CO₂ storage capacity assessment in the deep saline aquifers of southern Israel

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Abstract

CO₂ storage in geological formations is one of the techniques proposed for reducing anthropogenic greenhouse gas emissions to the atmosphere. This paper describes the first assessment of effective storage capacity within deep saline aquifers in southern Israel. On the basis of the current CO₂ emissions, the State of Israel needs to find storage site(s) for about 5 Gt of CO₂, which is the predicted accumulated CO₂ emissions for the period between 2025 and 2075. The effective storage capacity of the sedimentary basin in southern Israel, ranging in age from latest Precambrian to Early Cretaceous, was examined based on data from 180 boreholes. Three separated saline aquifers were recognized in the basin, each having its own sealing aquiclude. Each aquiclude is usually thicker than 100 m and will probably prevent CO₂ migration upward. The water salinity in these aquifers is usually high (>12,000 ppm Cl⁻). Capacity calculations are based on the DoE equation \( G_{CO₂} = A h E \phi \), using an effective coefficient (\( E \)) of 2%. The results of our study indicate that effective storage potential of the economic zone (800 m to 2,500 m below surface) is about 8.6 Gt, with an additional 10.7 Gt within deeper parts of the aquifers (below the 2,500 m optimum depth).

Keywords: CO₂ storage; Effective capacity assessment; Deep saline aquifers; Southern Israel;

Nomenclature

\[ G_{CO₂} \quad \text{The effective capacity (in mass unit) of CO₂ [Mt]} \]

\[ A \quad \text{2D net surface area [km}^2\text{]} \]

\[ E \quad \text{Effective coefficient factor [-]} \]

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1. Introduction

The increasing concentration of CO$_2$ in the atmosphere, as part of other greenhouse gases, is considered by many to be one of the major reasons for climatic global changes. Disposal of CO$_2$ in geological reservoirs as part of carbon capture and storage (CCS) strategy is probably the best and fastest way to mitigate atmospheric CO$_2$ [1]. CO$_2$ can be stored in deep underground formations; e.g., coal beds, depleted oil or gas reservoirs, or in deep saline aquifers [2]. Among those, deep saline aquifers probably offer the best, long-term, safe, and low-cost storage for large amounts of CO$_2$.

Paleo-geographically speaking, the geological history of southern Israel was determined by its position between the African plate in the south and the Tethys Ocean in the north. This tectonically-quiet cartonic regime characterizes most of the Israeli Phanerozoic geological history [3]. Relative sea-level changes occurring thorough time were accompanied by changes in the sedimentary depositional environments, and the formation of a very thick, several kilometer, sedimentary cover consisting mostly of terrestrial or delta mature, coarse clastics intercalated with marine limestone, shale and lagunal evaporites. Those rock units have a wide lateral extent in the subsurface of southern Israel, with small lateral facies changes [4] from continental siliciclastic facies in the south to shallow marine carbonate and deep marine shale in the north. This sedimentary sequence suggests a significant CO$_2$ storage potential.

Three saline aquifers are recognized within the subsurface Cambrian to Early Cretaceous section [5], each having its own sealing units (shale or evaporites). The salinities in these aquifers range from 140,000 ppm Cl$^-$ in the lower aquifer, to 12,000 ppm Cl$^-$ in the middle aquifer, and then to a much lower value of 2,000 ppm Cl$^-$ in the upper aquifer [5].

The goal of the current study was to characterize the reservoir and sealing units in the subsurface of southern Israel and to assess their effective CO$_2$ capacity. For an extended version of the current study see [6].

2. Methods

The geological section studied in southern Israel has been penetrated by 180 wells. Structural and thickness maps were prepared using the Spline interpolation method within the ArcGIS v.9.3 environment. The depth to structural units was calculated relative to the digital elevation model (DEM) of Israel [7]. The temperature at the top of each unit was calculated using a temperature gradient of 21.5°C/km beginning with a surface temperature of 15°C [8]. Hydrostatic gradient was used to calculate the pressure at the top of each unit, assuming a water-table depth of 100 m below surface and a water density of 1.03 gr/cm$^3$ [5]. The CO$_2$ density was numerically calculated using the Redlich and Kwong [9] equation of the state of CO$_2$ as a function of temperature and pressure. Accordingly, the transition of CO$_2$ into supercritical-CO$_2$ is found at a depth of about 800 m. To assess storage capacities potential reservoirs were truncated by two iso-depth surfaces of 800 m and 2,500 m. The volumes where the top of the

| Symbol | Definition |
|--------|------------|
| h      | Vertical net thickness of reservoir [m] |
| $\phi$ | Reservoir average porosity [-] |
| $\rho$ | Density of CO$_2$ at reservoir condition [gr/cm$^3$] |
reservoir is shallower than 800 m, where CO2 is not in a supercritical state, were excluded. Reservoirs
deeper than 2,500 m below surface, which are considered non-economic [10], were excluded and aquifers
sealed by aquiclude units which are too thin (>100 m) were also excluded.

The CO2 capacity was calculated using the USDOE [11] equation: \( G_{CO2} = A h \rho E \phi \). We used only the
\( E = 2\% \) case, which is the median value (\( P_{50} \)) for clastic lithologies [11]. Using \( E = 1\% (P_{15}) \) or \( E = 4\% (P_{85}) \)
would have changed our calculated \( G_{CO2} \) capacity by a factor of 0.5 and 2, respectively. The calculation
was made for 250 m by 250 m surface pixels.

3. Results

3.1. Stratigraphy and lithology

The lower aquifer (Cambrian to Early Triassic) consists mostly of non-fossiliferous sub-arkosic
sandstones, deposited in fluvial, littoral and shallow marine environments in its lower part [3], whereas its
upper part consists of terrestrial sandstones followed by alternating marine shales and carbonates with
some delta sandstones [12]. This aquifer is topped by a Middle Triassic to Early Jurassic aquiclude
consisting mostly of shales, carbonates and evaporites.

The middle aquifer (Early to Late Jurassic) consists of a wide variety of lithologies, ranging from
terrestrial coarse sandstone and silt to shallow marine limestone and dolostone [13]. This aquifer is topped
by a Late Jurassic aquiclude consisting predominantly of shales with a few carbonate layers, reflecting
extensive shallow marine mud flats.

The upper aquifer (Early Cretaceous) consists predominantly of sandstone [14]. The continental
sandstones of this aquifer interfingers with four marine limestone layers. The lateral changes in this
aquifer are from totally sandy in the south to largely marine shales in the northern parts of the study area.
The sediments of this aquifer were deposited on top of a regional unconformity, removing in places most
of the underlying aquifers and aquicludes; thus, while in most of the study area they are perfectly
separated, direct contact exists between the three aquifers in the very southern parts of the study area
(Figure 1). Some shaly and compacted limestone units top the upper aquifer and separate it from the main
freshwater aquifer of Israel. Differences in water-heads of the upper saline aquifer and the freshwater
aquifer attest to a good separation between them [15], while some geochemical indicators suggest small
leakage exists [16]. The upper saline aquifer was excluded in our effective capacity assessment because of
the low salinity of this aquifer and this unclear leakage possibility.

3.2. CO2 capacity assessments

Following a regional northward dipping trend, all aquifers are deeper in the northern part of the study
area (Figure 1b). The top of the lower aquifer is located at a suitable depth (800 to 2,500 m) in 51% of the
study area, with a maximum thickness of 950 m. About 32% of the total volume of the lower aquifer is
found at the optimum depth range of 800 to 2500 m, 58% of the volume is deeper than 2,500 m
(expensive storage), and the rest is too shallow for storage. In addition, 10% of the lower aquifer was
excluded due to thin sealing unit (less than 100 m thick). For the remaining volume the sealing unit is up
to 980 m thick. The capacity of CO2 in the lower aquifer is about 3.4 Gt in the economic zone, with
another 6.4 Gt below 2,500 m (Table 1). Figure 2a shows the capacity distribution of the lower aquifer.
Fig. 1. Hydro-geological cross-section along the study area, emphasizing the relationship between the reservoirs and the sealing units. A - east-west, and B - north-south directions.

Table 1. Aquifer properties.

|                           | Lower Aquifer | Middle Aquifer |
|---------------------------|---------------|----------------|
| Aquifer Surface Area [km²]| 7845          | 5586           |
| Aquifer Rock Volume [km³] | 6944          | 6973           |
| Aquifer Rock Volume (800-2,500 m) [km³] | 2503  | 3910          |
| Aquifer Rock Volume (>2,500 m) [km³] | 4441  | 3063           |
| Average Porosity [-]      | 0.10          | 0.10           |
| Aquifer Thickness [m]     | 770-953       | 217-1,436      |
| CO₂ Density [gr/cm²]      | 0.640-0.720   | 0.640-0.750    |
| GCO₂ [Gt]                 | 3.40+6.41     | 5.17+4.28      |

The top of the middle aquifer is located at a suitable depth (800 to 2,500 m) in 59% of the study area, with a maximum thickness of 1,450 m. About 42% of the total volume of this aquifer is at the optimum depth; with another 32% located below 2,500 m. Twenty-seven percent of the aquifer volume was
excluded from our capacity calculations because of a thin sealing unit (less than 100 m thick). For the remaining volume the sealing unit is up to 540 m thick. The capacity of CO$_2$ in the middle aquifer is about 5.2 Gt in the economic zone, with another 4.3 Gt below 2,500 m (Table 1). Figure 2b shows the storage capacity distribution of the middle aquifer.

Altogether, we conclude that the economic zone of southern Israel can store 8.6 Gt of CO$_2$ and an additional 10.7 Gt can be stored in deeper conditions (Table 1). The most promising aquifer is the middle aquifer, which alone can store Israel’s needs for 50 years (2025-2075).

4. Summary

The saline deep aquifers of southern Israel were studied in order to calculate their total effective CO$_2$ capacity. Three regional aquifers were studied, each with its own sealing unit. Due to a general northward dipping of all structural units in the subsurface, the lower most aquifer is located at a suitable depth mainly in the southern parts of the study area while the middle aquifer is at a suitable depth throughout the study area.

We conclude that geological storage within the two lowermost deep saline aquifers is feasible and does not threaten shallower freshwater aquifers. Considering only the economic depth of 800 to 2,500 m below surface, the total effective storage capacity found in our study is about 8.6 Gt. An additional 10.7 Gt can be stored at depths greater than 2,500 m. Although the study area covers about 40% of the country, it could hold about 20 Gt, which is about 4 times larger than the country’s needs for the next 50 years.

Due to its suitable depth and large thickness, the middle aquifer of Early to Late Jurassic age is the
most promising aquifer for CO₂ storage in the subsurface of southern Israel. This aquifer will be the main studied for expanded understanding and modeling of the subsurface (using also seismic data along with the boreholes data) and research (numerical simulations of storage scenarios).

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