Meyer et al describe the estimation of the porosity parameter in a steady-state groundwater flow model of a coastal region in Denmark, using 14C dated groundwater samples as a calibration target. We find this a very interesting work and welcome the effort to calibrate groundwater models on targets other than groundwater heads. Such efforts are crucial to improve our understanding of groundwater flow in coastal environments.

However, their paper did spark two comments we could not resist to raise.

1. The groundwater flow system cannot be assumed stationary over the timescales considered Meyer et al use a stationairy groundwater flow model to calculate the age of groundwater at measurement locations, and compare this with corrected 14C dates at these locations. Their model represents the present-day groundwater system, and is forced with present-day boundary conditions. However, the historical trajectory of the measured water droplets has likely been far more complex than assumed in the stationary flow model. Sea level changes, shifting of coastlines, marine transgressions and subsequent infiltration of sea water, drainage of arable land, land subsidence, development of well fields all significantly alter groundwater flow patterns over the timescales considered. See e.g. Delsman et al. (2014) in HESS (sorry to cite our own work), where we show – in a very similar hydrogeological setting – massive changes in groundwater flow patterns occurring over millennia, and even over the very last decades. The authors do acknowledge the non-stationarity of groundwater flow patterns at larger timescales, by discarding all samples over 5 pMC of activity. But that still leaves samples with a corrected age of 1800 years in the data set, a timeframe in which a lot can happen. For example, as described by Meyer et al., "low-lying marsh areas (with elevations below mean sea level) in the west were reclaimed from the Wadden Sea."

With profound effects on groundwater flow patterns: "the large drainage network, established in the reclaimed terrain keeping the groundwater table constantly below the sea level, acts as a large sink for the entire area." And while this dominant flow-defining feature has only been present for the last 200 years, the analysis presented by Meyer et al assumes the present-day groundwater flow pattern to have existed for at least 1800 years. Furthermore, the North sea level has risen about 2 m over the past 1800 years (Van de Plassche, 1982). Given the very shallow local bathymetry, the coastline of 1800 years ago may have been located as far as 25 km westward of its present-day position. Such significant changes should in our opinion be accounted for (for instance by paleo-hydrogeological modeling) before attempting to use age data as a calibration target.

2. Density effects may significantly affect groundwater flow patterns and should be addressed Our second point concerns the use of a constant-density groundwater flow model in the analysis. In this specific coastal groundwater system, saline groundwater has clearly been detected from an airborne electro-magnetic survey (Støvring Harbo, 2011; Jørgensen et al., 2012). This means density variations will significantly affect groundwater flow patterns and should have been addressed in the analysis, e.g. by using the computer code SEAWAT. Correcting the seaward boundary for density effects will unfortunately do little to improve modeled inland flow patterns (and hence calculated age distributions) affected by density variations. Simmons (2005) has a nice way of showing the importance of density variations, by equating a typical head gradient of 10-3 to the density effect caused by a density difference of only 1 kg/m3 (5% seawater). In addition, we wonder if the seaward boundary condition accurately represents the connection of the groundwater flow system to the *groundwater flow system underlying the North Sea. The boundary condition is located directly next to the system of interest, and seems to be applied without taking into account the likely seaward extension of the clay layers that are depicted in Figure 2. Therefore, given the issues outlined above, we wonder if the conceptualization of the groundwater flow model used by Meyer et al is indeed sufficient to accurately model groundwater age, and if the obtained results are not merely a case of "The right result, for the wrong reasons" (Beven, 1993)*

AC:

Conceptually, we agree with the comments that non-stationary boundary conditions and density effects have an influence on the age distribution. However, we would like to emphasize that the aim of our study is the calibration of porosities and the subsequent analysis of groundwater ages in the entire regional aquifer system. Our previous study (Meyer et al., 2018b) **showed that the area outside the marsh is relatively insensitive to changes in fluxes at the coastal boundary. Our data points, except at location A and B, are located quite far away from the marsh area and, more importantly, upstream from the coastal area where the boundary conditions change. Hence, we expect relative small changes in simulated ages, at least when compared to other uncertainties of our approach that are mostly related to measurement, analysis and correcting the C-14 derived ages.**

Still, in order to investigate the influence of density and non-stationary boundary conditions we made a few test runs with the particle tracking model and a preliminary SEAWAT model. We compare the 200 years travel length for 12 particles released in each location A1, B1, C1, D1, E1, E3 and F3 for the original case, presented in this study and in the density-dependent system (SEAWAT) (similar to the one presented in Meyer 2018, PhD thesis). The SEAWAT model accounts for density effects and simplified palaeo-hydraulic conditions (lower sea levels according to Behre (2007), absence of drainage canals) over three stages for the precedent 6000 years. The results in the table below correspond to stage 1 (oldest), where the sea level was 2 m below today's level and represent the highest changes in the particle tracking path length ("worst" case). The results indicate that the relative change in particle travel length is higher closer to the marsh area (A1 and B1) compared to the other locations further upstream. The relative differences are, however, relatively small (especially for the wells located to the east where relative differences below 10% are found) compared to the other uncertainties in our model approach. Therefore, we believe that our approach is applicable. It allows us to estimate a distributed porosity field, which of course is prone to uncertainties of different kinds.

We added the reference "Delsman et al. (2014)" to the discussion of uncertainties which are, among others, due to non-stationarity of the system. Moreover we have added a short discussion about the uncertainties that arises from neglecting density effects, which are mainly expected to be relevant close to the coast, but less in the upstream area. Our study highlights the importance of the effective porosity as a transport parameter and the benefit of using the 7-effective porosity model compared to the uniform one.

Changes made:

“The area close to the coast is not only affected by changing sea levels during the past thousands of years, but also by saltwater intrusion. In this study, the density effects on flow were accounted for in a simplified way by using a density-corrected constant head boundary at the coast. Both, sea level changes and density effects, would also have affected the age distribution. The impact on age calculations due to density effects would be largest close to the coast. However, most of the groundwater samples used for age estimations were collected several tens of km inland and are therefore expected to be affected to a minor extent. To quantify the impact of boundary conditions and saltwater intrusion on the particle tracking, the differences of particle travel path lengths for a 200 year period, investigated based on the present model and a preliminary density-driven model (SEAWAT) accounting for non-stationary and density effects (similar to the one presented in Meyer, 2018c) are computed. The relative differences are below 10% (except at location A and B). Also, the uncertainties introduced by simplifying the density boundary effects are likely less important compared to other uncertainties associated, e.g., with estimating the groundwater age by the procedures for correcting ^{14}C activities. A solution would, of course, be to use a fully density-driven model such as SEAWAT as in (Meyer et al., 2018a) or Delsman (2014). But, the very long computer run times for these kinds of models and the need of several thousands of model runs during calibration made it infeasible to use a variable-density flow model.”

MODPATH average particle path length [m] for 200 years	A1	B1	C1	D1	E1	E3	F3
steady-state MODFLOW	2645	2714	173	120	1215	5685	2407
sea level -2m, density-dependent	2238	2364	164	117	1235	5235	2422
rel diff (%) [abs((stage1-original)/original *100)]	15	12	5	3	2	8	1

Additional references

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