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Deep Saline Aquifers for Geological Storage of CO_2 and Energy
Stockage géologique du CO_2 et de l'énergie en aquifères salins profonds

Regional-Scale CO_2 Storage Capacity Estimation in Mesozoic Aquifers of Poland

B. Uliasz-Misiak

AGH University of Science and Technology, Faculty of Drilling, Oil and Gas, A. Mickiewicza 30 Ave., 30-059 Krakow - Poland
e-mail: uliasz@agh.edu.pl

Résumé — L'évaluation de la capacité du stockage du CO_2 à l'échelle régionale dans des couches aquifères Mésozoïques en Pologne — L'évaluation de la capacité de stockage des aquifères à l'échelle régionale donne une première approche quant à l'utilisation du stockage géologique de CO_2 pour réduire les émissions. Une telle évaluation est présentée pour les couches aquifères du Crétacé inférieur, du Jurassique inférieur et du Trias inférieur de la Basse Plaine de Pologne.

On propose l'utilisation de cartes de stockage unitaire du CO_2 dans des couches aquifères pour rendre compte des estimations du potentiel à l'échelle nationale, et pour la recherche des régions les plus prospectives.

Les formations du Crétacé inférieur présentent la moindre capacité de stockage du CO_2, celles du Trias inférieur ont une capacité plus importante, et ce sont les formations du Jurassique inférieur qui possèdent la plus grande capacité.

Abstract — Regional-Scale CO_2 Storage Capacity Estimation in Mesozoic Aquifers of Poland — *The CO_2 storage capacity estimated at the regional scale provides a preliminary recognition of as far as the possible uses of CO_2 sequestration as an option of emission reduction. There has been presented the estimation of CO_2 storage capacity for aquifers of Lower Cretaceous, Lower Jurassic and Lower Triassic of Polish Lowland. The Lower Jurassic deposits exhibit the greatest CO_2 storage capacity of all the horizons, storage capacity of the Lower Triassic deposits is lower, the smallest capacity was estimated for the Lower Cretaceous deposits.*

The use of specific capacity maps for carbon dioxide in aquifers has been suggested in order to estimate the potential on national and basin scale as well as the search for prospective areas for CO_2 storage.

INTRODUCTION

The capture and storage of CO_2 in deep-seated geological formations is considered to be a method of reducing greenhouse gas emissions into the atmosphere. The following structures are recommended for underground CO_2 storage: oil and natural gas fields, unmineable coal seams (accompanied by enhanced coalbed methane recovery) and deep aquifers (Holloway, 2002, 2005; Holloway and van der Straaten, 1995). To choose the best location for geological CO_2 storage, a number of aspects must be considered: emission source location, geological structure of the area, geothermal and hydrodynamic conditions, existense and properties of reservoir cap rocks, economic and regulatory aspects, etc. One of the crucial factors for the assessment of suitability of the geological formation for CO_2 storage is its storage capacity *i.e.* the amount of CO_2 that can be safely injected into the geological structure without any environmental damage.

Estimates of CO_2 storage capacity are made on a world, national, basin, local and storage site scale. The world-, national- and basin-scale estimates are carried out to recognize the general possibility of using this method of CO_2 emission reduction in a given region. Detailed and thorough storage capacity estimates are performed on a local and storage site scale. Depending on the assessment scale, different methods are used ranging from general assessment formulas to model and computer simulations on a local and site storage scale. The process of CO_2 storage in aquifers occurs through a number of storage mechanisms, including structural trapping, hydrodynamic, dissolution, mineral trapping and residual gas trapping. When estimating the storage capacity on a large scale (world, national and basin scale), we commonly do not take into account all the mechanisms, limiting ourselves to structural trapping and sometimes to hydrodynamic and dissolution. Local- and storage site-scale estimates are made based on most or all of the storage mechanisms.

This paper presents the estimation of CO_2 storage capacity in Mesozoic aquifers of Polish Lowlands in regional scale. To estimate the storage potential and to search for prospective areas suitable for CO_2 storage, maps of CO_2 storage capacity per unit area were constructed for individual aquifers.

1 GEOLOGICAL DESCRIPTION OF MESOZOIC AQUIFERS SUITABLE FOR CO_2 STORAGE IN POLAND

Poland distinguishes itself in Europe by its differentiated geological structure since the fragments of three large European geological units run across its territory. They are the East European Platform, the West European Variscan Platform, and the Alpine Carpathian Foldbelt. Due to complexity of the geological structure, they show variable suitability for CO_2 geological storage.

The East European Platform (NE Poland) and Sudetes Mts. (SW Poland) are not adequate areas to look for suitable locations for CO_2 storage due to the occurrence of shallow-seated crystalline and metamorphic rocks and small thickness of the sedimentary rock cover. The usefulness of the Carpathian Mts. (S Poland) for underground CO_2 storage is limited because Carpathian sedimentary rocks, in spite of their significant thickness, are strongly tectonized, revealing the lack of sealing sedimentary caprock. Good storage conditions can be found in the Polish Lowlands, where sedimentary rocks are featured with large thickness and good reservoir properties.

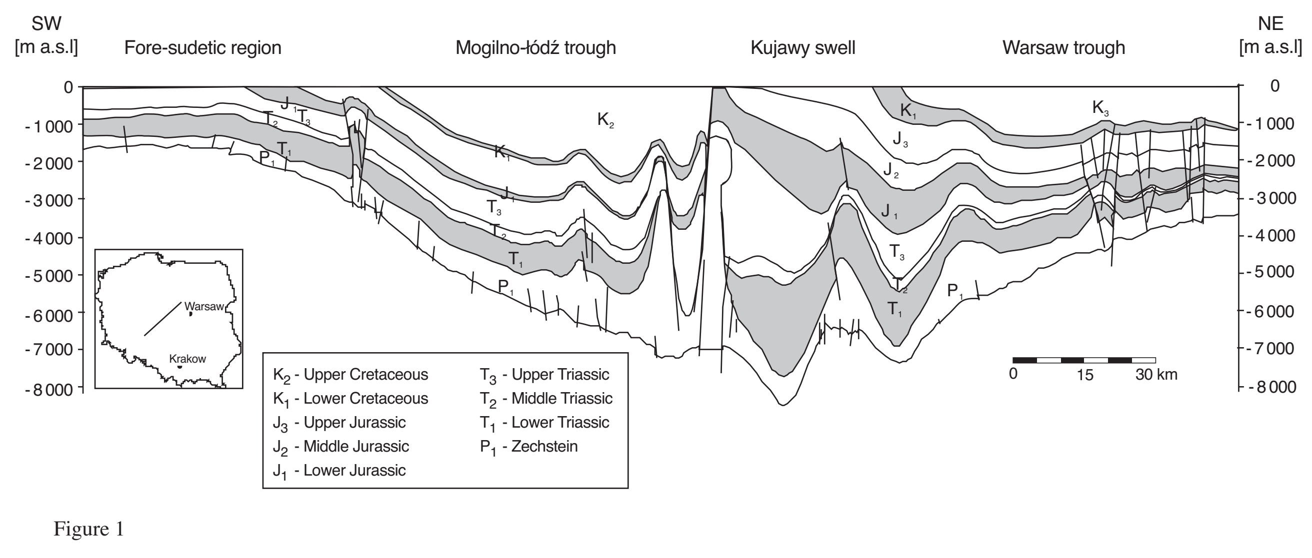

Figure 1

Geological cross-section through the Polish Lowlands (modified after Górecki (ed), 2006).

Lower Jurassic, Lower Cretaceous and Lower Triassic deposits are the aquifers prospective for underground carbon dioxide storage in Poland *(Fig. 1)*. All of them are widespread over much of the Polish Lowlands (central and north-west Poland), they contain thick permeable formations, show good reservoir properties and are overlain by a good caprock series *(Fig. 2)* (Tarkowski and Uliasz-Misiak, 2006; Uliasz-Misiak, 2008).

1.1 Lower Cretaceous

The Lower Cretaceous reservoir horizons consist mainly of sandstones and sandy and carbonate-sandy deposits of Barremian-Albian age. They are separated by discontinuous series of poorly and non-permeable sediments composed of siltstones and mudstones (Malinowski (ed), 1991).

The elevations of the Lower Cretaceous aquifer vary from +270 metres a.s.l. (in the areas of outcrops or incrops under the Cenozoic cover) to –2 800 metres in the central part of the basin (Mogilno - Łodź Depression).

Total thickness of the Lower Cretaceous formation varies from several metres to over 2 000 m. The largest thickness is usually observed in axial parts of troughs (over 2 000 m), decreasing to several metres towards their marginal parts. Local anomalies were observed in the vicinity of salt diapirs and faults.

Generally, the distribution of cumulative thickness of Lower Cretaceous groundwater horizons corresponds to the total thickness of this formation and varies from 150 to 300 m (Górecki (ed), 2006).

Effective porosity of the Lower Cretaceous sandstones ranges between 3 and 45%, most commonly it is 15-25%. The permeability coefficient determined from drill core rock samples is 11-4 265 mD (geometric mean is 334 mD).

The TDS concentration in Lower Cretaceous groundwater varies from below 2 g/dm^3 in the marginal part (outcrop areas) to 20 g/dm^3 in the central parts of structural units. Locally, the values TDS can exceed 50 g/dm^3 (Górecki (ed), 2006).

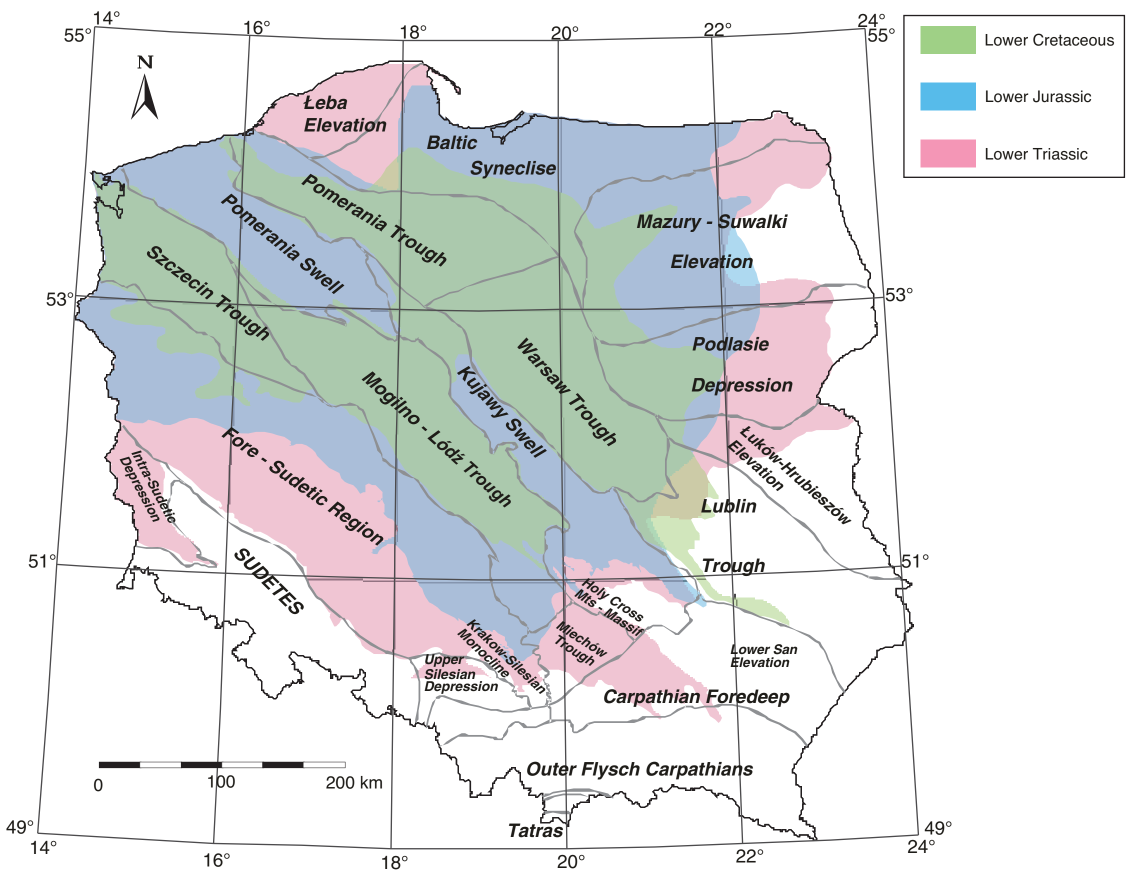

Figure 2

Extents of Lower Cretaceous, Lower Jurassic and Lower Triassic deposits in the Polish Lowlands against the Mesozoic tectonic units of Poland (modified after Pożaryski, 1974).

Within the Lower Cretaceous section, the Barremian – Middle Albian sandstones (Mogilno Formation) make up a potential reservoir suitable for CO_2 storage. Over most of the area, the Lower Cretaceous formations are overlain by Upper Cretaceous rocks (limestone, chalk). Due to low permeability and large thickness these are a very good seal for the underlying sandstones (Marek and Pajchlowa, 1997).

1.2 Lower Jurassic

The Lower Jurassic aquifers are composed of Hettangian, Sinemurian, Domerian and Upper Toarcian sandstone complexes. They are separated by discontinuous series of low permeability sediments (claystones, mudstones, fine-grained sandstones) (Malinowski (ed), 1991).

In the southern and south-western parts of the basin, Lower Jurassic subcrops under the Cenozoic formation (and local outcrops) occur at the elevations of between 0 and +350 m a.s.l. Along the south-eastern and eastern margins, the elevations vary from +200 to –1 800 m. The depth of –3 600 m has been found along the NW-SE-trending axis of the aquifer in the central part of the basin.

Total thickness of the Lower Jurassic formation varies from several metres to over 100 m in the marginal parts of the aquifer, and to 400-1 200 m in the central part of the basin (Górecki (ed), 2006).

The Lower Jurassic fine- and medium-grained sandstones and sands are featured with open porosity values ranging from 15 to 33%.

The permeability coefficient, determined based on pumping tests, varies from $1 \cdot 10^{-4}$ to $2 \cdot 10^{-7}$ m/s, while determined in the laboratory it ranges from 10^{-5} to 10^{-7} m/s. It has been assumed that the permeability coefficient is equal approximately to $5 \cdot 10^{-6}$ m/s (Górecki (ed), 2006).

The Lower Jurassic waters show higher mineralization values as compared to the Lower Cretaceous ones. The TDS content ranges from 0.2 to 174 g/dm^3. The lowest TDS values (below 2 g/dm^3) are recorded from southern and eastern margins of the aquifer, *i.e.* from the zones of sub-Quaternary and sub-Tertiary subcrops of Lower Jurassic beds (Górecki (ed), 2006).

The best conditions for geologic CO_2 storage are displayed by the Upper Toarcian (Borucice Beds) and Lower Aalenian sandstones (Upper Sławęcin Beds) occurring below the Upper Aalenian clay-mud cap, as well as by the Upper Pliensbachian sandstones sealed by the Lower Toarcian claystone-mudstone series (Marek and Pajchlowa, 1997).

1.3 Lower Triassic

The Lower Triassic deposits are facially differentiated. The Lower Buntsandstein lithology is dominated by mud-clay facies, the Middle Buntsandstein is composed of sandstones, whereas the Upper Buntsandstein (Röt) is represented by carbonate facies with claystone and mudstone interbeds (Marek (ed), 1983; Dadlez, 1989).

The top surface of the Lower Triassic formation occurs at the elevations ranging from several metres above sea level in the south-western part to below – 4 500 m a.s.l. in the central part of the basin. Total thickness of the Lower Triassic formation varies from several tens of metres to over 1 200-1 600 m (Górecki (ed), 2006).

Effective porosity is 15-30%. Permeability of these deposits is highly variable and ranges from approximately 70 to 140 mD, locally even up to 2 410 mD (Tarkowski and Uliasz-Misiak, 2005).

The TDS concentration in waters from the Lower Triassic aquifer varies from several g/dm^3 in the marginal parts of the basin to over 350 g/dm^3. Over about 90% of the aquifer's area, TDS values are in excess of 50 g/dm^3 (Górecki (ed), 2006).

The Middle Buntsandstein sandstones (Pomerania Formation and its lithofacies equivalents) behave as reservoir rocks within the Lower Triassic series. These sandstones are sealed at the top by Rhaethian silty and clastic-carbonate-evaporitic sediments (Upper Buntsandstein) (Marek and Pajchlowa, 1997).

2 STORAGE CAPACITY ESTIMATION METHODOLOGY

2.1 Estimation of Regional-Scale Storage Capacity in Mesozoic Aquifers of the Polish Lowlands

Estimation of regional-scale volumetric storage capacity was carried out for the Lower Cretaceous, Lower Jurassic and Lower Triassic horizons. The CO_2 storage capacity was estimated using a simplified formula, taking into account the following pieces of information: average porosities, average proportion of permeable beds, average CO_2 density in reservoir conditions, and structural and thickness maps of these horizons. The mechanisms such as dissolution and mineral trapping, affecting the storage capacity, were neglected during the assessment. The volume of rocks of individual reservoirs was estimated through a superposition of structural and thickness maps. It was calculated for deposits occurring at the depth (–1 000)-(–3 000) m. The pore volume of rocks was calculated taking into account the average porosity and proportion of permeable beds in individual aquifers.

To estimate the effective capacity of CO_2 storage in aquifers, a formula created based on the methodology proposed by Bachu *et al.* (2007) was applied:

$$M = A \cdot h \cdot \overline{\varphi} \cdot \overline{\rho_{CO_2}} \cdot C_{ew} \tag{1}$$

where:

M	Effective capacity of CO_2 storage in aquifer
A	Area
h	Aquifer thickness
$\overline{\varphi}$	Average porosity
$\overline{\rho_{CO_2}}$	Average in-reservoir CO_2 density
C_{ew}	CO_2 storage efficiency

The calculations were based on average proportions of aquifer in the total thickness of individual reservoirs (60% for the Lower Cretaceous and Lower Jurassic and 35% for the Lower Triassic), derived from literature sources (Górecki (ed), 2006). The percentage contribution of permeable beds to the Lower Cretaceous section are generally at the level of 30-90%. In the Lower Jurassic lithological column, permeable beds account for 40 to 80% of the total thickness. In the Lower Triassic lithological column, the percentages vary from 25 to 50% (Górecki (ed), 2006).

Average porosity of the aquifers was calculated (at the confidence level of 95%) from laboratory measurements made on rock samples collected from deep boreholes.

For the Lower Cretaceous deposits, data from 90 boreholes were analysed. The porosity varied from 10 to 34%, with the average of 20.5% and standard deviation of 6.4. For the Lower Jurassic deposits, data from 140 boreholes were analysed. The porosity varied from 10 to 46%, with the average of 17.3% and standard deviation of 6.7. For the Lower Triassic deposits, data from 140 boreholes were analysed. The porosity varied from 5 to 25%, with the average of 9.7% and standard deviation of 6.9 (Uliasz-Misiak, 2008).

For individual Lower Cretaceous, Lower Jurassic and Lower Triassic aquifers, constant values of CO_2 density in reservoir conditions were assumed: 730 kg/m^3, 770 kg/m^3 and 710 kg/m^3, respectively. The average values of carbon dioxide density were calculated on the basis of reservoir temperatures and pressures measured in wells located in the Mesozoic aquifers.

The effectiveness of CO_2 storage estimated on a national, basin and regional scale is understood as this part of the pore volume of the aquifer, which can be used for underground CO_2 storage. This coefficient calculated for the aquifers has a few components that reflect physical barriers preventing from filling the whole pore space. The effective storage capacity coefficient corresponds to this part of the basin's area, thickness and porosity, which is feasible to be used for CO_2 storage. It also refers to this part of the area and thickness that will be directly in contact with the CO_2 (DOE, 2008). Its value ranges from 1 to 8% (May *et al*., 2005; IPCC, 2006). In the present study, CO_2 storage capacity was estimated for the lowest (1%), medium (2%) and highest (4%) effective storage capacity coefficients. The choice of storage effectiveness coefficients was based on literature data, where in most publications it is assumed that the smallest value of this coefficient is 1% and the maximum is ca. 5-6% (van der Meer, 1995; May *et al*., 2005; Doughty, Pruess, 2004; IPCC, 2006).

2.2 Storage Capacity per Unit Area in Aquifers of the Polish Lowlands

It is proposed to express the potential of CO_2 storage in aquifers as a specific storage coefficient understood as the amount of CO_2 storage capacity expressed in mass units relative to the unit area. The CO_2 storage capacity per unit area is understood in a similar way as the groundwater resources coefficient is. The latter is the amount of groundwater resources expressed relative to the unit area of their occurrence. It usually refers to disposable and renewable groundwater resources and is expressed in volume units per time units and area units (km^2) (Dowgiałło *et al*. (eds), 2002).

The storage capacity per unit area enables estimating the storage potential within the area analysed. The greater its value, the more prospective is the area in terms of the occurrence of geological structures suitable for CO_2 storage. The magnitude of this coefficient is dependent mainly on the thickness of the deposits and the content of permeable rocks within them. This coefficient can be used in a preliminary estimation of the storage potential in a given region or basin, as well as to select the zones intended for further exploration in terms of storage possibility.

The CO_2 storage capacities per unit area for individual aquifers are presented in maps which can be the basis for exploration for geological structures suitable for geological CO_2 storage. The maps of CO_2 storage capacity per unit area were constructed by transformation of digital models of aquifers, as thickness and structural maps, and by taking into account constant parameters (porosity, proportion of water-bearing strata). The same constants (porosity, CO_2 density) as those taken for the calculations of storage capacity, were used for this purpose. The effective storage capacity coefficient was assumed to be 1%. CO_2 storage capacity per unit area in Mesozoic aquifers will be performed in deposits at a depth of (– 1 000)-(– 3 000) m, part of area of aquifers was eliminated.

3 RESULTS

3.1 Storage Capacity in Aquifers

Storage capacity in the Lower Cretaceous, Lower Jurassic and Lower Triassic reservoirs has been estimated for areas where the the top of the deposits occurs at depths greater than – 1 000 m. Below this depth, CO_2 will be in a supercritical phase. Low, best and high effective CO_2 storage capacities were estimated in selected aquifers for the effective storage capacity coefficients of 1%, 2% and 4%, respectively.

The Triassic deposits occupy the greatest area (147 500 km^2). The Lower Jurassic deposits occupy half of the area (74 000 km^2). The smallest area is occupied by the Lower Cretaceous deposits (24 700 km^2) *(Tab. 1)*. The pore volume of water-bearing rocks depends on the area of occurrence, on the proportion of permeable rocks and on their porosity. Despite a considerable difference between the areas of occurrence of the Lower Jurassic and Lower Triassic deposits, both the horizons have similar pore volumes (3 300 km^3 and 3 200 km^3, respectively). It is due to both a lower proportion of permeable rocks and porosity of the Triassic deposits. The pore volume of the Lower Cretaceous rocks shows the lowest values (about 500 km^3) despite good reservoir parameters.

The Lower Jurassic deposits exhibit the greatest CO_2 storage capacity of all the horizons. It varies from 25 700 Mt to 103 000 Mt of CO_2. Storage capacity of the Lower Triassic deposits is lower, ranging from 22 800 Mt to 91 000 Mt of CO_2. The smallest capacity was estimated for the Lower Cretaceous deposits – from 3 700 Mt to 15 000 Mt of CO_2 *(Tab. 2)*.

Total storage capacities of CO_2 in the Mesoszoic aquifers of Polish Lowlands are as follows: 52 200 Mt (for the lowest storage capacity), 104 500 Mt (best) and 209 000 Mt (highest).

TABLE 1

The area and volume of the Lower Cretaceous, Lower Jurassic and Lower Triassic deposits in the Polish Lowlands, recommended for CO_2 storage

Aquifer	Aquifer area (km^2)	Pore volume (km^3)
Lower Cretaceous	24 700	500
Lower Jurassic	74 000	3 300
Lower Triassic	147 500	3 200

TABLE 2

Carbon dioxide storage capacity in the Lower Cretaceous, Lower Jurassic and Lower Triassic deposits of the Polish Lowlands

Aquifer	Capacity (Mt)		
	Low (storage efficiency – 1%)	Best (storage efficiency – 2%)	High (storage efficiency – 4%)
Lower Cretaceous	3 700	7 500	15 000
Lower Jurassic	25 700	51 500	103 000
Lower Triassic	22 800	45 500	91 000
Total	52 200	104 500	209 000

3.2 CO_2 Storage Capacity per Unit Area

CO_2 storage capacity per unit area in the Lower Cretaceous deposits *(Fig. 3)*. The highest values (over 0.3 t/m^2) are observed in the central part of the basin. Over most of the area, the values are lower, ranging between 0.1 and 0.2 t/m^2.

The most prospective area for underground CO_2 storage in the Lower Cretaceous deposits is the central part of the basin where the depth to the top of the formation is 1 000-2 000 m. This is also the area of the greatest thickness of the Lower Cretaceous succession. The eastern and partly western parts of the basin cannot be considered areas suitable for underground CO_2 storage due to the lack of Lower Cretaceous deposits.

CO_2 storage capacity per unit area in the Lower Jurassic deposits *(Fig. 4)*. This coefficient attains the highest values in the central part of the basin, locally exceeding 1.3 t/m^2 CO_2. Lower values (0.2-0.4 t/m^2) are observed over the remaining area. The zero value area in the central part of the basin is due to a small depth to the top of Jurassic deposits.

The most prospective area for CO_2 storage in the Lower Jurassic deposits is the central part of the basin where the area of maximum values corresponds to the area of the greatest thickness of the succession (over 800 m).

CO_2 storage capacity per unit area in the Lower Triassic deposits *(Fig. 5)*. The highest values, exceeding 0.3 t/m^2, are observed in the central part of the basin. Over the remaining area, the values vary from 0 to 0.1 t/m^2 CO_2.

The area of the greatest storage capacity values in the Lower Triassic deposits coincides with the greatest thickness of the succession attaining 1 500 m. The most prospective area is the central part of the basin.

CONCLUSIONS

The estimation of CO_2 storage capacity in regional aquifers and the maps of CO_2 storage capacity per unit area provide information helpful in selecting geologic formations and searching for geological structures which are most suitable for geological CO_2 storage.

Of all the analysed regional aquifers of Polish Lowlands, the Lower Jurassic deposits show the greatest CO_2 storage capacity. The Lower Triassic deposits show lower capacity, and the Lower Cretaceous deposits – the lowest one.

The highest values of CO_2 storage capacity per unit area for all the analysed aquifers are observed in central Poland. The values are variable, however the highest ones are observed in the Lower Jurassic deposits (over 1.3 t/m^2). The Lower Cretaceous deposits show lower values (over 0.5 t/m^2), whereas the Lower Triassic deposits – the lowest ones (over 0.3 t/m^2).

The aim of the CO_2 storage capacity assessment conducted in the present research was to gain a preliminary estimation

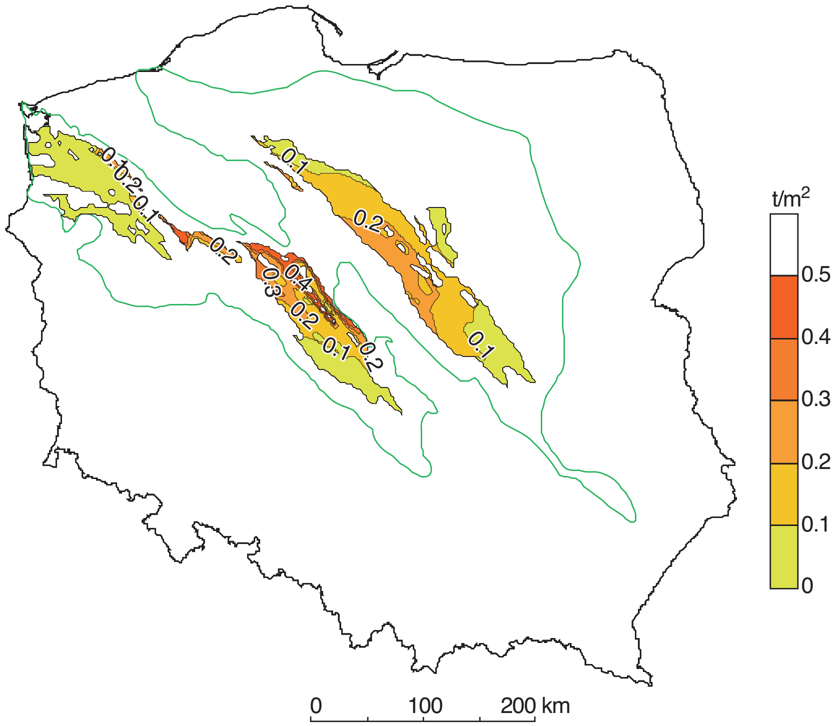

Figure 3

CO_2 storage capacity per unit area in the Lower Cretaceous deposits.

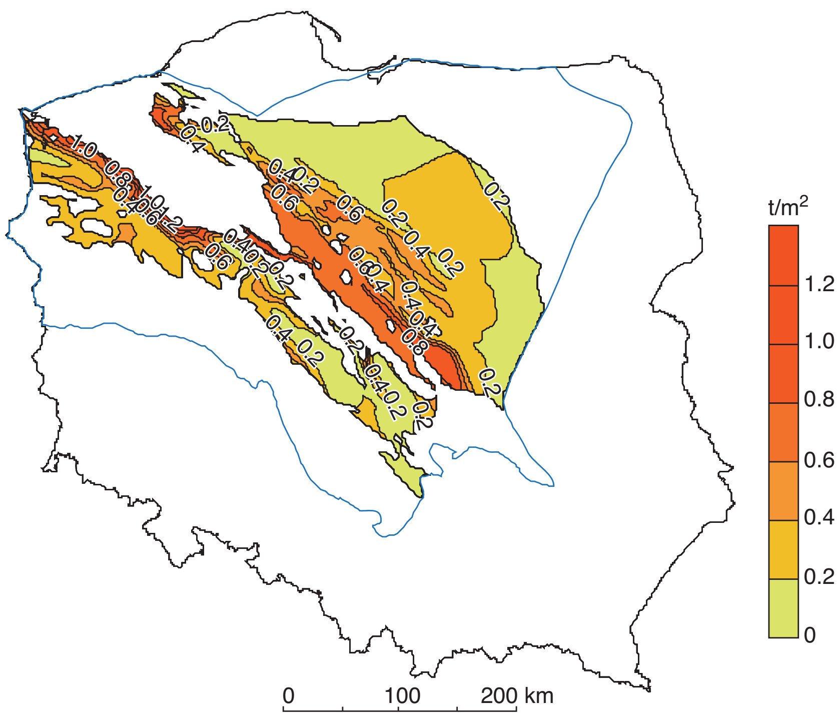

Figure 4

CO_2 storage capacity per unit area in the Lower Jurassic deposits.

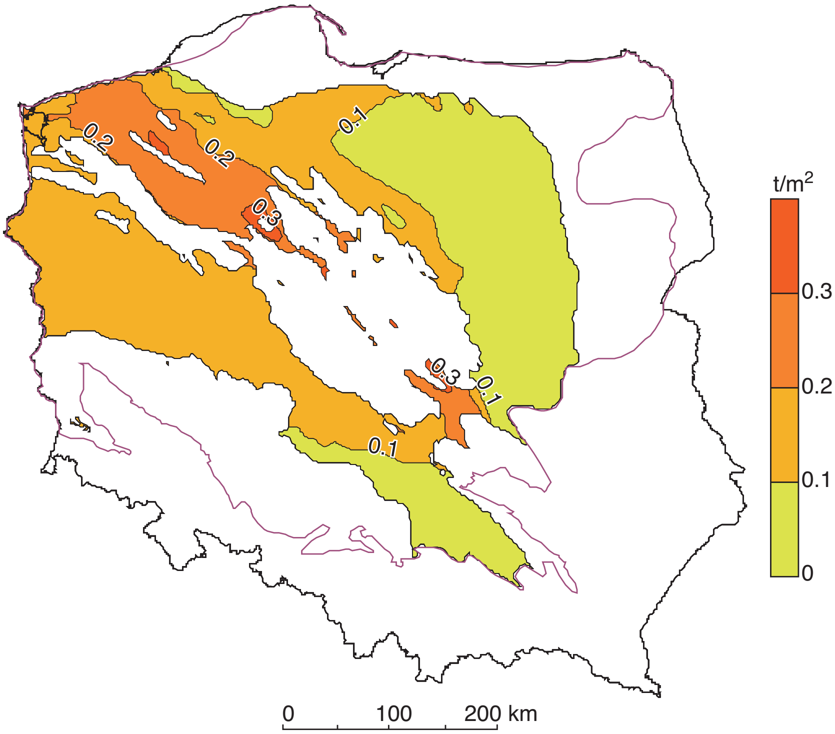

Figure 5

CO_2 storage capacity per unit area in the Lower Triassic deposits.

of the CO_2 storage potential as a means of reducing its emission in Poland. Further research on estimating storage capacity should be conducted on a local scale, for selected tectonic structures located in the aquifers of Lower Cretaceous, Lower Jurassic and Lower Triassic.

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