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# SYSTEMATIC APPROACH FOR THE SELECTION OF MONITORING TECHNOLOGIES IN $CO_2$ GEOLOGICAL STORAGE PROJECTS. APPLICATION OF MULTICRITERIA DECISION MAKING

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**ABSTRACT**

Geologic storage of carbon dioxide ($CO_2$) has been proposed as a viable means for reducing anthropogenic $CO_2$ emissions. Once injection begins, a program for measurement, monitoring, and verification (MMV) of $CO_2$ distribution is required in order to: a) research key features, effects and processes needed for risk assessment; b) manage the injection process; c) delineate and identify leakage risk and surface escape; d) provide early warnings of failure near the reservoir; and f) verify storage for accounting and crediting. The selection of the methodology of monitoring (characterization of site and control and verification in the post-injection phase) is influenced by economic and technological variables.

Multiple Criteria Decision Making (MCDM) refers to a methodology developed for making decisions in the presence of multiple criteria. MCDM as a discipline has only a relatively short history of 40 years, and it has been closely related to advancements on computer technology. Evaluation methods and multicriteria decisions include the selection of a set of feasible alternatives, the simultaneous optimization of several objective functions, and a decision-making process and evaluation procedures that must be rational and consistent. The application of a mathematical model of decision-making will help to find the best solution, establishing the mechanisms to facilitate the management of information generated by number of disciplines of knowledge.

Those problems in which decision alternatives are finite are called Discrete Multicriteria Decision problems. Such problems are most common in reality and this case scenario will be applied in solving the problem of *site selection for storing $CO_2$*. Discrete MCDM is used to assess and decide on issues that by nature or design support a finite number of alternative solutions. Recently, Multicriteria Decision Analysis has been applied to hierarchy policy incentives for CCS, to assess the role of CCS, and to select potential areas which could be suitable to store.

For those reasons, MCDM have been considered in the monitoring phase of $CO_2$ storage, in order to select suitable technologies which could be techno-economical viable. In this paper, we identify techniques of gas measurements in subsurface which are currently applying in the phase of characterization (pre-injection); MCDM will help decision-makers to hierarchy the most suitable technique which fit the purpose to monitor the specific physic-chemical parameter.

**KEYWORDS**: $CO_2$ geological storage, monitoring, tools, multicriteria decision tool, soil and atmosphere tools.

## 1 INTRODUCTION

Carbon Capture and geological Storage (CCS) Technology will play a key role on the technologies to be applied if we want to mitigate anthropogenic greenhouse gases emissions (Benson S. *et al.*, 2005; European Commission, 2011).

The success of this technology is based on several phases: pre-injection, injection, closure and post-closure (Carpenter *et al.*, 2011). Both phases are based on geological and engineering knowledge of the structure under consideration as $CO_2$ storage. (Fig. 1). Focusing on the second phase (injection or commercial phase of the emplacement), monitoring techniques are a key factor to detect any potential failure of the storage of the injected $CO_2$. Considering economics aspects, the application of several monitoring techniques will increase the cost of this phase.

Multicriteria decision algorithms have been used for several applications. Recently, it has been applied to hierarchy policy incentives for CCS (Stechow *et al.*, 2011) or to assess the role of CCS (Shackley and McLachlan, 2006), and to select suitable areas for storing $CO_2$ (Llamas and Cienfuegos 2012; Yang and Xu, 2001).

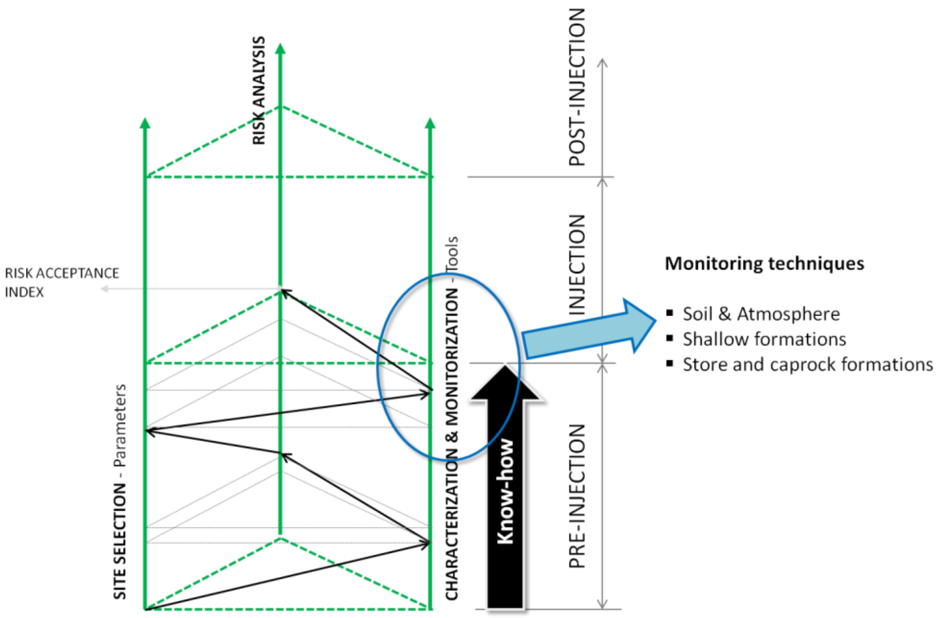


*Figure 1.* $CO_2$ storage phases and the key point to consider in each phase: parameters selection, characterization techniques and risk analysis

Soil and atmosphere monitoring techniques are significantly important, because the health, safe and environmental impact is higher when the injected $CO_2$ reach the atmosphere.
In this paper a Multicriteria Decision Algorithm is proposed to help decision maker to define an appropriate program (techniques selection) to monitor the selected parameters.
The techniques considered in this article have been tested in natural analogue (Campo de Calatrava, Spain) and the base line proposed to the Hontomin $CO_2$ storage structure (Burgos, Spain).

## 2 MATERIALS AND METHODS

### 2.1 Parameters to be monitored

A site of storage of $CO_2$ must be monitored in all phases: from the characterization phase and after in the injection and post-injection (closure) (Wielopolski and Mitra, 2010; Fabriol *et al.*, 2009; Pironon *et al.*, 2011; Simone *et al.*, 2009; Etheridge *et al.*, 2011; Klusman, 2011). One of the aims of CAC projects is to demonstrate that $CO_2$ storage is safe, and there is a control on the evaluation and fate of the $CO_2$ injected, and on the potential environmental effects. This objective requires a monitoring programme of the $CO_2$ fluxes at the soil-atmosphere interface before, during and after the injection operations and the measurements of other gases (radon, helium, $H_2$, $CH_4$) as complementary indicators.

In this paper, the comparative between methods of monitoring is been carried in the Technology Technology Demonstration Plant (TDP) for $CO_2$ storage in a deep saline aquifer (Hontomín, Burgos, Spain). All of these methods of monitoring have been also tested in natural analogues (i.e., Campo de Calatrava, Ciudad Real, Spain).

The soil $CO_2$ flux has been measured using an accumulation chamber. The equipment used is manufactured by the company West Systems (WS-LI820), which uses an LICOR LI-820 infra-red sensor as a detector (Elío *et al.*, 2012; Leuning *et al.*, 2008; Jones *et al.*, 2011). Seven surveys have been carried in Hontomin (Burgos, Spain) to estimate the baseline flux of $CO_2$ and its seasonal variation. The $CO_2$ data can be related with metabolic reactions (via plant roots and soil microbes). For this reason, a secondary objective in the characterization phase of CAC projects is to identify gas flux path to surface. Besides these techniques is necessary to design other monitoring programmes (hydrogeochemical monitoring of surface waters) (Nisi *et al.*, 2013).

The migration of carrier gas by bubbles is a transport mechanism explaining the distribution of $CO_2$ and $CH_4$ (carrier gases) and radon and helium (trace gases) (Etiope and Martinelli, 2002; Voltattorni *et al.*, 2009; Annunziatellis *et al.*, 2008). For this reason, the isotopes of radon (222Rn and 220Rn) have been measured by a) scintillation detector EDA RD-200, b) solid state nuclear track detectors (SSNTD), c) ionization chamber and d) alpha spectroscopy SARAD RTM 2100. Radon isotopes and other gases as helium, hydrogen and methane have been applied to distinguish between $CO_2$ emissions from deep sources and $CO_2$ related with biological activity in subsurface environments.

Besides, other methods (open path laser, remote sensing) were used in Campo de Calatrava (Ciudad Real, Spain), characterized by diffuse emission of $CO_2$ from a deep magmatic body through a fracture system. This site is a natural analogue of emission of $CO_2$ (Table 1).

*Table 1.* Technologies to monitor $CO_2$ storage sites

| Methods | Objectives | PDT (Hontomín) | Natural Analogue (Campo de Calatrava) |
|---|---|---|---|
| Flux Accumulation Chamber | Quantifies the $CO_2$ flux from the soil, | YES | YES |
| Radon isotopes | Measure concentrations of trace gases related with the migration of $CO_2$ | YES | YES |
| Groundwater monitoring | Sampling of water or vadose zone/soil (near surface) for chemical Analysis. | YES | YES |
| Remote Sensing | Multi-spectral imaging for detecting $CO_2$ leaking | NO | YES |
| Open Path | A laser to shine a beam with a wavelength that absorbs $CO_2$ | NO | YES |

### 2.2 Multicriteria decision making (MCDM)

Multiple criteria decision making refers to a methodology developed for making decisions in the presence of multiple, usually conflicting, criteria. MCDM as a discipline has only a relatively short history of 40 years [6]. Those problems in which decision alternatives are finite are called Discrete Multicriteria Decision problems. Such problems are most common in reality and this case scenario will be applied in solving the problem of site selection for storing $CO_2$. Discrete MCDM is used to assess and decide on issues that by nature or design support a finite number of alternative solutions.

Analytical Hierarchy Process (AHP) is one of the most extended and powerful MCDM. Nowadays it has become a method used by several companies in solving various multi-criteria problems, ranking these in the following categories: selection, prioritization and assessment, provision of resources against a standard assessment, management and quality management and strategic planning (Saaty, 1980; 1986; Carlsson and Fullér 1996).

Once the model is built, pair-wise comparisons are made with all individual elements (criteria, sub-criteria and alternatives). Pairwise comparisons are basic to the AHP methodology. Hence, when comparing a pair of criteria, subcriteria or alternatives, a ratio of relative importance can be established. The pairwise comparison process can be performed using words, numbers, or graphical bars. The process is based on a well-defined structure consisting of arrays, and the ability of the eigenvalues to generate values or to approximate weights of each criterion.

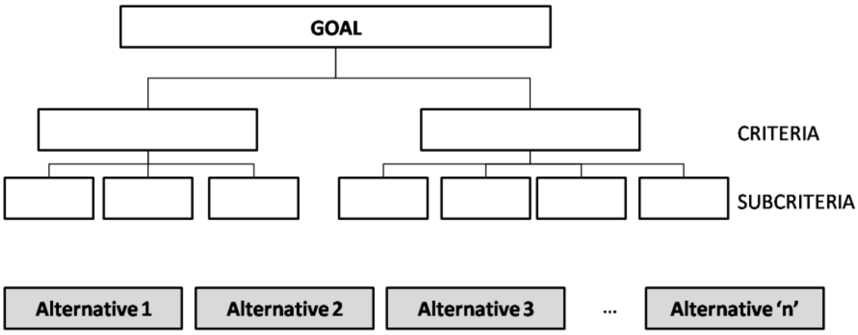


*Figure 2.* AHP Components: Four steps to build a hierarchy or network structure

## 3 DESCRIPTION OF A SPECIFIC APPLICATION

In the characterization phase and baseline setting, a number of strategies may be considered. Those strategies are classified into four groups: (a) geophysics (which is commonly used to define the geometry of the structure), (b) $CO_2$ flux-meter, (c) hydro-geochemical techniques and (d) teledetection techniques. The methodology described in this article is based on the techniques included in the $CO_2$ flux-meter group.

$CO_2$ flux-meter may be measured in different ways: accumulation chamber, Eddy covariance and open path. The measurement of radon or other trace gas could be an indirect signal of leakage of $CO_2$.

But not all the techniques could be deployed to use at an industrial scale. Campaign designs and *in situ* monitoring techniques should be decided in an objective way. Analytical Hierarchy Process will help decision-maker to reduce the risk of $CO_2$ emissions without control or detection and to increase the efficiency of the monitoring investment (technical and economical point of view).

The decomposition principle applied to *techniques to monitor $CO_2$ storage sites* is divided into a structure of clusters and different level of sub-clusters. The final levels of decomposition should be scientifically measurable. The figure below (Fig. 3) shows the proposed structure for this specific multicriteria issue.

The AHP model allows giving numerical values to the judgments provided by people, which are also able to measure how does each element contribute to each level of the hierarchy. Furthermore, the process is based on a well-defined structure consisting of arrays, and the ability of the eigenvalues to generate Weights of each criterion. The AHP uses a fundamental scale of numbers that have proven absolute in practice and that have been experimentally validated by physical problems and decisions. This scale (Carpenter *et al.*, 2011, Stechow *et al.*, 2011) assigns mathematical values with respect to quantitative or qualitative attributes equal to or better than other scales.
At the bottom of the hierarchy structure, measurable criteria should be included. These criteria allow to the decision maker to assign different Values for each alternative.
The evaluation of every alternative is made considering the AHP model described previously, with a specific Weight for each criterion (cluster and sub-cluster), and Values (math scale) for each Area.

$$A_1 = \sum_{i=1}^{n} W_i \cdot V_i$$

Whereas the weight evaluated is the same for each alternative, the values will differ from each alternative.

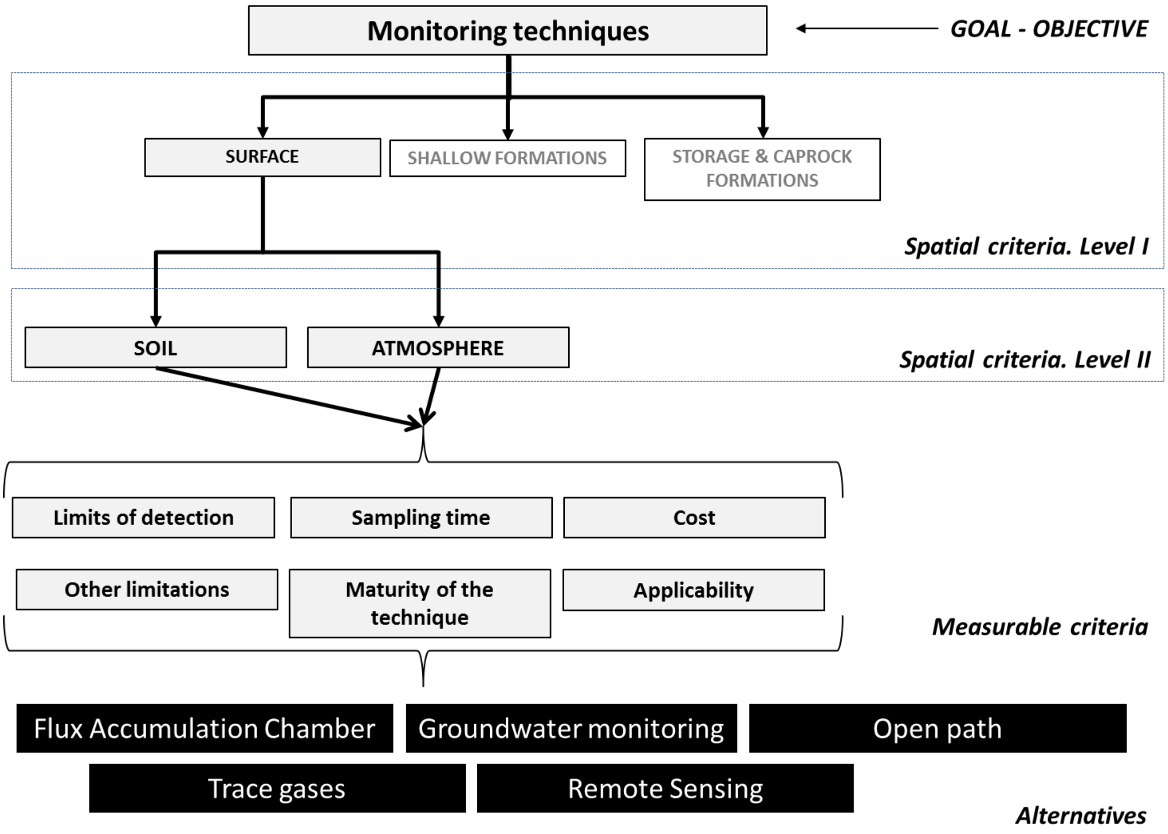


*Figure 3.* AHP model proposed for $CO_2$ monitoring: surface monitoring decomposition

In this study the AHP is applied in a relative mode; elements are compared with each other to derive values for them that are meaningful on a ratio scale. The approach itself makes these elements dependent on each other in measurement.

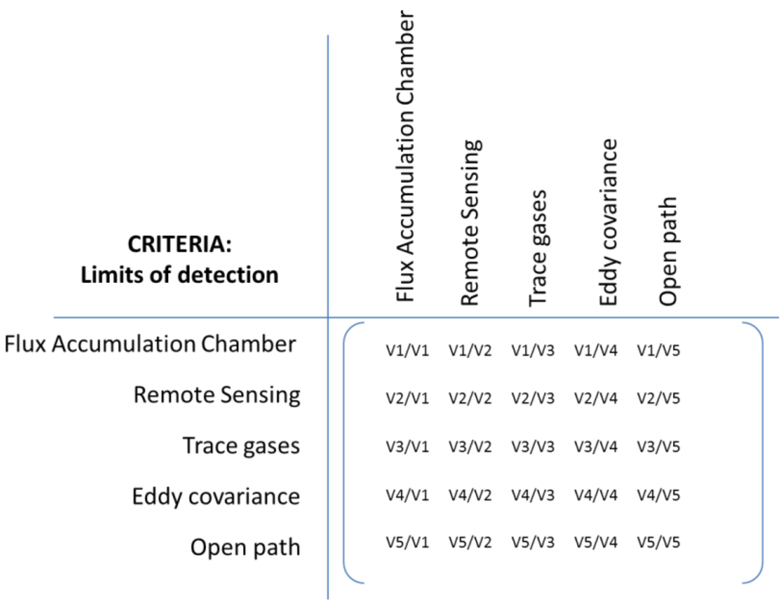


*Figure 4*. Pairwaise matrix comparison. Example taken from the atmosphere criteria evaluation

## 4 CONCLUSIONS

Monitoring techniques for storing $CO_2$ is a complex issue, especially when deep saline aquifers are under assessment. These geological structures used to be poorly characterised and the risk of migration is not well-known. For this reason the Multicriteria Decision Tool can be considered in order to evaluate different alternatives under consideration.

The AHP selects the best monitoring techniques in an objective way. Therefore, it contributes to decrease the risk associated to the design of the campaign, and it will easily show the strengths and weaknesses of the information or characteristics of the alternatives under study. Furthermore, it could also contribute to increase social acceptance by stakeholders: population, non-governmental-organizations and others.

The soil $CO_2$ flux can be measured in different ways, but none all the techniques are appropriate for different objectives. In this paper we suggest, as an example, the best technology for monitoring $CO_2$ fluxes. This selection is based on the AHP algorithm, and the identification of measurable parameters.

The parameters described in this paper has been defined based on several test carried out in a natural analogue (Campo de Calatrava, Spain) and in the baseline acquisition of $CO_2$ storage site (Hontomin, Spain).

## 5 ACKNOWLEDGMENT

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