petroleum industry shows that drilling new wells into mature reservoirs typically reveal structural and stratigraphic details that were not visible in state-of-the-art 3D/4D seismic surveys. The description of the geological heterogeneity will therefore have large uncertainties attached. Deep saline aquifers that have been identified as potential storage sites are typically much less characterized: the aquifer has typically been penetrated by a small number of wells, if any, and 3D seismic surveys often have limited coverage. If flow simulations are to be used to assess risks associated with a storage operation, the numerical flow model must properly account for the impact of uncertainty in the geological description. Yet, most studies of CO_2 injection commonly employ simplified or conceptualized reservoir descriptions, in which the medium is considered (nearly) homogeneous, or use a single petrophysical realization, and instead focus on developing complex models of the flow physics, discretization schemes, and solvers.

Early studies of the impact of heterogeneity consider 2D models with geostatistically populated permeabilities [33, 51]. Likewise, a layered heterogeneity is examined in [37]. Later, Hovorka at al. [26] studied the impact of heterogeneities in the Frio formation from the Texas Gulf Coast, including stratigraphic heterogeneities resulting from transitions between rocks deposited in sand and mud-dominated depositional facies and structural heterogeneity from growth faults, folds, and salt diapirs. The heterogeneities were parametrized and used as input to a solver to assess the effectiveness of CO_2 storage and its sensitivity to these parameters. Likewise, Obi and Blunt [44] investigate the heterogeneity in an oil field in the North Sea including fluvial and a prograding depositional environment. Flett et al. [20] constructed a suite of 3D models, in which a radial variogram was used to populate five models with varying net-to-gross ratios, and concluded that formations containing shale barriers are effective in containing an injected CO2 plume within the formation and that heterogeneity serves to limit the reliance of the formation seal as the only mechanism for containment. Nilsen et al. [41, 50] considered a large set of high-resolution models of the top surface and concluded that uncertainty in morphology effects at a small scale may have a significant impact on (large-scale) estimates of the non-trivial interplay between structural and residual trapping. The opposite case, with a single top-surface topology and multiple property realizations, was considered by Goater et al. [23].

The most comprehensive study geological uncertainty to day, however, was conducted in the SAIGUP project, which focused on how geological uncertainty impacts reserve estimates and production forecasts [38, 27, 39]. Here, an ensemble of synthetic but realistic models of shallow-marine reservoirs were generated and several thousand cases were run for different production scenarios. The results showed that realistic variations in the structural and sedimentological description have a strong influence on production responses. In general, one cannot expect that knowledge of how geological heterogeneity impacts flow predictions of oil-water systems can be carried directly over to CO_2-brine systems relevant for CO_2 injection scenarios, which involve temporal and spatial scales and density ratios that are quite different from those encountered in oil recovery. Potential storage sites may also have geological characteristics that differ from those seen in producible oil reservoirs. Nevertheless, we will herein try to leverage the comprehensive geomodeling effort from SAIGUP. To this end, we consider a scenario in which CO_2 is injected into an abandoned shallow-marine reservoir and use geological realizations generated as part of the SAIGUP project—which, geologically speaking, represent a viable storage site—to study the impact of geological heterogeneity on the short to medium term predictive modeling of CO_2 plume formation and migration. How heterogeneity impacts the injection operation will be studied in a separate work, in which we also discuss more realistic pressure constraints on injection well.

The outline of the paper is as follows: We start by describing the geological realizations, the underlying parameters, and the flow model in Section 2. In Section 3, we introduce a set of flow responses that we will use to describe the feasibility of the storage operation and the variations in the resulting flow patterns. Section 4 analyzes how the various geological parameters impact the formation and early-stage migration of the CO_2plume. In Section 5, we discuss how the contact between the CO_2 plume(s) and the caprock, and hence the leakage risk, is influenced by the geological parameters. Finally, some concluding remarks are given in Section 6.