices.

Table II – List of the stakeholders involved in the semi-structured interviews.

Stakeholder	Typology (Number of stakeholders)	Role
University of Bari - DiSAAT Department	Expert (1)	Economist of Water Resources
Polytechnic University of Bari - DICATECh Department	Expert (1)	Researcher in Urban Planning – Ex regional Alderman for Urban, Landscape and Regional Planning
Polytechnic University of Bari - DICATECh Department	Expert (1)	Researcher in Urban Planning
Regione Puglia - Regional Department of Environmental Protection, Rural Development and Agriculture	Agriculture - Decision Maker (1)	Regional Officer Water Management Sector
Consorzio di Bonifica Arneo	Water Manager – Decision Maker (1)	Local Water Manager for Irrigation Systems
Acquedotto Pugliese (S.p.A)	Water Manager – Decision Maker (1)	President of the regional agency for potable water supply
SOGESID S.P.A.	Consultant (1)	Designer of the "Piano di Tutela delle Acque 2009" (Water Protection Plan) - Apulia region
Autorità di Bacino Puglia	Water manager – Decision maker (1)	Public Officer – River Basin District of Southern Italy
Web Magazine "Ambiente-ambienti"	Civil society representative (2)	Journalists - Dissemination of knowledge in the Environmental Field
COLDIRETTI - Sezione di Lecce	Users' organizations (1)	Responsible of Labour Union of Farmers at province level
IRSA-CNR	Expert (1)	Researcher - National Research Council - Water Research Institute

Table III – Questions asked to the stakeholders involved in water management.

- Do you think there is a connection between droughts and salt-water intrusion? If so, what are the consequences in the short, medium, and long terms?
- Do you envision problems in salt-water use within agriculture? If so, what kind of problems?
- How is the landscape affected by salinized water use?
- Do you think industries, agriculture, and tourism can be economically affected by GWS? If so, how?
- Do you have any idea about the GWS monitoring and its consequences?
- Do you think energy consumption could change during droughts? If so, how?
- How would inhabitants be affected by GWS?
- What kind of conflicts, if any, can occur among stakeholders? What is the reason of the conflicts?
- Could it be useful to widen the decision-making process to other stakeholders? Who do you think should be involved? Why?

4.2 The structure of the problem: the cognitive map

To examine the semi-structured interviews, we used the text analysis method, to grasp crucial concepts expressing perceptions, defining impacts and criticalities describing cascading effects. Before focusing on the recognition of the cascading scenarios, we analysed the interviews to understand the complexity of the salinization problem of Lecce province and the result of which converged in the cognitive map in Figure 5. The latter summarises and integrates the plurality of points of views embedded in the interviews. The concepts mobilised by the interviewees describe the GWS as the result of the relationships among vulnerability changes in the groundwater system, the local economy, the evolutions of settlement and infrastructures, practices of management and decision-making processes, local culture, and the environment. The cognitive map distinguishes the different elements between causes or effects, by highlighting the role of some of the effects, which can in turn become causes of other effects ([42].

The cognitive map represents the necessary contextualisation of the processes involved in water crisis consequent to droughts, as above described (see also figure 3), and offers a reliable picture of the context. From this point of view, the cognitive map is central to understanding the relevance of the three CVSs that emerged through the interpretation of the interviews.

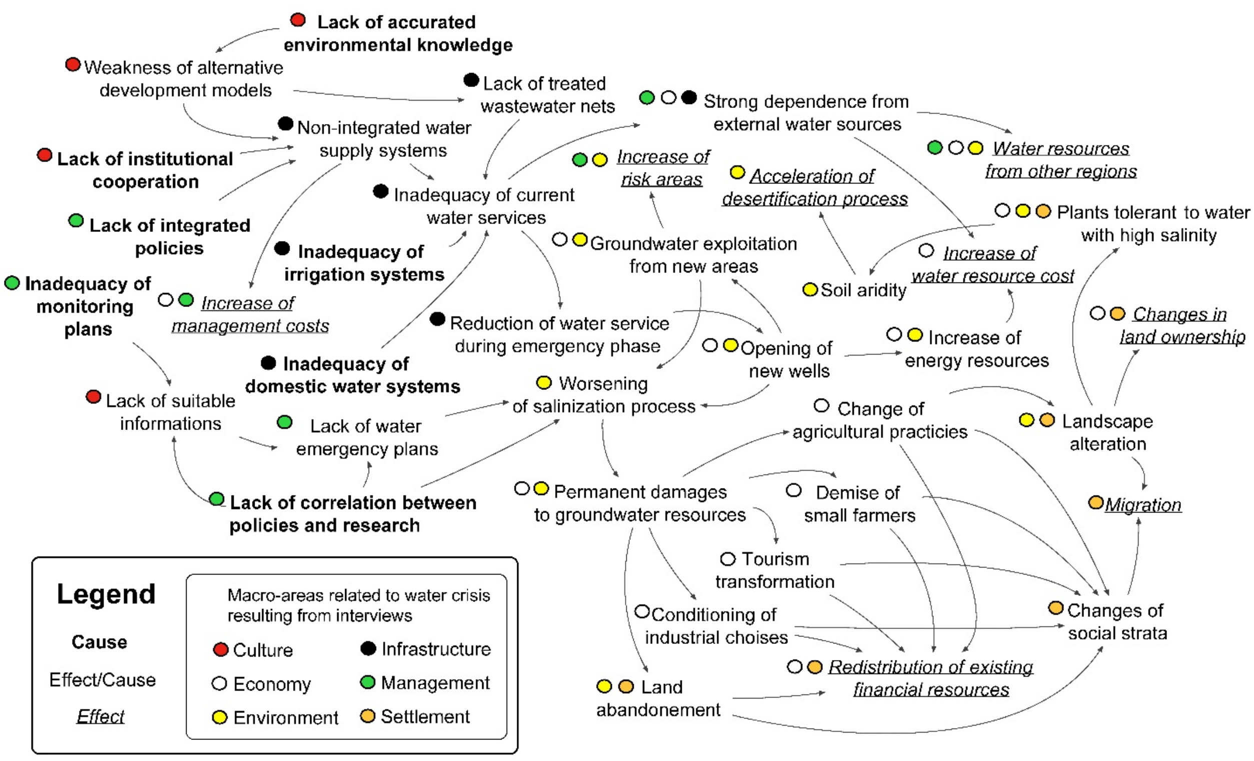

Figure 5 – The cognitive map. The elements are distinguished in cause, effect or effect/cause, and in relation to one or more macro-areas related to GWS. Arrows outline the connections among the elements.

4.3 Three potential scenarios: new narratives and possibilities of action

Here, there is no sufficient room to report the individual interviews. However, each of them offered useful insights to grasp specific cascading effect chains and water management practices to contrast them. Each CVS is made of two parts: the first part describes the cascading vulnerability by defining each element as cause, effect, or cause/effect ([42]; the second part is a description of management actions to cope with GWS and the vulnerability of the groundwater system.

As the idea of groundwater vulnerability and social-ecological relationships becomes central in considering GWS, the chains of cascading effects result more and more complexly related (requiring substantial changes in development models and water management practices) in the sequence of the three CVSs. These are respectively named “The resistant system”, “The jeopardised system: partial irreversibility”, and “The collapsed system: widespread irreversibility”.

The resistant system

In the first CVS (Figure 6) water crisis is perceived as a temporary phenomenon caused by high temperatures, lack of precipitation and high groundwater exploitation in a context characterised by ineffective practices of water management. For this CVS:

- *Perception of water crisis* – Water crisis is seasonal and depends on climatic changes. Considering the high ecological resistance (engineering resilience) of the groundwater system, earlier conditions can be restored with adequate control and management. GWS is not a worrying problem because it is a very well-known and recurrent phenomenon in semi-arid areas.

- *Impacts* – The activities that could suffer the most from water crisis during droughts are those that use water for non-potable purposes, in particular agriculture.
- *Cascading effects* – Cascading effects on human activities are plausible. They will be more apparent in relation to agricultural activities. In the attempt to minimise the expected loss of crops, there will be an increase of illegal water withdrawals from existing wells, as well as the drilling of new illegal wells. A few farmers will be not able to adapt their practices to a reduction of irrigation water or to a long-lasting drought. The necessary adaptations could bring about a slight change in agricultural patterns, which will not generate changes in the local culture and form of urbanisation. However, the propagation of these effects is just a matter of technologies that will allow to improve irrigation systems through rationing the use of water resource and contrast some criticalities.
- *Criticalities* –They depend on management practices, which suffer from lack of knowledge (lack of monitoring) and capability of controlling. As there is no coordination among these agencies responsible for water supply and maintenance, management practices are fragmented. At the same time, maintenance is highly problematic. The hydraulic infrastructural system plunges into crisis, accompanied by a greater use of energetic resources, increase of groundwater exploitation (emergency wells and new wells), and increase of costs and transformation of land ownership.
- *Actions/Practices* – The temporary character of the reduction of groundwater vulnerability caused by overexploitation does not require public agencies to take long-term actions. To cope with the crisis in the short term, technologies and control systems will innovate and adapt to the new situation. Water rationing of non-potable resources drives up withdrawals, which in turn is the cause of other effects, such as the increase of energy use, costs and of land ownership transformations. The use of waste-water in agriculture will end such a problem. Likely actions in this case include the temporary closure of some wells, the opening of new wells, but in other areas, the development of wastewater reuse and desalinization technologies. At the same time, there will also occur the modification of the agricultural water supply systems, the adjustment of water tariffs, and the integrated management of water resources for potable and agricultural uses.

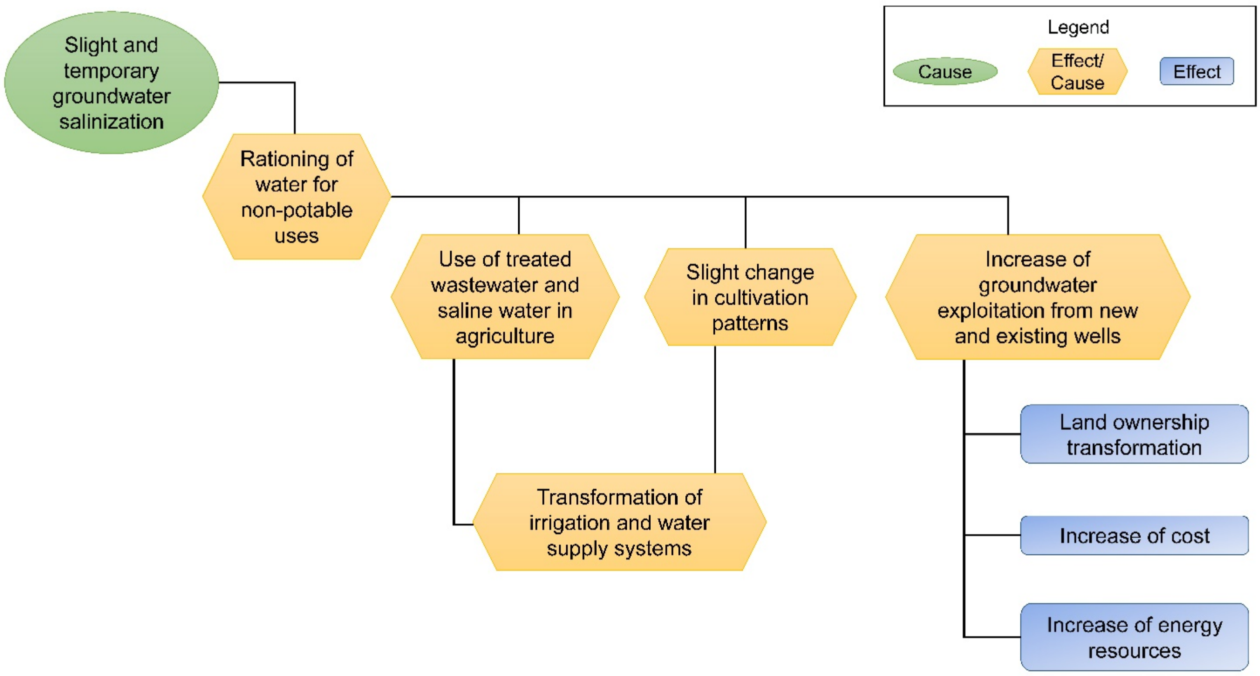

Figure 6 – "The resistant system" CVS.

The Jeopardised system: partial irreversibility

The second CVS (figure 7) describes an emerging water crisis that depends on a partial, yet irreversible crisis of the groundwater system. This scenario still considers the crisis as determined by the unsustainable use of groundwater resources by local agricultural practices. At the same time, the inadequacy and unpreparedness of decision- and policy-making, and unsustainable life styles exacerbated by tourism emerge as new structural causes producing overexploitation. In this case:

- *Perception of water crisis* – The extension and long duration of salinization reveal that the groundwater system resilience has changed, and its functioning is characterised by a series of critical crises corresponding to a permanent GWS and reduction of water availability. Luckily, it seems that the effects of an irreversible crisis can be still limited to some areas (mainly those in figure 4a). Thus, there are still several opportunities to avoid further worsening of the crisis. Surely structural changes will be necessary to contrast the deteriorating process. In the short term, they could concern life styles and water management practices adaptations to have short and medium-term effects.
- *Impacts* – The permanent but partial salinization of the groundwater system causes the deterioration of ecological systems, such as the coastal system. The fragmentation increases at critical levels and an impressive loss of crops in agriculture is also expected. Desertification, even linked to the use of saline water in agriculture, increasingly invades more and more wide areas in the coastal zone. Lack of water for non-potable uses creates conflicts with other activities.
- *Cascading effects* – As soon as groundwater undergoes a series of crises, strong impacts occur on several human activities, and a series of cascading effects can be envisioned. Among them, the transformation of coastal and rural landscape is worrying because of the changes of cultivations and progressive desertification. The consequent modification of the structure of land property and the abandonment of the countryside could transform

tourism driving towards a more intensive consumption and use of the coastal area. Conflicts among different water users (tourism, agriculture an industry) emerge.

- *Criticalities* – Besides the inadequacy of technologies used to cope with the reduction of water resources, relevant criticalities are: the inappropriateness of well-established and control-based management approaches, the fragmentation of decision-making process, the absence of integration between water and agricultural policies, and the structural lack of integrated knowledge bases and monitoring capability.
- *Actions/Practices* – The crisis calls for an urgent and profound change in the current approach to water management, in addition to setting up of adequate monitoring methodologies. The new approach should be characterised by a more integrated and interdisciplinary concern. No large changes in the crisis in terms of a conspicuous reduction of groundwater withdrawals can be otherwise reached. Water and agricultural policies integration could cause the redefinition of risk areas and associated rules concerning land use and agricultural development. An immediate reduction of groundwater vulnerability could be obtained if the new approach to water management is linked to a more cautious use of water for tourism and efficient use of treated wastewater and desalinized water.

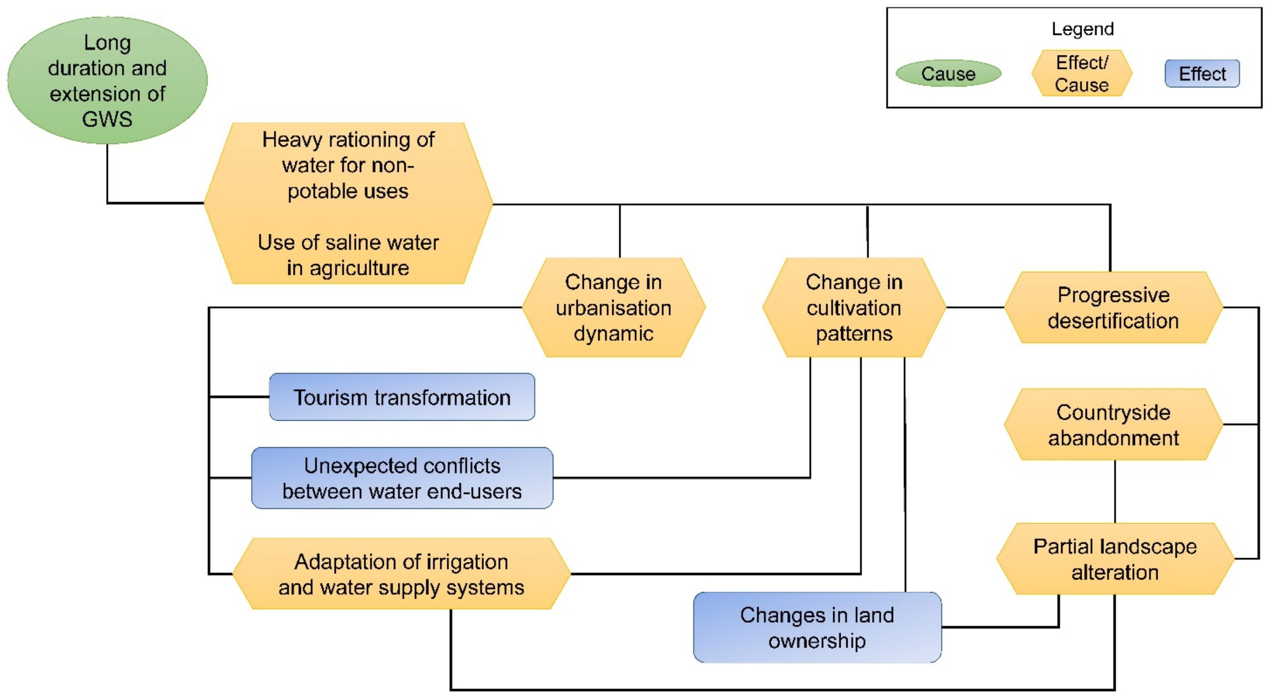

Figure 7 – "The jeopardised system: partial irreversibility" CVS.

The collapsed system: widespread irreversibility

The third CVS (figure 8) is about a dramatic shift in the vulnerability of the groundwater system, which, in this case, is seen as social-ecological rather than merely ecological. Radical changes in the local landscape and economy will occur. The only way to continue inhabiting the territory is linked to our ability to protect its qualities and cultural identity, and to govern the change as a whole. A change of development models must be associated to the implementation of actions that in the very long time could give to the groundwater system a chance to establish new regimes of vital functioning. In this last case:

- *Perception of water crisis* – The crisis is irreversible. The system is not able to heal itself in the short- and medium-term. The GWS as a stable state shows the inadequacy of development models that currently lead the local development. Changes in agriculture and tourism have caused a profound modification of local life styles and, above all, of relationships between people and places. The situation of deterritorialisation requires new development models, and complex and comprehensive actions.
- *Impacts* – Acute water shortage for potable and non-potable uses, and irreversible GWS in most areas; profound crisis of agricultural system
- *Cascading effects* – The complexity of the changes following the irreversible transformation of the groundwater system generates interwoven cascading effects. Among them, we could mention the set of rural landscape transformation, abandonment of countryside, modification of the structure of land property, rationing of water for potable uses and desertification as the main processes that generate migration from the Salento to other areas. Tourism survives although deeply transformed, with concentration on the coasts. Water management practices are governed by conflicts among water users, while local people increasingly depends on extra-regional water resources. The wealthy of local economy and social structure depends the onset of conflicts about the distribution of economic resources.
- *Criticalities* – The inadequacy of the development models and water management practices is evident. There is lack of sourcing patterns suitable for the changing climatic conditions and lack of integration between development and water policies.
- *Actions/Practices* – The urbanisation of coastal and rural areas, and the tourism and agricultural development models should be reorganized, in relation to the processes of restructuring of the local landscape, climate change and the local and global crisis of water and cropping systems. Simultaneously, a radical restructuring of water management practices should lead to innovative technological conceptions. Furthermore, they should be supported by cooperative and bottom-up management approaches that include local knowledge about water management. Short- and medium-term actions could be: aquifer protection, redefinition of risk areas, new patterns and modes of water supply in urban, rural and agricultural environments, investments in technologies for rain harvesting on urban and larger scales, redefinition of irrigation systems, controlled and systematic use of desalinated or treated wastewater, and redefinition of management and policy systems.

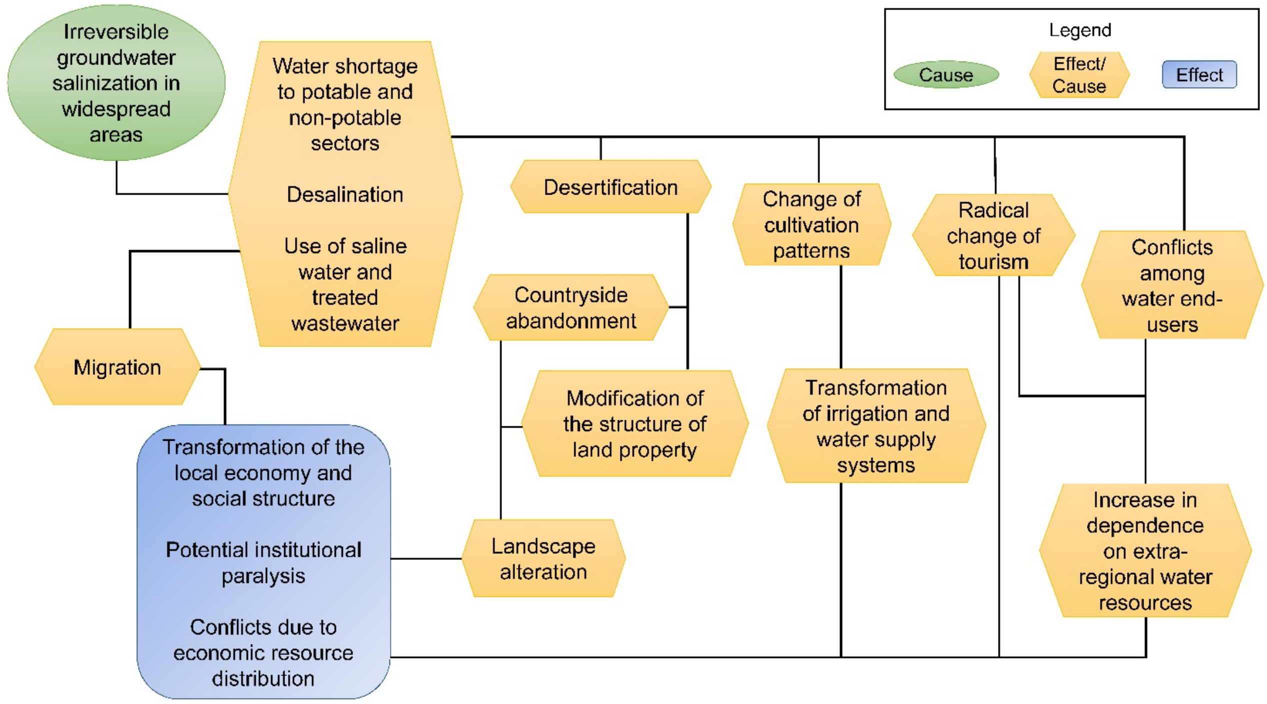

Figure 8 – The third CVS "The collapsed system: widespread irreversibility".

5) DISCUSSION

The three scenarios highlight some of the potentialities of the cascading vulnerability method. It can help reducing the vulnerability of groundwater systems in contexts characterised by water crisis and GWS. Considering the water management practices currently used in Salento, each of the CVSs highlights possible enhancements and necessary adaptations to contrast a salinization phenomenon strongly exacerbated by the effects of the climate change. Our method uses vulnerability as an indicator of resilience [38] to turn experts' points of views in scenarios. Each of them is characterised by specific peculiarities, limits, and possibilities to contrast water crisis, as well as by potential water management practices. As shown in table IV, the CVSs, through their focus on cascading effects, help better correlate the experts' perceptions of groundwater vulnerability to approaches to water management. Therefore, the method is useful to come upon proper solutions to contrast cascading effects and GWS, intended as a complex problem. Indeed, when compared, relevant differences appear among the three CVSs in terms of conceptualisation of the relationships between social and ecological systems.

The first CVS mirrors the hydraulic and anthropocentric approach to water management, which is a top-down technical commitment. Through a systemic approach, the complexity of water crisis is reduced to a matter of seasonality of salinization, intended as a stress that could be indefinitely absorbed by the groundwater system but that, unfortunately, affects human activities. According to stakeholder, the most important impact concern agriculture, probably because it is strategic to the local economic development. Therefore, both conflicts and effects caused by rationing and water shortages become more visible than in other human activities. The required technological improvement is led by such a conceptualisation of water crisis.

Yet, cascading effects, that sometimes become circular, reveal some contradiction (i.e. the exportation of crisis in other areas). They are due to the absence of a territory-based perspective on water crisis, a problem which limits the search for solutions in several ways. The logic that solves the problem by dislocating it to a different place is part of such narrow view. Foreseen solutions are the consequence of known criticalities in water management. Anyway, they must be solved by minimising conflicts (especially between agriculture and tourism so tightly intertwined in Salento) rather than by impacting on social and ecological systems. That is the reason why this approach is so efficient in the short-term. It gives the impression that nothing is changing in our surrounding living environment.

Table IV - Differences among the three CVSs.

	VULNERABILITY PERCEPTION	***ALTERNATIVES***	***APPROACH TO WATER MANAGEMENT***
THE RESISTANT SYSTEM	Systemic (Seasonality and high resistance of the system)	Rationing of non-potable use Improvements of water and government technologies Exportation of the crisis	Control-based management Coordination
THE JEOPARDISED SYSTEM: PARTIAL IRREVERSIBILITY	Eco-systemic (Compromised ecological resilience)	Rationing of non-potable use Improvements of water and government technologies Changes in agriculture and stiles of life Changes in knowledge	Integrated water management Conflict resolution Interdisciplinarity
THE COLLAPSED SYSTEM: WIDESPREAD IRREVERSIBILITY	Socio-ecological (Irreversible changes)	Alternative development models based on local identity and endogenous sustainable development Changing in water (local tradition and innovation) and government technologies (from top-down to bottom-up) Opposing deterritorialisation Sustainable and vernacular innovation of technologies Changes in knowledge/power relationships	Adaptive water management, co-production with local population involvement Not irrigated agriculture Sustainable tourism

In the second CVS, the perception of the crisis changes according to the prevalence of an ecosystem approach to water crisis. The ecological resilience plays a relevant role in shaping alternatives, since the groundwater system is perceived as under an unsustainable level of stress, that sometimes leads to an irreversible GWS. The interdependency among chains of cascading effects shows the relevance of the territorial dimension of water crisis, which lead to a more complex idea of changes needed in water management practices. The ecosystem perspective does not even allow to permit water importation from other regions. This creeping phenomenon partially alters the landscape, causing the countryside abandonment and slight changes of urban settlements, which in turn cause the change of the land ownership. However, the anthropocentric approach persists. Huge relevance is given to both technical and political water management solutions. The integration of different knowledge systems and policies fields is the key to the revitalisation of groundwater and territorial system in the long term. Conflicts can be managed through the diffusion of knowledge and actions specifically aimed at solving vicious circles connecting different streams of cascading effects, such as those produced in the agricultural and touristic sectors and urban systems. Changes in lifestyles are also crucial to managing each of them and to break the chain of relationships among them. In such a perspective, cascading effects could be constantly monitored and acted upon. Short- to medium- term actions need to be taken, thus allowing the transition from engineering to adaptive forms of management. Consequently, stakeholders look for new resources to cope with the *temporary* lack of water. Technological innovation and relevant changes in agricultural practices are seen as indispensable short-term actions. Most experts consider this approach necessary to change and preserve Salento from collapsing. We could say that this scenario is still informed by a control-based approach to management, so to produce the necessary adaptations in both the social and groundwater systems. This scenario is expected to protect the groundwater systems through a substantial change in agricultural practices and a rationalisation of water consumptions in every field of the human activity, tourism included.

The third CVS is a radical one, looking at short-term actions to be implemented for producing a change in water crisis that, in the long run, could preserve the landscape. Since social-ecological systems are inseparable, the widespread GWS becomes a logical consequence, which affects tourism, agriculture and resident people. New form of tourism and less aggressive agricultural practices should be at the core of water management practices contrasting salinization and water crisis. Cascading effects should not emerge at all. In this respect, policy integration and bottom-up decision-making are crucial. Groundwater monitoring becomes less relevant than in the jeopardised scenario. At the same time, the sustainability and efficiency of technologies used in water irrigation and supply systems, and the use of other sustainable resources should always be promoted and experimented.

These three CVSs stand for implementable water management options to cope with GWS and water crisis. They highlight many potentialities of the proposed method, although they should be just a first step in changing water management practices. By highlighting the similarities, but also the profound differences among experts' points of view, these scenarios can sustain a dialogue among the plurality of actors formally and informally involved and interested in finding ways to cope with GWS and water crisis under climate change. At the same time, the CVSs reveal technical, conceptual, cultural and institutional barriers that oppose to the change in water management. The focus on cascading effects enlarge experts' perspectives on crisis and forces them to seriously consider the strong connections between social and ecological systems, even when intentionally avoided. Inconsistencies strengths and weaknesses in each of them appear clear, thus favouring a process of integration among them.

6) Conclusions

Monitoring data and climatic scenarios highlight the risks of notable qualitative and quantitative worsening of ground waters in coastal areas, especially consequent to the increased frequency and intensity of droughts. In coastal areas, droughts exacerbate groundwater exploitation inducing negative effects on groundwater quantity (groundwater drought), with consequent salinization of groundwater. Groundwater droughts and salinization can have unexpected cascading consequences and crisis on social, economic and environmental systems.

Unfortunately, the role played by groundwater in water management is not yet well acknowledged. To the contrary, the CVSs highlight that groundwater is a crucial resource for our future and it is fundamental for avoiding worrying changes in socio-economic vulnerabilities.

As defined in our research, CVSs can lead to a more integrated management of water resources. These scenarios show the cascades of effects (and effects/causes) connected to GWS and ensuing different levels of system resilience. They capture tacit and explicit knowledge of interviewed experts and contribute to a better understanding of an unknown crisis and related cascading events. They also allow to understand the risks embedded in vulnerability changes of both groundwater and urban systems and outline both the stakeholders affected by the main event and those affected by the chains of secondary effects.

The outline of cascading effects can be used as a coordination tool, which merges stakeholder visions towards an integrated management in decision-making processes. The effects of drought propagation are both visible and invisible: the understanding of both effects to water managers, policy makers and politicians can improve their awareness about unexpected consequences, and favour the integration and coordination in the management, not only of water resources, but also of the activities and sectors that depend on such resources.

Giving stakeholders the opportunity to imagine the future while they explore vulnerability scenarios that consider cascading effects, has allowed to outline new management directions, which seem to move beyond the usual adaptive approach. Moreover, the increased managers' awareness has resulted in the emergence of the need of an integrated control system necessary, as opposed to a sectorial control of each part.

This is an important result of the CVSs. They show that engineering approaches and political argumentations, instrumentally used, still prevail in defining water management strategies. At the same time, the CVSs show that we do not really need an impressive technological change, but a cultural one, which should enable us to benefit from available solutions and best practices as much as possible.

These scenarios can help policy makers, politicians, and managers to find more suitable water management policies and structure more adaptive water management practices by increasing their awareness. Moreover, they can help them deal with unexpected cascading consequences due to groundwater depletion and salinization through effective actions.

However, the proposed approach has some limits. The recognition of cascading effects is strongly constrained by the cultural background of the interviewed stakeholders, their values and ethics. The differences among the three CVSs are the result of such a plurality. To obtain a holistic vision of them, it might be useful to include more stakeholders and experts in the interviewing process. Obviously, a parallel process should involve local communities. It is generally known that an integrated groundwater management can be also based on

bottom-up approaches, involving groundwater end-users, such as local people, tourists and farmers.
Actually, CVSs do not include any reference to classical groundwater-dependent ecosystems as transitional waters, or marine waters, which, in principle can be notably impacted by the changes of freshwater discharge to the coasts. Moreover, there is no perception of the role of seawater intrusion in triggering re-toxification processes at land-sea interface [7], which can threaten the biodiversity of coastal zone and contaminate the marine environment. This is quite an intriguing result that shows some lacks in environmental knowledge by the stakeholders: what is invisible is often unknown and is therefore unmanageable. The actual chain of vulnerabilities is not exhaustive, because many elements of knowledge are missing.
Finally, cascades need to be enriched with other drawbacks and feedback loops, which have the potential of varying the cascading vulnerability chains over time.
The present scenarios are only a basic representation of a hidden and unknown process that, however, is not static and simple to describe. Nevertheless, at this stage, they can be a suitable and plausible starting point to adapt current water management practices to the impacts of climate change and droughts and project needed mitigation actions.

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