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Disentangling the nexus between climate information and (mal)adaptation in socio-ecological-technical systems

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Abstract
Biella, R. 2025. Disentangling the nexus between climate information and (mal)adaptation in socio-ecological-technical systems. (Adaptation with Climate Services. Disentangling the nexus between climate information and (mal)adaptation in socio-ecological-technical systems). *Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology* 2600. 79 pp. Uppsala: Acta Universitatis Upsaliensis. ISBN 978-91-513-2632-0.

Adaptation to climate change is increasingly recognized as necessary for societal resilience. Yet, adaptation is neither straightforward nor inherently positive in today's complex, unequal and rapidly changing world, which characterized the Anthropocene. This thesis investigates the interplay between climate information and (mal)adaptation in socio-ecological-technical systems (SETSs), with a particular focus on drought risk management in Europe. Through five interlinked studies, this research examines how climate services are used, misused, or underutilized in climate change adaptation, and how their design, accessibility, and usability influence maladaptive outcomes.

Papers I and II analyse the European response to the 2022 drought, uncovering both the growing awareness of drought risk and the limitations of preparedness and institutional coordination. Findings highlight persistent fragmentation and reliance on short-term operational responses. The two papers also include a call for a European Drought Directive to enshrine systemic drought risk management into European governance. Paper III conceptualizes climate services through a system thinking lens, revealing how design and delivery may unintentionally reinforce path dependencies and systemic inequalities across a series of case studies. Paper IV develops a system dynamics model to explore trade-offs in adaptation pathways. It shows how short-term climate services may offer rapid economic gains but can heighten the risk of long-term system collapse. Conversely, long-term services foster resilience but demand delayed gratification and slower wealth generation. Paper V interrogates the format-function gap in climate service design, emphasizing how entrenched expectations and techno-scientific norms may stifle context-specific and transformative approaches.

Across these studies, the thesis argues that maladaptation is not simply the result of poor decisions, but often emerges from well-intentioned but narrowly framed interventions, shaped by institutional constraints, political priorities, and epistemic norms. Climate information is therefore not a neutral addition, it plays a key role in driving adaptive and maladaptive processes. The thesis contributes to the development of more inclusive, reflexive, and transformative climate services. It advocates for a pluralistic vision of adaptation that embraces complexity, acknowledges trade-offs, and centres the diverse needs and values of affected communities.

Keywords: climate change adaptation; climate services; maladaptation; system thinking; system dynamics.

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List of Papers

This thesis is based on the following papers.

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III. Biella, R., Mazzoleni, M., Brandimarte, L., Baldassarre, G.D., 2024a. Thinking systemically about climate services: Using archetypes to reveal maladaptation. Climate Services 34, 100490. https://doi.org/10.1016/J.CLISER.2024.100490

IV. Biella, R., Mazzoleni, M., Brandimarte, L., Di Baldassarre, G., Trade-offs in adaptation to water-related risks: Modelling how climate services can influence pathways to transformation. Frontiers in Water - Water and Human Systems *(Under review)*

V. Biella, R., Brandimarte, L., Mazzoleni, M., Di Baldassarre, G., 2025. Form over Function: Does Climate Service Design Bias Limit Adaptation? https://doi.org/10.2139/ssrn.5412809. Climate Services *(Under review)*

Additional Publications

During the course of the PhD, the author has contributed to the following publications, which are not included in the thesis.

VI. **Biella, R.**, Hoffmann, R., Upadhyay, Himani, 2022. Climate, Agriculture, and Migration: Exploring the Vulnerability and Outmigration Nexus in the Indian Himalayan Region. Mountain Research and Development 42 (2). https://doi.org/10.1659/MRD-JOURNAL-D-21-00058.1

VII. Van Loon, A.F., Kchouk, S., Matanó, A., Tootoonchi, F., Alvarez Garreton, C., Hassaballah, K.E.A., Wu, M., Wens, M.L.K., Shyrokaya, A., Ridolfi, E., **Biella, R.**, Nagavciuc, V., Barendrecht, M.H., Bastos, A., Cavalcante, L., Vries, F.T. de, Garcia, M., Mård, J., Streefkerk, I.N., Teutschbein, C., Tootoonchi, R., Weesie, R., Aich, V., Boisier, J.P., Baldassarre, G.D., Du, Y., Galleguillos, M., Garreaud, R., Ionita, M., Khatami, S., Koehler, J.K.L., Luce, C.H., Maskey, S., Mendoza, H.D., Mwangi, M.N., Pechlivanidis, I.G., Neto, G.G.R., Roy, T., Stefanski, R., Trambauer, P., Koebele, E.A., Vico, G., Werner, M., 2024. Review article: Drought as a continuum – memory effects in interlinked hydrological, ecological, and social systems. Nat. Hazards Earth Syst. Sci. 24, 3173–3205. https://doi.org/10.5194/NHESS-24-3173-2024

VIII. Wens, M., Hagenlocher, M., Shyrokaya, A., Werner, M., Toreti, A., Alencar, P., Amanambu, A., Bell, J., Nam, W., Rastogi, S., Rivera, J., Sanchez, C., Zampieri, M., Sabino-Siemons, A., Smith, K., Tootoonchi, F., Trambauer, P., van Vliet, M., van Tiel, M., Bonaccorso, B., **Biella, R.**, Biess, B., Sánchez, A., Masih, I. (2025) Ten key insights and gaps to inform drought risk research, policy and practice. Nature Water *(Under review)*

IX. Lindersson, S., Baldassarre, G.D., Parker, C., Bondesson, S., Koivisto, J., Olivetti, L., Akinyemi, F., Messori, G., Biella, R., Burchardt, S., Rosso, C.C., Herve, M. de G. de, Deegan, F., Döring, S., Dubois, K., Eriksson, L., Fernandez, J., Gebru, B., Goteman, M., Granberg, M., Haas, J., Hedelin, B., Hermansson, H., Holmberg, E., Johansson, M., Karagiorgos, K., Mård, J., Merli, C., Mondino, E., Nyberg, L., Pavlovic, E.P., Shrestha, S., Rutgersson, A., Shen, X., Shyrokaya, A., Thandlam, V., Troll, V., Turesson, K., Wennström, P., Nohrstedt, D., 2025. Unpacking and navigating complexity in disaster risk reduction. Communications Sustainability. https://doi.org/10.21203/rs.3.rs-6957900/v1 *(Under review)*

X. Koutroulis, A., Savelli, E., Tosic, M., Lazic, I., Fekete, A., Hernanz, V., Tenbrink, T., Stojanov, R., Tankiewicz, M., Pietrapertosa, F., Salvia, M., Ricart, S., Zorita, S., Gosling, S.N., Yazar, E.A., Anghel, S., Ballester, J., Barton, M., Bezdan, J., Bezdan, A., **Biella, R.**, Cantone, C., Coll, P., Dalkılıç, K., Erdoğan, Z., Erkoç, M.H., Fader, M., Garcia, N.P., Giannakis, E., Giray, F.H., Grillakis, M., Gurgun, A.P., Hochman, A., İnce, Z., Johnson, K., Kádár, J., Kalantari, Z., Karimov, R., Keklik, G., Ozgenc, E.K., Khazai, B., Kohnová, S., Kumer, P., Filipovska, O., Öztürk, E.Z., Pagé, C., Paisi, N., Pamukoglu, Y., Papa, K.-M., Pechlivanidis, I., Pilogallo, A., Popović, Z., Rezvani, A., Rustja, D., Suárez Gálvez, C., Tanarhte, M., Tsilimigkras, A., Velea, L., Vranić, P., Zittis, G., Flaounas, E. and Khodayar, S., 2025. Mapping the Mediterranean Climate Change Adaptation Toolscape across Promises, Pitfalls, and Ways Forward. Communications Earth & Environment. *(Under review)*

XI. **Biella R.**, Muller L., Mazzoleni M., Di Baldassarre G., 2022: Preliminary report on causal mechanisms between climate change, climate service information, and socio-economic behaviour. I-CISK Deliverable D4.1.

XII. Muller L., **Biella R.**, Ropero Szymańska N., De Stefano L., Hernández-Mora N., Rastogi S., Di Baldassarre G., Mazzoleni M., 2023: Preliminary report on causal mechanisms between climate change, climate service information, and socio-economic behaviour. I-CISK Deliverable D4.2.

XIII. **Biella R.**, Wamucii C. N., Mazzoleni M., Di Baldassarre G., De Stefano L., Hernández-Mora N., 2024: Quantifying long-term patterns between adaptation actions, socio-economic behaviours, and climate service information. I-CISK Deliverable D4.3.

XIV. Rastogi S., van Cauwenbergh N., Ziogas A., Mazzoli P., Castellana D., Ropero Szymańska N., Hernández-Mora N., van Andel S. J., Bela G., Nyamakura B., **Biella R**., Wamucii C., Muller L., 2025: Participatory modelling for allowing citizens, stakeholders and decision-makers to become active players in climate action. I-CISK Deliverable D4.4. Available online at www.icisk.eu/resources.

XV. **Biella R.**, Muller L., Ropero N., Wamucii C. N., De Stefano L., Di Baldassarre G., Mazzoleni M., (2025): Bidirectional feedbacks between adaptation actions and climate service information. I-CISK Deliverable D4.5. Available online at www.icisk.eu/resources

Contents

Introduction

Hydro-climatic hazards are increasingly disrupting human and natural activities due to anthropogenic climate change and humanity's growing influence and dependence on natural resources; first among them, water. Droughts, floods, and heatwaves cause mfatalities, economic losses, and human displacements, with cascading effects across human activities and ecosystems (IPCC, 2022). The current pattern is not only more frequent extremes, but also altered timing and compounding hazards (Barendrecht et al., 2024; Brito, 2021; Markonis et al., 2021), which reduce the effectiveness of conventional risk management strategies and expose structural vulnerabilities of the human-nature system (Bartelet et al., 2022b; Berkhout, 2024; BÏoschl and Montanari, 2010; Kreibich et al., 2022).

Despite progress in predicting changes in the intensity and frequency of hydro-climatic extremes, management and governance capacities remain heterogeneous and, in many places, insufficient to address the mounting complexity of these threats. In Europe for example, extreme droughts have increased over recent decades, driven by rising evapotranspiration and shifting snowmelt dynamics that weaken natural storage and seasonal buffering (Bakke et al., 2023; Balting et al., 2021; Ionita et al., 2022; Ionita and Nagavciuc, 2021; Kreibich et al., 2022; Spinoni et al., 2018, 2016). The 2022 drought event exemplified this trajectory. A dry winter and spring, followed by unusually early heatwaves and record summer temperatures, produced widespread soil-moisture deficits, depressed river flows, and extensive water stress across large parts of the continent (Avanzi et al., 2024; Biella et al., 2024a; Montanari et al., 2023a; Schumacher et al., 2022; Toreti et al., 2022; Tripathy and Mishra, 2023). Impacts were observed across sectors, including reduced crop yields, transport disruptions, constraints on hydropower production, as well as ecological degradation (Avanzi et al., 2024; Barker et al., 2024; Biella et al., 2024a; Montanari et al., 2023b; Sodoge et al., 2024). Seasonal forecasting played a crucial role in organizations enacting drought risk management measures, introducing water-use restrictions, increasing ground water abstraction, carrying out awareness campaigns, and enforcing bans on recreational water use (Biella et al., 2024a; Bonaldo et al., 2023). Yet, these measures were far from sufficient as, despite effective forecasting and vast resource mobilization, the ramifications and complexity of the disaster had severe impacts across the continent (Biella et al., 2024a, 2024b).

Because of magnitude of the threat, managing the climate crisis should be considered a global imperative – if not at least a European one. The growing climatic challenge demands a coordinated approach that links scientific knowledge with decision processes, and focusses on its the socio, ecological, political, and technological complexities (Birkmann, 2011; Naylor et al., 2020; Preiser et al., 2018). This imperative is not limited to hazard forecasting or emergency response. It encompasses long-term adjustments in how societies use, govern, and value water, land, and ecosystems under increasing climatic variability (Bartelet et al., 2022b, 2022a).

Technological advances have substantially expanded the suite of tools available to support these tasks. Progress in climate information services, including weather forecasting, climate projections, and modelling capabilities, has enhanced the capacity to anticipate hazardous conditions (Cortekar et al., 2016; Hewitt et al., 2012, 2020; Hewitt and Stone, 2021; Jacobs and Street, 2020). However, improved forecasts and projections have not nullified disaster impacts. To the contrary, the same period that saw the rise of climate services also saw a global increase in climate-related disaster damages (Hewitt et al., 2012; Tol, 2013). Forecast information alone does not reduce risk, if users cannot interpret and act on the information (Boon et al., 2021; Cash et al., 2006; Findlater et al., 2021), if exposure and vulnerability remain high (Boon et al., 2021; Fankhauser and McDermott, 2014; Naylor et al., 2020), if institutional mandates and resources are lacking (Engle, 2011; Fankhauser and McDermott, 2014), or if inequality remains rampant (Savelli et al., 2022, 2021; Tschakert et al., 2013). Effective climate risk reduction requires systemic intervention that couples climate information with effective decision-making, and long-term adaptation strategies (Boon et al., 2021; Fedele et al., 2020; Filho et al., 2022; McPhearson et al., 2021).

Within this context, the present thesis aims to disentangle the feedback-rich nexus between climate services and (mal)adaptation in the socio-ecological-technical system, as illustrated schematically in Fig. 1. First, I introduce the concepts and develop a comprehensive framework that can inform our understanding of this nexus and guide my research. Second, I present the articles that have constituted my thesis. Third, I discuss the implications that each article represents in trying to disentangle the afore-mentioned nexus as well as the contribution and lessons that can be taken from each article. Finally, I deliberate the implications of my research in fostering equitable, long-term adaptation by aligning climate services with decision-making needs.

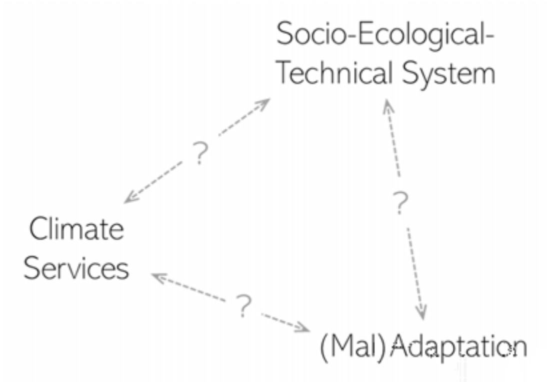


Figure 1: The central question of the thesis, how do we understand the three-way interaction between Climate Information, the Socio-Ecological System, and (Mal)Adaptation?

The socio-ecological-technical system

Systems thinking emerged in the mid-twentieth century from converging strands of cybernetics, control theory and general systems theory, which foregrounded feedback, delays and nonlinearity as core features of real-world problems (Forrester, 1994; Sterman, 2014). Building on these ideas researchers and practitioners have developed a slew of frameworks and methodologies for real world complex systems, from economies, to urban areas, to watersheds, and ecosystems (Forrester, 1997, 1970; Holling, 2001; Meadows et al., 1972; Mirchi et al., 2012).

Complex systems, are systems composed of numerous interacting components operating across multiple spatial and temporal scales, with feedbacks, nonlinearities, delays, thresholds and emergent properties that cannot be inferred from the parts alone (Elsawah et al., 2017; Forrester, 1994; Martinez-Moyano and Richardson, 2013; Mirchi et al., 2012; Sterman, 2014, 2001; Wolstenholme, 2003; Wolstenholme and Coyle, 1983). Their behaviour depends on their internal structure, they adapt in response to internal and external change, and they exhibit deep and sometimes irreducible uncertainty (Forrester, 1994; Martinez-Moyano and Richardson, 2013; Sterman, 2014, 2001; Wolstenholme and Coyle, 1983). Complexity is thus a property of systems, not only a feature of our knowledge about them. It is usually conceptualized across two dimensions. First, combinatorial complexity arises from the sheer number and heterogeneity of components and their interactions. Second, dynamic complexity arises from feedback-rich structures that produce counter-intuitive patterns over time (Martinez-Moyano and Richardson, 2013; Sterman, 2014).

Starting in the 1960s, researchers such as Jay Forrester began developing methodologies to work with complex systems. System dynamics has since established itself as the most prolific methodology. In system dynamics structural complexity is explicitly modelled by recreating feedbacks through series of differential equations connecting the elements of the system (Forrester, 1997, 1994, 1994, 1970; Sterman, 2014, 2001; Wolstenholme and Coyle, 1983). Another complementary approach is agent-based modelling, which recreates combinatorial complexity in-silico by modelling individual and heterogeneous decision-making units to explore how micro-level rules and behaviours can generate emergent macro-level patterns (Groeneveld et al., 2017; Haer et al., 2020; Martin and Schlüter, 2015; Wens et al., 2019; Zhuo and Han, 2020).

Socio-Ecological Systems (SES) scholarship embraces complexity as a feature of the human-nature nexus. SES theory argues that we cannot understand or model the parts of the human-nature system in isolation (Holling, 2001; McGinnis and Ostrom, 2014; Ostrom, 2009). In the SES, hydrological, soil, ecological, and socio-economic models, are dominated by cross-domain feedbacks that are crucial to understand their behaviour, and the emerging behaviour of the system as a whole (Fig. 2) (Bartelet et al., 2022b; de Vos et al., 2019; Elsawah et al., 2017; Fisher-Vanden et al., 2013; Gain et al., 2020; Ostrom, 2009; Preiser et al., 2018; Schlüter et al., 2017; Villamayor-Tomas et al., 2014, 2020b). Nevertheless, traditional scientific practices tend to work in disciplinary silos. SES therefore calls for a holistic understanding that embraces all aspects of the system and explicitly represents interdependencies and complexity when analysing risk, resilience and sustainability (Bartelet et al., 2022b; de Vos et al., 2019; Elsawah et al., 2017, 2017; Fisher-Vanden et al., 2013; Gain et al., 2020; Nabavi et al., 2017; Ostrom, 2009; Preiser et al., 2018; Richardson, 2011; Schlüter et al., 2017; Verburg et al., 2016; Villamayor-Tomas et al., 2014, 2020b).

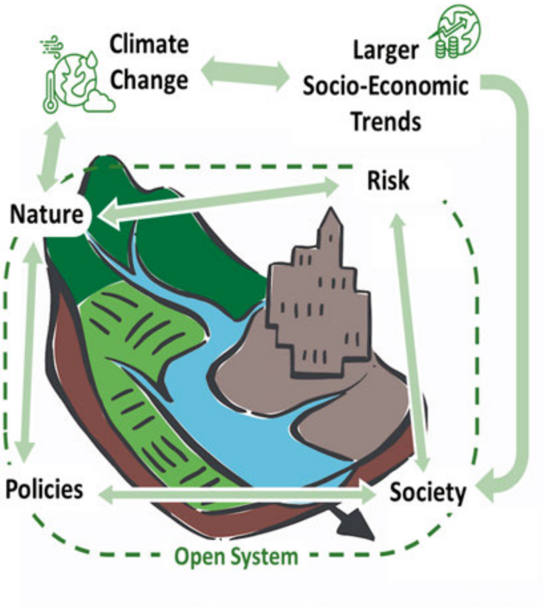


Figure 2: Example of a watershed as a socio-ecological system where natural and societal processes interact to shape risk. SESs are open systems dominated both by internal and external processes. *The icons were sourced from thenounproject.com and greeninfrastructurelab.com. They are sharable under license CCBY3.0. Individual credits to the creators are in the acknowledgements.*

A closely related line of work and arguably a sub-discipline, is socio-hydrology, which conceptualises human–water systems as complex systems and examines how human decisions, institutions and hydrological processes jointly shape risks over time (Di Baldassarre et al., 2015, 2013; Mostert, 2018; Penny and Goddard, 2018; Sivapalan et al., 2012, 2012). Socio-hydrological studies have illuminated mechanisms such as the safe-development paradox on floodplains (*levee effect*) and demand–supply feedbacks around reservoirs (*reservoir effect*), showing how risk reduction measures can unintentionally amplify exposure or risk (Avanzi et al., 2024; Di Baldassarre et al., 2018, 2015; Garcia et al., 2020; Haer et al., 2020; Tobin, 1995).

Socio-Ecological-Technical Systems (SETS) further expands on the SES framework by explicitly integrating technological infrastructures and informational systems into the analysis of human–environment interactions (Chester et al., 2023; Herreros-Cantis et al., 2025; Markolf et al., 2018; McPhearson et al., 2022). Unlike SES frameworks that may treat technologies as external tools, SETS recognize them as internal, interacting components that shape and are shaped by the system behaviour and adaptation outcomes. In this thesis, I adopt the SETS perspective as I argue that it is more effective at capturing how climate information services themselves are subject to complex system processes, as they themselves evolve and adapt in response to changing conditions (Fig. 3). By making these interdependencies explicit, SETS help identify trade-offs, path dependencies, and governance challenges that might otherwise be overlooked.

Ultimately, embracing SETS as a framework for this thesis enables us to interrogate how adaptation outcomes are shaped not only by environmental and social dynamics, but also by the politics and assumptions embedded in technical systems, especially those that produce and circulate climate information. Design choices can obscure vulnerabilities or marginalise local knowledge, weakening transformative potential; recognising and addressing these biases is therefore integral to SETS-informed adaptation (Herreros-Cantis et al., 2025; Olazabal et al., 2018).

Figure 3: The Socio-Ecological-Technical System (SETS) as complex open system. SETS are open systems affected by outside processes, as well as by the complex dynamics within the systems themselves.

Adaptation

Resilience theory emphasises four interdependent functions that together help keep SETSs within safe operating boundaries: anticipating, recognising, learning, and adapting (Becker, 2024a, 2024b, 2024c; Wamsler et al., 2012). Within this framing, adaptation refers to system adjustments made in anticipation or response to changing conditions with the aim of reducing harm or seizing opportunities (Becker, 2024c, 2024b; Eriksen et al., 2011; Fankhauser et al., 1999); such as farmers shifting to drought resistant crops in anticipation of a dry season. Adaptation is therefore a core function of a resilient SES, oriented toward maintaining or restoring a sustainable trajectory under changing hazard regimes.

In system thinking, adaptation is an emergent property of complex systems. It arises from decentralised, dynamic interactions among social, ecological, and technological components, where feedbacks, nonlinearity, and path dependence maintain the system in a state of dynamic equilibrium over time (Berkhout, 2012; Fankhauser et al., 1999; Richardson, 2011; Sterman, 2001). In this view, no single actor "controls" adaptation. Rather, it emerges as multiple processes of adjustment coalesce, sometimes stabilising the system after perturbations and sometimes shifting it into new regimes.

Adaptation is not only "spontaneous"; It is also the result of intentional measures intentionally undertaken through adaptive decision making by individuals, organisations, and institutions. Such actions can be reactive, occurring after a disruption, or proactive, motivated by the expectation of change (Becker, 2024b). Proactive adaptation encompasses preventing, mitigating, and preparing for risk, while reactive adaptation includes responding and recovering (Becker, 2024a, 2024b; Wamsler et al., 2012). Anticipatory processes, such as forecasting, and recognitory processes, such as monitoring and assessment, are essential enablers because they provide the risk awareness required to act while the system retains the capacity to respond effectively (Becker, 2024c; Boon et al., 2022; Cortekar et al., 2016; Grossi and Dinku, 2022; Scott et al., 2011).

Different typologies of adaptation describe different and complementary approaches. Coping and incremental adaptations aim to keep or steer the system onto a sustainable path without altering its core functions, whereas transformative adaptation tackles root vulnerabilities by significantly reconfiguring system structures and functions (Fedele et al., 2020, 2019; Filho et al., 2022; Kates et al., 2012; Naylor et al., 2020; Sediri et al., 2020; Tschakert et al., 2013). As examples of each typology in the case of urban flood adaptation, coping might involve constructing or raising levees and embankments to protect urban areas. Incremental measures include expanding green infrastructure, removing impermeable surfaces, or creating controlled retention areas in parks to lower urban runoff. Transformative adaptation may entail relocating parts of the settlements out of floodplains and restoring river corridors to reinstate natural hydrological buffers.

Yet, adaptive processes can backfire and lead to increased vulnerability. Complex systems can defy linear thinking (i.e. the expectation that a solution will yield one specific outcome) by giving rise to unintended consequences when measures are taken without keeping into account of system feedbacks. For example, seawalls can shift vulnerability to people elsewhere along the coast, because of changes in sediment deposits, with additional negative environmental consequences on marine ecosystem (Piggott-McKellar et al., 2020). Research has highlighted several such examples across various system-relevant disciplines (Di Baldassarre et al., 2018; Fusinato et al., 2024; Haer et al., 2020; Larrosa et al., 2016, 2016; Moallemi et al., 2022; Špicar, 2014; Tobin, 1995; Villamayor-Tomas et al., 2020a; Wolstenholme, 2003). ¨

The term *maladaptation* has therefore been coined to refer to responses intended to reduce climate risk that, in effect, increase vulnerability within the same system, transfer it to other places or social groups, or lock in future risk by undermining adaptive capacity (Barnett and O'Neill, 2010; Juhola et al., 2016; Magnan et al., 2016). In this view, adaptation and maladaptation are not separate processes but two faces of the same adaptive dynamics; they can co-occur and emerge from the same feedback processes (Eriksen et al., 2011; Magnan et al., 2016; Reckien et al., 2023; Schipper, 2020).

In this this thesis, I argue we can equate the term *unintended consequences* to that of *maladaptation*, when discussing climate adaptation. I believe the two terms describe the same processes but are used across different fields (the first being what has been traditionally used in system-thinking related fields, while the second one emerging from resilience and development sciences). I therefore argue that by explicitly recognizing the overlap of the two term one can enrich their understanding by accessing the wealth of research generated by the two fields.

In this thesis, adaptation is conceptualised as an emergent function of SETSs produced by the complex processes taking place within the systems themselves. It occurs in response to changing system conditions arising from climatic change, natural hazards, and socio-economic dynamics. Within this framing, adaptation and maladaptation are outcomes of the same adaptive processes. Adaptive decision-making drives intentional adaptation in the SETSs and is itself shaped by recognitory and anticipatory processes within the SETS (such as monitoring, and forecasting), and by the broader social, political, and governance contexts in which decisions are made and implemented. This conceptualisation is summarised schematically in Fig. 4.

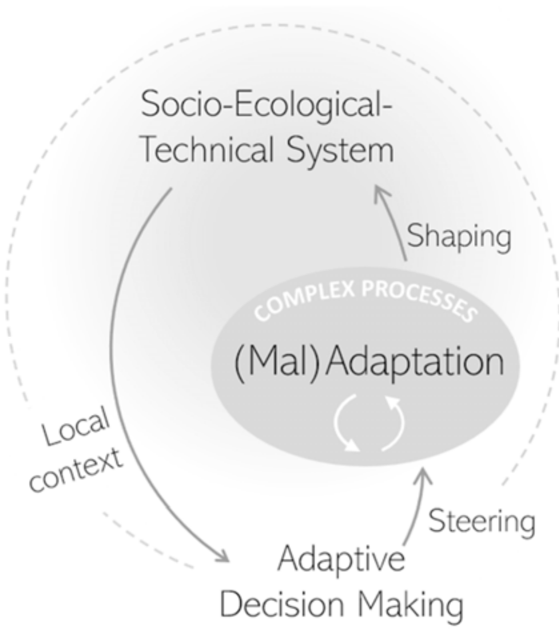


Figure 4: (Mal)Adaptation as an emerging property of complex Socio-Ecological-Technical Systems whereby the system adjusts in response to or anticipation of change. Adaptive decision making actively steers adaptation and is shaped by the context in which the decisions are taken.

Climate services

Over recent decades, advances in observation systems, numerical modelling, data analysis, digitalization, and more have substantially expanded the role of climate information in adaptation. National and international organizations started developing tools, platforms, and programmes that collect, transform, and translate this wealth of information into usable formats that can help decision makers to better adapt to a changing climate: climate services (Hewitt et al., 2012, 2020; Hewitt and Stone, 2021; Jacob et al., 2015; Jacobs and Street, 2020).

The proliferation of climate information has promised to revolutionize climate adaptation and disaster risk management. Examples of CSs include early warning systems and short- to seasonal-range forecasts for hazards, multi-decadal climate projections, impact and risk assessments, awareness raising campaigns, sectoral advisories, and digital portals and dashboards that provide maps, indices, decision support tools, and guidance for use in water, agriculture, energy, health, and urban management (Bessembinder et al., 2019; Bisaro et al., 2021; Cortekar et al., 2020, 2016; Hewitt et al., 2012, 2020;

Hewitt and Stone, 2021, 2021; Jacob et al., 2015; Vaughan et al., 2018, 2018). Such services can support adaptation across sectors by providing the information necessary for adaptation to act in anticipation of hazards or climate change (Ashley et al., 2020; Barnet et al., 2021; Bessembinder et al., 2019; Cortekar et al., 2016; Grossi and Dinku, 2022; Hewitt et al., 2012, 2020; Soares and Buontempo, 2019).

While the promise of CSs might seem a "no regret solution", SES science has taught us to be wary of "panaceas" (Ostrom, 2007). In this thesis, I argue that the study of CSs impact on (mal)adaptation should reflect the fields concern with complex processes and long-term outcomes, and avoid simplistic assumptions about the outcome of a measure in complex systems.

Despite their prevalence, no consensual definition of CS has been able to satisfy both practitioners and researchers. CS are broadly defined as objects, tools, and processes that make climate knowledge usable for adaptive decision-making (Brasseur and Gallardo, 2016; Hewitt et al., 2012), essentially moving the information from the source towards the users (Fig. 5).

CSs are not one size-fit-all tools, instead they should be understood as processes that are tailored to a specific use or context and that involve the transformation, production, translation, and transfer of climate. The nature of the information, and where it is collected and delivered remains fuzzy, as no agreed upon distinction exists with weather services, adaptation tools, and other climate-information related items (Brasseur and Gallardo, 2016). Tools to visualize satellite observations, crop impact forecasting, awareness raising campaigns, and early warning SMSs can all be considered CSs.

Most service frameworks depict a linear value chain that runs from observations and modelling to products and delivery, and finally to user adaptive decision making (Hamaker et al., 2018) (Fig. 5). While useful in some cases, a linear pipeline assumes information flows unidirectionally from source to user. This assumption falls into the trap of applying linear thinking to a complex system by underplaying the feedbacks processes of SETSs, within which adaptation actually takes place. As established above, adaptation emerges from interacting social, ecological, and technical processes. Decisions alter vulnerability and exposures, which in turn reshape information needs and incentives. If these feedbacks are ignored, services risk misalignment with decision contexts, possibly contributing to maladaptation (Boon et al., 2024, 2022, 2021; Hewitt et al., 2020; Kirchhoff et al., 2013; Lemos et al., 2012; Soares and Buontempo, 2019).

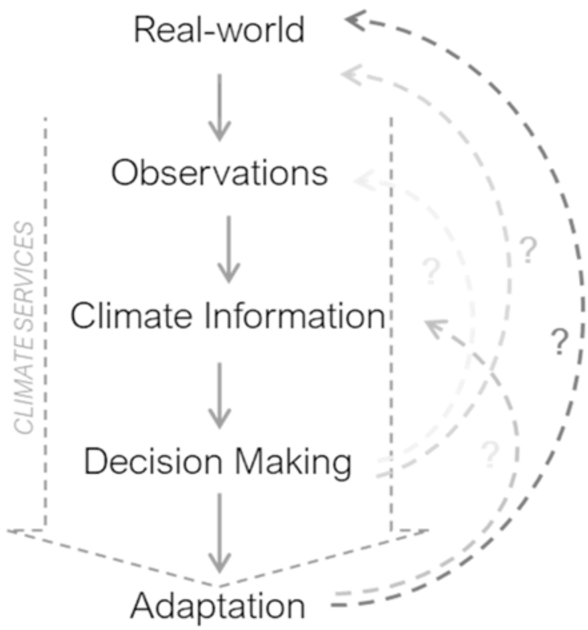


Figure 5: Simple conceptualization of how climate services transform real world observation into usable information, usually referred to as climate service value chain. This conceptualization simplifies this as a linear downstream process and does not account for feedbacks.

Researchers have questioned the validity of the assumption of better data leading to necessarily better adaptation outcomes. CS development tends to prioritise producing better climate data and models while under-addressing how information is interpreted, translated, and used within decision processes (Boon et al., 2024, 2022; Findlater et al., 2021; Tall et al., 2018; Vaughan and Dessai, 2014). Success metrics emphasise uptake, user numbers, and downloads. While useful for programme management, these indicators do not reveal whether CS reduce vulnerability, avoid lock-in, or redistribute risks fairly (Dilling and Lemos, 2011; Lemos et al., 2012; Perrels et al., 2020). Studies have also shown how preference for short-term information can crowd out longer-term perspectives, particularly when resources and attention are finite (Ashley et al., 2020; Boon et al., 2022, 2021; Findlater et al., 2021; Soares and Buontempo, 2019). As argued earlier, omitting long-term and systemic perspectives is consequential in SETS where feedbacks can generate unintended effects.

Additionally, a limited but growing number of studies have started investigating the role that CSs can play in socio-political processes, and how it can be instrumentalize to further development and political agendas (Dilling and Lemos, 2011; Greene and Ferguson, 2024; Lemos et al., 2002; Nost, 2019). These studies highlight how CS should not be considered as entirely value neutral and how their development and use should consider system's socio-political reality.

Finally, CS development often reflects Global North biases and technocratic epistemologies, with insufficient attention to Global South needs and to local or Indigenous knowledge systems (Georgeson et al., 2017). Market-led models can exacerbate disparities in access and relevance, privileging technical expertise over other forms of knowledge (Georgeson et al., 2017; Olazabal et al., 2018; Randalls, 2010). Addressing these biases is essential if CS are to support equitable, long-term adaptation rather than reproduce existing inequalities.

In view of these findings, this thesis treats CSs as processes within complex systems rather than static products. CSs are the sustained activities through which observations and knowledge of the natural and human system are delivered, translated, and synthesised into information that can be used in adaptive decision making. This information is not neutral. It is shaped by the needs, constraints, and biases of the adaptive processes that request and use it, and by the feedbacks those decisions generate. Operationally, I situate CSs partially within SETS, so that both the observations and the delivery mechanisms need to consider the local context. CSs are therefore iterative and reflexive. They evolve as monitoring and forecasting reveal new conditions, as users' goals shift, and as outcomes are evaluated against changing vulnerability. This framing is schematised in Fig. 6.

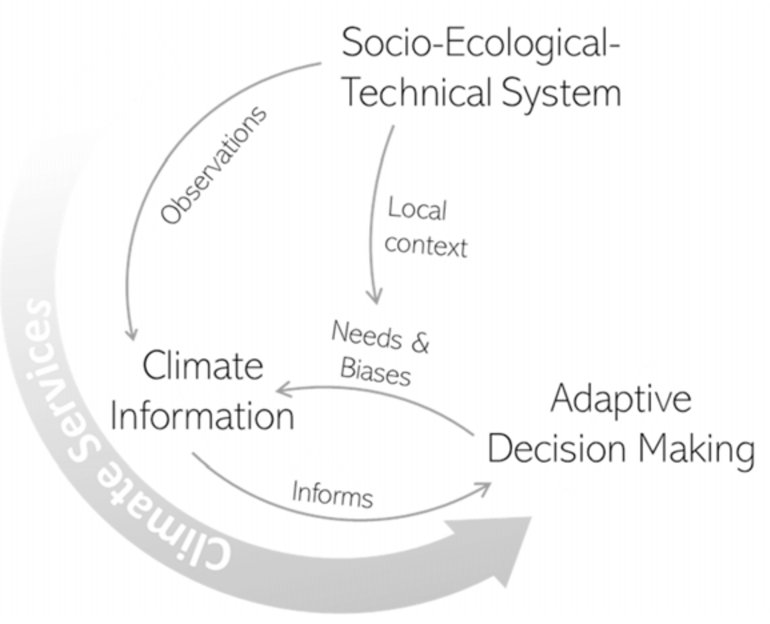


Figure 6: Conceptualization of the relation between climate services and adaptive decision making. This conceptualization views climate services as processes that generally move information downstream form the observation towards adaptation. While climate information shapes the type of adaptation that can be implemented, the needs and biases of adaptation define which type of information is requested for the specific context.

Aim of the research

Against the backdrop of the Anthropocene, understanding how climate information contributes to adaptation (and when it fails to do so) becomes increasingly urgent. CSs are frequently presented as a cornerstone of anticipatory adaptation, yet their actual long-term impact remains riddled with assumptions. As climate risks escalate and responses become more complex, it is vital to move beyond simplistic, linear models and instead examine the feedback-rich interactions between climate knowledge, adaptive decisions, and socio-ecological outcomes. This thesis takes up that task by exploring when and how CSs support adaptation, and when they may inadvertently reinforce vulnerability. In doing so, it advances both conceptual and practical understanding of climate information's role within complex adaptive systems.

The aim of this thesis is to disentangle the interactions between climate information and (mal)adaptation in socio-ecological-technical-systems across temporal scales and under climate change. Specifically, this thesis addresses the following research questions:

1. How does the availability and use of climate information influence the type, timing, and orientation of adaptation measures?
2. What are the mechanisms and processes through which climate services can enable or undermine sustainable adaptation in socio-ecological technical systems?
3. How do different types of climate information influence adaptation trajectories and system resilience?
4. How do prevailing norms and expectations about climate services affect their capacity to support context-relevant climate adaptation?

Methodology

The research follows a mixed-methods and interdisciplinary design, combining qualitative and quantitative approaches across five papers.

Structure of the research

Throughout the introduction I have described how the three core elements at the centre of this thesis, the SETS, (mal)adaptation, and CSs, should be understood form a system perspective. Figure 3, 4, and 6 give a schematic understanding of these concepts.

This section combines those frameworks into an overarching framework (Fig. 7), which describes how these three elements should be understood in relation with one another and how my research is structured around this understanding. This conceptualization of the research question is applied throughout the thesis and is used to guide how the individual research papers are developed and how they fit together within my research.

Within this understanding, CSs are treated as processes -not products- which deliver, translate, and synthesize observations and knowledge into information usable for adaptive decision making. This information is shaped not only by technological and technical capacity, but also decision-making needs, constraints, and biases, and by the feedbacks those decisions generate. CS design and delivery are situated within local SETS and are iterative and reflexive as conditions and goals change. Climate information informs adaptive decision-making which, in turns, shapes the (mal)adaptation processes taking place in the SETS. Needs and outcomes of adaptive decision making is defined by the local context of the SETS, as well as by external processes. (Mal)adaptive processes shape and reorganize the SETS according to the adaptive decision-making processes and in response to external stresses such as climate change and natural hazards. The changes in the SETS, whether current or predicted, are observed through various means and translated into climate information, thus completing the feedback.

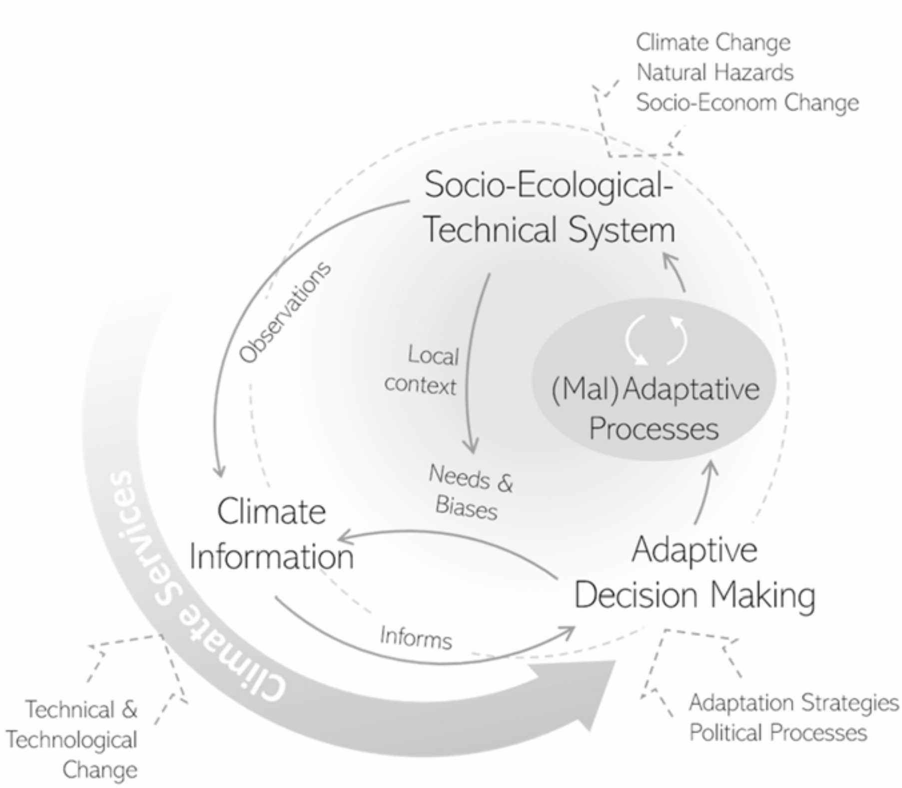
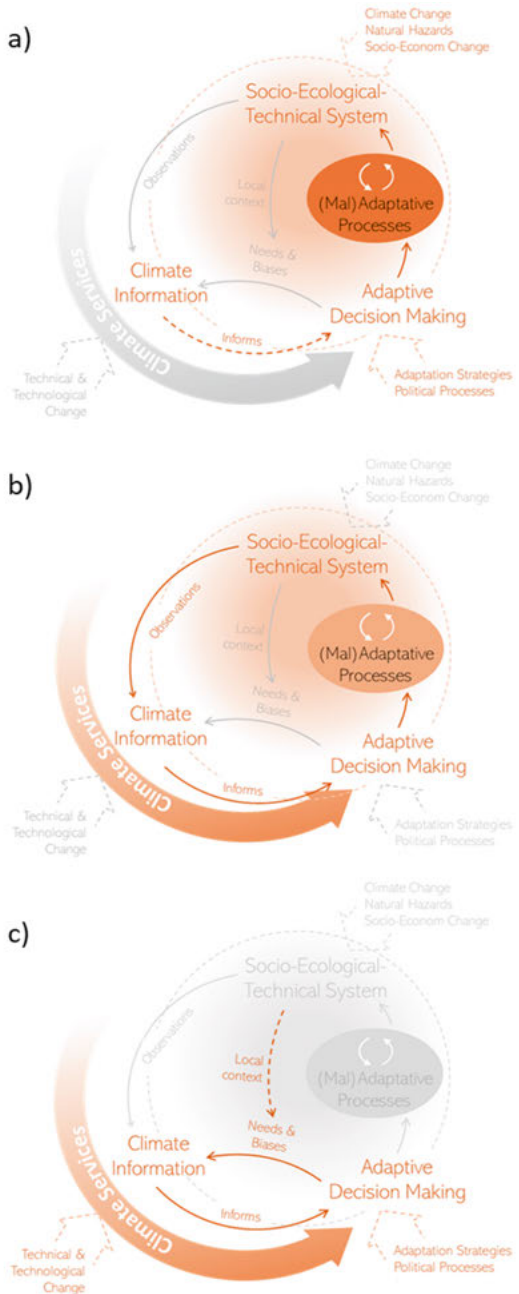


Figure 7: Conceptualization of the nexus between climate services and adaptation within Socio-Ecological-Technical Systems (SETS). SETS are complex, open systems governed by complex processes and feedbacks across human and natural elements. Adaptation processes are emerging processes of SETS which allow the system to respond to change. Unwanted systemic outcomes of the adaptive processes are called maladaptive. Adaptive decision-making shapes intentional climate adaptation according to the local context and to larger adaptive strategies and political processes. Climate services move different types of climate information downstream from the observation of the SETS towards adaptation and are, in turn, shaped by decision making needs and biases. Outside processes, such as socio-economic, political, technological, and climatic changes also impact the system.

Defining the framework has allowed us to structure the research around the main processes (i.e. feedbacks) identified. The thesis employs complementary mixed methodologies that reflect the SETS lens. Together, the papers examine how climate information is produced and delivered, and interpreted, and how resulting actions shape vulnerability and system trajectories over time. Below, I describe how each paper relates to the theoretical framework guiding this thesis (Fig. 8).



Papers I and II analyse a real crisis (i.e. the 2022 European Drought) to observe adaptation processes in situ (Fig. 8a). Papers III and IV synthetize and model the complex feedback dynamics governing the SETS and make the system explicit by focusing on the role that climate information plays in shaping adaptation, which in turn shapes the SETS, which ultimately leads to changes in climate information (Fig. 8b). Paper III will conceptually describe these dynamics while remaining grounded in the case studies. Paper IV expands on the findings from paper III by developing one of the conceptual models observed into a numerical system dynamics model. Paper V systematically explores the biases, expectations, and values that shape CS development and question how these can influence CSs' capacity to address adaptation's needs (Fig. 8c).

These methods combined allow to explore the full scope of the conceptual framework that was developed for this thesis.

Figure 8: How the conceptual framework presented in figure 6 was used to structure the thesis around its three main feedbacks: (a) (mal)adaptive processes within the SETS and the role that climate information plays within them; (b) how observations of the SETS are turned into climate information, defining which types of (mal)adaptative processes are favoured, which in turn reshapes the SETS; (c) needs and biases of the agents involved in adaptation shape the type of climate information delivered by climate services.

Europe-wide survey analysis (Papers I and II)

Paper I and II are the result of a collaboration with the Drought in the Anthropocene working group (DitA) of IAHS (International Organization of Hydrological Science) (https://iahs.info/Initiatives/Scientific-Decades/helping-working-groups/drought-in-the-anthropocene/). Both Paper I and Paper II investigate drought risk management in Europe during the 2022 drought event. They are based on a continent-wide survey conducted with DitA. This survey collected 487 responses from water managers across 30 European countries of which 481 were deemed valid. It was disseminated between March and October of 2023. The survey included 19 questions focusing on the impacts of drought in the respondents' regions and the risk management practices adopted by their organizations. Figure 9 shows the distributions of the responders to the survey across Europe and across areas of operations and type of organizations.

The survey was designed to capture both qualitative and quantitative insights, allowing for cross-country comparisons and analysis. Both papers use descriptive statistics to highlight commonalities and divergences in drought impacts and management responses across Europe.

However, the two papers diverge in focus and specific analytical methods:

- Paper I takes a broad and systemic approach. Its main goal is to provide a pan-European assessment of how drought risk is managed, how it is changing, and how the 2022 drought revealed structural deficiencies. Paper I adopts a diagnostic framing, combining the survey results with Standardized Precipitation Evaporation Index (SPEI). The paper presents the findings of the survey across countries and types of organizations, and discusses them within the perspective of the current European drought legislation. The methodology here is more exploratory and policy-oriented.
- Paper II, is analytical and narrows its scope to focus on preparedness. While still using the same survey, it links self-reported indicators of preparedness (i.e. use of forecasting and presence of Drought Management Plans; DMP) with reported response effectiveness and timeliness during the 2022 drought. This is done through statistical testing (chi-squared method) and correlation analyses. Additionally, it explores the effect that drought intensity (approximated using SPEI) have on preparedness. Paper II also tracks how experiences from previous droughts (i.e. the 2018–2019 drought) shaped current risk management practices by testing if organizations that have introduced DMPs after 2018 reported increased effectiveness in the response.

In summary, both papers use the same data source, but Paper I emph sizes systemic shortcomings, while Paper II quantifies how preparedness measures influenced drought responses.

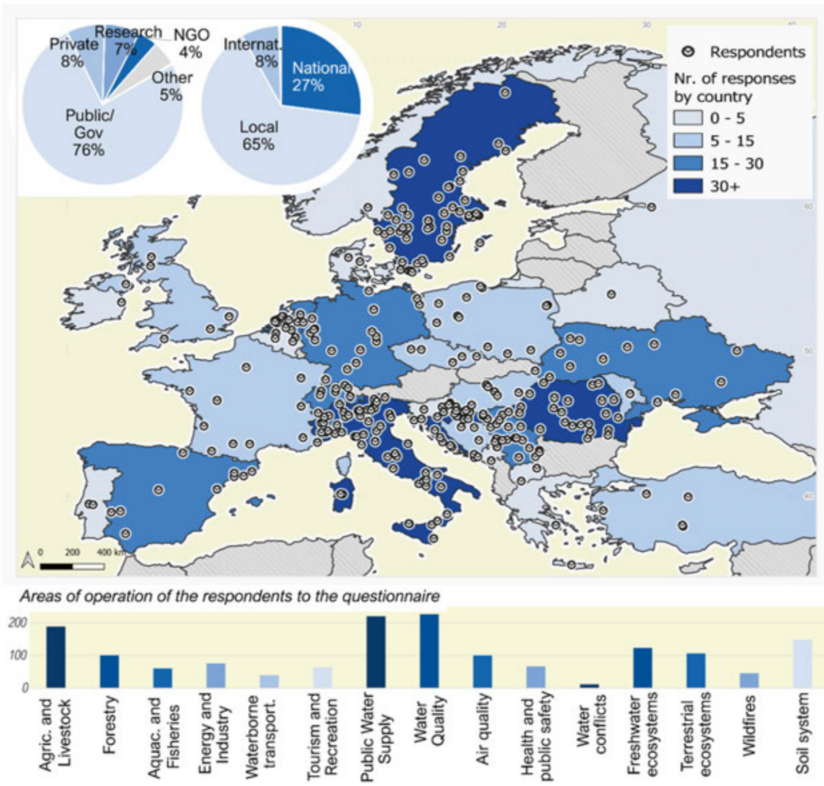


Figure 9: Overview of the distribution of respondents by (a) type of organization and operational level, (b) location and frequency across Europe, and (c) areas of operations. The total number of responses to the questionnaire was 481.

Conceptualizing maladaptation using system archetype (Paper III)

Paper III uses a mixed methodology approach to identify maladaptive dynamics in the development of CSs across five European case studies. The method is based on grounded theory and follows four iterative steps combining qualitative data collection, stakeholder engagement, and theoretical analysis (Fig. 10a).

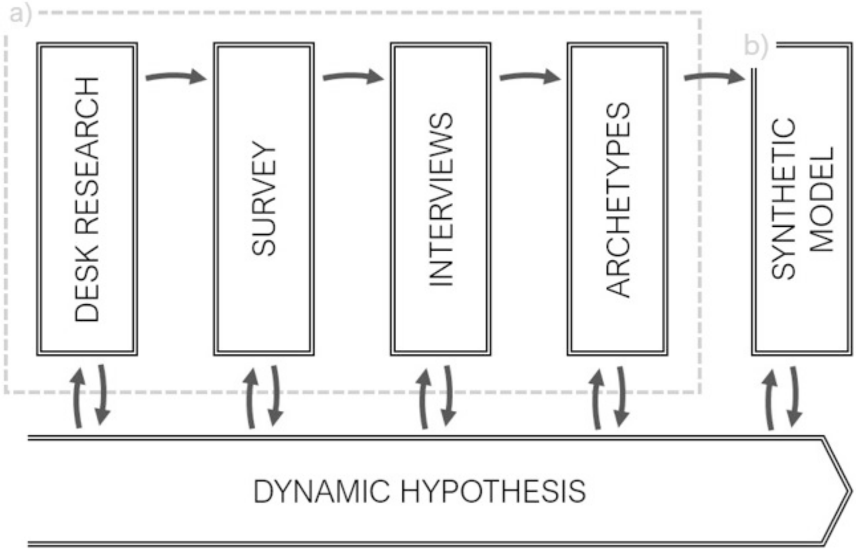


Figure 10 – Methodology followed in this paper III (a) and paper IV (b).

This methodology was applied across five diverse case studies from the located in Georgia, Greece, Italy, the Netherlands, and Spain. Each case involved the co-development of CSs and presented unique challenges related to drought, floods, water quality, or resource conflicts. The case studies are selected among the living labs of the I-CISK project (*European Union's Horizon 2020 research and innovation programme*).

First, we conducted in-depth desk research for each case based on the characterization reports created as part of the I-CISK project (Masih, 2022), as well as related literature. This included gathering data on environmental, social, and economic characteristics, climate hazards, existing climate services, their users and stakeholder needs. From this, we developed initial hypotheses about possible system archetypes relevant to each context.

Second, a targeted survey was designed to test for these archetypes. Each question was crafted to scope for the presence of specific feedback patterns and systemic issues. The survey was distributed to 1–3 key stakeholders per case, selected for their engagement in both the I-CISK project and in the local contexts. Thirteen responses were collected between March and June 2023. Questions were both closed and open-ended, allowing for extensive elaboration and minimizing misinterpretation through a shared glossary.

Third, results from the survey were used to construct preliminary system archetypes, each describing adaptive processes taking place within each case study and involving CSs. These were then evaluated in follow-up interviews with the same stakeholders between May and September 2023. The interviews allowed the researchers to validate and refine the archetypes based on local knowledge and stakeholder perspectives.

Fourth, the team applied two theoretical frameworks to assess if and how these processes could be defined as maladaptation. The pathways to maladaptation framework (Mangan et al., 2016) was used to determine whether the identified processes posed maladaptive risks. If so, they were classified using Juhola et al.'s (2016) typology of maladaptation.

System dynamics modelling (Paper IV)

In Paper IV, we use a System Dynamic (SD) modelling approach to investigate how CSs shape adaptation trajectories in a synthetic SETS under climate stress. Our model is based on the system archetype *Band-Aid Solutions* identified in Paper III and developed here into a numeric model (Fig. 10b).

We begin by formalizing the findings from Paper III into a SD model representing a managed catchment governed by a strategic-level decision-maker. The model is not site-specific but draws structural and parametric inspiration from the Italian case study from Paper III.

The model captures interactions between land use, water availability, adaptation strategies, wealth generation, and CSs. It includes two competing land-use types, intensive agriculture and ecological restoration, each with distinct water demands and contributions to wealth. The catchment's water system is modelled via a reservoir, whose volume (V) changes based on natural recharge (R) and agricultural use.

Short-term CSs promote response measures like reservoir expansion, which support agricultural production. Long-term CSs promote transformative adaptation, which supports ecological restoration. Feedback loops in the model represent both the Band-aid solutions archetype and the "reservoir effect." The model operates on an annual timestep.

We represent CSs through two proxies for short- and long-term CSs. These climate services are created artificially using normalized differences in recharge values over specific time windows, simulating sub-seasonal forecast (short-term CSs) and 50-year projections (long-term CSs). Recharge is stochastically generated to simulate climate variability and change over two centuries.

To analyses the output of the model, we defined a series of indicators working as proxies for aspects of the SETS such as tendency for crisis, risk of collapse, bias for short-term, and wealth generation. The model was run across five scenarios with varying CS orientations and three scenarios with varying intensity of climate change. Each scenario was run 200 times to allow for statistical analysis of the output indicators. Output indicators were analysed using regression to explore relationships among system variables and adaptation outcomes.

Critical content and survey analysis (Paper V)

This study uses a three-step mixed-methodology to investigate how CSs are defined and recognized in practice, and whether these perceptions are shaped more by their functions or by their format.

First, we conduct a systematic analysis of existing definitions of CSs using a simplified version of the Abstraction Hierarchy framework (Rasmussen, 1985). This method allows us to categorize definitions based on their level of abstraction, from purposes to functions. We then identify a series of purposes, functions, and forms that users and producers associate with CSs

Second, we design a survey grounded in the functional categories identified in the previous step. The core of the survey presents participants with diverse examples of CSs, each varying in both form and function (Fig. 11). Respondents are asked whether they consider each example to be a CS, thereby revealing whether their judgments are shaped more by form than by purpose or function. This step also helps identify which functions are perceived as most essential, and whether function-driven formats are systematically excluded when presented in unconventional formats.

Finally, we analyse the survey responses using statistical methods, including chi-squared tests and Pearson's correlation coefficients. These tests are used to identify significant differences in recognition patterns across respondent groups, allowing us to assess whether disciplinary background or professional role influences how CSs are understood and categorized.

Together, these three steps offer a structured approach to uncover potential biases in how CSs are conceptualized and recognized, especially regarding the exclusion of non-conventional formats.

EXAMPLE OF QUESTION FROM SURVEY

5. Flood Murals Beira *

Led by IHE Delft and local artists, this community-focused mural in Mozambique educates on flood preparedness using visual symbols and directs towards sources of information (online portal, radio and SMS). The Murals show historical as well as projected flood levels and risk.

- **Information Provided:** Visualization of flood risks and preparedness measures, including historical and projected risk .
- **Development:** Created with local artists and community input.
- **Delivery:** Public murals in flood-prone areas.
- **Users:** Local residents and community leaders.

Is this a Climate Service?

○ Yes ○ No

Figure 11: Example of question form the survey used in paper V. Responders were asked to identify whether a certain example of climate-information related "object" should be considered a climate service or not.

Limitations

This thesis combines empirical, conceptual, and modelling approaches. Each comes with limitations that limit inference.

First, the 2022 drought evidence relies on a large but non-probabilistic survey, and the respondents represent organizations that were reachable through professional networks or online searches. While the geographical coverage and sample size are strengths, selection bias remains possible. Some sectors and countries may be over- or under-represented. Additionally, as the survey relies on self-reporting, it cannot be considered entirely objective and in cases might may not capture the reality of the situation. Its findings should therefore be read as indicative of patterns rather than as a causal estimate. Nonetheless, we still believe our findings to be significant as they largely align with state-of-the-art literature on the subject.

Second, the archetype analysis uses a small set of cases to illustrate recurrent dynamics. Archetypes are useful for recognizing patterns and for informing design, but they are not exhaustive. Other maladaptive or adaptive dynamics may be present in different contexts, and the boundaries between archetypes can blur in practice. The ex-ante framework proposed is therefore a heuristic to support reflection, not a diagnostic instrument that can replace in-depth, context-specific inquiry.

Fourth, the system dynamics model is synthetic and simplistic. It aims to make mechanisms explicit rather than to reproduce any one basin. Parameter choices and functional forms are stylized, and many socio-ecological processes are represented implicitly. As such, numerical results should not be generalized beyond the qualitative insights they support, and should be seen as an exercise in "thinking outside the box" and "challenging assumptions" rather than predictive tools.

Finally, the recognition survey focuses on a limited set of public European research projects linked CSs. Preferences and biases may differ in other regions, sectors, or among private actors. While the findings point to shared expectations across disciplines in this sample, they should be extended and tested in other populations before drawing broader conclusions.

Findings

This section presents the findings of my research across the five papers. It follows the research logic, moving from empirical observation (Paper I and II) to conceptual abstraction (Paper III), to numerical modelling (Paper IV), to epistemic conditions (Paper V). Together, the papers trace the conditions under which climate information supports or undermines adaptation.

2022 European drought: climate services and adaptation in practice *(Papers I & II)*

Paper I and II are the result of a vast survey study carried out throughout the 2022 European drought. The survey leveraged on the DitA network to reach out water managers all across the European continent and interrogate them regarding their experiences about the management of the 2022 crisis.

The combined analysis of the 2022 European drought (Papers I and II) provides the empirical anchor for this thesis, demonstrating how climate information (here in the form of seasonal and sub-seasonal forecasting) was mobilized by organizations across 30 countries (481 respondents) and with what adaptive consequences. The study enriches the results from the survey with a visualization of the SPEI values across the continent (SPEI-3 and 6 were both used for different purposes) (Fig. 12).

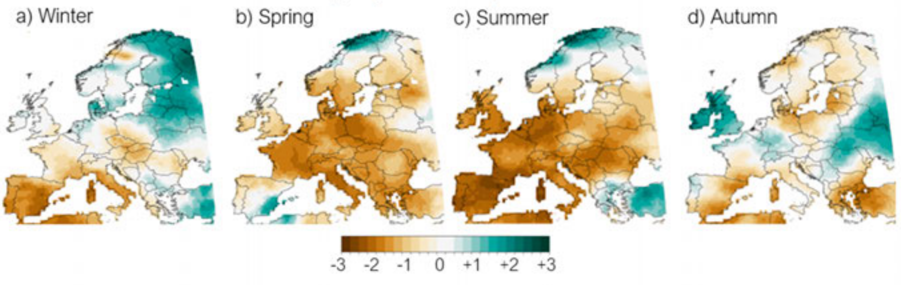


Figure 12: Seasonal evolution of the Standardized Potential Evapotranspiration Index for 3-month accumulation (SPEI-3) for Europe during 2022; (a) Winter (SPEI-3 February); (b) Spring (SPEI-3 May); (c) Summer (SPEI-3 August) and (d) Autumn (SPEI-3 November).

A first headline result is that organizations with preparedness measures in place, such as forecasting systems and DMPs, responded more effectively and quickly to the 2022 drought compared to those without. On average, organizations with forecasting systems implemented drought responses two months earlier (Figure 13a). On a 0 to 5 scale, organizations using forecasting rated their response effectiveness higher than those without by 0.3 (Fig. 12b). Similar results are observable among organizations with DMPs, responding one month earlier and being 0.5 more effective than those without. All of these results were found to be significant (95% significance), using a chi-squared test.

While different types of DMPs and forecasting also led to differences in response timeliness and effectiveness, these differences were minor and not statistically significant (Fig. 13b).

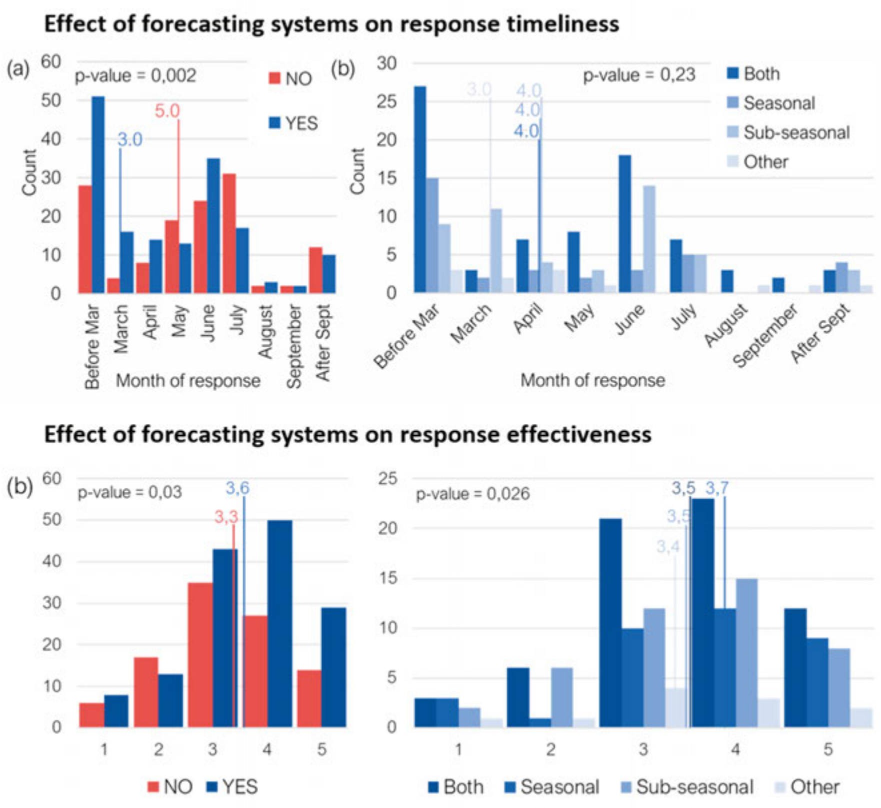


Figure 13: Histograms showing the difference in of perceived timeliness (a) and effectiveness (b) according to the presence or absence and typology of forecasting systems across the responses to the survey. The median (for the timeliness) and mean (for effectiveness) values of each subgroup are displayed on the graph, as well as the p-value resulting from the chi-squared tests.

Both papers converge on the finding that 2022 drought risk management measures were skewed towards short-term needs. Paper II distinguishes between sub-seasonal and seasonal forecasting, as well as short- and long-term DMPs (i.e. contingency plans vs management plans). Across the sample, it can be noticed how both in the case of forecasting and DMPs, short-term formats were wider spread than long-term ones (still, organizations using a combination of short and long-term remains the most common configuration).

Paper I further shows the extent of short-termism in the management measures use. The measures taken to reduce the impact of the drought were mostly concerned with increasing supply to maintain production rather than capping demand, such as reallocations, emergency abstraction (including groundwater pumping), and temporary transfers to maintain production. While not the only measures taken, short-term and supply-side response measures remained the widest spread, especially across agriculture dependent countries (Fig. 14). While these measures are necessary during crisis management, they also show a prioritization of status-quo maintenance and economic productivity, often postponing structural demand management, diversification, or ecosystem-based measures. Notably, ecosystem-oriented and long-term measures (e.g., restoration, nature-based, systemic efficiency gains) remained under-utilized, despite their repeated endorsement in EC communications (i.e. non-binding EU policy). This imbalance reflects the thesis's broader concern with maladaptation: when crisis response repeatedly leans on operational fixes, it crowds out transformative investments needed to address root vulnerabilities.

These patterns are consistent with Paper I's brief appraisal of Europe's continent-wide drought governance scaffolding. The only current binding EC directive which directly mentions droughts (i.e. the Water Framework Directive 2000/60/EC) frames them extraordinary, time-confined events.

This framing enables countries to allow in their own legislation the derogations of ecological and long-term need (such as ecological flow requirements) during periods of crisis. In the short run, such derogations allow for the safeguarding of agricultural and industrial production, yet in the long run, they erode ecosystems that buffer hydrological variability, transmitting risk to future seasons and downstream users (Di Baldassarre et al., 2018; Van Loon et al., 2024, 2016). This is emblematic of adaptation that externalizes costs to ecosystems and future generations (Barnett and O'Neill, 2010; Juhola et al., 2016; Reckien et al., 2023); maladaptive trajectories the thesis interrogates in later chapters.

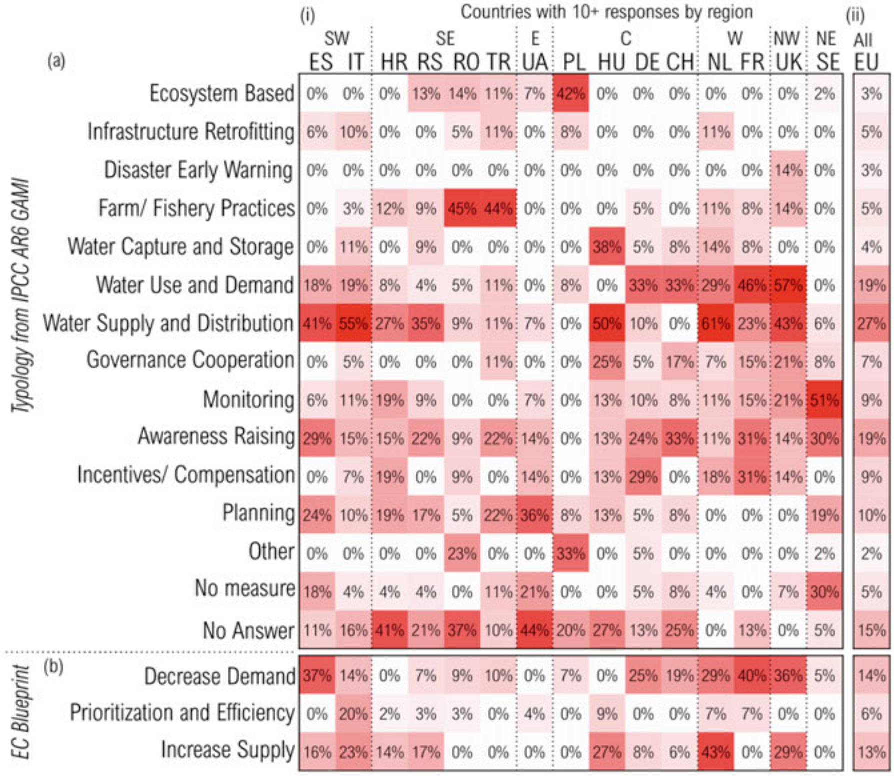


Figure 14: Measures taken by the respondents organised by country (only countries with 10+ responses), and region. IPCC AR6 GAMI and EC Blueprint indicate the two typology of adaptation used to reclassify the measures taken by the responders. The numbers represent the percentage of respondents using a specific measure to the total number of respondents by country. The European regions are described using the acronyms: SE (southeast), SW (southwest), E (east), C (central, W (west), N (Northwest), NE (northeast). Countries are indicated using their two-letter country code.

Additionally, papers I and II document marked heterogeneity across countries and sectors. Preparedness varied widely, with some national and basin authorities having widely adopted DMPs and used forecasting, while others have not. Prior drought experience (notably 2018-2019) appears to have shaped organizational learning, with some authorities reporting introducing and upgrading their plans and monitoring systems that improved 2022 performance (Paper II). Together, these differences underscore the central claim of the thesis the processes through which climate information becomes adaptation (or fails to) are shaped by larger socio-ecological conditions.

Paper I and II argue that the 2022 drought represents an ideal window of opportunity for systemic change. We advocate for a European Drought

Directive to harmonize drought risk management across the continent. The proposed directive represents a critical policy shift toward systemic drought risk management at the continental level. It calls for harmonized approaches across EU countries mandating long-term and systemic risk management perspectives, integrated drought risk management, and cross-border cooperation. The directive aims to address the root causes of drought vulnerability and avoid maladaptive practices, as well as enshrining drought preparedness, forecasting, and impact assessment (and by extension drought-related climate services) into strategic adaptation planning rather than crisis responses. This aligns closely with the thesis focus on integrating climate information within SETS to support sustainable adaptation. The directive provides a tangible institutional mechanism for operationalizing anticipatory governance and balancing short-term needs with long-term resilience in a changing climate.

In sum, in a year that multiple studies identify as record-breaking for European drought severity, my research shows that the presence and use of forecasting systems fundamentally shaped the timing and effectiveness of the type of response. At the same time, the type of measures carried out reflects a crisis-oriented approach in drought risk management and a preference for short-term operations and for maintenance of the status-quo in period of crisis. This is further highlighted by the European legislation, which frames drought as an extraordinary event. These two papers conclude with a call for European-wide governance.

Climate services and maladaptation (Paper III)

Paper III is a first attempt to explicitly interrogate the relationship between CSs and (mal)adaptation from a systemic perspective. This work operationalizes system thinking by using system archetypes to conceptualize maladaptive processes across a series of case studies from the I-CISK project. It then uses the *Pathways to Maladaptation Framework* (Magnan et al., 2016) to diagnose whether the processes identified should be classified as maladaptive and why. This study treats CSs as processes that interrelate within the complex processes and dynamics of the SETS, and shows how these interactions can steer trajectories toward or away from adaptation.

Through an iterative process, three archetypes were identified (Fig. 15): *Fixes that Fail*, where short-term measures address symptoms yet worsen root causes over time. *Band-Aid Solutions*, when quick fixes yield immediate relief while displacing or delaying structural change; and *Success to the Successful*, which describes how better-resourced actors capture a growing share of benefits, widening inequalities.

Fixes that Fail emerged in the Spain and Georgia cases, where reliance on seasonal forecasts helps sustain water-intensive production, encouraging further water exploitation pressure and causing ecological damage in the long-term. In both cases, the water system is limited in capacity and already overexploited, in Spain the due to over drilling of wells (often informally) and in Georgia due to the poor state of the water infrastructures in the region. *Band-Aid Solutions* were identified in Spain, Italy, and the Netherlands, where operational forecasting allows otherwise unsustainable agricultural productions to cope with increasing drought risk, all-the-while sidelining sustainable alternatives; hence reducing incentives to de-intensify agricultural production, or transition to more drought resilient activities (such as agropastoralism in the case of Spain). Finally, *Success to the Successful* was observed in the Netherlands and Greece, where organized sectors (such as tourism in Greece) were better positioned to shape co-creation processes and appropriate service benefits relative to less organized users; hence exacerbating already existing inequities. Two additional archetypes were considered during scoping, *Eroding Ambitions* and *Tragedy of the Commons*, but were ultimately discarded in the final analysis.

A central ontological contribution of this work is the challenge to the “no-regret” framing of CSs (or “panaceas”, using Ostrom’s terminology (Ostrom, 2007). Paper III shows that CSs are not necessarily always positively improving the outcome of adaptation, but rather that their use needs to be contextualized within ongoing (mal)adaptive SETS processes. CSs can yield immediate benefits while still heightening systemic risk, either by masking root causes, delaying structural change, or shifting burdens onto other social groups and ecosystems. This argument is consistent with the maladaptation literature that warns against responses that reduce risk in the short term, or for a specific group, while increasing vulnerability in the long term or elsewhere (Erikssen et al., 2011; Barnett and O’Neil; 2012, Juhola et al. 2016).

Beyond diagnosis, Paper III proposes an ex-ante framework as a practical way to test these risks during the design, development, and implementation of CSs. The intent is not to diminish the operational value of climate information, but to make explicit the systemic impact, who it accrues to, and what is traded off in the process.

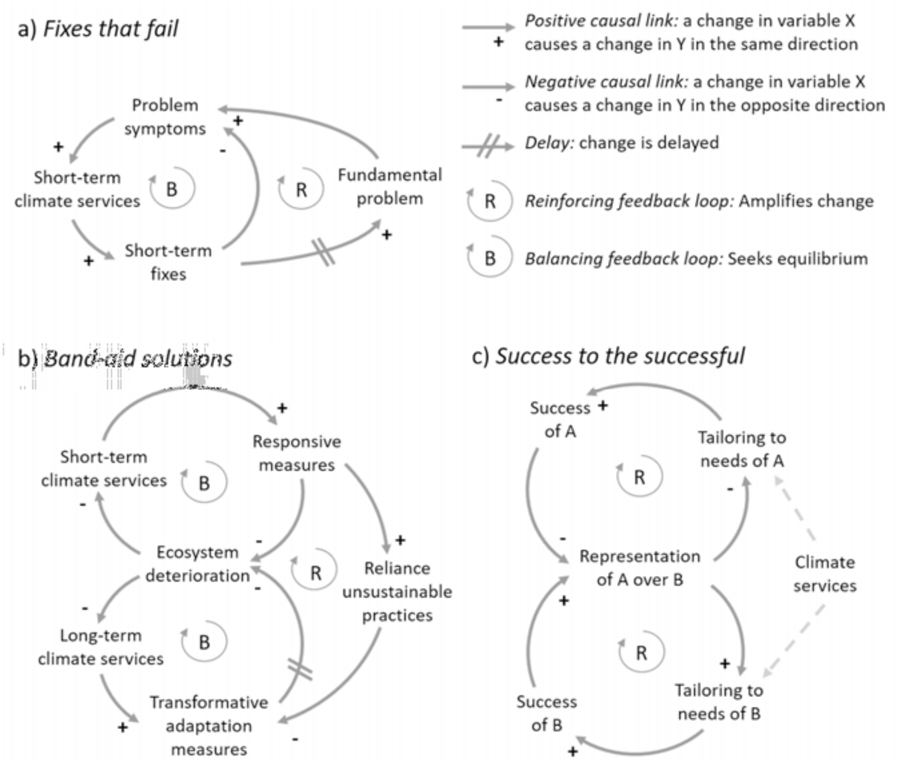


Figure 15: Causal Loop Diagram showing the Generalized archetypes of the interaction between climate services and adaptation identified across the five case studies from the I-CISK project using the methodology used in paper III. The arrows indicate whether a variable influence another, while the (+) and (-) signs next to the arrows indicate the relation type, with a (+) indicating a direct relation while (-) indicates an inverse one. Dashed arrows relations with variables that while are not part of a feedback loop. The (B) and (R) signs inside the feedback loops indicate balancing and reinforcing feedback loops respectively.

Our framework allows to critically assess the success metrics used for CSs, showing that uptake is an insufficient proxy for adaptation because it conflates delivery of information with reduction of risk. The paper supports the uptake–output–outcome–impact evaluation (Perrels et al, 2020) which embraces systemic perspectives and includes long-term impact on the ecosystems or vulnerable groups. This reframing connects directly to practice by encouraging teams to design monitoring & evaluation schemes that go beyond CS output and uptake and instead consider outcomes and impacts over relevant temporal, spatial, and social scales.

The findings of paper III reconnect to the evidence of the continental-level risk management reported in Paper I and II. Response to the 2022 European drought was dominated by short-term supply-side measures and with possible derogations of ecological flows. These dynamics echo Fixes that Fail and Band-Aid dynamics: immediate relief, deferred costs, and shrinking ecological buffers. At the same time, large disparities in preparedness mirror Success to the Successful, as institutions with plans and forecast were capable of implementing earlier and more effective actions.

Modelling competing time scale of CSs and adaptation CS (Paper IV)

Paper IV examines how different configurations of climate information shape adaptation pathways in a water-scarce SETSs by building a system dynamics model that explicitly represents short-term and long-term CSs and their feedbacks with production, water resources, and ecosystems. The study extends the diagnostic insight from Paper III by translating the *Band-Aid Solutions* archetype into a numerical socio-hydrological model that traces how short-term fixes compete with systemic needs. The model is a synthetic, yet realistic, representation of a watershed where agricultural production and ecological restoration compete as the two main land uses. The model is based on the challenges and dimensions observed in the Italian cases study from Paper I, as well as utilising comparable metrics as the region of the Italian case when defining climate change scenarios. In addition to the *Band-Aid-Solutions*, the model describes the reservoir effect described in many socio-hydrological studies, whereby increasing reservoir storage enables increased water consumption (Di Baldassarre et al., 2018; Garcia et al., 2020).

The model artificially defines two types of CSs. Short-term CSs are proxied by seasonal forecasting that support response operational measures, such as the expansion of the reservoir. Long-term CSs are proxied by end-of-the-century projections that inform strategic choices such as ecological restoration. Both types of CSs are defined by simple equations calculating the standardized difference between the average recharge at the corresponding time-frame with a running average of the current state. The magnitude of the difference is then used to define the extent of the short- and long-term measures. Figure 16 shows the model as a causal loop diagram.

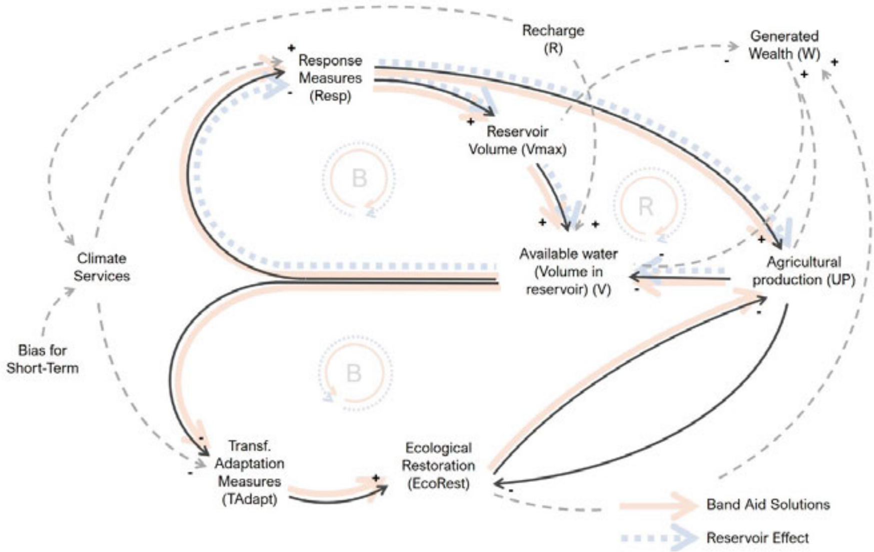


Figure 16: Causal Loop Diagram of the model. Arrows indicate whether a variable influences another, while the (+) and (-) signs next to the arrows indicate the relation type, with (+) indicating direct relation while (-) indicates an inverse one. Dashed arrows show relations that are not in a feedback loop. The (B) and (R) signs inside the feedback loops indicate balancing and reinforcing feedback loops respectively. The coloured arrows describe two system archetypes present within the model. The orange arrows represent the Band-aid solutions archetype identified by Biella et al. (2024), while the light-blue arrows represent the Reservoir Effect.

By toggling the relative weight of these levers and exposing the system to different degrees of climate variability a series of scenarios are created representing several types of short- and long-term regimes and of climate change regimes.

The scenarios with differing time horizon bias show a system where trade-offs between short-term gains and long-term sustainability are evident (Fig 16). When short-term information dominates decision making, the system achieves rapid wealth gains but cycles through frequent water crises, ultimately facing a higher probability of collapse (Fig. 17a). When long-term information dominates, returns are slower but crises are fewer and the probability of collapse declines sharply, yet the system produces limited wealth (Fig. 17c). Mixed CS scenarios can avoid the worst outcomes while maintaining wealth generations production, but remains highly volatile and sensitive to shocks (Fig 17b).

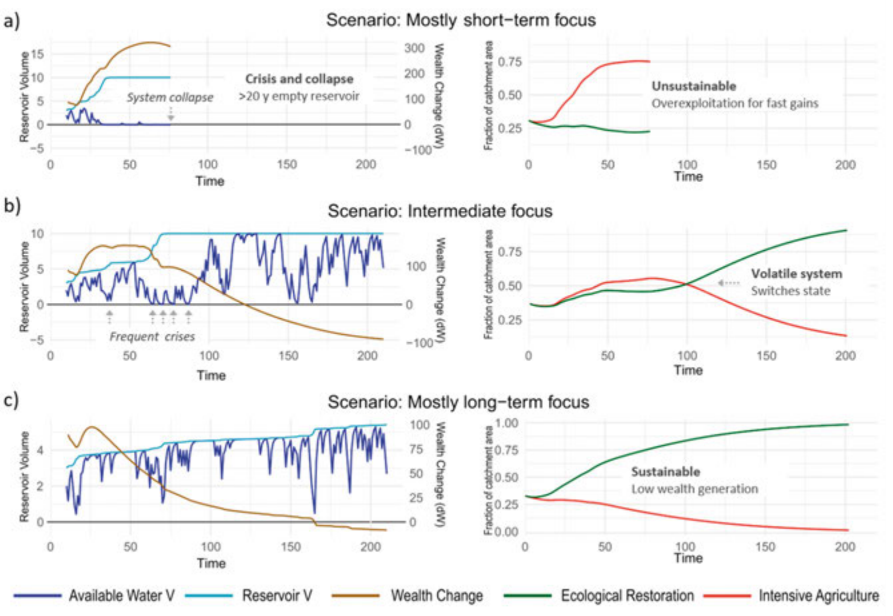


Figure 17: Selected output from the climate change scenarios. The three scenarios include: Mostly short-term focus (a); Intermediate focus (b); and Mostly long-term focus (c).

The study also explores the behaviour of the system under different climate change regimes. A central mechanism is the amplification of reactive feedbacks under climate change. As recharge variability increases, the perceived need for immediate coping rises, which further strengthens the weight of short-term signals in decision making. The model reproduces a feedback loop in which each crisis justifies additional reactive measures (i.e. expansion of the reservoir), which temporarily stabilises production but degrades ecosystem and amplifies the reservoir effect. These are dynamics that Paper III flagged as *Band-Aid Solutions* and *Fixes that Fail*, and it is consistent with adaptation literature warning that short-term measures can increase long-term risk and reduce the incentive for structural change (Barnett and O'Neill, 2010; Eriksen et al., 2011; Fankhauser et al., 1999; Fedele et al., 2019; Magnan et al., 2016; Reckien et al., 2023).

The model makes explicit the trade-offs that underpin adaptation decisions. Increasing wealth and maintaining production often draw down natural capital and compromise water security, while restoring ecosystems and reforming demand can constrain near-term output but enhance stability. These trade-offs are path dependent because the chosen sequence of actions changes the state of the system, for example by degrading or rebuilding ecological storage, which in turn reshapes the effectiveness of subsequent measures.

Paper IV provides a mechanistic explanation for the empirical imbalance seen in 2022 where short-term measures were preferred and long-term or ecosystem-based measures remained underused (Papers I and II). Taken together, these studies highlight how focusing predominantly on coping strategies, policymakers risk narrowing the temporal and political window needed to initiate long-term, structural reforms. This is a missed opportunity for reframing drought not only as a crisis, but also as a catalyst for deep governance transformation, as argued in our call for a European Drought Directive in Paper I. Recognizing crisis events as opportunities is key to shifting away from maladaptive trajectories and toward resilient and equitable water futures.

Three policy-relevant insights follow. First, relying on a single type of information increases the risk of path dependency and reduces adaptive flexibility. Dominant short-term signals privilege status-quo maintenance and delay transformation, and reflect crisis-centred and technocratic approaches mirroring what was reported during the 2022 drought (Paper I). A governance scaffold that institutionalises both horizons is required to avoid bias for the short-term and avoid lock-ins. Second, short-term gains and long-term goals can diverge markedly. Strategies that look successful on near-term output can accumulate hidden liabilities in groundwater and ecosystems and ultimately jeopardise the system, whereas strategies that appear costly initially can improve long-run stability. Finally, CSs do play an active role in defining the outcomes of adaptation, as the choice of climate information can define the time horizon at which risk is managed and at which trade-offs are understood.

Paper IV therefore provides a quantitative counterpart to Paper III's call to move beyond the idea of CSs as "panaceas" and instead assess long-term outcomes and impacts beyond uptake or immediate effectiveness.

Form over function, biases shaping CSs and their adaptive consequences (Paper V)

Paper V investigates the expectations about what CSs look like and the ways in which these can shape what gets produced, recognized, and used. We first apply a simplified Rasmussen Abstraction Hierarchy to five definitions of CSs to define their purpose, function, and form. This allowed us to identify shared purpose, functions, and forms across definitions of CSs (Fig. 18).

Building on this framing, we design a vignette-based survey targeted at researchers, providers, and practitioners involved in several public Europe-based CS projects. The survey presents respondents with a series of examples of CSs stratified by a matrix that crosses functional alignment (fitting vs not fitting functions) with form familiarity (conventional formats such as digital tools vs unconventional formats such as workshops or art-based tools). Respondents are then asked to classify each example as a CS or not. We then analyse responses with chi-squared tests and Pearson correlations to test for differences across groups and the salience of form versus function.

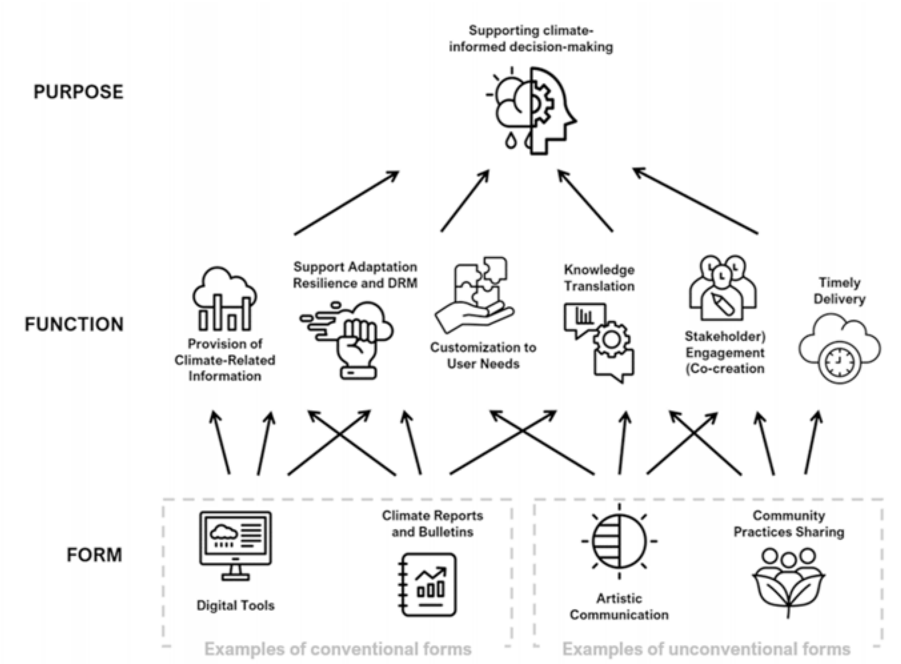


Figure 18: Schematic representation of the purpose, functions and forms of climate services. The purpose and functions presented are those identified from our analysis of the definitions of climate services, while the forms are a non-exhaustive list of examples of possible forms. *Icons taken from thenounproject.com. Credits to the authors in the acknowledgements.*

The results show a consistent preference for digital, data-driven, and online tools irrespective of whether those formats best deliver adaptation functions. Participants were more likely to recognise dashboards, portals, and web platforms as CSs than unconventional but functionally aligned formats such as participatory workshops and artistic creations.

Paper V shows that unfamiliar or non-digital formats are less likely to be seen as legitimate services even when they provide climate knowledge, support decision making, or are co-created with users. This preference matters for adaptation because recognition shapes funding, institutional support, and ultimately what information reaches whom. This limits usability for stakeholders who engage through processes relevant to their local context rather than through online tools, and it narrows the repertoire available to support transformative measures. In other words, the bias toward form can produce a misalignment with adaptation needs by privileging products that fit existing data infrastructures over services that fit decision contexts.

A second key finding is that these expectations are shared widely across disciplinary backgrounds (Fig. 19). Contrary to an assumption that interdisciplinarity would diversify recognition, the survey detects limited variance among natural sciences, social sciences, and humanities in classifying examples as CSs. This suggests that norms about what counts as a CS are internalised across domains, which helps explain the persistence of the usability gap despite years of calls for co-production and user-centred design.

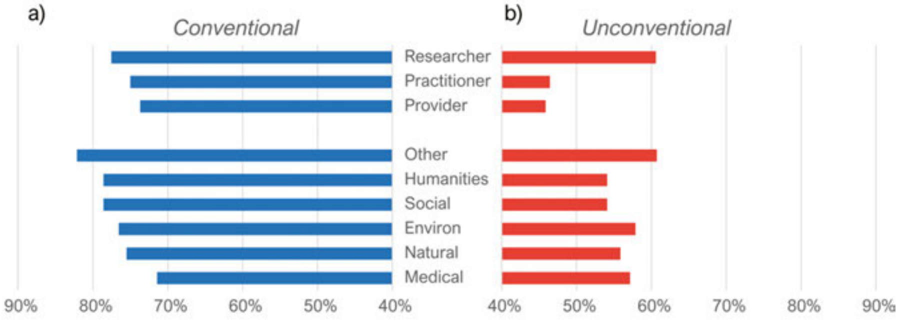


Figure 19: Percentage of recognition of the examples of conventional (a) and unconventional (b) CSs provided in the survey according to the responders professional and academic background. Only responders' groups with at least 10 answers are included in the figure.

Researchers were more likely than practitioners to identify unconventional CSs as valid; yet this difference was not found to be statistically significant. While not confirming it, this difference suggests an overall bigger open mindedness of researchers compared to practitioners, which signals the importance of having academia involved in the development process.

Both these results suggest a deep engraining of assumptions among CS producers, suggesting that interdisciplinarity (i.e. the collaboration between professionals from differing disciplines) alone might not be sufficient to address the usability gap. To this end our research encourages to move towards *transdisciplinarity*, where explicit effort is made to integrate knowledge and perspectives, and where cross-trained professionals, as well as stakeholders take a central role in the development of CSs (Biesbroek et al., 2009; Christel et al., 2018).

Paper V also supports the thesis that the type of information provided by CSs often misaligns with the adaptation needs and reality of stakeholders (Boon et al., 2024, 2022, 2021; Findlater et al., 2021). Formats that are most recognisable to producers, like forecasting platforms, tend to support incremental, technocratic responses, while formats that could be more effective for marginalised users and for catalysing transformation, like projects aimed at raising public risk awareness, are less recognised and therefore less likely to be funded or scaled. This aligns with the continental picture from Papers I and II, where adaptation during 2022 was dominated by short-term operational actions, and with the modelling in Paper IV, which shows how overweighting short-term signals fosters reactive feedbacks and frequent crises. Paper V shows a similar mechanism, where CSs that are less aligned with the status quo are also less likely to be recognized as legitimate.

Finally, Paper V encourages moving beyond narrow metrics of success. Counting tools or platform users is a weak proxy for adaptation because it conflates uptake with outcomes (Boon et al., 2024, 2022; Perrels et al., 2020). The paper argues for evaluation that privileges purpose and function, and recommends that calls and key performance indicators reflect these priorities such as usability, salience, equity of engagement, trust, and longer-term impacts. This argument complements the critique of uptake in Paper III.

In sum, paper V identifies institutional and epistemic conditions that determine what CSs are in practice, and thus which adaptation pathways they enable. By showing a shared preference for technocratic, digital formats, limited recognition of non-conventional services, and weak differentiation across disciplines, it explains why services that could support equitable and transformative adaptation remain marginal. The paper therefore links the production side of climate information to the socio-ecological outcomes documented elsewhere in the thesis. If services are defined and funded by form rather than by how they deliver adaptive function, then climate information will continue to flow into reactive, status-quo-preserving responses. If, instead, recognition and evaluation shift toward purpose, function, and context, then portfolios can include formats that are usable and used by diverse actors, including those most exposed, creating institutional space for long-term measures and reducing the risk of maladaptation.

Discussion

Climate services are endogenous to SETS

This thesis argues that CSs should be understood as endogenous elements of the SES rather than exogenous inputs to decision making. For that, it embraces a SETS perspective, where the technological system is explicitly described as a co-evolving and adaptive system within the SES (Chester et al., 2023; Markolf et al., 2018; McPhearson et al., 2022). Seeing CSs from within the system helps explain why the same information can yield very different adaptation outcomes across places and times, and why investments in data and models do not automatically translate into reduced vulnerability or avoided losses. It also clarifies how CSs are co-produced by institutions, infrastructures, ecologies, and (especially) people: their effects are mediated by feedbacks and path dependencies that are both adaptive and maladaptive (Bartelet et al., 2022b; Birkmann, 2011; Naylor et al., 2020; Preiser et al., 2018).

Across the thesis, CSs are shown to be endogenous to SETS, with their impacts emerging from how they are embedded in within it. During the 2022 drought, organisations with DMP could more effectively make use of forecasting, leading to faster and more effective response (Paper II). Despite the presence and use of forecasting, measures remain mostly short-term and supply side (Paper I), showing that the presence of information alone is not sufficient to sway adaptation towards longer perspectives. The archetype analysis of Paper III clarifies the mechanisms behind these system differences. When only focussing on short-term risk, actors can relieve symptoms while disregarding (or even worsening) the root causes, or delay structural change (Barnett and O'Neill, 2010; Fedele et al., 2020; Magnan et al., 2016; Reckien et al., 2023; Schipper, 2020). This is further shown in Paper IV, where the long-term sustainability of the system directly depended on the type of information that was given more weight. Paper IV also shows that when services are instead designed and embedded to expose trade-offs, they can help dampen maladaptive dynamics. Finally, biases and expectations about the format of CSs shape the way services are developed, potentially affecting which type of adaptation they will ultimately cater to and for whom (Paper

V). Together, the papers show that designing, using, and evaluating CSs must be systemic to avoid maladaptation and support resilient pathways

This endogenous view of CSs also clarifies why outcome-based evaluation is essential (Dilling and Lemos, 2011; Findlater et al., 2021; Perrels et al., 2020). Counting downloads or logins tells us little about how a service changed the system. The archetypes and the model both show how short-term effectiveness can conceal long-term maladaptation, and how success for one group can shift risk to others.

Finally, a systemic perspective changes how we understand the role of climate information in transformative adaptation (Boon et al., 2022, 2021). CSs can support transformation when they are part of transformative processes, helping identify lock-ins, reveal trade-offs, and sustain change (Boon et al., 2021). They can also inhibit transformation when they mainly optimise the status quo, especially if the status quo is ultimately unsustainable. The Spanish case from paper III exemplifies this, with drought forecasting playing a role in making an milk production (a water intensive activity which is unsustainable in the region) more capable to externalize its risk by relying more ground water, all the while decreasing the incentives to protect the traditional agroecological production (the *dehesa* system) which is shown to be drought resistant (Ropero Szymañska et al., 2025). The evidence assembled across the five papers suggests that both possibilities are present, and that design and governance choices tilt the balance.

In summary, if we see CSs as components of SETS, then their value lies less in how accurate their data are and more in how they are embedded within anticipatory, recognitory, learning, and adaptive functions. The empirical and modelling evidence presented here points to a simple conclusion. CSs shape and are shaped by institutions, infrastructures, and ecologies. Their design should therefore reflect this.

Balancing information horizons

The thesis shows that adaptation pathways are sensitive to the type of information used; particularly the time horizon which these cater to. The system dynamics model of Paper IV demonstrates that when short-term CSs dominate, the system tends to favour rapid gains in production and wealth, at the cost of drawing down ecological buffers and increasing the risk of crisis in later periods. As crises become more frequent, the perceived need for short-term measures increases, which further reinforces the weight of short-term information in decision making. This self-reinforcing loop is one mechanism behind path dependency and lock-in (Di Baldassarre et al., 2015; Haer et al., 2020; Moallemi et al., 2022; Sivapalan and Blöschl, 2015) (Fig. 20a). The same model shows that when long-term CSs carry greater weight, decisions shift toward restoration and demand reform, crises become less frequent, and the risk of collapse declines. Returns are slower and less visible at first, but system stability improves. Yet, as the system generates fewer wealth this also can constrain adaptation options (Fig. 20b). Ensuring that adaptation is provided with an adequate spectrum of information portfolios is necessary to avoid the worst outcomes (Birkmann, 2011; Preiser et al., 2018) (Fig. 20c).

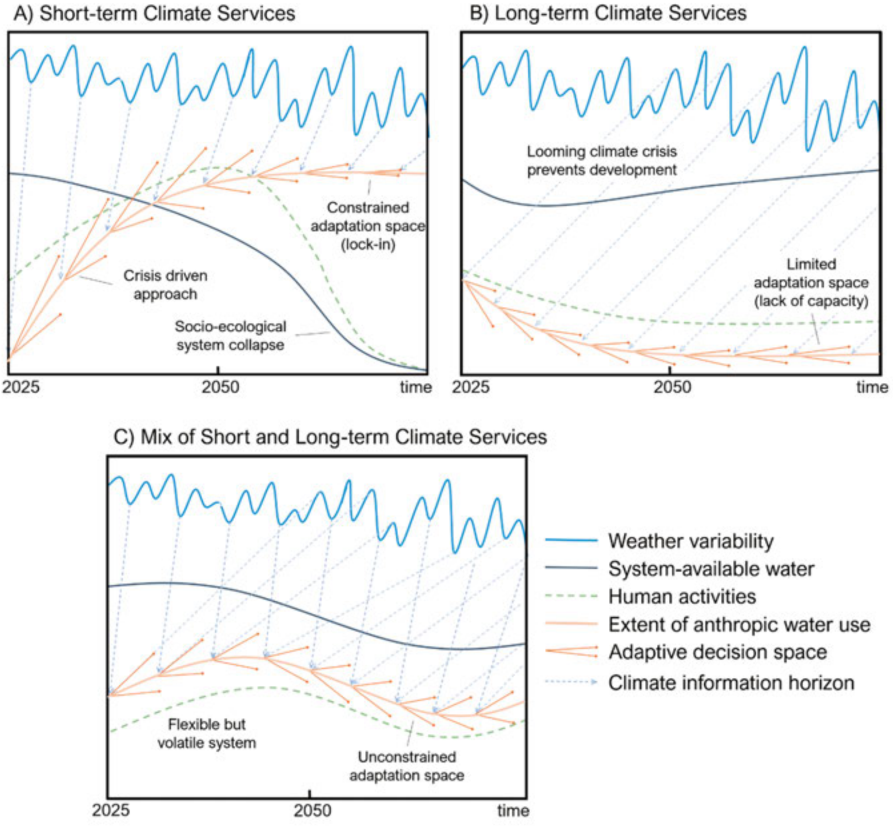


Figure 20: Trade-off between short- and long-term adaptation scenarios. A short-term scenario (a) where climate services allow to manage immediate crises initially performs better, but its reliance on short-term infrastructural adaptation leads to the system locking into unsustainable state and collapsing. In contrast, a scenario where the focus is entirely on the long-term (b) entirely forgoes human activities. An intermediate scenario (c) which balances short- and long-term needs allows to sustain human activity while maintaining a healthy ecosystem, but can be volatile to severe crises. The figure summarizes some of the results of this thesis by updating the work of Di Baldassarre et al., 2019.

The 2022 drought evidence fits this pattern (paper I and 2). Sub-seasonal and seasonal forecasts were widely used, and they supported a range of operational responses. Yet the measures most frequently adopted were short-term and supply oriented, including inter-sectoral reallocations and emergency abstractions. Ecosystem-oriented and long-term measures were relatively underused, even as European policy discourse pointed to their importance. These choices suggest that the informational environment and the pressures of crisis favoured short-term needs, at the expenses of long-term is ones (Ashley et al., 2020; Lemos et al., 2012; Perera and Nakamura, 2023; Perrels et al., 2020).

The archetype analysis provides a conceptual explanation of this in Paper III. *Band-Aid Solutions* capture how short-term information and measures can displace or delay structural change, while *Fixes that Fail* demonstrates how symptom relief can worsen root causes when feedbacks are ignored. In both cases, the informational horizon matters.

A systemic implication follows. Portfolios of CSs should be designed to make the long-term visible and actionable alongside the short-term, and governance should institutionalise their joint use. While short-term CSs are necessary to inform operations and preparedness, this should remain aligned with the larger goals of strategic level risk management, which in turn need to be informed by long-term and systemic CSs. It also means designing boundary processes that connect the two horizons, so that learning from operations feeds into strategy, and strategy sets guidelines for operations. The 2022 papers (I and II) already point toward such arrangements through the emphasis on DMPs and the call for a directive that would mainstream drought risk management.

Equity is a system property

The thesis presents a smaller but significant body of evidence on how CSs intersect with inequality. The archetypes identify a mechanism through which CSs can widen disparities. In *Success to the Successful*, better organised or better resourced actors are able to access, shape, and benefit from services more than others. This dynamic can manifest during (co-)development, where influential sectors set the agenda, or during deployment, where technical capacity and infrastructure determine who can use a service. Such asymmetries are not created by CSs alone, yet CSs can amplify or mitigate them depending on design choices and the social processes around them (Nost, 2019; Greene and Ferguson, 2024). These findings echo the broader evidence that inequality conditions adaptive capacity, and they support the view that equity is not only a normative aim but also a system property that shapes risk and resilience (Tschakert et al., 2013; Savelli et al., 2021, 2022; Rusca et al., 2023).

The format of the climate information delivered can also drive inequality. Respondents to the survey in Paper V were more likely to recognise digital, data-centred formats as CSs regardless of whether those formats best served adaptive functions. This bias preferentially benefits actors with the capacity and incentives to use such tools, and undercuts formats that embed knowledge through unconventional means. If recognition determines funding and institutional support, then this bias affects what gets built, maintained, and scaled (Lemos et al., 2002; Tschakert et al., 2013; Nost, 2019). The result can be a portfolio of services that fits existing power and knowledge structures more than it fits the needs of vulnerable or marginalised users, and helps maintaining status quo disregarding the sources of inequality.

The 2022 drought papers also document disparities in preparedness and response across countries and sectors, which translate into different abilities to act on information and to manage impacts.

This thesis does not claim to exhaust the topic. Rather, it shows that equity considerations are intrinsic to how CSs work in practice. Designing services as part of SETS implies designing them for use in the social processes through which information becomes action, and where inequity plays a central role.

Climate services as processes within processes

As CSs are processes embedded within SETS, they evolve alongside the system's dynamics, institutions, and power relations. Consequently, the biases and assumptions highlighted by paper V must be made explicit. This reflexivity is critical because it allows for ongoing learning and adjustment, ensuring that CSs remain responsive to changing needs, contexts, and risks. Without such awareness, services risk becoming static, misaligned, or even maladaptive.

Papers I and II also suggest the the importance of viewing CSs as processes. Where organisations had DMPs, making roles, thresholds, and protocols explicit, climate information became more usable, and actions could be taken earlier. This is not because the information was inherently more accurate. It is because the processes around it were aligned with decision needs (Findlater et al., 2021; Boon et al., 2022, 2024; Sillmann et al., 2024). The call for a European Drought Directive is therefore also a call to institutionalise processes that make CSs effective as part of the system, including preparedness planning, cross-border coordination, and shared learning (Kreibich et al., 2019; Blauhut et al., 2022; Hagenlocher et al., 2023).

If CSs are endogenous to SETS, then they must be designed and evaluated as processes, not only as products (Christel et al., 2018; Boon et al., 2024). Paper III proposes an ex-ante framework for checking maladaptive risks during design and implementation, evaluating their effectiveness as processes within complex systems rather than as products. It invites teams to consider how a proposed service could interact with existing feedbacks, which groups might capture benefits or bear costs, and how short-term gains could create long-term liabilities. It also invites consideration of alternative formats that may be less visible to funders but more effective for users, such as facilitated decision processes, brokering, and creative practices that support sense-making and engagement.

Paper V shows that current expectations about form can misalign services with decision contexts. Many adaptive decisions happen through relationships, deliberation, and negotiation, and many users interact with information through trusted intermediaries rather than directly through digital platforms (Dilling and Lemos, 2011; Kirchhoff et al., 2013; Findlater et al., 2021; Jacobs and Street, 2020; Vulturius et al., 2020; Sillmann et al., 2024). When recognition privileges standardised, high-technology outputs, it inadvertently reduces the diversity of formats and practices available to fit local contexts (Findlater et al., 2021; Sillmann et al., 2024).

Reflecting a process-oriented means rethinking monitoring and evaluation of CS impact. Output and uptake metrics remain informative for programme management, but they are not good proxies for adaptation in feedback-rich systems (Tall et al., 2018; Andreotti et al., 2020; Perrels et al., 2020; Vaughan and Dessai, 2014). Instead, ooutcome and impact metrics should track whether CS have long-term impacts, help foster transformative change, inform strategic policy, reduce vulnerability, protect ecological services, and distribute benefits fairly.

Ways forward

By showing how CSs should be considered as processes operating within the SETS, the insights of this thesis suggest several avenues for future research and practice.

Firstly, one area that deserves further exploration is how CS portfolios might balance short-term operational needs with long-term strategic visions. More work is needed to understand how institutional settings and learning processes shape their implementation and potential unintended consequences.

Another promising direction lies in testing simple, anticipatory tools that can help identify trade-offs and possible maladaptive dynamics early in the co-creation of CSs, expanding on the work of Paper III. Such approaches may reveal how different groups experience benefits and burdens, and could stimulate dialogue on equity and inclusion. Similarly, outcome-based evaluations, though methodologically challenging, may allow researchers and practitioners to capture the longer-term impacts of CSs beyond immediate uptake, offering insights into their role in shaping resilience, and systemic change.

The ecological dimension also warrants closer attention. Future studies might investigate how long-term projections and modelling can be translated into governance guardrails that protect environmental flows and natural buffers, especially under conditions of emergency management. This can be explored at the institutional scale by examining how CSs interact with systemic risk management and governance.

Finally, broadening what counts as a CS opens up space for more diverse epistemologies, and allows to recognize formats that are more process-based, creative, or embedded in local practices. This also raises questions about the role of "boundary" actors and organisations in mediating between knowledge and action, an area where future research may provide valuable insights into the conditions that foster trust, salience, and transformation.

Conclusions

The thesis sets out to disentangle the nexus between climate information and (mal)adaptation in Socio-Ecological-Technical Systems. The central message that emerges is that climate services (and by extension climate information) are not neutral tools delivered to passive users. They are integral elements of complex systems that co-evolve with institutions, infrastructures, and ecologies, and their effects are mediated by feedbacks, delays, and path dependencies. This systemic view explains why improved data do not automatically deliver improved outcomes, and why the same service can help or hinder adaptation depending on other system properties.

The empirical findings from the 2022 drought, the archetype analysis, the synthetic model, and the recognition survey are consistent with one another and with the thesis's framework. Where information, plans, and coordination were aligned, responses were earlier and more effective. Where short-term pressures dominated and ecological buffers were treated as expendable, risks accumulated. Where recognition followed form rather than function, services drifted away from decision contexts. These are not separate observations. They describe a system in which information and adaptation co-evolve.

Four messages shape the discussion. First, climate services are endogenous to Socio-Ecological-Technical Systems, and their value depends on how they are embedded in anticipatory, recognitory, learning, and adaptive functions. Second, balancing information horizons matters. Overweighting short-term climate information induces reactive cycles and lock-in and lead to maladaptation, while long-term perspectives are necessary to ensure sustainability. Third, equity is a system property. climate services can widen or narrow disparities depending on who can access, shape, and benefit from them. Fourth, climate services should be treated as processes embedded in local Socio-Ecological-Technical Systems, hence their impact evaluation should refrain from simplistic output indicators and instead understand their systemic impact.

Designing climate services for adaptation therefore requires attention to the system as a whole. It requires governance that elevates climate projections alongside seasonal and sub-seasonal forecast, evaluation that follows outcomes across time and social groups, and processes that enable learning and transformation. If we build portfolios of climate services as parts of Socio-Ecological-Technical Systems, and we evaluate them for what they do to systems rather than only for what type of information they provide, we have a better chance of steering trajectories toward equitable and lasting resilience.

The work presented here provides a set of concepts, empirical indications, and modelling insights that will hopefully be employed by future research and practice. It also points to areas of future research that still need to be explored. Above all, it argues for reframing climate services as systemic practices. When we do, the path to using information for adaptation becomes clearer, and the risk of reproducing maladaptation becomes easier to recognise and to avoid.

Populärvetenskaplig sammanfattning

Denna avhandling undersöker hur klimatinformation påverkar hur samhällen anpassar sig till klimatförändringar, särskilt när det gäller att hantera torka. I Europa blir torka både vanligare och allvarligare, och påverkar alla delar av vardagslivet, från jordbruk till energiproduktion och tillgången på dricksvatten. Människor och organisationer försöker anpassa sig till dessa förändrade förhållanden, men alla anpassningsåtgärder leder inte till positiva resultat. Vissa insatser kan till och med förvärra situationen på sikt – detta kallas maladaptation (felanpassning).

Klimattjänster, som säsongsprognoser, tidiga varningssystem eller framtidsscenarier för klimatförändringar, är verktyg som ska hjälpa beslutsfattare att agera mer effektivt och i god tid. Dessa verktyg blir allt viktigare i klimatanpassningen, men avhandlingen visar att de inte automatiskt leder till bättre beslut. Hur klimattjänster utformas, vem som använder dem, och hur de integreras i större system spelar stor roll. Ibland kan även välmenande tjänster förstärka redan existerande problem eller exkludera vissa grupper.

Avhandlingen betraktar klimattjänster inte bara som tekniska hjälpmedel, utan som en del av större system där människor, natur och teknik samverkar – det vi kallar socio-ekologisk-tekniska system. Ett exempel är ett avrinningsområde där vatteninfrastruktur, klimatdata och användarnas beteenden påverkar både människors livsvillkor och ekosystemets funktion. Genom att studera klimatinformationens roll i dessa system hjälper avhandlingen oss att förstå varför anpassning ibland misslyckas och hur den kan förbättras.

Metod

Avhandlingen bygger på fem delstudier med olika metoder för att undersöka klimattjänsternas roll i klimatanpassning.

Studie I och II bygger på en stor enkätundersökning med 481 vattenförvaltare i 30 europeiska länder efter torkan 2022. Enkäten undersökte hur förberedda organisationerna var, vilka verktyg de använde, och vilka åtgärder de vidtog. Genom statistisk analys identifierades mönster i hur olika länder och institutioner hanterade samma torkhändelse.

Studie III använde systemtänkande för att identifiera vanliga mönster där anpassningsåtgärder misslyckas. Genom så kallade systemarketyper – förenklade modeller som visar hur vissa beslut leder till återkommande problem – kunde man, tillsammans med intervjuer med användare av klimattjänster, förstå varför vissa anpassningsinsatser får motsatt effekt.

Studie IV tog fram en datorbaserad modell, baserad på resultaten i Studie III, för att simulera hur olika typer av klimattjänster påverkar långsiktiga beslut i ett område med vattenbrist. Till exempel jämfördes vad som händer om användare bara förlitar sig på kortsiktiga prognoser, långsiktiga klimatprojektioner, eller en blandning av båda.

Den sista studien (Studie V) byggde på en enkät med experter inom klimattjänster för att undersöka hur dessa definierar och känner igen olika typer av tjänster. Studien tog upp om mindre konventionella former, som lokala workshops eller konstnärliga insatser, ses som legitima klimattjänster eller om experter fortfarande föredrar digitala verktyg.

Tillsammans ger dessa metoder en bred bild baserad på verkliga data, teori, modellering och användarinsikter.

Huvudresultat

De två första studierna visade att organisationer med tillgång till prognoser och torkhanteringsplaner reagerade snabbare under torkan 2022. Men trots dessa verktyg var de flesta åtgärder kortsiktiga och reaktiva – till exempel att omfördela vatten akut eller pumpa upp mer vatten. Mer hållbara lösningar, som att återställa våtmarker eller minska vattenförbrukningen, var ovanliga. Många länder agerar först när torkan slår till, istället för att planera i förväg. Det pekar på behovet av bättre samordning och starkare torkpolicyer på EU-nivå.

Studien med systemtänkande identifierade tre vanliga mönster där anpassning misslyckas. Ett är “fixes that fail” – där en lösning fungerar tillfälligt men skapar större problem senare, till exempel när en damm byggs och leder till överutnyttjande av vatten. Ett annat är “band-aid solution” – där information hjälper på kort sikt men skjuter upp nödvändiga förändringar, som att använda prognoser för att fortsätta bevattna istället för att byta till mer tåliga grödor. Den tredje, “success to the successful”, visar hur de som redan har resurser får störst nytta av klimattjänster, medan andra halkar efter.

Datormodellen visade att olika typer av klimatinformation leder till olika långsiktiga utfall. Om människor bara använder kortsiktiga prognoser tenderar de att välja snabba lösningar, som att bygga ut bevattningen. Det gynnar ekonomin på kort sikt men kan skada ekosystemen och leda till kollaps. Om man istället använder långsiktiga scenarier, satsar man mer på hållbara lösningar som återbeskogning eller vattenbesparing. Dessa strategier är stabilare men kräver tålamod och investeringar. En blandning kan fungera men är känslig för yttre stress. Modellen visar att vilken information man använder har stor betydelse för framtiden.

Den sista studien visade att många fortfarande ser klimattjänster som digitala verktyg, till exempel webbportaler och kartor. Mindre traditionella former – som berättelser, teater eller lokala workshops – erkänns sällan som riktiga klimattjänster, trots att de ofta fungerar bra. Överraskande nog delar experter från olika fält denna snäva syn. Detta begränsar möjligheterna till kreativ och inkluderande design av klimattjänster, och riskerar att exkludera användare som inte nås av digitala lösningar.

Diskussion

Avhandlingen visar att klimattjänster inte bara är neutrala verktyg. De är en del av det system de försöker förbättra, och deras effekt beror på hur de används. I vissa fall hjälper de till att minska risker och förbättra planering, men i andra kan de fördröja nödvändiga förändringar, förstärka ojämlikhet, eller leda till övertro och riskabla beslut. Det räcker inte att bara leverera mer klimatdata – det är viktigt att tänka på hur informationen produceras, sprids och tolkas.

En viktig insikt är att tidsperspektivet spelar stor roll. Kortsiktiga klimattjänster hjälper till vid akuta beslut, men de kan uppmuntra till en reaktiv strategi som skjuter upp nödvändiga förändringar. Det är som att plåstra om ett djupt sår för att kunna fortsätta jobba, istället för att gå till sjukhuset. Långsiktiga tjänster möjliggör strategiska och hållbara beslut, men är svårare att agera på eftersom resultaten kommer senare. En balans mellan kort- och långsiktighet är nödvändig, men dagens system lutar ofta för mycket åt det kortsiktiga.

En annan viktig poäng är att rättvisa inte är ett sidospår, utan en grundläggande del av hur samhällen fungerar. Om klimattjänster bara når dem med makt, pengar eller digital tillgång, riskerar de att öka ojämlikheten. Det innebär att inkluderande design, erkännande av olika kunskapstyper och stöd till lokala röster inte bara är ideal – de är avgörande för effektiv klimatanpassning.

Avslutningsvis argumenterar avhandlingen för att vi ska se klimattjänster som processer, inte bara produkter. En visuellt attraktiv onlineprognos är bara användbar om den passar användarens behov och sammanhang. Utvärdering av klimattjänster bör inte bara handla om hur många som klickade på en hemsida. Vi måste fråga oss om tjänsten hjälpte människor att fatta bättre beslut, undvika skador, och bidra till långsiktig motståndskraft.

Sammanfattningsvis ger denna forskning en djupare förståelse av sambandet mellan klimattjänster och klimatanpassning. Den visar att anpassning inte alltid är positiv, och att klimatinformation både kan hjälpa och stjälpa, beroende på hur den används. Genom att kombinera verkliga data, teori, modellering och användarperspektiv erbjuder avhandlingen både kritisk reflektion och praktisk vägledning. För att stödja meningsfull anpassning i en osäker värld behöver vi klimattjänster som är inkluderande, reflekterande och utformade för komplexiteten i det samhäll-natur-system vi lever i.

Sommario divulgativo

Questa tesi esplora come le informazioni climatiche influenzano il modo in cui le società si adattano ai cambiamenti climatici, in particolare nella gestione della siccità. Samente in Europa, le siccità stanno diventando sempre più frequenti e intense, con impatti su tutti gli aspetti della vita quotidiana, dall'agricoltura alla produzione di energia, fino all'approvvigionamento idrico urbano. Individui e organizzazioni stanno mettendo in atto misure per adattarsi meglio a queste nuove condizioni. Tuttavia, non tutte queste misure portano a risultati positivi. Alcuni sforzi di adattamento possono addirittura peggiorare la situazione nel lungo periodo: un fenomeno chiamato *maladattamento*.

I servizi climatici, come le previsioni stagionali, i sistemi di allerta precoce o le proiezioni climatiche, sono strumenti pensati per aiutare a intervenire in modo più efficace e prima che si verifichi un disastro. Nonostante questi strumenti stiano diventando centrali nelle politiche di adattamento al clima, questa tesi mostra che i servizi climatici non sono automaticamente ad impatto positivo. Il modo in cui vengono progettati, chi li utilizza e come sono inseriti nei sistemi sociali e ambientali può fare una grande differenza. A volte, anche con le migliori intenzioni, possono rafforzare problemi esistenti o escludere alcuni gruppi sociali.

Questa ricerca considera i servizi climatici non solo come strumenti tecnici, ma come parte di sistemi complessi in cui persone, natura e tecnologia interagiscono. Questi sistemi sono chiamati *sistemi socio-ecologici-tecnici*, e un esempio concreto sono i bacini fluviali urbanizzati: qui, le infrastrutture e le misure adottate per sostenere la società influenzano i processi chimico-fisici degli ecosistemi, che a loro volta detrminano la disponibilità stessa dell'acqua per uso antropico. Analizzando il ruolo dei servizi climatici all'interno di questi sistemi, la tesi aiuta a capire perché l'adattamento spesso non raggiunge gli obiettivi sperati e come può essere migliorato.

Metodi

La tesi combina cinque studi (Paper), ognuno con un approccio diverso, per analizzare il ruolo dei servizi climatici nell'adattamento.

I Primi due articoli (Paper I e II) si basano su un ampio sondaggio condotto dopo la siccità del 2022, che ha coinvolto 481 gestori delle risorse idriche in 30 Paesi europei. Il questionario chiedeva quanto fossero preparate le organizzazioni, quali strumenti utilizzassero e quali azioni avessero intrapreso. L'analisi statistica delle risposte ha permesso di individuare tendenze e differenze tra Paesi e istituzioni.

Il terzo studio (Paper III) ha utilizzato un approccio di *system thinking (pensare per sistemi)* per individuare schemi ricorrenti di fallimento in diversi casi studio europei. Ha applicato il concetto di *archetipi di sistema*, ovvero modelli causali semplici che mostrano come certe decisioni portino a problemi ricorrenti. Questi sono stati combinati con interviste a utenti di servizi climatici per capire meglio perché certi sforzi di adattamento finiscono per essere controproducenti.

Il quarto studio (Paper IV) ha sviluppato un modello computerizzato basato sui risultati del Paper III, simulando come diversi tipi di servizi climatici influenzino le decisioni a lungo termine in un contesto di scarsità idrica. Il modello confronta cosa succede se si utilizzano solo previsioni a breve termine, solo proiezioni a lungo termine, oppure una combinazione di entrambe.

L'ultimo studio (Paper V) si basa su un sondaggio rivolto a esperti di servizi climatici, con l'obiettivo di capire come vengono definiti e riconosciuti questi servizi. Ha indagato se formati meno convenzionali, come workshop comunitari o attività artistiche, siano considerati validi tanto quanto i piú comuni strumenti digitali.

Questi cinque studi combinano dati reali, teoria, modellazione e prospettive degli attori coinvolti per offrire una visione completa del problema.

Risultati principali

I primi due studi mostrano che disporre di strumenti di previsione e di Piani di Gestione della Siccità ha aiutato le organizzazioni a rispondere più rapidamente alla siccità del 2022. Tuttavia, la maggior parte delle azioni intraprese sono state reattive e a breve termine, come il pompaggio d'emergenza o la riallocazione delle risorse idriche. Soluzioni più lungimiranti, come il ripristino delle zone umide o la gestione della domanda d'acqua, sono state relativamente rare. In molti Paesi si agisce solo quando la siccità è già in corso, invece di pianificare per tempo. Ciò evidenzia la necessità di maggiore coordinamento e politiche europee più forti.

Lo studio di *system thinking* ha identificato tre archetipi che spiegano perché molti sforzi di adattamento, seppur ben intenzionati, falliscono. Il primo è chiamato *fixes that fail* (soluzioni controptoducenti), ovvero soluzioni che funzionano nel breve periodo ma creano problemi più gravi in seguito, come costruire una diga che poi porta a un uso eccessivo dell'acqua. Il secondo è la *band-aid solution* (soluzioni apparenti), dove le informazioni aiutano a risolvere problemi immediati ma ritardano cambiamenti strutturali, come continuare con coltivazioni intensive ma usando metodi piu mirati invece di passare a colture meno intensive. Il terzo, *success to the successful* (vantaggi ai già avvantaggiati), mostra come i gruppi già ben equipaggiati traggano più vantaggio dai servizi climatici, aumentando il divario rispetto a chi ha meno risorse.

Il modello computerizzato ha dimostrato che diversi tipi di servizi climatici portano a risultati molto diversi nel lungo termine. L'uso esclusivo di previsioni a breve termine incoraggia soluzioni rapide, come l'espansione dell'irrigazione, che possono inizialmente favorire l'economia ma, col tempo, danneggiano gli ecosistemi e portano a un collasso. Al contrario, chi si affida a informazioni climatiche di lungo periodo tende a investire in pratiche sostenibili, come il risparmio idrico o la riforestazione. Queste strategie sono più stabili ma danno risultati più lenti. L'approccio misto può funzionare, ma è fragile e vulnerabile agli shock. Il modello mostra che il tipo di informazione a cui ci si affida oggi ha un impatto enorme sul futuro.

Infine, l'ultimo studio ha rivelato che molte persone continuano a pensare ai servizi climatici come a strumenti digitali, come mappe online o portali. Formati meno convenzionali, come laboratori locali, installazioni artistiche o il teatro, non sono spesso riconosciuti come servizi climatici, anche se si dimostrano efficaci. Sorprendentemente, questa visione ristretta è condivisa da scienziati e tecnici di diverse discipline. Questo pregiudizio limita la creatività e l'inclusività nella progettazione dei servizi climatici e rischia di ignorare i bisogni di chi è meno connesso al digitale.

Discussione

Questa tesi mostra che i servizi climatici non sono strumenti neutrali. Fanno parte dei sistemi che cercano di supportare, e il loro impatto dipende da come vengono usati. In certi casi possono migliorare la pianificazione e ridurre i rischi, in altri possono ritardare cambiamenti necessari, rafforzare disuguaglianze o portare a decisioni rischiose. Offrire più informazioni climatiche non basta: bisogna riflettere su come queste informazioni vengono prodotte, condivise e interpretate.

Un secondo messaggio chiave riguarda la finestra temporale coperta. I servizi climatici a breve termine aiutano nelle emergenze, ma possono generare una spirale di azioni reattive che lasciano i sistemi vulnerabili; un po’ come mettere una benda su una ferita profonda per continuare a lavorare, invece di andare in ospedale. I servizi a lungo termine supportano decisioni più strategiche e trasformative, ma sono più difficili da attuare perché i benefici sono protratti nel tempo. In generale, serve un equilibrio tra visione a breve e lungo termine, ma sistema attuale tende a privilegiare il breve termine.

Un altro punto fondamentale è l’equità. Se i servizi climatici raggiungono solo chi ha risorse, conoscenza scientifica, o accesso digitale, rischiano di aumentare le disuguaglianze. Progettare servizi più inclusivi, riconoscere diversi tipi di conoscenza e dare voce alle comunità locali non è solo un gesto etico, è una condizione necessaria per un adattamento efficace.

Infine, la tesi sostiene che i servizi climatici vanno considerati come *processi*, non solo come *prodotti*. Una portale di previsioni online serve solo se è utile a chi le usa. Valutare l’efficacia di un servizio non significa solo contare quanti utenti lo visitano, ma capire se ha aiutato a prendere decisioni migliori, a evitare danni e a costruire resilienza nel lungo periodo.

In conclusione, questa ricerca aiuta a comprendere meglio il rapporto tra servizi climatici e adattamento. Mostra che adattarsi non è sempre positivo, e che le informazioni climatiche possono aiutare o danneggiare, a seconda di come sono integrate nei sistemi socio-ecologici. Combinando dati reali, teoria, modellazione e prospettive degli attori coinvolti, la tesi offre sia una riflessione critica che indicazioni pratiche per migliorare i servizi climatici. Per affrontare il futuro con efficacia, abbiamo bisogno di servizi climatici che siano inclusivi, riflessivi e progettati per la complessità del sistema umano-naturale in cui viviamo.

Acknowledgements

A word about Palestine

There is no need to explain why what is happening in Palestine matters, or why it is urgent to end the ongoing genocide. What I do want to express is my profound disappointment with Uppsala University's refusal to take a stand. While the university was quick to cut ties with Russian institutions after the invasion of Ukraine, it has repeatedly ignored appeals to take similar action in the face of Israeli state violence. This double standard is indefensible.

Groups such as Academics for Palestine (AFP) and Workers and Students in Swedish Academia for Palestine (WASSAP) have consistently called on Uppsala University to end collaborations with Israeli universities. These groups have submitted multiple petitions signed by thousands of academics, students, and staff at Uppsala and across Sweden. Yet the university insists on remaining "neutral," claiming science should stay out of politics. Only, in May 2025, Uppsala University finally released a statement calling on the Swedish government to condemn Israel's actions and resume funding to UNRWA. But this is too little, too late, and comes after almost two years of petitions, protests, and demands from Uppsala's own students and employees.

How can Uppsala University claim to be a world-leading institution while staying silent in the face of atrocity? Hundreds of universities worldwide have already taken action. Until now, Uppsala has refused to do so.

The first people who I want to acknowledge are therefore those who have kept speaking out. To AFP Uppsala and WASSAP, and to the colleagues who occupied, camped, marched, walked out, signed, organized, and refused to look away; your courage is what I choose to be proud of.

For more information on the collaborations between Swedish and Israeli universities, the ties between Israeli academia and the military, and the censorship of Palestinian support in Sweden, you can read the reports by WASSAP (wassap.se/reports).

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Figure attributions

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