The Strategy of Horizons: Underinvestment in Municipal Water Networks During Sum mer Droughts.

David Crommelynck[1] Alexandre Mayol[2] Simon Porcher[3] Stéphane Saussier[4]

March 15, 2026

[1]BETA, Université de Lorraine
[2]LEM, Université de Lille
[3]Université Paris Dauphine–PSL
[4]IAE de Paris, Université Paris 1 Panthéon-Sorbonne

Abstract

Climate change is increasing the frequency and severity of drought episodes, raising new challenges for drinking water services. While the physical determinants of drought have been widely studied, less is known about how water service management affects the ability of local systems to cope with climatic stress. This paper examines how management choices interact with drought conditions to shape the implementation of water-use restrictions in France.

We assemble a panel dataset combining municipal-level drought restriction records (2013–2024), meteorological drought indicators based on the Standardized Precipitation–Evapotranspiration Index (SPEI), and information on water service management from the SISPEA database. Using fixed-effects panel models and spline specifications, we analyze how drought intensity translates into restriction days and how this relationship varies with water tariffs and network leakage.

Across specifications, municipalities with higher tariffs and lower leakage rates tend to experience fewer restriction days and different responses to drought intensity. The results consistently suggest that pricing policies and infrastructure management are closely linked to the resilience of local water systems to drought conditions.

Keywords: drought; water utilities; resilience; tariffs; leakage; panel data; France
JEL codes: L95; Q25; Q54; H41

1 Introduction

In south Europe, the summers of 2022 and 2023 marked a turning point for water services in France. Unprecedented drought conditions led to widespread restrictions on water use, affecting thousands of municipalities (Tripathy and Mishra, 2023). In several french rural areas, drinking water had to be supplied by tanker trucks as local sources became temporarily unavailable (Bertrand et al., 2023). These emergency measures, once considered exceptional, have become emblematic of a new hydrological regime in which water scarcity is no longer a peripheral risk but a central operational constraint for local utilities.

Climate projections suggest that such episodes are likely to become more frequent and more intense in Southern and Western Europe (Böhnisch et al., 2025). Rising temperatures increase evapotranspiration, while precipitation patterns are becoming more volatile and seasonally concentrated. As a result, droughts are expected to combine longer duration with higher intensity, placing increasing pressure on surface and groundwater resources (Kundzewicz et al., 2006). For water utilities, this implies that extreme scarcity events may no longer be rare shocks but recurring stress tests.

Importantly, climatic stress does not operate in isolation. Anthropogenic pressures on ecosystems (soil artificialization, wetland destruction, deforestation, and intensive agriculture) reduce the capacity of landscapes to retain and gradually release water. Impermeable surfaces accelerate runoff and limit aquifer recharge (Blanchy et al., 2023; McDermid et al., 2022; Tóth et al., 2022). The cumulative effect is a reduction in natural buffering capacity: identical rainfall deficits now translate into stronger hydrological scarcity. In this context, droughts are not purely meteorological phenomena but the outcome of interactions between climate dynamics and long-term land-use patterns.

This evolving context is particularly challenging in countries where water infrastructure was historically developed under the paradigm of abundance (Barraqué et al., 2008). In many European regions, policy choices have not kept pace with the increasing frequency and severity of drought events. Water prices often remain below scarcity-reflective levels, thereby limiting their capacity to curb demand and reduce pressure on the resource Wheeler et al. (2025). At the same time, infrastructure renewal rates remain insufficient relative to asset depreciation, reflecting persistent underinvestment that undermines network efficiency and long-term resilience (Salvetti, 2023). Governance arrangements may further constrain effective adaptation: excessive local fragmentation and coordination failures can weaken both quantitative management and water quality outcomes (Guelmamen et al., 2025; Kim et al., 2015). Taken together, these structural features suggest a growing mismatch between hydrological realities and institutional responses.

From a theoretical perspective, such dynamics can be understood through two complementary mechanisms. First, public infrastructure investment is subject to intertemporal and political economy constraints. The benefits of network renewal typically materialize over long time horizons, often extending beyond the electoral cycles of local decision-makers. At the same time, water infrastructure is largely financed through user tariffs, and increases in water prices tend to be politically unpopular. As a result, local politicians may face incentives to prioritize short-term affordability over long-term system resilience, leading to systematic underinvestment in maintenance and renewal (Mullin and Hansen, 2023). Second, preventive investments in water infrastructure generate benefits that become particularly valuable under conditions of water scarcity, but may appear less necessary during periods of resource abundance. However, meteorological conditions are inherently uncertain. In this context, the theory of investment under uncertainty suggests that decision-makers may optimally delay irreversible investments when future states of the world are uncertain (Adey et al., 2021; Huberts et al., 2015; Pindyck, 1990). Together, these mechanisms can lead to structurally low renewal rates and persistent leakage levels in water distribution networks.

France provides a particularly illustrative case. The average renewal rate of drinking water networks implies a full replacement cycle of approximately 150 years. Leakage rates are estimated at around 20% of distributed volumes, with substantial heterogeneity across municipalities (Perrot et al., 2026). Such structural inefficiencies and low investment levels are not necessarily problematic for the provision of drinking water under conditions of resource abundance.. However, during drought episodes, they may amplify vulnerability by increasing pressure on already constrained resources. In this sense, the observed severity of recent water use restrictions may partly reflect not only meteorological shocks but also accumulated management choices.

Recent research has increasingly focused on the tools that water service managers can mobilize to improve the capacity of water networks to withstand drought conditions and continue providing safe water in contexts of increasing resource scarcity (Edwards et al., 2024). Among these contributions, several studies emphasize the role of infrastructure investment and management decisions in strengthening the resilience of water services (Cassottana et al., 2023; Pot, 2023). In particular, reducing non-revenue water—defined as water losses that are not billed to users, often due to leaks in distribution networks—can help make water systems more resilient (Serafeim et al., 2024). Such reductions can be achieved through management contracts based on operator performance incentives (Kingdom et al., 2018). Infrastructure investments can also improve resilience by increasing interconnections between supply basins, thereby enhancing the overall flexibility of water systems (Murgatroyd and Hall, 2020). More broadly, investments may support the development of more ecological and intelligent infrastructure systems (Fu et al., 2023; Schifman et al., 2017), the diversification of water supply sources, or the expansion of storage capacity (Hoekstra et al., 2018; Larsen et al., 2016).

Beyond investments in infrastructures, other economic instruments can also play an important role in strengthening the resilience of water systems. In particular, water pricing policies can encourage more efficient water use and reduce pressure on water resources during periods of scarcity (Maas

et al., 2024; Olmstead and Stavins, 2007). Well-designed pricing schemes may therefore contribute to demand management and improve the capacity of water systems to cope with drought conditions (Grafton et al., 2020). Other forms of management may also enhance resilience, including education and capacity-building for water service operators (Khedun et al., 2025) and more efficient approaches to water governance (Dai et al., 2018; Folke, 2016; Johannessen and Wamsler, 2017; Lund and Medellín-Azuara, 2018).
Overall, studies addressing drought resilience frequently call for increased investment in aging water infrastructure and improved management practices. However, to our knowledge, relatively few empirical studies measure how these management and investment decisions affect the ability of water networks to maintain normal supply conditions without restrictions during drought events.
This paper contributes to the literature by analyzing how local management decisions affect the resilience of drinking water services to meteorological drought shocks. We define resilience as the capacity of a local water service to maintain normal supply conditions (i.e., to limit the number and severity of usage restrictions) when exposed to drought (Cubillo and Martínez-Codina, 2019; Johannessen and Wamsler, 2017). In this context, we examine how water utility decisions, such as pricing strategies or efforts to reduce leakage, affect the number of days during which water use restrictions are implemented to maintain service provision, for a given level of meteorological shock.

Our empirical strategy exploits annual panel data at the municipal level over the period 2013–2024. We combine three sources of information. First, meteorological conditions are measured using the Standardized Precipitation-Evapotranspiration Index (SPEI), which captures both precipitation deficits and temperature-driven evapotranspiration. We focus primarily on six-month horizon indicators that integrate both intensity and persistence of drought episodes. Second, we use administrative data on water service management drawn from the SISPEA database, including tariff levels and network leakage rates. Third, we compile detailed information on drought-related usage restrictions, measured as the annual number of days spent under different levels of regulatory constraint.

Using fixed-effects panel models with municipality and year effects, we estimate the impact of drought intensity on the number of restriction days, and we examine how this effect interacts with management proxies. By distinguishing between baseline (pre-period) variables and contemporaneous lagged indicators, we aim to separate structural heterogeneity from potential adaptive responses. Additional specifications explore non-linearities through spline interactions applied to both management indicators and drought intensity, allowing for heterogeneous marginal effects across different segments of their respective distributions.

By focusing on realized service restrictions rather than solely on physical water availability, our approach captures the operational dimension of resilience: the extent to which infrastructure and management choices translate climatic stress into user-level constraints. In doing so, the paper provides new empirical evidence on the economic determinants of infrastructure resilience in the water sector.

Across specifications, our results reveal a consistent pattern. For comparable meteorological conditions, municipalities characterized by higher water tariffs and lower leakage rates tend to experience fewer days under drought-related restrictions. These patterns suggest that both pricing policies and infrastructure management are associated with a greater capacity of water services to cope with drought shocks.

The remainder of the paper is organized as follows. Section 2 first describes the institutional framework governing drought management in France and presents the different data sources used in the analysis, including meteorological indicators, water service management variables, and administrative records of usage restrictions. It then outlines the empirical strategy and explains how fixed-effects panel models and spline specifications are used to analyze the relationship between drought intensity, management choices, and restriction days. Section 3 presents the main empirical results and explores heterogeneous and non-linear responses across different segments of drought intensity and management variables. Section 4 discusses the interpretation of the findings.

2 Data and Methods

2.1 Drought restriction data

Information on drought-related water use restrictions is obtained from the administrative database of drought decrees (*arrêtés sécheresse*) available on the Vigieau website[1]. This platform, developed by the French government, provides daily maps of restriction perimeters for all drought decrees issued since 2013. These decrees constitute the main regulatory instrument used by public authorities to manage water scarcity during drought episodes.

In France, drought management follows a regulatory framework defined at the national level but implemented at the departmental level. When hydrological conditions deteriorate, the Departmental Directorates of Territories (DDT) are responsible for monitoring water resources and assessing the need for regulatory measures. Based on this assessment, the DDT may request that the prefect issue a drought decree imposing restrictions on water uses.

While the prefect formally signs the decree, the decision-making process typically involves consultations with multiple stakeholders through departmental "drought cells" (*cellules sécheresse*). The composition of these drought cells varies across departments, and in some cases the decision may be taken directly by the DDT without extensive consultation.

Importantly, the implementation of drought restrictions does not rely on a single threshold indicator. Instead, decisions are based on the joint evaluation of multiple hydrological indicators, including river flows, groundwater levels, soil moisture conditions, and meteorological forecasts (Mazzega

---

[1] `https://vigieau.gouv.fr/`

et al., 2014). As a result, the timing and intensity of restrictions may vary across departments even under similar hydrological conditions.

The regulatory framework distinguishes four levels of restrictions, each associated with progressively stronger limitations on water uses. Table 1 summarizes the main characteristics of these levels and provides examples of typical measures based on Ministère de la Transition Écologique (2022).

Table 1: Examples of drought restrictions by level, based on Ministère de la Transition Écologique (2022)

Usage	Vigilance	Alert	Reinforced alert	Crisis
Garden watering	No formal restriction; public awareness campaigns encouraging water savings	Prohibited between 11am and 6pm	Prohibited between 9am and 8pm	Prohibited between 9am and 8pm
Facade cleaning	No formal restriction	Prohibited for private individuals	Prohibited for private individuals	Prohibited for all users (except sanitary reasons)
Sprinkler Irrigation	No formal restriction	Prohibited between 11am and 6pm	Prohibited between 9am and 8pm	Prohibited

In practice, drought restrictions are implemented progressively as hydrological conditions deteriorate. Municipalities may therefore experience sequences of increasingly stringent restrictions during the same drought episode.

To capture these dynamics, we process the Vigieau daily maps to construct annual indicators measuring the number of days during which each municipality is subject to drought restrictions. Because restriction levels are hierarchical, the variables we construct systematically incorporate more stringent levels of regulation.

More precisely, we construct four measures of restriction exposure. The first variable measures the total number of days during which a municipality is subject to any drought decree, regardless of the restriction level. The second variable measures the number of days under alert, reinforced alert, or crisis levels. The third variable captures the number of days under reinforced alert or crisis conditions. Finally, the most restrictive indicator measures the number of days under crisis-level restrictions.

Unlike purely hydrological indicators, these administrative data capture the operational response of water management authorities to scarcity conditions and therefore provide a direct measure of the extent to which drought conditions translate into effective constraints on water users.

2.2 Measuring meteorological drought: SPEI indicators

Meteorological drought conditions are measured using the Standardized Precipitation-Evapotranspiration Index (SPEI). The SPEI combines precipitation deficits with temperature-driven evapotranspiration, thereby capturing both water supply and atmospheric demand (Vicente-Serrano et al., 2010). The index is constructed from the climatic water balance (precipitation minus potential evapotranspiration) and is subsequently standardized, allowing comparisons across locations and time periods. By construction, negative values of the SPEI indicate drier-than-normal conditions (meteorological drought), while positive values correspond to wetter-than-normal conditions.

Unlike precipitation-only indicators, SPEI explicitly accounts for the effect of temperature on water balance. This feature is particularly important in the context of climate change, as rising temperatures increase evapotranspiration and amplify drought intensity.

A key feature of the SPEI is that it can be computed over different temporal horizons, typically ranging from 1 to 24 months. Short horizons capture short-term meteorological variability, while longer horizons reflect cumulative hydrological stress affecting groundwater or reservoirs.

In this paper, we focus primarily on the six-month horizon SPEI (SPEI-6). This horizon provides a suitable compromise between short-term variability and medium-term hydrological persistence. The SPEI data are obtained from the Copernicus European Drought Observatory.[2] The dataset provides monthly maps of the SPEI at different accumulation horizons. In this article, we retain the six-month horizon.[3]

The Copernicus data are provided on a regular grid of 10×10 kms. Each map reports the SPEI value for the first day of each month. To construct municipal-level indicators, we spatially aggregate the grid values to municipalities by computing the area-weighted average of the SPEI across all pixels intersecting each municipality, where weights correspond to the share of each pixel's surface lying within the municipal boundaries.

Drought conditions are inherently multidimensional. Their impacts depend not only on the magnitude of precipitation deficits but also on their duration and cumulative effects over time. To capture these different dimensions, we construct an indicator derived from monthly values of the Standardized Precipitation–Evapotranspiration Index (SPEI).

---

[2] `https://drought.emergency.copernicus.eu/`

[3] Models estimated using the twelve-month horizon (SPEI-12) yield very similar results.

Specifically, we measure drought conditions using the cumulative magnitude of negative SPEI values within each year:

$$AreaNeg_{it} = \sum_{m \in t} |SPEI_{im}| \cdot \mathbf{1}(SPEI_{im} < 0) \tag{1}$$

where $SPEI_{im}$ denotes the monthly SPEI observed in municipality i during month m. The indicator therefore accumulates the absolute value of SPEI whenever it is negative.

This measure captures both the intensity and the persistence of drought conditions. A severe drought episode will generate large negative SPEI values, while a prolonged period of moderate deficits will also increase the cumulative area. As a result, the indicator reflects the overall severity of drought conditions experienced during the year.

2.3 Water service management indicators

To analyze how local management decisions affect drought resilience, we rely on administrative data from the SISPEA database (*Observatoire national des services d'eau et assainissementt*)[4]. This database provides detailed information on the organization and performance of water services in France.

We focus on two variables capturing key aspects of water service management: water tariffs and network leakage rates.

Water tariffs Our main management variable is the price of drinking water, measured as the tariff paid by households for an annual consumption of 120 m^3. This indicator corresponds to the standard reference consumption commonly used in the analysis of water tariffs and allows for consistent comparisons across municipalities.

In the French institutional context, tariffs play a central role in financing water services. Under the widely applied principle that "water pays for water", operating and investment costs must largely be covered through user charges.

Tariff levels therefore provide information on several underlying mechanisms. First, higher tariffs may reflect greater investment capacity, as higher revenues allow utilities to finance infrastructure renewal and maintenance. Second, pricing policies can serve as demand-management instruments by encouraging more efficient water use during periods of scarcity. Finally, tariff levels may also reflect the ability of local decision-makers to resist political pressures for maintaining artificially low water prices.

Tariff data are available at the municipal level in the SISPEA database, although coverage is incomplete for some municipalities and years.

---

[4] https://www.services.eaufrance.fr/pro/telechargement

Network leakage Our second management indicator is the rate of water losses in distribution networks, commonly referred to as non-revenue water.
Leakage rates capture the share of treated water that is lost before reaching final consumers, typically due to pipe deterioration or network inefficiencies. High leakage levels often reflect insufficient investment in network renewal, whereas reductions in leakage generally require sustained maintenance efforts and capital expenditures.

Leakage data are reported at the service level rather than the municipal level. Because many services operate across multiple municipalities, we restrict the analysis to services operating at the municipal scale in order to maintain a consistent mapping between management indicators and local drought outcomes.

2.4 Empirical strategy

Our empirical analysis relies on a municipality-level panel dataset covering the period 2013–2024. We estimate fixed-effects panel models of the following form:

$$Restrict_{it} = \beta Drought_{it} + \gamma Management_{it-1} + \delta(Drought_{it} \times Management_{it-1}) + \alpha_i + \lambda_t + \varepsilon_{it} \quad (2)$$

where $Restrict_{it}$ is the number of restriction days in municipality i in year t, $Drought_{it}$ represents one of the SPEI-based drought indicators, and $Management_{it}$ denotes water management variables such as tariffs or leakage rates. The terms α_i and λ_t denote municipality and year fixed effects respectively.

Municipality fixed effects control for time-invariant characteristics that may influence both water management and drought vulnerability, including hydrogeological conditions, infrastructure characteristics, or institutional arrangements. Year fixed effects capture nationwide shocks affecting all municipalities simultaneously.

A potential concern with this specification is reverse causality. Municipalities experiencing severe drought restrictions may respond by increasing water tariffs or accelerating infrastructure investments in subsequent years. In such cases, part of the estimated relationship between management variables and restriction outcomes may reflect adaptation responses rather than causal effects.

To better capture structural differences in management strategies, we therefore construct a baseline management indicator defined as the water price (or leakage rate) observed in the first available year (2013 or 2014 depending on data availability). We then estimate models interacting this baseline price with drought indicators:

$$Restrict_{it} = \beta Drought_{it} + \delta(Drought_{it} \times Management_i^{baseline}) + \alpha_i + \lambda_t + \varepsilon_{it} \quad (3)$$

Because baseline management variables are constant within municipalities, their direct effect is absorbed by municipality fixed effects. As a result, the model identifies only the interaction between baseline management strategies and drought intensity.

This specification allows us to examine how pre-existing management characteristics shape the response of administrative water-use restrictions to meteorological drought conditions, measured by the SPEI, while controlling for all time-invariant structural characteristics of municipalities through fixed effects. However, the estimated interaction coefficient should not be interpreted purely as the causal effect of pricing or investments strategies. Although structural characteristics are controlled for in levels, they may still interact with drought intensity. Consequently, the coefficient may also capture the influence of other time-invariant structural features that are correlated with baseline strategies and that themselves affect how municipalities translate meteorological drought into administrative restrictions.

Finally, to allow for potential non-linearities, we estimate two sets of specifications using linear spline functions. In the first set, spline functions are applied to the management variables in order to allow their marginal effect to vary across different segments of the management distribution. In the second set, spline functions are applied to the drought indicator in order to capture potential non-linear responses of administrative restrictions to drought intensity.

Let $S(x)$ denote a spline transformation of variable x with K segments defined by quantile-based knots.
When splines are applied to management variables, the specification becomes:

$$Restrict_{it} = \beta Drought_{it} + \gamma S(Management_{it-1}) + \delta Drought_{it} \times S(Management_{it-1}) + \alpha_i + \lambda_t + \varepsilon_{it} \tag{4}$$

This specification allows the response of restrictions to drought intensity to vary across different segments of the management distribution.

Alternatively, when splines are applied to the drought indicator, the specification becomes:

$$Restrict_{it} = \beta S(Drought_{it}) + \gamma Management_{it-1} + \delta S(Drought_{it}) \times Management_{it-1} + \alpha_i + \lambda_t + \varepsilon_{it} \tag{5}$$

In this case, the marginal effect of drought on restrictions is allowed to vary across different ranges of drought intensity, making it possible to examine whether management characteristics play different roles during moderate versus extreme drought conditions.

3 Results

3.1 Specification with lagged indicators

Table 2 and Table 3 report the baseline estimates of equation (4), which relates the number of drought restriction days to meteorological drought conditions and water service management variables. In these specifications, drought intensity is measured using the cumulative negative SPEI indicator ($AreaNeg_{it}$), and management variables correspond to lagged tariff levels or leakage rates.

Across all specifications, meteorological drought is strongly associated with an increase in the number of restriction days. Municipalities experiencing more severe or persistent drought conditions systematically implement more regulatory restrictions on water uses. This result confirms that the administrative measures recorded in the drought decree database respond closely to underlying climatic stress.

The management variables themselves display relationships with restriction outcomes. In particular, higher water tariffs are associated with fewer restriction days on average. This negative coefficient suggests that pricing policies may contribute to reducing pressure on water resources, either by encouraging more efficient water consumption or by providing utilities with greater financial capacity to maintain infrastructure and secure supply. A similar pattern emerges for network leakage: municipalities with higher leakage rates tend to experience more crisis restriction days, consistent with the idea that inefficient networks amplify vulnerability during periods of water scarcity. However, in specifications that include less restrictive decrees (particularly vigilance and alert levels) the coefficient becomes negative, suggesting the opposite pattern. This result, however, remains marginally significant, with p-values between 0.05 and 0.10.

A key feature of the baseline specification is the interaction between drought intensity and management variables. For the tariff variable, the interaction term is positive: the marginal effect of drought on restrictions becomes larger as prices increase. At first glance, this result may appear counterintuitive. If higher tariffs improve resilience by moderating demand, one might expect the sensitivity of restrictions to drought conditions to be lower in municipalities with higher prices.

Several mechanisms may explain this pattern. One possibility is a "catch-up effect". Municipalities with higher prices tend to experience fewer restriction days under moderate drought conditions. However, when drought intensity becomes sufficiently severe, restrictions become unavoidable across all municipalities. In this situation, the difference between high-price and low-price municipalities narrows, mechanically producing a steeper relationship between drought intensity and restrictions in the high-price group. A similar mechanism may also help explain the interaction observed between SPEI indicators and network leakage rates in the specifications focusing on crisis-level decrees.

Table 2: Lagged management indicators specification: drought and water tariffs

	(1) crise	(2) niv12	(3) all_niv123	(4) niv1234
spei6_area_neg	0.995***	2.941***	4.971***	3.408***
	(0.104)	(0.125)	(0.149)	(0.155)
L_price	-3.221***	-4.164***	-2.924***	-6.633***
	(0.251)	(0.356)	(0.399)	(0.529)
spei6_area_neg × L_price	0.870***	0.839***	0.807***	1.224***
	(0.043)	(0.050)	(0.061)	(0.063)
ln_pop	-0.477	4.031***	7.893***	-1.064
	(1.016)	(1.336)	(1.544)	(1.780)
annee=2014	0.000	0.000	0.000	0.000
	(.)	(.)	(.)	(.)
annee=2015	-3.492***	-3.663***	6.004***	12.558***
	(0.252)	(0.303)	(0.376)	(0.424)
annee=2016	-0.576***	-1.168***	-4.776***	1.912***
	(0.192)	(0.230)	(0.288)	(0.342)
annee=2017	-0.405	4.456***	30.157***	61.244***
	(0.449)	(0.518)	(0.594)	(0.696)
annee=2018	-1.342***	5.684***	9.457***	25.168***
	(0.283)	(0.337)	(0.423)	(0.510)
annee=2019	8.397***	22.325***	38.899***	67.870***
	(0.353)	(0.422)	(0.484)	(0.583)
annee=2020	7.165***	19.630***	27.593***	58.866***
	(0.238)	(0.311)	(0.394)	(0.479)
annee=2021	4.435***	7.273***	8.251***	29.750***
	(0.157)	(0.213)	(0.284)	(0.407)
annee=2022	24.975***	47.308***	65.043***	103.875***
	(0.363)	(0.404)	(0.445)	(0.503)
annee=2023	22.410***	47.407***	75.654***	148.066***
	(0.247)	(0.383)	(0.453)	(0.531)
annee=2024	7.579***	10.812***	10.965***	21.280***
	(0.259)	(0.334)	(0.379)	(0.467)
Constant	8.955	-16.236*	-38.900***	32.309***
	(6.474)	(8.530)	(9.858)	(11.386)
Observations	303 053	303 053	303 053	303 053
R^2 within	0.2215	0.3445	0.4478	0.5258

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 3: Lagged management indicators specification: drought and network leakage

	(1) crise	(2) niv12	(3) all_niv123	(4) niv1234
spei6_area_neg	3.568***	5.873***	6.659***	5.370***
	(0.173)	(0.200)	(0.209)	(0.243)
L_perte	0.227**	0.023	-0.196*	-0.249*
	(0.091)	(0.108)	(0.117)	(0.143)
spei6_area_neg × L_perte	-0.040***	-0.014	0.033*	0.030
	(0.014)	(0.017)	(0.017)	(0.020)
ln_pop	0.130	5.185	15.076**	9.959
	(4.766)	(5.594)	(6.583)	(7.150)
annee=2014	0.000	0.000	0.000	0.000
	(.)	(.)	(.)	(.)
annee=2015	-7.970***	-9.880***	6.304***	13.505***
	(0.822)	(0.999)	(1.224)	(1.461)
annee=2016	-4.089***	-5.602***	-7.721***	-0.926
	(0.553)	(0.692)	(0.830)	(1.068)
annee=2017	-13.215***	-12.361***	17.168***	47.767***
	(1.394)	(1.644)	(1.849)	(2.243)
annee=2018	-3.715***	5.180***	13.098***	32.493***
	(1.007)	(1.219)	(1.400)	(1.906)
annee=2019	0.588	16.892***	35.886***	68.056***
	(1.163)	(1.394)	(1.588)	(1.784)
annee=2020	5.477***	18.067***	27.053***	55.764***
	(0.786)	(1.008)	(1.184)	(1.530)
annee=2021	-0.289	0.138	-1.483	21.485***
	(0.486)	(0.717)	(0.926)	(1.290)
annee=2022	17.175***	40.632***	62.384***	101.872***
	(1.209)	(1.358)	(1.374)	(1.708)
annee=2023	22.557***	48.043***	79.714***	139.769***
	(0.829)	(1.185)	(1.461)	(1.634)
annee=2024	11.816***	12.140***	11.474***	20.243***
	(1.170)	(1.338)	(1.526)	(1.762)
Constant	-3.708	-34.230	-90.244**	-45.871
	(31.010)	(36.389)	(42.815)	(46.506)
Observations	32 609	32 609	32 609	32 609
R^2 within	0.1937	0.3633	0.4459	0.4846

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

An alternative interpretation relates to *reactivity.* Municipalities with higher tariffs may also have more proactive or responsive water management practices. In such cases, higher prices could reflect governance arrangements in which authorities react more rapidly to deteriorating hydrological conditions by implementing restrictions earlier in the drought cycle. Under this interpretation, the positive interaction term would reflect a more responsive regulatory strategy rather than greater vulnerability.

Distinguishing empirically between these two mechanisms is not straightforward, and the baseline specification does not allow a definitive interpretation.

3.2 Limits to causal interpretation

A central challenge in interpreting these results concerns potential reverse causality between drought outcomes and management decisions. In particular, water tariffs may adjust in response to past drought episodes. Municipalities that experience frequent or severe restrictions may react by increasing tariffs in subsequent years in order to finance investments, reduce demand, or improve network management.

In a fixed-effects framework, this type of dynamic adjustment can generate a mechanical bias. If drought restrictions in year t lead municipalities to increase tariffs in year $t+1$, then periods with many restriction days tend to be preceded by relatively low tariffs compared with the municipality's long-run average price. Because the fixed-effects estimator effectively relies on deviations from the within-municipality mean, the lagged tariff variable $Price_{it-1}$ may therefore appear artificially low in years with severe restrictions. In such a setting, the estimated relationship between tariffs and restriction outcomes may partly capture these adaptive responses rather than the causal effect of pricing policies on resilience.

For this reason, the coefficients obtained from the baseline model should be interpreted cautiously. They capture correlations between management indicators and drought outcomes, but these correlations may reflect both structural management strategies and reactive adjustments to past drought conditions.

3.3 Baseline management indicators

To mitigate this concern, we estimate alternative specifications using baseline management indicators. These variables correspond to the tariff level or leakage rate observed in the first available year of the dataset. Because they are fixed over time within municipalities, their direct effects are absorbed by municipality fixed effects. The specification therefore identifies only the interaction between baseline management characteristics and drought intensity.

Table 4: Baseline tariffs and drought interaction

	(1) crise	(2) niv12	(3) niv123	(4) niv1234
spei6_area_neg × baseprice	1.230***	1.992***	2.819***	2.610***
	(0.024)	(0.032)	(0.043)	(0.042)
ln_pop	-0.982	3.819***	7.895***	1.627
	(0.974)	(1.311)	(1.495)	(1.706)
annee=2013	0.000	0.000	0.000	0.000
	(.)	(.)	(.)	(.)
annee=2014	-2.260***	-3.411***	-0.551***	3.291***
	(0.100)	(0.140)	(0.207)	(0.283)
annee=2015	-4.773***	-5.241***	7.357***	16.513***
	(0.263)	(0.361)	(0.493)	(0.503)
annee=2016	-2.264***	-3.206***	-4.357***	4.557***
	(0.189)	(0.247)	(0.328)	(0.367)
annee=2017	-0.777*	4.555***	33.903***	66.842***
	(0.471)	(0.624)	(0.804)	(0.850)
annee=2018	-2.584***	4.487***	11.743***	29.502***
	(0.292)	(0.409)	(0.557)	(0.609)
annee=2019	8.261***	22.497***	43.229***	73.525***
	(0.373)	(0.512)	(0.657)	(0.716)
annee=2020	5.288***	17.839***	28.743***	62.901***
	(0.242)	(0.342)	(0.468)	(0.542)
annee=2021	1.905***	4.308***	7.944***	31.862***
	(0.142)	(0.179)	(0.241)	(0.403)
annee=2022	25.085***	46.951***	67.782***	109.637***
	(0.385)	(0.489)	(0.610)	(0.633)
annee=2023	20.456***	44.495***	74.063***	148.201***
	(0.244)	(0.393)	(0.475)	(0.543)
annee=2024	3.830***	6.055***	8.621***	19.236***
	(0.221)	(0.283)	(0.324)	(0.412)
Constant	7.772	-20.722**	-44.298***	-0.904
	(6.238)	(8.401)	(9.585)	(10.941)
Observations	300 593	300 593	300 593	300 593
R^2 within	0.2280	0.3496	0.4566	0.5445

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 5: Baseline leakage and drought interaction

	(1) crise	(2) niv12	(3) niv123	(4) niv1234
spei6_area_neg × baseperte	0.128***	0.278***	0.358***	0.308***
	(0.017)	(0.023)	(0.027)	(0.026)
ln_pop	-2.610	2.917	10.285**	6.489
	(3.132)	(4.506)	(5.107)	(5.566)
annee=2013	0.000	0.000	0.000	0.000
	(.)	(.)	(.)	(.)
annee=2014	-2.384***	-3.549***	0.928	8.309***
	(0.280)	(0.367)	(0.598)	(0.854)
annee=2015	2.008***	6.693***	30.298***	40.186***
	(0.464)	(0.657)	(0.916)	(1.023)
annee=2016	0.298	2.529***	5.845***	16.328***
	(0.341)	(0.465)	(0.607)	(0.857)
annee=2017	6.485***	19.929***	60.363***	90.845***
	(0.854)	(1.167)	(1.448)	(1.653)
annee=2018	8.593***	26.935***	42.445***	61.658***
	(0.639)	(0.931)	(1.177)	(1.387)
annee=2019	14.777***	40.210***	69.436***	101.062***
	(0.829)	(1.031)	(1.202)	(1.403)
annee=2020	11.015***	30.408***	44.426***	78.977***
	(0.581)	(0.817)	(0.998)	(1.327)
annee=2021	-0.327	3.054***	6.979***	36.768***
	(0.313)	(0.441)	(0.611)	(1.125)
annee=2022	33.563***	66.011***	94.159***	135.710***
	(0.836)	(1.040)	(1.156)	(1.290)
annee=2023	26.707***	57.377***	93.562***	162.063***
	(0.800)	(1.189)	(1.354)	(1.417)
annee=2024	6.810***	9.839***	12.762***	27.267***
	(0.827)	(0.962)	(1.113)	(1.324)
Constant	19.995	-15.881	-62.819*	-33.567
	(21.397)	(30.800)	(34.914)	(38.057)
Observations	39 681	39 681	39 681	39 681
R^2 within	0.1645	0.3183	0.4172	0.5074

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

The results obtained with baseline management variables display a similar pattern to the baseline specifications regarding the effects of tariffs. The interaction between drought intensity and baseline tariffs remains positive and statistically significant. However, because the level effect of baseline tariffs is absorbed by municipality fixed effects, this specification does not allow us to determine whether municipalities with higher initial tariffs experience fewer restriction days on average. As a result, we cannot distinguish whether the estimated interaction reflects a catch-up effect (where higher baseline prices are associated with fewer restrictions under moderate drought conditions) or a greater responsiveness of municipalities with more proactive water management practices.

Importantly, because baseline management variables are time invariant, their level effect is absorbed by municipality fixed effects. As a consequence, these models identify only whether municipalities with different initial management strategies respond differently to meteorological drought shocks, but not whether they differ in their average level of restrictions.

In contrast, the results are more unambiguous for network leakage. Across all restriction levels, the interaction between drought intensity and leakage rates is positive and strongly significant. This suggests that structurally poorer network management (reflected in higher baseline leakage) directly weakens municipal resilience to drought conditions. Municipalities with higher leakage rates tend to react more quickly to deteriorating climatic conditions by implementing restrictions, consistent with the idea that water losses increase pressure on already constrained resources.

Nevertheless, the interpretation remains complex. Although municipality fixed effects control for time-invariant structural characteristics in levels, they do not account for the possibility that these characteristics interact with meteorological conditions. If certain structural features (such as hydrogeological constraints, the availability of alternative water sources, or long-run water scarcity) affect how municipalities respond to drought shocks, their interaction with drought intensity may still influence the estimated coefficients. In such cases, baseline management variables may partly capture these interactions when they are correlated with underlying structural factors. For instance, municipalities with historically higher tariffs may also be located in areas with structurally tighter water resources or more fragile hydrological systems. The interaction between drought intensity and baseline tariffs may therefore reflect not only differences in management practices but also the influence of structural conditions that amplify the impact of drought.

3.4 Spline specifications on management variables

To further investigate these mechanisms, we estimate specifications in which management variables are modeled using linear spline transformations. This approach allows the marginal effect of management indicators to vary across different segments of their distribution.

Table 6: Spline specification on lagged tariffs

	(1) crise	(2) niv12	(3) niv123	(4) niv1234
spei6_area_neg	2.757***	4.805***	6.397***	6.387***
	(0.064)	(0.075)	(0.081)	(0.090)
L_price: (.,-.1)	-1.583*	-4.990***	-4.909***	-6.790***
	(0.837)	(1.030)	(1.105)	(1.387)
L_price: (-.1,-.01)	1.732	2.624	-1.634	25.904***
	(3.674)	(4.431)	(5.373)	(6.604)
L_price: (-.01,.09)	-38.415***	-41.274***	-47.203***	-42.880***
	(3.733)	(4.403)	(4.855)	(5.649)
L_price: (.09,.)	-2.078***	-4.520***	-3.111***	-8.969***
	(0.514)	(0.801)	(0.842)	(1.181)
spei6_area_neg × L_price: (.,-.1)	0.696***	1.125***	1.020***	1.037***
	(0.204)	(0.244)	(0.243)	(0.259)
spei6_area_neg × L_price: (-.1,-.01)	-1.991**	-7.676***	0.975	-9.448***
	(0.783)	(0.938)	(1.056)	(1.180)
spei6_area_neg × L_price: (-.01,.09)	12.210***	18.395***	13.774***	11.536***
	(0.847)	(0.994)	(1.016)	(1.057)
spei6_area_neg × L_price: (.09,.)	0.217	0.624***	0.749***	2.407***
	(0.165)	(0.215)	(0.242)	(0.268)
ln_pop	-0.582	3.700***	7.578***	-1.173
	(1.003)	(1.320)	(1.525)	(1.779)
Year FE	YES	YES	YES	YES
Constant	2.860	-23.649***	-43.389***	17.069
	(6.373)	(8.396)	(9.694)	(11.307)
Observations	303 053	303 053	303 053	303 053
R^2 within	0.2220	0.3465	0.4487	0.5256

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 7: Spline specification on lagged leakage

	(1) crise	(2) niv12	(3) niv123	(4) niv1234
spei6_area_neg	2.988^{***}	5.342^{***}	6.448^{***}	5.515^{***}
	(0.195)	(0.234)	(0.251)	(0.298)
L_perte: (.,-.75)	-0.213	0.175	0.057	-0.409
	(0.202)	(0.269)	(0.320)	(0.471)
L_perte: (-.75,-.07)	-4.465^{***}	-3.722^{**}	-0.915	0.064
	(1.364)	(1.724)	(2.032)	(2.483)
L_perte: (-.07,.52)	6.088^{***}	4.849^{***}	1.986	4.229^{*}
	(1.426)	(1.786)	(2.080)	(2.560)
L_perte: (.52,.)	0.150	-0.211	-0.406^{***}	-0.657^{***}
	(0.111)	(0.137)	(0.154)	(0.223)
spei6_area_neg × L_perte: (.,-.75)	-0.003	-0.069	-0.067	0.078
	(0.042)	(0.049)	(0.054)	(0.071)
spei6_area_neg × L_perte: (-.75,-.07)	1.793^{***}	1.294^{***}	0.496	0.125
	(0.283)	(0.356)	(0.394)	(0.445)
spei6_area_neg × L_perte: (-.07,.52)	-1.938^{***}	-1.150^{***}	-0.387	-0.643
	(0.313)	(0.393)	(0.437)	(0.481)
spei6_area_neg × L_perte: (.52,.)	-0.022	0.009	0.065^{*}	0.065^{*}
	(0.023)	(0.029)	(0.035)	(0.039)
ln_pop	0.695	4.264	13.284^{**}	8.127
	(4.457)	(5.198)	(6.060)	(6.716)
Year FE	YES	YES	YES	YES
Constant	-4.932	-25.399	-81.465^{**}	-44.316
	(29.183)	(34.038)	(39.673)	(44.000)
Observations	34 340	34 340	34 340	34 340
R^2 within	0.1976	0.3692	0.4546	0.4975

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Beyond capturing potential non-linearities, this specification also provides indirect information about the role of reactive adjustments in management variables. If the patterns observed in the baseline models were primarily driven by municipalities reacting to drought episodes by adjusting their tariffs, such effects should be most pronounced in the lower segments of the demeaned management variables.

Indeed, when a municipality increases its tariff in response to past drought conditions, the lagged price $Price_{it-1}$ will tend to be relatively low compared with the municipality's average price over the full sample period. As a result, reactive dynamics should primarily affect the lower part of the within-municipality distribution of management variables. Observing significant interaction effects in the upper segments of the spline distribution would therefore provide additional evidence that the observed relationship is not driven exclusively by reactive price adjustments.

The spline estimates reveal a clear non-linearity in the relationship between management variables and drought restrictions. When focusing on tariffs alone, the direct effect of prices on the number of restriction days follows a non-monotonic pattern across the distribution. In the lowest segment of the price distribution, the coefficient associated with tariffs is negative, indicating that higher prices are associated with fewer restriction days. In the lower-intermediate segment, the effect becomes weaker and in some specifications even turns slightly positive (when less restrictive decrees such as vigilance are included). In the upper segments of the distribution, however, the coefficient becomes negative again. The interaction terms between drought intensity and prices almost systematically display the opposite sign of the direct price effect.

One possible interpretation is that both mechanisms discussed earlier may coexist. The negative price effect in the lowest segment may partly reflect reactive adjustments: municipalities experiencing frequent drought restrictions may increase tariffs ex post, which can mechanically generate a negative association between lagged prices and restrictions. In contrast, the negative coefficients observed in the upper segments are more consistent with a genuine management effect. When tariffs are already substantially higher than the municipality's long-run average, it becomes less plausible that they reflect reactive adjustments, and they may instead capture structural differences in management strategies or demand management capacity.

The fact that the interaction coefficients systematically display the opposite sign of the direct price effect also provides suggestive evidence of a catch-up mechanism. Tariffs may reduce the number of restriction days under moderate drought conditions, but this advantage gradually disappears as meteorological drought intensifies. As drought conditions deteriorate, even municipalities with stronger management practices eventually face binding resource constraints, leading to a convergence in restriction outcomes.

The interpretation of spline results for network leakage is more complex. The direct effect of leakage rates is generally negative in the lower half of the distribution and positive in the upper half. One possible explanation for the negative effect in the lower segments relates to measurement dynamics during severe drought episodes. Prolonged drought conditions may lead to rapid deterioration of distribution networks. In such cases, leakage rates observed in $t-1$ may appear artificially low relative to their long-run average, generating a negative association between lagged leakage and restriction days in the lower segments of the distribution.

3.5 Non-linear responses to drought intensity

In this section, we attempt to distinguish between a catch-up effect and a reactive management effect associated with water tariffs. To do so, drought intensity is divided into linear spline segments. This approach allows the marginal effect of drought on restriction days to vary across different levels of meteorological stress. Because the objective of this exercise is to analyze how tariffs interact with drought intensity, only the specification including tariffs is presented here.

The most informative coefficients are those associated with the interaction terms between drought intensity and tariffs. The estimates reveal a clear non-linear pattern. In the first non-zero drought segment, the interaction between drought intensity and tariffs is positive. In the intermediate segment, the interaction becomes smaller and is often statistically insignificant for the crise specifications and significantly negative for the others. Finally, in the highest drought segment, corresponding to severe drought episodes, the interaction becomes positive again. At the same time, the direct effect of tariffs remains negative across specifications, indicating that higher tariffs are systematically associated with fewer restriction days, all else equal.

This non-linearity provides suggestive evidence that both mechanisms discussed previously may be present. In the first drought segment, the positive interaction is consistent with a catch-up effect: higher tariffs reduce restrictions under very mild drought conditions, but as drought intensity increases, municipalities with high and low tariffs progressively converge toward similar restriction outcomes.

In the intermediate drought segment, the interaction becomes weak or negative, suggesting a period in which municipalities with higher tariffs exhibit greater resilience to drought conditions. In this range of drought intensity, better demand management or stronger infrastructure maintenance associated with higher tariffs may allow municipalities to delay the introduction of restrictions.

Finally, in the highest drought segment, the interaction becomes positive again. By this stage of drought intensity, much of the catch-up mechanism identified in the previous segments has likely already taken place, as municipalities with initially different restriction levels have progressively converged. The renewed positive interaction observed in the most severe drought range therefore

Table 8: Spline specification on drought intensity

	(1) crise	(2) niv12	(3) niv123	(4) niv1234
L_price	-4.078***	-8.147***	-8.501***	-8.419***
	(0.354)	(0.495)	(0.582)	(0.670)
spei6_area_neg: (.,0)	0.000	0.000	0.000	0.000
	(.)	(.)	(.)	(.)
spei6_area_neg: (0,1.7)	7.956***	10.633***	15.278***	14.346***
	(0.170)	(0.214)	(0.249)	(0.330)
spei6_area_neg: (1.7,5.6)	1.894***	4.019***	7.211***	7.777***
	(0.055)	(0.082)	(0.097)	(0.115)
spei6_area_neg: (5.6,.)	3.056***	4.581***	5.005***	3.395***
	(0.081)	(0.090)	(0.089)	(0.086)
L_price × spei6_area_neg: (.,0)	0.000	0.000	0.000	0.000
	(.)	(.)	(.)	(.)
L_price × spei6_area_neg: (0,1.7)	1.419***	6.289***	8.324***	5.345***
	(0.380)	(0.506)	(0.639)	(0.724)
L_price × spei6_area_neg: (1.7,5.6)	0.259	-2.158***	-2.822***	-1.390***
	(0.215)	(0.338)	(0.374)	(0.431)
L_price × spei6_area_neg: (5.6,.)	2.989***	5.257***	5.692***	3.661***
	(0.332)	(0.460)	(0.439)	(0.443)
ln_pop	-1.057	3.193**	6.278***	-2.536
	(1.002)	(1.319)	(1.524)	(1.770)
Year FE	YES	YES	YES	YES
Constant	3.156	-23.267***	-39.700***	22.205**
	(6.359)	(8.374)	(9.675)	(11.242)
Observations	303 053	303 053	303 053	303 053
R^2 within	0.2244	0.3480	0.4544	0.5307

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

suggests that another mechanism may be at work. In particular, it may reflect a reactive policy response: municipalities facing extreme drought conditions may intensify restrictions more rapidly when prices are high.

Overall, these spline results suggest that the relationship between tariffs and drought restrictions cannot be fully explained by a single mechanism. Instead, the evidence points to a combination of structural management effects and catch-up dynamics that vary across levels of drought intensity.

4 Discussion

This paper provides new empirical evidence on how local water service management interacts with meteorological drought conditions to shape the implementation of water-use restrictions. By combining detailed administrative data on drought decrees with information on tariffs and network leakage, the analysis offers an operational perspective on drought resilience, defined as the ability of water services to maintain normal supply conditions in the face of climatic stress.

Across a wide range of specifications, the results consistently indicate that management variables are associated with the number and severity of restriction days. Municipalities characterized by higher water tariffs or lower leakage rates tend to display different responses to drought conditions. Taken together, these patterns suggest that the economic and technical management of water services plays an important role in shaping how meteorological drought translates into administrative restrictions on water use.

At the same time, interpreting these relationships in strictly causal terms remains difficult. Each model taken individually should be viewed primarily as documenting empirical correlations rather than causal effects. Establishing a credible causal identification strategy in this context is particularly challenging for several reasons.

First, water service management variables partly reflect structural characteristics of local systems. Tariff levels and leakage rates depend on long-run institutional, financial, and hydrogeological conditions that are not randomly distributed across municipalities.

Second, administrative responses to drought involve complex institutional processes. In France, the implementation of drought restrictions results from consultations between technical services, scientific experts, and administrative authorities. Decisions rely on the joint assessment of multiple hydrological indicators, meteorological forecasts, and local institutional considerations. Because this decision-making process integrates many dimensions simultaneously, identifying an instrumental variable that would affect water management decisions without also influencing the administrative response to drought is particularly difficult. In practice, many factors capable of shifting tariffs or infrastructure investments are also likely to affect restriction decisions, raising concerns regarding the exclusion restriction.

Despite these identification challenges, the results obtained across the different specifications reveal a consistent pattern. Both pricing policies and network efficiency indicators appear systematically related to drought outcomes. While fixed-effects panel models cannot fully disentangle whether these patterns reflect causal management effects or reactive adjustments by water services, they nevertheless highlight the central role of economic and technical management choices in the adaptation of water systems to climatic stress.

The spline specifications further suggest that multiple mechanisms may coexist. Part of the observed relationship may reflect reactive adjustments following past drought episodes. At the same time, the patterns observed in the upper segments of the management distribution are more consistent with differences in management strategies that affect the ability of municipalities to cope with drought shocks.

From a policy perspective, these findings contribute to a growing body of evidence emphasizing the importance of strengthening water service management in the face of increasing climatic variability. The consistent associations observed between tariffs, leakage rates, and drought outcomes suggest that pricing policies and sustained investment in distribution networks may play an important role in improving the adaptive capacity of water systems.

These results are particularly relevant in the context of climate change, where drought episodes are expected to become more frequent and more severe across many European regions. In such an environment, maintaining artificially low tariffs or postponing infrastructure renewal may increase the vulnerability of local water systems to hydrological shocks. Conversely, policies that encourage adequate pricing and greater investment in network maintenance may contribute to strengthening the long-term resilience of water services.

References

Adey, B. T., C. Martani, and J. Hackl (2021): “Investing in water supply resilience considering uncertainty and management flexibility,” *Proceedings of the Institution of Civil Engineers - Smart Infrastructure and Construction*, 175, 104–115.

Barraqué, B., R. M. Formiga Johnsson, and A. L. Nogueira de Paiva Britto (2008): “The development of water services and their interaction with water resources in European and Brazilian cities,” *Hydrology and Earth System Sciences*, 12, 1153–1164, iSBN: 1607-7938 Publisher: Copernicus Publications Göttingen, Germany.

Bertrand, N., P. Blanc, P. Cazin, C. Debrieu-Levrat, V. Kles, and S. Plante (2023):

“Retour d’expérience sur la gestion de l’eau lors de la sécheresse 2022,” Tech. Rep. 014714-01 / 22087R / 22105, Inspection générale de l’environnement et du développement durable (IGEDD) and Conseil général de l’alimentation, de l’agriculture et des espaces ruraux (CGAAER) and Inspection générale de l’administration (IGA), Paris.

Blanchy, G., G. Bragato, C. Di Bene, N. Jarvis, M. Larsbo, K. Meurer, and S. Garré (2023): “Soil and crop management practices and the water regulation functions of soils: a qualitative synthesis of meta-analyses relevant to European agriculture,” *Soil*, 9, 1–20, iSBN: 2199-398X Publisher: Copernicus Publications Göttingen, Germany.

Böhnisch, A., E. Felsche, M. Mittermeier, B. Poschlod, and R. Ludwig (2025): “Future patterns of compound dry and hot summers and their link to soil moisture droughts in Europe,” *Earth’s Future*, 13, e2024EF004916.

Cassottana, B., S. Balakrishnan, N. Y. Aydin, and G. Sansavini (2023): “Designing resilient and economically viable water distribution systems: a multi-dimensional approach,” *Resilient Cities and Structures*, 2, 19–29.

Cubillo, F. and Martínez-Codina (2019): “A metric approach to measure resilience in water supply systems,” *Journal of Applied Water Engineering and Research*, 7, 67–78, iSBN: 2324-9676 Publisher: Taylor & Francis.

Dai, L., R. Wörner, and H. F. M. W. van Rijswick (2018): “Rainproof cities in the Netherlands: approaches in Dutch water governance to climate-adaptive urban planning,” *International Journal of Water Resources Development*, 34, 652–674, publisher: Routledge _eprint: https://doi.org/10.1080/07900627.2017.1372273.

Edwards, E., L. Sanchez, and S. Sekhri (2024): “The economics of drought,” *Annual Review of Resource Economics*, 16, 105–124, iSBN: 1941-1340 Publisher: Annual Reviews.

Folke, C. (2016): “Ecology and Society: Resilience (Republished),” *Ecology and Society*, 21.

Fu, G., S. Sun, L. Hoang, Z. Yuan, and D. Butler (2023): “Artificial intelligence underpins urban water infrastructure of the future: A holistic perspective,” *Cambridge Prisms: Water*, 1, e14, iSBN: 2755-1776 Publisher: Cambridge University Press.

Grafton, R. Q., L. Chu, and P. Wyrwoll (2020): “The paradox of water pricing: dichotomies, dilemmas, and decisions,” *Oxford Review of Economic Policy*, 36, 86–107, iSBN: 0266-903X Publisher: Oxford University Press UK.

Guelmamen, M., S. Garcia, and A. Mayol (2025): “Inter-municipal cooperation in drinking water supply: Trade-offs between transaction costs, efficiency and service quality,” *International Review of Law and Economics*, 84, 106303.

HOEKSTRA, A. Y., J. BUURMAN, AND K. C. VAN GINKEL (2018): "Urban water security: A review," *Environmental research letters*, 13, 053002, iSBN: 1748-9326 Publisher: IOP Publishing.

HUBERTS, N. F., K. J. HUISMAN, P. M. KORT, AND M. N. LAVRUTICH (2015): "Capacity choice in (strategic) real options models: A survey," *Dynamic Games and Applications*, 5, 424–439, iSBN: 2153-0785 Publisher: Springer.

JOHANNESSEN, AND C. WAMSLER (2017): "What does resilience mean for urban water services?" *Ecology and Society*, 22, publisher: Resilience Alliance Inc.

KHEDUN, C. P., A. C. LEWIS, AND R. A. KAISER (2025): "Building Resilience into the Public Water Supply System through Targeted Data-Driven Conservation Strategies," *Journal of Irrigation and Drainage Engineering*, 151, 04025011, iSBN: 0733-9437 Publisher: American Society of Civil Engineers.

KIM, J. H., T. D. KEANE, AND E. A. BERNARD (2015): "Fragmented local governance and water resource management outcomes," *Journal of Environmental Management*, 150, 378–386.

KINGDOM, B., J. SY, AND G. SOPPE (2018): "The Use of Performance-Based Contracts for Nonrevenue Water Reduction," *World Bank Publications - Reports*, number: 30433 Publisher: The World Bank Group.

KUNDZEWICZ, Z. W., M. RADZIEJEWSKI, AND I. PINSKWAR (2006): "Precipitation extremes in the changing climate of Europe," *Climate Research*, 31, 51–58.

LARSEN, T. A., S. HOFFMANN, C. LÜTHI, B. TRUFFER, AND M. MAURER (2016): "Emerging solutions to the water challenges of an urbanizing world," *Science*, 352, 928–933, publisher: American Association for the Advancement of Science.

LUND, J. AND J. MEDELLÍN-AZUARA (2018): "California: Water Security from Infrastructure, Institutions, and the Global Economy," in *Global Water Security: Lessons Learnt and Long-Term Implications*, Singapore: Springer, 267–279.

MAAS, A., R. PURI, AND C. GOEMANS (2024): "A review of residential water conservation policies and attempts to measure their effectiveness," *PLoS Water*, 3, e0000278, iSBN: 2767-3219 Publisher: Public Library of Science San Francisco, CA USA.

MAZZEGA, P., O. THEROND, T. DEBRIL, H. MARCH, C. SIBERTIN-BLANC, R. LARDY, AND D. SANT'ANA (2014): "Critical multi-level governance issues of integrated modelling: An example of low-water management in the Adour-Garonne basin (France)," *Journal of Hydrology*, 519, 2515–2526.

MCDERMID, S. S., E. WENG, M. PUMA, B. COOK, T. HENGL, J. SANDERMAN, G. J. DE LANNOY, AND I. ALEINOV (2022): "Soil carbon losses reduce soil moisture in global climate model simulations," *Earth Interactions*, 26, 195–208, iSBN: 1087-3562.

Ministère de la Transition Écologique (2022): "Guide de mise en œuvre des mesures de restriction des usages de l'eau en période de sécheresse," Guide technique, Ministère de la Transition Écologique.

Mullin, M. and K. Hansen (2023): "Local news and the electoral incentive to invest in infrastructure," *American Political Science Review*, 117, 1145–1150, iSBN: 0003-0554 Publisher: Cambridge University Press.

Murgatroyd, A. and J. W. Hall (2020): "The resilience of inter-basin transfers to severe droughts with changing spatial characteristics," *Frontiers in Environmental Science*, 8, 571647, iSBN: 2296-665X Publisher: Frontiers Media SA.

Olmstead, S. M. and R. N. Stavins (2007): "Managing water demand: Price vs. non-price conservation programs," *A pioneer institute white paper*, 39.

Perrot, A., A. Reynaud, and S. Saussier (2026): "L'eau sous tension : concilier sobriété hydrique, équité et investissement," Tech. Rep. 87, Conseil d'analyse économique, Paris.

Pindyck, R. S. (1990): *Irreversibility, uncertainty, and investment*, National Bureau of Economic Research Cambridge, Mass., USA.

Pot, W. (2023): "Deciding for resilience: Utilizing water infrastructure investments to prepare for the future," *Wiley Interdisciplinary Reviews: Water*, 10, e1661, iSBN: 2049-1948 Publisher: Wiley Online Library.

Salvetti, M. (2023): "An approach to the financial stakes of water security faced by water and sanitation services in France," *Economia pubblica: L, 3, 2023*, 329–365, iSBN: 1972-5566 Publisher: Franco Angeli.

Schifman, L. A., D. L. Herrmann, W. D. Shuster, A. Ossola, A. Garmestani, and M. E. Hopton (2017): "Situating green infrastructure in context: A framework for adaptive socio-hydrology in cities," *Water resources research*, 53, 10139–10154, iSBN: 0043-1397 Publisher: Wiley Online Library.

Serafeim, A. V., N. T. Fourniotis, R. Deidda, G. Kokosalakis, and A. Langousis (2024): "Leakages in water distribution networks: Estimation methods, influential factors, and mitigation strategies—A comprehensive review," *Water*, 16, 1534, iSBN: 2073-4441 Publisher: MDPI.

Tripathy, K. P. and A. K. Mishra (2023): "How unusual is the 2022 European compound drought and heatwave event?" *Geophysical Research Letters*, 50, e2023GL105453, iSBN: 0094-8276 Publisher: Wiley Online Library.

Tóth, G., E. Ivits, G. Prokop, M. Gregor, J. Fons-Esteve, R. Milego Agràs, and E. Mancosu (2022): "Impact of Soil Sealing on Soil Carbon Sequestration, Water Storage

Potentials and Biomass Productivity in Functional Urban Areas of the European Union and the United Kingdom," *Land*, 11, 840, publisher: Multidisciplinary Digital Publishing Institute.

VICENTE-SERRANO, S. M., S. BEGUERÍA, AND J. I. LÓPEZ-MORENO (2010): "A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index," *Journal of climate*, 23, 1696–1718, iSBN: 1520-0442.

WHEELER, S. A., C. NAUGES, AND R. Q. GRAFTON (2025): "Water pricing and markets: Principles, practices and proposals," *Applied Economic Perspectives and Policy*, 47, 487–514, iSBN: 2040-5790 Publisher: Wiley Online Library.