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Guideline for integrating and managing the use of SGE in urban areas

Principles of adaptive management approaches for the governance of shallow geothermal energy use in urban areas

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General description of the deliverable in the application

This document addresses decision-makers, planners and management authorities in cities, and lists and describes sound concepts for integrating and managing the use of SGE from a joint geoscientific expert view. The guidelines will show criteria and indicators of efficient and sustainable use, and offer concepts to include SGE in energy planning and environmental as well as climate protection actions in cities. It will provide a template for developing general strategies and to derive specific actions, summarized in a roadmap. It addresses both, Geological Survey Organizations (consulting) and local stakeholders (realization of strategies). It will also showcase the strategies developed in selected pilot areas of MUSE.

Version

Version	Description
29-03-2019	Initial version
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List of abbreviations

Abbreviation	Full name
SGE	Shallow Geothermal Energy
PROB	Management problem
MO	Management objective
STGY	Management strategy
MS	Management measure
GWHP	Groundwater heat pump
GCHP	Ground-coupled heat pump
BHE	Borehole heat exchanger
COP	Coefficient of Performance

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1 AIM AND SCOPE OF THE DOCUMENT

Success in the electrification of cities heating and cooling demands depends on the sustainable implementation of geothermal heat pump systems. During the last decades, the use of **shallow geothermal energy** (SGE) in urban areas has boosted the establishment of an emerging renewable energy resource.

However, the intensive market incorporation experienced by this technology entails different responsibilities towards long-term technical and environmental sustainability to maintain this positive trend.

To overcome possible SGE technology development barriers, policy principles of adaptive management approaches for the governance of shallow geothermal energy use in urban areas are proposed and discussed in this report. Here we present a SGE management framework structure and a governance model agreed between 13 European Geological Surveys, providing a science based concept for the different levels of management development, adaptable to any urban scale, and independent of the hydrogeological conditions and the grade of development of SGE technology implementation. The management approach reported is based on the **adaptive management** concept, thus offering a workflow for the non-linear relationship between planning, implementation, and control that establishes a cyclical and iterative management process. The generalized structure of the SGE management framework provided allows the effective analysis of policy planning to identify management problems and to select the best management objectives, strategies, and measures according to the proposed policy principles, thus helping policymakers to take informed decisions.

Please note that this report is focusing on the science based concept. A second report, associated to the deliverable D3.2 will translate the derived theoretical concepts into a practical guideline addressing stakeholders outside the academic sector.

2 INTRODUCTION

Evidence of anthropogenic **climate change** with detrimental consequences for human health and the World's ecology have required urgent action on a global scale to reduce CO_2 emissions. One of the most important measures is the decarbonisation of the energy sector, i.e., to transform the global energy sector from fossil-based to a zero-carbon system also known as "sustainable energy transition" (IRENA, 2014). The Paris Agreement (UNFCCC, 2015) established two main objectives to take action toward combating climate change. The first objective was to keep the rise in average global temperatures below 2°C, and the second, to limit warming to 1.5°C in the present century, in comparison with pre-industrial levels. Although large economies in the world are increasingly powered by renewable energies (33-40% of total power generation (IRENA, 2019), to meet Paris Agreement objectives, the decarbonisation of the global energy system needs to be substantially accelerated.

Electrification, when paired with clean electricity, is emerging as a key driver for accelerating this energy transformation. While electric mobility is a revolution, the **electrification of heat** is now rising along with geothermal heat pump development. Geothermal heat pumps use the shallow subsurface (<400 m depth) as a energy source/sink for heating and cooling mainly in cities.

Geothermal heat pump technology allows efficient thermal energy transfer directly from the heat stored in rocks, soils, and groundwater to infrastructures, and vice versa. The amount of thermal energy that can be recovered from depths up to 400 m below the surface is refered to as **shallow geothermal energy** (SGE) resources. There are two main categories or technologies to exploit SGE resources (Sanner et al., 2003). The first type, ground-coupled heat pumps (GCHPs) or simply known as closed-loop systems, uses a borehole heat exchanger (BHE) to transfer thermal energy between the infrastructure and the terrain acting as a heat source-sink. The BHE consists in a 50 to >100 m vertical (or horizontal) borehole where u-pipes or coaxial pipes, connected to the geothermal heat pump, are introduced in the subsurface filled with heat carrier fluid. The second type, groundwater heat pumps (GWHPs) or open-loop systems, extracts groundwater to take advantage of its heat capacity to produce an efficient heat exchange with the infrastructure. Once the heat has been extracted or dissipated, the water is usually reinjected into the aquifer. Shallow geothermal systems have been classified as the most efficient and clean technology for the climatization of buildings (EPA, 1997).

The number of shallow geothermal systems has been steadily rising for the past two decades (Bayer et al., 2012; Lund et al., 2005; Lund et al., 2011; Rybach, 2005; Rybach, 2015; Sanner et al., 2013). Between 2010 and 2015, the **total installed capacity of geothermal heat pumps** in the globe increased at a 13.2% annual rate, reaching 50,258 MWt (Lund and Boyd, 2016), which represents 4.19 million equivalent installed 12 kW units (typical of residential/domestic use). According to Lund and Boyd (2016), the energy utilization by geothermal heat pumps in the year 2014 was 326,848 TJ, accounting for energy savings of 194 million barrels of equivalent oil and preventing the release of 82.2 million tonnes of CO_2 to the atmosphere. This tendency is coherent with the H2020 strategy of the European Union (EC, 2010) and its revised directive 2009/28/EC on the promotion of the use of energy from renewable sources.

Although the technology involved in geothermal heat pumps is generally considered as renewable and environment friendly, in certain cases with already-existing problems in the subsurface, these systems may amplify them an pose important physical, chemical and biological effects on the subsurface environment, which must be taken into consideration. Its high rate of development and use has to be conducted in a technical, ecological and social sustainability **management of SGE resources** (Hähnlein et al., 2013).

Inevitably, any heat transfer produced during the shallow geothermal systems operation will produce a temperature change in the subsurface media (Banks, 2009; Banks, 2012; Rivera et al., 2017; Stauffer et al., 2013). Although these changes are very variable, most systems documented present subsurface and groundwater temperature changes in the range of 4 to 8 K above and below the undisturbed subsurface temperature. Nevertheless, greater changes of 13 and 25 K can also be found (García-Gil et al., 2016b; García-Gil et al., 2014). These thermal impacts of the exploitation systems do, not only induce changes in temperature-dependent physical properties of groundwater (Carslaw and Jaeger, 1986; Hecht-Méndez et al., 2013), but also hinder the design, optimization, and performance of both GCHP (Li and Lai, 2015; Yang et al., 2010; Zhang et al., 2014) and GWHP (Lo Russo et al., 2014; Lo Russo et al., 2012; Piga et al., 2017; Pophillat et al., 2018) systems. Concretely, temperature anomalies in the subsurface produced by the systems can affect their own coefficient of performance (Casasso and Sethi, 2015; Galgaro and Cultrera, 2013) or that of other shallow geothermal systems. Those processes are referred to in general as "**thermal interferences**" and have been identified and modelled in different cities (Epting et al., 2013; García-Gil et al., 2014; Herbert et al., 2013; Mueller et al., 2018; Sciacovelli et al., 2014). The intensive use of the shallow subsurface in urban areas where there is a high density of installations can lead to thermal overexploitation of SGE resources, thus endangering it renewability. In this context, technical sustainability refers to reaching and maintaining a high performance in a geothermal system, i.e., to sustain production levels over long periods (> 30 years) (Rybach and Mongillo, 2006; Shortall et al., 2015) and maintain its renewability as an energy resource. In very low-enthalpy reservoirs (shallow), stable production levels depend highly on hydrogeological characterization of the terrain, which will condition the steady-state regime during operations (Banks, 2009; García-Gil et al., 2015a; Hähnlein et al., 2010). Nevertheless, thermal interference between systems might also compromise technical sustainability of the systems, especially in urban environments where shallow geothermal systems are affected by and contribute to the subsurface urban heat island effect (Zhu et al., 2011).

Thermal anomalies produced by shallow geothermal exploitation systems will change kinetics and thermodynamic equilibria of existent or possible **geochemical** reactions (Appelo and Postma, 2005; Langmuir, 1997). Endothermic and exothermic reactions controlling major elements, heavy metals and trace elements contents have all been related to geothermal exploitation in the field (García-Gil et al., 2016b; Saito et al., 2016) as well as in both column (Bonte et al., 2014) and batch (Griebler et al., 2016) laboratory experiments. In addition, GWHPs where pumped groundwater is re-injected into the aquifer after heat transfer could also cause the exsolution of CO_2 or a gain in O_2 by inducing mineral precipitation (Abesser, 2010; García-Gil et al., 2016a) or preserving existing emerging organic contaminants (García-Gil et al., 2018a) if groundwater is not properly insulated from atmospheric conditions. During GWHPs systems operation mixing processes in groundwater can also be triggered (Bonte et al., 2011).

Complex biotopes comprising diverse microbial biocenoses are found in **groundwater ecosystems**, including bacteria, fungi, viruses and protozoa (Griebler and Lueders, 2009; Griebler et al., 2014). This fauna contributes to groundwater purification and filtration, thus becoming crucial components of subsurface ecosystems (Hahn, 2006; Hancock et al., 2005; Hunt and Wilcox, 2003). All subsurface ecosystems, together with groundwater-dependent ecosystems on the surface, can be affected by thermal impacts produced by SGE exploitation. It has been shown that elevated groundwater temperatures downgradient GWHP systems impacted the composition of groundwater microorganism communities as well as their diversity in an oligotrophic aquifer (Brielmann et al., 2009). Although subsurface temperature changes of up to ±6 K have been assumed to be acceptable, wider ranges have not been studied. Furthermore, these observations may not apply to groundwater systems with different concentrations in nutrients and/or exploitation regimes of GWHPs. In addition, direct effects of warming could be far less important than the nutrient effects (Christoffersen et al., 2006). Microbiological contamination studies assessing the effect of GWHPs on pathogen bacteria contents have shown a relative decrease of their concentration inside thermally affected areas (García-Gil et al., 2018b), probably related to a pseudo-pasteurization effect occurring inside the heat exchangers of these systems. Hence, the lack of more scientific studies related to the impact of thermal discharge in groundwater ecosystems makes it very difficult to determine the magnitude of its effects.

Other consequences derived from SGE use have been discussed in the past, including geomechanical problems due to evaporite dissolution subsidence (Cooper et al., 2011; Garrido et al., 2016; Goldscheider and Bechtel, 2009), water table rise in urban environments affecting the stability of building foundations (Huber et al., 2003), infiltrating groundwater into subsurface infrastructures (Karpf and Krebs, 2004), and even pollutant remobilization that compromises safe drinking water (Engeler et al., 2011).

An overview of the **legislative framework** on SGE at the European level (Haehnlein et al., 2010; Tsagarakis et al., 2018) has shown an extremely heterogeneous legislation as well as discordant regulations, standards, and institutional support. Existing regulations show a high inconsistency in minimum distances between neighbouring systems (5–300 m) and tolerable temperature changes in the subsurface. Furthermore, most countries in Europe have no legally binding regulations or even guidelines. The lack an unified and scientifically-based posture among European countries acts as a barrier to the further development of the SGE market (Jaudin, 2013). This fact highlights the urgent need for the improvement of the legal framework of shallow geothermal installations.

Nevertheless, an important effort has been made by the scientific community to develop management concepts addressing this problem. A first **sustainable geothermal energy use strategy based on the precautionary principle**, which implies an intrinsic principle of the European Water Framework Directive (EU-WFD, 2000), was proposed by Hähnlein et al. (2013). The strategy proposed follows a systematical licensing procedure based on the type, usage and heating capacity of the exploitation system considered. Depending on these variables, the procedure would require more or less exhaustive technical and/or environmental assessment before licensing. To perform any technical or environmental assessment it is necessary to understand the thermal regime of the subsurface and to describe its ‘‘present state’’ referred to a derived ‘‘potential natural state’’ (Epting and Huggenberger, 2013). Understanding thermal regimes of the subsurface, especially in urban areas, has become a rising challenge since there is a high number of important transient boundary conditions such as the river-level variations (García-Gil et al., 2014), the deep building foundations and infrastructures (Attard et al., 2016; Epting et al., 2017b), the unsaturated zone (Rock and Kupfersberger, 2018) and the shallow geothermal systems themselves (Lo Russo et al., 2014; Muela Maya et al., 2018). As an introduction of the equity policy principle in the management of SGE resources, a relaxation factor was included and applied to a generalised licensing procedure proposal using new thermal impact indicators (García-Gil et al., 2015b). The relaxation factor concept proposed is based on a thermal impact indicator defined for the reservation of a fraction of shallow geothermal energy resources for third-party installations, thus preventing their monopolization. Additionally to this indicator, a balanced sustainability index (BSI) was proposed as a management indicator applicable to GWHP systems where a quantitative value of sustainability is assigned to each system considered to evaluate the intrinsic potential to produce thermal interferences (García-Gil et al., 2019). A methodology to establish a market of SGE use rights was applied to the city of Barcelona in Spain (Alcaraz et al., 2016). The methodology is based on the definition of a basic unit of management related to a given plot of land registered in a cadastral map of a city, where the SGE potential is calculated and assigned based on analytical solutions of heat transport equations in porous media. Other management concepts in SGE exploitation include the subdivision of aquifers into smaller bodies considered as management units for thermal resources in order to effectively manage urban aquifers; the definition of the thermal retardation concepts due to the lag of thermal signals with respect to groundwater flow; the thermal memory effect accounting for the characteristic time-lags of thermal alterations in the aquifers managed; the thermal fingerprints concept with regard to other temperature fluctuations in the subsurface due to boundary conditions in the managed groundwater body that are not genetically related to geothermal activity (Epting et al., 2017a).

The **management of SGE resources is a collective action problem** requiring the involvement of governments, stakeholders, businesses and communities to integrate their activities to achieve the SGE sustainable development goals. In this context, the governance of SGE resources is crucial to establish the distribution of competencies and responsibilities between the science, policy, and civil society spheres in order to define the process of decision-making and their implementation. To our knowledge, the governance of SGE has not been addressed in the literature to date (García-Gil et al., 2020) and it is important to discuss on the establishments of the governance principles as the basis for the fundamental rules that will guide decisions.

The main objective of this document is to analyse and **identify the elements of good governance for SGE resources management**. To do that, first an exhaustive complete management framework structure **based on four policy principles** is proposed. The management structure prioritizes each policy into plausible management strategies, management objectives, and management problems, followed by a list of management measures (or tools) that decision-makers can analyse during their management planning phase. All management concepts considered in this structure were included in a questionnaire designed to measure the grade of relevancy by an expert panel constituted by **13 geological surveys participating at GeoERA MUSE**. The results of the questionnaire were used to assign a relevancy score to each management concept listed. The management structure aims to be useful for the management process that is lastly introduced and discussed in this manuscript according to the relative relevancy scored by the expert panel, and obtained from the questionnaire´s survey. The key output from this work is a set of principles that will be used as a basis for **adaptive SGE resources governance** and to establish a road map for the development of SGE management plans in urban environments.

3 GOVERNANCE OF SHALLOW GEOTHERMAL ENERGY RESOURCES

3.1 Policy principles

To achieve a holistic management system for SGE resources, the first step is to define a number of key policy principles. In the beginning of this work, 4 main ways in which the use of SGE resources can preclude sustainable development are presented.

Firstly, the **intensive and biased exploitation of SGE energy resources** towards heating or cooling in urban areas can be interpreted as a **reduction of renewable energy reserves**. The scarcity associated could then compromise the access to this resource for future generations. The first policy principle proposed is the "**Sustainable development and exploitation of SGE resources**". This policy attempts to prevent the following management problems; (I) geothermal overexploitation and unsustainable development, (II) thermal interferences and (III) inefficient use of geothermal resources.

Secondly, in worst case scenarios, where subsurface contaminants already exist, SGE use can result in the mobilization of existing contaminants, thus indirectly creating potential threat to human health or in a reduction of the quality of the natural environment in general. The management problems arising around this issue include the (I) hydrodynamic remobilization of existing contamination in aquifers due to GWHP system´s operation wells. In contaminated areas, these wells are susceptible of triggering the movement of contaminant solutes, due to the flowing groundwater transporting them. SGE use can also unleash homogeneous and heterogeneous geochemical reactions which, in the end, might increase the contents of existent (II) inorganic trace metals, (III) organic and (IV) microbiological contamination as additional management problems. (V) Thermal groundwater discharge to surface water bodies might lead to a management problem affecting groundwater-dependent ecosystems in the surface. Furthermore, SGE activity could make a (VI) contribution to UHI effect. All these 6 management problems would require a second policy response; concretely, the "**Environmentally friendly use of SGE resources**" is proposed to deal with these issues.

A third way preluding sustainable development of SGE is the potential conflict between new and other pre-existing or higher priority uses of the subsurface in urban areas. Management problems arising from this fact are: SGE could compromise (I) groundwater quality as water supply or other (II) groundwater use conflicts such as irrigation, industrial, recreational uses, among others. Furthermore, SGE use can compromise (III) geochemical impacts associated with induced subsidence or generate different (IV) SGE impacts on subsurface infrastructures. Potential conflicts with other urban subsurface use should be coordinated and, therefore, the "**SGE coordination with other urban subsurface uses**" is introduced as a third key principle policy.

Finally, the sustainable development of SGE depends on the successful application of the management approaches planed. Therefore, the fourth policy proposed is to adopt a "**successful SGE management approach**". The different management problems compromising the successful application of management plans in SGE considered in this work are: (I) managing in the context of data-poor urban subsurface bodies, (II) conflict of interests, (III) inefficient management of the SGE resources, (IV) management measures dependent to site-specific conditions, (V) disabling environment with authorities missing awareness, (VI) uncertainty of prediction and (VII) illegal activity and heavy enforcement costs.

3.2 Structure of the SGE management framework

The general structure of the proposed management framework consists in the conceptual development of each of the management policies described above using a hierarchy system (Fig. 1). The highest rank level is assigned to management policies. A management problem can be assigned to each policy as a second rank level. Since management problems are identified within the system managed, decision-makers are expected to establish their own policies. Once a policy has been defined, decision-makers could propose management objectives following the policy's direction. Considering that one or more objectives can be assigned to improve a management problem, here we propose the management objective as a third level. To achieve each management objective, decision-makers can enact different strategies (fourth level) for which specific management measures (fifth level) can be proposed. As an example, following the branch developed in Fig 1, the strategic allocation of SGE systems, licensing procedures and planning of district heating grids are three possible measures to follow the strategy of sustainable development. This strategy can be adopted to fulfill the objective of preventing overexploitation. This objective will contribute to the management problem of geothermal overexploitation and unsustainable development if detected in a managed system. Then, all those management measures would be justified by the "sustainable development and exploitation" policy. This structure provides clarity in the decision, thus making this process transparent to stakeholders (including the system's users).

An exhaustive conceptual review of all management concepts has given rise to a complete list of 289 management elements or concepts organized in 5 hierarchical management levels: 4 SGE management policies; 21 management problems; 27 management objectives; 58 management strategies; and 179 management measures considered of importance. Management policies and problems are provided above and a complete list of objectives, strategies and measures that complete the structure of the management framework proposed here are provided in the annex (Table A).

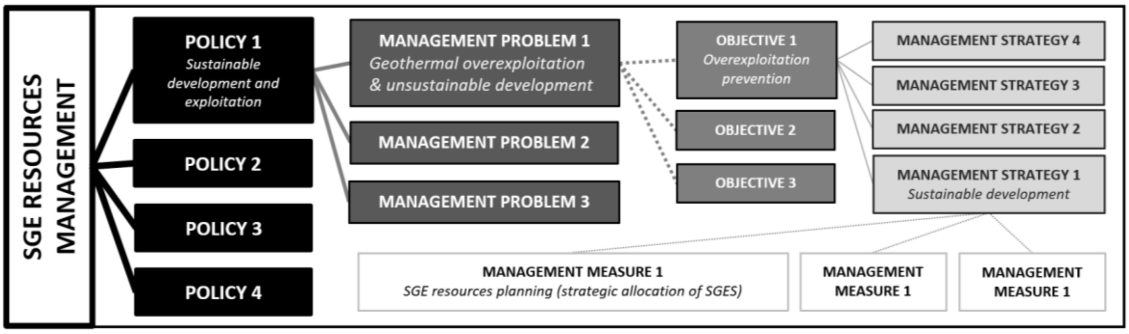

Figure 1: Simplified structure of the management framework proposed to shallow geothermal (SGE) resources showing 5 management levels. Only management measures proposed to follow one of the four management strategies are represented. This simplification is applied to the rest of management levels proposed. Only extended management levels developed in the diagram are named. Complete structure of the management framework arranged in tables for each management policy are provided in the annex (Table A).

3.3 Governance model of SGE resources

The **adaptive management approach** (Holling and Programme, 1978; Walters, 2001) is the most accepted and applicable path to govern natural and renewable resources in highly dynamic and complex environments. This approach offers a working framework for non-linear relationships between planning, implementation and control, thus establishing a cyclical and iterative activity during the management process. Therefore, to define the decision-making and the decision-implementation processes of SGE resource management, it is proposed to follow the adaptive management cycle introduced in renewable resources, e.g., Savenije and Van der Zaag (2008) for water resource management (Fig. 2). Nevertheless, the adaptive management approach requires high efforts from all the involved stakeholders and this is not always necessary. To identify the necessity to use the adaptive management approach, it is important to define critical thresholds associated to management indicators; e.g., baseline values considering the number of installed systems by surface unit. Such indicators should be monitored from the beginning to enable the identification of critical thresholds.

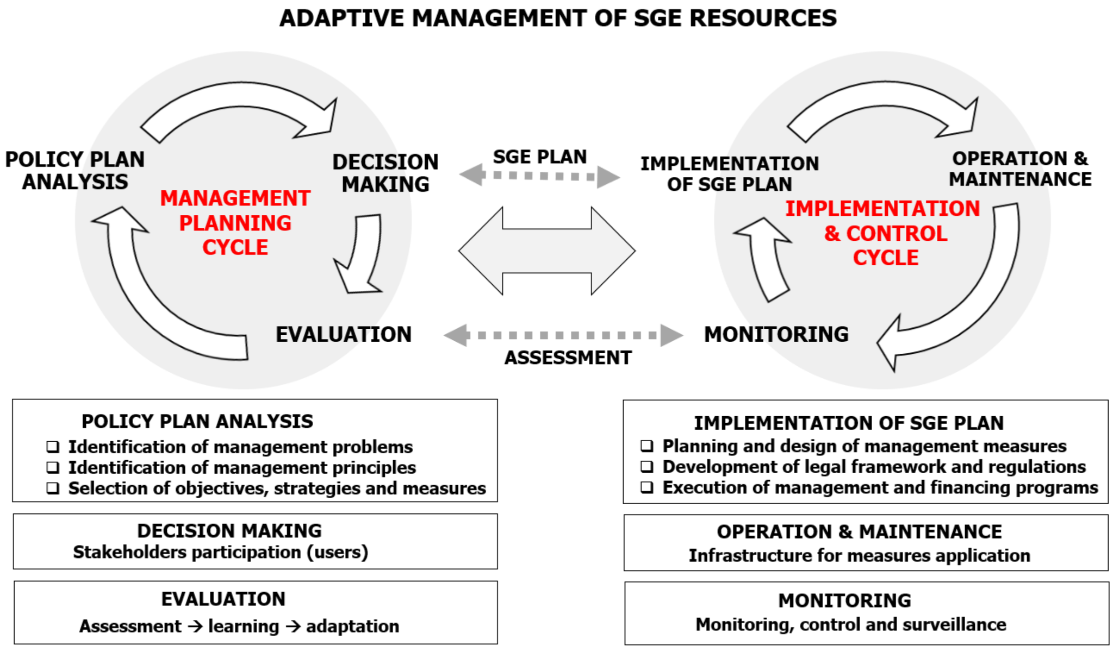

Figure 2: Conceptual diagram of the proposed double adaptive management cycle for shallow geothermal energy resources. Concept based on Savenije and Van der Zaag (2008) management cycle concept

In the case of SGE resources management, two main activities or processes are proposed: the process of management planning and the process of implementation and control.

Management planning consists of three cyclic and iterative tasks (Fig. 2). The first task is to **perform a policy plan analysis** identifying appropriate management problems and selecting the proper management objectives, strategies and measures according to established policy principles. This task is crucial and thus it also is to provide a generalized structure for the SGE management framework as a checklist or roadmap to set the foundations for the SGE management plan (Table S1). Decision-makers can only select the management concepts from this general management framework structure affecting their specific conditions but, at the same time, it is useful to do a checklist and go through all possible issues related to SGE exploitation that might not be considered in a first approach to the problem or it might be the case that more research and extended services are required. During the policy plan analysis it is also necessary to obtain an integrative view of SGE exploitation on the local context. This gathers knowledge on the existing SGE systems, estimates the SGE potential (resource assessment) and obtains a view of the existing socioeconomic framework.

Once an initial assessment has revealed the existing problems, SGE resources exploitation trends and management policies to follow need to be analysed, the second task is to go through a decision-making process and select the actions to be taken. To do that, it is necessary to prepare and adopt the strategies to befollowed and the management measures to be included in each strategy considered.

The third task on management planning is the **progress monitoring** of the management plan adopted, i.e., to evaluate the effectiveness of the management measures according to the management objectives. This evaluation is the key of adaptive management that ends the planning cycle and so decision-makers learn about the potential deficiencies of the managed system that will be considered in the next planning cycle. The SGE management plan should consider the definition of key performance indicators to measure the progress of any measures taken.

After the first planning cycle is completed, a **second implementation and control cycle** starts (Fig. 2). The main task in this cycle is the implementation of the management plan of action considering data collected from users and obtained from monitoring. This task includes establishing a detailed design and implementation of the planned management measures, to promote enforcement of laws and regulations and to strengthen the enabling environment and governance. A second task is to maintain operative the possible infrastructure required to implement the management measures planed. The task that closes this cycle is monitoring. By monitoring, controlling and surveilling, the resources demand and trends can be quantified and the effectiveness of the implemented management plan, assessed. Furthermore, monitoring outputs are crucial for the evaluation and policy plan analysis tasks from the planning cycle.

The reason why those cycles are separated is to facilitate the whole management process. After the first planning cycle finishes, each cycle can evolve independently as information keeps flowing between cycles. For example, two implementation and control cycles can be going through the same strategic action plan defined in the first planning cycle, or two planning cycles could be required to initiate a realistic implementation and control cycle.

4 DATA AND METHODS

To develop and harmonize a generalized governance policy approach on SGE resources, underpinned by 13 European Geological Surveys, including the Geological Survey of Spain (IGME), Austria (GBA), Croatia (HGI-CGS), Catalonia (ICGC), United Kingdom (BGS), Belgium (RBINS-GSB), Slovenia (GeoZS), Sweden (SGU), Poland (PIG-PIB), Czech Republic (CGS), Ireland (GSI), Nederland (TNO) and Slovak Republic (SGIDS), an exhaustive questionnaire related to management policies (block I) and management cycle (block II) related to SGE resources was issued to each institution. The first block of the questionnaire, oriented to management policies, was structured into the following 4 policies: (I) *sustainable development and exploitation*; (II) *environmentally-friendly use of SGE resources*; (III) c*oordination of SGE exploitation with other urban subsurface uses*; and (IV) *successful management approach*. This block of the questionnaire considered a total of **289 management concepts** organized in **4 hierarchical levels of detail** which were, from top to bottom: **4 exposed SGE management policies**; **21 management problems**; **27 management objectives**; **58 management strategies**; and **179 management measures** considered of importance. The second block of the questionnaire, oriented to the management process, considered a total of 151 management concepts related to the adaptive management of SGE resources. Each Geological Survey was asked to evaluate each management concept using a 9-rank scale of relevance (1 = not relevant and 9 = very relevant). The survey was undertaken between December 2018 and January 2019.

The results from the 13 questionnaires, containing the 9-rank scale of relevance score for each management concept, were transformed to a proportional percentage scale where a rank value of 1 accounted for 0% relevancy, a rank value of 9 accounts for 100% relevance, and so on. This allowed assessing the results obtained from the questionnaires and describing them in terms of descriptive statistics, by calculating the arithmetic mean value and standard deviation of the data. Based on the average values assigned to each management concept, the questionnaire was reordered by sorting the management concepts of each level, starting with the most relevant concepts first. This reorganization maintaining the 4 hierarchical levels of detail in the first block allowed to obtain a management concept checklist for SGE managers, containing the average relevance as it was contemplated by Geological Surveys.

The **principal component analysis** (PCA) method was applied to analyse the National Geological Surveys' appraisal to the management problems proposed in this work. This method allowed investigating the variance found in the data obtained from the project survey and conducted by using a smaller number of uncorrelated variables (principal components). The principal components obtained during the application of the method helped in the interpretation and analysis of the observed appraisal of problems found in the management of SGE resources. **Varimax rotation method** was used to maximize the squared factor loadings for each factor (gamma = 1). Statistical significance was established for p-values below 0.05. All the statistical analyses were performed using SPSS Statistics version 20.0 software (IBM; Armonk, New York, USA).

5 RESULTS AND DISCUSSION

5.1 Structure of the SGE management framework

Results obtained from the survey on the relevancy assessment of the different management concepts considered in the structure framework are shown for each management policy presented in this manuscript in Table 1, Table 2, Table 3 and Table 4, respectively. The complete list of management measures associated to each strategy is provided as supplementary material (Table S1). In this report, only relevant (>70%) management concepts are discussed.

The results obtained from the survey (Table 1) indicate that the most important problem endangering the sustainable development and exploitation of SGE resources is **geothermal overexploitation and unsustainable development**. This problem can be overcome preferably by establishing two management objectives. Firstly, the highest-rated management objective (85%) is to prevent overexploitation of SGE resources by considering the sustainable development as the most relevant strategy to be adopted. The best way to follow this strategy is to control the allocation of SGE exploitation systems according to an established plan. Therefore, a baseline monitoring and defined critical thresholds are needed and should be included in the plan. Another measure would be to limit the access to the resource by licensing procedures. In this sense, input controls should be considered, including the size and number of SGE systems and the exploitation technology used. These results suggest the use of a rights-based approach to manage SGE resources by the allocating limited rights in a particular city area. The shift from open access of new SGE users towards a managed access regime would limit the number of participants with rights and responsibilities to exploit SGE resources and, thus, it would prevent overexploitation. A second management strategy found relevant is the identification of areas at risk of overexploitation and, as a preventive measure, the mapping of intensively exploited areas is proposed (Identification of areas at risk of overexploitation).

Table 1: Relevant management concepts for the sustainable development and exploitation policy, Scores are given for the different management levels: Management problems (PROB), management objectives (MO) and management strategies (STGY) assessed by 13 Geological National Surveys.

Management policy: Sustainable development and exploitation of SGE resources		
Level	**Name**	**Relevance [-]**
PROB	**Geothermal overexploitation & unsustainable development**	**85%**
MO	-Overexploitation prevention	84%
STGY	▪ Sustainable development	83%
STGY	▪ Identification of areas at risk of overexploitation	72%
STGY	▪ Control of exploitation efforts	65%
STGY	▪ Management of growing demand for SGE to pursue sustainability	65%
MO	-Long-term sustainable use of SGE resources	78%
STGY	▪ Understanding of heat and hydraulic regimes in the subsurface	84%
STGY	▪ Prioritization of SGE demands	81%
STGY	▪ Sustainable development	74%
STGY	▪ Enforcement/compliance for a rights-based system	72%
STGY	▪ Control of exploitation efforts	65%
STGY	▪ Long-term stability of production temperatures in SGES	63%
STGY	▪ Promotion of a balanced use of the resources	60%
STGY	▪ Stand-still principle: Maintenance of COP of SGES at its current level, at minimum	42%
MO	-Recovery of sustainability in areas under overexploitation	64%
STGY	▪ Characterization of overexploited areas	63%
STGY	▪ Increase of SGE supply in areas under overexploitation (remediation)	48%
STGY	▪ Reduction of overexploitation (mitigation)	45%
PROB	**Thermal interferences**	**78%**
MO	-Reduction of thermal interferences	77%

STGY	▪ Precautionary measures	88%
STGY	▪ Limitation of the number of participants with rights and responsibilities	75%
STGY	▪ Reduction of thermal interferences between/within exploitation	73%
STGY	▪ Allocation of limited rights to net annual heat transfer into the aquifer	56%
STGY	▪ Prevention of unbalanced heat transfer in peak demands	47%
MO	-Minimization of thermal shortcut (autointerference)	76%
STGY	▪ Adequate SGES design	78%
MO	-Minimization of thermal interference between SGES	75%
STGY	▪ Reduction of unbalanced energy transfer of neighboring installations	73%
PROB	**Inefficient use of geothermal resources**	**73%**
MO	-Efficient use SGE resources	74%
STGY	▪ Efficiency principle	69%

The second management objective in order of relevance (78%) is the **long-term sustainable use of SGE resources**. To achieve this objective, the highest rated strategy is understanding the heat and hydraulic regimes in the subsurface managed, thus requiring research and extension services. The second strategy in order of perceived importance is the prioritization of SGE demands during the licencing of the SGE systems. The strategy of sustainable development and the measures considered for the overexploitation prevention objective are also considered to be important to this objective. The last most relevant strategy would be to enforce a **rights-based system where licensing procedures are considered**. It is observed that the adoption of a licencing procedure measure contributes for the improvement of both management objectives gaining greater interest for the efficient management of SGE resources. Additional relevant measures are the assignation of exploitation rights during the licensing process and a limitation on the total allowable unbalanced heat transfer to the subsurface during a year of operation. The balanced heat transfer of heating and cooling have been identified as good indicators of sustainability for SGE systems (García-Gil et al., 2019).

The second most important problem to reach a sustainable development and exploitation of SGE resources are thermal interferences. The most decisive management objective to be considered is the reduction of thermal interferences by adopting precautionary measures, i.e., limiting the number of SGE users, followed by the reduction of thermal interferences. Limiting the number of SGE users to mitigate thermal interference inherently involves prioritization of use (e.g., balanced use above pure cooling, or prioritization to community use). However, limitation of use needs to be appropietely justified to avoid legal discrimination. A defined strategy should be defined to ensure priorization based on time does not occur («*first come, first served*»), such as prioritization by public interest and/or environmental care. The **precautionary measures are already considered in international regulations** (Haehnlein et al., 2010), such as determining the minimum distance between borehole heating exchangers, operation wells, or limitations on temperature changes in the subsurface and temperature differences between extracted/reinjected water. A significant precautionary measure proposed is to monitor groundwater temperatures between two adjacent GWHP systems. On the other hand, reducing the existent distance restrictions for thermal interferences is again considered as the most crucial measure, followed by the adoption of threshold values as maximum/minimum operation temperatures in SGE systems, and the establishment of a monitoring, surveillance and control system for subsurface temperatures.

A second management objective recommended consists in the **minimization of thermal shortcuts** (autointerference or thermal recycling) by designing an adequate SGE systems set-up and a licensing process that considers a thermal shortcut assessment. Other management objectives of importance when trying to reduce thermal interferences include minimizing them by the reduction of unbalanced energy transfer of neighbouring installations and efficiently using SGE resources.

The third management problem in order of perceived relevance is the inefficient use of geothermal resources, the proposed objective management is the **efficient use of SGE resources**. To achieve this objective is recommended to follow a management strategy based on the principle of efficiency. Thermal shortcut assessment during the licensing process and increasing COPs of SGES as much as possible are the measures considered as decisive for this strategy. It should be noted that efficient use of SGE resources also needs to consider other posible causes of efficiency loss, including inappropriate technical concepts for climatization or the heat exchanger (wells, BHE), among others.

The survey outcome (Table 2) indicates that maintaining an environmentally-friendly use of SGE resources requires coping with indirect threats to human health or the environment related to SGE exploitation, which is possible but unlikely in general, and impossible in prestine aquifers where contaminantion does not exist. When preexistent contamination exists, there is a general agreement that hydrodynamic remobilization of existing contamination in aquifers due to the operation wells of GWHP systems is the problem considered to be the most worrying (88%). Open loop systems operating in contaminated sites might cause the spreading of existing contamination to other places, thus contributing to a potential groundwater quality decline in extended areas of the urban subsurface. The fact that point-source contamination, especially persistent pollutants such as heavy metals and polycyclic aromatic hydrocarbons, has often been found in subsurface urban environments (Bonneau et al., 2017; Schirmer et al., 2013) does not only endanger groundwater resources as water supply, but also risks the contaminants' release to surface water bodies hydraulically connected to urban aquifers (Engelhardt et al., 2011). The management objective linked to this problem is to operate SGE systems using good groundwater quality. The strategy to follow is to operate GWHP systems outside of contaminated areas by licensing and area closures measures. Also is recommended to adopt precautionary measures, such as monitoring of pumped groundwater quality.

Table 2: Relevant management concepts for the environmentally friendly use of SGE resources policy, Scores are given for the different management levels: Management problems (PROB), management objectives (MO) and management strategies (STGY) assessed by 13 Geological National Surveys.

Management policy: Environmentally friendly use of SGE resources		
Level	**Name**	**Relevance [-]**
PROB	**Activities raising threats to human health or the environment**	**78%**
MO	-Reduction of environmental impacts	80%
STGY	▪Precautionary measures	78%
STGY	▪Understanding how SGE exploitation impact the ecosystem function	73%
MO	-Establishment of a cause and effect relationship for environmental impacts	79%
STGY	▪Use of the best available science for decision-making	76%
STGY	▪Study of physical, biological and chemical processes triggered by SGE use	76%
MO	-Identification of potential subsurface quality deterioration	77%
STGY	▪ Environmental MSC system	76%
PROB	**Contribution to Urban Heat Island (UHI) effect**	**56%**
MO	-Prevention of a potential contribution to Urban Heat Island effect in case of conflict	51%
STGY	▪Control of SGES contribution to the Urban Heat Island effect	50%
PROB	**Enhancement of existent microbiological contamination**	**55%**

MO	-Prevention of the potential enhancement of microbiological contamination	55%
STGY	▪Control of GE activities in microbiologically-contaminated areas	45%
PROB	**Thermal groundwater discharge to surface water bodies**	**52%**
MO	-Prevention of potentially negative environmental impacts on hyporheic zones	52%
STGY	▪Control of thermal groundwater discharge to surface water bodies	52%
PROB	**Enhancement of existent (emergent) organic contamination**	**48%**
MO	-Prevention of the potential enhancement of emergent organic contamination	48%
STGY	▪Control of SGE activities in emergent organic contamination areas	47%
PROB	**Enhancement of existent inorganic trace metals contamination**	**47%**
MO	-Prevention of possible enhancement of inorganic trace metals contamination	51%
STGY	▪Control of SGE activities within areas affected by inorganic trace metals contamination	51%

The second most relevant problem this policy faces are the activities raising threats to human health or the environment in general (78%), while specific approaches to specific types of contaminants are not considered of special relevance. The objectives considered important to the general approach include the **reduction of environmental impacts**, followed by the establishment of a cause and effect relationship for environmental impacts and the identification of potential subsurface quality deterioration. To reduce environmental impacts, two strategies are considered essential. The first one considers the use of **precautionary measures during the construction phase**, such as leakage tests of the closed-loop refrigerant tubing, specific regulations on the heat carrier fluid type, evaluation and risk assessment during the licensing process, operation depth restrictions, borehole sealing in decommissioning SGE systems, and establishment of specific regulations on borehole heat exchanger grouting and licensing. The second strategy consists in **understanding how SGE exploitation impacts to the ecosystem function through research** and extension services. Establishing the objective of finding a cause and effect relationship for environmental impacts is also seen as very relevant. This objective aims to reduce the uncertainty that can limit the benefits of SGE exploitation according to a precautionary principle embedded in the European union (TFEU, 2010). Therefore, the strategies suggested are to use the best available science for decision-making, and to study the physical, biological and chemical processes triggered by SGE use, both through monitoring and risk assessment and by using research and extension services. The third management objective considered relevant is the identification of potential subsurface quality deterioration, proposing the establishment of an environmental monitoring, surveillance and control system as a management strategy against this potential issue.

The results obtained from the survey (Table 3) also indicate that the most critical problem, showing the highest score of 92% when facing the appropriate SGE coordination with other urban subsurface uses, is to maintain groundwater quality at acceptable levels for water supply. The management objective here is to **maintain the groundwater quality standards for human consumption** and the strategy proposed to be adopted is to follow the precautionary approach. This would suggest banning any kind of SGE activity in protected areas for drinking water supply. The second management problem in order of scored importance (84%) is the consideration of plausible groundwater use conflicts related to irrigation, industrial, recreational or any other uses. General problems related to urban subsurface use conflicts also received a score of 74%. The management objective considered as most essential for this point was the prevention and control of crosscutting conflicts by making use of prevention and mitigation strategies. Hence, the management measures proposed are the mapping of urban subsurface uses and the assessment of the resulting mapped zones in the licensing process.

Table 3: Relevant management concepts for the SGE coordination with other urban subsurface uses policy, Scores are given for the different management levels: Management problems (PROB), management objectives (MO) and management strategies (STGY) assessed by 13 Geological National Surveys.

Management policy: SGE coordination with other urban subsurface uses		
Level	**Name**	**Relevance [-]**
PROB	**Groundwater quality as water supply**	**92%**
MO	-Maintenance of groundwater quality standards	85%
STGY	▪*Precautionary approach*	81%
PROB	**Groundwater use conflicts (irrigation, industrial, recreational, etc.)**	**84%**
PROB	**Urban subsurface use conflicts (general approach)**	**74%**
MO	-Prevention/control of crosscutting conflicts	74%
STGY	▪*Prevention and mitigation of crosscutting issues*	75%
PROB	**Geotechnical impacts (subsidence)**	**61%**

MO	-Prevention of fines migration into groundwater heat pumps systems	69%
STGY	▪ *Ensurance of laminar flow in pumping/injection wells*	62%
MO	-Prevention of dissolution subsidence (Chemical reaction equilibria changes with T)	58%
STGY	▪ *Groundwater isolation from atmospheric conditions*	61%
PROB	**SGE impacts on subsurface infrastructure**	**50%**
MO	-Reduction of thermal impacts in tunnels (ventilation design)	39%
STGY	▪ *Consideration of temperature-sensible subsurface infrastructures in thermal impact assessment during the licensing process*	41%

Survey results (Table 4) have shown that the most vital problem (with a score of 83%) to improve the **successful management of SGE resources** involves the management in the **context of data-poor urban subsurface bodies**. Since subsurface datasets are very limited and expensive to obtain, and management of SGE resources is an emerging branch in science, it is necessary to provide an efficient management approach while efforts are done to improve data-poor contexts. To achieve this objective, improving the overall SGE data system through the reporting, assessment, collection and management of data has been recommended. Other strategies considered relevant are the use of **simplified management approaches**, the implementation of simple statistics to manage SGE resources and also relying on the knowledge of SGE system users. A second important (82%) management problem would be the **conflict of interest between all stakeholders (”management dilemmas”)**, i.e., all the involved parties in the management process. To ensure the objective of reducing the number of conflict cases, considering the co-management of SGE resources has been proposed as a potential solution. This would make the resources become self-regulated making a diminishment of enforcement and compliance. Furthermore, co-management can be implemented by including the affected parties in the decision-making during all the planning process. In this report, co-management makes reference to the share of responsibilities between authorities and stakeholders.

The third management problem in order of perceived relevance (76%) is the inefficient management of SGE resources. Management objectives suggested for this matter are to **diminish enforcement problems and compliance by providing legal and economic certainty in the licensing process**, and to achieve a flexible iterative management approach. The problem of dealing with management measures dependent to site-specific conditions has also been highlighted (75%). To mitigate this problem, establishing the objective of adapting the management measures to the specific local boundary conditions has been suggested. Such measures require spatial resource plans as a basis. Finally, the last relevant (72%) problem potentially hindering the successful management of SGE resources is the disabling environment (authorities missing awareness) and developing capacity building through development of appropriate policy and legal frameworks is considered necessary.

Table 4: Relevant management concepts for the successful management approach policy, Scores are given for the different management levels: Management problems (PROB), management objectives (MO) and management strategies (STGY) assessed by 13 Geological National Surveys.

Management policy: Successful management approach		
Level	**Name**	**Relevance [-]**
PROB	**Managing in the context of data-poor urban subsurface body**	**83%**
MO	- Providing an efficient management of SGE while improving a data-poor context	83%
STGY	▪ *Improvement of the overall SGE data system*	83%
STGY	▪ *Simple management approaches (low information gathering)*	83%
STGY	▪ *Use of simple statistics to manage the SGE resources*	82%
STGY	▪ *Relying on the knowledge of SGES users*	76%
PROB	**Conflict of interest**	**82%**
PROB	**Inefficient management of the SGE resources**	**76%**
MO	-Diminishing of enforcement problems and compliance	73%
STGY	▪ *Providing legal certainty (economic stability)*	72%
STGY	▪ *Co-management approach*	69%
STGY	▪ *Maximization of economic profits for SGE users*	59%
STGY	▪ *Establishment of a SGE market*	59%
STGY	▪ *Adoption of a rights-based system*	58%
STGY	▪ *Increase of investments' security*	51%
MO	-Flexible iterative management approach	70%
STGY	▪ *Adaptive management*	68%
PROB	**Management measures dependence to site-specific conditions**	**75%**
MO	-Adaptation of management measures to local boundary conditions	71%

STGY	▪ *Decentralization of SGE resources management*	68%
PROB	**Disabling environment**	**72%**
MO	- SGE capacity development (building)	73%
STGY	▪ *Development of appropriate policy and legal frameworks*	80%
STGY	▪ *Capacity development is a requirement to institutional sustainability*	68%
STGY	▪ *Development of institutions needed for sustainable SGE utilization*	63%
PROB	**Uncertainty**	**68%**
MO	-Coping with uncertainty	68%
STGY	▪ *Adaptive approach (adjustments and improvements mid-stream)*	72%
STGY	▪ *Management measures applicable to a wide range of scenarios*	59%
PROB	**Illegal activity and heavy enforcement costs**	**53%**
MO	-Implementation of an integrative and inclusive approach	58%
STGY	▪ *All the parties involved need a voice in the decision-making*	61%
STGY	▪ *Ensuring an inclusive and participatory approach*	58%
STGY	▪ *Co-management approach*	61%

Inevitably, each social community will attribute distinct relevance to the different management problems raised due to their own site-specific condition and/or social priorities and concerns. To understand the different positions of the different National Geological Surveys on their approach for the management of SGE resources, a PCA was performed (Table 5). Six significant main components, accounting for 91% of the total variance, were extracted according to the sharp bend found in the scree plot for six of the components. The first two principal components explain 56.4% of the variation observed in the data, and the contribution of each Geological Survey is represented in a score plot in Fig. 3. The first component, accounting for 40.5% of the total variance, is marked by relative high tendency of the geological surveys when rating the relevance of the management problems related to a successful management approach and an environmentally-friendly use of SGE resources policies. In particular, the dependence of the management measures to site-specific conditions, uncertainty, managing in the context of data poor urban subsurface body and enhancement of existent groundwater contamination. The second component is marked by low loadings of successful management approach and high loadings of environmentally friendly use of SGE resources and SGE coordination with other urban subsurface use policies. In particular to inefficient management of the SGE resources, conflict of interest for the first policy and activities raising threats to human health or the environment and geotechnical impacts for the rest of policies. The Score-loading plot (Fig. 3) shows how Geological Surveys are split in two clusters. The first one includes PIG-PIB, ICGC, GBA, GSI, GeoZS, UKRI and IGME (known as group A), showing a relatively positive trend towards a positive rating for the management problems of the first component. The second group would consist of SGIDS, CGS and HGI-CGS (known as group B), presenting a flat tendency in the first component and a negative relative tendency for the second component. In contrast, SGU shows a clearly negative tendency relative to other surveys for both components. RBINS-GSB show a negative tendency for the first component but a very high tendency for the second component.

The PCA has shown a group of Geological Surveys (group A) differenting from the other organizations due to their big concern about activities raising threats to human health or the environment, enhancement of existent microbiological contamination, the dependence of management measures to site-specific conditions, geotechnical impacts and uncertainty of prediction. This group is also differentiated due to their low concern about inefficient management approach of the SGE resources and conflict of interest. Group B includes organizations more concerned about inefficient management approach of the SGE resources and conflict of interest and less concerned about the other issues mentioned for group A. RBINS-GSB organization, in contrast, is significantly more concerned about activities raising threats to human health or the environment and geotechnical impacts, than about the other management problems considered. SGU organization showed low concern about all these management problems in favor of low management/regulation of SGE resources.

Table 5: Component loading for management problems that determine the management approach adopted by of the different Geological National Surveys considering four main management policies. Results obtained from principal component analysis explaining % of the variance found in 12 valid cases.

Management policy	Management problem	Principal components*					
		PC1	PC2	PC3	PC4	PC5	PC6
Sustainable development and exploitation	Geothermal overexploitation & unsustainable development	0.17	0.25	**-0.38**	0.22	-0.01	0.06
	Thermal interferences	0.16	-0.20	-0.05	**0.39**	-0.06	**-0.48**

	Inefficient use of geothermal resources	0.20	0.22	-0.13	0.24	-0.08	**0.48**
Environmentally friendly use of SGE resources	Activities raising threats to human health or the environment	0.17	**0.37**	-0.17	-0.08	-0.19	**-0.37**
	Enhancement of existent inorganic trace metals contamination	0.27	0.09	0.19	-0.18	**-0.35**	0.01
	Enhancement of existent (emergent) organic contamination	0.26	0.16	0.27	-0.11	-0.23	0.03
	Enhancement of existent microbiological contamination	**0.30**	0.14	0.17	0.08	-0.05	-0.25
	Thermal groundwater discharge to surface water bodies	0.18	0.05	**-0.39**	**-0.36**	-0.13	0.02
	Contribution to Urban Heat Island (UHI) effect	0.23	-0.02	0.17	0.13	**0.47**	0.20
SGE coordination with other urban subsurface uses	Urban subsurface use conflicts	0.22	-0.02	-0.10	-0.03	**0.51**	-0.20
	Groundwater use conflicts (irrigation, industrial, recreational, etc.)	0.15	-0.19	-0.05	**-0.48**	**0.35**	-0.02
	Groundwater quality as water supply	0.20	-0.23	0.19	-0.28	-0.10	-0.01
	Geotechnical impacts	0.26	**0.32**	-0.02	0.03	0.17	-0.05
	SGE impacts on subsurface infrastructure	0.25	-0.09	0.03	**0.39**	0.11	0.19
Successful management approach	Inefficient management of the SGE resources	0.08	**-0.42**	**-0.36**	0.02	-0.02	-0.07
	Illegal activity and heavy enforcement costs	0.23	-0.21	-0.10	-0.07	-0.15	**0.41**

	Management measures dependence to site-specific conditions	**0.30**	-0.13	0.17	-0.09	-0.03	0.12
	Disabling environment	0.14	-0.24	**-0.43**	0.03	-0.15	-0.04
	Uncertainty	**0.30**	-0.12	0.20	0.02	0.03	-0.19
	Conflict of interest	-0.01	**-0.38**	0.20	0.25	-0.24	-0.04
	Managing in the context of data-poor urban subsurface body	0.27	-0.07	-0.07	0.06	-0.07	-0.01

*Bold values indicate variables with absolute loadings ≥ 0.3.

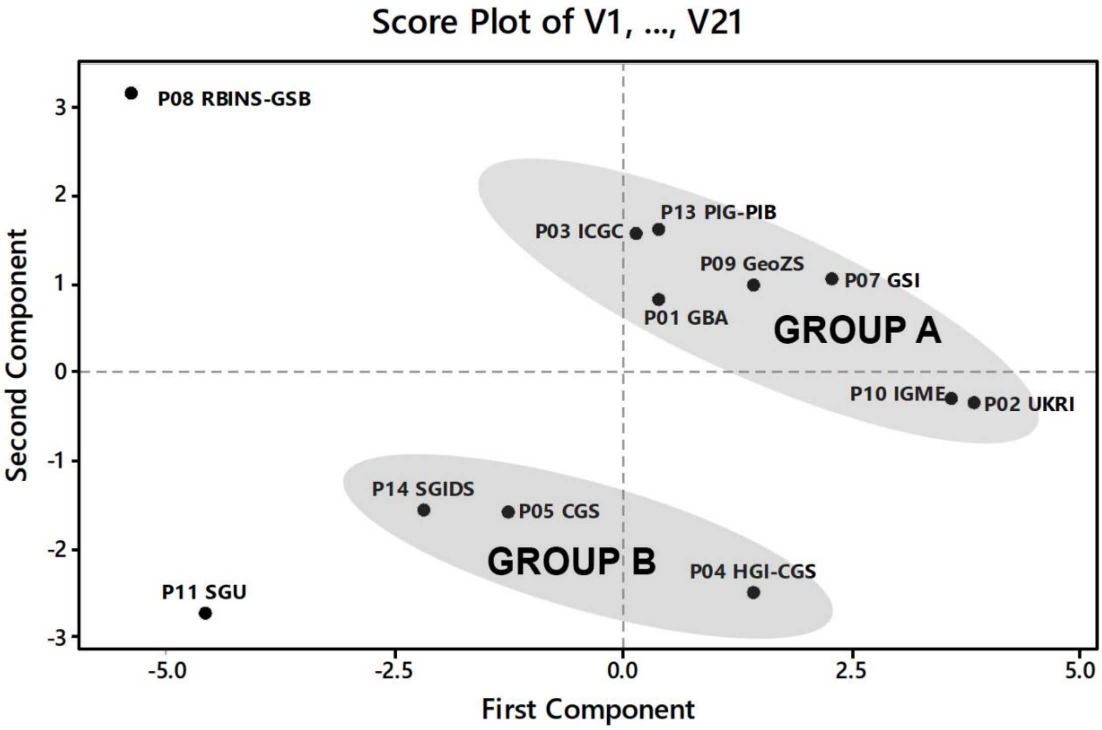

Figure 2: Principal component analysis score plot. The plot shows the tendency of each Geological Survey considered rating management problems separated into two clusters, group A and B. Geological Surveys abbreviations stand for Spain (IGME), Austria (GBA), Croatia (HGI-CGS), Catalonia (ICGC), United Kingdom (UKRI), Belgium (RBINS-GSB), Slovenia (GeoZS), Sweden (SGU), Poland (PIG-PIB), Czech Republic (CGS), Ireland (GSI) and Slovak Republic (SGIDS).

5.2 Governance of SGE resources

There is a general consensus in the relevancy (82%) when referring to the adaptive management approach for the governance of SGE resources, where the learning process consist in monitoring and evaluating to make iterative adjustments within the planning process.

The first phase of the planning cycle (Fig. 2) is based on analysing the policy plan to follow. This analysis starts with the problem identification and assessment. For that purpose, it is recommended to go through the management problems checklist (e.g., Table S1 provided as supplementary material). To effectively identify and assess these management problems of the system managed, performing a SGE resource assessment to provide past and current status of SGE resources considering overexploited extent and its plausible potential future trends is considered essential (84%). In addition, having proper knowledge on the local context of SGE systems, including the current status and trends of the SGE resources exploited is also considered relevant (84%). This also includes identifying the conflict areas between SGE systems and the hydrogeological characterization of the shallow urban subsurface. Afterwards, in the establishment of management objectives, it is considered important to clearly define the objectives, which should be specific, measurable, achievable, realistic and time-related. Moreover, management objectives should be directly linked to management measures, listing the expected outcomes. The final task for the analysis of the policy plan, i.e., the identification of possible strategies and measures appears as essential to identify the priorities upon which to focus effort and resources. The second phase in the planning cycle is the decision making. In this phase the participation of stakeholders during all phases should be considered is described as important (78%). In addition, management measures adopted should widely accepted by stakeholders.

In the implementation and control cycle (Fig. 2), the first phase consists in the implementation of policies and it is considered most relevant (82%) to perform such implementation in the context of data-poor environments. It is needed that managers improve the overall SGE data system by using data collection and reporting these data. It is also recommended to use simple management approaches based in simple statistics to manage the SGE resources and to rely on the knowledge of SGE systems users. In the last phase of this cycle, the results of the survey see the relevance (78%) of setting a monitoring, control and surveillance system under a low financial requirements framework relying on cost effectiveness, payer and low-cost approaches. The monitoring, control and surveillance system will provide compliance through instrumental measures. Finally, the monitoring of effectiveness of the management measures planed is described as a very important aspect too (76%). Complete results obtained from the survey are provided as supplementary material (Table S2).

6 CONCLUSIONS

In this report, the complexity of the thermal regime in the shallow subsurface of the cities determining the renewable energy resources and the existent environmental barriers to SGE development have been addressed. The steady increase in the implementation of SGE systems in the urban environments has triggered major concerns about the long-term technical, environmental and social sustainability of this technology. The existent legal frameworks all over the world have failed to some degree to give a scientific-based solution to this problem and aimed to use simple approaches that have ended in disperse incoherent legal enforcements. Although the management concepts developed in those legal frameworks are appropriate, the fixed thresholds proposed are still not scientifically-based and are sometimes questionable, thus rising uncertainty among operators, possible investors and, eventually, authorities. In GeoERA MUSE, a comprehensive theoretical concept for an adaptive management approach for the governance of SGE resources, harmonized by 13 European Geological Surveys has been elaborated.

First, a **complete management framework structure** configuring a roadmap for policymakers is proposed. The management structure mainly consists of an open but exhaustive checklist of management problems, objectives, strategies and measures organised according to four policy principles proposed here; (I) "*Sustainable development and exploitation of SGE resources*", (II) "*Environmentally friendly use of SGE resources*" (III), "*SGE coordination with other urban subsurface uses*" and (IV) "*Successful SGE management approach*". This management framework structure is then proposed in the management process by the definition of a **governance model adaptable to poor-data systems** and the uncertainty associated. This governance model follows a **double-adaptive management cycle** to define the process of decision-making in the planning stages and the decision-implementation processes.

The MUSE partners in general consider that the adaptive management approach would support shallow geothermal energy governance in some specific cases, mostly in urban areas where high density of installations is found. It is believed that it accounts for two major problems: summation effects and management in poor data environment. Nevertheless, it is also considered that this management approach has to be implemented in a way that it does not send a bad message to the community, by making clear that SGE resources do not cause important environmental problems and surveillance control and monitoring is not causing market shifts to other energy alternatives. It is also concluded that current legal framework or governance procedures need to be updated to consider the adaptive management approach presented in this report. In some cases, adaptive approaches are not yet introduced in legal procedures. Finally, Geological Surveys organizations find that there are still hurdles for applying an adaptive management approach in their country/pilot areas, such as not having a clear/strong strategy for SGE at the regional level, not enabling of legal instruments for allowing alternatives to first come first served, financing of data assessment and data analyses being linked to adaptive management procedures, a need for adaptating existing licenses to adaptive management procedures, a lack of monitoring data, and assessment/evaluation (key indicators and threshold values) still being under development.

The discussion made on the governance of SGE resources shows the potential need to enforce the elaboration of SGE management plans by legal frameworks and regulations, thus appearing as more crucial than the definition of fixed threshold values for all plausible scenarios. To this end, enforcements should be preferably imposed throughout an adaptive management approach where transparency, co-management and research and extension services guide the process.

The experience gained in the field of SGE exploitation has proven that the electrification transition of heating and cooling in the cities cannot be yet achieved through technology advancement alone, as policies are needed to effectively implement SGE exploitation within city energy and climate plans through a scientific-based adaptive SGE management plan and sustainable governance environment. For that matter, the governance approach proposed shows a strong potential to support EU initiatives to contribute to the decarbonization of the European economy.

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8 ANNEX

Table A. Complete list of management problems (PROB), management objectives (MO), management strategies (STGY) and management measures (MS) that completes the structure of the management framework.

MANAGEMENT POLICY: SUSTAINABLE DEVELOPMENT AND EXPLOITATION

LEVEL	NAME	RELEVANCE [-]
PROB	**Geothermal overexploitation & unsustainable development**	**85%**
MO	**-Overexploitation prevention**	**84%**
STGY	**▪ Sustainable development**	**83%**
MS	SGE resources planning (strategic allocation of SGE systems)	83%
MS	Licensing procedures (sustainable exploitation assessment)	81%
MS	Planning of district heating grids	57%
STGY	**▪ Identification of areas at risk of overexploitation**	**72%**
MS	Mapping of intensively exploited areas at risk of overexploitation	73%
MS	MSC system for subsurface/production temperatures (positive trends)	66%
MS	MSC system for exploitation regimes of SGE systems (positive trends)	64%
MS	MSC system for COP of SGE systems (positive trends)	62%
STGY	**▪ Control of exploitation efforts**	**65%**
MS	Limitation of new entry of SGE systems into potential conflict areas	70%
MS	Licensing procedures (exploitation limits enforcement)	70%
MS	MSC system for subsurface/production temperatures	67%
MS	MSC system for exploitation regimes of SGE systems	64%
MS	MSC system for COP of SGE systems (positive trends)	60%
STGY	**▪ Management of growing demand for SGE to pursue sustainability**	**65%**
MS	Limitation of heating/cooling capacity (Flow rates, T, ΔT)	77%
MS	Identification of the key drivers of the demand's change	61%
MS	Identification of the demand's current status and trends	60%
MS	Incentives to non-exploited areas	47%
MO	**-Long-term sustainable use of SGE resources**	**78%**
STGY	**▪ Understanding of heat and hydraulic regimes in the subsurface**	**84%**
MS	Research and extension services	86%
STGY	**▪ Prioritization of SGE demands**	**81%**
MS	**Licensing**	**79%**

STGY	**▪ Sustainable development**		**74%**	
MS	Licensing procedures (sustainable exploitation assessment)	73%		
MS	SGE resources planning (strategic allocation of SGE systems)	70%		
MS	Planning of district heating grids	58%		
STGY	**▪ Enforcement/compliance for a rights-based system**		**72%**	
MS	Licensing	81%		
MS	Exploitation rights	73%		
MS	Limit on total allowable unbalanced heat transfer per year	70%		
MS	Access rights	66%		
MS	Territorial resource rights	64%		
STGY	**▪ Control of exploitation efforts**		**65%**	
MS	Limitation of new entry SGE systems into potential conflict areas	76%		
MS	MSC system for exploitation regimes of SGE systems	72%		
MS	Licensing procedures (exploitation limits enforcement)	72%		
MS	MSC system for subsurface/production temperatures	71%		
MS	MSC system for COP of SGE systems (positive trends)	48%		
STGY	**▪ Long-term stability of production temperatures in SGE systems**		**63%**	
MS	MSC system for subsurface/production temperatures (no trends)	72%		
MS	MSC system for exploitation regimes of SGE systems (no trends)	68%		
MS	MSC system for COP of SGE systems (no trends)	57%		
STGY	**▪ Promotion of a balanced use of the resources**		**60%**	
MS	Encouragement of nested SGE systems (SGE systems inside heat plumes)	60%		
MS	Subsides to SGE systems reducing asymmetry of exploitation regime	57%		
MS	Fines and penalties to SGE systems with extremely biased exploitation regimes	27%		
STGY	**▪ Stand-still principle:**		**42%**	
MS	Management actions that will maintain or reduce SGE systems' COP	48%		
MS	MSC system for COP of SGE systems (minimum values)	43%		
MS	Management actions that require thermal (COP) impact assessment	41%		
MO	**-Recovery of sustainability in areas under overexploitation**			**64%**
STGY	**▪ Characterization of overexploited areas**		**63%**	
MS	Mapping of areas under SGE overexploitation	66%		
MS	MSC system for subsurface/production temperatures (unacceptable values)	63%		
MS	MSC system for exploitation regimes of SGE systems (unacceptable values)	63%		
MS	Identification of abandonment of installations (worst case scenario)	58%		

MS	MSC system for COP of SGE systems (unacceptable values)	46%			
STGY	**▪ Increase of SGE supply in areas under overexploitation (remediation)**		**48%**		
MS	Subsides to SGE systems biased balance towards recovery	45%			
STGY	**▪ Reduction of overexploitation (mitigation)**		**45%**		
MS	Nested SGE systems (Strategic SGE systems requiring heat inside heat plumes)	51%			
MS	Revokement/limitation of existing licenses	45%			
MS	Incentives for conflictive users to reduce unbalanced exploitation	44%			
PROB	**Thermal interferences**				**78%**
MO	**-Reduction of thermal interferences**			**77%**	
STGY	**▪Precautionary measures**		**88%**		
MS	Minimum distance between pumping and reinjected wells	88%			
MS	Limitation of the absolute allowed temperature range of the RJ water	88%			
MS	Minimum distance between the borehole heat exchangers	88%			
MS	Limitation of the allowed temperature change in the aquifer	82%			
MS	Limitation of the T difference between extracted/reinjected water	77%			
MS	Monitoring of groundwater temperature between two neighbor SGE systems	74%			
MS	Limitation on reinjection of used groundwater	66%			
STGY	**▪ Limitaion of the number of participants with rights and responsibilities**		**75%**		
MS	**Controlled access to the managed area**	**69%**			
STGY	**▪ Reduction of thermal interferences between/within exploitation**		**73%**		
MS	Distance restrictions between SGE systems	81%			
MS	Maximum/minimum operation temperature restrictions in SGE systems	78%			
MS	MSC system for subsurface temperatures (groundwater)	77%			
MS	Temperature change restrictions in exploitation regimes of SGE systems	73%			
MS	MSC system for subsurface/production temperatures	71%			
MS	MSC system for exploitation regimes of SGE systems (unacceptable values)	70%			
MS	Operation depth restrictions for SGE systems	60%			
MS	MSC system for COP of SGE systems	57%			
MS	Time-area closures (Protection areas for existent SGE installations)	50%			
STGY	**Allocation of limited rights to net annual heat transfer into the aquifer**		**56%**		
MS	Total Allowable Unbalanced Heat Transferred (TAUHT) per year	57%			
MS	▪ Soft TAUHT (guiding)	68%			
MS	▪ Hard TAUHT (obligatory)	49%			

MS	Input-output energy transfer controls	55%			
STGY	▪ **Prevention of unbalanced heat transfer in peak demands**		**47%**		
MS	Punctual discharge of heat to urban collectors (e.g. sewers)	33%			
MO	**-Minimization of thermal shortcut (autointerference)**			**76%**	
STGY	▪ **Adequate SGE systems design**		**78%**		
MS	Hydrogeothermal characterization of the SGE systems domain	79%			
MS	Thermal shortcut assessment during the licensing process	79%			
MS	Assurance of correct emplacement of SGE systems boreholes	75%			
MS	Licensing	72%			
MO	**-Minimization of thermal interference between SGE systems**			**75%**	
STGY	▪ **Reduction of unbalanced energy transfer of neighboring installations**		**73%**		
MS	Operation temperature/flow rate threshold values	64%			
MO	**-Efficient use SGE resources**			**74%**	
STGY	▪ **Efficiency principle**		**69%**		
MS	Thermal shortcut assessment during the licensing process	67%			
MS	Maximize COPs of SGE systems	66%			
MS	Licensing	64%			
MS	Minimum COP exigible	63%			
MS	Minimum energy quota related to the quote granted in the license	62%			
MS	Mandatory thermal response tests	55%			

PROB	**Inefficient use of geothermal resources**				**76%**
MO	**-Efficient use SGE resources**			**77%**	
STGY	▪ **Efficiency principle**		**72%**		
MS	Thermal shortcut assessment during the licensing process	71%			
MS	Maximize COPs of SGE systems	70%			
MS	Licensing	68%			
MS	Minimum COP exigible	67%			
MS	Minimum energy quota related to the quote granted in the license	66%			
MS	Mandatory thermal response tests	60%			

MANAGEMENT POLICY: ENVIRONMENTALLY FRIENDLY USE OF SGE RESOURCES

LEVEL	NAME	RELEVANCE [-]
PROB	**Activities raising threats to human health or the environment (general)**	**78%**
MO	**-Reduction of environmental impacts**	**80%**
STGY	**▪Precautionary measures**	**78%**
MS	Leakage tests of the closed-loop refrigerant tubing	82%
MS	Specific regulations on the heat carrier fluid type	76%
MS	Evaluation and risk assessment during the licensing process	71%
MS	Operation depth restrictions	71%
MS	Boreholes sealing in decommissioning SGE systems	71%
MS	Specific regulations on borehole heat exchanger grouting	70%
MS	Licensing	70%
MS	Tightness tests of the closed-loop refrigerant tubing	66%
MS	Exact measurement of borehole depth of SGE systems	58%
MS	Time-area closures	57%
STGY	**▪Understanding how SGE exploitation impact the ecosystem function**	**73%**
MS	Research and extension services	72%
MO	**-Establishment of a cause and effect relationship for environmental impacts**	**79%**
STGY	**▪Use of the best available science for decision-making**	**76%**
MS	Monitoring and risk assessment throughout SGE exploitation	79%
MS	Research and extension services	74%
STGY	**▪Study of physical, biological and chemical processes triggered by SGE use**	**76%**
MS	Research and extension services	77%
MO	**-Identification of potential subsurface quality deterioration**	**77%**
STGY	**▪ Environmental MSC system**	**76%**
MS	MSC system for subsurface quality (groundwater)	79%
PROB	**Contribution to Subsurface Urban Heat Island (SUHI) effect**	**56%**
MO	**-Prevention of a potential contribution to Subsurface Urban Heat Island effect in case of conflict**	**51%**
STGY	**▪Control of SGES contribution to the SUHI effect**	**50%**
MS	Mapping of city areas potentially harmed by SUHI	59%
MS	Licensing	43%
MS	Assessment of risks to human health/comfort or to the environment	39%

MS	Time-area closures	28%
MS	Operation depth restrictions	28%

PROB	**Enhancement of existent microbiological contamination**	**55%**
MO	**-Prevention of the potential enhancement of microbiological contamination**	**55%**
STGY	**▪Control of GE activities in microbiologically-contaminated areas**	**45%**
MS	Licensing	51%
MS	MSC system for subsurface quality (groundwater)	46%
MS	Time-area closures	45%
MS	Mapping of microbiologically-contaminated areas in the city	42%
MS	Assessment of risks to human health or to the environment	41%
MS	Operation depth restrictions	35%

PROB	**Thermal groundwater discharge to hyporheic zone (exfiltration)**	**52%**
MO	**-Prevention of potentially negative environmental impacts on hiporreic zones**	**52%**
STGY	**▪Control of thermal groundwater discharge to surface water bodies**	**52%**
MS	Assessment of risks to the environment	56%
MS	Mapping of groundwater discharge areas in the city	48%
MS	MSC system for GW discharge to surface water bodies	46%
MS	Licensing	46%
MS	Time-area closures	37%
MS	Operation depth restrictions	32%

PROB	**Enhancement of existent (emergent) organic contamination**	**48%**
MO	**-Prevention of the potential enhancement of emergent organic contamination**	**48%**
STGY	**▪Control of SGE activities in emergent organic contamination areas**	**47%**
MS	Licensing	53%
MS	MSC system for subsurface quality (groundwater)	50%
MS	Time-area closures	46%
MS	Mapping of emergent organic contamination areas in the city	44%
MS	Assessment of risks to human health or to the environment	40%
MS	Operation depth restrictions	37%

PROB	**Enhancement of existent inorganic trace metals contamination**	**47%**

MO	-Prevention of possible enhancement of inorganic trace metals contamination	51%
STGY	▪Control of SGE activi	51%
MS	Mapping of areas in the city affected by trace metals contamination	59%
MS	Licensing	52%
MS	Time-area closures	50%
MS	MSC system for subsurface quality (groundwater)	48%
MS	Operation depth restrictions	46%
MS	Assessment of risks to human health or to the environment	43%

MANAGEMENT POLICY: SGE COORDINATION WITH OTHER URBAN SUBSURFACE USES

LEVEL	NAME	RELEVANCE [-]
PROB	Groundwater quality as water supply	92%
MO	-Maintenance of groundwater quality standards	85%
STGY	▪Precautionary approach	81%
MS	Protection of areas for drinking water supply (quality and quantity)	88%
MS	Groundwater management maps (priorization of use)	67%
PROB	Groundwater use conflicts (irrigation, industrial, recreational, etc.)	84%
PROB	Urban subsurface use conflicts (general approach)	74%
MO	-Prevention/control of crosscutting conflicts	74%
STGY	▪Prevention and mitigation of crosscutting issues	75%
MS	Inventory/mapping of other uses of urban subsurface	78%
MS	Licensing	71%
MS	MSC system in conflict areas	67%
MS	Depth restrictions	65%
MS	Time-area closures	48%
PROB	Geotechnical impacts (subsidence)	61%
MO	-Prevention of fines migration into groundwater heat pump systems	69%
STGY	▪ Ensurance of laminar flow in extraction/injection wells	62%
MS	Quality standards for well design, construction and maintenance	51%
MO	-Prevention of dissolution subsidence	58%
STGY	▪ Groundwater isolation from atmospheric conditions	61%

MS	Pressurized groundwater pipe lines and closed water reservoirs in SGE systems	75%

PROB	**SGE impacts on subsurface infrastructure**	**50%**
MO	**-Reduction of thermal impacts in tunnels (ventilation design)**	**39%**
STGY	**▪ Consideratio**	**41%**
MS	MSC systems near subsurface infrastructures sensible to temperature	37%
MS	Inventory/mapping of temperature-sensible subsurface infrastructures	36%
MS	Time-area closures	33%
MS	Licensing	32%
MS	Depth restrictions	21%

MANAGEMENT POLICY: SUCCESSFUL MANAGEMENT APPROACH

LEVEL	NAME	RELEVANCE [-]
PROB	**Managing in the context of data-poor urban subsurface body**	**83%**
MO	**- Providing an efficient management of SGE while improving a data-poor context**	**83%**
	▪ Improvement of the overall SGE data system	**83%**
MS	Reporting data	84%
MS	Assessment data	83%
MS	Data collection	82%
MS	Management data	82%
STGY	**▪ Simple management approaches (low information gathering)**	**83%**
STGY	**▪ Use of simple statistics to manage the SGE resources**	**82%**
STGY	**▪ Relying on the knowledge of SGE systems users**	**76%**

PROB	**Conflict of interest**	**82%**

PROB	**Inefficient management of the SGE resources**	**76%**
MO	**-Diminishing of enforcement problems and compliance**	**73%**
STGY	**▪ Providing legal certainty (economic stability)**	**72%**
MS	Licensing	70%
MS	Legal protection of rights/benefits	67%
STGY	**▪ Co-management approach**	**69%**

MS	Share of responsibility and authority for managing SGE resources	68%			
MS	Sustained stakeholder participation through all planning and implementation phases	66%			
STGY	**▪ Maximization of economic profits for SGE users**		**59%**		
MS	Licensing	57%			
MS	Guaranty of background/capitation temperatures of SGE systems	50%			
STGY	**▪ Establishment of a SGE market**		**59%**		
MS	Permanent or temporal transference of SGE rights	58%			
MS	Inclusion of individual transferable quotas in the licensing process	58%			
STGY	**▪ Adoption of a rights-based system**		**58%**		
MS	Conferring certain rights to the user	59%			
MS	Licensing	58%			
MS	Long-term licenses (long-term user rights are granted)	58%			
STGY	**▪ Increase of investments' security**		**51%**		
MS	Licensing	52%			
MS	Guaranty of background/capitation temperatures of SGE systems	43%			
MO	**-Flexible iterative management approach**			**70%**	
STGY	**▪ Adaptive management**		**68%**		
MS	Standardized indicators for evaluating SGE management performance	68%			

PROB	**Management measures dependence to site-specific conditions**				**75%**
MO	**-Adaptation of management measures to local boundary conditions**			**71%**	
STGY	**▪ Decentralization of SGE resources management**		**68%**		
MS	Shifting of responsibilities from central government to lower levels	59%			
MS	Rights-based system approach (Licensing)	59%			

PROB	**Disabling environment**				**72%**
MO	**- SGE capacity development (building)**			**73%**	
STGY	**▪ Development of appropriate policy and legal frameworks**		**80%**		
STGY	**▪ Capacity development is a requirement to institutional sustainability**		**68%**		
STGY	**▪ Development of institutions needed for sustainable SGE utilization**		**63%**		

PROB	**Uncertainty**				**68%**
MO	**-Coping with uncertainty**			**68%**	
STGY	**▪ Adaptive approach (adjustments and improvements mid-stream)**		**72%**		
MS	Program management cycle	74%			

STGY	**▪ Management measures applicable to a wide range of scenarios**		**59%**		
MS	Scenario assessment	65%			
PROB	**Illegal activity and heavy enforcement costs**				**53%**
MO	**-Implementation of an integrative and inclusive approach**			**58%**	
STGY	**▪ All the parties involved need a voice in the decision-making**		**61%**		
MS	Perceived benefit to stakeholders	64%			
MS	Adaption of the planning, decision-making and implementation process	61%			
STGY	**▪ Ensuring an inclusive and participatory approach**		**58%**		
MS	Stakeholder mapping	56%			
MS	Sustained stakeholder participation through all planning and implementation phases	56%			
MS	Vulnerability and capacity analysis	53%			
MS	Avoidance command and control actions (are costly and ineffective)	43%			
STGY	**▪ Co-management approach**		**61%**		
MS	Assessment of existing capacity of enforcement	63%			
MS	Stakeholders involvement in the decision-making process during the planning and implementation phases	59%			
MS	Assessment of existing capacity of stewardship development	58%			
MS	Co-management approach	57%			