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Development of the Chrono-Systemic Timeline as a Tool for Cross-Sectional Analysis of Droughts—Application in Wallonia

Kevin Thibaut [1,*], Pierre-Alain Ayral [2] and Pierre Ozer [1]

[1] Department of Environmental Sciences and Management, UR SPHERES, University of Liege, 185 Avenue de Longwy, 6700 Arlon, Belgium; pozer@uliege.be

[2] ESPACE, UMR 7300, Aix Marseille University, Côte d'Azur University, Avignon University, CNRS, Cévennes location, 410 Chemin de Boissières, 30380 Saint-Christol-Lez-Alès, France; pierre-alain.ayral@cnrs.fr

* Correspondence: kevin.thibaut@uliege.be

Abstract: Drought is a complex hazard with multiple and often dramatic impacts, depending on the environmental and societal context of the affected area. In recent years, due to global warming, this phenomenon has been occurring more intensely and frequently, affecting regions worldwide, including Wallonia, the southern part of Belgium. This study aims to enhance our understanding of the interdisciplinary dynamics of drought in order to improve its anticipation and crisis management by stakeholders. To achieve these objectives, a cross-disciplinary analysis tool has been developed: the chrono-systemic timeline. Applied here to the severe drought of 2018 in Wallonia, this tool provides a comprehensive visual representation of the crisis, simultaneously offering temporal and multi-sectoral perspectives. The data incorporated into the model encompass environmental conditions, economic and social contexts, as well as political and administrative decisions made during the case study. The analysis of the chrono-systemic timeline reveals numerous interdisciplinary connections, a prolonged period of significant impacts, a gradual return to a 'normal' situation, and a reactive form of crisis management. In conclusion, the study emphasizes the importance of giving due consideration to the risks associated with water deficits and advocates for the implementation of anticipatory and adaptive management strategies to enhance our ability to effectively address droughts.

Keywords: meteorological drought; water scarcity; climate change; chrono-systemic timeline; cross-sectional analysis; risk management; multiple impacts; Belgium; Wallonia

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1. Introduction

1.1. Context and Purposes

Drought is an increasingly recurrent term in Belgian news. Previously reserved for more distant regions of the world and, therefore, often considered insignificant in temperate latitudes, the risk of drought is little studied here [1]. Yet this vast phenomenon, which is difficult to define unequivocally, has been recurring almost every summer for some years now. Temperature records are regularly broken, and the duration and number of summer heatwaves continue to increase, while rainfall totals seem to be falling. Apart from more regular and sometimes exceptional rainfall experienced during the summer of 2021 [2], the state of drought appears to be well established in Belgium and Europe. Furthermore, the climate changes that have been underway worldwide for several decades are likely to considerably upset the usual temperate climate characterized by a succession of mild, rainy winters and relatively cool, wet summers. Climate projections for Belgium are, in fact, marked by an increase in temperatures in all seasons, a decrease in precipitation in summer, and an increase in winter, a gradual disappearance of snow cover, and more extreme weather events [3–6]. The first part of the IPCC's latest assessment report, dealing with the physical aspects of climate, confirms that continued global warming—for which the burning of fossil fuels by anthropogenic production systems is largely responsible [7–10]—will lead to an increase in the frequency and intensity of droughts [11].

In recent years, Belgium has been hit hard by consequent impacts of droughts, such as in 2003 when the significant water deficit associated with an intense heatwave is thought to have been responsible for almost 1500 premature deaths, as well as agricultural losses estimated at 130 million euro [12], or as in 2020, when estimates of heat-related deaths were even higher [13]. The environmental damage (abnormal low water levels, loss of biodiversity, forest fires, etc.) and the impact on other economic sectors (reduction in public water supplies, agricultural losses, cessation of tourist activities, etc.) are just as significant, especially as Belgium, and Wallonia in particular, has a poor drought risk culture [14]. The recurrent multiplication of water shortages is relatively new, and infrastructures and operating methods are not well adapted to this phenomenon. In this respect, however, it is worth noting that the authorities and stakeholders are currently investing more and more in mitigating the impact of drought. Given the context of climate change, which is set to increase these deficits in Wallonia, it seems necessary to take a closer look at this issue now in order to better anticipate and manage future droughts in the area under study.

Therefore, this study was carried out in order, on the one hand, to better decipher the overall process of drought kinetics in a context where this event can be considered as emerging—which can reasonably be said in the case of Belgium—and, on the other hand, to better understand the holistic and interdisciplinary nature of this climatic phenomenon. The study was conducted as part of a wider project on the management of hydrological climate extremes in Belgium, the main research question of which is aimed at improving stakeholder anticipation and crisis management of such events. These objectives were achieved through the use of an original and innovative tool, the chrono-systemic timeline, which offers a wide range of analytical inputs. The approach used to tackle this issue and build the timeline is feedback analysis—a concept that can be defined as the learning engine of the risk management cycle with the aim of improving a system's resilience [15,16]. In this case, the feedback used as a basis for the descriptive analysis is the experience of an institutional structure present at the heart of a recent water deficit event. The scope of the study was chosen to be regional—in this case Wallonia (the southern part of Belgium)—rather than national, because of the many disparities between the north and south of the country in terms of meteorology, natural resources, and regional planning, as well as the regionalization of many of the political powers affected by a drought crisis. The experience thus gathered was then transcribed into the chrono-systemic timeline, so as to obtain a globalized and multi-sectoral visualization of the crisis.

This article is divided into three parts. To begin, the complex nature of a drought and its multiple impacts are discussed. Next, more details are provided on the chrono-systemic timeline as an analytical tool and on how it was constructed for the event studied here. Finally, the results obtained are discussed for each of the sub-systems covered by the chrono-systemic timeline.

1.2. Drought Complexity

A drought is a meteorological event that can be described as exceptional in the sense that it occurs following a lack of rainfall compared with normal or average rainfall over a significant period, leading to an unusual deficit in water availability over a given area [17–19]. It should not be confused with aridity, which refers to a delimited climatic region whose almost permanent rainfall deficit is the normal consequence of meteorological conditions [20]. Drought can theoretically occur almost anywhere in the world and can be regional, national or international in scope [21,22]. This phenomenon is characterized by slow dynamics, both in terms of its onset (progressive accumulation of a lack of rainfall) and its end (gradual return to normal of all the parameters affected, depending on the properties of the system and the level of the water deficit), and extends over fairly long periods (several weeks, months, or years).

Given the specific characteristics of a drought, there is no single definition that correctly defines this phenomenon [23]. However, a typology, recognized by the World Meteorological Organization (WMO), makes it possible to characterize droughts based on the chronological development of the phenomenon, taking into account the persistence of the water deficit and the increase in impacts over time. The four successive types of droughts identified are as follows [24,25]:

- Meteorological (or atmospheric) drought, linked to atmospheric conditions and characterized by an abnormal shortfall in rainfall;
- Agricultural (or pedological) drought, resulting from a lack of water available in the surface layers of the soil for natural vegetation or agricultural crops; high temperatures and sustained winds favor the occurrence of this type of drought by increasing evapotranspiration;
- Hydrological drought, defined as a deficit in surface and groundwater reserves compared with a normal situation;
- Socio-economic drought, which occurs when the demand for water as an economic good or service is greater than the amount of water available.

It is interesting to note that the human dimension in this issue is not only involved in socio-economic drought but is also influencing the occurrence of agricultural and hydrological droughts. This influence is exerted through land use and land cover changes, varying levels of water resource utilization, and its undeniable role in global warming, of which one of the consequences is an increase in the frequency of dry spells. Drought is, therefore, a risk that can be described as both natural and highly anthropogenic. It should also be noted that numerous drought indicators or indices have been developed around the world to describe drought conditions and measure their level of intensity, some requiring a wide range of data and complex calculations, others being simpler but nonetheless effective [26]. However, not all of these indices are applicable to every affected region, and not all of them allow the phenomenon to be detected in the same way, whether in terms of extent, temporality or impact [27].

The complexity of droughts, highlighted by the numerous definitions and the multitude of different indicators of the phenomenon, stems essentially from the fact that this type of event is not just a climatic issue, because even if the origin of droughts is linked to meteorological factors, their consequences and their magnitude depend strongly on the environmental and societal context of the affected territory [28]. A drought is in fact a disaster with multiple impacts which, even though the drying process is slow and supposedly predictable, can have dramatic effects in extreme cases [29]. It is not so much the meteorological phenomenon itself that is devastating, but rather the indirect effects of rainfall deficits, such as famines following the loss of crops or livestock due to lack of water, or socio-political conflict following the displacement of people from regions that have become uninhabitable. Southern countries, already affected by aridity or desertification, are particularly sensitive to droughts because their economies are often dependent on rainfall to meet their food needs [30]. However, northern countries are not exempt from the impacts of this phenomenon.

The negative effects of drought episodes are felt, through a domino effect, in all areas of society [31,32]. The main sectors of activity directly and indirectly impacted by a severe water shortage are drinking water distribution, agriculture, the environment, energy production, shipping, public health, tourism, and industry. The global problem of drought risk is, therefore, multidisciplinary by definition [24]. Although not as dramatic as in certain regions of the world, the consequences of drought in Belgium are also significant. As part of a study focusing on the issue of water deficits in Wallonia conducted by Thibaut [33], a list of direct and indirect impacts by type of drought was drawn up. An adapted version of this list is presented in Table 1.

Table 1. Direct and indirect impacts of droughts in Belgium according to their type (source: adapted from [33]).

	Direct Impacts	→Indirect Impacts (1st Level)	→Indirect Impacts (2nd Level)
Type of drought		Socio-economic and environmental drought	
←Meteorological drought	- Precipitation deficit - High temperatures - Increased evapotranspiration - Reduced infiltration and run-off	Air pollution (dust, fine particles, etc.)	Impacts on human and animal health
		extreme heat	Impacts on human and animal health
		Appearance or proliferation of new parasites and/or diseases	Impacts on human, animal, and plant health
		Psychological shock for disaster victims	Depression, suicide, etc.
←Agricultural drought	- Insufficient soil moisture	Deterioration of crops and meadows	Reduced yields, financial losses
		Deterioration in livestock farming	Lack of food resources, use of winter fodder, financial losses
		Deterioration of forest ecosystems	Reduced tree growth, increased mortality and risk of disease or pest attack, financial losses, reduced CO_2 sequestration by trees
		Deterioration of fragile and/or protected ecosystems	Loss of biodiversity
		Landslides, wind erosion of the soil	Increased risk of building instability
		Drying out of vegetation cover	Increased risk of fire, ban on access to natural areas, cessation of tourist activities, financial losses, etc.
Hydrological drought	- Reduced river flow - Dwindling freshwater reserves (surface and underground)	Shortage of mains water	Conflicts of use, restrictions on use, additional pressure on scarce renewable water reserves, alternative supplies (tanker trucks, aid from neighboring countries, etc.), reduction in the quality of the water distributed, increase in the cost of water, etc.
		Deterioration of aquatic ecosystems and water quality, increase in water temperature	Loss of biodiversity, fish mortality, reduction in fish farming yields, financial losses, proliferation of bacteria
		Stopping hydroelectric production, limiting thermal discharges, restricting water abstraction	Electricity shortages, higher energy costs, disruption to water-using industrial processes, financial losses for operators
		Restrictions on navigation (shallower draught, grouping together at locks, etc.)	Reduction in river freight transport, longer journey times
		Stopping tourist activities (kayaking and other leisure craft, fishing, swimming, etc.)	Fewer tourist visits, financial losses, job losses
		Limiting water abstraction for irrigation	Increased agricultural drought

2. Materials and Methods

2.1. Analysis Tool: Chrono-Systemic Timeline

In the feedback process, the main aim of which is to improve future crisis management by using learning methods to correct identified past malfunctions, it is vital to understand the ins and outs of a disaster as well as the interactions between the events that mark it. In the context of drought events, where the impacts and consequences are extremely varied, whether in terms of sector, space, or time, the difficulty of obtaining an overall view of the facts and understanding the links between them is very real. There is, however, a tool that can be used to bring these complex elements together in a synthetic diagram: the chrono-systemic timeline.

A chrono-systemic timeline can be defined as an interdisciplinary tool for analyzing the processes of change in an area [34]. The term ‘chrono’ symbolizes the timescale over which the event under study takes place. The term ‘system’ encompasses a set of multidisciplinary and multifactorial approaches to the issue under study. On the timeline, these temporal and systemic elements are connected by logical links. Ultimately, the chrono-systemic timeline tool enables an event to be viewed globally on a single graph, highlighting the complex processual dynamics at work in several dimensions simultaneously. This tool has already been used in various contexts, such as territorial evolution (Madelrieux in [34]), territorial conflict (Bergeret in [34]), global change (Lamarque in [34]), or water policy (Girard in [34]), with different temporal dimensions and involving different scientific disciplines (geography, anthropology, sociology, agronomy, etc.). It is, therefore, an ideal tool for modeling complex systems and aggregating interdisciplinary knowledge [34]. This tool is of particular interest for a holistic analysis of drought episodes during which processes linked to the human and social sciences on the one hand and to the environmental sciences on the other intersect, connect, or even come into conflict. Bergeret et al. [34] go on to say that, in the convergence of the multiple factors leading to a crisis, the timelines can reveal the thresholds that lead to a paradigm shift in the face of the event, and that they can also contribute, through the analysis of lived experiences, to improving the management of similar future situations. As part of the application of this tool to the Walloon drought of 2018, the methodology for constructing the six-stage chrono-systemic timeline presented below is largely inspired by the work of Bergeret et al. [34] and Hassini [35].

Since the purpose of a timeline is to model in a single diagram a process that we wish to discuss, the first step is to problematize the phenomenon concisely and precisely in order to target the process to be studied. During this phase, the spatial scale of the timeline is also determined. The second step is to define the timescale—placed on the x-axis of the timeline—which can be linear, logarithmic, or even made up of cuts or zooms on certain periods to suit the pace of events. The initial and final milestones, which determine the beginning and end of the process being analyzed, are also set.

In the third stage, the ‘ingredients’, also known as sub-systems, will be prioritized and represented as bands on the timeline’s ordinate. These components are the multidisciplinary elements of the process, allowing for the characterization of the process and providing context to its dynamics. The selection of these ‘ingredients’ depends on the existence and availability of information related to the problem, as well as the author’s interpretation of the research objective. This subjectivity may initially appear as a limitation of the tool, but it represents an accepted expression of the researcher’s approach to understanding the system’s kinetics. As noted by Bergeret et al. [34], the model constructed is not intended to be an exhaustive representation of the studied event. Instead, it represents, through the choice of ingredients, one of an infinite number of systems that could be developed based on the reality of a given territory.

The first three stages described above form the framework of the chrono-systemic timeline, onto which the milestones, i.e., the points of reference in the process being analyzed, are grafted in the next stage (the fourth). There are three types of milestones: events, trends, and configurations. Events correspond to actions, decisions, observations, or facts which are part of the process, and which reveal the targeted problem. They may hold a special significance as they are considered to trigger a new situation through a rupture, a forcing, a bifurcation, or a resolution. Trends are used to indicate the evolution of an ingredient within a specific time window, whether it involves growth, decline, or stability. Configurations symbolize the different states or statuses of an ingredient during the process.

The fifth stage in constructing the chrono-systemic timeline involves establishing dynamic connections among the various pieces of information placed on it. This approach highlights the inherent movements within the process and illustrates the interactions between milestones. These interactions can occur horizontally within the same ingredient, or vertically between different sub-systems. The types of relationships can vary, and include causality, succession, adaptation, synergy, resistance, conflict, and feedback. The development of the timeline concludes with the sequencing stage, which aims to identify the major periods that constitute the process under study. These periods, or sequences, can be defined globally for the entire timeline, or individually for each ingredient. They represent a coherent sequence of milestones, delineated by a pivotal event or a set of facts signifying a transition. As the timeline is a dynamic representation of the issue's trajectory, the concepts of rupture, transition, and bifurcation can be associated with these sequences.

The diagram of a chrono-systemic timeline showing the main features described above is shown in Figure 1.

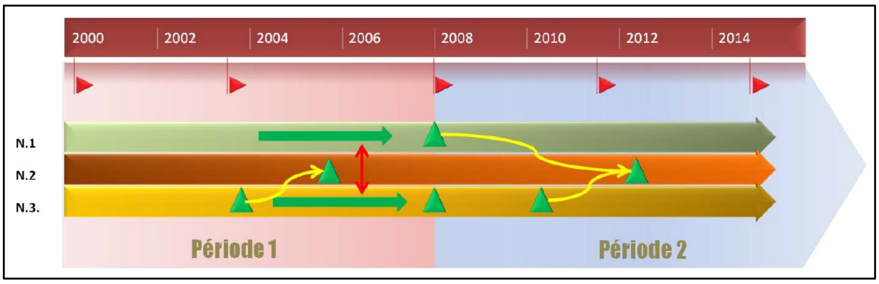

Figure 1. Diagram of the main characteristics of a chrono-systemic timeline (red triangles: key dates; N.x: ingredients or sub-systems; green triangles: milestones; arrows: connections and relationships). (Source: [34]).

2.2. Case Study

Several criteria were considered when choosing the drought event to be analyzed using the chrono-systemic timeline. Firstly, it had to be a significant event in Belgium, both in terms of its meteorological characteristics and its impacts and consequences. Secondly, it had to be a recent event, to ensure greater availability and accessibility of the data relating to it, and to be in step with the current climatic reality and its future challenges. Therefore, the drought of 2018 was chosen. From a meteorological point of view, the year was marked by much higher-than-normal sunshine and temperatures, as well as exceptionally low rainfall, both in terms of frequency and quantity [36]. Two successive intense heat waves in the summer also accentuated the water deficit and put pressure on water resources. The graph in Figure 2 shows the extent to which rainfall, temperature, and sunshine conditions made this year exceptional.

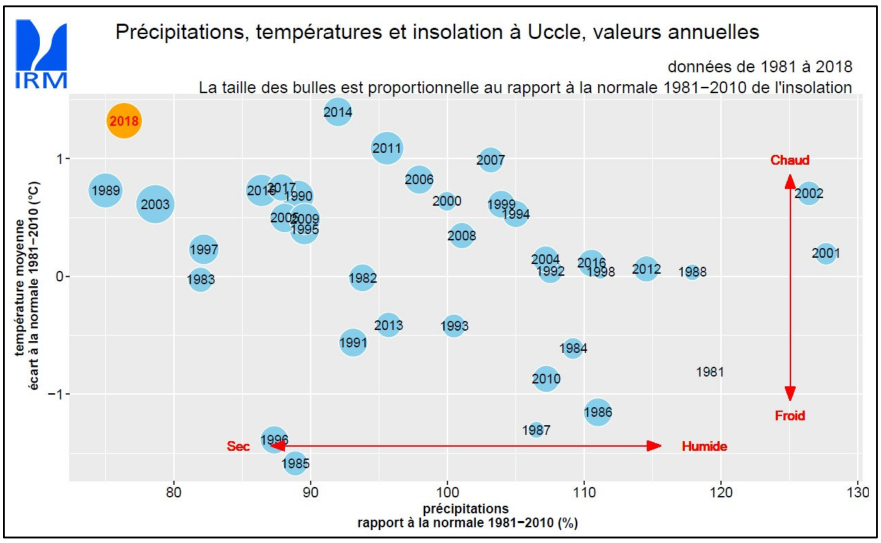

Figure 2. Relationship between departures from normal precipitation, temperature, and insolation (1981–2010) at Uccle (Brussels-Capital Region) for the years 1981 to 2018. (Source: [37]).

The extreme conditions of 2018 resulted in a significant meteorological drought for much of the year. In Wallonia, rainfall deficit anomalies were observed from mid-March and continued until the end of the year. The year 2018 is all the more remarkable in that it followed on from 2017, which was already marked by persistent drought, and preceded 2019, which was also dry and hit by three heat waves and record temperatures. Moreover, the events of these three years were not confined to Belgium but affected a large part of Europe. A recent study by Hari et al. [38] shows that the occurrence of consecutive summer droughts in Europe in 2018 and 2019 is unprecedented in the last 250 years and is likely to be repeated much more often in the future as a result of global warming.

2.3. Data Acquisition

Selecting the 2018 drought episode as analysis material also aligned with the other established criteria, notably its recent occurrence and the availability of relevant data. 2018 marked the inaugural full year of operation for the 'drought unit' within the Wallonia Regional Crisis Centre (CRC-W) (The Wallonia Regional Crisis Centre (CRC-W) was created in May 2008 by decision of the Walloon Government. Its origins lie in the PLUIES plan (Prevention and Fight against Floods and their Effects on Disaster Victims) which, in its fifth objective, aimed to improve crisis management. The objective of the CRC-W is to ensure coordination of regional matters relating to crisis management and to provide support to the various authorities responsible for crisis management in accordance with the Royal Decree of 22 May 2019 on emergency planning and the management of emergency situations at municipal and provincial level). This unit's responsibility includes conducting comprehensive assessments of drought impacts, implementing regional measures for water resource preservation, and providing relevant authorities with situational updates. It convenes approximately ten to fifteen times a year, contingent upon weather conditions, and comprises various Walloon Public Service administrations (overseeing surface water, groundwater, navigable and non-navigable waterways, dams, waterways, hydrology, forests, natural environment, fisheries, agriculture, etc.), water producers and distributors, representatives from the energy sector, the General Commissariat for Tourism, and delegates from the Walloon Government.

As part of the research carried out, all the 'drought unit' meeting reports for 2018 (the list of 'drought unit' minutes analyzed is presented in Appendix A, Table A1) were made available in their entirety by the CRC-W. The data systematically available in these reports includes the meteorological balance, the conditions of surface water, groundwater and water catchments, navigation conditions, the operation of hydroelectric power stations, the risk of forest fires, the state of agricultural land, and the administrative decisions taken at the various levels of government. This information is based on public data from the Royal Meteorological Institute of Belgium (IRM), flow and water level measurements from the various sensors managed by the Walloon Public Service (SPW), any field observations made by SPW staff and information provided by the stakeholders taking part in the 'drought unit' (water producers/distributors, public/private representatives from the sectors affected, etc.). These meeting reports—the actual experience of the drought studied here—were used as raw material to construct the chrono-systemic timeline.

As climatic conditions are an important component in analyzing and understanding a drought episode, additional data were also used as part of this work in order to develop indicators to put 2018 into a meteorological context. For this, we used the complete monthly climate reports from the IRM (monthly climate reports are available online on the website of the Royal Meteorological Institute of Belgium (https://www.meteo.be/fr/climat, accessed on 19 December 2021).

The data sources (reporters and producers) are available in Table 2.

Table 2. Categories, subsystems, axes, and origin of data for the 2018 drought chrono-systemic timeline in Wallonia (* IRM: Royal Meteorological Institute of Belgium; CRC-W: Wallonia Regional Crisis Centre; SPW: Walloon Public Service; Aquawal: union of public water cycle operators; Engie: main producer of hydroelectricity).

Categories	Subsystems	Axes	Data Sources *	
			Data Reporters	Data Producers
Environmental conditions	Weather conditions	Temperatures	IRM	IRM
		Precipitation	IRM	IRM
	Hydrological conditions	Underground water	CRC-W	SPW: groundwater direction
		Surface water	CRC-W	SPW: dams' direction, hydrological management direction, direction of non-navigable waterways
		Water quality	CRC-W	SPW: surface water direction
Economic and social context	Production/distribution of drinking water	-	CRC-W	Aquawal + water producers
	Agriculture, livestock, and fish farming	-	CRC-W	SPW: agriculture, natural resources, and environment
	Forests and natural environments	-	CRC-W	SPW: Department of Nature and Forests
	Energy	-	CRC-W	Engie
	Navigation and tourism	-	CRC-W	SPW: General Commissariat for Tourism, direction of non-navigable waterways
Political and administrative decisions	Regional level	-	CRC-W	Regional authorities + SPW
	Provincial level	-	CRC-W	Provincial Governor
	Municipal level	-	CRC-W	Municipal authorities

2.4. Methodology

As the objective of this study is to analyze a drought crisis using a multidisciplinary approach, the central issue addressed in the development of the chrono-systemic timeline can be summarized as the observation of the overall process—considering environmental sciences and human and social sciences—of the kinetics of a drought. Regarding the geographical scope of the analysis, we have chosen to focus on the regional level, specifically Wallonia. However, certain aspects of the timeline, particularly those related to political and administrative decisions, were further disaggregated to provincial and municipal sub-levels. This approach allows for a comprehensive understanding of the problem that aligns with the realities of decision-making in Belgium. In terms of temporal considerations, we opted to construct the timeline over a full calendar year, spanning from January 2018 to December 2018. We used a linear time scale to provide equal visual weight to all periods of the year, irrespective of the extent of drought impact during those periods.

The sub-systems or 'ingredients'—components through which the dynamic process of the event is described—are divided into three categories of information applicable to the characterization of a drought: environmental conditions, the economic and social context, and political and administrative decisions. The sub-systems derived from the environmental category are also subdivided into several axes in order to gain a more detailed understanding of the course of the crisis. A summary of the ingredients developed on the chrono-systemic timeline, including the origin of the data used, is presented in Table 2.

On the chrono-systemic timeline, the description of climatic conditions is deliberately limited to simple indices relating to temperature and precipitation. This choice is justified, firstly, because these are basic concepts that characterize a drought and contribute to its development and, secondly, because these data are generally accessible and understandable by a wide audience. Furthermore, the main objective of these meteorological indicators is to contextualize and frame the core of the event studied, which lies in the dynamics of the facts reported and in the logical links between them. In the context of a holistic tool, it is, therefore, appropriate not to overload the timeline with strictly climatic elements in order to leave more room for interdisciplinary analysis.

The selected indicators include the deviation of monthly temperature from the normal at Uccle (The Uccle weather station is considered by the IRM to be the reference station for meteorological data in Belgium. As far as the temperature index is concerned, this station can be considered representative in terms of temperature deviation from normal, since for 2018 the difference between Uccle (+ 1.4 °C) and Wallonia (around + 1.5 °C, based on the IRM's annual map of the geographical distribution of temperature anomalies for 2018) is relatively similar) and the relative deviation of monthly total rainfall from the average normal for Wallonia (With regard to the rainfall index, the Uccle weather station is not sufficiently representative of the Walloon rainfall context due to the wide disparity in geographical conditions (altitude, relief, distance from the sea, etc.). Rainfall anomalies have, therefore, been assessed on the basis of an average normal calculated for Wallonia as a whole). The norms are defined in relation to the most recent 30-year reference period at the time of the study, specifically 1981–2010. The monthly values obtained (Values calculated from data available on the IRM's monthly climate reports for temperature deviations from normal in Uccle and values supplied by the IRM's meteorological information and external communication services for relative rainfall deviations from normal in Wallonia) were then categorized based on their deviations from the norm, with six steps for temperature ranging from −2 °C to +3 °C and five steps for precipitation ranging from very low to very high accumulation. On the chrono-systemic timeline, the use of a colour gradient for these categories facilitates the visualization of how meteorological indicators change. Table 3 presents the values of these indicators for each month of 2018.

Table 3. Monthly weather indicators for 2018 and classification according to departure from norms [n: normal, <lower (<85%), <<much lower (<60%), ≈nearly equal (85–115%), >higher (>115%), >>much higher (>140%)].

Monthly Indicators 2018	J	F	M	A	M	J	J	A	S	O	N	D
Average temperature (°C, Uccle)	6	0.8	5.4	13	16.3	18.1	22	19.4	15.4	12.6	7.4	5.8
Mean/normal temperature difference (°C, Uccle) + classification	+2.7 >+2°	−2.9 <−2°	−1.4 <−1°	+3.2 >+3°	+2.7 >+2°	+1.9 >+1°	+3.6 >+3°	+1.4 >+1°	+0.5 ≈ n	+1.5 >+1°	+0.6 ≈ n	+1.9 >+1°
Cumulative rainfall/normal deviation (%, Wallonia) + classification	130.2 >n	37.7 <<n	103.8 ≈n	102.2 ≈n	104.8 ≈n	63.6 <n	18.8 <<n	71.6 <n	81 <n	55.7 <<n	55.1 <<n	115.3 >n

On the subject of hydrological conditions, the CRC-W's information on groundwater and surface water—based on the level of water tables and dams and the flow of rivers—has been transposed onto the chrono-systemic timeline using a visual scale made up of colour codes (seven levels indicating the level compared with what is usually observed) and geometric codes (four shapes indicating the trend). These provide a relative and evolving assessment of the state of water resources over the course of 2018.

For the economic and social context as well as the political and administrative decisions, each piece of information—relating to the development of the case study—recorded in the minutes of the CRC-W 'drought unit' is included on the chrono-systemic timeline at the effective date (or period) of the event and in the sub-system concerned. Once these milestones have been placed, their analysis enables us to highlight any dynamic links between them, the impact chains, societal responses, and the sequencing of the drought kinetics studied.

3. Results and Discussion

The final result of the construction of the transversal analysis tool using the proposed methodology and the implementation of the acquired data is a chrono-systemic timeline relating to drought kinetics in Wallonia in 2018. This timeline, the formatting of which is based on the model developed by Hassini [35], is presented in Figure 3. An analysis and discussion of this result are proposed below.

3.1. Environmental Conditions

On the chrono-systemic timeline, the selected weather indicators for describing climatic conditions in 2018 highlight the following elements:

- Temperatures consistently higher than normal, with January, April, May, and July experiencing deviations more than two degrees above average;
- Below-normal rainfall for much of the year, with lower rainfall totals (around 20–40% less precipitation) in June, August, and September, and much lower totals (over 40% less precipitation) in February, July, October, and November.

The combination of these meteorological factors had significant consequences for hydrological conditions in Wallonia, resulting in a cascade of negative impacts typical of a drought.

In Wallonia, freshwater resources—groundwater, rivers, lakes, and reservoir dams—are considered to be significant and not inherently subject to the risk of shortages (the water exploitation rate (the Water Exploitation Index is the ratio of total volumes abstracted—minus volumes returned: leakage and cooling water—to total water resources; however, it is not very appropriate for estimating the sustainability of water use because it does not take into account the water requirements of the essential natural functions provided by groundwater and surface water) in Wallonia was estimated at 5% in 2013, which is well below the European water stress threshold set at 20%). However, a substantial proportion of this freshwater leaves Wallonia via its rivers for neighboring regions and countries, and only the portion of the annually renewable resource that is abstracted sustainably can be considered truly available. In addition, given the high population density and significant annual water withdrawals (of the order of 2000 million m^3), as well as the ecological importance of surface and groundwater, water management in Wallonia poses a significant issue to maintaining a balance between withdrawals and recharge, and preventing overexploitation or local shortages [39,40].

Regarding hydrological conditions in 2018, the chrono-system chart shows that groundwater recharge from winter rainfall is considered good for most aquifers, especially the shallow ones, with the exception of certain aquifers (Haine chalk, Brussels sands, Péruwelz-Ath-Soignies limestone) which were already considered low at the start of the year. After a normal seasonal decline, the situation worsened significantly and abnormally, reaching a critical state in places with levels lower than those of 2017 (a year in which a major drought had already occurred). The situation stabilized by the end of the year at low to very low levels, potentially leading to difficulties during the following year if the winter rains were insufficient. For surface water, the pattern is relatively similar to that for groundwater, with normal levels at the start of the year and a relatively significant, or even completely abnormal, fall during the year. The situation is particularly catastrophic in non-navigable rivers, where low water levels are high and occur early in the season. Many negative environmental consequences have resulted from this state of affairs. The temporary change in the water balance of aquatic ecosystems led to unusually high fish mortality and a deterioration in water quality (lack of oxygen, higher concentration of pollutants, proliferation of bacteria, etc.). Water quality was also affected by heavy sedimentation (with increased turbidity) during the brief, intense storms that coincided with the drought. Navigable rivers, which are larger in size and, therefore, are fed by larger catchment areas (some of which extend beyond the Belgian border), did not experience as low levels as non-navigable rivers. Nevertheless, low flows were observed towards the end of the summer and into the autumn, and the Sambre, and by corollary the Meuse, had to be supported by releasing water from the Eau d'Heure dam complex. The last quarter of 2018 also saw an unusual drop in freshwater reserves in the reservoir dams.

3.2. Economic and Social Context

Drinking water is one of the few sectors in Wallonia where all operators, from production to distribution and even purification, are public bodies. Depending on the location of the place of consumption, water is supplied by a single public supplier (SWDE, Société Wallonne Des Eaux), an intermunicipal company, or directly by municipal services [41]. The volume of water abstracted in Wallonia for public distribution purposes has changed little over the last twenty years, and fluctuates between 380 and 400 million m^3 per year, of which an average of 80% comes from groundwater, the quality of which generally allows it to be made drinkable at lower cost than surface water, from which the remaining 20% is abstracted [42].

As the chrono-systemic timeline shows, the public water supply situation in 2018 was initially under control at the start of the summer period, but became tense, even critical depending on the location, as groundwater and surface water reserves dwindled as a result of the persistent drought. Moreover, demand for water from residents did not diminish, especially as rainwater tanks very quickly ran dry. Alternative supplies were, therefore, put in place to cope with local shortages of mains water, including transfers by tanker (from other municipalities in the country or abroad), requisitioning of wells from private companies, and increased abstraction of surface water from reservoirs and the Meuse, even though the levels or flows at these abstraction points were already being affected by the drought.

Agriculture, which occupies almost 40% of Wallonia [43], and livestock farming are sectors of activity that are directly impacted by droughts, mainly by the so-called agricultural droughts. These droughts, often combined with agricultural methods and plant species that are poorly adapted to these meteorological extremes, have major consequences in terms of yields and the sustainability of crop and livestock production. In Wallonia, six of the last twenty years, including 2018, have been affected by a drought recognized as a natural disaster, giving rise to compensation [44]. The extremely dry period, early and long, experienced that year had a major impact on farming throughout Wallonia. Many crops (mainly maize, beetroot, and potatoes) suffered from the lack of water, resulting in a loss of productivity and, consequently, of income for farmers. Meadows quickly dried out, forcing farmers to feed their animals winter fodder. In addition to the health risks for livestock (increased disease and mortality), this chain of circumstances generated an additional cost the following winter to replenish a sufficient stock of feed.

While the fish farming sector in Wallonia is comparatively small when compared to meat farming, it remains highly vulnerable to episodes of drought and heatwaves. This vulnerability primarily arises from the reduction in water levels in ponds and the occurrence of exceptionally high water temperatures, both of which contribute to significant excess fish mortality. These adverse effects, closely tied to climatic conditions, were particularly pronounced in Walloon fish farms in 2018.

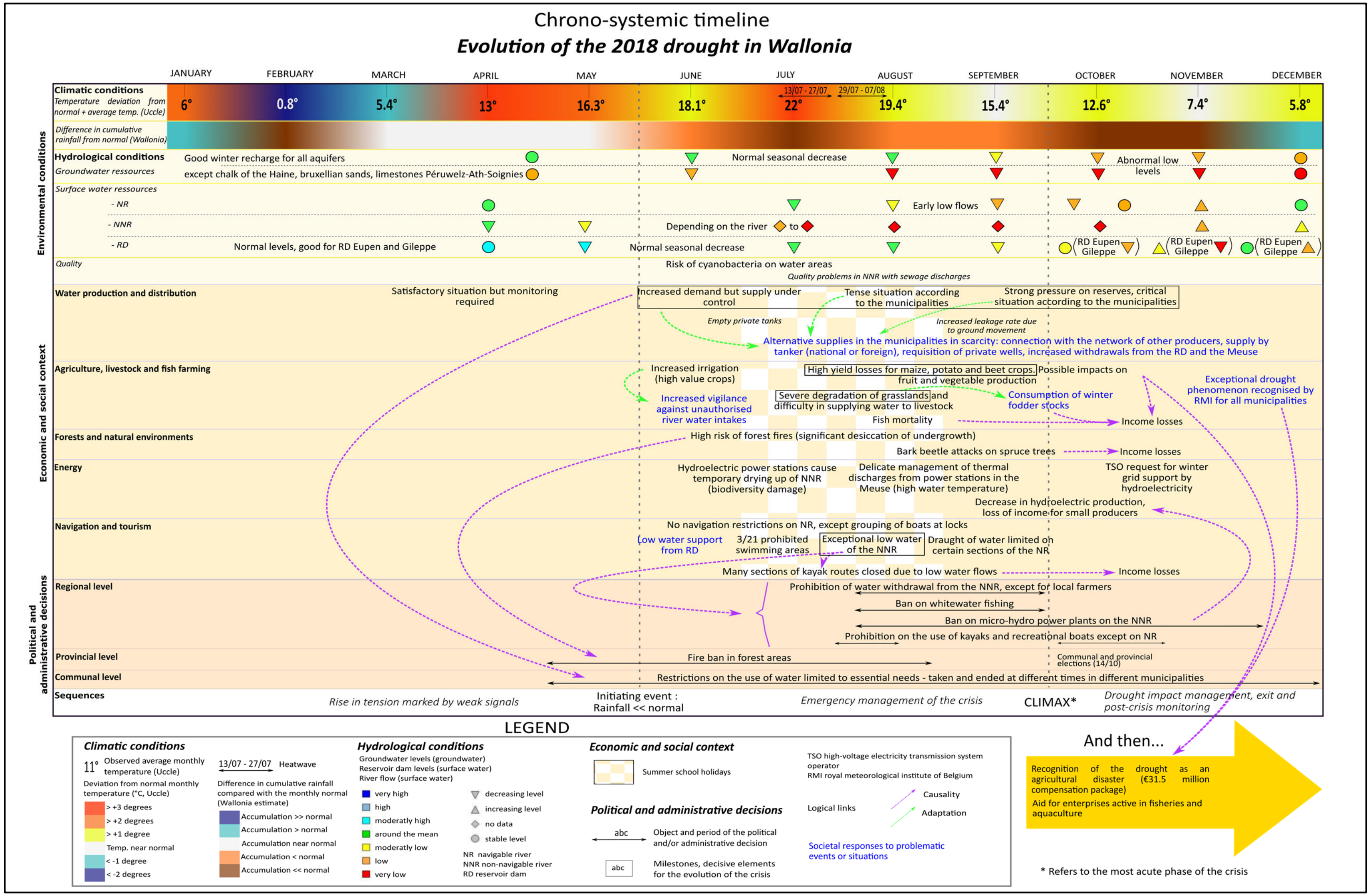

Figure 3. Chrono-systemic timeline of the 2018 drought in Wallonia.

Almost a third of Wallonia's territory, or around 550,000 ha [39], is covered by forest formations. These are of major importance in the Walloon landscape because of their multifunctional nature. In addition to the traditional economic functions, including harvesting and sale of timber, income from hunting, etc., forest ecosystems offer both environmental services (soil and water protection, improved air quality, climate regulation, ecological diversity, etc.), and social services (walks, sporting, and tourist activities, etc.). Yet these ecosystems are sensitive to drought [45,46] and were hit hard by the extreme summer weather of 2018. In addition to the excess mortality and reduced growth observed in many species that are poorly adapted to water deficit and high temperatures, a significant increase in attacks by bark beetles, which is a xylophagous insect of the Coleoptera order, was observed in conifer stands. This parasite requires diseased trees to be felled and the cut wood to be disposed of quickly to avoid further contamination of the stands. The poor quality of the wood and its early felling—often before the end of the development cycle initially planned—result in significant losses of income for forestry operators and associated industries. It should also be noted that, due to the increased risk of fire following the drying out of the forest cover and the outbreak of several forest fires, wooded areas were placed under high surveillance during the summer of 2018, resulting in additional work for the emergency services.

Droughts and heatwaves have an impact on the energy production sector, mainly because surface water that is already heavily used during these meteorological extremes is used in the production process. On the one hand, so-called "run-of-river" hydroelectric power stations, and to a lesser extent, those with a retaining dam, use part of the flow of a river to drive a turbine. These plants are, therefore, dependent on water levels and cannot operate in the event of persistent low water. In 2018, as a result of the severe hydrological drought, many of these power stations were shut down or saw their production capacity reduced. Thermal and nuclear power stations also draw large quantities of surface water to cool their installations. This cooling water is then systematically discharged back into the original environment, resulting in a slight increase in the temperature of the receiving water. This excess thermal discharge can cause significant damage to aquatic ecosystems. During the drought of 2018, the operation of some of these power stations had to be adapted by a slight reduction in production due to the lower flows in the rivers, and to limit the thermal load discharged.

Wallonia has around 450 km of inland waterways and is an important link between France and the Netherlands. Over the past ten years, with the exception of 2020 and 2021 when the coronavirus crisis reduced flows, almost 40 million tons of goods travelled on Wallonia's waterways every year (according to information available on the portal of the Direction Générale Opérationnelle de la Mobilité et des Voies hydrauliques—Service Public de Wallonie (http://voies-hydrauliques.wallonie.be, accessed on 18 February 2022)). However, droughts can have an impact on navigation by reducing river flows. During the dry spell in 2018, boats were grouped together at locks, and, on certain stretches, the draught was limited to reduce water consumption and avoid partial closure of waterways.

Many tourist and leisure activities are regularly compromised when drought strikes. Water-based leisure activities, such as fishing, kayaking, swimming, water-skiing, and tourist boating all require water of sufficient quality and quantity. As these characteristics were not always met during the water shortage of 2018—as was also the case during those of 2017, 2019 and 2020—these activities were regularly forced to stop or were banned. The social and recreational functions of forests were also affected by this drought, as access to forest areas was restricted to reduce the risk of fire. This restriction had significant economic repercussions on the surrounding tourist areas and infrastructures, including shops, accommodation, catering establishments, leisure activities, etc.

3.3. Political and Administrative Decisions

The data concerning environmental conditions and the economic and social context, as presented in the preceding sections, provide the chrono-systemic timeline with the facts, findings, or statements that characterize the core of the Walloon drought of 2018. Nevertheless, the analysis of this event would remain incomplete, and valuable information within the dynamics of the process would be lost, if we did not consider the decisions made by the authorities in response to this crisis. These decisions can either be responses to events or triggers for subsequent events.

Belgium's institutional complexity—a federal state with a federal government that manages national matters and three regions and three communities that act with decentralized powers—means that decision-making is dispersed between these different authorities. Added to this are the provinces and municipalities, which also have prerogatives in a number of areas within their territory. In the context of a drought which, as already mentioned above, has an impact on many different sectors, this organization is not likely to facilitate its management and, therefore, requires increased cooperation between the different levels of authority for greater coherence and efficiency. In the chrono-systemic timeline considering the 2018 drought in Wallonia, the political and administrative decisions (the term "political and administrative decisions" covers decisions taken by both elected representatives (mayor, minister, etc.) and public officials (SPW, provincial governor, etc.)) that were identified come from the regional, provincial, and municipal levels.

At a regional level, the exceptionally low water levels in rivers, mainly non-navigable, forced the authorities to take a number of measures designed to make up for the lack of water and to preserve aquatic ecosystems as far as possible, sometimes to the detriment of other sectors of activity. For example, a ban on taking water from non-navigable rivers—except with specific authorization (from farmers, local residents, etc.)—and a ban on whitewater fishing were imposed during the summer of 2018. Kayaks and other leisure craft were also regularly banned from many stretches of the river. Several bathing lakes were also temporarily closed due to a health risk (presence of cyanobacteria). The energy sector was also forced to shut down its hydroelectric micro power stations for a long period between August and the end of November 2018.

At provincial level, in order to limit the risk of fires, all the provincial governors in Wallonia (Walloon Brabant, Hainaut, Liège, Luxembourg, and Namur) issued a ban on fires in woodland areas from the beginning of May to the end of August.

At a municipal level, many authorities issued orders restricting the use of water to essential requirements, which mainly consisted of guaranteeing the supply of drinking water to citizens, and ensuring uses linked to public safety. According to CRC-W information, between 2017 and 2019, 30 municipalities (11 in the province of Namur, 13 in the province of Luxembourg, and 6 in the province of Liège) took this measure at least once. During the drought of 2018, depending on the degree and timing of the shortage, these restrictions were maintained for periods of a few weeks to a few months. Some municipalities (Nassogne, Rouvroy, and Gouvy) did not lift the restrictions until early 2019. It should be noted that half of the municipalities that issued this order have their own water distribution network and are mainly located in the province of Luxembourg, in an area where available groundwater reserves are low. The municipalities located in the northern part of Wallonia, at the level of the aquifer formations where most of the groundwater is extracted, did not experience any shortages. Nevertheless, some water tables in these intensively exploited areas reached exceptionally low levels during the drought.

To conclude this section on decision-making, it is worth noting that the Walloon regional authorities, in response to the Royal Meteorological Institute of Belgium classifying the 2018 drought as an exceptional phenomenon, officially recognized it as an agricultural disaster [47]. This recognition resulted in the provision of financial aid, amounting to approximately EUR 31.5 million, to farmers impacted by the drought [48]. Furthermore, financial assistance was also extended to professionals in the fishing and fish farming sectors.

3.4. Dynamic Links and Sequencing

Analysis of the chrono-systemic timeline of the Walloon drought of 2018 showed that such a phenomenon impacts a multitude of different sectors, while creating a chain of events and actions that very often connects several sub-systems together. Many causal links (the relationship between a cause and its effects or consequences) as well as adaptive links (the ability to modify a state or process and find alternatives) were highlighted during the drought. The multi-factorial and dynamic nature of this event is clearly evident.

Sequencing also makes it possible to visualize the overall kinetics of the crisis. The Walloon drought of 2018 was subdivided into three successive sequences. The first corresponds to the slow build-up of the drought, marked by weak signals including very low cumulative rainfall in February, which was not offset in the following months, and high temperatures in April and May, which encouraged evapotranspiration. Then came the triggering event, which was a total rainfall level in June well below normal, and which acted as a hinge or trigger for what is known as immediate crisis management. The latter is defined as the period during which most of the impacts of the drought are felt. It continues until a key moment—the climax—which corresponds to the peak of the event in terms of cumulative consequences and which occurred around the second half of September. The most severe period of the 2018 drought in terms of negative impacts can, therefore, be delineated between early June and mid-September. From October onwards, despite a still marked rainfall deficit, the difficulties associated with the drought tended to subside due to lower pressure on water resources and lower temperatures than in the summer. The final phase, which will see the crisis end and the situation managed more calmly, then begins. Nevertheless, the situation remains problematic for certain sectors of activity and certain areas of Wallonia. A return to a more favorable situation, particularly as regards freshwater reserves, whether underground or surface, would not be achieved until 2019, after winter recharge levels were considered to be adequate. It should be noted that this return to a certain normality is relative and that, following the successive droughts of 2017 and 2018, the situation at the start of 2019 for groundwater remained worrying, with levels still relatively low in comparison with previous years.

3.5. Study Limitations

In concluding the analysis of this chrono-systemic timeline, it is important to note that this tool was constructed solely based on information from the CRC-W drought unit and meteorological data from the IRM. While these data are relatively abundant and encompass various sectors of activity, it is essential to acknowledge that the approach to studying this drought remains non-exhaustive. Notably, there is an absence of information regarding the public health sector. Even though heatwaves, with their often significant mortality rates, may appear to be a more prominent concern in our regions than droughts, it is crucial to recognize that droughts are still associated with high temperatures and prolonged sunshine, which can pose potential risks to vulnerable people.

4. Conclusions

In addition to the abnormal environmental conditions that led to this extreme weather event, the feedback from the Walloon drought of 2018, as analyzed using a chrono-systemic timeline, has underscored the following key points: (i) the direct and indirect impacts of a drought are numerous and multi-sectoral, (ii) the dynamics of the drying-up process are slow and generate numerous interconnected aspects between the key events in this process, spanning environmental, socio-economic, and political levels, and (iii) the highlights of a drought episode can be broken down into three sequences, namely a slow build-up, an often long period of major impacts, and a slow return to a so-called normal situation.

The results highlight the high degree of connectivity between the key events and consequences of a drought, suggesting that we should move away from single-sector management—which is still all too often the case—towards management that is decompartmentalized, globalized, and concerted between the stakeholders. This observation is striking when we look at the chrono-systemic timeline (Figure 3). The strength of this tool lies in the fact that it brings together a multiplicity of quantitative and qualitative indicators that enable a cross-sectoral analysis of the phenomenon under study and the possible identification of flaws in the management process. This instrument is useful for "post-crisis" analysis, but it could also be developed as part of a drought impact forecasting system.

The chrono-systemic timeline created here presents a form of crisis management that could be described as reactive. Most of the decisions taken by the authorities were taken when the crisis was already underway, following the identification of major impacts on a particular sector, whether environmental or societal. Moreover, the domino effect of these decisions generated other negative secondary impacts. This management style observed during the Walloon drought of 2018 could be explained, among other things, by a lack of consideration for the potentially catastrophic nature of such a phenomenon, the absence of an overall emergency and intervention plan specific to drought, or the complexity and division of Belgian decision-making power.

In the future, it will be crucial to transition from reactive to anticipatory management, so as to better cope with severe water shortages. This becomes especially relevant because droughts are slow-developing phenomena that exhibit numerous warning signs. Initiatives have already been undertaken at the national or regional level in Belgium to address this risk. Some focus on providing information about the meteorological phenomenon and its consequences, while others aim to manage the phenomenon comprehensively, or mitigate its impact on specific sectors. However, there is a need to take further steps. Integrating the notion of urgency and crisis into the perception of drought, optimizing the organization of prevention, planning and crisis management, introducing alert thresholds with concrete measures, and encouraging adaptation and anticipation are all actions that could prove extremely useful in reducing the scale of the impact of drought episodes, and whose implementation in our latitudes should be studied [28]. This is especially crucial considering the recurrence of such events in recent years and the anticipated increase in the frequency of droughts due to climate change.

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Appendix A

Table A1. List of minutes of meetings of the "drought unit" (CRC-W) used to construct the chrono-systemic timeline of the 2018 drought in Wallonia.

Date of Meeting	Author(s)	Version of the Minutes
19 April 2018	C. Régnier	Version 20/04/18
25 July 2018	P. Racot	Version 04/08/18
6 August 2018	P. Racot et C. Régnier	Version 10/08/18
14 August 2018	P. Racot et C. Régnier	Version 17/08/18
30 August 2018	P. Racot et C. Régnier	Version 03/09/18

Table A1. *Cont.*

Date of Meeting	Author(s)	Version of the Minutes
19 September 2018	C. Régnier	Version 21/09/18
2 October 2018	P. Racot	Version 04/10/18
19 Octobre 2018	C. Régnier	Version 23/10/18
25 October 2018	P. Racot	Version 05/11/18
30 October 2018	C. Régnier et V. Lucas	Version 06/11/18
26 November 2018	V. Lucas	Version 30/11/18
14 November 2018	V. Lucas	Version 14/12/18

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