Δελτίο της Ελληνικής Γεωλογικής Εταιρίας, τόμος L, σελ. 2304-2313
Πρακτικά 14ου Διεθνούς Συνεδρίου, Θεσσαλονίκη, Μάιος 2016

Bulletin of the Geological Society of Greece, vol. L, p. 2304-2313
Proceedings of the 14th International Congress, Thessaloniki, May 2016

SAFETY ISSUES WHEN MONITORING CO_2 STORAGE IN THE PRINOS AREA, GREECE

Koukouzas N.[1], Lymperopoulos P.[1] and Tasianas A.[1]

[1]*Centre for Research and Technology Hellas, Chemical Process and Energy Resources Institute, 15125, Maroussi, Greece, koukouzas@certh.gr, lymperopoulos@certh.gr, tasianas@certh.gr*

Abstract

Geological storage of CO_2 in geological structures in the subsurface can mitigate global warming. A safe storage of CO_2 can be ensured through the development of comprehensive monitoring programs that prevent any possible leakage of CO_2. This paper presents various monitoring strategies of CO_2 subsurface movement in the Prinos reservoir, northern Greece, the results of a simulation of a CO_2 leak through a well, and an environmental risk assessment study related to the leakage of CO_2 or oil from the seafloor. After only 13.7 years, from the beginning of injection, the CO_2 leak reaches the seabed in the form of gas. For the 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. Assumptions were also made related to the flow rate of CO_2. Modeling results show that it only takes a period of 10 days from the start of oil leakage until the "Natura" protected areas start to be affected. CO_2 leakage modelling results show CO_2 to be initially flowing along a preferential flow direction, which is towards NE. However, 5 days after the start of leakage of CO_2, it is also flowing towards ENE. The consequences of a potential CO_2 leak are considered spatially limited and the ecosystem is capable of recovering by itself.
Keywords: *leakage, risk level, environmental impact.*

Περίληψη

Η γεωλογική αποθήκευση του CO_2 σε γεωλογικές δομές κάτω από την επιφάνεια της γης μπορεί να μετριάσει την υπερθέρμανση του πλανήτη. Μια ασφαλής αποθήκευση του CO_2 μπορεί να εξασφαλιστεί μέσω της ανάπτυξης ολοκληρωμένων προγραμμάτων παρακολούθησης που αποτρέπουν οποιαδήποτε πιθανή διαρροή CO_2. Η εργασία αυτή παρουσιάζει διάφορες στρατηγικές παρακολούθησης της υπόγειας μετακίνησης του CO_2 στον ταμιευτήρα του Πρίνου, στη Βόρεια Ελλάδα, τα αποτελέσματα προσομοίωσης μιας διαρροής CO_2 μέσω μιας γεώτρησης, και μια εκτίμηση των περιβαλλοντικών κινδύνων που σχετίζονται με πιθανή υποθαλάσσια διαρροή CO_2 ή πετρελαίου. Μετά από μόλις 13.7 χρόνια, από την αρχή της έγχυσης, η διαρροή του CO_2 φθάνει στον πυθμένα με τη μορφή αερίου. Για την περιβαλλοντική αξιολόγηση έχουμε δημιουργήσει ένα μοντέλο, με τη χρήση του λογισμικού ArcGIS, που βασίζεται στη χρήση των δεδομένων σχετικά με τις ταχύτητες των ανέμων και των ρευμάτων που συναντώνται στην περιοχή. Επίσης, έγιναν εκτιμήσεις σχετικά με τον ρυθμό ροής του CO_2. Τα αποτελέσματα της προσομοίωσης δείχνουν ότι αρκεί ένα διάστημα 10 ημερών από την έναρξη της διαρροής πετρελαίου μέχρι να αρχίσουν να επηρεάζονται οι προστατευόμενες περιοχές "Natura". Τα αποτελέσματα της προσομοίωσης δείχνουν το CO_2 που έχει διαρρεύσει να ρέει αρχικά κατά μήκος της επικρατούσας κατεύθυνσης ροής, η οποία είναι προς τα ΒΑ. Εντούτοις, 5 ημέρες μετά την έναρξη της διαρροής του CO_2, αυτό ρέει επίσης και

προς τα ΑΒΑ. Οι συνέπειες μιας ενδεχόμενης διαρροής CO_2 θεωρούνται χωρικά περιορισμένες και το οικοσύστημα είναι ικανό από μόνο του να επανέλθει στην πρωταρχική του κατάσταση.

Λέξεις κλειδιά: *διαρροή, επίπεδο κινδύνου, περιβαλλοντικές επιπτώσεις.*

1. Introduction

Geological storage of CO_2 is a valuable means of reducing greenhouse gases in the atmosphere and restricting the planet's global warming. The main aim of Carbon Capture and Storage (CCS) activities is to store CO_2 in geological structures, both onshore and offshore, which would be geologically secure without any CO_2 leaks from the reservoir to the overlying formations and at a later stage to the sea or atmosphere (Bachu *et al.*, 2003; Bentham *et al.*, 2005). The idea of underground CO_2 storage in an oil reservoir, such as that of Prinos, in northern Greece, is reinforced by the reality that the geological morphology of the area is known. Geotechnical studies have also already been carried out in the area, in order to find and exploit oil in the past, therefore facilitating further development of the area. After taking a look at the various stages involved in a safety and monitoring program for the Prinos area, we will focus on a hypothetical leak of oil and CO_2 from the Prinos reservoir and the potential consequences that it may have on the surrounding ecosystems.

To ensure the safety of CO_2 storage and to be able to control the monitoring techniques, there is a need to develop comprehensive monitoring programs (Chadwick *et al.*, 2014). The monitoring program proposed in this study should be designed in such a way that it can be applied during injection of CO_2 into the Prinos reservoir. This method will allow controlling the safety of CO_2 storage both during and after the injection phase. The proposed monitoring program would help prevent leakage of CO_2 that can occur at various stages of the project but we will also consider the possibility of CO_2 leakage and its effects on local ecosystems.

2. Geological setting

The study area concerns the Prinos - Kavala sedimentary basin which is located in the Northern Aegean Sea between the city of Kavala and the island of Thassos. The location of the basin and its hydrocarbon reserves is shown in Figure 1. The Prinos basin formed at the southern end of theRhodope 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.

The Prinos-Kavala basin is characterized as a sub-basin and is evolved at a fast speed on an annual basis (Pasadakis *et al.*, 2005). It developed separately from the other areas of the North Aegean Sea; thus, it began to form in the lower Miocene and started to receive sediments from Middle to Upper Miocene and thereafter (Proedrou, 1986).

3. Material and Methods

3.1 Prinos CO_2 monitoring program

To prevent any potential CO_2 leakage and any possible negative effects on the environment, monitoring the reservoir in Prinos becomes a key component in the design of the security system. The monitoring program will cover the entire lifecycle of the project of geological storage of CO_2, and thus the total duration of the project. One of the main reasons for implementing a CO_2 monitoring program is for the protection of the environment and natural resources from leaks of CO_2. By monitoring, we can minimize or even prevent any impact on people, wildlife and ecosystems found in the area surrounding the Prinos field.

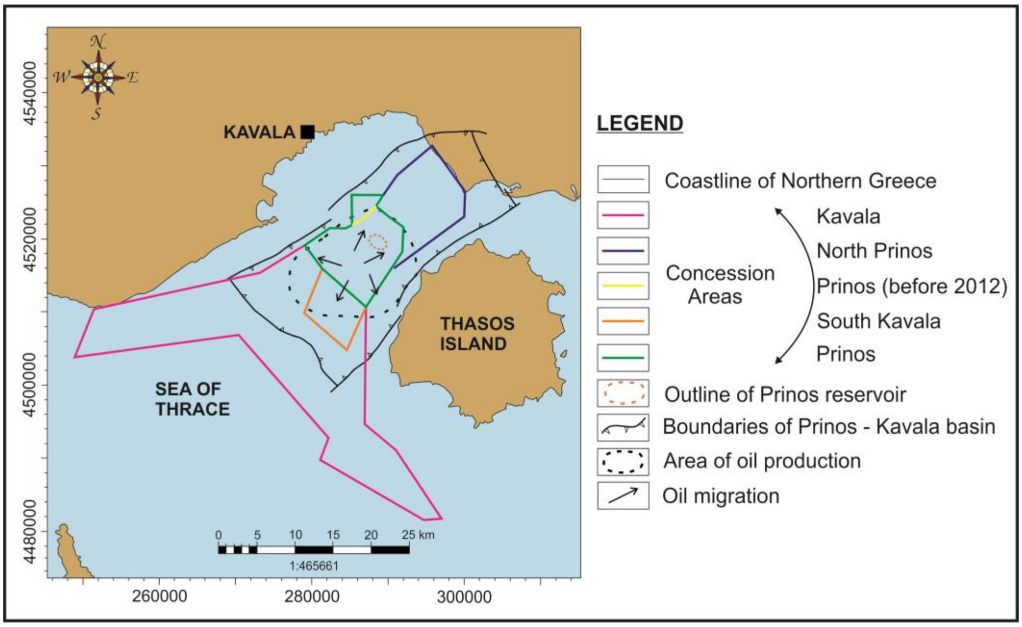


Figure 1 - Geologic sketch map of the Prinos - Kavala sedimentary basin in the Northern Aegean Sea, with the location of oil and gas resources.

3.2 Strategies for monitoring the subsurface

To detect any possible leakage of CO_2 in shallow waters close to the surface, background data related to the level of CO_2 in the atmosphere and in the shallow waters should be characterized prior to injection of CO_2. “Background” CO_2 values in the atmosphere vary between 350 ppm and 380 ppm. The CO_2 background concentration in shallow water does not exceed 320 ppm under a pH of 6-8. Recorded measurements that exceed the above values of "background" CO_2 could be interpreted as resulting from a CO_2 release. If the monitoring in the reservoir and the adjacent cap rock lithology shows an unexpected migration through the cap rock, then the monitoring of the overlying sediments will be necessary and the injection of CO_2 should be halted. 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 use of seismic data 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 in order to detect any leaks from the CO_2 storage reservoir, is best done by acquiring 3D seismic data over time (e.g. every year if possible or every few years) and then comparing them for discrepancies. Seismic data acquisition, using high resolution P-Cable seismic, (Figure 2), can also be used in order to focus on understanding the shallow subsurface and any leakage phenomena that may take place there.

The substitution of brine by CO_2 causes changes in the reflectance of the subsurface, which can be visualized in 3D seismic data. Analyzing the differences in signal between 3D seismic data that will be acquired over the years, the best opportunity to determine if there is a leak or not is provided. Moreover, the spatial and volumetric coverage provided by the seismic data (time-lapse), enables us to have a high detection capability (high resolution seismic, Figure 2).

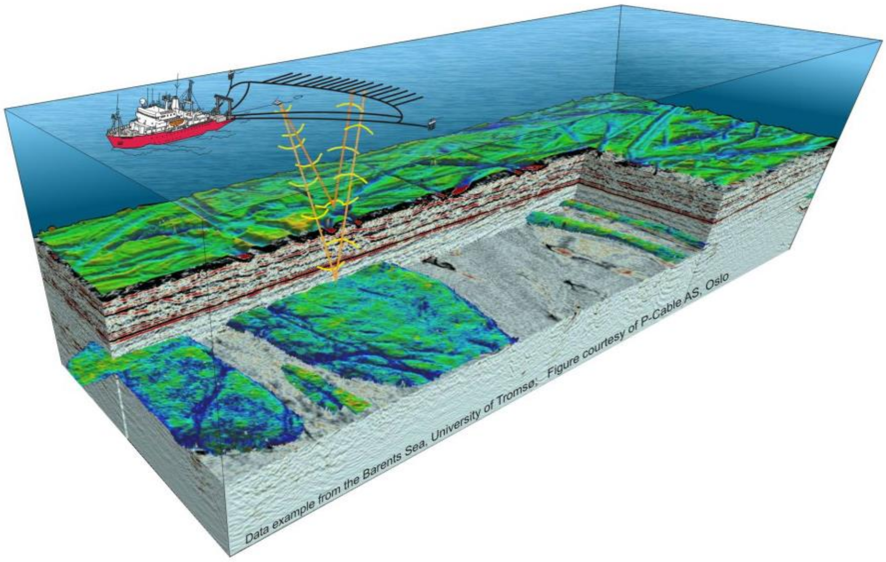


Figure 2 - Diagram of the P-cable high resolution seismic aquisition system using up to 24 streamers (from P-cable AS Oslo).

Possible CO_2 leakage can use the following escape pathways and it can be identified in the following ways: either in layers, which should produce observable seismic reflections or as diffuse flow of CO_2, with formation of “gas chimneys”, which correspond to areas of chaotic reflections.

3.3 Monitoring CO_2 movement in the Prinos reservoir

It is important to focus our interest in monitoring the movement of the CO_2 also within the Prinos reservoir and identify any effects from the CO_2 injection. Sampling from oil production data from Prinos is the key instrument for monitoring the effects of CO_2 injection into the reservoir. Using a multibeam echosounder, we can obtain a better picture of the seabed bathymetry in the area of the Prinos field. The Multibeam echosounder is already on the market and usually available in many research vessels, something that 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

3.4 Simulation of a CO_2 leak in the Prinos field

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.

The model contains 5 regions, with the upper most region 1 corresponding 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. The limitations of the model include changes that we made to the properties of the top layer in the model. We assumed that this top layer corresponds to the seabed. In order to simulate a CO_2 leakage, we have also 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. We also assumed that CO_2 leakage is controlled by the leakage pathways in the subsurface.

3.5 Estimation of the level of risk in the Prinos field

Using the ArcGIS software, we will present a potential assessment model of the degree of risk to the Prinos field caused by a possible CO_2 or oil leak from the reservoir or through a pipeline penetrating it. This model was based on the use of data regarding the speeds of the winds and the currents encountered in the region and making certain assumptions as we will see below. Measurements and information received from the National Meteorological Service and the National Observatory of Athens, contributed significantly to a better understanding of the conditions in the Gulf of Kavala and generally in the region.

By estimating the speed of the flow of oil to be 20 cm/s and the wind speed to be 2 m/s, based on data collected by the National Meteorological Institute, we could then estimate the daily spread of oil into the sea. Assuming that the daily rate of oil spreading at sea is about 1.2 km/day and the prevailing direction of the currents and winds, we computed the possible spread of oil in the Prinos-Kavala basin and the time it would take for the spill to reach coastal areas as illustrated in the following sections. For the environmental risk assessment study related to the leakage of CO_2 we also used the ArcGIS software and based our study on some key elements such as the flow rate of CO_2 at the seabed level, the speed of CO_2 at the sea surface, the speed of the winds and currents and their predominant direction.

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, within the water column). However, in our own calculations 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 or 1.91 m/s for 2014 and to 7.1 km/h or 1.94 m/s for 2015. The wind direction is quite changeable so for this assessment we used the annual mean wind direction for 2014 which is ESE. It should be noted that when making our estimations of the flow rates of CO_2 or oil 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. Simulation of a CO_2 leak in the Prinos field

The results can be presented in terms of saturated $CO_{2,}$ (Figure 3), in the form of free gas, or CO_2 as a mole fraction, corresponding to the dissolved liquid form of CO_2, partly dissolved in brine.

From the seabed curve on Figure 3 above, we observe that after approximately 5000 days or 13.7 years, from the beginning of injection, CO_2 reaches the seabed in the form of gas. From that point onwards the amount of CO_2 reaching the seabed increases until it reaches a peak at around 12000 days or 32.9 years. The impermeable cap rock curve is close to 0 relative gas saturation throughout the simulation as there is no pore space to host CO_2 in there. The top of the reservoir, region 3 in dark blue in Figure 3, shows how the CO_2 saturation rises steadily during the beginning of the experiment and how it remains almost constant during the entire injection and post injection period. Both regions 4, light blue curve, and 5, purple curve, show a higher saturation in the early years with the peak at the beginning corresponding to the end of the injection period. When comparing the 3 regions of the reservoir we notice the highest saturations in region 3, because this region is at the top of the reservoir. CO_2 gas migrates upwards, thus it is accumulated in the uppermost region just below the caprock (region 2). For both regions 4 and 5, CO_2 saturation drops after post injection because the CO_2 gas leaves these regions and migrates upwards into region 3, which is characterised by higher permeability.

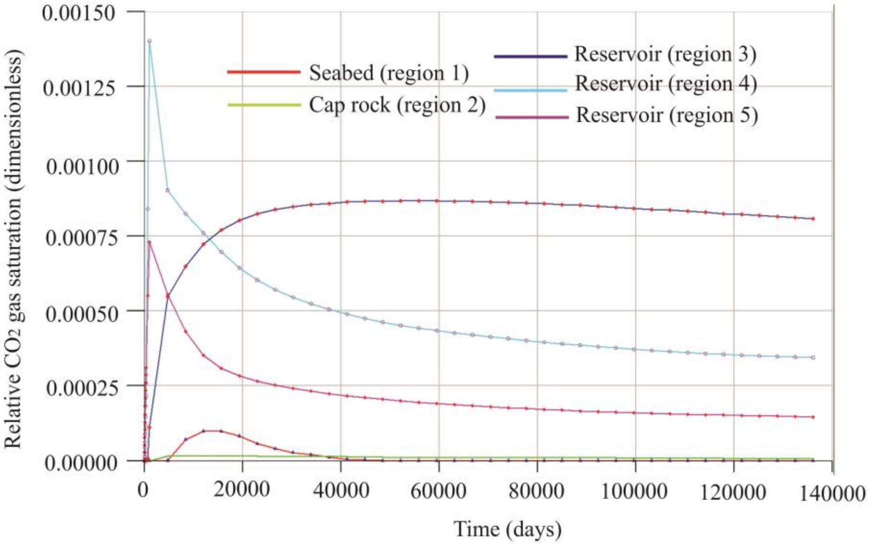


Figure 3 - Graph of relative CO_2 gas saturation for the various 5 regions of the model against time in days.

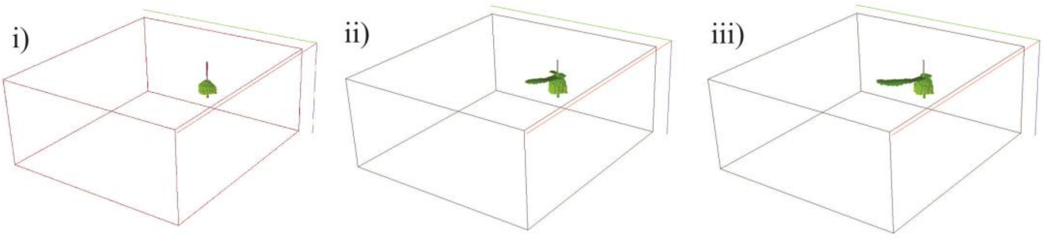


Figure 4 - Graph of the CO_2 plume development in terms of CO_2 saturation i) at the end of the injection, ii) 50 years and iii) 2363 years after the beginning of injection.

The CO_2 plume development in terms of CO_2 saturation graph above (Figure 4) shows that during the injection period (Figure 4i) 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 upper most 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 4ii and 4iii), CO_2 has reached the seabed and develops side branches, corresponding to preferential lateral flow pathways of the CO_2 along certain formations characterised by better flow parameters.

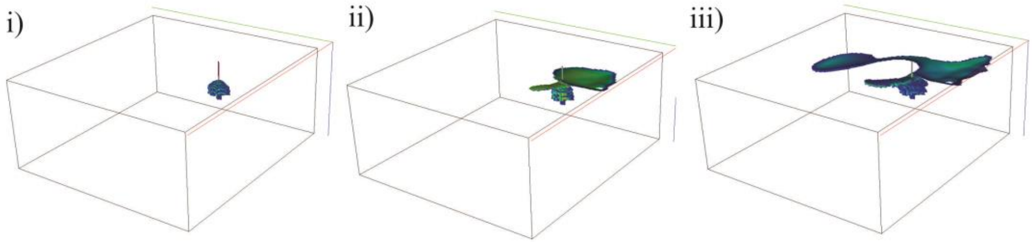


Figure 5 - Graph of the CO_2 plume development in terms of CO_2 mole fraction, i) at the end of the injection, ii) 50 years and iii) 2363 years after the beginning of injection.

Dissolved CO_2 tends to go downwards (Figure 5) whereas saturated CO_2 gas goes upwards (Fugure 4), thus explaining the difference in plume development between the previously mentioned 2 figures. Figure 5shows the plume distribution at various times after the beginning of injection. Both at 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 that for the saturated gas (Figure 4). 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 2^{nd}, less accurate estimation of the time the CO_2 has reached the seabed, as this estimation is based on visual detection than on a graphical method.

We will now present the results from the leakage model assessing the potential degree of risk and consequences to the study area, caused by a possible oil and/or CO_2 leak from the reservoir or through a pipeline penetrating it.

4.2. Potential leakage of oil and consequences

On the 2^{nd} day after the beginning of the leakage process, we observe that the oil leak is being spread towards NE by the prevailing currents and winds blowing in the area (Figure 6). After eight days of oil leakage (Figure 7) we observe that the oil has covered more than half the distance, i.e. 9.2 km, between the point of storage and the coastal areas to the north of Thassos, which correspond to a total distance of 13 km.

Figure 6 - Direction of flow and magnitude of the oil leak during the 2^{nd} day after the s tart of leakage.

Figure 7 - Extent of the leak 8 days after the start of leakage.

Twelve days after the onset of leakage, we start to observe the gradual contamination of “Natura” protected areas and thus the gradual pollution of the sea located between Thassos Island and the mainland (Figure 8). The rate of oil spreading in this closed sea is generally lower compared to the open sea and this is due to the fact that this area is protected from strong winds and severe weather.

Observing the area 16 days after the start of leakage and on the basis of the statistical data that we have and the assumptions that we made, we find that the oil spill reaches the northern coast of Thassos island (Figure 9).

From the above results obtained, we observe that there is only a period of 12 days (Figure 8) from the moment the leakage starts until the “Natura” areas start to be affected.

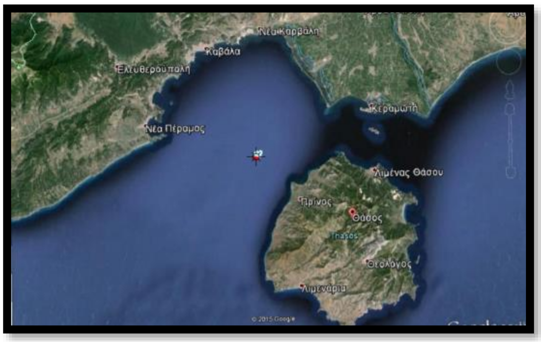
The public authorities have thus at their disposal a maximum of 12 days to take the necessary measures to protect the flora and fauna of the “Natura” sites from contamination. Also noting that the “Natura” areas in the above maps cover not only marine but also terrestrial areas we can thus understand that a possible leak would affect both marine and terrestrial ecosystems.

Figure 8 - Extent of the oil leak 12 days after start of leakage.

Figure 9 - Extent of the oil leak 16 days after the start of leakage.

4.3 Potential leakage of CO_2 and consequences

In the following figures we observe the dispersion of the CO_2 gas at various times since the start of leakage of CO_2. Already during the second day after the start of leakage, CO_2 flows along a preferential flow direction, which is towards NE (Figure 10), corresponding to the direction of surface sea currents and bottom sea currents in the area. Additionally, figure 8 illustrates a possible estimate of the expansion of CO_2, 5 days after the beginning of leakage of CO_2. The CO_2 continues to flow in accordance with the preferential flow direction, which is towards NE, but we observe also a part of the leaked gas to flow towards ENE (Figure 11).



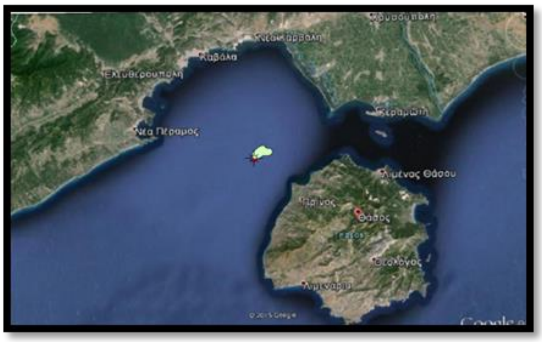


Figure 10 - Possible extent of CO_2 leak 2 days after the start of leakage.

Figure 11 - Possible extent of CO_2 leak 5 days after the start of leakage.

The dispersion of the CO_2 gas 10 days from the start of leakage (Figure 12) shows that CO_2 has spread considerably compared to the previous days, now approaching the northeastern coast of Thassos. The quantities of gas to be released from the original source will play an important role in the spread of CO_2 and the impact that it will have on the environment.

5. Discussion

The simulation has shown that there is CO_2 leak in the well, which reaches the seabed. Even with a small leak, CO_2 would still reach the seabed. Therefore in terms of the quality of data that we possess, it's important to emphasise the development and application of monitoring techniques and invest on safety issues if we are to mitigate the risk of CO_2 leakage. In order to assure that there will be no CO_2 leakage around the wellbore, different monitoring techniques should be favoured. Also by assuring that the wells are cemented properly we will minimise the risk of leakage around the wellbore.

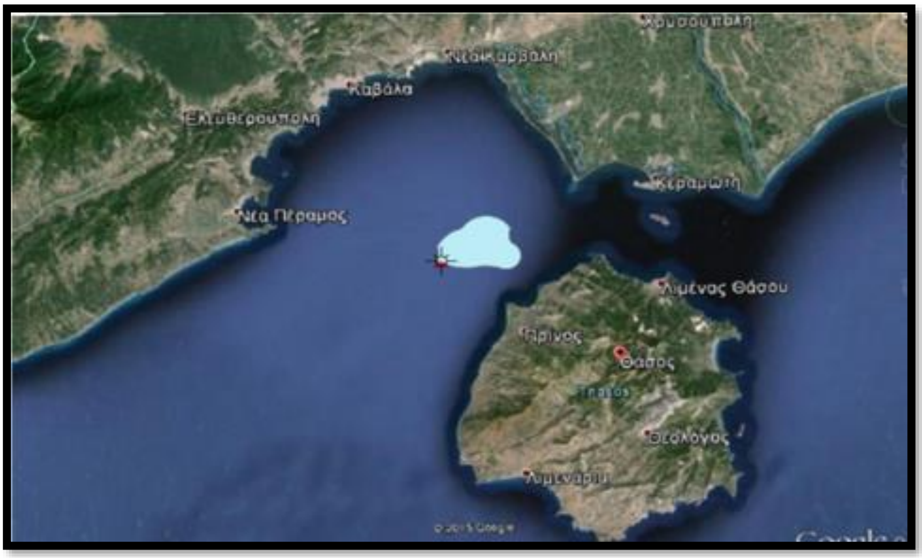


Figure 12 - Possible extent of CO_2 leak 10 days after the start of leakage.

A potential CO_2 leak in the marine area could also have negative effects on both the environment and the marine ecosystems. In our case study, 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 protected from the CO_2 spill. However, the consequences of a potential CO_2 leak are considered spatially limited and the ecosystem is capable of recovering by itself in a short time after the retreat of the leak.

One of the consequences that can result from the release of CO_2 is its ability 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. Nevertheless, surveys carried out in areas where CO_2 is released naturally by bubbles in the ocean through leaking faults affecting submarine volcanoes have shown that after long periods of time the ecosystems can adapt to the new conditions (Apostolaki *et al.*, 2014). There is therefore no fear of any direct negative impacts of the dispersion of CO_2 on marine ecosystems. Possible long-term effects in the Prinos-Kavala basin will mainly concern shells and corals that will not be able to develop a shell.

However, it should be noted that due to the specific situation 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.

6. Acknowledgements

This research has been co-financed by funds from the Greek national project "NOVEL Technologies on the implementation of CCS". The authors are grateful to Dimitrios Alexopoulos and Nikolaos Tsoukalas, from CERTH, for their contributions regarding the graphic design and reading of the proof paper, as well as to Seyed Mohamed Shariatipour, from the University of Coventry, for running the CO_2 simulations in ECLISPE software. In additional they are grateful to the manufacturer of the software, the Schlumberger Co.

7. References

Apostolaki, E.T., Vizzini, S., Hendriks, I.E. and Olsen, Y.S., 2014. Seagrass ecosystem response to long-term high CO_2 in a Mediterranean volcanic vent, Marine Environmental Research, 99, 9-15.

Bachu, S. and Adams, J.J., 2003. Sequestration of CO_2 in geological media in response to climate change: capacity of deep saline aquifers to sequester CO_2 in solution, *Energy Conversion and Management*, 44, 20, 3151-3175.

Bentham, M. and Kirby, G., 2005. CO_2 storage in saline aquifers, *Oil & Gas Science and Technology*. *IFP Energies Nouvelles*, 60(3), 559-567.

Chadwick, R.A., Marchant, B.P. and Williams, G.A., 2014. CO_2 storage monitoring: leakage detection and measurement in subsurface volumes from 3D seismic data at Sleipner, *Energy Procedia*, 63, 4224-4239.

Kiomourtzi, P., Pasadakis, N. and Zelilidis, A., 2008. Source Rock and Depositional Environment Study of Three Hydrocarbon Fields in Prinos–Kavala Basin (North Aegean), *The Open Petroleum Engineering J*.,1, 16-29.

Pasadakis, N.A., Koutsotheodorou, E., Manoutsoglou, M., Papakonstantinou, K., Kiomourtzi, P. and Zelilidis, A., 2005. A comparative study of oils from Kavala basin using biomarkers analysis, *2nd Congress of the Commission of Economic Geology, Mineralogy and Geochemistry*, 309-317.

Proedrou, P., 1986. New age determination of the Prinos Basin, *Bull. Geol. Soc. Greece*, 20(2), 141-147.