Dykstra or Dijkstra? Tortuosity due to heterogeneity using the shortest path algorithm for evaluating trapping mechanism

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DOI
10.3997/2214-4609.202522084

Publication date
2025

Document Version
Final published version

Citation (APA)
Dos Santos, E., Kreutz Erdtmann, M. J. K., & Lira, F. (2025). *Dykstra or Dijkstra? Tortuosity due to heterogeneity using the shortest path algorithm for evaluating trapping mechanism*. Paper presented at World Carbon Capture, Utilisation and Storage Conference 2025, Bergen, Norway. https://doi.org/10.3997/2214-4609.202522084

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Introduction

Although implementing Carbon Capture and Storage (CCS) projects involves several important steps, site screening stands out as critical. As many efforts in this area are new, establishing where to storage CO2 permanently or to compare between many potential reservoirs are hot topics throughout the industry. This process is challenging. It involves compiling all the reservoir data, analyzing many parameters and modeling the phenomenon with complex numerical simulations, all of which aim to estimate better targets for CO2 permanent storage. Normally there are fewer reservoir data acquired in saline aquifers than in depleted hydrocarbon reservoirs because of the lower commercial interest in the former, with that, surveying CO2 trapping sites in water-bearing reservoirs tends to be even harder. Also, as this reservoir models easily surpass 10 million cells due to their huge areas, the computation cost in surveying best positions for injection may be computationally intensive.

In contrast to oil production, where well placement is strongly controlled by the reservoir structure, permeability and porosity quality and fluid saturation, when dealing with CCS in saline aquifers these controls are not that tight. The objective is to guarantee the injection rate demanded and that the CO2 plume does not reach the surface. As discussed by (Bump, A. P. et al. 2023) the plume navigates in paths formed by heterogenous composite seals, so this property has important role in site screening in Carbon Capture projects.

The proposition of (Dykstra H., Parsons, R. 1950) is a classical approach to quantify and qualify heterogeneity in different geological contexts and it is natural that this approach is being used as a tool to characterize CCS reservoirs. However, as this work demonstrates, reservoirs with the same Dykstra-Parsons index can exhibit entirely different CO2 plume migration behaviors due to the spatial organization of heterogeneities. This brings out the importance Tortuosity — defined as the complexity of flow paths in heterogeneous media — in evaluating the CCS potential of saline aquifers. And here, a parallel classical approach, Dijkstra's algorithm (Dijkstra, E.W. 1959) could be of hand.

Dijkstra's algorithm is well known in computer science; it is designed to solve the Shortest Path Problem (SPP) in which one needs to find the fastest or least costly path between two points within a network. This kind of algorithm has wide use in different fields such as transportation systems (Benjamin Zhan, F. 1998), transmission networks (Abderrahim, M. 2019) and robot path planning (Luo, M. 2020). As shown by (Madalimov, M. 2023), the Dijkstra algorithm can map graph networks with 60 million vertices within just a few minutes.

This interdisciplinary approach uses the Dijkstra algorithm to map the shortest path from an injection point to the reservoir top, enabling the quantification of tortuosity. This provides a clearer understanding of how heterogeneity impacts CO2 plume migration and offers a computationally efficient tool for CCS site screening.

While Dykstra-Parsons characterization includes an statistical view of reservoir permeability, it lacks spatial context. Other heterogeneity characterization methods, such as the Lorenz Coefficient (Schmalz, J. P. 1950) and its dynamic generalization (Shook et al., 2009), incorporate some spatial factors but are still limited. The Dijkstra proposition presented is an alternative to include localized information effectively with good performance, while evaluating the easiest path for the plume to migrate.

Method and/or Theory

The methodology presented in this conceptual work integrates classical reservoir characterization tools with computational algorithms to address the challenges of CO2 plume migration in saline aquifers. The primary objective is to develop a fast and reliable approach for understanding and quantifying the impact of reservoir heterogeneity on CO2 plume behavior, aiding decision-making in CCS site screening.

The reservoir was represented as a 2D grid, where each cell contains permeability data. This grid serves as the foundation for evaluating heterogeneity and tortuosity and their impacts on flow pathways.

The Dykstra-Parsons index, V (Equation 1), is used to quantify the variability in permeability. Values near 0 indicate homogeneous reservoirs, while values near 1 indicate highly heterogeneous formations. For the two presented grids in this work (Figure 1), V value is the same. Although useful for comparing reservoirs, the Dykstra-Parsons index does not capture the spatial organization of permeability contrasts. This happens because the number of cells with low and high permeability the same between the two of them.

$$V = \frac{stdev(Log(k))}{avg(Log(k))} = \frac{Log(k)_{P50} - Log(k)_{P84.1}}{Log(k)_{P50}} \quad \text{(eq. 1)}$$

Tortuosity, defined as the complexity of the flow path through a heterogeneous medium, shows up as an important factor in understanding CO2 plume migration. Directed tortuosity refers specifically to the flow from the injection point toward the reservoir top. This concept captures the influence of both the heterogeneity and the spatial arrangement of permeability barriers and pathways.

To quantify the tortuosity, the Dijsktra algorithm was employed. This graph-based computational algorithm was implemented in Python aiming to map the shortest path from the injection point to the reservoir top, considering the permeability contrasts within the grid. To keep the algorithm fast and suitable for site screening we chose to only consider static properties. By treating the reservoir grid as a network of nodes (grid cells) and weighted edges (permeability relationships), the algorithm identifies the least resistive path to flow. This shortest path corresponds to the most direct migration route for the CO2 plume, allowing for the characterization of tortuosity in a straight-forward manner.

It was needed to transform the reservoir grid into a graph structure before applying the Dijkstra algorithm (Figure 2). Each cell in the grid is treated as a node, and the edges connecting nodes represent permeability relationships between adjacent cells. The equivalent permeability in horizontal direction is the arithmetic mean between adjacent cells, in vertical direction the harmonic mean. Weights are assigned to these edges based on these equivalent permeability values, with lower permeability contributing to higher weights (resistance to flow in mD^{-1}), representing greater resistance to flow. This graph representation enables the application of graph theory algorithms to efficiently analyze the reservoir's heterogeneity and flow pathways.

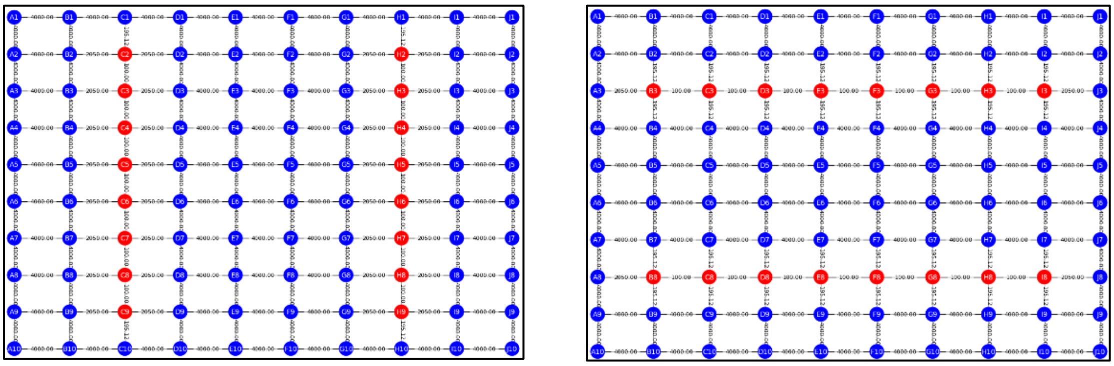

Figure 1 – Two graphs A and B with nodes representing grid cells and edges representing the mean permeability between cells. The blue nodes represent cells with 4000mD the red nodes represent cells with 100mD. Both grids have the same Dykstra-Parsons index (V = 0.5), but their heterogeneity is organized differently.

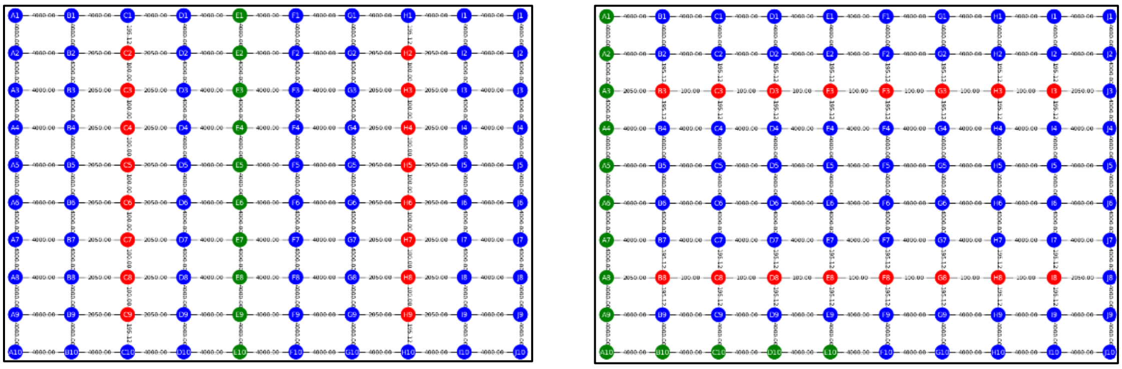

Figure 2. Minimum paths calculated using the Dijkstra algorithm for grids A and B. Green nodes represent the shortest path from the central bottom cell to the reservoir top.

Conclusions

Although Dykstra-Parsons have been widely used in reservoir engineering since 1950s, alternative approaches to heterogeneity characterization may yield better insights for CCS projects. While grids with vertical and horizontal barriers may share the same Dykstra-Parsons index, the spatial organization of heterogeneous blocks has a significant impact on CO2 plume migration paths.

The Dijkstra algorithm proves to be a powerful tool for mapping tortuosity as a trapping mechanism for CO2. It offers a computationally efficient alternative to traditional numerical simulations, helping to identify reservoir areas with longer travel times from the bottom to the top. The information provided supports well placement and reservoir comparison by allowing fast and effective mapping of the shortest path from any potential injection point to the reservoir top.

Acknowledgements

The authors would like to express their gratitude to Petrobras for providing the necessary resources to conduct this study. We further acknowledge the technical, theoretical, and academic support provided by the Federal University of Espírito Santo (UFES). Special thanks are extended to Filipe Lira, Thomas Rauber and Marcos Machado for their mentorship throughout the development of this work.

References

Alexander P. Bump, et al. [2023]. Composite confining systems: Rethinking geologic seals for permanent CO2 sequestration. *International Journal of Greenhouse Gas Control, Volume 126.*

Dykstra, H., Parsons, R. [1950]. The Prediction of Oil Recovery by Water Flood. *Secondary Recovery of Oil in the United States, 2nd ed.* American Petroleum Institute, 1950

Dijkstra, E.W. [1959]. A Note on Two Problems in Connection with Graphs. *Numerische Mathematik,* vol.1, pp. 269–271.

F. Benjamin Zhan, Charles E. Noon. [1998]. Shortest Path Algorithms: An Evaluation Using Real Road Networks. *Transportation Science 32(1):65-73.*

M. Abderrahim, H. Hakim, H. Boujemaa and F. Touati. [2019]. Energy-Efficient Transmission Technique based on Dijkstra Algorithm for decreasing energy consumption in WSNs. *19th*

International Conference on Sciences and Techniques of Automatic Control and Computer Engineering (STA), 599-604. Sousse, Tunisia,pp.

M. Luo, X. Hou and J. Yang. [2020]. Surface Optimal Path Planning Using an Extended Dijkstra Algorithm. *IEEE Access, vol. 8.*

Madalimov, Medet, Li, Dachang, Saifutdinov, Raif, and Yernaz Satybaldiyev. [2023]. A Method of Reservoir Connectivity Analysis for Single- and Dual-Porosity/Dual-Permeability Models. *Paper presented at the SPE Annual Technical Conference and Exhibition.* San Antonio, Texas, USA.

Schmalz, J. P. and Rahme, H. D. [1950]. The Variation of Waterflood Performance With Variation in Permeability Profile. *Producer Monthly 15 (9):9–12.*

Shook, G. Michael, and Kameron M. Mitchell. [2009]. A Robust Measure of Heterogeneity for Ranking Earth Models: The F-PHI Curve and Dynamic Lorenz Coefficient. *Paper presented at the SPE Annual Technical Conference and Exhibition*. New Orleans, Louisiana.