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4D numerical modelling to predict facies heterogeneity and brine migration pathways for CCS risk assessment around legacy wells in the UK North Sea

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Project context and objectives

Carbon Capture and Storage (CCS) is a key component of the UK's net-zero strategy, and the UK North Sea offers substantial storage potential in depleted hydrocarbon fields and deep saline aquifers (Agada et al., 2017; Karvounis and Blunt, 2021; Worden, 2024). Although these subsurface settings are attractive because of their scale and existing geological knowledge base, they also contain numerous legacy oil and gas wells that may compromise long-term containment if they intersect connected fluid-migration pathways in a CCS reservoir. A key challenge in CCS risk assessment is to determine how injected CO_2 and pressure-driven brine migration may interact with pre-existing well infrastructure (Lackey et al., 2026; Smith et al., 2025). This challenge is amplified by the fact that conventional geological models used in screening and in permitting commonly rely on seismic interpretation and sparse well control, and therefore do not adequately resolve sub-seismic stratigraphic heterogeneity, such as thin baffling units, discontinuous sealing facies, or high-permeability thief zones. These smaller-scale geological features can strongly influence connectivity, pressure transmission and migration behaviour, and may therefore control whether a legacy well is effectively isolated, else is positioned within a potentially transmissive pathway (Issautier et al., 2014; Sohal et al., 2021).

The broader scientific and applied context for this project is the growing need for subsurface models that move beyond static description and explicitly represent the geometry, facies distribution, topology and flow significance of heterogeneous sedimentary successions relevant to CCS. This project is based on Permo-Triassic fluvial and aeolian reservoirs and seals, with the aim of improving prediction of CO_2 plume behaviour, storage performance and leakage risk. The project employs the Dune Architecture and Sediment Heterogeneity (DASH; Yan et al., 2024) model to generate 3D representations of aeolian dune sedimentary architectures, reflecting the recognition that sub-seismic facies

heterogeneity and connectivity, rather than bulk reservoir properties, are the primary controls on fluid migration behaviour and legacy well risk.

The aim of the project is to develop and demonstrate a workflow that couples 3D forward stratigraphic modelling with brine-migration pathway analysis to inform legacy-well risk assessment in representative UK North Sea CCS settings, positioning the work between geological characterisation and applied decision support with emphasis on reusable workflows and metrics, rather than a single site-specific interpretation. Specifically, the objectives are as follows:

(i) to parameterise forward stratigraphic models for UK North Sea-relevant reservoir and seal successions using subsurface, analogue and database constraints, ensuring that modelled facies architectures are representative of CCS target intervals;

(ii) to generate ensembles of 3D stratigraphic realisations that capture plausible ranges of facies heterogeneity at reservoir and caprock scales, recognising that uncertainty in depositional architecture is a key control on uncertainty in migration pathways and well risk;

(iii) to derive facies-based connectivity metrics and brine-pathway descriptors, thereby translating static architectures into measures of likely brine movement;

(iv) to integrate these geological metrics with legacy-well data to produce practical risk indicators that indirectly inform screening, monitoring priorities, remediation targeting and permitting decisions in CCS developments.

Methodology

This project employed a multi-stage numerical workflow that couples forward stratigraphic modelling with facies connectivity analysis and brine-migration pathway characterisation to derive stratigraphy-aware risk indicators for legacy wells in UK North Sea CCS settings. The workflow integrates (i) subsurface and analogue geological constraints, (ii) forward stratigraphic models of fluvial and aeolian successions, (iii) derivation of facies-based connectivity and pathway metrics, and (iv) integration of these metrics with legacy-well information in a form suitable for decision support. The methods are designed to generate ensembles of geologically plausible 3D facies architectures at reservoir and caprock scales, to quantify how sub-seismic heterogeneity influences potential brine pathways, and to represent this information in formats directly compatible with industry-standard reservoir and flow modelling tools.

Forward stratigraphic modelling

The Dune Architecture and Sediment Heterogeneity model (DASH; Yan et al., 2024) is a 3D forward stratigraphic model developed to reproduce the complex sedimentary architectures and internal facies distributions produced by migrating dune bedforms of a wide range of morphologies. DASH uses a geometric, rule-based modelling approach, built upon the deterministic bedform framework of Rubin (1987) and Rubin and Carter (2006), and is coded in MATLAB. The algorithm models bedform morphology using modified sine curves whose displacement over successive time steps mimics the migration and aggradation of naturally occurring sedimentary bedform (i.e. dune) types, accumulated deposits of which make up many clastic reservoirs being considered for CCS. Aspects of bedform (dune) morphology and migratory behaviour that are modelled include planform morphology, crestline sinuosity, dune height, steepness and asymmetry, each of which can be varied independently or as functions of time, thereby enabling simulation of transverse, longitudinal, and compound superimposed dunes. Internal facies distributions within modelled dune and interdune architectural elements are assigned through a series of rule sets based on two principal physiographic variables — the true dip of preserved strata and position along the depositional profile of the dune — which together control the three-dimensional extent of six default facies domains, ranging from interdune-flat deposits through lower and upper dune plinth, lower and middle foreset, to the crest-brink and upper foreset region. Model inputs, including facies-domain thresholds, proportions and petrophysical properties, can be constrained using quantified sedimentological data from modern and ancient analogue aeolian systems held in the Database of Aeolian Sedimentary Architecture (DASA) (Cosgrove et al., 2021), ensuring that modelled architectures are empirically grounded in natural observations. Vector outputs from DASH models can be exported as fully 3D Cartesian geocellular grids in ASCII or GSLIB format, suitable for subsequent stochastic petrophysical modelling using Sequential Gaussian Simulation (Yan et al., 2024), use as training images for multiple-point geostatistical approaches (Montero et al., 2021; Montero et al., 2024), and flow-based upscaling, making them a practical and computationally efficient tool for characterising facies heterogeneity and fluid-migration pathways in fluvial and aeolian reservoir and seal successions relevant to CCS settings.

Connectivity and brine-migration pathways

In this project, forward stratigraphic modelling is used to generate 3D grids showing the distribution of facies in the reservoir and caprock (Fig. 1). These grids are then simplified into binary maps, in which relatively permeable facies representative of effective net reservoir are coded as 1, and all other facies as 0, so that connectivity can be analysed

directly. The analysis identifies groups of neighbouring permeable cells that form connected clusters, and for each cluster calculates its size, extent, shape complexity and whether it spans across the model vertically or laterally. Connectivity functions are also calculated to show how the likelihood of connection changes with distance and direction, which helps to identify anisotropy in potential flow pathways. Legacy well locations are then overlain on the labelled cluster grids to determine whether a well intersects a connected permeable body and whether that body forms a vertically continuous route between the reservoir and the overlying seal. In addition, clusters that contain the largest geobody and extents are interpreted as potential brine-migration pathways, and these are visualised in 3D to support geological screening of legacy-well risk.



Fig. 1. Workflow illustrating the modelling and analysis steps used to evaluate connectivity and brine-migration pathways. Forward stratigraphic modelling with DASH generates 3D facies grids for reservoir and caprock, which

are converted to binary permeability maps and analysed to identify connected permeable clusters, their size, extent, shape and vertical/lateral continuity. Connectivity functions quantify how the likelihood of connection varies with distance and direction, while legacy wells are overlain on the labelled clusters to assess caprock–reservoir linkage and potential vertically continuous routes. Major clusters and candidate brine-migration pathways are then visualised in 3D to support geological screening and risk assessment for legacy wells.

Idealised examples

To demonstrate how sedimentary architecture and facies heterogeneity influence connectivity and generate varied brine-migration pathways, we use a common set of model parameters (dune migration rate, dune height, and aggradation rate) but systematically vary dune morphology. In all scenarios, dune height is 30 m, dune migration rate is 0.5 m/yr, and the aggradation rate is 10 mm/yr. These are representative of values that are recorded from dunes developed in modern natural dune systems. This allows us to isolate the impact of dune morphology on facies heterogeneity, connectivity, and resulting brine-migration pathways.

The aeolian bedforms types chosen for modelling are 2D transverse, 3D transverse, longitudinal and superimposed bedforms (*sensu* Rubin, 1987). The 2D transverse dunes show parallel ridges with crests oriented perpendicular to the prevailing wind direction (Figs. 2A & 3A). The 2D transverse dunes produce laterally extensive planar cross-bedded sandstone sets that internally incorporates cross-bedding that itself dips down-wind at high angles (typically up to 26° in compacted sand, and up to 34° in non-compacted sand); sets are bounded by gently inclined interdune migration bounding surfaces that rise (typically no more than a few tenths of a degree) in a down-wind direction. The 3D transverse dunes have a sinuous crest line and a slipface with overall crest orientation perpendicular to the wind direction (Figs. 2B & 3B). Commonly, successive dunes in a migrating train possess crestline sinuosities that are 180° out of phase with each other. In such cases, the migration of these 3D transverse dunes generates trough cross-bedded sandstone with concave-up basal bounding surfaces and variable foreset dip directions. The longitudinal dunes have a long, narrow ridge with a sinuous crest, the overall trend of which is aligned parallel to the resultant sand-transport direction. Such dunes form under conditions of two dominant wind directions that are each oblique to the dune elongation (Figs. 2C & 3C). Perfectly longitudinal dunes preserve cross-bedded sandstone dipping in two dominant directions (Rubin, 1987). Superimposed dunes consist of hierarchically organized bedforms whereby smaller transverse dunes migrate across the surface of larger transverse dunes. Superimposed dunes develop bounding surfaces and cross-strata of different scales with major set-bounding surfaces produced by the migration of the primary dunes and subset-bounding surfaces linked to the smaller riding dunes. For example, Fig. 2D and 3D illustrate

superimposed bedforms in which smaller dunes migrate across the larger, primary dunes in a direction that is perpendicular to the migration direction of the primary bedforms.

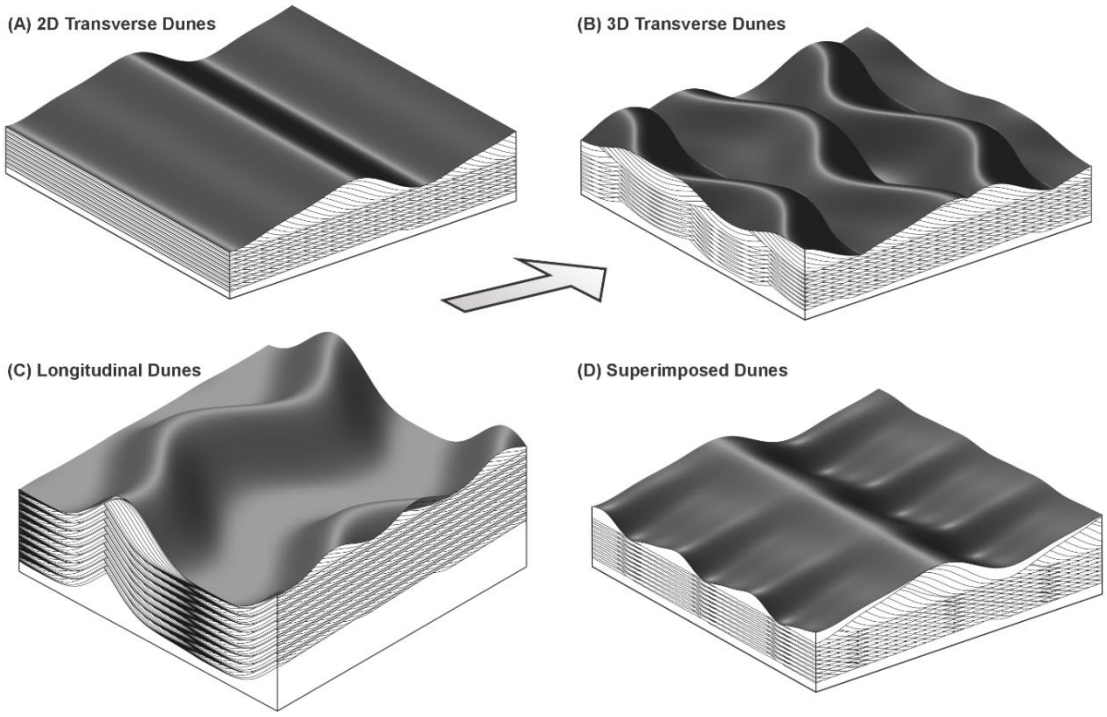


Fig. 2. Modelled examples of dune morphology and stratigraphic architecture generated by DASH with a dune height of 30 m, dune spacing of 220 m, bedform migration rate of 0.5 m/yr and aggradation rate of 10 mm/yr. The arrow shows the primary bedform migration direction. The size of the modelled domain is 330×330 m^2. Example (C) is shown with 2x vertical exaggeration. In example (D), the secondary superimposed bedforms have 1/4 dune height and 1/2 dune spacing of the primary bedforms over which they migrate; they migrate 10 times faster than the primary bedforms and perpendicular (90^o clockwise) to their migration direction.

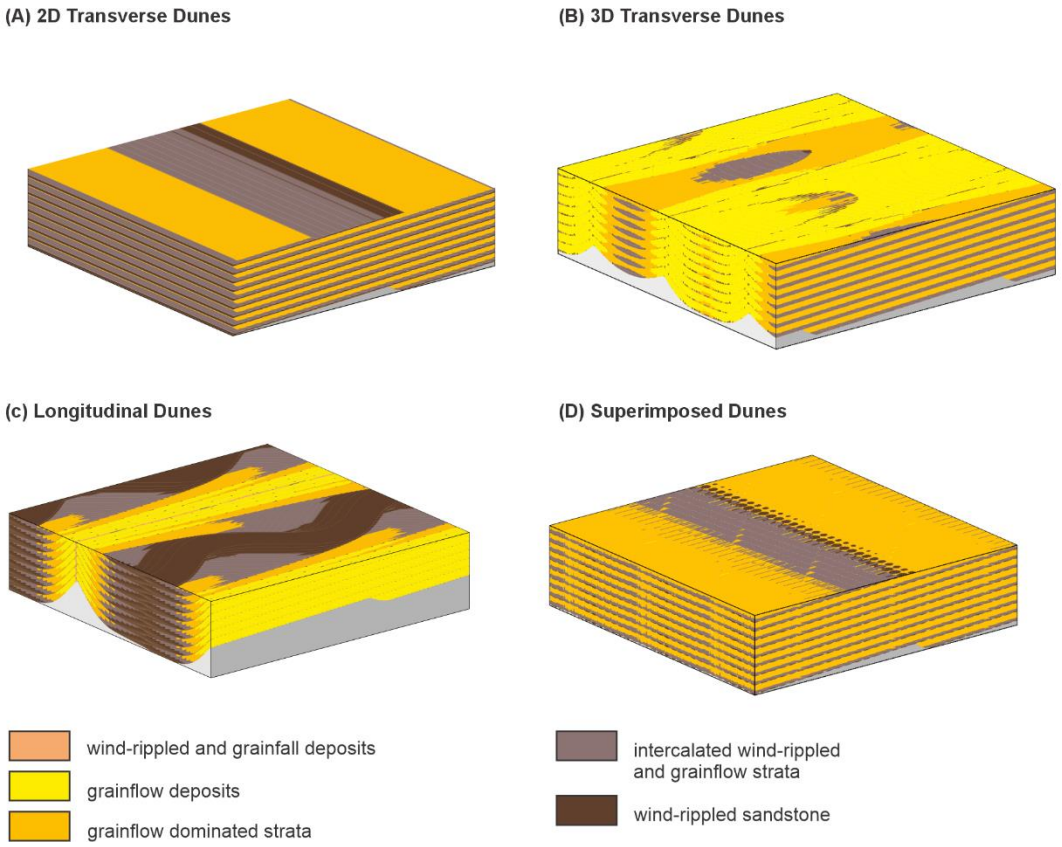


Fig. 3. Modelled examples of dune morphology and stratigraphic architecture generated by DASH with a dune height of 30 m, dune spacing of 220 m, bedform migration rate of 0.5 m/yr and aggradation rate of 10 mm/yr.

In this workflow, 3D facies grids generated with the DASH forward stratigraphic model are first converted to binary permeability maps in which permeable facies (i.e., wind-rippled sandstone, intercalated wind-rippled and grainflow strata and interdune deposits) are coded as 1 and all other facies as 0. Connectivity analysis is then applied to these binary grids to identify groups of neighbouring permeable cells that form connected clusters. The number of connected clusters provides a quantitative measure of how fragmented or continuous the permeable phase is in each simulated scenario: fewer clusters indicate more continuous pathways, implying greater potential for long-range brine or CO_2 migration and an increased probability that a legacy well lies on a connected route, whereas a larger number of clusters reflects stronger compartmentalisation, with shorter, more isolated pathways and reduced large-scale connectivity, even though small local connections can still be important near individual wells (Issautier et al., 2014; Pardo-Igúzquiza and Dowd, 2003; Renard and Allard, 2013; Western et al., 2001). When multiple realisations are available, the number and properties of connected clusters are compared across realisations and scenarios and used as key descriptors of connectivity behaviour and associated risk.

The total number of clusters for each simulation is defined by counting all connected permeable bodies with volumes greater than 10 m³, which excludes very small, isolated cells

that are unlikely to be geologically significant. On this basis, both the 2D transverse-dune and superimposed-dune simulations yield 10 clusters each, whereas the 3D transverse-dune and longitudinal-dune simulations contain only 1 and 2 clusters, respectively, reflecting markedly different degrees of connectivity and compartmentalisation across dune morphologies.

For each simulation, the properties of the largest cluster are summarised in Table 1. The cluster volume provides a direct measure of the size of the connected geobody, indicating how much permeable rock is continuously linked (Larue and Hovadik, 2006; Renard and Allard, 2013; Scarpa et al., 2025). The spatial extent of each cluster is described by its dimensions in the two horizontal directions and in the vertical direction (extent_x, extent_y, and extent_z), measured as the range between the minimum and maximum coordinates of the cluster in each axis, thereby characterising how far the connected body reaches across the model domain. The total external surface area of the cluster is also reported. A morphological tortuosity index is derived as the ratio of surface area to volume, which serves here as a geometric proxy for shape complexity rather than a true flow-based tortuosity, the latter of which would require fluid-flow simulation. A higher tortuosity value, at a given volume, indicates a more geometrically complex and convoluted cluster shape, which can strongly influence the nature of potential flow pathways and the efficiency with which brine or CO_2 might migrate through the connected body (Deutsch, 1998; Mateos et al., 2024; Renard and Allard, 2013). Finally, the centroid of each cluster, defined as the mean x, y, and z coordinates of all cells belonging to it (centroid_x, centroid_y, centroid_z), is reported as a measure of the spatial position of the centre of mass of the connected geobody within the model. Together, these metrics characterise how large, how elongated, how geometrically complex, and where each connected cluster is situated, providing the key descriptors needed to interpret potential brine-migration pathways and to assess the risk posed to nearby legacy wells.

Table 1. The largest cluster analysed based on 3D models generated from DASH.

	Volume (m^3)	Extent_x (m)	Extent_y (m)	Extent_z (m)	Surface area (m^2)	Tortuosity (m^{-1})	Centroid_x (m)	Centroid_y (m)	Centroid_z (m)
2D Transverse	218000	319	320	8.3	221000	1.01	161	160	6.30
3D Transverse	2960000	309	310	39.8	954000	0.32	155	153	17.26
Longitudinal	887000	319	129	37.0	490000	0.55	159	215	15.22
Superimposed	261000	309	310	9.9	229000	0.88	155	155	10.76

The cumulative volume curves reveal marked differences in connectivity structure across the four dune-morphology scenarios (Fig. 4; Deutsch, 1998; Hovadik and Larue, 2010). The 3D transverse-dune case exhibits the highest connectivity, with a single cluster accounting for approximately 78% of the total permeable volume, forming a near-continuous, well-connected body throughout the model. The longitudinal-dune case contains two clusters, with the largest contributing approximately 33% of the total permeable volume, indicating more limited overall connectivity than the 3D transverse-dune case. The 2D transverse-dune and superimposed-dune cases each contain 10 clusters, and both show a gradual cumulative increase with increasing cluster number. The relatively gentle slopes of their cumulative curves indicate that permeable volume is distributed across many clusters, reflecting highly fragmented and compartmentalised connectivity structures. The superimposed-dune curve rises more steeply, suggesting that individual clusters in the superimposed-dune scenario tend to be larger on average. Overall, the results demonstrate that dune morphology exerts a strong control on connectivity: 3D transverse dunes produce the most connected permeable architecture, whereas 2D transverse and superimposed dunes generate highly fragmented systems with many small, isolated clusters, and longitudinal dunes represent an intermediate case with a small number of clusters of moderate volume.

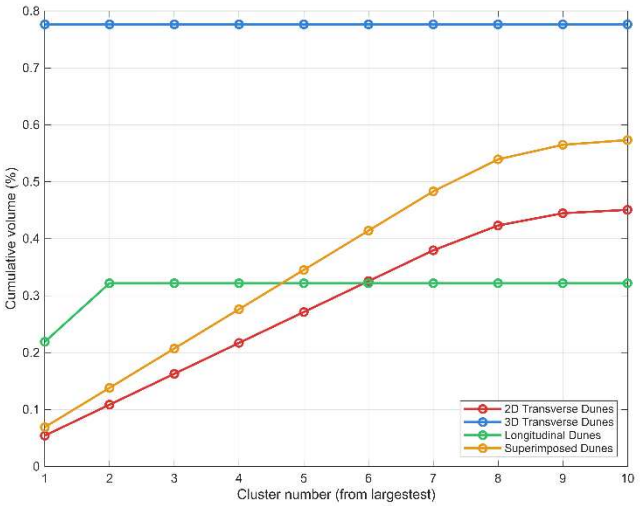


Fig. 4. Cumulative volume is evaluated as cluster number increases from the largest to the smallest cluster, using 3D facies models generated with DASH. The total number of clusters is defined by counting all clusters with volumes greater than 10 m³. In this study, both 2D transverse-dune and superimposed-dune cases contain 10 clusters, whereas the 3D transverse-dune and longitudinal-dune cases contain 1 and 2 clusters, respectively.

The connectivity function, γ(h), is the probability that two points in the same facies, separated by a lag distance h, are connected via a continuous path of permeable cells (Pardo-Igúzquiza and Dowd, 2003). It is calculated separately in different spatial directions

(X, Y, and vertical H), which means it captures not only how far connectivity extends but also whether it is isotropic or anisotropic, a critical property for understanding preferential flow directions. For brine migration and CO_2 storage, the connectivity function directly quantifies the spatial reach of permeable pathways in the reservoir and caprock system (Zhang et al., 2025). A high γ(h) sustained over a long lag distance in the vertical direction (H) indicates that permeable facies remain connected across large vertical intervals, raising the probability that brine or CO_2 can migrate upward through the stratigraphy towards a seal or a legacy well. Anisotropy in the connectivity function, whereby γ(h) declines more slowly in one horizontal direction than another, reveals the dominant orientation of permeable pathways and therefore the most likely direction of large-scale fluid migration. Both the 2D transverse-dune and superimposed-dune cases show a rapid decline in γ(h) at short lag distances in the vertical direction (H) (Fig. 5), indicating strong compartmentalisation and a reduced risk of vertical brine migration. Meanwhile, both cases exhibit greater connectivity along the X and Y directions, with compartmentalisation becoming apparent at mid-range lag distances along the X direction, before connectivity declines to zero. The longitudinal-dune case shows the opposite pattern, with strong compartmentalisation in the Y direction but sustained connectivity along the X direction, reflecting the preferential along-crest orientation of permeable bodies in longitudinal dune systems.

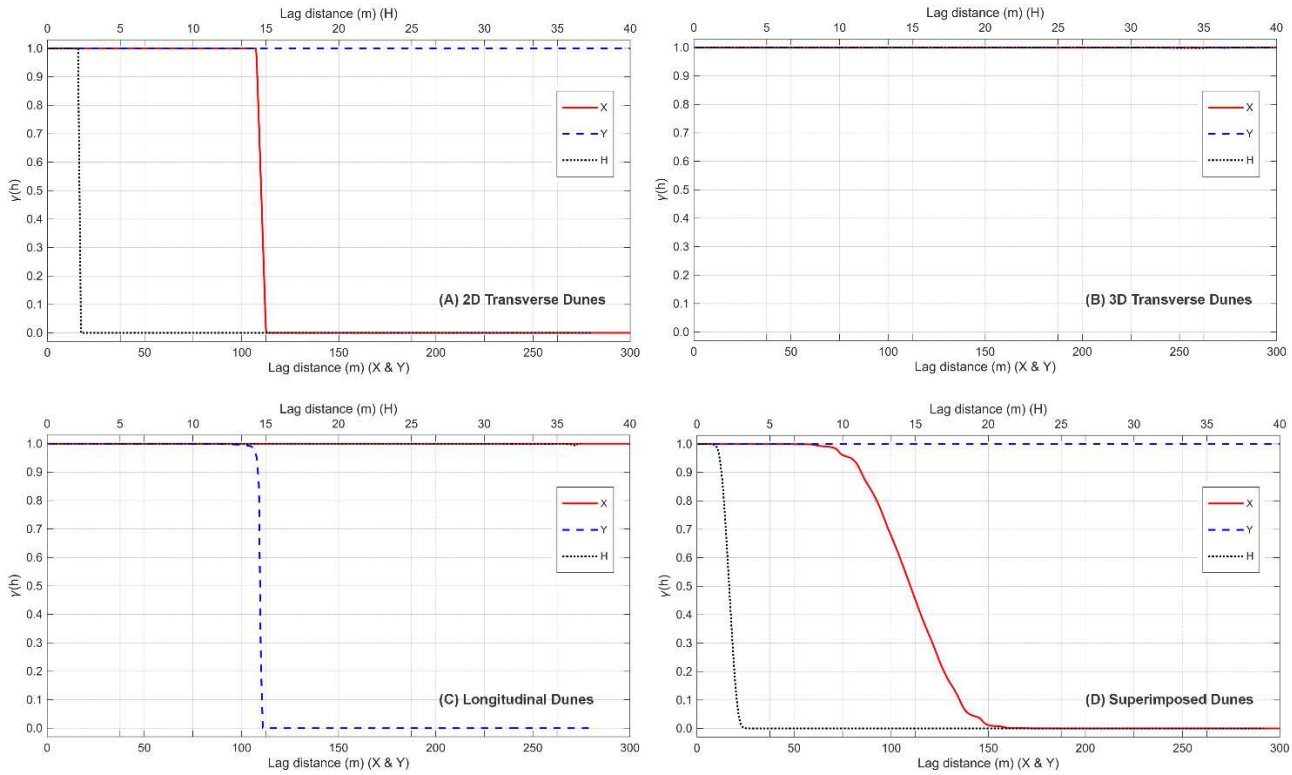


Fig. 5. Connectivity functions along horizontal (X & Y) and vertical directions (H) from 3D models of 2D transverse dunes, 3D transverse dunes, longitudinal dunes and superimposed dunes generated from DASH.

Figure 6 visualises the largest connected permeable cluster in three dimensions for each dune-morphology scenario. This cluster represents the most likely brine migration pathway — the continuous permeable body through which injected CO_2 or displaced brine could potentially move from the reservoir towards the caprock or a legacy well. The geometry, spatial extent, and orientation of each cluster directly reflect the underlying sedimentary architecture generated by each dune morphology. The 3D transverse-dune scenario is the most voluminous and three-dimensionally connected of all four scenarios, occupying a large proportion of the model domain in all three directions. The cluster forms a densely interconnected, irregular body. This highly connected geometry indicates that 3D transverse dunes present the greatest risk for long-range brine migration in all directions, including vertically towards the overlying seal. The 2D transverse-dune and superimposed-dune scenarios form a series of laterally extensive, sub-horizontal, sheet-like bodies that are broadly continuous in the horizontal directions but thinly stacked with limited vertical connectivity. In addition, the superimposed-dune scenario exhibits a dense and complex internal geometry, reflecting the heterogeneous facies arrangement produced by superimposed dune migration. Brine migration in both scenarios would therefore be predominantly lateral, with limited potential for upward migration through the stratigraphy. The longitudinal-dune scenario has substantial vertical extent and is laterally continuous in the X direction. This geometry is consistent with the elongated dune morphology and suggests that brine migration would be preferentially channelled along the dune trend, with greater potential for vertical migration.

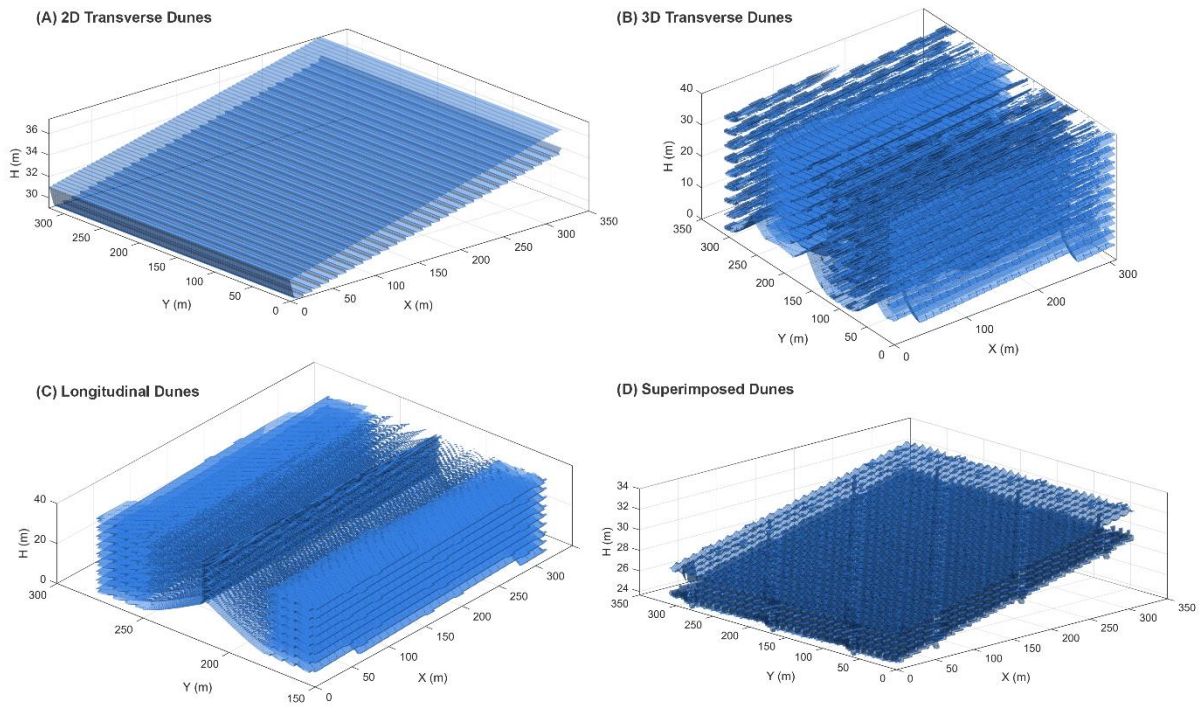


Fig. 6. Three-dimensional visualisation of the largest connected permeable cluster, representing the most likely brine migration pathway, for each of the four modelled dune-morphology scenarios: (A) 2D transverse dunes, (B) 3D transverse dunes, (C) longitudinal dunes, and (D) superimposed dunes. Connected permeable cells are shown in blue. The geometry and spatial extent of each cluster reflect the contrasting sedimentary architectures produced by different dune morphologies, with implications for the potential reach and directionality of brine migration pathways.

In this workflow, 20 well locations and depths are randomly sampled within the model domain to represent potential legacy wells and to assess CO_2 and brine migration risk. For each simulation, it is first determined whether a well lies in a non-permeable region or intersects a connected permeable cluster; for intersecting wells, the properties of the associated cluster (volume, 3D extent and morphological tortuosity) are used to quantify the scale and complexity of the pathway and therefore the likelihood of brine migration from the reservoir towards the seal. The same connectivity framework can be applied to source–target analysis: given specified source and target locations, we can determine whether they belong to the same cluster or to connected clusters, and use this information to evaluate the probability of source-to-target brine migration, where sources represent injection or pressure build-up zones and targets represent sensitive locations such as the top seal, shallow aquifers, or legacy wells. Figure 7 shows how the same set of 20 vertical well locations interact with connected permeable clusters in each dune-morphology scenario, and how the volume of the intersected clusters varies between cases. In the 3D transverse-dune scenario, most wells (15/20) intersect a connected permeable cluster, and all of these are linked to a single large, well-connected body rather than to clusters of varying size, indicating

a high proportion of wells lying on potential long-range brine-migration pathways. By contrast, in the 2D transverse-dune and superimposed-dune scenarios, a substantial subset of wells (9/20 and 8/20, respectively) are plotted as red crosses, showing that they do not intersect any connected cluster and are therefore not directly linked to a continuous permeable pathway; wells that do intersect clusters in these scenarios tend to be associated with smaller cluster-volume percentages than in the longitudinal-dune case, reflecting a more fragmented, compartmentalised connectivity structure. Although the longitudinal-dune case has the largest proportion of wells (12/20) that do not intersect any permeable cluster, those wells that do intersect permeable pathways may be connected to particularly voluminous and laterally extensive geobodies, reinforcing the potential for significant brine migration along the dune trend.

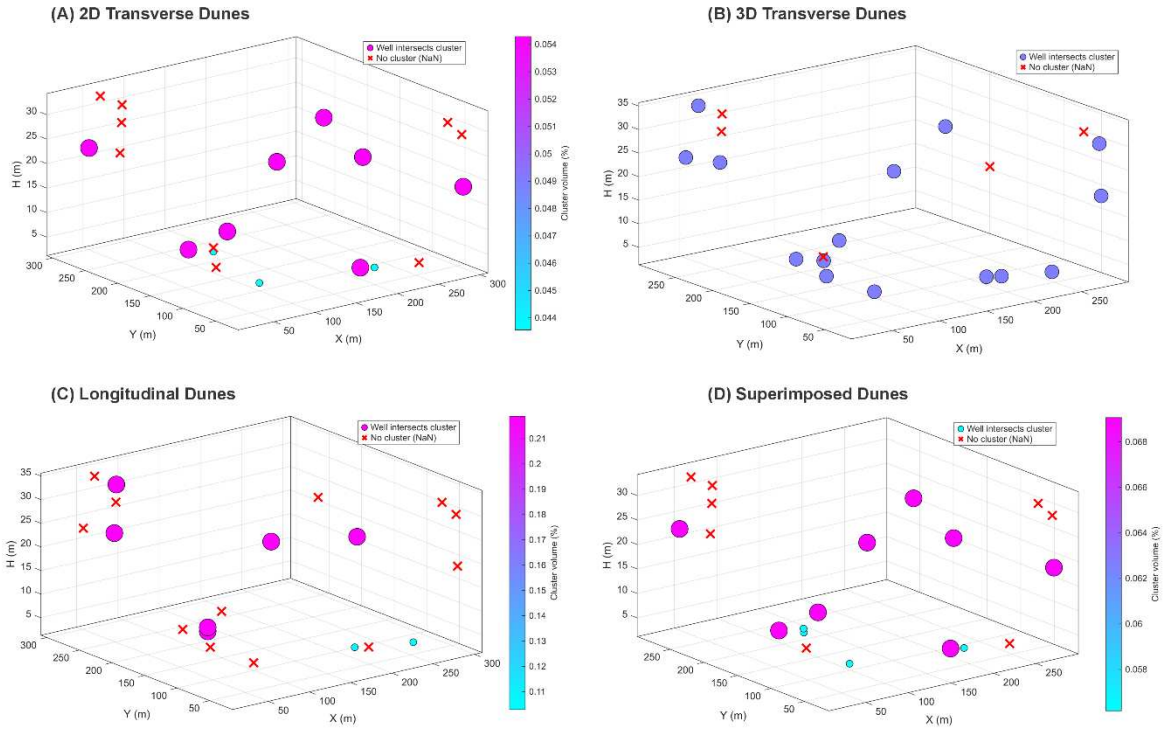


Fig. 7. Three-dimensional distribution of 20 randomly sampled vertical legacy well locations overlain on the connected permeable cluster analysis for each of the four modelled dune-morphology scenarios. All 20 well locations are identical across all scenarios. Filled circles indicate wells that intersect a connected permeable cluster, with circle size and colour representing the volume of the intersected cluster as a percentage of the total permeable volume; larger and warmer-coloured circles indicate wells associated with larger connected bodies. Red crosses indicate wells that do not intersect any connected cluster. The results illustrate how dune morphology controls the proportion of legacy wells that are at risk of lying on a connected brine-migration pathway.

Triassic Helsby Sandstone Formation, Cheshire Basin

Following the four idealised dune-morphology simulations described above, the same modelling and connectivity-analysis workflow is applied to a real-world case study: the aeolian-dominated interval of the Triassic Helsby Sandstone Formation, Cheshire Basin, UK. The Triassic Sherwood Sandstone Group, of which the Helsby Sandstone Formation forms the uppermost unit, represents one of the UK's most strategically important geological successions for CCS (e.g., Cosgrove et al., 2025; English et al., 2024). The aeolian component of the Helsby Sandstone Formation records the deposits of transverse and oblique dunes with sinuous, out-of-phase crestlines and superimposed bedforms, interbedded with damp and wet interdune deposits (Cosgrove et al., 2023; Mountney and Thompson, 2002), producing complex facies heterogeneities that are likely to exert a strong control on fluid connectivity and brine-migration pathways. Here, DASH is applied to reconstruct the three-dimensional sedimentary architecture and facies distribution of the Helsby Sandstone Formation, using the same input parameters as Mountney and Thompson (2002), constrained by outcrop data collected from Frodsham and Helsby Hill and supplemented by DASA database (Cosgrove et al., 2021; Yan et al., 2024). The resulting geocellular model is then processed through the binary permeability mapping and connectivity analysis framework described above, to evaluate connected cluster properties, well–cluster intersections and brine-migration risk for this geologically constrained, real-world reservoir analogue.

Two DASH model scenarios were generated to account for differences in dune size and the resulting complexity of facies distributions (Fig. 8). In both scenarios, secondary bedforms migrate obliquely to the primary transverse dune migration direction, producing sinuous, out-of-phase crestlines; dune toesets are restricted to the very bases of trough cross-strata, and interdune depressions are spatially isolated in planform. Compared with Scenario 1, Scenario 2 comprises smaller dunes and produces a more topographically complex surface characterised by closely spaced troughs and scour-pit geometries, resulting in a greater proportion of preserved interdune deposits and a more spatially heterogeneous distribution of facies domains.

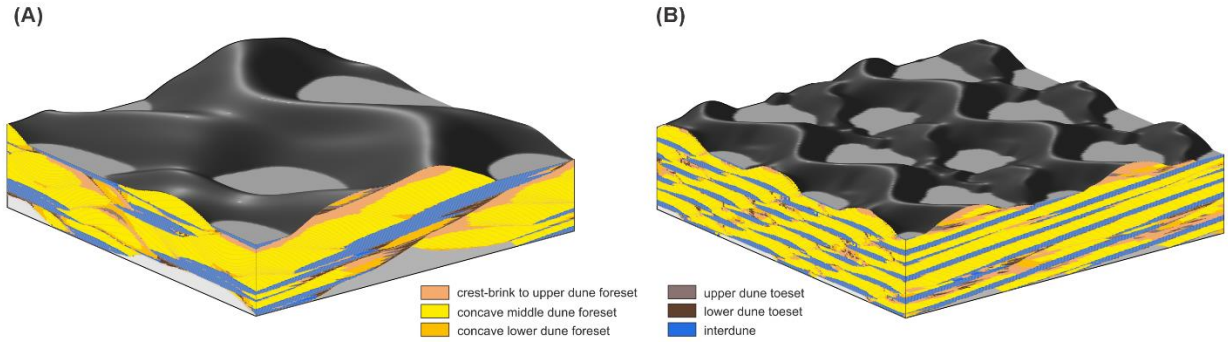


Fig. 8. The 3D geomorphological surface and sedimentary architecture of two modelled scenarios constrained by data from the Triassic Helsby Sandstone Formation, Cheshire Basin, UK, generated using the DASH model. (A) Scenario 1, showing primary transverse to oblique bedforms with sinuous, out-of-phase crestlines; interdune areas form spatially isolated depressions in planform. (B) Scenario 2, showing out-of-phase superimposed bedforms migrating obliquely over the parent forms, producing a more complex topographic surface with closely spaced troughs.

Table 2 presents the properties of the two largest clusters for both scenarios, and Fig. 9 shows cumulative volume as a function of cluster number. Scenario 1 has a single dominant geobody with a volume of 7,464 m³, accounting for approximately 40% of the total model volume, extending across the full model extent in both horizontal and vertical directions, with a moderately tortuous connected pathway. Scenario 2 has two large geobodies, accounting for approximately 24% and 5% of the total volume respectively, indicating that a greater proportion of reservoir volume is partitioned into subsidiary, moderately connected clusters compared with Scenario 1. Relative to Scenario 1, both clusters in Scenario 2 exhibit considerably higher tortuosity (8.72 m^{-1} and 8.36 m^{-1} respectively), reflecting the more geometrically complex and heterogeneous facies architecture associated with this scenario.

Table 2. Properties of the two largest connected clusters identified from the DASH-modelled 3D geocellular models of the aeolian-dominated part of Triassic Helsby Sandstone Formation, Cheshire Basin, UK.

	Volume (m^3)	Extent_x (m)	Extent_y (m)	Extent_z (m)	Surface area (m^2)	Tortuosity (m^{-1})	Centroid_x (m)	Centroid_y (m)	Centroid_z (m)
Senario 1	7464	79.5	80	2.90	26098	3.50	41.30	39.85	1.20
	75	36.6	29	1.18	956	12.82	12.63	54.78	2.28
Senario 2	4938	79.5	80	3.10	43065	8.72	37.08	40.04	1.27
	1097	65.1	80	1.38	9169	8.36	49.85	40.85	2.57

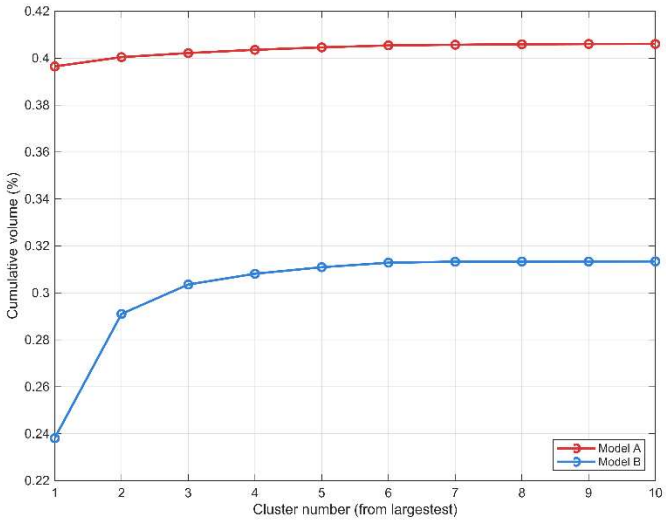


Fig. 9. Cumulative volume as a function of cluster number (ranked from largest to smallest) for the two modelled scenarios of the aeolian-dominated part of Triassic Helsby Sandstone Formation, derived from DASH-generated 3D geocellular models.

Connectivity functions were computed in the X, Y, and vertical (H) directions for the largest connected cluster in each scenario to characterise the spatial continuity of high-permeability facies (Fig. 10). In Scenario 1 (Fig. 10A), all three directional connectivity functions remain at consistently high values across the full range of lag distances, indicating strong, near-isotropic spatial connectivity consistent with a largely homogeneous, well-connected reservoir geobody with high lateral and vertical continuity. In contrast, Scenario 2 (Fig. 10B) shows a significant reduction in X and vertical connectivity, whilst the Y-direction function remains high across lag distances, suggesting that the greatest degree of spatial connectivity is preserved in the Y direction, broadly parallel to the primary dune crestline orientation. This is further demonstrated by the three-dimensional visualisation of the largest connected permeable cluster and brine migration pathway shown in Fig. 11. These results are consistent with the greater facies heterogeneity, higher tortuosity, and more compartmentalised cluster geometry identified in Scenario 2, together indicating that the smaller, more complex dune architecture of this scenario introduces substantially greater resistance to fluid migration in both the vertical and X directions.

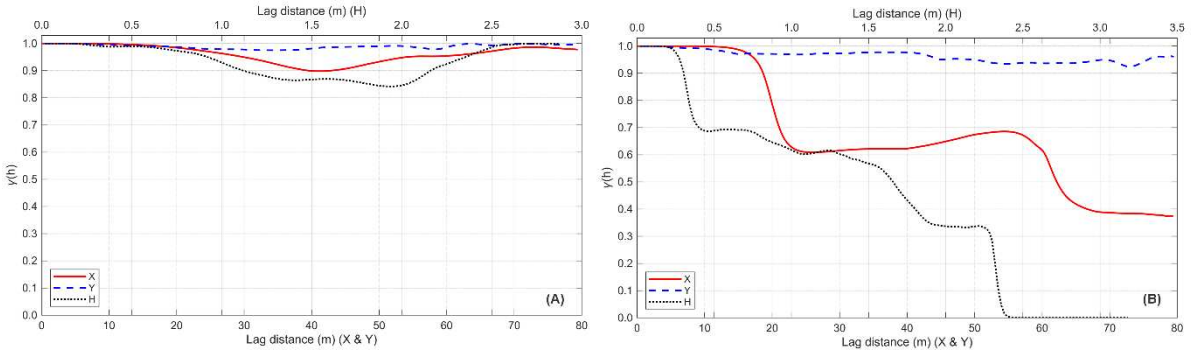


Fig. 10. Connectivity functions along horizontal (X & Y) and vertical directions (H) for the two modelled scenarios of the aeolian-dominated part of Triassic Helsby Sandstone Formation, derived from DASH-generated 3D geocellular models.

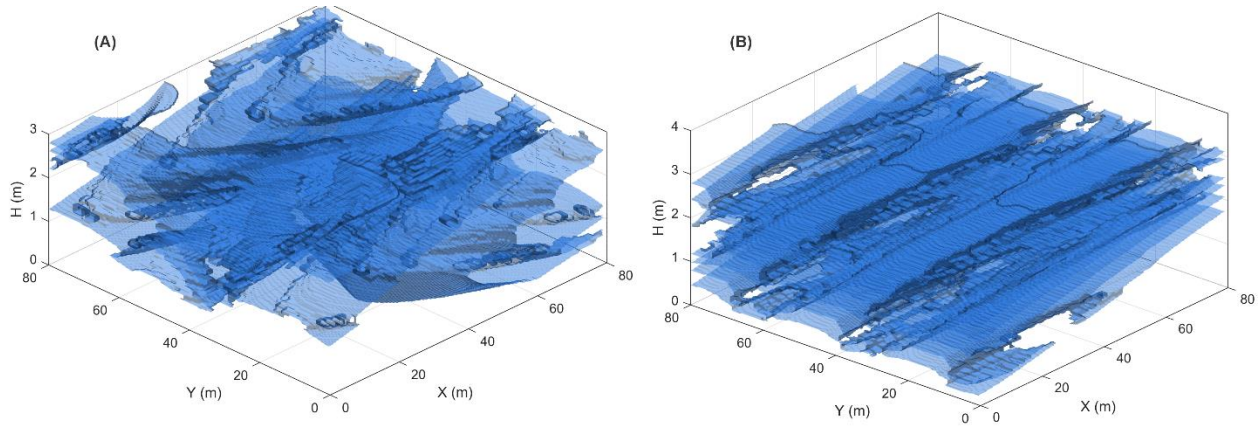


Fig. 11. Three-dimensional visualisation of the largest connected permeable cluster, representing the most likely brine migration pathway, for two modelled scenarios of the aeolian-dominated part of Triassic Helsby Sandstone Formation, derived from DASH-generated 3D geocellular models.

Due to a lack of subsurface well data, 20 well locations were randomly sampled to compare connectivity and brine migration pathways for the two modelled scenarios (Fig. 12). In Scenario 1, 9 out of 20 wells intersect a single connected permeable cluster, whereas in Scenario 2 only 5 out of 20 wells intersect connected permeable clusters, which are distributed across two geobodies of contrasting sizes. This reduced intersection frequency, combined with the greater number of smaller, more compartmentalised geobodies in Scenario 2, results in more heterogeneous and spatially discontinuous CO_2 brine migration pathways relative to Scenario 1.

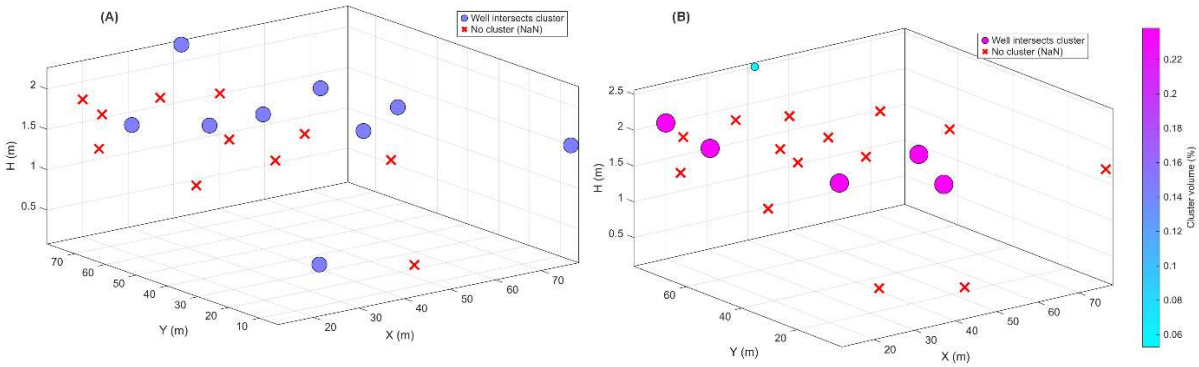


Fig. 12. Three-dimensional distribution of 20 randomly sampled vertical legacy well locations overlain on the connected permeable cluster analysis for two modelled scenarios of the aeolian-dominated part of Triassic Helsby Sandstone Formation, derived from DASH-generated 3D geocellular models. All 20 well locations are identical across both scenarios. Filled circles indicate wells that intersect a connected permeable cluster, with circle size and colour representing the volume of the intersected cluster as a percentage of the total permeable volume; larger and warmer-coloured circles indicate wells associated with larger connected bodies. Red crosses indicate wells that do not intersect any connected cluster.

Discussion

This project set out to develop and demonstrate a reproducible workflow coupling 3D forward stratigraphic modelling with brine migration pathway analysis to improve legacy well risk assessment in UK North Sea CCS settings. It demonstrates that forward stratigraphic modelling can be effectively parameterised using subsurface, outcrop, and database constraints — specifically the Database of Aeolian Sedimentary Architecture (DASA; Cosgrove et al., 2021) for aeolian systems and the Fluvial Architecture Knowledge Store (FAKTS; Colombera et al., 2013) for fluvial systems — ensuring that modelled facies architectures are geologically representative of targeted reservoir and seal successions. Ensembles of 3D stratigraphic realisations were generated across four idealised aeolian dune morphologies and two geologically constrained scenarios based on the Triassic Helsby Sandstone Formation, capturing a plausible range of facies heterogeneity at reservoir scale. Furthermore, facies-based connectivity metrics and brine pathway descriptors including connected cluster volume, spatial extent, morphological tortuosity, and directional connectivity functions analysis were derived and used to translate static sedimentary architectures into practical measures of fluid migration potential. These metrics were integrated with randomly sampled legacy well locations to produce direct risk indicators in the form of well cluster intersection probabilities and pathway characterisation, demonstrating how the workflow can inform screening and monitoring priorities.

This study demonstrates that sedimentary architecture, specifically dune morphology, exerts a first-order control on reservoir connectivity and brine migration pathways. The

idealised examples demonstrate a wide spectrum of connectivity behaviour: 3D transverse dunes generate a single, near-continuous permeable body and posing the greatest risk for long-range brine migration in all directions, whereas 2D transverse and superimposed dunes produce highly fragmented, compartmentalised systems with limited vertical connectivity. Longitudinal dunes represent an intermediate case, with strong anisotropy, showing high connectivity along the dune trend but compartmentalisation perpendicular to it, illustrating how the orientation of permeable pathways is as important as their overall connectivity for assessing directional migration risk. The real-world case study of the Triassic Helsby Sandstone Formation of the Sherwood Sandstone Group reinforces these findings: the two modelled scenarios, differing in dune size, yield markedly different cluster geometries, tortuosity values, and well intersection probabilities, demonstrating that sub-seismic architectural differences invisible to conventional well-log, seismic, or 2D field-panel based models can significantly alter legacy well risk.

The workflow developed here is intentionally designed to be reusable and applicable across multiple CCS storage sites, rather than being tied to a single site-specific interpretation. The output metrics — cluster volume, tortuosity, connectivity functions, and well-intersection flags — are expressed in formats directly compatible with industry-standard reservoir modelling and flow-simulation tools, enabling straightforward integration into existing CCS screening and permitting workflows. In practical terms, a well that intersects the large, low-tortuosity cluster characteristic of Scenario 1 or the 3D transverse-dune case would be identified as high-risk and prioritised for integrity assessment, enhanced monitoring, or remediation, whilst wells in compartmentalised scenarios such as Scenario 2 would carry lower large-scale migration risk but may still require local evaluation. This stratigraphy-aware screening approach directly supports the UK North Sea CCS development programme by providing a cost-effective means of improving the precision of legacy-well risk assessments, reducing uncertainty in storage-complex permitting, and better targeting monitoring resources.

It is important to acknowledge that the scope of this project was necessarily constrained by the short funding timeframe. The connectivity metrics derived here are based on static geometric analysis of binary permeability maps rather than dynamic fluid-flow simulation; whilst this approach is computationally efficient and captures the first-order structural controls on migration risk, it does not account for pressure gradients, capillary effects, multiphase flow behaviour, or time-dependent processes such as dissolution trapping. The binary permeability simplification, in which facies are coded as either permeable or impermeable, also represents an idealisation: in reality, permeability varies continuously across facies domains, and more nuanced petrophysical models would refine the connectivity estimates. Additionally, the well-intersection analysis used randomly

sampled locations in the absence of real legacy-well data for the Helsby Sandstone outcrop analogue; application to actual North Sea CCS sites with real well coordinates would significantly increase the operational value of the workflow.

Future work will seek to extend and validate the workflow across a broader range of geological settings and operational contexts. Integration of the Point-Bar Sedimentary Architecture Numerical Deduction fluvial model (PB-SAND; Yan et al., 2017) fluvial model outputs into the same connectivity framework will extend the workflow to mixed fluvial-aeolian successions and caprock seal intervals, addressing a wider range of stratigraphic targets in the North Sea and beyond. The generated 3D geocellular models can further be used to predict the spatial distribution of porosity and permeability within identified facies domains using Sequential Gaussian Simulation, providing petrophysical property fields that more realistically represent reservoir heterogeneity and can be directly coupled to flow modelling workflows. Coupling the static connectivity outputs to dynamic flow simulators — using the 3D geocellular grids as direct inputs or training images for geostatistical petrophysical models — will enable time-dependent migration predictions and pressure-response analysis. Generating larger model ensembles with Monte Carlo parameter sampling will allow formal uncertainty quantification of connectivity metrics and well-risk probabilities, which is essential for regulatory permitting and investment decisions in CCS projects. Finally, collaboration with industry partners to test the workflow against real North Sea storage complexes with documented legacy-well inventories will validate the approach and accelerate its uptake across the CCS community.

Deliverables and knowledge products

The following deliverables have been produced or are in progress as part of this project.

(1) **3D Stratigraphic Model Ensemble.** A series of 3D geocellular model realisations (more than 80) has been generated using the DASH forward stratigraphic model, systematically varying dune morphology (2D transverse, 3D transverse, longitudinal, and superimposed), dune size, bedform migration rate, and aggradation rate. These models capture a broad and representative range of aeolian sedimentary architectures and associated facies heterogeneities and are provided as open-access datasets in formats that can be readily converted to those compatible with industry-standard reservoir modelling workflows. They are suitable for further use in connectivity analysis, brine migration pathway assessment, and coupling to dynamic flow simulators.

(2) **Peer-Reviewed Publications.** A manuscript ‘Quantifying controls on facies heterogeneity in aeolian dune successions using forward stratigraphic modelling’ has

been drafted and is being prepared for submission to *Geoscience Frontiers* or a similar academic journal. A second manuscript, focusing on the integration of forward stratigraphic modelling with the connectivity and brine migration pathway analysis framework, is currently in preparation and is planned for completion and submission by the end of 2026.

(3) **Workflow Documentation**. A concise, documented workflow (Fig. 1) has been developed and is presented in this report, illustrating all modelling and analysis steps from forward stratigraphic model parameterisation through to legacy well risk indicators. This is intended to serve as a reusable, transferable decision-support resource for CCS practitioners, regulators, and researchers working on UK North Sea storage complexes.

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