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Feasibility Study for The Setting Up of a Safety System for Monitoring CO_2 Storage at Prinos Field, Greece

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Abstract. Geological storage of CO_2 in subsurface geological structures can mitigate global warming. A comprehensive safety and monitoring system for CO_2 storage has been undertaken for the Prinos hydrocarbon field, offshore northern Greece; a system which can prevent any possible leakage of CO_2. This paper presents various monitoring strategies of CO_2 subsurface movement in the Prinos reservoir, the results of a simulation of a CO_2 leak through a well, an environmental risk assessment study related to the potential leakage of CO_2 from the seafloor and an overall economic insight of the system. The results of the simulation of the CO_2 leak have shown that CO_2 reaches the seabed in the form of gas approximately 13.7 years, from the beginning of injection. From that point onwards the amount of CO_2 reaching the seabed increases until it reaches a peak at around 32.9 years. During the injection period, the CO_2 plume develops only within the reservoir. During the post-injection period, the CO2 reaches the seabed and develops side branches. These correspond to preferential lateral flow pathways of the CO_2 and are more extensive for the dissolved CO_2 than for the saturated CO_2 gas. For the environmental risk assessment, we set up a model, using ArcGIS software, based on the use of data regarding the speeds of the winds and currents encountered in the region. We also made assumptions related to the flow rate of CO_2. Results show that after a period of 10 days from the start of CO_2 leakage the CO_2 has reached halfway to the continental shores where the "Natura" protected areas are located. CO_2 leakage modelling results show CO_2 to be initially flowing along a preferential flow direction, which is towards the NE. However, 5 days after the start of leakage of CO_2, the CO_2 is also flowing towards the ENE. The consequences of a potential CO_2 leak are considered spatially limited and the ecosystem is itself capable of recovering. We have tried to determine the costs necessary for the creation of such an integrated CO_2 monitoring program both during the CO_2 injection phase as well as during permanent storage. The most prevalent solution consists of purchasing both seismic equipment and Echosounder systems as well as privileging a monitoring system, which uses selected boreholes. The necessary period required for monitoring the study area is at least 20 years after the end of the CO_2 storage period at Prinos. To the overall monitoring time, we should also add a further 20 years that are required for the injection phase as well as 12 years for the storage phase. The operating costs for monitoring the CO_2 amount to 0,38 \$/ton CO2 and the total cost for EOR at Prinos amounts to 0,45 \$/ton CO_2.

1. Introduction

Geological storage of CO_2, through the application of Carbon Capture and Storage (CCS) techniques, corresponds to an effective tool for reducing greenhouse gases in the atmosphere and restricting the planet's global warming. There are various potential sites for CO_2 storage in Greece, with a total storage capacity in deep saline aquifers and hydrocarbon fields estimated at 2190 Mt (GeoCapacity 2009; Rütters and partners 2013). The assessment of CO_2 storage capacity in deep saline aquifers in Greece has concerned the Tertiary sedimentary basins of Prinos, Western Thessaloniki and the Mesohellenic Trough (GeoCapacity 2009) (Figure 1).
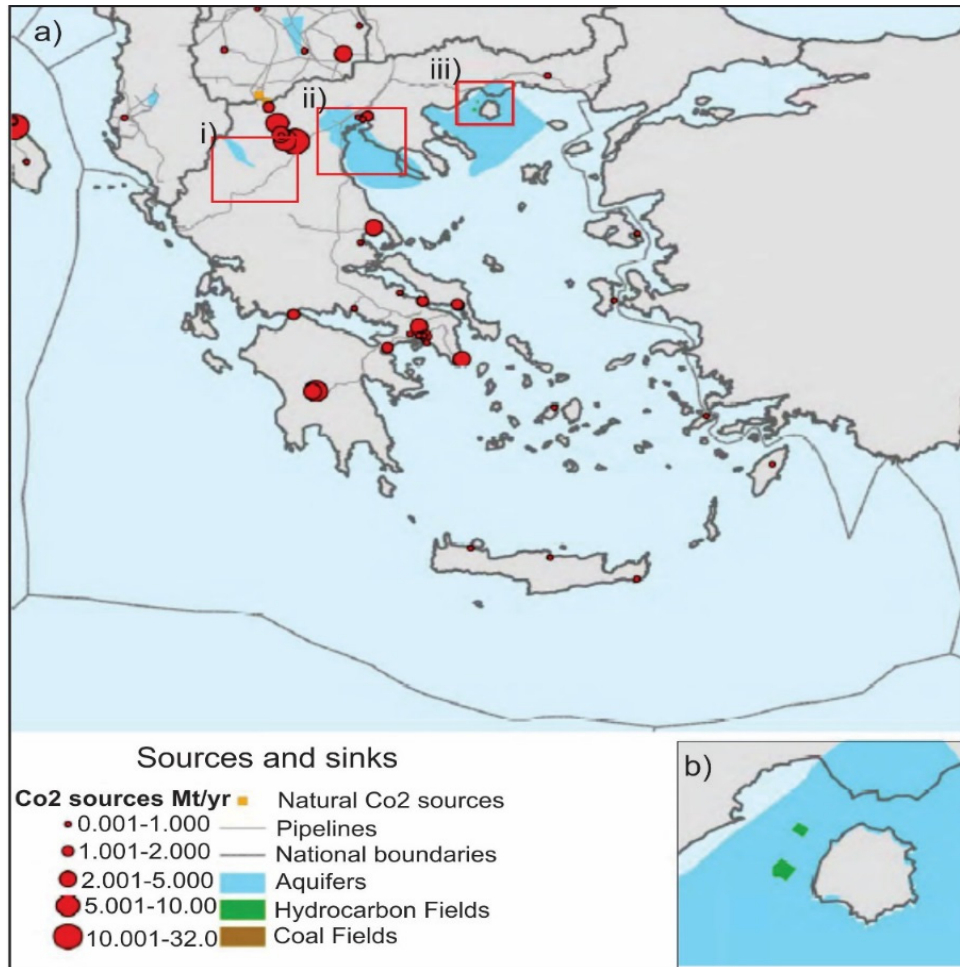
Figure 1. Map of CO_2 emissions, infrastructure and storage capacity in Greece, at ai) the Mesohellenic Trough, aii) Western Thessaloniki, aiii) the Prinos basin and b) further detail of the hydrocarbon fields in the Prinos basin (modified from [2])

2. Location and geological setting

The potential storage site that we will focus upon in this case study concerns the underground CO_2 storage site in the partially depleted Prinos oil reservoir, in northern Greece. The geological morphology of the area is known since the Prinos hydrocarbon field is being exploited for the last few decades. Furthermore, geotechnical studies have already been carried out in the area, in order to find and exploit oil in the past, therefore facilitating further development of the area.

The location of the basin and its hydrocarbon reserves are shown in Figure 2 below. The Prinos basin is formed at the southern end of the Rhodope Massif, between Thassos island and the mainland. It has a length of 38 km and a width of 20 km (Pasadakis et al., 2005; Kiomourtzi et al., 2008). The main axis

has a NE-SW direction covering an area of about 800 km^2. The maximum thickness of the sediments is about 5 km (Figure 2).
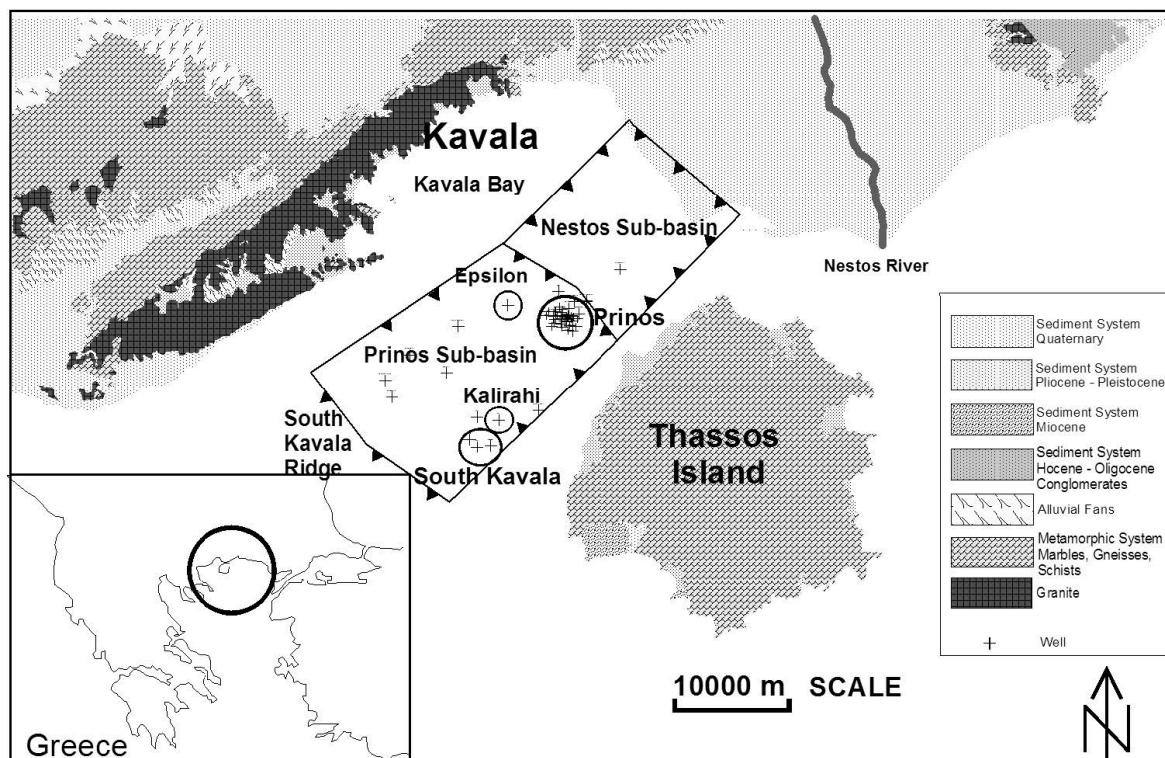
Figure 2. Geologic sketch map of the Prinos - Kavala sedimentary basin in the Northern Aegean Sea, with the location of oil and gas resources

3. Methods

After introducing the safety and monitoring program for the Prinos area, we will focus on a hypothetical leak of CO_2 from the Prinos reservoir and the potential consequences that it may have on the surrounding ecosystems. With the aid of the ECLIPSE reservoir simulation software, we were able to carry out a simulation of the flow of CO_2 within a single injector well in the Prinos field and follow the development of the CO_2 plume through time over a few thousand years. We modelled a single injector well with an injection rate of 500,000 m^3/day. The injection period was for 3 years, followed by the post injection period. In order to simulate a CO_2 leakage, we made several assumptions. We assumed that the cells located within the well have a higher permeability than the surrounding ones. We attributed a permeability of 10 mD to all cells in the well.

For the environmental risk assessment, it was set up a model, using ArcGIS software, based on the use of data regarding the speeds of the winds and currents encountered in the region. We computed the possible spread of CO_2 in the Prinos-Kavala basin and the time it would take for the spill to reach coastal areas. The maximum flow rate of CO_2 at the seabed is estimated to be at 0.75 m/s and the maximum flow rate of CO_2 at the sea surface to be at 1.5 m/s (close to the sea surface). However, we used more moderate values, such as 0.3 m/s and 0.8 m/s, for each one of the above flow rates, respectively. The maximum wind speed can even reach a value of 15-20 m/s during the winter months. In this environmental risk assessment study, we used the value of 2 m/s. The wind speed recordings made by the National Meteorological Institute resulted to 6.9 km/h for 2014 and to 7.1 km/h for 2015. The wind direction is quite changeable so we used the annual mean wind direction for 2014, which is ESE. When making our estimations of the flow rates of CO_2 within the seawater we suggested that the contribution of the speed of sea currents was greater than that of the wind speed.

4. Results

4.1 Monitoring strategies of CO_2 subsurface movement in the Prinos reservoir

To ensure the safety of CO_2 storage there is a need to develop comprehensive monitoring programs (Chadwick et al., 2014). The monitoring program proposed in this study is designed in such a way that it can be applied during the injection of CO_2 into the Prinos reservoir.

The strategy that we propose to follow for baseline studies and monitoring of the seabed above the Prinos CO_2 storage area, in the wider basin of Kavala, includes the analysis of hydroacoustic data to see if bubbles of CO_2 are leaking from the seafloor during the course of the CO_2 injection in the reservoirs.

Another strategy corresponds to the widespread and repeated use of seismic data, either 2D, 3D or 4D, in order to obtain information about the structures that exist beneath the seabed. This will allow to check the retention capacity of the cap rock at Prinos, the existence of channels, natural openings or other possible escape pathways for CO_2 or to even detect tectonic discontinuities. Monitoring of the sedimentary deposits overlying the reservoir is best done by acquiring 3D seismic data over the area over time (e.g. every year if possible or every few years) and then comparing the reflectors for discrepancies.

Seismic data acquisition, using high resolution P-Cable seismic can also be used in order to focus on understanding the shallow subsurface and any leakage phenomena that may take place there. Moreover, the spatial and volumetric coverage provided by the seismic data (time-lapse), enables us to have a high detection capability (high resolution seismic).

When monitoring the movement of CO_2 within the Prinos reservoir and identifying any effects from the CO_2 injection, sampling from oil production data from Prinos is the key instrument to use. Using a multibeam echosounder, we can obtain a better picture of the seabed bathymetry in the area of the Prinos field, as it enables us to create topographic maps of the seabed. In the Prinos storage area, we could also drill wells for monitoring the CO_2 storage. The monitoring wells could be positioned at some distance from the injector wells, in order to measure the temperature and pressure conditions in the reservoir and the underlying aquifer and analyse the composition of the subsurface fluids by taking samples.

4.2 Simulation results of a CO_2 leak through a well

Before carrying out the simulation, we had to build a geological model that contains 5 regions. The uppermost region 1 corresponds to the seabed, region 2 to the cap rock and regions 3, 4 and 5 to the reservoir. Region 3 is the top part of the reservoir, whereas region 5 corresponds to the bottom part of the reservoir.

Simulations show that the CO_2 reaches the seabed in the form of gas approximately 13.7 years, from the beginning of injection, suggesting that measures should be taken to mitigate any adverse effects that this leak may have on the environment. From that point onwards the amount of CO_2 reaching the seabed increases until it reaches a peak at around 32.9 years. During the injection period, the CO_2 plume develops only within the reservoir. During the post-injection period, the CO_2 reaches the seabed and develops side branches. These correspond to preferential lateral flow pathways of the CO_2 and are more extensive for the dissolved CO_2 than for the saturated CO_2 gas.

The CO_2 plume development in terms of CO_2 saturation graph above (Figure 3) shows that during the injection period (Figure 3i) the CO_2 plume develops only within the reservoir. We have perforated and injected CO_2 in the water leg of the reservoir, in the uppermost part of the reservoir, corresponding to cells 45-52 of the model, and the plume's upward migration stops at the cap rock level. During the post injection period (Figure 3ii and 3iii), CO_2 has reached the seabed and develops side branches, corresponding to preferential lateral flow pathways of the CO_2 along certain formations characterized by better flow parameters.
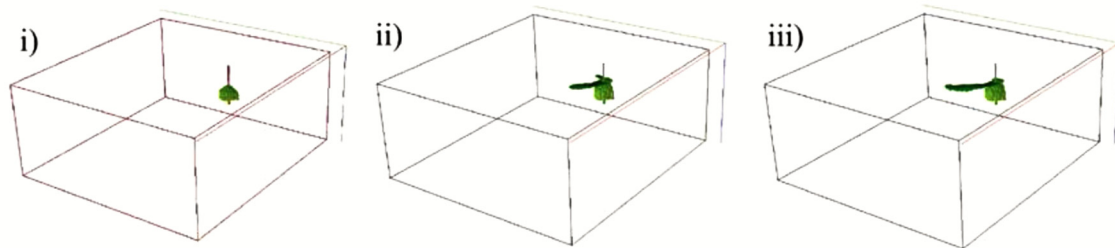
Figure 3. Graph of the CO_2 plume development in terms of CO_2 saturation i) at the end of the injection, ii) 50 years and iii) 2363 years after the beginning of injection.

Dissolved CO_2 tends to go downwards (Figure 4) whereas saturated CO_2 gas goes upwards (Figure 3), thus explaining the difference in plume development between the previously mentioned two figures. Figure 4 shows the plume distribution at various times after the beginning of injection. At both 50 years and 2363 years from the beginning of injection, we see the CO_2 plume developing laterally across the seabed and in a more extensive way than that for the saturated gas (Figure 3). From the simulation runs, we can actually determine that the CO_2 plume has actually reached the seabed surface at year 2028 from the beginning of injection, corresponding to 10 years after the end of the post injection period. This corresponds to a 2nd, less accurate estimation of the time the CO_2 has reached the seabed, as this estimation is based on visual detection rather than on a graphical method.
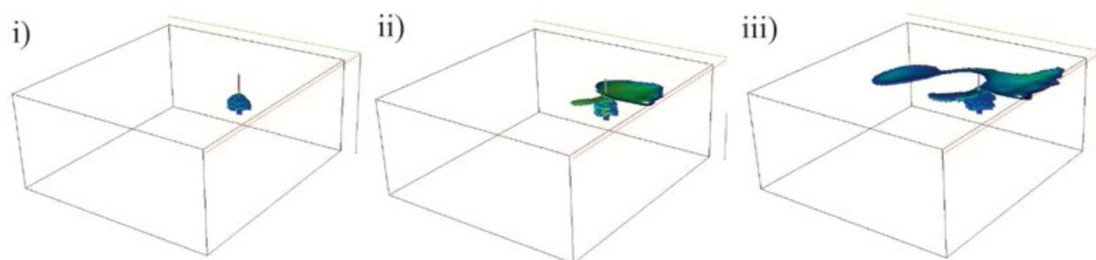
Figure 4. Graph of the CO_2 plume development in terms of CO_2 mole fraction, i) at the end of the injection, ii) 5 years and iii) 2363 years after the beginning of injection

4.3 Environmental risk assessment study related to the potential leakage of CO_2 from the seafloor
Once CO_2 manages to reach the seabed it's important to understand its fate in the water column and the possible effects on the ecosystems. For this, we carried out the following environmental risk assessment study. The results from the potential CO_2 leakage model, assessing the potential degree of risk and consequences to the study area are explained hereafter. At the beginning, the CO_2 leak spreads towards the NE due to the prevailing winds that carry it along this direction. The CO_2 continues to flow in accordance with the preferential flow direction, which is towards the NE, but we also observe a part of the leaked gas to flow towards the ENE. The dispersion of the CO_2 gas 10 days from the start of leakage (Figure 5) shows that CO_2 is approaching the northeastern coast of Thassos.
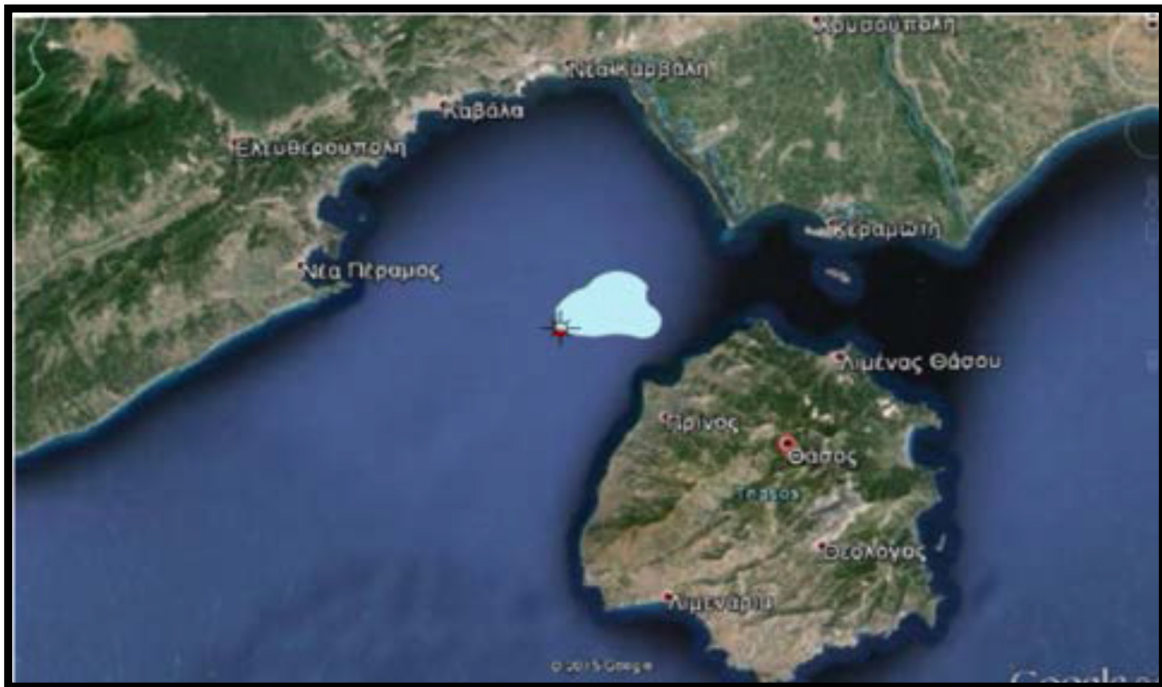
Figure 5. Extent of the CO_2 leak 10 days after start of leakage

A potential CO_2 leak from the Prinos reservoir will significantly affect the marine ecosystems, leading to a rapid local pH reduction. Related effects primarily concern the animals that live attached on the seabed, which could not be removed in time and thus be protected from the CO_2 spill. Released CO_2 is able to change the acidity of seawater in the area where the leak is taking place. The pH may decrease from 8.2 to 6.5, which can have various effects on marine ecosystems.

4.4 Overall economic insight of the system
The most prevalent solution consists of purchasing both seismic equipment and Echosounder systems as well as privileging a monitoring system, which uses selected boreholes. The necessary period required for monitoring the study area is at least 20 years after the end of the CO_2 storage period at Prinos. To the overall monitoring time, we should also add a further 20 years that are required for the injection phase as well as 12 years for the storage phase.
As shown by Table 1 below, the yearly operating costs for monitoring the CO_2 amount to 348,744 \$ which corresponds to a yearly cost of 0,38 \$/ton CO_2. The total cost for EOR at Prinos amounts to 0,45 \$/ton CO_2. Furthermore, the cost of investment for monitoring amounts to 2,057,440 \$ (Table 1).

Table 1. Summary table of the cost of monitoring the stored CO_2

Monitoring cost	
Investment cost	2,057,440 \$
Yearly operating and verifying cost	348,744 \$/yr.

In the detailed model of monitoring costs presented in Table 2 below, we have included the various expenses that need to be made in order to buy various equipment as well as the annual operating and maintenance costs. We also intend to convert some of the existing wells into monitoring wells for CO_2 and thus have included an estimate of the operating cost for these wells, which amounts to 103,940\$ per year. The following table below, Table 2, gives a detailed analysis of the overall investment and monitoring costs.

The total investment costs, which include the cost for investing in the use of echo sounders, 3D and 4D seismic and monitoring wells, amounts to 2,057,440 $ (Table 2). The yearly total operating costs for the aforementioned three monitoring tools amounts to 348,744 $. If we take into account that the monitoring period is planned to last for 52 years then the total operating cost for this entire period amounts to 18,134,688 $ (Table 2). Finally, the total overall cost of the monitoring program for the whole 52 year monitoring period is estimated at 20,192,128 $.

Table 2. Detailed table of the overall monitoring costs of the stored CO_2 for the total 52 year monitoring period

Monitoring cost	Cost	Total cost for the total 52 year monitoring period
Investment cost		
1. Echosounder cost	117,602 $	117,602 $
2. 3D/4D equipment cost	501,508 $	501,508 $
3. Well conversion cost	1,438,330 $	1,438,330 $
Total investment cost	2,057,440 $	2,057,440 $
Operating cost		
A. Yearly operating and verifying costs for the Echosounder	48,220 $	2,507,440 $/yr.
B. Yearly operating costs for the 3D/4D	196,584 $	10,222,368 $/yr.
C. Yearly operating costs for the wells	103,940 $	5,404,880 $/yr.
Yearly total operating costs	348,744 $	18,134,688 $
TOTAL COST		20,192,128 $

5. Conclusions

After only 13.7 years, from the beginning of injection, the CO_2 leak reaches the seabed in the form of gas. There is thus an urgent need to focus on the development and the application of monitoring techniques and invest on safety issues if we are to mitigate the consequences of CO_2 leakage. CO_2 leakage modelling results show CO_2 to be initially flowing along a preferential flow direction, which is towards the NE. However, 5 days after the start of leakage of CO_2, the CO_2 is also flowing towards the ENE. There is only a period of a few days, (Figure 5), from the moment the leakage starts, until the "Natura" areas start to be affected. The public authorities have thus at their disposal a short period of time to take the necessary measures to protect the flora and fauna of the "Natura" sites from contamination. Also taking into account that the "Natura" areas cover not only marine but also terrestrial areas we can thus understand that a possible leak would affect both marine and terrestrial ecosystems.

Due to the specific form in which CO_2 is found in, and its specific mode of dispersion, it is quite difficult to predict the way it will spread, the size of the leak and to what degree the ecosystems will be affected. The consequences of a potential CO_2 leak are considered spatially limited and the ecosystem is itself capable of recovering. There is no fear of any direct negative impacts of the dispersion of CO_2 on marine ecosystems. Possible long-term effects in the Prinos basin will mainly concern shells and corals that will not be able to develop a shell.

Concerning the economic aspects of CCS application, in this case study we can conclude that with a relatively low cost, we are thus able to accommodate a major portion of the CO_2 captured in various industrial facilities across Greece. Furthermore, the revenues (or cost reduction) from the sale of CO_2 to EOR helps CCS economics by producing oil with a lower CO_2 emission "footprint."

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