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A Preliminary Basin Scale Evaluation Framework of Potential Sedimentary Basins in Malaysia for Carbon Dioxide Sequestration

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This paper presents workflow and method to preliminarily evaluate the potential storage sites suitability for carbon dioxide (CO_2) sequestration in sedimentary basins of Malaysia. There are 14 sedimentary basins all around Malaysia that has been identified as potential CO_2 storage. This study concentrates on the assessment of major sedimentary basins in Malaysia both onshore and offshore where potential geological formations which carbon dioxide could be stored exist below 800 m and where suitable sealing formations are present. Those potential sites are screened and ranked in terms of their suitability for CO_2 storage. The screening and ranking of potential sedimentary basins for CO_2 storage is conducted quantitatively by assigning scores and weight to each of screening criteria and analysed based on parametric normalization. The screening criteria were modified from previous study to suit the geology setting of Malaysia. The data is compiled using Excel-based evaluation tools to rank the potential storage sites for carbon dioxide sequestration in Malaysia. Malay basin is ranked as the most potential basins for offshore CO_2 storage hence it deserves extra attentions in the next phase of basin scale assessment The results from screening and ranking exercise later should be used in detailed basin scale assessment in future works.

1. Introduction

Worldwide interest in carbon emission reduction in atmosphere has increased at an exponential rate in recent years. According to projections of energy use worldwide, global carbon dioxide (CO_2) emissions are expected to increase by 55 % between 2004 and 2030 or 1.7 %/y. The predicted increment of CO_2 emission into atmosphere has encouraged manufacturers worldwide to reduce CO2 emissions and increase energy efficiency (Mohd Nawi et al., 2014). Malaysia possesses unique and distinctive geological characteristics and is one of the main oil-producing countries. CO_2 emission as a result of petroleum production has been identified as one of the contributor to the emission of CO_2 in Malaysia. Taking into account the expected increase of energy demand for sustainable development in Malaysia, the potential for CO_2 geological sequestration opportunities in Malaysia should be investigated as a potential way of reducing CO_2 emission. However, identifying the most potential areas for CO_2 sequestration based on a set of criteria is necessary to be done before proceeding with any deployment stages. Before large-scale deployment of CO_2 sequestration can commence, a framework is needed to aid the selection of promising CO_2 storage sites with characteristics suitable for long term storage. Many methodologies and frameworks are being used previously for site suitability evaluation and site selection for example site selection guideline by Bachu (2003), multi-criteria analysis by Ramirez et al. (2009) and others. This paper presents workflow and method for preliminary evaluation of potential storage sites suitability for carbon dioxide sequestration in sedimentary basins of Malaysia.

2. Preliminary basin scale evaluation framework

The preliminary evaluation to identify potential geologic CO_2 storage sites involves 4 main tasks which consist of 1) Development of site suitability evaluation methodology 2) Development of screening criteria 3)

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Extensive data gathering on key indicators that influence the performance of geological storage media 4) Basin screening and ranking based on the criteria selected using Excel-based tool.

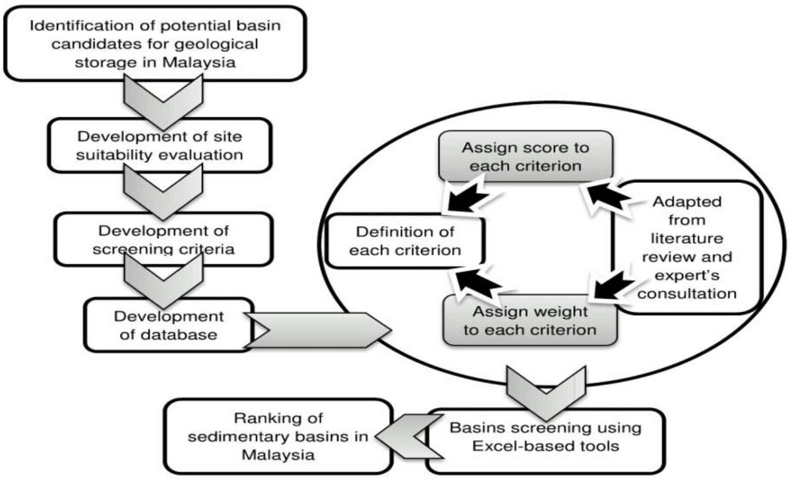

Figure 1: Schematic map of the methodology used in preliminary evaluation of sedimentary basins in Malaysia (modified from Ramirez et al, 2009)

Figure.1 shows the schematic diagram of methodology and workflow to evaluate potential sedimentary basins for CO_2 sequestration in Malaysia. The screening is based on the criteria which possibly influencing the performance of basin as a geological storage for CO_2. The selection of criteria and key indicators for basin screening was developed from literature survey and opinion from a panel of experts. The scores and weight for each indicator were also adapted from literature review and were aggregated in screening tools. The following section will qualitatively discuss the value of the selected indicators, the characteristics and importance of selected criteria.

2.1 Identification of basins

Based on regional study and amount of data available, there are 14 sedimentary basins all around Malaysia that has been identified as potential CO_2 storage. Most of them are well explored and possess a good sealing formation. A set of 12 criteria has been modified to suit the geological characteristics of Malaysia for assessment and ranking of sedimentary basins in terms of their suitability for CO_2 storage.

2.2 Selection of criterion

The selection of criteria and indicators is basically fulfilling 3 main conditions to develop a safe and effective storage site.1) Storage optimization 2) Risk minimization 3) Feasibility. Storage optimization aims at finding a site with maximal storage volumes with good sealing formation, in which injection can be performed in favourable conditions. Risk minimization seeks to limit the occurrence and impact of CO_2 migration and leakage from the storage zone (Wei et al., 2013). It also will consider possible natural (faults, tectonic setting, etc.) and manmade (wells, etc.) geological defects that might jeopardize the storage security. Feasibility study determines the ease to deploy CO_2 sequestration considering the accessibility of the storage sites, public perceptions, economic considerations, and land use issues for onshore sequestration. Therefore, the development of screening criteria should satisfy these conditions to arrive at a quantitative evaluation in terms of basin suitability for CO_2 sequestration. The criteria have been reselected to suit the geological characteristic of Malaysia for example the type of tectonics setting. The weights and scores of each criterion were determined based on their relative importance with respect to the Malaysian basins as CO_2 storage

2.2.1 Tectonic setting

There are five categories of tectonic setting commonly discussed in the evaluation of site suitability for CO_2 storage. The least favourable one is oceanic convergent basins because they are located in tectonically active areas, mostly along subduction zones where oceanic plates move toward and dip under continental plates (Bachu, 2003). Tectonic unstable regions increase the effort needed to understand and manage possible risk for they have higher leakage risk and seismically prone to have earthquakes activity and have large potential risk of catastrophic escape or continues leakage of CO_2 into the atmosphere.

2.2.2 Faulting intensity
Faulting intensity reflects the amount of risk for potential leakage and catastrophic escape of CO_2 to the surface. Conversely, the amount of faulting can be used to categorize the individual basins if the faults are sealing which reflect the lesser storage capacity.

2.2.3 Reservoir seal pair
Reservoir seal pairs are a crucial prerequisite to selection of most CO_2 storage sites. Reservoirs provide the storage volume, and seals, due to their low permeability, provide the vertical containment. The quality of the reservoirs and seals are determined by the lithology of the basin fill and its stratigraphy.

2.2.4 Depth
Reservoir depth (in m), is measured from the top of the reservoir to the surface. The safe storage of CO_2 in a sedimentary basin requires that CO_2 is stored in favourable geological porous media at depths greater than 800 m storage as it will significantly increase storage capacity in porous media. It was previously deemed necessary to inject CO_2 at depths greater than 800 m, where supercritical conditions would be met assuming a hydrostatic pressure gradient and geothermal gradient of 25 °C/km.

2.2.5 Size
The basin size and depth reflect the overall storage volume achievable, as the larger the basin the greater the chance of having laterally extensive reservoir and seal pairs, possibly in multiple stratigraphic intervals, and therefore the greater the likelihood of injectable pore volume (CO2CRC, 2008).

2.2.6 Geothermal
Geothermal conditions are relevant to the density of CO_2 to become supercritical phase. The temperature of reservoirs increases while CO_2 density decreases with higher geothermal gradients at the same depth (Bachu, 2003). As a result, basins with higher geothermal gradients tend to have lower storage capacity and higher buoyancy force. Cold basins tend to have higher storage capacity and lower buoyancy force (Bachu, 2003).

2.2.7 Hydrogeology
Understanding the hydrodynamic regime of formation waters is critical for CO_2 injection in deep saline aquifers, especially for evaluating long-term migration of the CO_2 plume. The less favourable type of hydrogeology is shallow, short flow systems for it does not meet the geological requirements for maintaining supercritical CO_2 and does not have a long enough residence time to immobilize the injected CO_2 by one of the other trapping mechanisms.

2.2.8 Maturity
The geology, hydrogeology, hydrocarbon reservoirs, and hydrocarbon production of many basins with low hydrocarbon maturity are not well known due to limited explorations of such sites (Bachu, 2003). Sites that have high hydrocarbon maturity and are near oil and gas fields also have a higher degree of certainty because of the large amount of existing data in these areas, potentially making them particularly attractive locations for implementation of CO_2 sequestration project (Wei et al., 2013).

2.2.9 Hydrocarbon potential
The presence of oil and gas resource accumulations indicates the presence of good local seal reservoir pairs that contribute to better retention of hydrocarbon resources in the long term, which translates to better potential to retain injected CO_2 (Wei et al., 2013).

2.2.10 Onshore/offshore
The location of a sedimentary basin is also an important to be considered because of the implications regarding access and infrastructure, notwithstanding the level of exploration. On the other hand, public perception and land use issues may dictate that offshore sites are preferential for many CO_2 storage projects.

2.2.11 Accessibility and infrastructure
Accessibility and infrastructure reflect the technological feasibility and ease of future developments.

2.2.12 Climate
It is vital to recognize that with the increased capacity and decreasing buoyancy, basins with low surface temperature such as those in cold regions and offshore, is preferable compared to on-shore in tropical climates. However, from an operational point of view the former would rank low compared with the latter.

3. Screening criteria

Table 1 is a modified version of the basin scale criteria for CO_2 storage developed by Bachu (2003) and lists the criteria that can be used for the assessment and ranking of sedimentary basins in terms of their suitability for CO_2 sequestration or storage. For each criterion, the classes are arranged from least favourable to most favourable from left to right across the table.

Table 1: Evaluation criteria for preliminary evaluation of CO_2 geological storage in Malaysia (modified from Bachu, 2003)

	Criterion, i	Classes, j						
		1	Score	2	Score	3	Score	W
1	Tectonic setting	For arc	1	Back arc	3	Platform	7	0.09
2	Faulting intensity	Extensive	1			Moderate	5	0.1
3	Reservoir seal pair	Poor	1			Medium	3	0.1
4	Depth	Very shallow (<300 m)	1	Shallow (300 – 800 m)	3			0.08
5	Size	Very small (<1,000 km^2)	1	Small (1,000-5,000 km^2)	3	Medium (5,000 – 25,000 km^2)	5	0.06
6	Geothermal	Warm basin (>40 °C/km)	1			Moderate (30 - 40 °C/km)	3	0.09
7	Hydrogeology	Shallow, short flow systems	1			Intermediate flow system	3	0.08
8	Maturity	Unexplored	1	Exploration	2	Developing	4	0.08
9	Hydrocarbon potential	None	1	Small	3	Medium	7	0.06
10	Onshore/ Offshore	Deep offshore	1			Shallow offshore	4	0.1
11	Accessibility	Inaccessible	1	Difficult	3			0.03
12	Infrastructure	None	1	Minor	3			0.05
13	Climate	Arctic	1	Sub-arctic	2	Desert	4	0.08

(Cont)Table 1: Evaluation criteria for preliminary evaluation of CO_2 geological storage in Malaysia (modified from Bachu, 2003)

	Criterion, i	Classes, j				
		4	Score	5	Score	W
1	Tectonic setting	Deltaic	15	Rift valley	15	0.09
2	Faulting intensity			Limited	9	0.1
3	Reservoir seal pair			Excellent	7	0.1
4	Depth	Deep (> 3,500m)	5	Intermediate (800 - 3,500 m)	15	0.08
5	Size	Large (25,000 - 50,000 km^2)	9	Very large (>50,000 km^2)	15	0.06
6	Geothermal			Cold basin (30 °C/km)	7	0.09
7	Hydrogeology			Long range flow system	7	0.08
8	Maturity	Mature	8	Super-mature	10	0.08
9	Hydrocarbon potential	Large	13	Giant	21	0.06
10	Onshore/Offshore			Onshore	10	0.1
11	Accessibility	Acceptable	6	Easy	10	0.03
12	Infrastructure	Moderate	7	Extensive	10	0.05
13	Climate	Tropical	7	Temperate	11	0.08

4. Development of the screening tool

The method to assess the suitability of sedimentary basins in Malaysia for their CO_2 storage potential was adapted from the basin screening criteria of Bachu (2003). Each of the criteria presented in Table 1 is given a value based on criterion-specific defined classes, where the lowest and highest values characterize the least and the most suitable classes. These scores reflect the relative importance of the categories within a given indicator. Each indicator is divided into categories. Each indicator is divided into categories. The scores and weights were adapted from previous studies and literature reviews modified to suit Malaysia geological condition. The input generated in the tool is then used to calculate an average score per site. The basic calculation is a simple linear aggregation using the scores and weights between categories and indicators using the approach of Bachu (2003). The resulting scores per site from the assessment are representative for the relative scoring without indicating an absolute site performance. For each criterion, i (i=1,2,3,..13) in Table 1, an exponential parameterization of a function (F_i) is used to define the range of numerical values for each class of that criterion. The numerical values of F_i are assigned to describe a value placed on the specific class, j (j=1,2,3…n) for that criterion. The lowest and highest values of this function characterize the worst and best class in terms of suitability for that criterion. Table 1 presents the numerical values assigned here to the various classes for the criteria. For any sedimentary basin, k that is evaluated in terms of its general suitability for CO_2 sequestration or storage, the corresponding class j for each criterion i is identified (see Table 1), resulting in a corresponding score $F_{i,j}$. Because the function F_i has different ranges of values for each criterion, making comparisons and manipulations difficult, the individual scores $F_{i,j}$ are normalized according to:

$$P_i^k=\frac{F_{i,j}-F_{i,1}}{F_{i,n}-F_{i,1}} \qquad (1)$$

where P_i=0 for the least favourable class and P_i=1 for the most favourable class for all the criteria. These can subsequently be used in the basin ranking process to produce a general ranking score(R) (method is adapted from Bachu (2003) that latter be used in the final ranking of sedimentary basins of Malaysia.

$$R^k=\sum_1^{15} w_i\, P_i^k \qquad (2)$$

where w_i are weighting functions that satisfy the condition,

$$\sum_1^{15} w_i=1 \qquad (3)$$

5. Ranking of Sedimentary Basins

By compiling data on the criteria above, different basins can be compared, contrasted and ranked for their suitability for CO_2 storage quantitatively if scores are given for each criterion (as per Bachu, 2003). This allows the sedimentary basins in Malaysia to be ranked in order of their suitability for geological storage of CO_2. The range of numerical values (function, F_i) for the classes in a given criterion has an exponential form because subjectively these classes differ in importance. It is critical to determine if the sedimentary basins of Malaysia can provide a safe storage for CO_2 before commencing the sequestration as potential leakage and catastrophe escape may cause remnant of disputes in terms of environmental issues and might have some problems with public perceptions.

6. Result and Discussions

Table 2 below shows the ranking of 14 identified sedimentary basins in Malaysia that have potential for CO_2 storage. From the screening and ranking exercises, it is obvious that Malay Basin, Central Luconia Province, West Baram Delta and Balingian Province are among the best candidates for CO_2 storage. These basins hold the same attributes such as possessing an excellent sealing formation, actively explored by energy industries therefore plenty of data available for evaluation of CO_2 storage and also a major oil-producing provinces in the nation. It can be concluded that the potential basins for CO_2 sequestration are not equally suitable in terms of its suitability. There are various factors that influence the evaluation of sedimentary basins mostly due to lack of crucial data for poorly explored basins.

Table 2: List of Ranking for Sedimentary Basins in Malaysia

Rank, R	Basin, k	Score
1	Malay Basin	0.8113
2	Central Luconia Province	0.7356
3	West Baram Delta	0.7041
4	Balingian Province	0.6938
5	Sabah Basin	0.6864
6	East Baram Delta	0.6260
7	Straits of Melaka	0.6200
8	Penyu Basin	0.5554
9	Tatau Province	0.4938
10	West Luconia Province	0.4553
11	Tinjar Province	0.4200
12	Northeast Sabah Basin	0.3543
13	Southeast Sabah Basin	0.3370
14	North Luconia Province	0.2659

7. Future Directions

The results from screening and ranking exercise later will be used for detailed basin scale assessment in future works. Once a sedimentary basin has been identified as potentially suitable for CO_2 storage, a basin scale assessment can be conducted to locate possible injection sites. Potential sites then can be scored and ranked in order to identify those that have the highest prospect of successful CO_2 storage and warrant further detailed site characterization.

8. Conclusions

It is necessary to recognize that the list of criterion selected in the screening criteria can be expanded further if more criteria are developed and more data are available for assessment. Among the 14 identified sedimentary basins, Malay basin, Central Luconia, West Baram Delta and Balingian Province areranked as the top four in the ranking system. Malay basin is ranked as the most potential basins for offshore CO_2 storage hence it deserves extra attentions in the next phase of basin scale assessment. This can then be used in making decisions for large scale implementation of such operations. Adequate amount of data due to active exploration, well known geological structure, relatively stable geological structure are the main factors that make these basins possess a higher suitability.

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