Kempka, T., Norden, B. (2017): Inverse modelling of hydraulic testing to revise the static reservoir model of the Stuttgart Formation at the Ketzin pilot site. - *Energy Procedia*, *125*, pp. 640—649.

DOI: http://doi.org/10.1016/j.egypro.2017.08.264

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 125 (2017) 640–649

Energy Procedia

www.elsevier.com/locate/procedia

European Geosciences Union General Assembly 2017, EGU
Division Energy, Resources & Environment, ERE

Inverse modelling of hydraulic testing to revise the static reservoir model of the Stuttgart Formation at the Ketzin pilot site

Thomas Kempka[a,*], Ben Norden[b]

[a]GFZ German Research Centre for Geosciences, Fluid Systems Modelling, Telegrafenberg, 14473 Potsdam, Germany
[b]GFZ German Research Centre for Geosciences, Geothermal Energy Systems, Telegrafenberg, 14473 Potsdam, Germany

Abstract

Pilot-scale CO_2 storage has been performed at the Ketzin pilot site in Germany from 2007 to 2013 with about 67 kt of CO_2 injected into the Upper Triassic Stuttgart Formation, focussing on efficient monitoring and long-term prediction strategies. We employed inverse modelling to revise the latest static geological reservoir model, considering bottomhole well pressures observed during hydraulic testing. Simulation results exhibit very good agreement with the observations, providing one reasonable permeability realization for the Ketzin pilot site near-well area. Furthermore, an existing hypothesis on the presence of a low-thickness sandstone channel between two wells is supported by our findings.

Peer-review under responsibility of the scientific committee of the European Geosciences Union (EGU) General Assembly 2017 – Division Energy, Resources and the Environment (ERE).

Keywords: Geological model revision; Inverse modelling; Hydraulic testing; Bottomhole pressure; Ketzin pilot site; CO_2 storage

1. Introduction

CO_2 storage has been performed at the Ketzin pilot site in Germany from 2007 to 2013 with about 67 kt of CO_2 injected into the Upper Triassic Stuttgart Formation at 620-650 m depth to investigate efficient strategies to monitor and predict long-term CO_2 behaviour in the storage reservoir [1–6]. Static geological modelling and numerical simulations accompany these efforts since their very beginning [7–15], with a static geological reservoir model that has been developed, revised and matched against field observations to allow for predictions over short- to long-term periods [12, 16–19]. In this context, the static geological model has been continuously further developed and updated with the availability of new field data. Furthermore, many efforts have been undertaken to integrate field observations and laboratory experiments with numerical simulations [10, 12, 17, 18, 20–29], especially considering the four 3D seismic campaigns carried out at the Ketzin pilot site [30–35].

* Corresponding author. Tel.:+49-331-288-1865 ; fax: +49-331-288-1529.
E-mail address: kempka@gfz-potsdam.de

1876-6102
Peer-review under responsibility of the scientific committee of the European Geosciences Union (EGU) General Assembly 2017 – Division Energy, Resources and the Environment (ERE).
10.1016/j.egypro.2017.08.264

The present study aims at validation of the latest revised reservoir model [11, 13] against bottomhole pressure data recorded during hydraulic testing of the Stuttgart Formation, undertaken after drilling the wells Ktzi 200, Ktzi 201 and Ktzi 202. Further, we employ high-performance inverse modelling to revise the static reservoir model by calibrating the spatial permeability distribution by means of the field observations made during the hydraulic tests. Our simulation results are then discussed in the context of previous findings [36–39].

2. Numerical forward model implementation

Implementation of the numerical model is based on the latest revised static geological model [11, 13], with parameters upscaled to a new simulation grid using the Petrel software package [40]. Local grid refinements (LGRs) are introduced to increase the resolution in the near-well area (6-8 m element edge lengths in horizontal direction), while the remaining grid is relatively coarse (about 90 m element edge lengths in horizontal direction, Fig. 1). Introducing nested LGRs allowed us to reduce the number of grid elements to 102,336, resulting in acceptable computational efforts in view of inverse modelling and meeting the required accuracy of the simulation results.

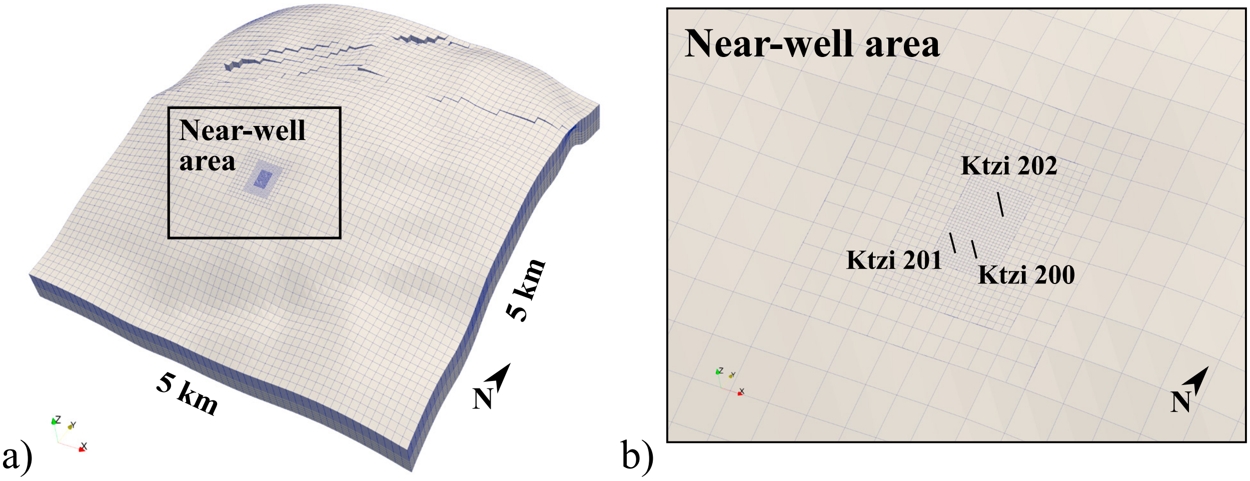

Fig. 1. Revised reservoir model grid with 102,366 elements and LGRs (a). Close-up view of near-well area, showing well locations and nested LGR structure (b). Distance between Ktzi 201 and Ktzi 200 is 50 m.

The BLACKOIL module of the scientific numerical simulator MUFITS [41, 42] is used in the present study, whereby previously undertaken benchmark simulations demonstrate that simulation results, absolutely identical to those produced with a standard industry simulator, can be achieved even over a long-period simulation of CO_2 injection at the Ketzin pilot site [42]. The interested reader is kindly referred to Kempka et al. [9, 11], Kempka and Kühn [10] and Class et al. [43] for detailed information on the numerical multiphase flow model parametrization and its impacts on the simulation results.

3. Static reservoir model validation against hydraulic testing data

We employed the bottomhole pressures and fluid flow rates recorded during hydraulic testing at the Ketzin pilot site [36, 38] to investigate the response of the static reservoir model revision presented by Kempka et al. [11]. Flow rates as well as observed and simulated bottomhole pressures are shown in Fig. 2.

Simulated pressure drawdown in any of the wells is about one order in magnitude below the observed bottomhole data, indicating that reservoir permeabilities assigned in the static reservoir model are not representing those in the Stuttgart Formation. This is confirmed by a hydraulic testing interpretation [36], previous simulations using the hydraulic testing data [37, 38], and the permeability multipliers required to match the bottomhole pressure history using the revised model [10, 11, 43]. The authors of the latter studies found that permeability reductions by factors of 0.05

to 0.25 are required in the near-well area to successfully simulate the pressure response of the Stuttgart Formation during the first three years of CO_2 injection. Further, a diverging far-field permeability multiplier has to be employed for that purpose, ranging between 0.10 and 0.38 [43]. Consequently, the next step in the revision of the static geological model is the integration of the hydraulic testing data by means of inverse simulations to calibrate the spatial distribution of reservoir permeability, whereby the near-well area is specifically focussed due to the relatively short distances between the three wells (112 m in maximum).

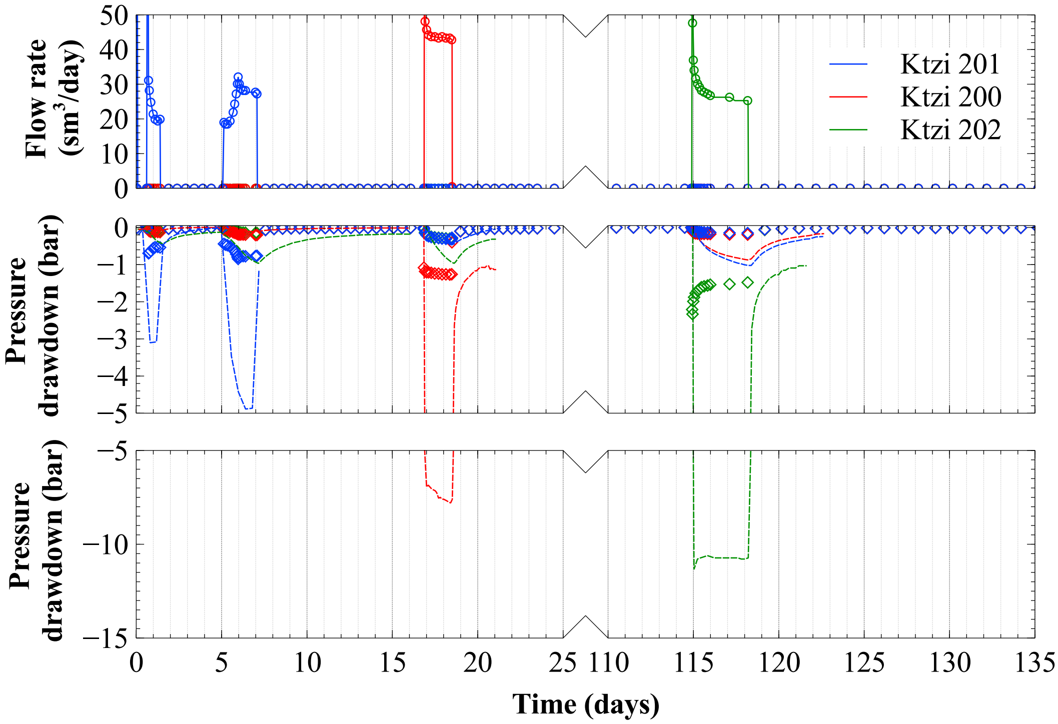

Fig. 2. Flow rates as well as observed and simulated bottomhole pressure drawdown in the three wells Ktzi 200, Ktzi 201 and Ktzi 202. Solid lines indicate applied flow rates and dashed lines the observed pressure drawdown, while circles represent the flow rates applied in the reservoir simulator and diamonds the simulated pressure response of the initial static reservoir model.

4. High-performance inverse modelling to revise permeability in static reservoir model

For calibration of the spatial reservoir permeability distribution, we integrated the MUFITS simulator with the parameter estimation tool PEST++ [44] in our flexible simulation framework [45]. High-performance inverse modelling is achieved by running PEST++ in parallel mode on multiple computational nodes, which in turn execute the MUFITS simulator in parallel with up to ten processes, determined by the grid element count. The PLPROC software package [46] is used to carry out 2D interpolation of pilot-point data onto the numerical simulation grid, with 52 pilot points applied in total (cf. Fig. 5).

Inverse simulations are run in the PEST++ regularization mode with 157 parameters, of which 53 are set adjustable: 52 permeability multipliers tied in the three principle directions at the pilot points, allowed to vary over a range of 1×10^{-4} to 3×10^{0}, while one global vertical permeability multiplier is used with an allowed variation bandwidth of 1×10^{-2} to 1×10^{0}. Further, 32 time-dependent data on pressure drawdown, observed during hydraulic testing are considered in our simulation runs. Pilot points are grouped into super parameters during specific iterations of the inverse simulation run, resulting in a significant reduction of total computational time.

Following a total number of 622 forward model runs within 13 inverse modelling iterations, the pre-defined termination criterion, i.e., reduction of the relative objective function over a specific number of successive iterations is met. Fig. 3 shows the simulated pressure drawdown based on the revised spatial distribution of permeability (cf. Figs. 6 and 7). A very good agreement with the observed pressure drawdown is achieved with the static reservoir model, revised by the inverse simulation procedure: pressure responses of the pumping wells exhibit identical values, indicating that local permeabilities in the close vicinities of the respective wells are properly represented; and further, also the pressure drawdown simulated in the observation wells shows an excellent agreement with the observations, emphasizing that the hydraulic connections between all three wells are reasonably quantified by the calibrated spatial distribution of permeability. Minor deviations between simulated and field data are observed (Fig. 4), i.e., the local response of the Ktzi 201 well on pumping during the first week may result from errors in flow rate and pressure measurements, minor time shifts between both data and local near-well permeabilities that may not be represented by the near-well grid discretization chosen in our model [38]. Nevertheless, a correlation coefficient of R^2 = 0.981 emphasizes the high quality of the achieved calibration results.

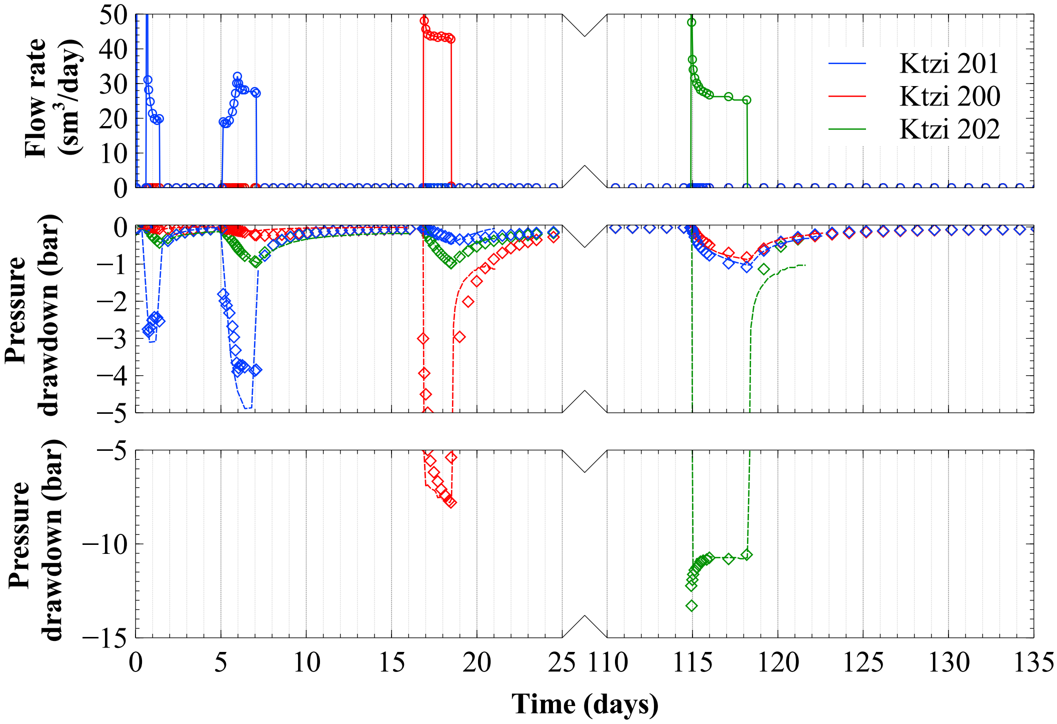

Fig. 3. Flow rates as well as observed and simulated bottomhole pressure drawdown in the three wells Ktzi 200, Ktzi 201 and Ktzi 202. Solid lines indicate applied flow rates and dashed lines the observed pressure drawdown, while circles represent the flow rates applied in the reservoir simulator and diamonds the simulated pressure response of the static reservoir model, revised by inverse simulations.

Fig. 5 shows the spatial distribution of permeability multipliers, resulting from the presented inverse modelling procedure. For the far-field (Fig. 5 (a)), a permeability reduction by a factor of about 0.18 is calculated, exhibiting higher permeability multipliers in the West of the three wells, while all other directions indicate non-continuous no-flow boundaries (0.05-permeability multiplier regions around the wells). The near-well area (Fig. 5 (b)) exhibits a low-permeability region between the wells Ktzi 201 and Ktzi 200, in agreement with previous findings [36–38]. High-permeability regions are present in the north-west and south-east near-fields of the three wells, while low-permeability regions evolve in the North-East and South. Global vertical permeability reduction is calculated to a factor of 0.025, resulting in an average vertical-to-horizontal permeability ratio of about 1/7.

Considering the latest observations [30–32, 34] and numerical simulation results [10, 12, 43] on gaseous CO_2 migration at the Ketzin pilot site, the calculated realization of spatial permeability multiplier distribution represents a reasonable scenario, since CO_2 migration is mainly taking place in north-west-north direction, as suggested by the increased permeability region in the North-West of the near-well area here. Further, late CO_2 arrival times at the

Ktzi 202 well can be also explained by this realization, since only a low-permeable direct connection between the injection well (Ktzi 201) and the first observation well (Ktzi 200) exists. Simulation results in view of CO_2 arrival times at the Ktzi 200 well [9, 10, 43] further support the hypothesis on the likely presence of a low-thickness sand channel or low-permeability anhydrite-filled fracture between the wells Ktzi 201 and Ktzi 200, introduced by Chen et al. [38], since this is one reasonable explanation for the weak hydraulic connectivity between both wells and the fast CO_2 arrival at the Ktzi 200 well.

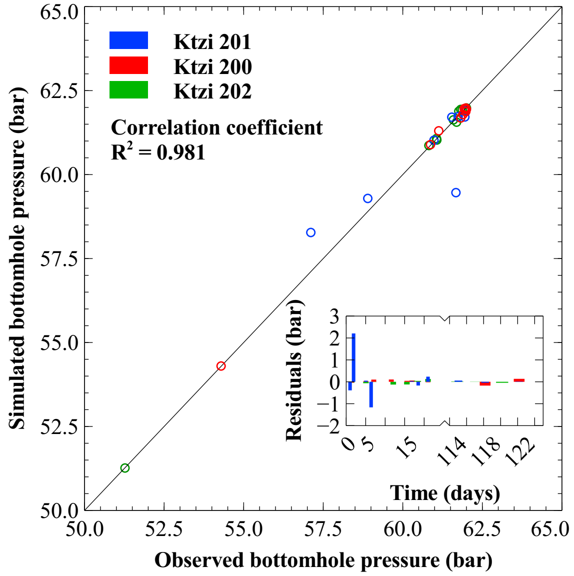

Fig. 4. Observed versus simulated bottomhole pressures exhibit a correlation coefficient of R^2 = 0.981. Residuals versus time are plotted in the inset.

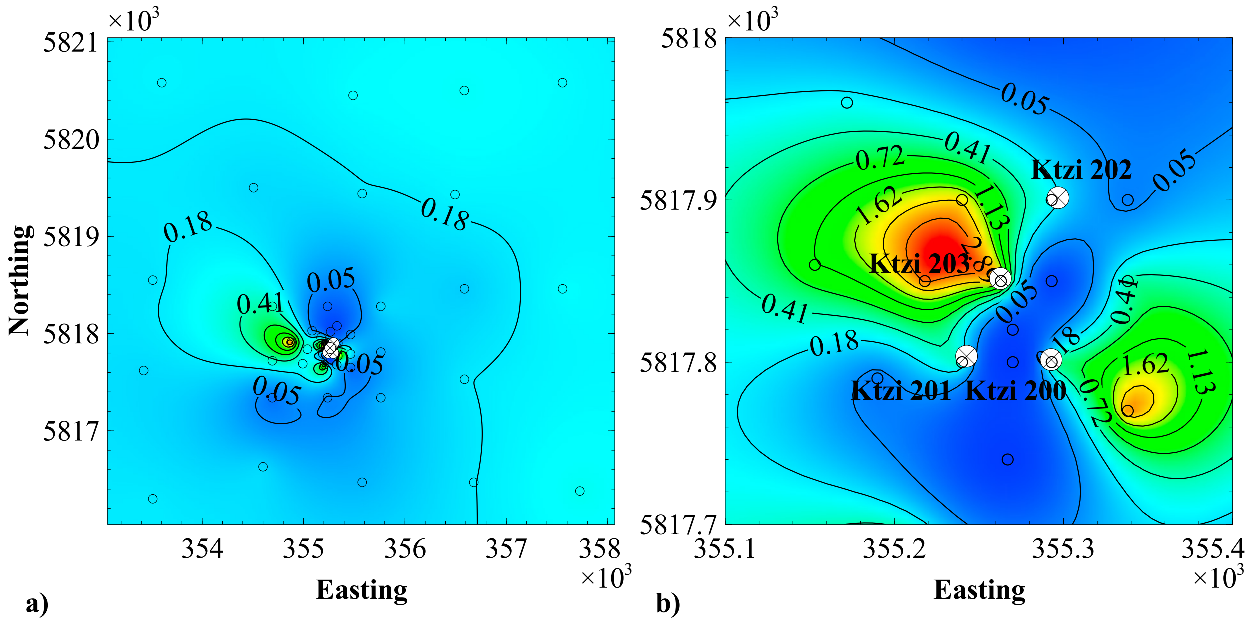

Fig. 5. Calculated permeability multipliers for the far-field (a) and near-well model areas (b). Pilot point locations are depicted by empty circles and well locations by circles with white filling, isolines represent permeability multiplier contours (UTM-WGS84 projection).

A comparison between the initial and revised spatial distributions of permeability in the static reservoir model at the Stuttgart Formation top is plotted in Figs. 6 and 7, illustrating the previously addressed overall permeability reduction in the calibrated model. Increased permeabilities apply for the sandstone channels, located about 500 m west of the wells, in addition to the regions in the near well-area as discussed before. The low-permeability region striking in north-south direction in the near-well area is also well depicted (Fig. 7 (b)), complemented by different localized regions of reduced permeability.

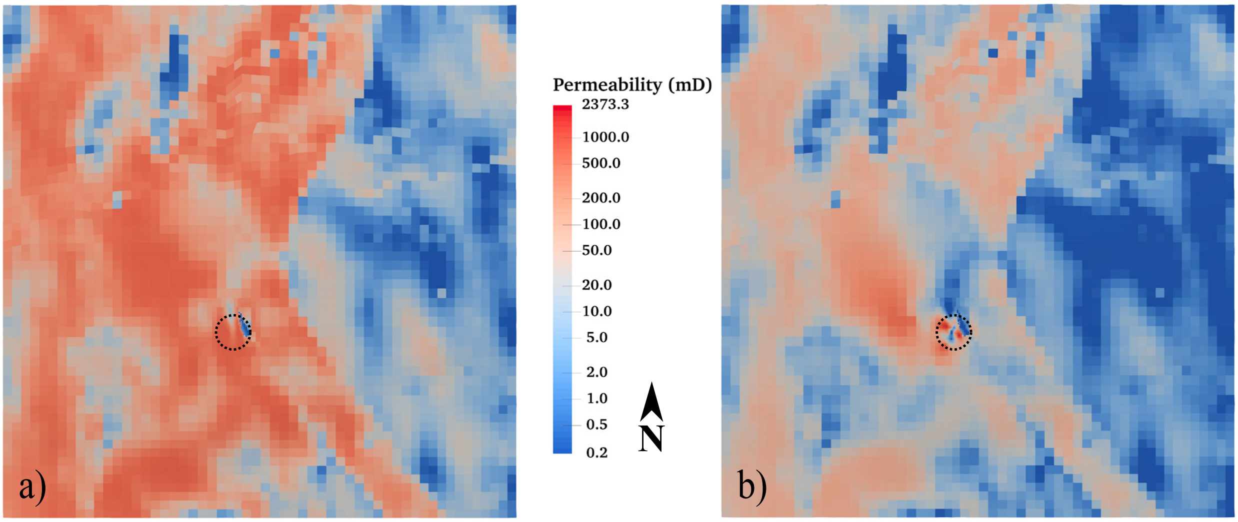

Fig. 6. Plane view of initial model far-field permeability distribution (a) and of that revised by inverse modelling (b) in the fourth upper grid layer of the reservoir model (Stuttgart Formation). Dotted circles indicate the location of the near-well area (cf. Fig. 7). Lateral model dimensions are 5 km × 5 km.

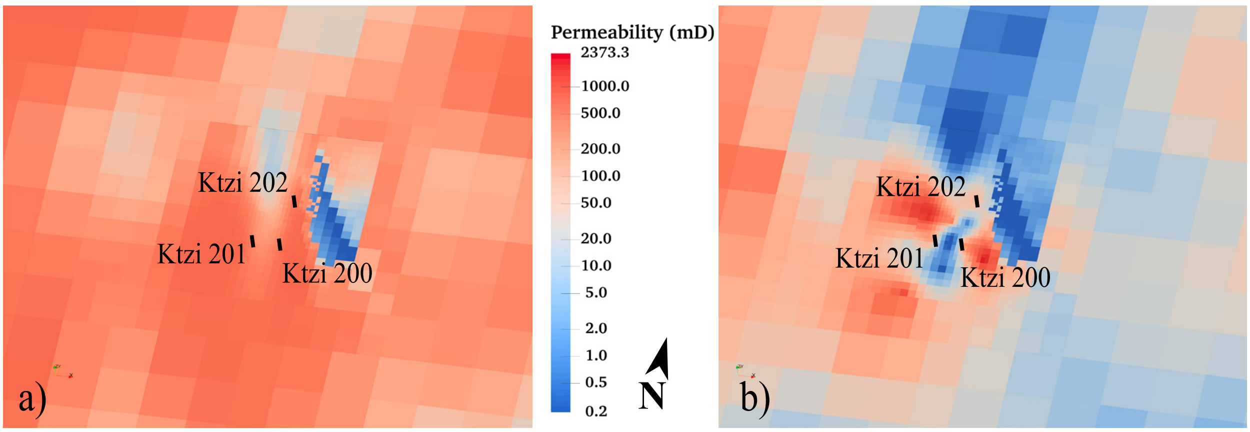

Fig. 7. 3D view of initial model near-well permeability distribution (a) and of that revised by inverse modelling (b) in the fourth upper grid layer of the reservoir model (Stuttgart Formation). Distance between Ktzi 201 and Ktzi 200 wells is 50 m.

Fig. 8 illustrates the standard deviations in the far-field and near-well area to provide a measure for the parameter uncertainty in the calibrated model. Near-well standard deviations (Fig. 8 (b)) are notably below those of the far-field, indicating the achieved uncertainty reduction close to the wells. Since the hydraulic tests undertaken at the Ketzin pilot site mainly account for the near-well are due to their implementation and design, far-field uncertainties are only insignificantly reduced by the calibration process (Fig. 8 (a)), taking into account the applied initial standard deviation of $\log_{10}(\sigma)$ = 1.1193 at all 52 pilot points. Standard deviation ($\log_{10}(\sigma)$) of the vertical-to-horizontal permeability ratio was reduced from 0.5 to 0.4626 in the calibrated model.

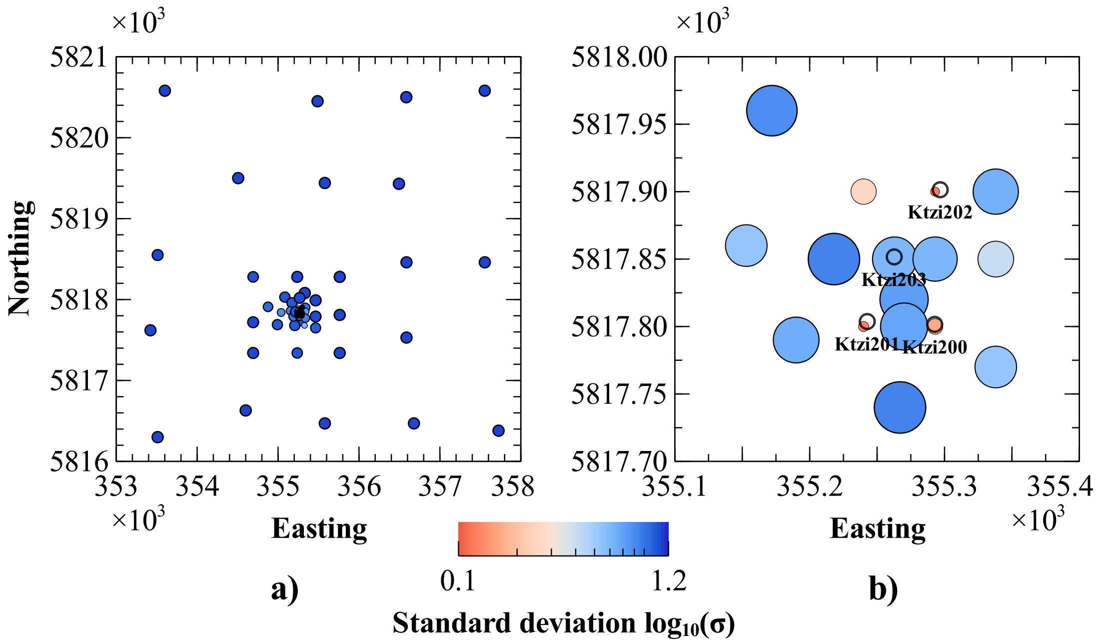

Fig. 8. Parameter uncertainty at pilot points of the calibrated model for the far-field (a) and the near-well area (b), expressed by standard deviation ($\log_{10}(\sigma)$). Initial standard deviations were defined to $\log_{10}(\sigma) = 1.1193$ at all 52 pilot points. Empty circles represent well locations. Other circle sizes correlate with calculated standard deviation values (UTM-WGS84 projection).

5. Discussion and conclusions

We validated the latest revised static reservoir model of the Stuttgart Formation at the Ketzin pilot site against observations made during hydraulic testing after drilling of the first three wells. Simulation results emphasize that reservoir permeabilities are significantly below those in the static reservoir model. This is in agreement with previous findings, analysing the observations made during hydraulic testing by analytical and numerical modelling [36–39] as well as numerical simulations of CO_2 injection into the storage reservoir [10–12, 43]. Consequently, we calibrated the spatial distribution of reservoir permeability in a first step of a thorough model revision by high-performance inverse modelling based on the hydraulic testing data. Our results clearly demonstrate that reservoir permeabilities, required to match the pressure response to the hydraulic testing observations, are more than 80% below those in the initial static reservoir model, with a vertical-to-horizontal permeability anisotropy of about 1/7. Permeabilities, increased by a factor of up to three in the maximum were determined in the western region of the wells, while a region of low permeability was found in between the three wells. Considering these revisions in spatial permeability distribution, simulated and observed pressure responses to the hydraulic tests are in very good agreement.

As previously discussed by Wiese et al. [36] and Chen et al. [37, 38], a region of low permeability likely exists in between the wells, e.g., in form of a low-thickness sandstone channel or anhydrite-filled low-permeable fracture striking in north-south direction. This theory supports the late CO_2 arrival, observed at the Ktzi 202 well, delayed by a factor of three compared to former model predictions [9, 10, 43]. Further, this theory can also explain the reduced hydraulic conductivity between the Ktzi 201 and Ktzi 200 wells, derived from the hydraulic testing pressure response, while CO_2 is able to migrate across this low-permeability region to arrive at the Ktzi 200 well according to initial numerical model predictions [9, 10]. Our simulation results support these findings, when only the hydraulic testing data is considered.

The next steps in static model revision will include validation of the new spatial permeability distribution elaborated in the present study against data of the operational phase at the Ketzin pilot site [47–54], comprising at least three years of CO_2 injection. Integrated inverse simulations of hydraulic testing and CO_2 injection operation will be very likely required due to the fact that inverse modelling of hydraulic testing mainly adjusts permeabilities in the near-well area, while previous studies show that specific permeability multipliers for the far-well area are of paramount importance to fit the long-term bottomhole pressure development in the injection well [10, 43].

Acknowledgments

The authors gratefully acknowledge the funding for the Ketzin project received from the European Commission (6^{th} and 7^{th} Framework Program), two German ministries - the Federal Ministry of Economics and Technology and the Federal Ministry of Education and Research - and industry since 2004. The ongoing R&D activities are funded within the project COMPLETE by the Federal Ministry of Education and Research within the GEOTECHNOLOGIEN program. Further funding is received by VGS, RWE, Vattenfall, Statoil, OMV and the Norwegian CLIMIT program. We are also very grateful to the two anonymous reviewers for their valuable comments that supported us in improving the manuscript's quality.

References

[1] Schilling F, Borm G, Würdemann H, Möller F, Kühn M, and CO_2SINK Group. (2009) "Status Report on the First European on-shore CO_2 Storage Site at Ketzin (Germany)." *Energy Procedia* 1 (2009): 2029–2035.

[2] Würdemann H, Möller F, Kühn M, Heidug W, Christensen NP, Borm G. et al. (2010) "CO_2SINK - From site characterisation and risk assessment to monitoring and verification: One year of operational experience with the field laboratory for CO_2 storage at Ketzin, Germany." *Int J Greenh Gas Con* 4.6 (2010): 938–951.

[3] Martens S, Liebscher A, Möller F, Würdemann H, Schilling F, Kühn M. et al. (2011) "Progress Report on the First European on-shore CO_2 Storage Site at Ketzin (Germany) - Second Year of Injection." *Energy Procedia* 4 (2011): 3246–3253.

[4] Martens S, Kempka T, Liebscher A, Lüth S, Möller F, Myrttinen A. et al. (2012) "Europe's longest-operating on-shore CO_2 storage site at Ketzin, Germany: A progress report after three years of injection." *Environ Earth Sci* 67 (2012): 323–334.

[5] Martens S, Liebscher A, Möller F, Henninges J, Kempka T, Lüth S. et al. (2013) "CO_2 storage at the Ketzin pilot site: Fourth year of injection, monitoring, modelling and verification." *Energy Procedia* 37 (2013): 6434–6443.

[6] Martens S, Möller F, Streibel M, Liebscher A, and the Ketzin Group. (2014) "Completion of five years of safe CO_2 injection and transition to the post-closure phase at the Ketzin pilot site." *Energy Procedia* 59 (2014): 190–197.

[7] Bielinski A. (2007) "Numerical Simulation of CO_2 Sequestration in Geological Formations." Mitteilungsheft Nr. 155, Ph.D. thesis, Department of Hydraulic Engineering, University of Stuttgart, Germany.

[8] Probst P. (2008) "Numerical Simulations of CO_2 Injection into Saline Aquifers: Estimation of Storage Capacity and Arrival Times using Multiple Realizations of Heterogeneous Permeability Fields." Master Thesis, Department of Hydraulic Engineering, University of Stuttgart, Germany.

[9] Kempka T, Kühn M, Class H, Frykman P, Kopp A, Nielsen CM. et al. (2010) "Modelling of CO_2 arrival time at Ketzin - Part I." *Int J Greenh Gas Con* 4.6 (2010): 1007–1015.

[10] Kempka T, and Kühn M. (2013) "Numerical simulations of CO_2 arrival times and reservoir pressure coincide with observations from the Ketzin pilot site, Germany." *Environ Earth Sci* 70.8 (2013): 3675–3685.

[11] Kempka T, Class H., Görke UJ, Norden B, Kolditz O, Kühn M. et al. (2013) "A Dynamic Flow Simulation Code Intercomparison based on the Revised Static Model of the Ketzin Pilot Site." *Energy Procedia* 40 (2013): 418–427.

[12] Kempka T, De Lucia M, and Kühn M. (2014) "Geomechanical integrity verification and mineral trapping quantification for the Ketzin CO_2 storage pilot site by coupled numerical simulations." *Energy Procedia* 63 (2014): 3330–3338.

[13] Norden B, and Frykman P. (2013) "Geological modelling of the Triassic Stuttgart Formation at the Ketzin CO_2 storage site, Germany." *Int J Greenh Gas Con* 19 (2013): 756–774.

[14] Norden B. (2011) "Modelling of the near-surface groundwater flow system at the CO_2SINK site Ketzin, Germany." *Z Dtsch Ges Geowiss* 162.1 (2011): 63–77.

[15] Ouellet A, Berard T, Frykman P, Welsh P, Minton J, Pamucku Y. et al. (2010) "Reservoir geomechanics case study of seal integrity under CO_2 storage conditions at Ketzin, Germany." Ninth Annual Conference on Carbon Capture and Sequestration. May 1013 2010.

[16] Kempka T, Klein E, De Lucia M, Tillner E, and Kühn M. (2013) "Assessment of Long-term CO_2 Trapping Mechanisms at the Ketzin Pilot Site (Germany) by Coupled Numerical Modelling." *Energy Procedia* 37 (2013): 5419–5426.

[17] Klein E, De Lucia M, Kempka T, and Kühn M. (2013) "Evaluation of long-term mineral trapping at the Ketzin pilot site for CO_2 storage: An integrative approach using geochemical modelling and reservoir simulation." *Int J Greenh Gas Con* 19 (2013): 720–730.

[18] De Lucia M, Kempka T, and Kühn M. (2015) "A coupling alternative to reactive transport simulations for long-term prediction of chemical reactions in heterogeneous CO_2 storage systems." *Geosci Model Dev* 8 (2015): 279–294.

[19] Govindan R, Babaei M, Korre A, Shi JQ, Durucan S, Norden B. et al. (2014) "CO_2 Storage Uncertainty and Risk Assessment for the Post-closure Period at the Ketzin Pilot Site in Germany." *Energy Procedia* 63 (2014): 4758–4765.

[20] Kempka T, Klapperer S, and Norden B. (2014) "Coupled hydro-mechanical simulations demonstrate system integrity at the Ketzin pilot site for CO_2 storage, Germany." Rock Engineering and Rock Mechanics: Structures in and on Rock Masses. Proceedings of EUROCK 2014, ISRM European Regional Symposium 2014.
[21] Baumann G, Henninges J, and De Lucia M. (2014) "Monitoring of saturation changes and salt precipitation during CO_2 injection using pulsed neutron-gamma logging at the Ketzin pilot site." *Int J Greenh Gas Con* 28 (2014): 134–146.
[22] Fischer S, De Lucia M, and Liebscher A. (2014) "Kinetic modeling of laboratory CO_2-exposure experiments performed on whole rock reservoir samples." *Greenh Gases* 4.2 (2014): 244–256.
[23] Fischer S, Liebscher A, Zemke K, De Lucia M, and the Ketzin Team (2013) "Does Injected CO_2 Affect (Chemical) Reservoir System Integrity? - A Comprehensive Experimental Approach." *Energy Procedia* 37 (2013): 4473–4482.
[24] Fischer S, Liebscher A, De Lucia M, Hecht L, and the Ketzin Team (2013) "Reactivity of sandstone and siltstone samples from the Ketzin pilot CO_2 storage site-Laboratory experiments and reactive geochemical modeling." *Environ Earth Sci* 70.8 (2013): 3687–3708.
[25] Lengler U, De Lucia M, and Kühn M. (2010) "The impact of heterogeneity on the distribution of CO_2: Numerical simulation of CO_2 storage at Ketzin." *Int J Greenh Gas Con* 4.6 (2010): 1016–1025.
[26] Bergmann P, Lengler U, Schmidt-Hattenberger C, Giese R, and Norden B. (2010) "Modelling the geoelectric and seismic reservoir response caused by carbon dioxide injection based on multiphase flow simulation: Results from the CO_2SINK project." *Chem Erde Geochem* 70.3 (2010): 173–183.
[27] Martens S, Kempka T, Liebscher A, Möller F, Schmidt-Hattenberger C, Streibel M. et al. (2015) "Field Experiment on CO_2 Back-production at the Ketzin Pilot Site." *Energy Procedia* 76 (2015): 519–527.
[28] Unger V, and Kempka T. (2015) "Hydro-mechanical Simulations of Well Abandonment at the Ketzin Pilot Site for CO_2 Storage Verify Wellbore System Integrity." *Energy Procedia* 76 (2015): 592–599.
[29] Wagner FM. (2016) "New developments in electrical resistivity imaging with applications to geological CO_2 storage". Ph.D. thesis. ETH Zürich, The Switzerland.
[30] Huang F, Juhlin C, Han L, Sopher D, Ivandic M, Norden B. et al. (2017) "Feasibility of utilizing wavelet phase to map the CO_2 plume at the Ketzin pilot site, Germany." *Geophys Prospect* 65.2 (2017): 523–543.
[31] Huang F, Bergmann P, Juhlin C, Ivandic M, Lüth S, Ivanova A. et al. (2016) "The First Post-injection Seismic Monitor Survey at the Ketzin Pilot CO_2 Storage Site: Results from Time-lapse Analysis." *Geophys Prospect*, in press. doi:10.1111/1365–2478.12497
[32] Huang F, Juhlin C, Han L, Kempka T, Lüth, and Zhang F. (2016) "Quantitative evaluation of thin-layer thickness and CO_2 mass utilizing seismic complex decomposition at the Ketzin CO_2 storage site, Germany." *Geophys J Int* 207.1 (2016): 160–173.
[33] Huang F, Juhlin C, Kempka T, Norden B, and Zhang, F. (2015) "Modeling 3D time-lapse seismic response induced by CO_2 by integrating borehole and 3D seismic data A case study at the Ketzin pilot site, Germany." *Int J Greenh Gas Con* 36 (2015): 66–77.
[34] Lüth S, Ivanova A, and Kempka T. (2015) "Conformity assessment of monitoring and simulation of CO_2 storage: A case study from the Ketzin pilot site." *Int J Greenh Gas Con* 42 (2015): 329–339.
[35] Ivanova A, Juhlin C, Lengler U, Bergmann P, Lüth S, and Kempka T. (2013) "Impact of temperature on CO_2 storage at the Ketzin site based on fluid flow simulations and seismic data." *Int J Greenh Gas Con* 19 (2013): 775–784.
[36] Wiese B, Böhner J, Enachescu C, Würdemann H, and Zimmermann G. (2010) "Hydraulic characterisation of the Stuttgart formation at the pilot test site for CO_2 storage, Ketzin, Germany." *Int J Greenh Gas Con* 4.6 (2010): 960-971.
[37] Chen F, Zhou Q, Birkholzer JT, Wiese B, Norden B, and Kempka T. (2012) "TOUGH2 simulation of the pumping tests at Ketzin site: heterogeneity effects and model calibration." Proceedings, TOUGH Symposium, Lawrence Berkeley NationalLaboratory, Berkeley, CA, September 17-19 2012.
[38] Chen F, Wiese B, Zhou Q, Kowalsky MB, Norden B, Kempka T. et al. (2014) "Numerical modelling of the pumping tests at the Ketzin pilot site for CO_2 injection: Model calibration and heterogeinity effects." *Int J Greenh Gas Con* 22 (2014): 200–212.
[39] Otto C. (2013) "Hydraulische Characterisierung der Stuttgart Formation mittels Auswertung von Crosshole-Pumpversuchen und inverser Modellierung." Diploma Thesis, University of Potsdam, Potsdam, Germany (in German).
[40] Schlumberger (2011) "Petrel Seismic-to-Evaluation Software, Version 2011.2."
[41] Afanasyev A. (2015) "Hydrodynamic modelling of petroleum reservoirs using simulator MUFITS." *Energy Procedia* 76 (2015): 427–435.
[42] Afanasyev A, Kempka T, Kühn M, and Melnik O. (2016) "Validation of the MUFITS Reservoir Simulator Against Standard CO_2 Storage Benchmarks and History-matched Models of the Ketzin Pilot Site." *Energy Procedia* 97 (2016): 395–402.
[43] Class H, Mahl L, Ahmed W, Norden B, Kühn M, and Kempka T. (2015) "Matching Pressure Measurements and Observed CO_2 Arrival Times with Static and Dynamic Modelling at the Ketzin Storage site." *Energy Procedia* 76 (2015): 623–632.
[44] Welter DE, White JT, Hunt RJ, and Doherty JE. (2015) "Approaches in highly parameterized inversion: PEST++ Version 3, a Parameter ESTimation and uncertainty analysis software suite optimized for large environmental models: U.S. Geological Survey Techniques and Methods." Book 7, Section C12.
[45] Kempka T, Nakaten B, De Lucia M, Nakaten N, Otto C, Pohl M. et al. (2016) "Flexible Simulation Framework to Couple Processes in Complex 3D Models for Subsurface Utilization Assessment." *Energy Procedia* 97 (2016): 494–501.
[46] PLPROC (2017) "PLPROC - A Powerful Parameter List Processor." Available online: http://www.pesthomepage.org/PLPROC.php (last accessed: 31 May 2017).
[47] Möller F, Liebscher A, Martens S, Schmidt-Hattenberger C, and Kühn M. (2012) "Supplement 2008 to: Möller F, Liebscher A, Martens S, Schmidt-Hattenberger C, and Kühn M.: Yearly Operational Datasets of the CO_2 Storage Pilot Site Ketzin, Germany." doi:10.5880/GFZ.b103-12066.2008.
[48] Möller F, Liebscher A, Martens S, Schmidt-Hattenberger C, and Kühn M. (2012) "Supplement 2009 to: Möller F, Liebscher A, Martens S, Schmidt-Hattenberger C, and Kühn M.: Yearly Operational Datasets of the CO_2 Storage Pilot Site Ketzin, Germany." doi:10.5880/GFZ.b103-12066.2009.

[49] Möller F, Liebscher, A., Martens, S., Schmidt-Hattenberger, C., Kühn, M. (2012) "Supplement 2010 to: Möller F, Liebscher A, Martens S, Schmidt-Hattenberger C, and Kühn M.: Yearly Operational Datasets of the CO_2 Storage Pilot Site Ketzin, Germany." doi:10.5880/GFZ.b103-12066.2010.

[50] Möller F, Liebscher A, Martens S, Schmidt-Hattenberger C, and Kühn M. (2012) "Supplement 2011 to: Möller F, Liebscher A, Martens S, Schmidt-Hattenberger C, and Kühn M.: Yearly Operational Datasets of the CO_2 Storage Pilot Site Ketzin, Germany." doi:10.5880/GFZ.b103-12066.2011.

[51] Möller F, Liebscher A, Martens S, Schmidt-Hattenberger C, and Kühn M.(2013) "Supplement 2012 to: Möller F, Liebscher A, Martens S, Schmidt-Hattenberger C, and Kühn M.: Yearly Operational Datasets of the CO_2 Storage Pilot Site Ketzin, Germany." Deutsches Geo-ForschungsZentrum GFZ. doi:10.5880/GFZ.b103-12066.2012.

[52] Möller F, Liebscher A, Martens S, Schmidt-Hattenberger C, and Kühn M.(2015) "Supplement 2013 to: Möller F, Liebscher A, Martens S, Schmidt-Hattenberger C, and Kühn M.: Yearly Operational Datasets of the CO_2 Storage Pilot Site Ketzin, Germany." Deutsches Geo-ForschungsZentrum GFZ. doi:10.5880/GFZ.b103-12066.2013

[53] Möller F, Martens S, Liebscher A, and Streibel M. (2015) "Supplement to: Dataset of the Back-production Test at the CO_2 Storage Pilot Site Ketzin, Germany." doi:10.5880/GFZ.CGS.2015.001.

[54] Möller F, Liebscher A, and Schmidt-Hattenberger C. (2016) "Dataset of the Brine Injection at the CO_2 Storage Pilot Site Ketzin, Germany." doi:10.5880/GFZ.6.3.2016.001.