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Hydrology and Earth System Sciences
Discussions

Interactive comment on "Are maps of nitrate reduction in groundwater altered by climate and land use changes?" *by* Ida Karlsson Seidenfaden et al.

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Reply: Referee #3 General comments The authors investigate how nitrate reduction is affected by climate and land use changes for one Danish catchment. This is important as nitrate reduction maps are usually considered to be constant in time, which might not be appropriate for water quality management. With a modelling approach using MIKE SHE and Daisy, the authors show that climate has a stronger impact on nitrate reduction.

General comments: - The introduction is too brief; it should inform why land use and climate changes are relevant to NO3-reduction. This is not explicitly mentioned. The key word “denitrification” also needs to be included. Thank you for pointing out this issue. We have included the denitrification term and added a paragraph on climate change/land use influences on reduction in L73-80: Even as, the link between climate change, land use change and nitrate reduction has been established in previous studies (e.g. Fleck et al., 2017; Mas-Pla and Menció, 2019; Olesen et al., 2019; Ortmeyer et al., 2021; Sjøeng et al., 2009). Ortmeyer et al. (2021) used a water balance model combined with a lumped-parameter nitrate mass model for an area in Germany, finding that nitrate concentrations in the groundwater increased towards the end of the century by up to 89 % as a result of changes in temperature, evapotranspiration and precipitation. Mas-Pla and Menció (2019) found that climate change in turn affects groundwater recharge and thus the dilution of nitrate in the subsurface in a study in Catalonia. While, Paradis et al. (2016) found that new agricultural practices under changing climate conditions led to substantial nitrate increases on an Island in eastern Canada.

Fleck, S. et al., 2017. Is Biomass Accumulation in Forests an Option to Prevent Climate Change Induced Increases in Nitrate Concentrations in the North German Lowland? , 8(6): 219. Mas-Pla, J., Menció, A., 2019. Groundwater nitrate pollution and climate change: learnings from a water balance-based analysis of several aquifers in a western Mediterranean region (Catalonia). Environ Sci Pollut Res Int, 26(3): 2184-2202. DOI:10.1007/s11356-018-1859-8 Olesen, J.E. et al., 2019. Nitrate leaching losses from two Baltic Sea catchments under scenarios of changes in land use, land management and climate. Ambio, 48(11): 1252-1263. DOI:10.1007/s13280-019-01254-2 Ortmeyer, F., Mas-Pla, J., Wohnlich, S., Banning, A., 2021. Forecasting nitrate evolution in an alluvial aquifer under distinct environmental and climate change scenarios (Lower Rhine Embayment, Germany). Science of The Total Environment, 768: 144463. DOI:https://doi.org/10.1016/j.scitotenv.2020.144463 Paradis, D. et al., 2016. Groundwater nitrate concentration evolution under climate change and agricultural adaptation scenarios: Prince Edward Island, Canada. Earth Syst. Dynam., 7(1): 183-202. DOI:10.5194/esd-7-183-2016 Sjøeng, A.M.S., Kaste, Ø., Wright, R.F., 2009. Modelling future NO3 leaching from an upland headwater catchment in SW Norway using the MAGIC model: II. Simulation of future nitrate leaching given scenarios of climate change and nitrogen deposition. Hydrology Research, 40(2-3): 217-233. DOI:10.2166/nh.2009.068

- The methods should be more clearly described and structured. It is hard to follow the steps sometimes. Why are there three subsections on the nitrate model in the Method section? Is there potential to merge them? From reading the titles I do not directly know where to expect what content. Why do you define the terms in the very end of the chapter, not when talking about the data or modelling periods? Consider restructuring. Thank you for this comment. Yes, the section was unfortunately somewhat unclear. We have restructured and added extra information to the method section and changed the headlines, as well as added some extra introductory sentences to the method section (L121-L137). The reason for defining the period terms at the end of the chapter is due to the fact that the future scenarios have not yet been introduced in the Study site chapter, and that calibration/validation periods are not the same as the complete observational period.

- The evaluation of the model needs to be more in depth. The calibration approach needs to be better explained. Was there no calibration with nitrate concentrations? Validation results should be presented and model uncertainties in relation to the calibration/parameters need to be discussed. Maybe a sensitivity analysis would be helpful. The results are very long compared to a very short discussion and no conclusion section, consider streamlining and moving content to supplemental material. Thank you for pointing out this weakness. We have restructured and added text to the method section to improve the paper and added information and restructured the results section (4.1) on validation of the model. As suggested, we have moved figures to the supplementary material and added a conclusion (see response to L516).

- Please revise the consistency (e.g. N, nitrate, nitrogen usage (e.g. L124) or L 126) and language (e.g. sometimes singular and plural are mixed or incomplete) Thank you, we have gone through the text to streamline definitions.

Specific comments: - L9-11 long first sentences, consider splitting. This sentence has been revised: Nitrate reduction maps have been used routinely in Northern Europe for calculating efficiency of remediation measures and impact of climate change on nitrate leaching. These maps are therefore valuable tools for policy analysis and mitigation targeting.

- L10: impact “of” climate change Corrected.

- L14: consider rewording “potential errors”, what errors? This is unclear to me at this point Thank you, this sentence has been revised.

- L20: What do the authors propose to constrain the uncertainty of model formulation and assumptions? This is a valid and important question, but unfortunately not one that can be answered easily. One approach could be testing multiple model setups or types on the same study area, however due to computational and time limitations this is however not always feasible. We have added a few reflections on this in the abstract: To account for this uncertainty multiple approaches, assumptions and models could be applied for the same area, however as these models are very time consuming this is not always a feasible approach in practice. An uncertainty in the order of 10% on the reduction map may have major impacts on practical water management. It is therefore important to acknowledge if such errors are deemed acceptable in relation to the purpose and context of specific water management situations.

Introduction: - L35: “The amount of nitrate reduction occurring in groundwater depends on the flow paths and the depth to the redox interface.” is very brief considering for example the Damköhler number. This part would benefit from a bit more in depth. What about availability of electron donors? We have added some more text on this: In the groundwater zone, nitrate reduction (nitrate reduction) takes place when nitrate containing water migrates from aerobic to anaerobic conditions and inherent reduced compounds are available (Hansen et al., 2014; Postma et al., 1991). For quaternary sediments these reduced compounds are mainly organic carbon and pyrite and ferrous ion from clay minerals (Ernstsen and Mørup, 1992; Postma et al., 1991). This transition zone between aerobic and anaerobic conditions is denoted the redox interface.

Ernstsen, V., Mørup, S., 1992. Nitrate reduction in clayey till by Fe(II) in clay minerals. Hyperfine Interactions, 70(1): 1001-1004. DOI:10.1007/BF02397497 Hansen, A.L., Christensen, B.S.B., Ernstsen, V., He, X., Refsgaard, J.C., 2014. A concept for estimating depth of the redox interface for catchment-scale nitrate modelling in a till area in Denmark. Hydrogeology Journal, 22(7): 1639-1655. DOI:10.1007/s10040-014-1152-y Postma, D., Boesen, C., Kristiansen, H., Larsen, F., 1991. Nitrate Reduction in an Unconfined Sandy Aquifer: Water Chemistry, Reduction Processes, and Geochemical Modeling. Water Resources Research, 27(8): 2027-2045. DOI:10.1029/91wr00989

- L36: “In areas with Quaternary sediments characterized by groundwater dominated flow patterns and a relatively shallow redox interface, the N-reduction in groundwater can be the dominant removal process.” Please provide a reference Thank you, a reference has been provided: In areas with Quaternary sediments characterized by groundwater dominated flow patterns and a relatively shallow redox interface, the nitrate reduction in groundwater can be the dominant removal process (Hansen et al., 2009).

Hansen, J.R. et al., 2009. An integrated and physically based nitrogen cycle catchment model. Hydrology Research, 40(4): 347-363.

- L43: I do not know why showing maps is considered as “a new approach”. Merz et al. 2009, for example, also showed retention maps and NO3 half-life times. Yes, that is true. The sentence has been revised: An approach for utilizing and illustrating the results and the spatially varying nitrate removal fractions (percentages) are through a nitrate reduction map

– L47: “produced N-reduction maps with a 100 m spatial resolution for a 101 km2 catchment in Denmark," is not helping the argumentation, can be removed.

The sentence has been revised: Hansen et al. (2014) produced nitrate reduction maps for a 101 km2 catchment in Denmark, showing that nitrate reduction may vary from 20% to 70% between neighboring agricultural fields located only a couple of hundred meters apart.

Hansen, A.L., Christensen, B.S.B., Ernstsen, V., He, X., Refsgaard, J.C., 2014. A concept for estimating depth of the redox interface for catchment-scale nitrate modelling in a till area in Denmark. Hydrogeology Journal, 22(7): 1639-1655. DOI:10.1007/s10040-014-1152-y

- L50: This sentence has to be checked for grammar. It is also partly redundant with the next sentence. Thank you, this sentence has been removed.

- L55: "the effect hence is relatively large" please be more specific, "effect" is too vague here. We have specified that it is mitigation effects.

- L57: This sentence is not clear to me. You are saying that N-reduction maps can be used more easily than hydrological models, but actually those models are used to produce the maps. This contradicts. Thank you for this comment. This was indeed not very clear. We have revised the sentence in L68-L70: Using nitrate reduction maps based on a single model run, is clearly a much faster method than running multiple complex hydrological simulation models for large ensembles of scenarios and is therefore a practical tool for policy analysis

And a few places in the section above we have changed "nitrate maps" to singular form, to indicate more clearly that nitrate reduction maps are based on a single run.

- L60: Please revise the sentence. Thank you, this sentence has been revised: It is therefore very relevant to investigate the potential error arising when nitrate reduction maps are assumed to be constant in time. No studies have been reported on that issue.

Methods: - L74: “best”, “long”, “near-complete” Please, specify Thank you, the details of the timeseries have been specified: The discharge station at Kratholm has one of the best nutrient time series in Denmark starting in the 1980s, with near-daily sampling from 1989 (Windolf et al., 2016). The station, therefore, provides a long and near-complete data set for nutrient modelling as well as an extensive water discharge time series (Trolle et al., 2019). The average discharge amounts to 4.4m3/s and the load is approximately 14 kg NO3-N/ha/year.

Trolle, D. et al., 2019. Effects of changes in land use and climate on aquatic ecosystems: Coupling of models and decomposition of uncertainties. Science of The Total Environment, 657: 627-633. DOI:https://doi.org/10.1016/j.scitotenv.2018.12.055 Windolf, J. et al., 2016. Successful reduction of diffuse nitrogen emissions at catchment scale: example from the pilot River Odense, Denmark. Water science and technology : a journal of the International Association on Water Pollution Research, 73(11): 2583-9. DOI:10.2166/wst.2016.067

- L76: “The average discharge amounts to 4.4m3/s and the load is approximately 14 kg NO3-N/ha/year.” Reference or more details needed Time period for the averages are added, as well as a reference on trends in the nitrate time series. See the comment above.

- L79: reformulate “There were measurements” Sentence has been revised: 226 measurements of the redox depth are available from boreholes in the area, the redox depths were mainly interpretated based on sediment colour as described by e.g. Ernstsen and Mørup (1992), and a few by measurements of reduced compounds.

Ernstsen, V., Mørup, S., 1992. Nitrate reduction in clayey till by Fe(II) in clay minerals. Hyperfine Interactions, 70(1): 1001-1004. DOI:10.1007/BF02397497

-L84: revise “100 meter redox depth map“, I assume you mean the resolution Thank you, this has been corrected.

- L84: “This map” reference unclear, as citations mismatch, it is not clear to me. Thank you, this has been revised: A recent redox depth map of Denmark was created in 2019, where measurements and system variables were used in a machine learning environment to create a detailed redox depth map in 100 meter resolution. This newer map also indicates that the redox depth in the study area is predominantly shallow with 1-10 meter depth, and very few sites of 10-15 meters depth (Koch et al., 2019a; Koch et al., 2019b).

Koch, J., Ernstsen, V., Højberg, A.L., 2019a. Dybden til redoxgrænsen, 100 m grid. In: (GEUS), D.N.G.U.f.D.o.G. (Ed.), Copenhagen, GEUS. DOI:https://data.geus.dk/geusmap/?mapname=denmark#baslay=baseMapDa&optlay=&extent=-139925.69284407864,5929490.944444444,1254925.6928440786,6520509.055555556&layers=redox_dybde_100m_grid
Koch, J. et al., 2019b. Modeling Depth of the Redox Interface at High Resolution at National Scale Using Random Forest and Residual Gaussian Simulation. 55(2): 1451-1469. DOI:10.1029/2018wr023939

- L110: Please give a reference or indication why drains are needed, if locations are unknown. How do you define the “drain level” without this information? A more detailed explanation is now provided in L145-149: The study is heavily tile drained, and it can be assumed that drainage will always be present when it is need in the agricultural areas. However, the actual site-specific location of tile drains are unknown and therefore drains are specified across the entire catchment at a depth of -0.5 meters . Drain flow is however only activated when groundwater level rise above drain level. Apart from representing tile drainage the drainage system also represents small ditches and stream, too small to incorporate into the river system following the approach of Troldborg et al. (2010).

Troldborg, L. et al., 2010. DK-model2009 - Modelopstilling og kalibrering for Fyn. GEUS Report.

- L119 typo “percolation” Thank you, corrected.

-L119: "following methods" specify. Do you use several? Thank you. Yes, the section is very unclear. The complete section on Daisy modelling and calibration have been rewritten: The Daisy model setup for the Odense is contains on roughly 12,000 1D Daisy columns, and the water balance module is based on a previous calibration of the catchment (Børgesen et al., 2013), where root zone leaching and groundwater abstraction is compared with river discharge (Børgesen et al., 2013; Refsgaard et al., 2011). The model is setup so that each column represent unique combinations of soil type, climate, crop rotation and groundwater depth. The Daisy model uses the same climate input and soil parameter setup as MIKE SHE and the sensitive and calibrated unsaturated soil parameter from MIKE SHE were therefore transferred to Daisy. A more detailed description of the Daisy setup can be found in Karlsson et al. (2016). The water balance performance of Daisy was evaluated in the same calibration (2004-2007) and validation periods (2000-2003/2008-2009) as MIKE SHE.

Daisy also simulates nitrate leaching for each soil column that represents a unique combination of soil type, climate, crop rotation and groundwater depth. Crops are fertilized with mineral and organic nitrogen dependent on the farm type and soiltype. The crop recommended nitrogen rate for the years 2004-2007 was used to setup the fertilization scheme. Nitrate leaching input are simulated on daily basis based on the leaching from the permutated crop rotations simulated for the dominating soil type within a 200m x 200 m square grid (Karlsson et al., 2016). Because of the close feedback mechanism between nitrogen yields and nitrate leaching, the simulated mean nitrogen yields were recalibrated to observed annual mean nitrogen yields on Funen (Statistikbanken, 2015) for the dominating soil type for the period 2004-2007. The calibration is conducted by adjusting the crop parameters, following the methodology of Styczen et al. (2004). Nitrogen concentrations of yields were extracted from table values of mean nitrogen contents for different crops (Møller et al., 2005). For crop rotations including clover grass and peas nitrogen biological fixation is calculated using Høgh-Jensen et al. (2004) and nitrogen atmospheric deposition is included as input to the soil using standard Daisy settings for dry and wet deposition

(Hansen et al., 2012). Børgesen, C.D. et al., 2013. Udviklingen i kvælstofudvaskning of næringsstofoverskud fra dansk landbrug for perioden 2007-2011. Evaluering af implementerede virkemidler til reduktion af kvælstofudvaskning samt en fremskrivning af planlagte virkemidlers effekt frem til 2015, DCA - Nationalt Center for Fødevarer og Jordbrug, Tjele, Denmark. Hansen, S., Abrahamsen, P., T. Petersen, C., Styczen, M., 2012. Daisy: Model Use, Calibration, and Validation. Transactions of the ASABE, 55(4): 1317. DOI:https://doi.org/10.13031/2013.42244 Høgh-Jensen, H., Loges, R., Jørgensen, F.V., Vinther, F.P., Jensen, E.S., 2004. An empirical model for quantification of symbiotic nitrogen fixation in grass-clover mixtures. Agricultural Systems, 82(2): 181-194. DOI:https://doi.org/10.1016/j.agsy.2003.12.003 Karlsson, I.B. et al., 2016. Combined effects of climate models, hydrological model structures and land use scenarios on hydrological impacts of climate change. Journal of Hydrology, 535: 301-317. DOI:http://dx.doi.org/10.1016/j.jhydrol.2016.01.069 Møller, J. et al., 2005. Fodermiddeltabel - Sammensætning og foderværdi af fodermidler til kvæg. 64. Refsgaard, J.C. et al., 2011. Vandbalance i Danmark - Vejledning i opgørelse af vandbalance ud fra hydrologiske data for perioden 1990-2010, Copenhagen, Denmark. Statistikbanken, 2015. Statistical regional registrated annual mean yields. (In Danish) https://www.statistikbanken.dk/jord3. Styczen, M. et al., 2004. Standardopstillinger til Daisy-modellen. Vejledning og baggrund, Institut for Vand og Miljø, DHI.

- L121: when is the simulation period? Calibration was mentioned, but what about validation period? This has been added: The water balance performance of Daisy was evaluated in the same calibration (2004-2007) and validation periods (2000-2003/2008-2009) as MIKE SHE.

- L129: this is not a sentence The sentence has been corrected: Nitrogen concentrations of yields were extracted from table values of mean nitrogen contents for different crops

- L135: bad title The title has been changed to: 3.3 Calibration of the nitrate model (Phase 3)

- L139: “If the particle penetrates the redox interface, the nitrate is assumed to be removed completely and instantaneously by denitrification.” Please, reflect more on this assumption. This is a generally accepted assumption in geochemistry (Postma et al., 1991; Hansen et al., (2014). We have added reference to validate this assumption. Hansen AL, Christensen BSB, Ernstsen V, He X, Refsgaard JC (2014) A concept for estimating depths of the redox interface for catchment scale nitrate modelling in a till area. Hydrogeology Journal, 22, 7, 1639-1655. Postma D, Boesen C, Kristiansen H, Larsen F (1991) Nitrate reduction in an unconfined sandy aquifer: water chemistry, reduction processes, and geochemical modeling. Water Resources Research 27:2027–2045.

- L143: section 0 Corrected to section 3.4

- L175-181: Please, specify how you can state that this was or was not the case? How did you further investigate the stuck particles? How many particles get stuck? It seems quite a lot if the correction causes changes between -7 and 9%. Yes, this issue is very frustrating. The issue has been observed before, when running Mike She with particle tracking. From the tracking file we can see that these particles do not leave their cell of origin. We have tried different approaches to eliminate the stuck particles (e.g. placement of the particles in different locations within the cell). Unfortunately, there was no fix for this issue, even as it was reported to the responsible company behind Mike She (DHI). We have estimated the number of stuck particles in the model an average of 9 % of particles.

- L183: Revise the sentences. Also, what was tried to improve the numerical difficulties? This sentence has been revised and more information added: Mike She is a commercial modelling tool and therefore there is no possibility to access the modelling code in order to correct this numerical error, or in any other way account for this model limitation. Therefore, it was necessary to introduce a correction scheme.

- L184: I did not understand how the correction was done and also why this approach was used. Please, explain. We have added a better explanation on how this correction was done: The actual fate of these stuck particles (reduced/non-reduced) are unknown. At an early stage the assumption was made that the captured particles, if they had moved correctly through the system, would be subject to a fate similar to the non-captured particles, i.e. that the relationship between reduced/non-reduced was the same. If this assumption is valid the calculation the reduction potential in each grid cell is the same with/without the stuck particles. Unfortunately, this assumption may not always be valid. Furthermore, the arrival percentage estimated by the two methods are not the same as not all particles are released in the complex particle arrival count, the data from which is the only way to calibrate the nitrate model. For the two methods to be comparable it is therefore necessary to exclude the particles that are stuck in the unsaturated zone. The correction factor is therefore introduced to eliminate the particles that are stuck from changing the reduction map. The correction uses a simple linear equation, where a correction factor is manually fitted so that the arrival percentage (originating from the reduction map multiplied by the nitrate input) matches the particle arrival percentage. These corrections are done individually for all reduction maps, and the correction causes a change in the reduction in the range of -7% to 9% with a mean of 2%.

- L196: The reference seems quite old for climate projections. Thus projections for the end of this century might contain much higher uncertainty. Please explain why you used this one and not a newer study. Thank you for this comment, it is entirely true that the newer projection may be less uncertain. Unfortunately, the study was conducted some years ago and is therefore using the climate projections available at the time. We, unfortunately, do not have the possibility to rerun the complete modelling suite with the updated climate change scenarios.

- L197: I do not know why bias-corrections are necessary, please explain. Thank you for your question. The bias correction is done because the regional climate model operates on much larger scale than hydrological models. Local precipitation patterns are thus not necessarily correct represented in the regional models. Bias correction to local observations is therefore a common approach for dealing with this issue e.g., Chen et al. (2011), Pasten-Zapata et al., (2019); Refsgaard et al., (2016). We have added the word downscaled to the sentence to help.

Chen, J., Brissette, F.P., Leconte, R., 2011. Uncertainty of downscaling method in quantifying the impact of climate change on hydrology. Journal of Hydrology, 401(3–4): 190-202. DOI:http://dx.doi.org/10.1016/j.jhydrol.2011.02.020

Pasten-Zapata, E., Sonnenborg, T.O., Refsgaard, J.C., 2019. Climate change: Sources of uncertainty in precipitation and temperature projections for Denmark. Geological Survey of Denmark and Greenland Bulletin, 43: e2019430102-01-e2019430102-06. DOI:https://doi.org/10.34194/GEUSB-201943-01-02

Refsgaard, J.C. et al., 2016. Climate change impacts on groundwater hydrology – where are the main uncertainties and can they be reduced? Hydrological Sciences Journal, 61(13): 2312-2324. DOI:10.1080/02626667.2015.1131899

- L200: a “combined” median model? Thank you, this has been explained better: The four selected realizations represent a wet, +19% in precipitation (ECHAM-HIRHAM5), a dry, -11% decrease in precipitation (ARPEGEâĂŤRM5.1), a warm, +3.4 °C temperature increase (HadCM3-HadRM3) and a model representing a median projection, +10% in precipitation and +2.1 °C in temperature (ECHAM5-RCA3).

- L210 I do not understand “3% point reduction”. What is point telling here? We wanted to indicate that it is percentage point difference and not a difference in percentage. We have change it to p.p. which may be a more common way to write it.

- L218f.: I do not understand this combination that was done: “compared to the climate model results found for the reference period 1990-2009 using the same land use scenarios, resulting in 32 scenarios.” I think formulations are overcomplicated and Table 3 should be placed here. Thank you for this comment. We have moved table 3 to this location and revised the sentence: All 20 combinations of future climate projections (4) and land use (5) were specified as input to the hydrological model. The model was run for both future (2088-2099) and reference period (1990-2009) resulting in 40 scenarios. Additionally, the model was run with observed climate for the period 1990-2009 (5 scenarios using observed land use and the four land use scenarios).

Results: - L240: “observed trends in nitrate yields” where are these trends shown? Yes, trends is the wrong word. We have changed it to: observed values of nitrate yields

- Table 3: I think this should be presented in the Methods? 3.6 scenarios? What does the grey shade mean? How can the climate scenarios be used for 1990-2009? Or is it necessary? I do not see them later in the presented maps. Thank you, the table has been moved accordingly. The grey shades indicate the scenarios displayed in the coming figures 3,4,6,7,8, and the baseline scenario. We have added text in the figure caption to explain.

Thank you for you question on the climate scenarios. Climate models are commonly run for both a reference period in the present time and a future period. As climate model results are affected by biases, even though they are bias corrected/downscaled, the way of dealing with this issue is mainly solved by displaying only changes from past to future. This is done under the assumption that the climate model biases are constant (the same for present and future conditions), thereby changes in the impact results are deemed more trustworthy than actual values from the future projections. This is the reason why figure 4-9 all focus on the changes from past to future. We have added an extra explanatory sentence in line 312: Future climate model runs are always compared with results from this period for the relevant climate model to ensure that climate model biases do not dominate the results.

- Table 4: Do you have an idea why the standard deviations of all models are that similar (Table 4, 0.36-0.39)? Can you comment on that, please? This could be related to the fact that most changes in the reduction map are happening for values close or around the mean. Areas with 0% og 100% reduction are perhaps less likely to change reduction potential, as they are either very close to surface water (0% reduction) or located at areas with a deep groundwater level (long deep flow paths and limited drain flow) (100% reduction).

- L295: “To investigate to what degree land use changes and climate change affect the reduction map, the difference between these scenarios and the reference scenario is shown in Figure 4.” Does not seem to fit here if the next section title is “4.4 Impact of land use change on reduction maps”. Yes this is confusing. We have moved this sentence and incorporated it into L391: To investigate the impact of land use change on the reduction maps, only land use is changed while climate remains constant, shown as the difference between land use changes scenarios and the baseline scenario (Figure 4, top row).

- Figure 3 and Figure 4 seem a bit redundant to me, considering that 4 is just the difference between the map shown in Fig2 and Fig3. I think one Figure could be economized here by merging or moving to the supplements Thank you for this suggestion, we have moved Fig. 3 to supplementary material, and moved the sentence in L274-276 connected to the figure with it.

- I think it is not necessary to show Fig7 and Fig8, especially because Fig.8 is mainly a reprint of Fig.12 in Karlsson et al. 2016, while the maps in Fig.7 do not allow to recognize more details than the general observation of land use changing little, two climate scenarios becoming wetter and two drier, which is also clear from Fig.5. Again I think redundancy should be reduced and plots removed or to the supplements. Thank you for this suggestion, we have moved Fig. 7 and 8 to supplementary material.

Discussion/Conclusions: - L510: “such effects” reference unclear. Please explain further how 10% change in nitrate reduction over almost a century relates to the uncertainties of nitrate reduction maps. Is it really essential to consider changes in nitrate reduction for management, if the tool itself is already quite uncertain? Thank you, we have made this sentence more clearly: The uncertainty of using a fixed reduction map for future scenarios should of course be seen in the context of the inherent uncertainties of the nitrate reduction maps (Hansen et al., 2014b). We have also added some reflections on the impact for management, L593-595: 10% error on the reduction map may potentially have major impacts on practical water management. Considering for instance the baseline scenario in Table 4, where the average N-reductions vary between 55% and 67% reduction, this implies that the net impact of a 100 kg N reduction in leaching from the root zone will vary between 45 kg and 33 kg (i.e. 30%). Such changes are larger than the effects of sophisticated mitigation measures (Hansen et al., 2017). Hansen, A.L., Gunderman, D., He, X., Refsgaard, J.C., 2014b. Uncertainty assessment of spatially distributed nitrate reduction potential in groundwater using multiple geological realizations. Journal of Hydrology, 519, Part A: 225-237. DOI:http://dx.doi.org/10.1016/j.jhydrol.2014.07.013 Hansen AL, Refsgaard JC, Olesen JE, Børgesen CD (2017) Potential benefits of a spatially targeted regulation based on detailed N-reduction maps to decrease N-load from agriculture in a small groundwater dominated catchment. Science of the Total Environment, 595, 325-336.

- L512-516: “single case study” how representative is this case? What do you expect for other sites? Compare to other studies. General spatial differences between nitrate reduction could be considered. Thank you for this valid point. Unfortunately, we are not aware of any other studies evaluating uncertainties from application of a fixed reduction map vs. a full nitrate modelling scenario estimation. We have added a few remarks: The indication that errors can be up to 10% is based on only a single case study with one catchment, one model and a limited number of land use and climate change scenarios. While similar results may be found when applying the same approach for catchments governed by the same dominant flow processes and land use types, like the one investigated in this study. The error must be expected to be site and context specific and therefore causes . . .

- L513-516: You mention uncertainties of input data (climate and land use) and model structure (though very briefly) but do not discuss the uncertainties related to the model and its parameters. Thank you, yes this is not mentioned. We have added text on this issue in L606-615: The error must be expected to be site and context specific and therefore causes projection uncertainties that should be addressed along with other known sources of uncertainty such as climate model projections, land use projections, parameter uncertainties, geological uncertainty, and hydrological model structural uncertainty (Hansen et al., 2014b; Karlsson et al., 2016). Furthermore, during calibration and setup of the model assumptions must be made, adding to the uncertainty. Parameter estimation are here done in a stepwise fashion, and the catchment scale calibration of Daisy along with a particle tracking approach limits the evaluation of performance of the nitrate component to mean catchment figures, and the dynamic of the nitrate system is thus impossible to verify. To account for this a full solute transport solution would be necessary but was unfortunately not possible in the framework of this study; but would be a relevant next step in investigating uncertainties and improve model verification.

- L516: This is not a nice ending. I would collect the conclusions in an extra Conclusion section. Thank you for this suggestion. We have added a conclusion section: Nitrate reduction maps are valuable tools used for calculation of remediation and climate change effects on nitrate leaching, and are generally considered constant in time, even though the timing of nitrate leaching, and flow paths may change. In this study we investigate the potential consequence for estimation nitrate climate and land use change impact projections when assuming a fixed reduction map. For an agricultural dominated catchment in Denmark, the Daisy model was used to provide nitrate leaching input, while the hydrological model Mike She was used to simulate the flow regime and nitrate flow path through particle tracking. Four land use scenarios and four climate change projections were evaluated. The main finding of the study was: âĂć Changing climate conditions lead to reduction map changes of up to 10%; whilst effects from land use changes where minor. However, land use effects may be underestimated due to drainage formulations in non-agricultural areas. âĂć Thus, the uncertainty of the reduction maps is dependent on both model setup and assumptions, the catchment flow regime as well as affected by the span of the chosen land use and climate change scenarios. âĂć The error will therefore be specific for the study site and context and it should, consequently, be tackled along with other sources of uncertainty, like geological, parameter, and model structure uncertainties that are not evaluated in this study.

Data/code availability: - “owned by the DMI” - what does this mean? Where and how to access it? The data is currently not pubplily available from the Meteorological service, but will be in the future. We have added this information in L576-569: An exception to this is the observed climate data input which is currently the property of the Danish Meteorological Institute (DMI), but will be made publicly available through https://www.dmi.dk/frie-data/ before end of 2023.

Figures: - F1: typo at “Market driven”. Odd start of the caption as the Figure is showing the study area and land use scenarios and not a “red square”. Thank you, we have corrected the typo and the formulation in the figure text.

- F2: I think the map titles should be linked to the legend color bars. Maybe increase letter size of legend, add unit at left panel. To me it is unclear, what the text on the y axis refers to “Observed climate. . .”, it seems unconnected. In the caption specify what the reduction refers to e.g. from. . . to. . .. Thank you for these suggestions. We have changed the figure according to the comments.

- F5: I suggest to remove redundant subplot titles, this should be explained in the caption. It has been removed

- F9: The caption is unclear to me. What combinations are shown? What is meant here “or the reduction map from the scenarios”? We have tried to explain better what we mean: Bars denote the change in nitrate flux at the catchment outlet that arises from using either a fixed nitrate reduction potential map (baseline) or using a reduction map based on the individual scenarios.

References: - There seems to be an error in the display of the references – is it double or some other problem? Yes, it is double, sorry. This has been corrected.

Please also note the supplement to this comment:
https://hess.copernicus.org/preprints/hess-2020-570/hess-2020-570-AC3-supplement.pdf

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Interactive comment on Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2020-570, 2020.