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The Ecosystem Resilience Concept Applied to Hydrogeological Systems: A General Approach

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Abstract: We have witnessed the great changes that hydrogeological systems are facing in the last decades: rivers that have dried up; wetlands that have disappeared, leaving their buckets converted into farmland; and aquifers that have been intensively exploited for years, among others. Humans have caused the most part of these results that can be worsened by climate change, with delayed effects on groundwater quantity and quality. The consequences are negatively impacting ecosystems and dependent societies. The concept of resilience has not been extensively used in the hydrogeological research, and it can be a very useful concept that can improve the understanding and management of these systems. The aim of this work is to briefly discuss the role of resilience in the context of freshwater systems affected by either climate or anthropic actions as a way to increase our understanding of how anticipating negative changes (transitions) may contribute to improving the management of the system and preserving the services that it provides. First, the article presents the basic concepts applied to hydrogeological systems from the ecosystem's resilience approach. Second, the factors controlling for hydrogeological systems' responses to different impacts are commented upon. Third, a case study is analyzed and discussed. Finally, the useful implications of the concept are discussed.

Keywords: ecosystems; hydrogeological system; sustainability; significant damage; resilience

1. Introduction

Groundwater and surface water resources are heavily exploited in many parts of the world, and freshwater demands are increasing globally [1]. Any alteration of the baseline conditions of the system may lead to an undesirable state (degradation of quality or quantity). Anthropogenic effects disturb the natural processes of aquifers, and the equilibrium within the unsaturated and saturated zones, and may also increase the contents of undesired substances in groundwater. There are different types of impact affecting hydrogeological systems at different scales. The impacts or disturbances may be either natural or anthropic. Natural disturbances include any type of catastrophe that can affect a hydrogeological system, such as earthquakes, climate (extreme events but also climate variability), or fires. Anthropic disturbances include pumping and various polluting activities such as discharges; agricultural, industrial and nuclear activities; the filtration of substances stored underground; injection into wells; and urban solid waste deposits, among others. Groundwater quality and quantity degradation owing to intensive aquifer exploitation is recorded in many countries [2–8].

This article aims to contribute to develop a better understanding of the concept of resilience when applied to hydrogeological systems, which, in turn, will help develop a better understanding of the buffering capacity of hydrogeological systems. This represents a step to be able to anticipate the potential impacts on the system of specific changes and the system's response. This requires focusing attention on the internal variables which are more sensitive to impacts. The concept of resilience can be helpful to avoid these problems. For example, based on the established groundwater baseline patterns, changes can be identified from the very beginning and can provide an early warning signal to make decisions on sustainable groundwater management. Resilience is also related to water security as groundwater is regarded as one of the most reliable yet also vulnerable sources of drinking water in many countries. This is important since the substantial decline of groundwater levels may affect the water security of a growing economy [9].

There exists an extensive literary record dealing with the resilience of natural systems to different impacts, although most of this literature does not deal with resilience explicitly. Until very recently, the term "resilience" did not appear in hydrogeology glossaries. The idea of the resilience of a "hydrogeological space" or "hydrogeological medium" was developed by LV Demidyuk, NI Lebedeva and GA Golodkovskaya in the 1970s and 1980s, but unfortunately these reports were published in Russian only, e.g., Golodkovskaya and Eliseyev (1989) [10]. There are barely 20 publications in the Web of Science (WOS) returned by the search terms "resilience" and "hydrogeology", and most of these are articles do not treat resilience as a central topic [11–20]. In the field of hydrogeology, the most frequent works dealing with resilience are specific and local, and the concept of resilience is not approached from a generic point of view. Our work aims to contribute to these conceptual reflections.

There is often some confusion in the literature regarding the application of the concept of resilience. Some works apply the concept to groundwater or water resources (liquid phase), and others to aquifers (physical environment). This is an important difference as the intrinsic properties of the system vary in each case. The confusion stems from the fact that the descriptor variable most frequently selected is the same: the piezometric level.

Most literature uses aquifer resilience (AR) as a conclusion derived from the research (Cuthbert et al. (2019) [11] Maurice et al. (2019) [12], Mazi et al. (2014) [14], Chinnasamy et al. (2018) [16], De Eyto et al. (2016) [17], Hejazian et al. (2017) [21]), with the largest number of works focused on the analysis of drought as a disturbing element (Lorenzo-Lacruz et al. (2017) [13], McDonald et al. (2017) [22]. Two references present a deeper study of the resilience of aquifers. First, Bouska et al. (2019) [23] apply the concept of general resilience to the restoration of large river ecosystems in the Upper Mississippi. However, their approach is more biological [24,25] than hydrogeological, i.e., they develop indicators for three principles of general resilience: diversity and redundancy, connectivity, and controlling variables. The latter includes historical water level fluctuations, water clarity, nutrient concentration, and invasive aquatic species. Wurl et al. (2018) [26] adopt an approach that is closer to the resilience concept from a hydrogeological perspective. The authors designed and used a set of indicators as outcomes for combined human–water systems to predict water trajectories under different human impacts.

This literature review identifies a number of tools that have been used indirectly to build the application of resilience into hydrogeology: the use of tracers or isotopes to determine groundwater age [27], the analysis of piezometric evolution trends in aquifers [28], and the quantification of water consumption for agriculture in restricted aquifers [29]. Quantification also relies on qualitative indicators as an auxiliary tool [16]. However, the term "resilience" in the hydrogeological literature is presented as an attribute that is not analyzed in itself, but which is frequently cited within the framework of processes (recharge, precipitation) associated mostly with climatic variability, and, to a much lesser degree, with other processes (extreme events).

The aim of this work is to increase our understanding of how hydrogeological systems deal with disturbances as a way to anticipate transitions (changes in the system affecting their functioning) and to propose a conceptual model for the analysis of the resilience of aquifers. In turn, this knowledge can support the more sustainable management of the system. The paper compiles the key knowledge around this concept that can be applied to hydrogeological systems and discusses a relevant case for illustrative purposes.

The article is structured as follows: first, the article presents the basic concepts applied to hydrogeological systems, and the conceptual model proposed, including factors controlling the responses of aquifers to different types of impacts. Second, a series of considerations are made regarding its scope. It concludes with a discussion and considerations of how to deal with the resilience property in the framework of long-term data series to obtain analytical and useful results.

2. Hydrogeological Systems and the Resilience Concept

2.1. Hydrogeological Systems as Complex Systems

Hydrogeological water systems operate with a certain behavior for a certain period at the human time scale [30–35]. For example, depending on their water regime, rivers can be classified as permanent, seasonal, temporary or intermittent; wetlands can be permanent, temporary, seasonal or erratic based on their hydroperiod; and aquifers can be classified as unconfined, confined, semi-confined or perched according to their operation.

In many areas of the planet, hydrogeological systems (water systems) are subject to different types of stressors, such as the extraction of water for irrigated agriculture, or in urban coastal areas contamination from localized or extended sources and changes in recharge regimes due to climate change, which may cause the systems to exceed the limits of sustainability [36]. If this occurs, the systems become unbalanced, leading to a tipping point [37] in their behavior, bringing them to a new state of equilibrium [38].

2.2. The Resilience Concept and Theory

Resilience is fundamentally directed to the way a system responds to a disturbance [39,40] that can be punctual or a long-term process, for example one implying gradual alterations (slow onset changes) [41]. This concept originated in metallurgy and has subsequently been applied in many other disciplines. In the field of ecology, the concept is based on the theory that systems are in a natural state of flux rather than an equilibrium [42]. In this work, we define resilience as a system's ability to recover a situation of equilibrium or metastability (known as state, see the definition below), characterized by a known behavior. We do not see it as a return to its pristine conditions for two reasons: (a) in many areas, there is no information available to define the pristine conditions, i.e., it refers to a period prior to registration for which there is no data; (b) in general terms, the systems are altered (by humans or by other natural processes) in one way or another, so that their return to an pristine state may be a goal that is significantly outside the realms of possibility.

The literature on the resilience of complex systems is highly fragmented [43,44]. One of the main problems that emerges is the lack of terminological consensus among the authors [44,45]. Different authors use a range of terms to refer generically to the same concept of "complex systems", including "complex adaptive ecosystems" [46,47], "complex adaptive systems", "complex, coupled Socio-Ecological Systems (SESs)", and "complex, multi-scalar SESs" [48]. In some cases, they include references to impacts, events, shocks, pulses, threats or stress, leading to a terminological confusion that must be avoided in a scoping study such as the one presented here.

From a biological perspective, the concept of resilience is especially applicable to natural systems that adapt to different degrees of disturbance while maintaining the same processes and structures that reinforce each other [49,50], and whose connection is known as a "regime" [51] (Table 1). The transition from one regime to another (regime shift) occurs through thresholds (Figure 1); and the new regime is characterized by a different set of processes and structures (behavior) [52]. Regime changes are typically associated with significant consequences in processes or structures (e.g., a change in water composition that leads to a loss of water quality), and do not always occur in sudden leaps or at turning points in their trajectory, but may be the result of long system periods [53] or slow and progressive changes [41]. Not all regime changes entail a tipping point. Indeed, Bertalanffy (1968) [54] identifies six mechanisms that can trigger a regime change (slow–fast cyclic transition, stochastic resonance, noise-induced transition, long transient upon extreme events, big stepwise changes in drivers), but only one of them involves a tipping point: slowly changing driver to tipping point. Four out of these six transition indicators can be used as early-warning signals [37,55,56]. In the field of hydrogeological ecosystem research, the aspects of the dynamics of changes between the states of equilibrium are relatively unexplored.

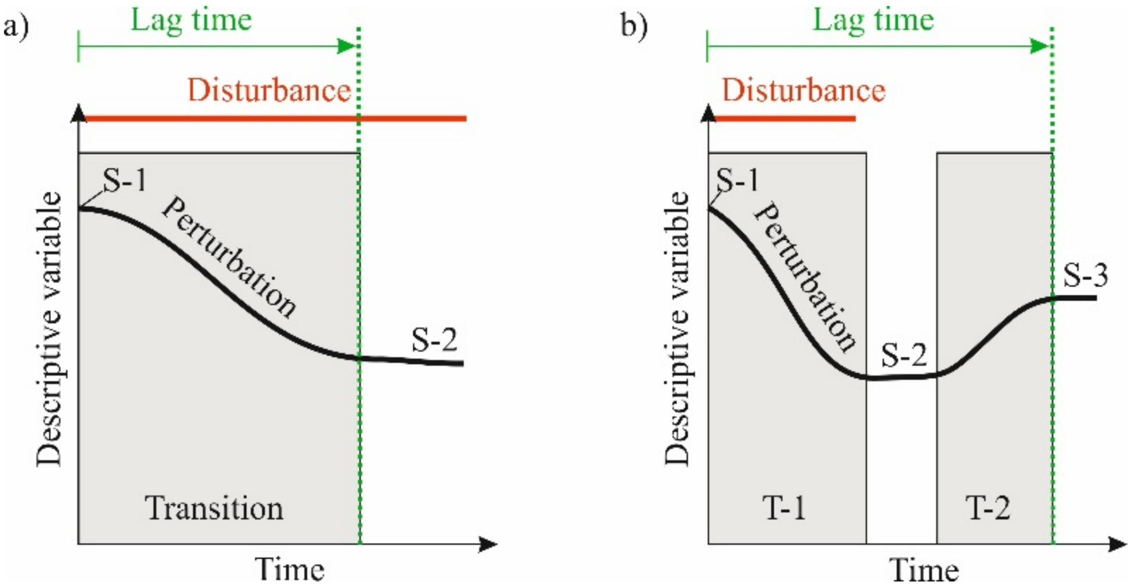

Figure 1. Scheme of the aquifer resilience (AR) through the temporal evolution of a descriptive variable. The black lines indicate the time series observed of the aquifer system, and the red lines represent the time series of the underlying environmental conditions. (**a**) In a theoretical example, the pumping of groundwater from an aquifer (disturbance) prolonged over time will cause a water table depletion (parameter) which could reflect the aquifer response to the impact. (**b**). If the pumping ceases (disturbance stops), the aquifer may recover a new equilibrium (State-3). Both behaviors (**a**,**b**) are useful to understand aquifer resilience and must be taken into account in the interpretation of the AR (Source: authors' own).

Table 1. Extended definition of terms associated with resilience in a biological environment. Text in italics indicates the literal definition of the authors. Text in brackets are comments from the authors. When the source is not indicated, the reference is proper.

Word	Definition	Source
Adaptive capacity	Latent potential of an ecosystem to alter resilience in response to change. Similarly, in the ecological sciences, adaptation, adaptedness, adaptability and adaptive capacity, terms with different meanings, have often been used interchangeably.	[57]
Alternative state/regime	A potential alternative configuration of a system in terms of the structural and functional composition, processes, and feedbacks.	[57]
Critical slowing down (CSD)	CSD occurs as the system approaches the threshold, the distance to the critical threshold is reduced, the recovery rate decreases and ecological resilience declines.	[37]
Early-warning signal (EWS)	A statistical signal indicative of a system approaching a critical transition. (Often used interchangeably with leading indicator. Examples are variance or autocorrelation.)	[56] (p. 906)
Forcing	External pressures that destabilize a system, pushing it towards a tipping point.	[56] (p. 906)
Hydrogeological systems	Set of geological formations whose hydrogeological functioning should be considered together.	
Linear system	System whose behavior is expressible by adding the behaviors of its descriptors.	

Table 1. *Cont.*

Word	Definition	Source
Perturbance/ disturbances	Alteration in the order or the permanent characteristics that comprise the normal development of a process.	
Pressure	Activities subject to generate impacts on groundwater	[58]
Regime shift ("change" in other references)	Persistent change in structure, function, and feedback of an ecosystem. (This term is used interchangeably with "critical transition" in the literature.) We will use "state" instead of "regime" in this paper.	[57]
Scale	The geographic extension over which a process operates and the frequency with which a process occurs.	[1,51]
Stability	A system characteristic whereby system properties remain unchanged following disturbance. Adaptive capacity can increase stability, but system components can fluctuate (and are therefore unstable) while still remaining within the range of values that signify a particular state.	[57]
Stressor	Stimuli or situations capable of producing certain changes that trigger the stress response.	
Transient regime	Response of a system that changes over time, as opposed to the permanent regime.	
Tipping point (threshold, bifurcation point)	The point at which a system is so unstable that even small perturbations cause dramatic shifts in its state.	[59]
Variables describing change (fast variables, controlling variables and control variables)	Fast and slow variables. "Fast" variables are those that are of primary concern to system users. The dynamic of these fast variables is strongly shaped by other system variables that generally change much more slowly. "Slow" variables or controlling variables are not the same as control variables.	[45]

The scope of the concept of ecosystems resilience is broader than initially considered. When discussing ecosystems alone, resilience is closely related to sustainability ([60,61]). Scheffer et al. (2001) [62] report that a loss of ecosystem resilience generally paves the way for a change to an alternative state and suggest that sustainable management should be directed towards maintaining ecosystem resilience [62].

Resilience also refers to the system's adaptive capacity [57] and vulnerability, given that it offers another approach to the changes produced by a disturbance; however, this idea is controversial, as some authors consider that the concept of adaptive capacity is muddled with multiple meanings in current use often being indistinguishable from resilience [41]. Resilience is an intrinsic property of the system that emerges from certain changes. Some authors define the adaptive capacity of ecosystems as a latent potential quality to alter resilience in response to change [57].

Resilience has implications in the socio-economic and political spheres, since knowing the dimensions of this attribute enables managers to intervene in the natural environment before a change of regime or favoring one state of equilibrium over another.

Although the term "resilience" is increasingly used by political and environmental managers, it remains vague, variable and difficult to quantify [39]. This work clarifies what it means from the hydrogeological perspective, without attempting to review the state of the art of the concept or to list an inventory of works in which the concept is applied to geological and hydrogeological studies.

2.3. Resilience from Ecology to Hydrogeology: A Conceptual Framework for Its Analysis

The analysis of resilience focuses on the dynamics of the system, particularly looking at two areas: the cause effect (disturbance), and its consequence in the system (system response to the disturbance). The disturbance leads the system to alter certain internal variables, which define the new equilibrium state (regime). Based on the concept of resilience and on the literature dealing with the resilience of hydrogeological systems, we propose a conceptual model that can use aquifer resilience to support its management (Figure 2).

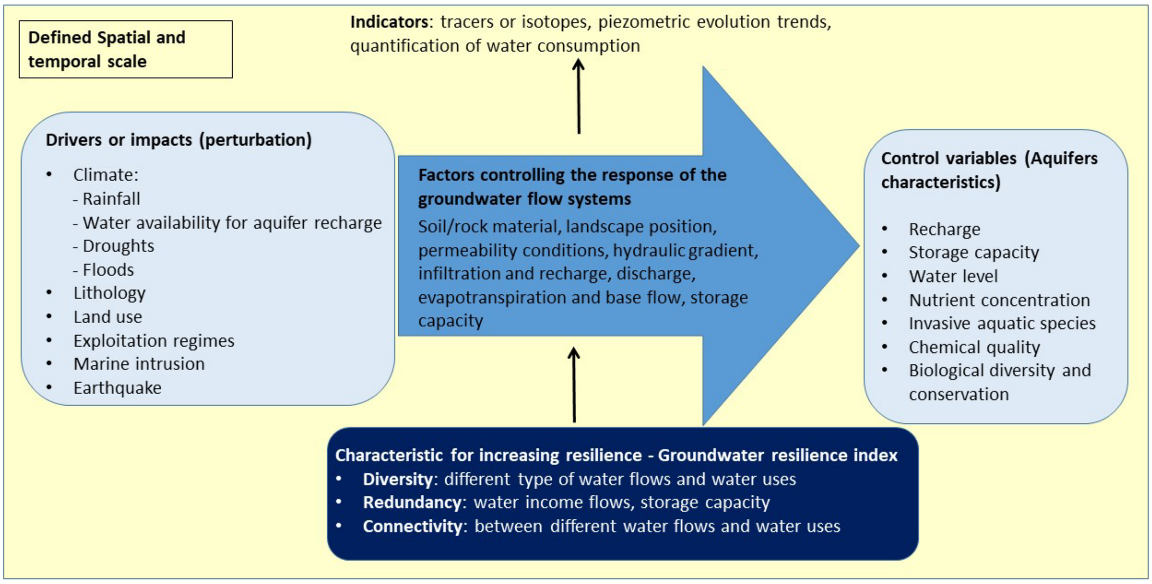

Figure 2. Proposed conceptual model for using the resilience concept in the management of aquifers (Source: authors' own).

Step 1. The first step must be the system definition, including its geological boundaries and its main characteristics, flows and functions. An important issue to be addressed in any resilience analysis is the scale of work (space–time dimensions).

To understand hydrogeological system resilience, cause–effect relationships, and impacts, it is necessary to have information about its functioning. Groundwater flow systems depend on both the hydrogeological characteristics of the soil/rock material and on the landscape position [3]. These factors control the permeability conditions and the hydraulic gradient differences which regulate the groundwater flow movement. Not every impact affecting the Groundwater Flow System (GWFS) affects its hierarchical structure and functioning; this will depend on the nature, magnitude and duration of the impact, and the factors controlling the response of GWFS to those pressures.

Step 2. The second step is to describe the process triggered by the disturbance (some authors refer to them as descriptive variables of the change and the interactions between them) that is, to describe its magnitude, duration and scale. This involves monitoring the variables, describing the change before, during and after the change. The second step is therefore to define and describe the disturbance that acts on the system (state 1) causing a series of internal changes that lead to a situation of instability for a certain or indefinite time (Figure 1). The usual process is for systems to tend to a new state of equilibrium (state 2) through internal changes and interactions between the variables that describe the change.

In describing the disturbance, there are a set of elements that need to be considered when analyzing resilience. One of them is the time scale of the system and of the disturbing forces. In the natural environment, some internal changes occur over short time periods and are visible on a human time scale (for example, change in the eutrophication conditions of a lake, reduction in the population of a certain insect, etc.). In other cases, the effect of a disturbing agent may not become evident for years, millennia or millions of years, and thus be difficult to determine, for example given the different temporal scales of geological processes.

Another element to consider is the possible overlap of effects due to the vast dimensions of a system and the difference in the periodicity and breadth of the various antagonistic processes. For example, in a large detrital aquifer with an immense storage capacity, a short extremely dry period can be obliterated by the hyper annual natural recharge of average and humid years, i.e., the overlapping of the previous and subsequent average recharge would have cushioned these effects.

Step 3. The third step is to describe the new state of equilibrium (regime) [45].

The analysis of resilience focuses on the disturbance, the processes of change, and the system's recovery into a new state of equilibrium. If the concept of resilience is to be made operational, we need to find ways to measure it. Therefore, an element to consider is the fact that the transition from one state (or "alternative state" according to some authors) to another occurs through thresholds [63]. Some authors argue that these thresholds are crucial for measuring resilience as these offer a way to quantify how much disturbance can be absorbed by a system before switching to another regime. The identification of these thresholds requires experimental or observational data on the changes between regimes in a certain system and, if possible, on its recovery trajectory [39]. Although there is considerable work done on transition indicators in biological systems [56], this is not the case for geological systems. A long time series of data is not always possible. In these cases, there are other resources to carry out this analytical study, as we show in the next section.

3. Conceptual Model Applied to a Real Case: The Upper Guadiana Basin in Central-West Spain

The case study presented here is for illustrative purposes to show through an example why the lens of resilience is valuable to gain a better, more anticipative knowledge of the system. It is also a pertinent case because it is applied to the functioning of a very large aquifer, its relation with an important groundwater-dependent wetland (the Tablas de Daimiel National Park, TDNP), and the dynamic of the system from a starting point, to highly degraded systems (both aquifer and wetland), and to a current significant recovery.

In the following sections, a description of the main steps mentioned above is presented. Figure 3 summarizes the main factors considered.

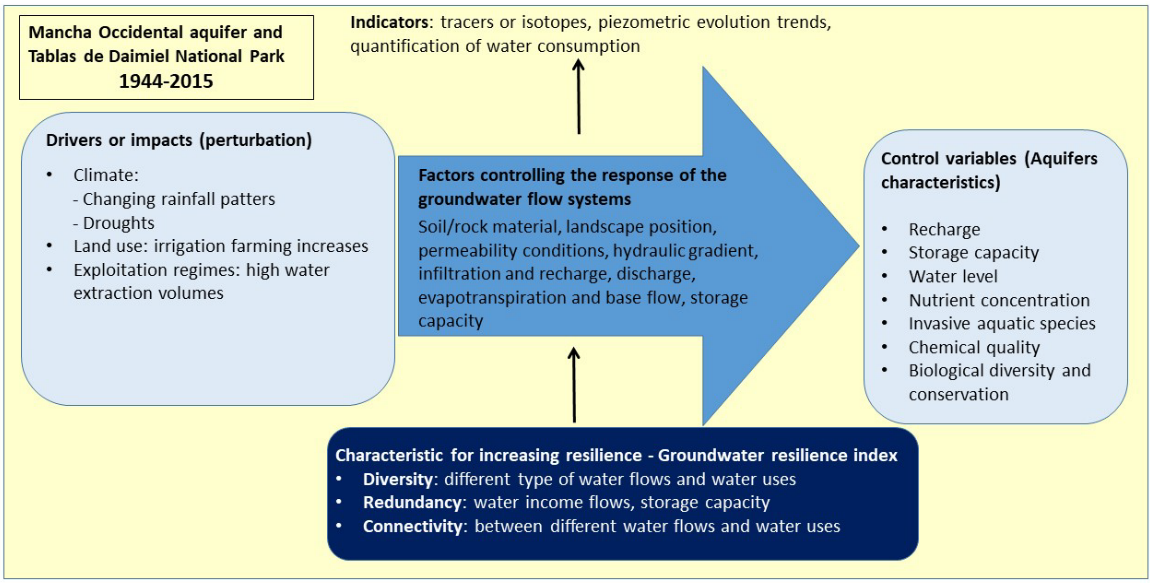

Figure 3. Conceptual model applied to the Upper Guadiana Basin (Source: authors' own).

3.1. First Step: Description of the System, Flows and Functions

This case provides, on the one hand, the aquifer perspective through the Mancha Occidental aquifer, and, on the other hand, the wetland perspective represented by a groundwater-dependent ecosystem affected by multiple impacts with enough data to allow its analysis. The equilibrium in wetland ecosystems is very fragile, showing high sensibility and vulnerability [64–67].

Tablas de Daimiel is a groundwater-dependent ecosystem subject to different types of impacts, both climatic and anthropogenic. This wetland is the main discharge outlet of the Upper Guadiana basin's aquifers (Figure 4), in such a way that it can be considered the "thermometer" of the 16,000 km^2 groundwater system [4]. The Tablas de Daimiel wetland has existed for over 250,000 years, evolving from a deep lake to a fluctuating shallow system, with different reversible intermediate phases depending on hydroclimatic conditions [8]. In 1960, the system water inflows combined brackish surface water from the Cigüela River with freshwater inputs from the Guadiana River and the underlying aquifer.

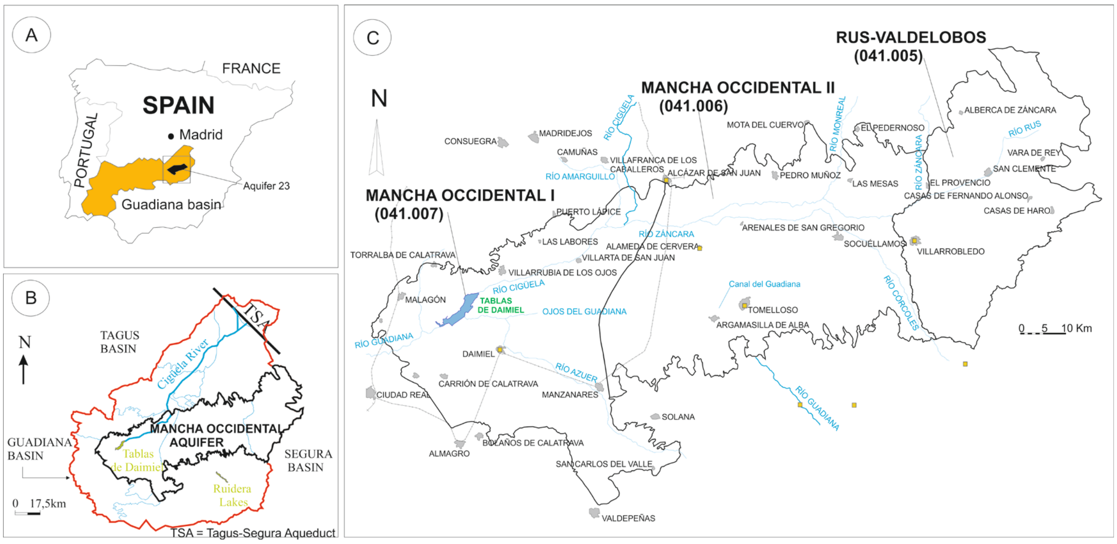

Figure 4. (**A**) General geographical setting. (**B**) Upper Guadiana basin. (**C**) The Mancha Occidental Aquifer (currently divided into three groundwater bodies: Mancha Occidental I, Mancha Occidental II and Rus-Valdelobos) (Source: Authors' own).

The analysis of the flood data series for the period 1944–1974 (Figure 5), prior to the overexploitation of the aquifer, reveals that in that period changes in rainfall (Figure 6) determined changes in water variability: changes in rainfall determined changes in the wetland surface covered by water [68].

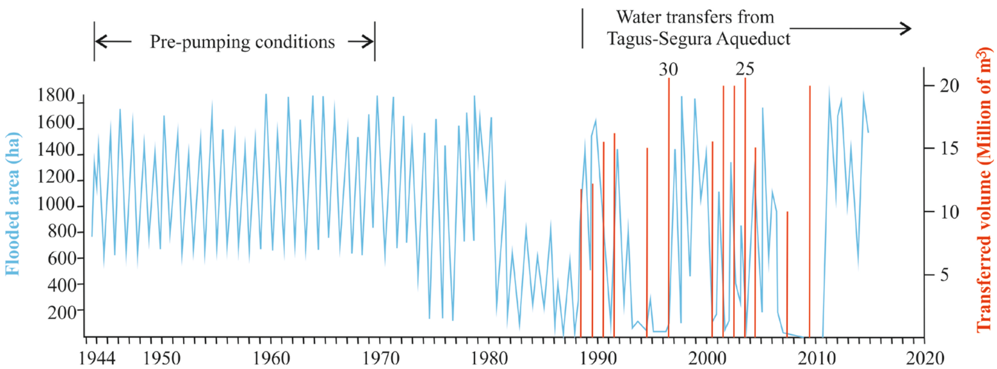

Figure 5. Flooded area evolution of Tablas de Daimiel National Park. Data from Sánchez-Carrillo et al. 2016 [68]. At the end of May 2020, the flooded area is less than 80 ha, and a new water transfer has been requested by the Tablas de Daimiel National Park (TDNP) Director to the Government (Source: Authors' own).

In resilience terms, 1944–1970 corresponds to the pre-pumping stage of the system and can be used as a reference stage for our purpose.

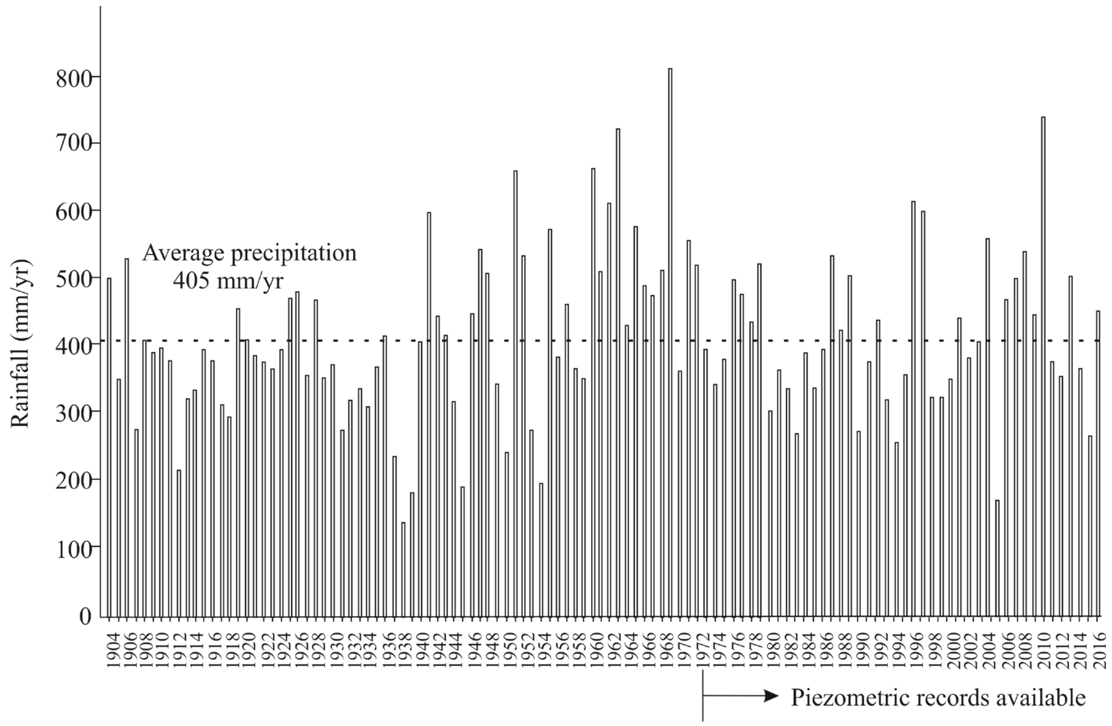

Figure 6. Long-term rainfall patterns in Mancha Occidental Aquifer 1904–2014. Rainfall data from weather stations 4121 and 4121C (data from [8]) (Authors' own).

3.2. *Water Quality in Tablas de Daimiel National Park: Baseline Stage (September–October 1974)*

Electrical conductivity ranged between 800 and 1600 µS/cm, with a minimum of 300 and a maximum of 5400 µS/cm. The dominant anions were sulphate and bicarbonate, whereas the dominant cations were calcium and magnesium [69]. Calcium bicarbonate waters predominated to the northwest and northeast of the national park, as well as in the vicinity of the Ojos del Guadiana springs, with the lowest conductivity sampled. Meanwhile, calcium sulphate waters predominated around the left bank of the wetland [4].

3.3. *Second Step: Description of the Perturbation*

Since the mid-1970s, the intensive exploitation of the aquifer for agricultural irrigation caused the desiccation of the wetland and neighboring springs. The cause of the hydrological situation of the Tablas de Daimiel in the 1980s can be well explained due to the length of the time series covering period 1975–2008. Extensive descriptive publications exist about this period examining its origin, reasons and social-ecological consequences [5–7].

Based on data provided by Aguilera and Moreno (2018) [69], the impact of drought caused a decrease in groundwater levels, which, at the same time, produced the burning of peat underlying the wetland, causing a smoldering peat fire in 2009 [69]. In this case, the descriptive variables observed were soil moisture, temperature and organic matter content for the period 2006–2010 [70]. Continuous soil moisture and temperature monitoring is recommended as an indicator of potential combustion and auto-ignition fire risk but does not work as alert system for an already active fire. In fact, the presence of active smoke columns is a late warning. A new fire means to arrive late. Fire modifies irreversibly the physical structure of affected soils, which implies a damage to the ecosystem.

In resilience terms, this analysis shows how the system faces the burning of peat impact. This provides the added value of the reaction to the change in the hydrological conditions of the soil.

3.4. Third Step: Description of the New State of Equilibrium

The longest water table records show the evolution of the system through the different described impacts (Figure 7). With depleted piezometric levels, the TDNP wetland operates as a recharge system for a local shallow perched multi-layer aquifer disconnected from the deeper regional groundwater flow towards main irrigation areas [71]. Water-table records show the tendency of the system to behave in a roughly similar manner across its entire extension.

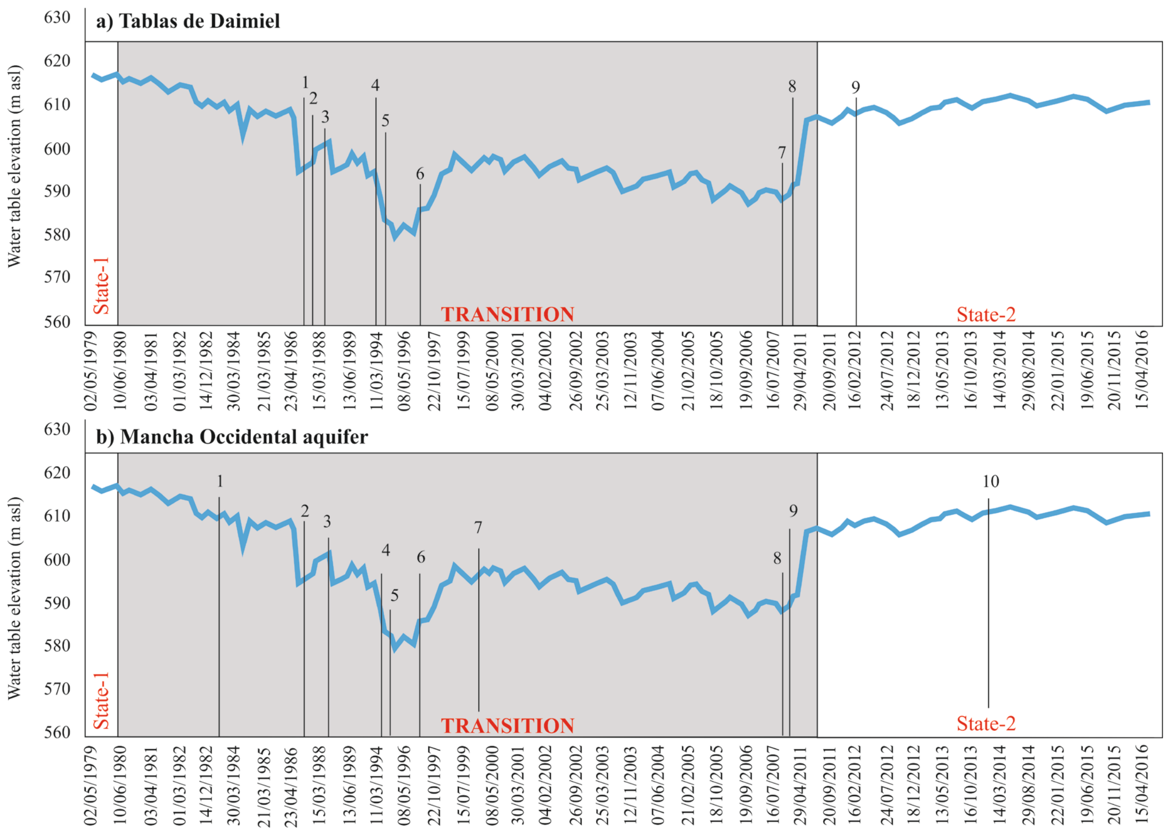

Figure 7. Water table evolution in a representative monitoring well (1930.4.0040) located near the Ojos del Guadiana springs and Tablas de Daimiel National Park. It ranks among the longest available piezometric records. The figure also shows the main historical events occurred in the (**a**) Tablas de Daimiel National Park: 01/1986–87: peat fires; 02/1987: Tablas de Daimiel was dry up for the first time; 03/1988: the first water transfer from Tagus-Segura Aqueduct; 04/1994: peat fires; 50/1995: flooded area, 30 out of 2000 ha; 06/1996–98: heavy rains; 07/2009: peat fires; 08/2010: water transfer from Tagus-Segura Aqueduct; 09/2012: groundwater feed Tablas de Daimiel. (**b**) Mancha Occidental Aquifer: 01/1983: Ojos del Guadiana springs dried; 02/1987: provisional declaration of aquifer overexploitation; 03/1988: maximum pumping peak (570 million m^3); 04/1994: declaration of aquifer overexploitation (pumping regulation); 05/1995: water level depth 47 m in Ojos del Guadiana springs; 06/1996–98: heavy rains; 07/2000: Water Framework Directive (2000/60/EC); 08/2009: water level depth 35 m in Ojos del Guadiana springs; 09/2010: heavy rains; 10/2014: Declaration of the Upper Guadiana basin's groundwater bodies (GWBs) at risk of not achieving the good quantitative and chemical status. (Data from [7]) (Authors' own).

For three decades, the wetland remained in precarious hydrological conditions, with the only exception of rapid floods due to extreme rainfall events and sporadic water transfers from the Tagus river basin. The water transfers from the Tajo-Segura Aqueduct started in 1988 and have often been carried out during spring or summer when evaporation and infiltration rates are highest and when increased demands of water for irrigation promote illegal extractions. Flooding the wetland with pumped groundwater was a management tool used constantly during dry periods to keep a minimum flooded area. Both management tools induce quantitative and qualitative impacts on the system [69].

There are several stressors acting simultaneously on the Tablas de Daimiel National Park: droughts (drying) and flooding situations, pumping, fires, treated wastewater, water transfer from other basins, and land use changes, among others. It is not possible to isolate just one cause and one effect for the analysis.

3.5. Water Quality in Tablas de Daimiel National Park: Pumping Stage

In 2007, the number of analyses is smaller than in the other two stages due to the water table dropping below the bottom of some piezometers and all springs drying up [7]. Electrical conductivity ranged between 2000 and 11,000 µS/cm. In the vicinity of the wetland, the main cations evolved into sodium and magnesium, while the dominant anions leaned towards sulphate and chloride. The surface water exerts little influence on groundwater chemistry across most of the system.

In the case study, an unusual situation has recently occurred: in 2011, a decrease in groundwater abstraction and an extraordinary wet period reversed the trend. Following a wet period (2006–2009) capped by an exceptionally humid year (2010), the aquifer experienced an unexpected recovery of groundwater levels (almost 20 m in some areas), restoring groundwater discharge to springs and wetlands, which came back to life for the first time since the early 1980s (Figure 7). For the sake of brevity, this history may be found in [8,68]; for a more recent perspective and hydrogeological functioning, details are presented in Castaño et al. (2018) [7] and Martínez-Santos et al. (2018) [8]. Here, we just mention those aspects relevant to the aim of the paper.

3.6. Water Quality in Tablas de Daimiel National Park: Restoring Stage

Data from 2014 show that the hydrological recovery has not yet been mirrored by a similar recovery in water quality. In fact, the groundwater is more saline than it used to be before the 1970s, and the predominant hydrochemical facies have shifted with meaningful spatial gradients [7]. The descriptive variable is the water quality of the groundwater around the wetland considering three stages: (i) prior to degradation of the wetland (1974, baseline); (ii) during a period of major degradation (2007); and (iii) after the most important recovery on record (2014). The pictures of Stiff diagrams obtained for each one of these milestones respond to a different state of the wetland, in this case, without data of transition among them, which is key to identify the beginning of the changings and provides the most valuable information to make responsible management decisions. In spite of this, the second picture (2007) shows an important change in water quality which indicates a remarkable internal change in the ecosystem after 33 years of pumping. The 2014 hydrochemical data indicate that the hydrological recovery of the system refers exclusively to the water balance and not to the water quality. This means that the lag time for water quality to reach a new equilibrium is shorter than the lag time of water levels to reach the position close to that of the 1970s. In fact, the reaction of groundwater levels to rainfall and decrease of pumping is fast (a short period of a few months), whereas the evolution of groundwater quality is much slower. Moreover, there are no studies to predict whether or not it will be reached or when. Considering the high level of hydrogeological knowledge existing in this area, including hydrogeological flow models, some research could be done along these lines in order not only to predict whether a new equilibrium will be reached, but also whether the system is able to keep such a state for a long time. Perhaps new actions will be needed in the context of sustainable management decisions.

3.7. Surface Flaming Fires and Smoldering Peat Fires

Both surface flaming fires and smoldering peat fires have been relatively frequent in the TDNP surroundings (1977, 1987 and 1991) [7,72]. In fact, most natural peatlands outside the park limits have disappeared. Smoldering peat fires have even been reported inside the park in 1986, 1987 and 1994 [67] (see Figure 6). But they occurred under relatively wet soil conditions, with a shallow water table located less than 1 m below the surface, and only affected small areas. In the 2009 fires, on the contrary, the soil moisture was much lower, and the water table was located deep below the surface, so the fires represented a much bigger problem [70]. This means that this fire posed an enormous risk for both the physical structure supporting the ecosystem and the quality of groundwater beneath it. The analysis of key parameters monitored in several locations of the TDNP at different depths shows that there was enough previous evidence to foresee the peat self-combustion and the risk that any surface fire could be transmitted to the subsoil. Data were taken in the vadose zone of the TDNP up to a depth of 2 meters at 12 points.

In resilience terms, this analysis shows that the soil's organic carbon content and moisture are two key variables in smoldering fires. The first is related to the amount of fuel available in the soil. The second represents a threshold condition, as below a certain moisture content peat can burn. This means that the peat combustion could be predictable allowing for pro-active management.

In resilience terms, this analysis shows that the system is more resilient to water quantity than to groundwater quality. This provides an added value for the assessment of conservation strategies.

4. Discussion—The Need for Good Quality Long-Term Data

From the analysis undertaken above, on understanding a complex hydrogeological system like the Upper Guadiana aquifer, through the lens of resilience we can gather new insights on the functioning of the system. For example, this wetland has been exposed to impacts that are not always evident and reversible [73]. The first signals of a change in water quality could have been detected if an adequate system of monitoring and data interpretation had been performed since 1970. An earlier intervention in the system could have avoided the degradation of water quality suffered currently in the wetland. Most of the processes triggered by global changes were not detectable in the short term; instead, it is necessary to adopt a longer decadal scale to understand their dynamics and evaluate their consequences [68].

The most frequent controlled variables in flow river systems are discharge data. In large rivers, these records are normally well registered. Nevertheless, in many areas, gauging stations do not have continuous records, making it difficult to undertake long-term series analysis. It is important to note that over recent decades, hydrological regimes have been changing at a very fast pace. Some progress has been made in extracting long-term signals of change from hydroclimatic data. However, further studies investigating long-term changes in river runoff, and focusing on the detection of underlying mechanisms and the disentanglement of their effects are needed [73].

The most frequent variable observed in hydrogeological studies are groundwater level fluctuations and periodical groundwater samples analysis. These are the variables controlled in most groundwater monitoring networks. It is important, therefore, to have good quality data records on groundwater abstractions to investigate the links between groundwater abstractions and their potentiometric surfaces to better understand future aquifer responses to climatic and anthropogenic stresses [74].

It is not easy to find continuous flow records from springs, since only a reduced number of springs have this information available. However, in order to identify flow patterns, other variables are needed, such as electrical conductivity and temperature, that would need to be monitored simultaneously and synchronically to the flow record. In wetlands, as in any other surface water body, monitoring the height of water in the wetland flooding control [68], the groundwater level in some close wells, and water samples from the wetland's water and groundwater [75] should also be recorded continuously [67].

While many groundwater and surface water flow systems have long-term operation histories, they do not have long-term series of data to assess such operation in depth. Very frequently, this is due to a lack of budget or a lack of staff and time to interpret these records. The hidden information behind those long-term series data should be extracted through long-term trends analyses from which some processes can be identified. Galassi et al. (2014) [15] studied the results of the effects of a 6.3 Mw earthquake on 6 April 2009 on the Gran Sasso karst aquifer in L'Aquila (Italy) by comparing biotic and abiotic data from two years prior to the event (1997 and 2005) and another post-event (year 2012), although not with contiguous hydrological years. This highlights the lack of data available to conduct this type of analysis.

A sufficient length of the time series is vital to be able to distinguish between different impacts, for example, natural climate variability and signals of climate change. When adopting strict criteria regarding data length and data quality, the available information probably decreases.

Different time horizons of observations and measurements can lead to different conclusions, and therefore time extrapolations are always risky. Hierarchy theory states that there is a control mechanism in the temporal order of systems and suggests that long-term processes (that operate mainly on wide spatial scales) restrict fast processes (that work on small spatial scales), which limits their degrees of freedom [76,77]. Although these concepts have theoretical strength, their empirical evidence has not been widely demonstrated so far due to the lack of data sets [68].

It is thus argued that better management decisions could be made if they were based on managing the resilience of systems rather than maintaining them as if these systems were inherently static and thus aim to return them to the statistics of, e.g., 50 years ago. In reality, natural systems are dynamic, and even more so when combined with anthropic influences, with the impacts of multiple factors of global change not present or, at least, not having the same intensity [78].

It is essential to identify the descriptive variables of the changes in order to monitor the analysis. Without adequate monitoring of these variables, it is impossible to understand the change dynamics and their scope, duration and characterization. This monitoring should be ex ante, taking a good design of the spatial observation network into account as well as an adequate periodicity of reading or sampling. Moreover, this monitoring should be permanent in order to allow data from the pre-disturbance phase to be available during and after the disturbance. Precisely, one of the reasons for the scarcity of these studies in hydrogeology is undoubtedly the absence of monitored information on geological processes. Long-term data records are required, combined with an observation network with good spatial coverage [79,80], to facilitate the analysis of the system's resilience. Furthermore, data limitations and the lack of information on mechanisms and processes pose significant limitations to research in many systems [19,75]. Some anthropogenic interventions may imply permanent or long-term durable changes, like the construction of buildings or the start of a new groundwater competing sector, such as agriculture. Permanent or long-term durable changes (in a human scale) imply that it is often difficult to return a system to its initial conditions in the temporal and socio-economic spheres. It makes more sense to talk about resilience today in terms of considering that the system attains a new state of equilibrium under the new conditions of change caused by a disturbance [79,80]. After the cessation of a disturbance, it can be possible to return to the initial state if no new disturbances occur, although this depends on the recovery capacity of the system. Nevertheless, it is important to point out that initial does not mean pristine. In cases where an initial state is known, the management could try to return the system to this initial state as opposed to the pristine state.

To date, transition indicators can be defined in certain natural systems, including volcanic (terrain changes prior to eruption) and hydrological systems (surface water and groundwater quality changes). However, many system state changes, let alone state change thresholds, can only be roughly recognized [79,80]. Also, early-warning signals are an open field of work and will be the next step once the system transitions can be identified.

The study of the resilience of natural systems requires multidisciplinary research including teams of experts in different fields. For the case of wetlands, it is necessary to know not only their characteristic functions but also the interrelation between hydrogeological and biological processes, and particularly the dynamic of governing and socio-ecological variables. The compartmentalization of the natural environment into separate disciplinary fields merely reduces the visual scope and skews the dynamics of the natural processes that develop between both spheres conceptually. Collaboration between the different disciplines enriches this vision, guarantees a more effective approach to reality, and is the safeguard of true scientific advancement.

5. Conclusions

The analysis of the resilience of any natural system must be defined based on its twofold nature, that is, from what to what, and how. The work must focus on analyzing the type of disturbance and identifying the changes produced by this disturbance in the internal dynamics of the system (the operation of the system), both within and between states.

It is important to consider the different scales of analysis and precisely define the trigger for the changes (impact) as the external agent acting from a higher scale, and the space–time scope of what is considered the "system" under study. Within this system, the variables that describe the change must be identified, along with their evolution, the interaction between them, and their potential recovery once the disturbance ceases or the shock is cushioned.

Our exemplification through the case of the case of Tablas de Daimiel describes how a set of changes have been caused by a series of impacts. These impacts act simultaneously making difficult any correlation of cause–effect binomial. Since the system is changing in a complex way, as a consequence of global changes, the only option is to obtain good quality data with a long enough time series to be able to discriminate a system's responses to different causes. The changes occurred in the Tablas de Daimiel are a response to multiple disturbances, and their interpretation varies with the time scale considered [68]. The response of many processes triggered by different changes is reflected in a time lag that is impossible to detect with short observation periods. The Tablas de Daimiel is currently a system in a new state. In this paper, some examples have been shown covering how and at what speed ecosystems have moved their structure to this new state, using flooding, rainfall and groundwater records jointly with additional short periods of specific data (water quality, and soil moisture, temperature and organic matter content). The Tablas de Daimiel shows a high resilience to droughts and flood events and a low resilience to pumping and fires. This means that the system copes better with natural disturbances than anthropic disturbances. However, no measurements or estimations of the resilience change starting point could be made due to the lack of continuous flow recording data. Thus, good data series are key to having a strong conceptual understanding of the resilience of hydrogeological systems that in turn allow for a more adaptive style of management that better reflects that systems are not static but rather are constantly evolving. It is thus critical to understand this so that system resilience is in line with the protection of key hydrogeological system functions.

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