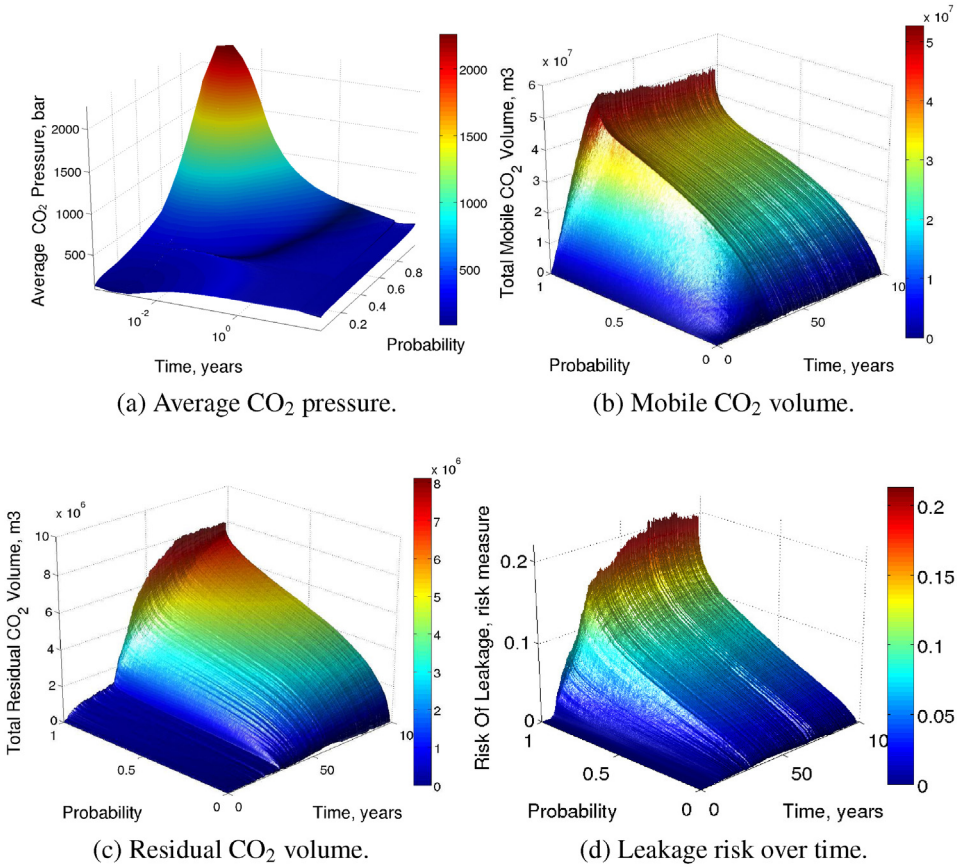

(a) Average CO_2 pressure. (b) Mobile CO_2 volume.

(c) Residual CO_2 volume. (d) Leakage risk over time.

Fig. 13. Evolution of the cumulative distribution function of different response values over time.

remain in the subsurface, or via the related costs for CO_2 emission certificates.

The other part is the probability of these consequences to happen. This depends on the stochastic behavior of the process which results in the respective outcomes.

We use the polynomial-based reduced model for risk analysis, because it is fast enough to perform a Monte-Carlo analysis with a large number (here: 10,000) of realizations on the polynomials. Thanks to the higher-order approximation via the aPC, the principal non-linear physical behavior of CO_2 storage is included in the analysis, and detailed probabilistic risk assessment becomes feasible. We analyze here the same quantities as in Section 4, i.e., average CO_2 pressure, the volume of mobile or immobile CO_2, and leakage risk. For definitions, see Section 3.1.

5.1. Quantification of expected values in CO_2 storage

Average response values can be calculated analytically from the polynomial (e.g., Oladyshkin et al., 2011) or via the Monte-Carlo post-process as mentioned above. Fig. 14a–d shows some of the calculated expectations as functions of time. In Fig. 11a, the mobile CO_2 volume increases linearly in the medium because of the constant injection rate during the first thirty years. After injection, the mobile volume of CO_2 is reduced due to the trapped volume in residual form and the migration of CO_2 across open boundaries.

Fig. 11b shows the expected values for the volume of residually trapped CO_2 as a function of time. The plot shows the significance of imbibition during the plume migration period, when water replaces CO_2 that is moving upward because of gravity segregation. During injection, CO_2 invades the aquifer and drainage is dominant. Therefore, the expected residual CO_2 plot shows a smaller slope during injection than what it shows later in time.

When injection starts, a pressure pulse travels through the medium at a finite velocity because of the slight compressibility of brine. The initially built-up pressure releases through open boundaries over time and the average pressure drops in the aquifer (Fig. 11c). The large pressure build-up in the very early time steps occurs because large pressure values have to be exceeded in the injection cell before CO_2 becomes mobile at saturations above the residual value. During this period, the CO_2 pressure is defined almost only by the pressure in the injection cell (compare the definition of CO_2 pressure in Section 3.2). Under realistic injection settings, a pressure rise of up to 400 bars (from 270 to 670 bar in the first simulation time step, not visible in Fig. 11c) would be very unrealistic and would not be allowed to occur. At the end of Section 5.2, we will investigate this issue in more detail.

Also, during early injection time, the pressure is larger than at the end of injection. There are a few realizations where the contributions from the external aquifer support, a dense barrier system close to 100% areal coverage, an adverse aggradation angle of the formation and extremely low fault transmissibilities interact to effectively block the CO_2 flow close to the well. This has strong effects on pressure when the rock at the injector position happens to be poorly permeable, leading to a very poor injectivity. An adapted CO_2 injection strategy would react by lowering the injection rate, by choosing a different injection position, or by even abandoning the entire site.

Based on the results of the current study, it is possible to identify such adverse combinations and guide site investigation strategies to pay attention to such situations. In a follow-up study (ready for submission), we are currently investigating an active injection strategy controlled by an upper allowable pressure limit.

However, the initial sharp pressure increase is released very quickly. This happens, when first parts of the CO_2 plume have found