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The vulnerability of thermal ecosystems to climate change and the ThermEcoWat project: how to approach the study of their resilience from a multidisciplinary point of view.

La vulnerabilidad de los ecosistemas termales frente al cambio climático y el proyecto ThermEcoWat: cómo afrontar el estudio de su resiliencia desde una perspectiva multidisciplinar.

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Abstract: Although thermal waters are generally ancient waters of deep origin, during their ascent to the surface they can mix with shallower and younger waters that have different chemical characteristics and lower temperatures. These shallower waters are more susceptible to current changes in precipitation and temperature patterns and are the ones most likely to be affected in the medium term by the impacts of climate change. The ThermEcoWat project addresses the impacts of climate change on thermal waters and their dependent ecosystems in the SUDOE region (Southwest Europe). This potential threat to the quality of groundwater may put pressure on water resources, and in extreme cases, make it impossible to use them as medicinal mineral waters. The analysis of the regulatory frameworks related to the exploitation and use of thermal waters also plays a key role in the project, as it may limit the adaptive capacities of each territory to promote green energy, sustainable tourism development, and the valorisation of their endogenous resources. The project promotes cooperation between scientists, governmental entities, and economic stakeholders, for developing planning tools that facilitate the sustainable and coordinated use of thermal resources, while also enhancing territorial resilience to the effects of climate change.

Key words: ThermEcoWat, thermal waters, governance, territorial resilience, sustainability, thermal ecosystem, energy transition.

Resumen: *Si bien es cierto que las aguas termales son, por lo general, aguas antiguas de origen profundo, en su ascenso hacia la superficie pueden mezclarse con aguas más superficiales y jóvenes de características químicas y temperaturas más bajas. Estas aguas más someras están más fácilmente afectadas por los cambios en los patrones de precipitación y temperatura actuales y son las que pueden verse afectadas a medio plazo por los efectos del cambio climático. El proyecto ThermEcoWat aborda los impactos del cambio climático sobre las aguas termales y sus ecosistemas dependientes en la región SUDOE (Sudoeste Europeo). Esta amenaza potencial sobre la calidad del agua subterránea puede ejercer presión sobre los recursos hídricos y en casos extremos inhabilitar su uso como agua mineromedicinal. El análisis de la reglamentación asociada a la explotación y uso de las aguas termales tiene también un papel fundamental en el proyecto puesto que puede limitar las capacidades de adaptación de cada territorio para el fomento de las energías verdes, el desarrollo del turismo sostenible y la valorización de sus recursos endógenos. El proyecto fomenta la cooperación entre científicos, entidades gubernamentales y actores económicos, para crear herramientas de planificación que favorezcan el uso sostenible y coordinado de las fuentes termales, además de fortalecer la resiliencia territorial ante los efectos del cambio climático.*

Palabras clave: *ThermEcoWat, aguas termales, gobernanza, resiliencia territorial, sostenibilidad, ecosistema termal, transición energética.*

INTRODUCTION AND OBJECTIVES

Thermal waters play a fundamental role in the healthcare systems and economies of countries such as France, Portugal, and Spain. These mineral-medicinal waters, rich in minerals with therapeutic properties, have been used since antiquity to treat various conditions, especially those related to the musculoskeletal, digestive, and respiratory systems. In all three countries, thermal tourism represents a significant economic sector, attracting thousands of visitors each year and generating substantial economic activity in regions that capitalize on these establishments not only as treatment establishments but also as engines of economic development. In doing so, they promote employment and social well-being, giving rise to what are referred to as "thermal

ecosystems." The economic dependence on activities sustained by thermal resources is especially evident in rural, mid-mountain areas.

In France and Portugal, the therapeutic use of mineral-medicinal thermal waters is also deeply integrated into their healthcare systems, playing an essential role in the treatment and prevention of various diseases. These treatments are officially recognized and regulated, allowing patients to access them through medical prescriptions, often partially covered by social security systems.

From a hydrogeological perspective, thermal waters are groundwater sources that have been geothermally heated. When the right geological and hydrogeological conditions are present—such as permeable fracture zones—this heated, mineral-rich groundwater can rise to the surface through springs or thermal wells. On its way up, it may mix with younger, cooler, shallower water that is directly influenced by current and future climate patterns and more vulnerable to anthropogenic pollution. This mixing can compromise the exploitation models of these resources and the thermal ecosystems that depend on them.

Mineral-medicinal thermal waters provide health benefits but can also be used for energy production. The direct and indirect effects of climate change, combined with the uneven knowledge about the origin and characteristics of thermal resources, underscore the need to improve definitions of the vulnerability criteria for water quality. This is essential to assess how these resources may respond to medium- and long-term changes in temperature and precipitation patterns (2040–2100) and to evaluate the adaptive capacity of thermal regions to these emerging scenarios.

The ThermEcoWat project has the following objectives:

• **To analyse the resilience of thermal ecosystems** through a multidisciplinary approach, fostering joint and integrated work among various key stakeholders involved in the management of thermal waters and their socioeconomic environment (spa operators, scientists from the fields of geology, sociology, and economics, as well as elected officials and their governmental bodies).

• **To identify the limitations and/or opportunities within current regulatory frameworks** that will influence the development and potential adaptations of thermal regions.

• **To develop a common transnational strategy** that leverages the geographic, geological, and hydrogeological differences of the three pilot sites involved (Fig. 1). This strategy will be validated through the joint development of action plans that include concrete measures for climate change adaptation in thermal regions.

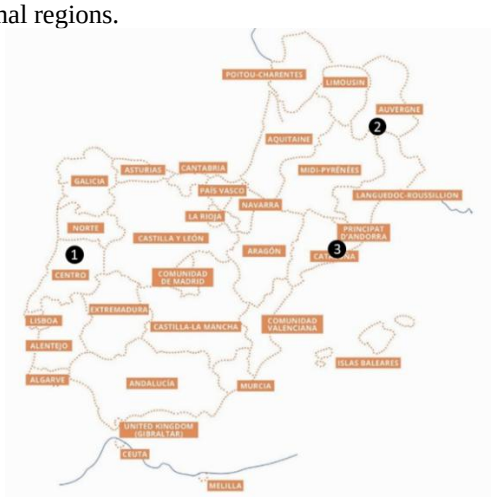

FIGURE 1. SUDOE region and pilot site locations of the ThermEcoWat project where a common transnational strategy on thermal waters and climate change will be applied; (1) Sao Pedro do Sul, (2) Chaudes-Aigues and (3) Caldes de Montbui.

Launched in January 2024 and running through 2026, the ThermEcoWat project serves as a platform to raise awareness about thermal waters, encouraging their responsible use and preservation, recognizing their energy and tourism potential, and informing on the necessary solutions and adaptations to be implemented in thermal regions to enhance resilience and ensure the continuity of their thermal ecosystems.

THE THERMECOWAT CONSORTIUM

The ThermEcoWat consortium involved in this project is composed of the following members: Association Thermauvergne (France), BRGM - Bureau de Recherches Géologiques et Minières (France), Caldes de Montbui Municipality and Cartographic and Geological Institute of Catalonia (ICGC) and Province of Ourense (Spain), Termalistur, Termas de S. Pedro do Sul E.M., S.A. and Laboratório Nacional de Energia e Geologia (LNEG) (Portugal), CSIC-IGME (Spain). The consortium also benefits from the collaboration of CERTOP-CNRS (*Centre d'Étude et de Recherche Travail, Organisation, Pouvoir*) from France.

PROJECT DEVELOPMENT STRATEGY

ThermEcoWat is structured around five strategic lines of development to achieve its goals:

In the field of **NATURAL SCIENCES**, the thermal resource and its vulnerability to climate change are characterized, considering both the quantity and quality of water. To this end, existing geological and hydrogeological information from the three pilot sites is collected and centralized.

During 2025, new hydrogeological data will be collected. By integrating this knowledge with climate change projections, a medium-term impact assessment on thermal resources will be carried out.

Additionally, the project provides the opportunity to apply advanced microbiological analysis techniques, such as DNA sequencing. These markers could potentially serve as future indicators for monitoring the effects of climate change on thermal water systems.

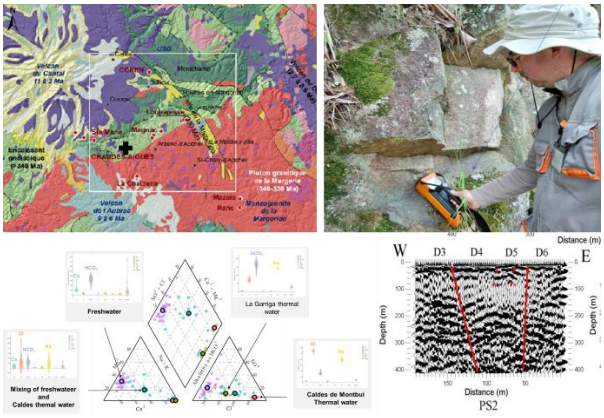

FIGURE 2. Geological, hydrogeological and geophysical characterization works within the natural resources strategic line in the ThermEcoWat pilot sites. Source: ThermEcoWat Consortium.

The **HUMAN AND SOCIAL SCIENCES** strategic line focuses on identifying vulnerabilities in thermal regions and how stakeholders in the thermal industry perceive energy and ecological transitions. These actors are becoming more aware of climate change's impact on water resources and sustainable tourism, prompting some spa operators to adopt renewable energy and reduce their carbon footprint in response to social and regulatory pressures.

Key challenges include transition costs, internal resistance, and limited information on climate impacts. However, operators who see potential in diversifying services—like wellness tourism or renewable energy use—are more likely to invest in sustainable changes.

The **ANALYSIS OF THE CURRENT LEGISLATIVE FRAMEWORK** represents another strategic pillar of the project. Existing regulations related to the use of thermal waters may become a source of vulnerability for thermal regions if they are not adapted to the emerging needs arising from climate change. Many current regulations do not consider technological advances, changes in consumption patterns, or new service applications, which can limit these areas' capacity for adaptation. Furthermore, certain aspects of the current legal framework may be incompatible with efforts to promote energy transition or innovation in the use of thermal waters.

To remove regulatory barriers and address existing contradictions, the current legal framework in each country is being reviewed to identify future changes that could support innovation and enable more efficient resource management.

Such legislative modifications should help facilitate the implementation of adaptation and resilience projects, maximizing the potential of thermal waters in the SUDOE territories and ensuring the long-term sustainable management of thermal ecosystems.

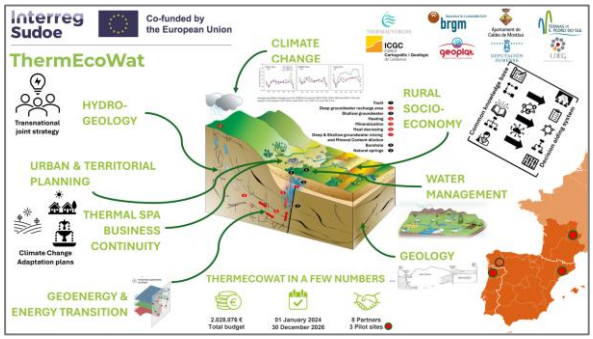

FIGURE 3. Conceptual diagram of the ThermEcoWat project illustrating its holistic approach to characterizing thermal ecosystems for long-term, socially sustainable solutions. Source: ThermEcoWat Consortium.

In the **TECHNOLOGICAL** domain, the consortium is co-developing a digital ecological transition tool, basically a common knowledge base, designed to address the challenge of adapting the use of thermal water in Southwestern Europe to climate change.

The ThermEcoWat Knowledge Graph (TEW KG) is being developed using the "ExG" approach: an innovative methodology developed by BRGM (*Bureau of Geological and Mining Research*) for analysing complex information with the aim of improving knowledge management in complex contexts. Its design is based on a semantic model and a reference ontology (see Figure 4) making it easier to interconnect different types of information.

It systematically transforms and aggregates narratives and testimonies, as well as quantitative data, into semantic and multiperspective graphs, thereby facilitating the discovery of new interrelationships not evident in the original datasets and the inference of new knowledge. The harmonised integration of interdisciplinary information and its graphical representation, enables the participation of different sort of stakeholders, such as political actors, managers, and scientists in agreeing on the complex processes involved in managing the spa industry, in order to optimise the sector's processes and anticipate crises related to climate change.

Within the scope of the project, we utilize this graphical knowledge management tool as the foundation

for the Decision Aiding System (DAS), providing relevant, updated, and contextualized information to support both individuals and organizations in making informed decision. The result of this decisional process will consist in the adaptation action plans of the 3 pilot sites.

Finally, for ThermEcoWat, **COMMUNICATION** is the cross-cutting strategic line that ensures the effective dissemination of its objectives, progress, and results among various stakeholder groups, while also strengthening the project's visibility and reach at both local and international levels.

PROJECT RESULTS

The development of the five strategic lines described above is being applied to the three pilot areas.

Beyond the production of deliverables aimed at disseminating the knowledge gained—such as technical data sheets on geothermal resources relevant to the project and their potential, explanatory reports, press articles, or testimonial videos—the main results of the project include:

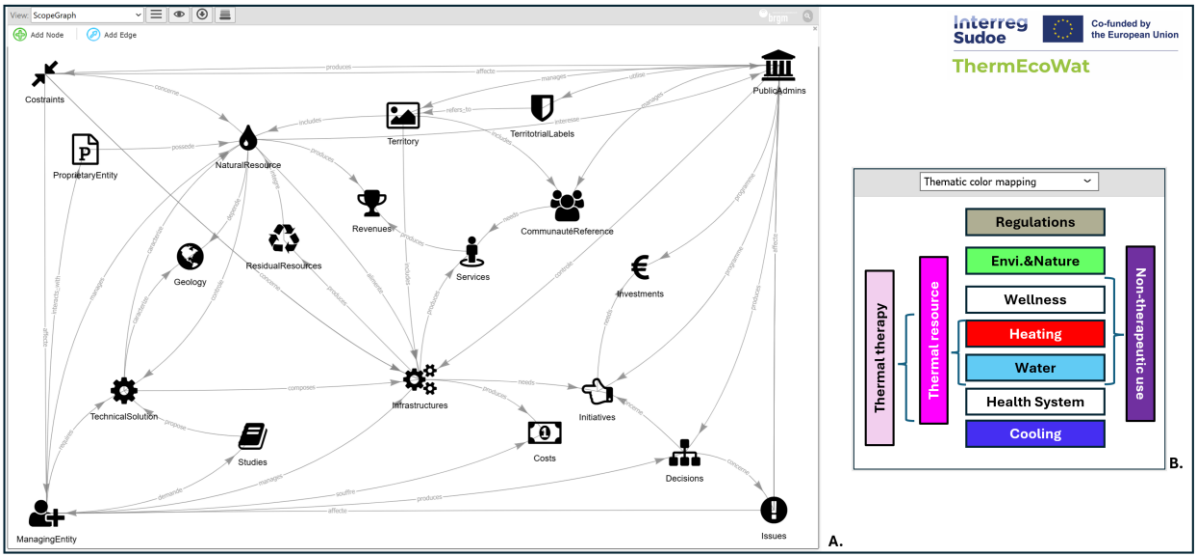

FIGURE 4. ThermEcoWat Knowledge Graph legend used within the scope of the ThermEcoWat project to represent: A. Elements and typical relationships considered for the studies aimed at defining climate change adaptation action plans for thermal towns; B. Distinct themes considered in the context of diversifying thermal source usage. Source: ThermEcoWat Consortium.

A **common transnational strategy** on thermal waters and climate change, which will define sustainable measures such as energy efficiency and responsible thermal water management to strengthen the resilience of thermal facilities and their dependent ecosystems in the SUDOE region.

An **action plan for each pilot site,** serving as a locally adapted implementation tool derived from this strategy. Each plan will be designed using a collectively built methodology based on a detailed analysis of vulnerabilities, available resources, regulatory frameworks, and key stakeholders involved. The plans will also consider good practices in the management of thermal resources, energy, and infrastructure.

These plans, which address three different challenges and scales—technological solutions, governance models, and urban development—are being developed through a series of steps that include the collection of local data, identification of needs and specific conditions in each region, and the organization of participatory workshops with experts, authorities, and local communities.

A **white paper** compiling the methods and criteria developed within the project, illustrating the process used to define the three action plans, and serving as a reference tool to support the implementation of the project's transnational strategy in other thermal regions.

This guide will also include the results of the regulatory analysis within the SUDOE area, along with proposals for legal reforms aimed at improving the climate resilience of thermal regions.

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