Suitability of Brine Disposal in SW Ontario: The Lucas Formation and the Cambrian Age Strata

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ABSTRACT
In southwestern Ontario, salt caverns are utilized for disposing oil field wastes, storing liquid and gaseous hydrocarbon products, and in the future, such caverns are planned to be used for grid-scale compressed air energy storage (CAES). Solution mining salt caverns generate large volumes of brine that must be disposed; deep well injection offers a practical and safe option to dispose large volumes of brine. The aim of this study is to evaluate the potential of brine disposal in southwestern Ontario based on geological, geomechanical, and petrophysical parameters. Multi-criteria analysis is utilized to develop an evaluation system that would compare various strategically chosen sites in southwestern Ontario. The main criteria used in the study are permeability, porosity, depth, thickness, reservoir lithology, and caprock lithology. The assessment technique developed is intended to yield a "first-order" estimate of preferred brine disposal areas in the Lucas Formation and the Cambrian age strata within southwestern Ontario.

RÉSUMÉ
Dans le sud-ouest de l'Ontario, les cavernes lessivées dans le sel gemme sont utilisées pour enfouir les déchets des usines pétrolières, stocker des hydrocarbures liquides et gazeux et, à l'avenir, de telles cavernes devraient être utilisées pour le stockage à grande échelle de l'énergie renouvelable comme l'air comprimé (CAES). La creation d'une caverne génère de gros volumes de saumure qui doivent être utilisés ou éliminés, et l'injection dans les puits profonds offre une option pratique et sûre pour l'élimination. L'objectif de cette étude est d'évaluer le potentiel de l'élimination de la saumure dans le sud-ouest de l'Ontario en fonction des paramètres géologiques, géomécaniques et hydrogéologiques. Une analyse multi-critère est utilisée pour élaborer un système d'évaluation qui compare divers sites stratégiquement choisis dans le sud-ouest de l'Ontario. Les principaux critères utilisés dans l'étude sont la perméabilité, la porosité, la profondeur, l'épaisseur, la lithologie des couches salifères, et la lithologie des couches supérieures. La technique d'évaluation développée vise à produire une estimation du «premier ordre» des zones préférées dans la formation Lucas et les couches d'âge cambrien dans le sud-ouest de l'Ontario.

1 INTRODUCTION

In the past, salt caverns in southwestern Ontario and elsewhere in North America have been used for disposing oil field wastes, storing liquid and gaseous hydrocarbon products, and producing salt for commercial use. Now, with the demand for energy storage growing rapidly, salt caverns will be utilized as a storage medium in compressed air energy storage (CAES). Apart from pumped hydro, CAES is the only technology that can provide grid-scale energy storage. For this to occur, implementation of CAES in southwestern Ontario would require solution mining large salt caverns to be used as storage vessels. This, in turn, would generate large volumes of brine that must be disposed of safely.

Historically, the three most common ways to dispose brine were discharge to surface waters, disposal into surface ponds, and deep well disposal. However, because of environmental issues such as soil and groundwater contamination, discharge to surface waters and disposal into surface ponds is discouraged or prohibited by regulations. Deep well disposal has fewer environmental issues as compared to other options, but requires a suitable aquifer with an effective caprock that can be shown to provide containment and is also subject to approval by the regulatory process, supervised by the Petroleum Operations Section of the Ontario Ministry of Natural Resources and Forestry.

Though deep brine disposal has been used by industries in Ontario, there is a lack of a comprehensive investigation of site suitability for deep brine disposal. This study aims to investigate suitable sites for brine disposal in southwestern Ontario based on geological, geomechanical, and petrophysical parameters. A multi-criteria analysis evaluation system is developed based on relevant disposal parameters and applied to sites throughout southwestern Ontario. The assessment technique developed is intended to yield a "first-order" estimate of preferred brine disposal sites in southwestern Ontario.

2 FEASIBILITY CONSIDERATIONS

The geological, geomechanical, and petrophysical parameters that affect brine disposal into the subsurface are permeability, porosity, depth, thickness, areal extent, confining rock mass, formation pressure, proximity to formations with valuable resources, proximity to faults, and unplugged wells.

Permeability is the most important parameter in deep brine disposal as the main goal of disposal project is to store and transmit fluid through the formation. Injection pressure is also largely dependent on permeability; low permeability would require high injection pressure that can make the project expensive and even impractical. Formations with permeability greater than 100 mD are preferred for large volumes of brine disposal, i.e., they are considered as aquifers.

Porosity is the measure of the rock's ability to store fluid. In brine disposal, only effective porosity is of importance since only the interconnected void space will transmit and store the brine. High effective porosity is desired for an economical disposal operation. As a reference, porosity values greater than 15 % are desired for large brine disposal operations.

The minimum and maximum constraints for the depth depend on environmental issues and drilling costs, respectively. At shallower depths, the confining rock mass is at a low stress condition and would fracture under high injection pressure. This can result in major environmental issues such as polluting the shallow potable water formations (McLean 1968). Therefore, in southwestern Ontario, a minimum depth constraint of 120 m is advised in this study. The maximum depth constraint is controlled by the cost of drilling and operational machinery. Drilling is expensive and deeper reservoirs can significantly increase the capital cost of the project. Also, deeper formations have higher formation pressures and therefore, require higher injection pressure to maintain the flow. Higher injection pressure would require high-powered surface equipment and this would increase the operation cost of the project. In fact, in deeper formations, it is possible to have formation pressures so high that the disposal operation becomes unfeasible.

The thickness of the disposal formation is an important parameter due to its impact on transmissivity, injection pressure, and confinement of fluid. Since transmissivity is defined by the product of thickness and hydraulic conductivity, the formations with large thickness will have larger transmissive potential. In addition, given that other disposal formation conditions are the same, thinner formations require higher injection pressure and vice-versa to achieve the same injection rates. Higher injection pressure would be uneconomical, as it would require high-power surface equipment. Also, the thickness of the disposal formation controls the spread of the injected fluid. In a comparison of two homogeneous formations with similar effective permeability, brine would spread farther in a thin formation as compared to thick formation (McLean 1968). It is crucial to contain brine near the well so that it does not pollute valuable resources or pose other environmental issues. Confinement of the brine will also assist in developing an effective monitoring system that can be placed in close vicinity of the well.

A disposal formation with a large areal extent is preferred to accommodate large volumes of brine and avoid pressure build-up during long-term injection. First, given adequate permeability and thickness, the amount of brine stored is directly related to the areal extent of the formation. The amount of brine storage increases with increasing areal extent or reservoir volume. In addition, formations with large areal extent are necessary to avoid pressure build-up during long-term injection. Injected brine pushes and compresses the formation fluids while moving radially away from the well. Since the formation fluids are only slightly compressible, pressure builds up quickly in an aquifer with small areal extent. Therefore, McLean (1968) suggests that a formation with large areal extent is needed to distribute the pressure.

All disposal formations require a caprock that confines the injected fluid into the disposal formation; confinement is necessary to avoid polluting formations containing groundwater, oil and gas, and other minerals. The main requirements of an adequate caprock are impermeability to reservoir fluid, strength, thickness, and continuity. Preferred and proven caprock include shale and dense carbonates (Rudd 1972). Having said that, even other rocks that are dense can act as a barrier to the injected fluid; for example, sandstones that are heavily cemented can become impermeable to brine and act as an adequate seal.

For successful long-term disposal, it is required that the formation pressure be below certain limits which depend on other factors such as permeability and volume of the reservoir. High formation pressure would increase the operational cost by requiring higher injection pressure. In addition, high injection pressures needed to achieve design rates could cause environmental problems by damaging the caprock and possibly polluting other formations.

According to the government regulations, injection of brine should not affect any formation containing valuable resources such as potable water, oil and gas, and other mineral deposits (McLean 1968). A safe distance must be maintained from these resources, and multiple confining layers should exist between the disposal formation and the valuable resource formation.

It is also desired that the disposal site be located in a tectonically stable area. Large earthquake activity can pose a threat to reservoir stability through generation of fractures or faults. Seismic activity can also open existing faults or fractures through which brine can escape under the influence of pressure and pollute other formations. Fortunately, southwestern Ontario is seismically stable.

During the last decades of the 19^{th} century, many exploratory and production wells were drilled for oil and gas. Unfortunately, many of these wells were left unplugged or inadequately plugged. These wells create an environmental concern during subsurface disposal by allowing the brine to escape the disposal formation and pollute other formations. In the past, environmental incidents occurred in Ontario where industrial waste escaped the disposal formation through unplugged wells (Raven et al. 1990). McLean (1968) suggests that, at least, an area covering the radius of 2.5 km around the well should be surveyed for unplugged wells.

3 GEOLOGICAL SETTING

Sedimentary rocks in southwestern Ontario belong to the Paleozoic era, and overlie the Precambrian rocks of the southern margin of the Canadian Shield.

Sedimentary strata in southwestern Ontario consist of two major sedimentary basins: the Michigan Basin and the Appalachian Basin. A northeast-southwest direction trending structurally high feature, the Algonquin Arch, separates these two basins throughout southwestern Ontario (Armstrong and Carter 2010). The Michigan Basin has a bowl-shaped geometry with its depositional center near Saginaw Bay in Michigan. The sedimentary strata in southwestern Ontario consist of the eastern flank of the Michigan Basin. The Appalachian Basin is a foreland basin that was formed due to collisional tectonic events at the eastern edge of North America. Sedimentary strata in southwestern Ontario consist of northern edge of the Appalachian Basin (AECOM Canada Ltd. and Itasca Consulting Canada, Inc. 2011).

Disposal formations in southwestern Ontario are located in strata of the Paleozoic era during which the Michigan Basin and the Appalachian Basin were formed. Paleozoic rocks are mainly made from marine sediments as southwestern Ontario was intermittently covered by basin-centered inland seas during the Paleozoic era. Due to the isolation of the Michigan Basin, rocks in the basin tend to be carbonate rich and also contain evaporite beds. However, due to the supply of clastic sediments from the highlands, rocks in the Appalachian Basin tend to be siliciclastic in nature (Armstrong and Carter 2010).

The general stratigraphy of southwestern Ontario is shown in Table 1.

Table 1: General stratigraphy of southwestern Ontario

Period	Era	Group/Formation
Devonian	Upper	Port Lambton Group
		Kettle Point Formation
	Middle	Hamilton Group
		Dundee Formation
		Lucas Formation (Brine Disposal Potential)
		Amherstburg Formation
	Lower	Bois Blanc Formation
Silurian	Upper	Bass Islands Formation
		Salina Group
	Middle	Guelph Formation
		Lockport Formation
		Clinton Group
	Lower	Cataract Group
Ordovician	Upper	Queenston Formation
		Georgian Bay – Blue Mountain Formation
	Middle	Trenton Group
		Black River Group (Coboconk, Gull River and Shadow Lake Formations)
Cambrian Age Strata (Brine Disposal Potential)		
Precambrian		

The disposal potential in southwestern Ontario is limited as compared to the areas in the United States that share the Michigan and the Appalachian Basins. This is indeed due to southwestern Ontario's location on the flanks of the Michigan and Appalachian Basin; the sedimentary strata in southwestern Ontario are thin and limited in areal extent as compared to the thick and extensive strata in the neighbouring areas.

Nevertheless, the sedimentary strata in southwestern Ontario contain a few formations that possess adequate brine disposal potential. The two rock strata that can take large quantities of brine are the Lucas Formation and the Cambrian age strata. Locally, other formations such as the Guelph, Bois Blanc, and Bass Islands Formations have limited potential as well (McLean 1968). In this study, the focus is on the Lucas Formation and the Cambrian age strata.

3.1 Lucas Formation

The Detroit River Group is from the Middle Devonian Period and is comprised of three formations: the Sylvania, Amherstburg, and Lucas Formations. Of these three formations, only the Lucas Formation is suitable for large volumes of brine disposal.

It is comprised mainly of limestones and dolostones; however, anhydrite beds and local sandy limestones are also encountered (Armstrong and Carter 2010). Typically, anhydrite beds thicken towards the center of the basin. In some areas of southwestern Ontario, especially towards the basin center, anhydrite beds have been dissolved and have created karstic features. These locations have very high permeability and have been termed as "lost circulation" zones.

Similar to other formations of the Michigan Basin, the Lucas Formation is thickest in the center of the basin. It attains a maximum thickness of 96 m in Sarnia and thins out southeastwardly towards Lake Erie (Armstrong and Carter 2010).

Permeability and porosity values are relatively high in Lambton and Kent Counties. Thick salt beds are present in the Salina Formation under these counties, and the differential dissolution of the salt beds creates fractures in the Lucas Formation; hence, an improvement is seen in porosity and permeability values.

In Lambton County, the Lucas Formation has porosities ranging from 8 to 20 % and permeability values ranging from 10 mD to 50 mD; zones of over 200 mD are also present locally due to karstic features (McLean 1968). Note that core data is limited for the Lucas Formation and very rare in counties other than Lambton.

3.1.1 Karst Potential in the Lucas Formation

Karstification refers to the dissolution of soluble rocks, such as carbonates and evaporites, from undersaturated water. Dissolution enhances the permeability of the soluble reservoir through enlargement of joints and fractures, and subsequently, formation of conduits and/or caves. Karstification normally occurs in shallower formations due to presence of freshwater.

In southwestern Ontario, karstic features/systems are present in the near surface formations containing carbonates. The karstic formations in southern Ontario belong to the carbonate and evaporitic rocks from the Ordovician, Silurian, and Devonian ages. For brine disposal purpose, only the carbonate formation of the Devonian age is considered. The Lucas Formation, containing limestone and dolomite beds interbedded with anhydritic beds, is reported to be karstic. Hurley et al. (2008) reports that drill cores from boreholes in the Lucas Formation have consistently indicated the presence of karst. After deposition of the Lucas Formation, continental uplift drained the sea that had covered Ontario for millions of years, and this resulted in an unconformity between the Lucas Formation and the Dundee Formation. Hurley et al. (2008) suggested that the uplift and subaerial exposure could have created faults, fractures, and solution channels in the Lucas Formation. Even the past drilling and disposal activities near the Sarnia region has confirmed the presence of karstic networks in the Lucas Formation.

3.2 Cambrian Age Strata

The Cambrian strata unconformably rest on the crystalline rocks of the Precambrian basement. Rocks in the Cambrian strata are dominated by sandstone, and the three major rock types include, in ascending lithologic order, quartzose sandstones, interbedded sandstone and dolostones, and dolostones (Armstrong and Carter 2010).

The Cambrian age strata contains three formations: the Mount Simon Formation, the Eau Claire Formation, and the Trempealeau Formation. Due to relatively similar characteristics of the three Cambrian formations mentioned above, it is difficult to differentiate between them. Therefore, geologists tend to treat the Cambrian strata as a single unit. The petroleum industry has been treating the Cambrian strata as a single unit, and so do most of the well log interpretations for correlation analysis.

Average porosity values in the Cambrian strata can range from 5 to 15 %; however, values as high as 20 % have been recorded in sandy facies. Average permeability values range from 50 to 60 mD; though, streaks of 250 mD are also recorded (McLean 1968).

The limit for potable water is around 5,000 parts per million (p.p.m.). of total dissolved solids, and no disposal should take place near potable water sources. It is shown that the range of total dissolved solids in the waters of the Cambrian strata is 200,000 to more than 400,000 p.p.m. However, the Cambrian strata closer to the surface might have significantly lower total dissolved solid values, and exceptionally (locally and when shallow) might be suitable as a potable water resource.

4 MULTI-CRITERIA ANALYSIS

Due to a large number of parameters involved in the rating of the brine disposal sites, a formal evaluation system was developed to aid in decision-making. Multi-criteria analysis (MCA) is a decision-making tool that evaluates alternatives based on multiple criteria based on decision rules. There are three major components of the MCA: value scaling (criteria scoring), criteria weighting, and decision rule (Malczewski and Rinner 2015). A major benefit of MCA is that it can include both quantitative and qualitative criteria, as long as the qualitative criteria can be scored on a continuous scale.

Weighted linear combination (WLC), a type of MCA approach, is used in this study. WLC is a simple but effective technique to rate potential disposal sites. It works by multiplying the normalized criterion score (v_i) by the assigned criterion weighting (w_i) for each criterion and then summing the product over all criteria; the result is a total score (S) for each site.

$$S(a) = \sum_i w_i * v_i(a) \quad [1]$$

Where S(a) is the total score for each site a, w_i is the weighing factor for the i^{th} criterion, and $v_i(a)$ is the criterion score for the i^{th} criterion for each site a.

Normalized criteria scores are assigned to each criterion. Criteria scoring is a mathematical representation of experts' judgement on the criteria. In this study, scores between 0 and 100 are assigned; 0 represents the least suitable and 100 being the most suitable.

Each criterion is assigned a weighting factor based on opinion of experts. This will allow a comparison between multiple criteria used in the disposal study. A weight factor between 0 and 1 is given to each criterion; the sum of the weights for all criteria will equal to 1. Higher weights will represent more importance and vice versa.

5 CRITERIA SCORING AND WEIGHTING

A major step for evaluating and comparing the potential disposal sites is generating standardized scores for important criteria and providing a weighting factor for each criterion. The scores and weights are developed through discussion with experts, information gathered from the literature, and performance of previous disposal wells.

The criteria used in the MCA are selected from the various feasibility parameters that were discussed previously in section 2. Because of limited data availability and the large extent of the study area, only the most relevant parameters were chosen for scoring and weighting process: permeability, porosity, depth, thickness, disposal formation lithology, and caprock lithology. The criteria included in the evaluation system should provide a first order estimate of the brine disposal potential in southwestern Ontario. Table 2 displays the scoring for criteria used in this study.

Permeability is given the highest weight of 0.25 as the overall goal of the project is to transmit brine through the formation. Permeability values of more than 100 mD are preferred for large volume of brine storage. In southwestern Ontario, permeability values for the potential disposal sites average around 50 mD; however, near the Sarnia region, the Lucas Formation contains karstic features that have much larger permeability. Since the location of karst is not mapped yet, the sites that show a potential for karst are given an additional weight of 0.10. This additional weight will allow the potential karstic sites to be rated higher when comparing to non-karstic sites from the same formation or other formation.

Porosity is assigned a weighting factor of 0.20 and is an important characteristic as it signifies the storage capacity of a formation. Porosity values of 15 % or greater are preferred for large disposal operations. In southwestern Ontario, porosities up to 20 % are encountered in the Lucas Formation and the Cambrian strata.

The thickness of the formation is the third most important parameter as the injection pressure and storage capacity are directly related to thickness. It is given a weighting of 0.15. Thickness of greater than 15 m is given a high score as a disposal formation with 15 m of thickness and a large areal extent can store an adequate volume of brine. Potential disposal formations in southwestern Ontario are thick and receive a high score in this category. As a reference, the Lucas Formation can be up to 96 m thick in the Sarnia region.

Depth to the disposal formation is given a weight of 0.15. The shallower limit of depth is an important number as some environmental issues are related to shallow formations. At shallow depths, injection pressures must be kept in check as the caprock can be breached if the formation stresses are low and the injection pressures high (exceeding the fracture pressure of the strata). Also, freshwater is encountered at shallow depths, and it must be protected. Therefore, disposal strata at depths of less than 120 m are given a score of 0. In fact, disposal at less than 180 m should be performed with extreme caution and should be carried out with a strong monitoring program. Formations deeper than 300 m are given a high score as they can support relatively high injection pressures and do not typically pose a threat to freshwater sources. The deeper limit of depth is not as important as the shallower limit; one issue related to the deeper limit is that drilling costs are high for deeper caverns. In southwestern Ontario, the shallower limit of depth is an issue. The Lucas Formation in the Sarnia region is located at shallow depth, and injection in those areas must be performed with caution.

Disposal formation lithology is assigned a weight of 0.10, and it gives an initial measure of the disposal potential in the formation. The ideal formation should consist of sandstone, limestone or dolomite. Compared to the other rocks (e.g., shales, mudstones, etc.), these rocks tend to have larger permeability and porosity values. Formations containing medium to coarse grained sandstone and carbonates are given high scores; whereas formations containing shale interbeds are given a relatively low score.

Caprock lithology is an important criterion as the caprock acts as a barrier to the formation fluid and stops the fluid from escaping the disposal formation. It is assigned a weighting factor of 0.15. An ideal caprock is impermeable, strong, thick, and laterally extensive. In this study, the caprock lithology is selected as a criterion as it provides a qualitative idea of the strength and permeability characteristics of the caprock. Shale and dense crystalline rocks are given the highest score due to their ability to trap fluid in the formation. Even fine-grained rocks can provide an acceptable seal since the pore radius is small, and that limits flow through the pores.

Table 2: Criteria scoring for permeability, porosity, thickness, depth, disposal formation lithology, and caprock lithology

Parameter	**Parameter Value**	**Score**
Permeability (mD)	<10	0
	10 – 50	0 - 20
	50 - 100	20 - 40
	100 – 500	40 - 60
	500 – 1000	60 - 80
	1000 - 2000	80 - 100
	>2000	100
Porosity (%)	< 5	0
	5 – 10	0 – 40
	10 – 15	40 – 60
	15 – 20	60 – 80
	20 – 30	80 – 100
	> 30	100
Thickness (m)	< 5	0
	5 – 10	0 – 25
	10 – 15	25 – 50
	15 – 20	50 – 75
	20 – 25	75 – 100
	> 25	100
Depth (m)	< 120	0
	120 - 150	0 – 20
	150 - 180	20 – 40
	180 - 300	40 – 80
	300 - 400	80 – 100
	400 – 800	100
	800 – 1300	100 – 80
	1300 – 1800	80 – 60
	1800 – 2300	60 – 40
	> 3300	0
Disposal Formation Lithology	Medium to coarse-grained sandstone; porous carbonates (shelf setting)	100
	Fine to medium-grained sandstone; carbonates: limestone and dolomite	80
	Sandstone with shale interbeds	60
	Carbonates with shale interbeds	40
	Fractured shale	20
	Shale; dense crystalline limestone; igneous or metamorphic rocks	0
Caprock Lithology	Shale	100
	Dense crystalline carbonates; shale and carbonate interbeds	80
	Dense carbonates with shale interbeds	60
	Dense sandstone or siltstone	20
	Fractured rock mass	0

6 RESULTS AND DISCUSSION

The MCA evaluation system was applied to various strategically chosen sites in southwestern Ontario. An attempt was made to select and evaluate at least one site per township. However, the well logs are spread unequally due to large concentration of wells in the potential oil and gas areas, and lack of drilling in the other areas. To counter this situation, interpolation is used around the sites with sufficient data.

The evaluation results were divided into 4 categories:

- S1, Suitable – Level 1: This category was assigned to sites that achieved a score of more than 65 in the MCA evaluation system. Typically, to be a part of this category, sites have to display relatively high permeability and porosity values.
- S2, Suitable – Level 2: This category was assigned to sites that scored between 45 and 65 in the MCA evaluation system. Sites in this category tend to have lower permeability and porosity values as compared to S1 category.
- P – Potentially Suitable: This category is assigned to sites that lack porosity and permeability data, but otherwise, show potential for disposal based on depth, thickness, reservoir rock, and caprock.
- X – Unsuitable: This category is assigned to sites that do not meet the minimum criteria of one or more of the following parameters: depth, thickness, permeability, porosity, reservoir rock, and caprock.

6.1 Lucas Formation

Until now, majority of the brine disposal activities have been conducted in the Lucas Formation. Companies prefer brine disposal into the Lucas Formation due to the karstic nature of the formation. Areas with karstic network or 'lost circulation zones' provide high permeability values and storage space for large volumes of brine. Even though the karst networks have not been mapped yet, previous drilling and disposal operations have shown occurrence of karsts in the Lucas Formation.

One of the major limitations of disposal into the Lucas Formation is its shallow depth. In fact, a large part of southwestern Ontario is not suitable for disposal into the Lucas Formation, as it does not meet the minimum depth requirement. Disposal at shallow depth comes with various environmental issues due to lower caprock strength at shallow depth and higher risk of caprock breach.

Figure 1 displays the areas in the Lucas Formation that fall under the four disposal categories: suitable – level 1, suitable – level 2, potentially suitable, and unsuitable.

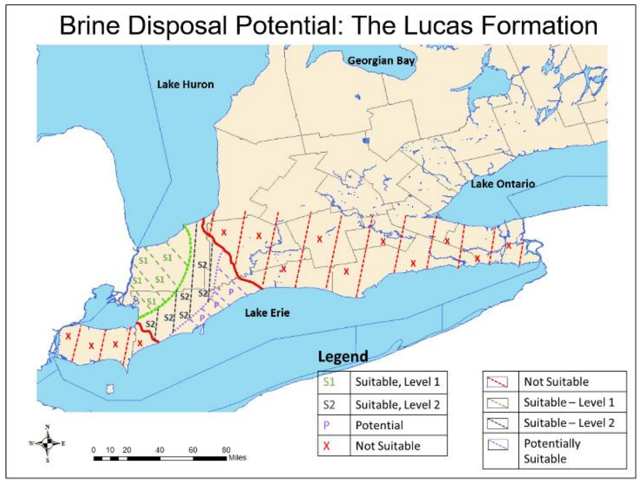

Figure 1: Brine disposal potential result: the Lucas Formation

The majority of Lambton County and the northwest corner of Kent County fall into the 'suitable – level 1' category. Since Sarnia has the thickest salt beds and is a potential site for CAES facilities, evaluation results from a site in Sarnia are discussed. Through the past disposal operations in the Sarnia region, it was discovered that the formation is karstic and displays high permeability. Table 3 shows the MCA evaluation system for a site in the Sarnia Township; the site scores 73 out of 100. The site has relatively high permeability of 100 mD as compared to the average range of 10 to 50 mD in Lambton County. An additional 10 points are added to the total score due to the area being potentially karstic. In addition to permeability, the site scores high in all other criteria, except depth. As is the case with most of the sites in the Lucas Formation, the site in Sarnia scores low in depth, with the depth of 137 m. At shallow depth, such as in this case, the operator would need to be very cautious with the injection pressures so that the caprock integrity is not breached. Also, an appropriate monitoring system must be established with continuous monitoring of freshwater sources and the changing reservoir conditions, such as formation pressure.

Areas with level 2 suitability include parts of Lambton, Kent, Middlesex, and Elgin Counties. Areas in this category score less than 65 on the evaluation system, and the low score is due to depth, permeability, and porosity criteria.

A few areas in parts of Kent, Elgin, and Middlesex Counties lack porosity and permeability data, but still show disposal potential based on depth, thickness, disposal formation lithology, and caprock lithology. These areas belong to the 'potentially suitable' category.

A large part of southwestern Ontario, shown in Figure 1, is not suitable for brine disposal into the Lucas Formation. This area does not meet the minimum depth criteria of 120 m.

Table 3: MCA evaluation table for the Lucas Formation in the Sarnia Township

County	Lambton			
Township	Sarnia			
Formation	Lucas			
	Parameter Value	Score (v)	Weight (w)	Si = v*w
Criteria:				
Depth (m)	137	12	0.15	1.8
Thickness (m)	95	100	0.15	15
Permeability (mD)	100	40	0.25	10
Porosity (%)	20	80	0.20	16
Disposal Formation Lithology	Limestone and Dolomite	80	0.10	8
Caprock Lithology	Shale and Limestone interbeds	80	0.15	12
Karst Potential	Yes	If yes, add 10 to total score		10
			Total Score (S)	73

6.2 Cambrian Age Strata

During the late 1960s, industrial waste and brine from a few disposal wells escaped to the surface in the Sarnia region. All of these wells were located in the Lucas Formation. This prompted industry to look into alternative disposal options, such as, utilizing the Cambrian age strata.

The Cambrian strata hosts various oil and gas fields in southwestern Ontario, which resulted in many exploratory and production wells being drilled into the Cambrian strata. Due to this, the porosity and permeability data is more readily available as compared to data in the Lucas Formation.

One of the major advantages of the Cambrian strata over the Lucas Formation is its relatively greater depth. The majority of the areas in the Lucas Formation received a poor score in the depth criterion as the Lucas Formation is less than 120 m in most of southwestern Ontario. However, the depth of the Cambrian strata is greater than 500 m in most of southwestern Ontario and does not pose groundwater or surface water contamination issues.

The general disadvantages of the Cambrian strata over the Lucas Formation are limited thickness, high formation pressure, and low permeability. A large part of southwestern Ontario is not suitable for disposal into the Cambrian strata due to the thickness of the strata being less than 5 m. It is also reported that the Cambrian strata is over pressurized, which might lead to large operational costs. Furthermore, the permeability values in the Cambrian strata are relatively less than the Lucas Formation as it does not contain karstic networks. .

Figure 2 displays the areas that fall under the four disposal categories: suitable – level 1, suitable – level 2, potentially suitable, and unsuitable.

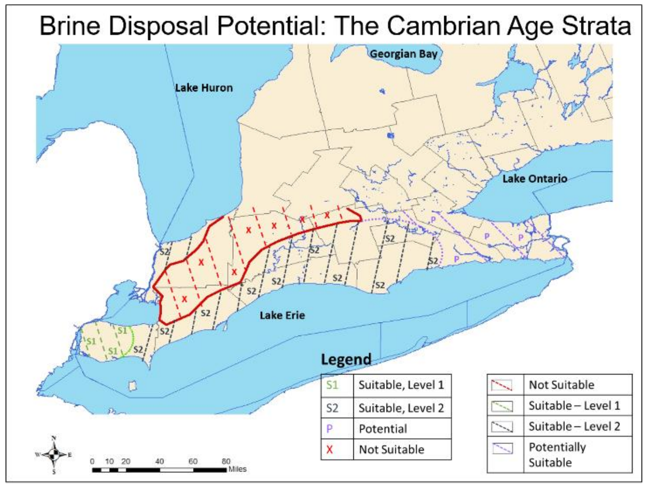

Figure 2: Brine disposal potential results: the Cambrian age strata

The Cambrian age areas with high disposal potential, suitable- level 1, are concentrated in Essex County. Table 4 shows the evaluation table for one of the sites in Essex County. Sites in Essex County contain relatively high permeability, greater than 100 mD, as compared to the average permeability of about 50 mD for the rest of southwestern Ontario. Essex county also scores high in the depth criterion with depths ranging close to the 1000 m mark; at this depth, the disposal site will be far away from freshwater sources, and still shallow enough that the drilling and operational costs are not tremendously high. The county also scores perfect in the thickness criterion with the formation thickness much larger than 25 m.

Table 4: MCA evaluation table for the Cambrian age strata in Essex County

County	Essex			
Township	Colchester South			
Formation	Cambrian age strata			
	Parameter Value	Score (v)	Weight (w)	Si = v*w
Criteria:				
Depth (m)	883	97	0.15	14.55
Thickness (m)	75	100	0.15	15
Permeability (mD)	100	40	0.25	10
Porosity (%)	18	72.5	0.2	14.5
Disposal Formation Lithology	Coarse to medium grained quartzose sandstone	80	0.1	8
Caprock Lithology	Dolomitic shale	60	0.15	9
Karst Potential	No	If yes, add 10 to total score		0
			Total Score (S)	71

Areas with mediocre disposal potential, suitable – level 2, consist of Elgin County, Norfolk County, Haldimand County, Brant County, and parts of Lambton County, Essex county, Kent County, Middlesex County, and Oxford County. Sites in this category typically score less in permeability and porosity criteria. The township of Sarnia, a potential CAES facility, falls under this category

Some areas of the Cambrian strata lack porosity and permeability data, but still show a potential for disposal based on depth, thickness, reservoir lithology and caprock lithology; these areas are termed as ‘potentially suitable’. From Figure 2, these areas include Welland County, Lincoln County, and Wentworth County.

A large part of southwestern Ontario also falls under the ‘unsuitable’ category. The areas in this category include parts of Lambton County, Kent County, Middlesex County, and Oxford County. These areas are not suitable for disposal because they do not meet the thickness criteria. The formation is less than 5 m thick in all of these areas.

6 SUMMARY

Large salt caverns in size range between 100,000 m^3 to 1,000,000 m^3 would be required for grid–scale compressed air energy storage (CAES). Since solution mining 1 m^3 of salt generates 7-8 m^3 of brine, large volumes of brine would need to be disposed. A practical and safe way to dispose brine is through deep well disposal. The formations in southwestern Ontario, especially the Lucas Formation and the Cambrian age strata, contain geological and hydrogeological parameters that are adequate for large volumes of brine disposal.

The aim of this study was to investigate the suitable sites in southwestern Ontario based on geological, geomechanical, and petrophysical parameters. Multi-criteria analysis was utilized to develop an evaluation system that would compare various strategically chosen sites in southwestern Ontario. The main criteria used in the study are permeability, porosity, depth, thickness, reservoir lithology, and caprock lithology. Scoring and weighting for criteria was assigned by consulting with academic and industrial experts.

The evaluation results were divided into 4 categories: Suitable – Level 1, Suitable – Level 2, Potentially Suitable, and Unsuitable. The most suitable areas for disposal into the Lucas Formation are Lambton County and the northwest corner of Kent County. A large part of the Lucas formation in southwestern Ontario is unsuitable due to being too shallow and not meeting the minimum depth criteria of 120 m. The most suitable area for disposal in the Cambrian age strata is Essex County. A major part of southwestern Ontario shows mediocre potential for disposal into the Cambrian age strata; this area consists of Elgin County, Norfolk County, Haldimand County, Brant County, and parts of Lambton County, Essex County, Kent County, Middlesex County, and Oxford County. A large portion of southwestern Ontario is also not suitable for disposal due to receiving bedrock formations being too thin and not meeting the minimum thickness criteria of 5 m.

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