Climate model uncertainty versus conceptual geological un certainty in hydrological modeling

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4 T. O. Sonnenborg¹, D. Seifert² and J. C. Refsgaard¹

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6 [1] {Geological Survey of Denmark and Greenland (GEUS), Department of Hydrology

7 Øster Voldgade 10, DK-1350 Copenhagen}

8 [2] {ALECTIA A/S, Water & Environment, Teknikerbyen 34, DK-2830 Virum}

9 Correspondence to: T.O. Sonnenborg (tso@geus.dk)

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11 Abstract

12 Projections of climate change impact are associated with a cascade of uncertainties in-13 cluding CO₂ emission scenario, climate model, downscaling and impact model. The 14 relative importance of the individual uncertainty sources is expected to depend on sev-15 eral factors including the quantity that is projected. In the present study the impacts of 16 climate model uncertainty and geological model uncertainty on hydraulic head, stream 17 flow, travel time and capture zones are evaluated. Six versions of a physically based and 18 distributed hydrological model, each containing a unique interpretation of the geological 19 structure of the model area, are forced by 11 climate model projections. Each projection 20 of future climate is a result of a GCM-RCM model combination (from the ENSEM-21 BLES project) forced by the same CO₂ scenario (A1B). The changes from the reference 22 period (1991-2010) to the future period (2081-2100) in projected hydrological variables 23 are evaluated and the effects of geological model and climate model uncertainties are

quantified. The results show that uncertainty propagation is context dependent. While the geological conceptualization is the dominating uncertainty source for projection of travel time and capture zones, the uncertainty due to the climate models is more important for groundwater hydraulic heads and stream flow.

28

29 **1 Introduction**

30 Climate change will have major impacts on human societies and ecosystems (IPCC, 31 2007). Climate change adaptation is, however, impeded by the large uncertainties aris-32 ing from climate projection uncertainties as well as the uncertainties related to hydro-33 logical modelling (Foley, 2010; Refsgaard et al., 2013). Uncertainties related to climate 34 projections are often considerable (Déqué et al., 2007; Seaby et al., 2013; IPCC, 2013), 35 and may be divided into internal variability, model uncertainty and scenario uncertainty. 36 Several studies (e.g., Hawkins and Sutton, 2011; Kjellström et al., 2011) have shown 37 that model uncertainty dominates for lead times exceeding a couple of decades, while 38 uncertainties on greenhouse gas emissions will take over towards the end of the present 39 century. Assessments of uncertainties on climate change impacts on water resources 40 become complicated, because climate projection uncertainties should be propagated 41 through hydrological models, where a range of additional uncertainty sources needs to 42 be considered. These sources include uncertainties in input data, parameter values and 43 model structural uncertainties, i.e. conceptualisation of the representation of vegetation, 44 soils, geology, etc. and process descriptions (Refsgaard et al., 2007). In hydrological 45 modelling of groundwater conditions, the conceptual geological uncertainty often turns 46 out as the dominant source of uncertainty (Neumann, 2003; Bredehoeft, 2005; 47 Refsgaard et al., 2012).

49	Because of the complexities and computational aspects involved, it is not feasible to
50	explicitly consider all sources of uncertainty in a single study. It is therefore interesting
51	to know in which contexts the different sources of uncertainties will be dominating.
52	Several studies have assessed the uncertainty propagation from climate projections
53	through hydrological modelling (Minville et al., 2008; Bastola et al., 2011; Poulin et al.,
54	2011; Dobler et al., 2012) concluding that in some cases climate model uncertainty
55	dominates over hydrological model uncertainty and vice versa in other cases. These
56	studies have focussed on surface water hydrological systems, while we are not aware of
57	studies that have investigated the relative importance of conceptual geological model
58	uncertainty versus climate model uncertainty.
59	
60	The objective of the present study is to assess the effects of climate model uncertainty

and conceptual geological uncertainty for projection of future conditions with respect to
different river flow and groundwater aspects.

63

64 2 Study area and model setup

65 2.1 Study area

66 The study site has an area of 465 km^2 and is located in the central part of Zealand,

67 Denmark (Fig. 1) where focus is given to the area covered by the Langvad Stream val-

68 ley system. The model area is bounded by Køge Bay in the east and by Roskilde Fjord

69 in the north. The area is relatively hilly, with maximum elevations of approximately 100

70 m above sea level. Land use within the model area is dominated by agriculture (80 %),

71	while the remaining area is covered by forest (10 %), urban areas (10 %) and lakes (<1
72	%). The main aquifer in the area, the Limestone formation, is overlain by Quaternary
73	deposits of interchanging and discontinuous layers of clayey moraine till and fluvial
74	sand. Groundwater is abstracted at six main well fields in the focus area and exported to
75	Copenhagen for water supply. The study area is described in details in Seifert et al.
76	(2012).

78 2.2 Model setup

79 Based on the national water resource model developed by the Geological Survey of 80 Denmark and Greenland (Henriksen et al., 2003; Højberg et al., 2008; Højberg et al., 81 2013) a hydrological model of the catchment area has been developed. The model is 82 constructed using the MIKE SHE / MIKE 11 modeling software (DHI, 2009a and DHI, 83 2009b). MIKE SHE includes a range of alternative process descriptions and here the 84 modules for evapotranspiration, overland flow, a two-layer description of the unsaturat-85 ed zone, and the saturated zone incl. drains is used. The river model MIKE 11 links to 86 MIKE SHE, so that water are exchanged between streams and the groundwater aquifers. 87

Six alternative geological models using between 3 and 12 hydrostratigraphical layers (Table 1) have been established (Seifert et al., 2012). The basis of the geological models comprises two national models (N1 and N2), two regional models (R1 and R2) and two local models (L1 and L2). All models consist from bottom to top of Paleocene Limestone, Paleocene clay and Quaternary deposits. In the more complex geological models the Quaternary unit is divided into several alternating sand and clay layers. The location of the limestone surface and the extent of the sand aquifers differ significantly between

95 the geological models. The six geological models were incorporated into the hydrologi-96 cal model resulting in six alternative hydrological models (Seifert et al., 2012). Horizon-97 tally, the models are discretized in 200 x 200 m cells. Vertically, the numerical layers 98 are discretized according to the geological layers, though in model N1 and N2 the three 99 top layers are combined into one numerical layer. Between three and ten numerical lay-910 ers are used in the six models.

101

102 The models are calibrated against hydraulic head and stream discharge data from 2000-103 2005 and validated in the period 1995-1999 (Seifert et al., 2012) where the validation 104 period is characterized by a groundwater abstraction that is about 20% higher than in the 105 calibration period. Generally, the simulation results for the validation period are slightly 106 inferior to the results for the calibration period, but the statistical values have the same 107 magnitude for the two periods. The calibration results (Table 1) reveal quite large dif-108 ferences in the match to hydraulic head (represented by the mean error, ME, and the 109 root mean squared value, RMS), the stream discharge (given by the Nash-Sutcliffe coef-110 ficient, E, and the relative water balance error, F_{bal}) using the different geological mod-111 els. Some models are more suitable for stream flow simulations (e.g., N2) while other 112 models are stronger on hydraulic heads (e.g., L2). However, based on an integrated 113 evaluation the calibration/validation statistics no model is generally superior to the oth-114 ers. More details on the model setup including historical climate data and model calibra-115 tion and validation can be found in Seifert et al. (2012).

116

117 The period 1991-2010 is used as a reference to the future scenarios. In this period the 118 abstraction decreased from 23 million $m^3 yr^{-1}$ in 1990 to less than 15 million $m^3 yr^{-1}$ in

2010. To minimize transient effects a constant groundwater abstraction of about 16 million m³ yr⁻¹ (based on average data from 2000-2005) is used for both the reference period and future scenarios.

122

123 2.3 Climate data

Climate projections representing the period 2081-2100 are obtained from Seaby et al.
(2013) using results from 11 climate models from the ENSEMBLES matrix (Christensen et al., 2009) of Global and Regional Climate Model pairings (GCM-RCM), Table 2.
Seaby et al. (2013) analyzed the impact of the length of the reference and the future
periods and found that period lengths over 15 years appeared suitable for precipitation.
Hence, comparing two 20-years periods is assumed to be adequate for the particular
study area.

131

132 The delta change (DC) method (Hay et al., 2000; van Roosmalen et al., 2007) is used as 133 downscaling approach on precipitation (P), reference evapotranspiration (ET_{ref}) and 134 temperature (T). The delta change factors for Zealand are derived by comparing month-135 ly mean values of past and future climate data from the climate models (Seaby, 2013). 136 The model projections of the future climate changes vary significantly with both drier 137 and wetter future climate indicated by delta change factors on precipitation ranging be-138 tween 0.83 and 1.17 on an annual basis. However, major differences between the mod-139 els are also found with respect to the seasonal signal. To obtain time series of future 140 climate, observed records of P and ET_{ref} in the control period (1991-2010) are multi-141 plied by the monthly delta change factors (ΔP and ΔET_{ref}), while the temperature delta 142 change values (ΔT) are added to the observed time series of T. The reliability of the DC

143 method for projecting changes has rightfully been questioned by Teutschbein and 144 Seibert (2013) who found that more advanced methods were more reliable. In our spe-145 cific case Seaby et al. (2013) compared the DC method with a double gamma distribu-146 tion based scaling (DBS) showing that both methods were equally good in capturing the 147 mean monthly as well as the seasonal climate characteristics in temperature, precipita-148 tion and potential evapotranspiration when tested against observed data for 1991-2010. 149 Seaby (2013) further showed that, when propagating climate projections for 2071-2100 150 through the same hydrological model type as used in our study, the results for the dis-151 charge and groundwater head characteristics used in our study are almost identical for 152 the two bias correction methods. This confirms the results of van Roosmalen et al. 153 (2011) and justifies the use of the simple DC method for our particular application.

154

155 Here, an ensemble of results based on eight RCMs and four GCMs are used and only 156 one downscaling method is used. Using another ensemble of climate models or another 157 downscaling method would probably affect the mean/median of the results. However, in 158 the present study the results from different climate projections are only used for com-159 parison against results obtained using different geological models, and not for predict-160 ing the actual changes in the hydrological system as a result of climate changes. Hence, 161 the ensemble used here is assumed to represent the (unknown) full variability found in 162 climate model projections.

163

164 **3 Methodology**

165 Results from the six hydrological models forced by climate projections from the 11 cli-166 models (total of 66 model simulations) are extracted and the variance caused by

168	representing the reference period 1991-2010 that covers both the calibration and valida-
169	tion periods, to quantify the changes in hydraulic head (Δh) in the Limestone aquifer in
170	the focus area (Fig. 1), changes in stream discharge (ΔQ) at a downstream gauging sta-
171	tion in the Langvad Stream system, travel time (ΔT) and capture zone area (ΔA_{cap}) for
172	the well fields in the focus area. The change in hydrological variables is caused by cli-
173	mate change only as the geology is the same for both reference and scenario climate.
174	
175	3.1 Hydraulic head and stream discharge
176	The mean hydraulic head (h) in the Limestone aquifer within the focus area are extract-
177	ed from all model simulations and the change in hydraulic head (Δh) as a result of
178	changing climate is calculated.
179	
180	A large part of the precipitation is expected to flow directly to the streams, either as
181	surface runoff or through the drains, especially during the winter season. Hence, the
182	total stream discharge is expected to be highly sensitive to changes in climate. In order
183	to capture the effect of climate change on the groundwater dominated base flow, stream
184	discharge results from the summer period (June, July and August) are extracted at the

geological model and climate model is derived. The results are also compared to results

185 downstream discharge station, st. 52.30 (see Fig. 1).

186

167

187 3.2 Travel time

188 Travel times from the water table to the well fields are estimated by forward particle189 tracking using MIKE SHE. Particles are initially located randomly in the upper 1-3 nu-

190 merical layers depending on how the geology is represented by the numerical layers in 191 the models. The sum of particles in the vertical direction is 200 particles per cell, result-192 ing in about 2 mio. particles per model. The flow solution on which the particle tracking 193 simulation is based is obtained by recycling the flow results for the simulation period 194 (1991-2010 for the reference period and 2081-2100 for the future climate period). After 195 1000 years of simulation the end points are registered and particles with end points at 196 the well fields are extracted. Since the thickness of the numerical layers vary considera-197 ble between the models, only particles originating from the upper 10 meters of the satu-198 rated zone are used for the travel time assessment in order to get comparable results. 199 The median travel time (T) at each well field is calculated for each of the 11 future cli-200 mate projections and for the reference climate. The changes in travel time (ΔT) from the 201 reference climate to the future climate projections are also calculated. Precipitation may 202 affect the hydraulic heads and the hydraulic gradients in a specific area which affects 203 groundwater discharge and hence the flow velocity. Additionally, flow paths to the ab-204 straction well may change as the size of the recharge area changes, see below. Climate 205 change is therefore expected to impact travel time to the abstraction wells.

206

207 3.3 Capture zone

The capture zones to the well fields are also simulated by forward particle tracking where the particles are tracked for 1000 years as described above. Particles are initially located randomly in the upper layers and in all aquifers. Particles with end points at the well fields are extracted and the origin of the particles is projected to the 2D horizontal plane. The capture zones are delineated as the grid cells that contain particle start locations (Fig. 2) and the capture area (A_{cap}) is defined as the area of these grid cells. The

214 change in capture zone area from the reference climate to a future climate is defined as 215 the capture area included in the future climate simulation but not in the reference cli-216 mate simulation (ΔA_{cap}). The location and shape of the capture zone depends on geolog-217 ical characteristics. However, it also depends on groundwater recharge since the water 218 abstracted at the well corresponds to the spatially integrated groundwater recharge 219 which in turn depends on precipitation. Thus, the less groundwater recharge the larger 220 the capture zone will be. Therefore, climate change is expected to affect the capture 221 zone area.

222

223 **4 Results**

4.1 Uncertainty on hydraulic head

The matrix of results on mean hydraulic head within the focus area as a function of climate scenario and geological model is presented in Table 3. In the two columns to the right and the two bottom rows the mean and standard deviation of the results are listed. Changes in hydraulic head between the reference climate simulation and the scenario climate simulation are indicated in brackets.

230 No reference geology is defined and as due to the DC method, the same reference cli-

231 mate is used for all projections, the uncertainty on the change in hydraulic head caused

by climate (Std. dev. climate, bottom row) therefore equals the uncertainty on the abso-

- 233 lute heads. In Table 4, the uncertainty on the absolute head values is summarized to-
- 234 gether with results on the change in heads due to climate change. In Fig. 3 the results
- are illustrated using box plots both with respect to absolute values (Fig. 3a) and with
- respect to changes from the reference to the future period (Fig. 3b). Hence, Fig. 3a cor-

237 responds to the left two columns in Table 4 while Fig. 3b illustrates the results summa-238 rized in the three columns to the right in Table 4. With respect to the absolute hydraulic 239 head values, Fig. 3a and Table 4, the impact of geological model and climate model is 240 comparable. The difference between the mean hydraulic head using the six geologies is 241 primarily caused by differences in calibration results given by the mean errors (ME), see 242 Table 1, since climate change affects the mean hydraulic head of the individual geologi-243 cal model comparatively. For model R2 changes in mean head between -1.12 m and 244 0.82 m are found with a standard deviation of 0.66 m. The mean standard deviation on 245 all six models is 0.52 m, Tables 3 and 4, which is in the same order of magnitude as the 246 standard deviation caused by the different geological models amounting to 1.03 m.

247

248 When the changes in hydraulic head are compared across geological models, Fig. 3b 249 and Table 4, it is clear that the effect of geology is relatively small. Some of the geolog-250 ical models are more sensitive to the changes in climate (e.g., R2) than others (e.g., L2), 251 represented by the length of the whiskers for each geological model in Fig 3. Changes 252 in hydraulic head that are up to twice as high are found for the most sensitive models 253 compared to the models that are relatively insensitive. However, larger differences in 254 hydraulic head change are found across climate models represented by the difference 255 between the upper and lower end of the whiskers. A two-factor analysis of variance 256 shows that the climate model has more impact on the change in hydraulic head than the 257 geological model, as $F_{climate} = 104.6$ (>> $F_{crit} = 2.0$) and $F_{geology} = 1.2$ (< $F_{crit} = 2.4$). The 258 same conclusion can also be drawn from Table 4 by comparing the standard deviation 259 on the changes in hydraulic head (h) caused by geological models (0.11 m) with the 260 standard deviation caused by climate models (0.52 m).

262	Fig. 4 also shows that the direction and the magnitude of the change in hydraulic head
263	depend primarily on the climate model. Three of the climate models result in decreasing
264	hydraulic heads, with values ranging between -0.28 m and -1.16 m depending on the
265	geological model and the climate model. The remaining eight climate models all result
266	in increasing hydraulic heads in the Limestone aquifer between 0.08 m and 0.82 m.
267	
268	From Fig. 4 it is also observed that the difference between the head results from the six
269	geological models is larger when the mean change in hydraulic head caused by climate
270	changes increases in positive or negative direction. For example, climate model BCM-
271	HIRHAM5 that is characterized by delta change values for precipitation close to one
272	during winter season $(0.99 - 1.13)$ results in a small change in mean hydraulic head and
273	the response from the six geological models is almost the same. In contrast, relatively

274 large differences are found between the response from the geological models when the

275 climate model ECHAM-HIRHAM5 is used. Here, the delta change values during 276 winter, where groundwater primarily is generated, are relatively large (up to 1.38) and 277 the mean change in hydraulic head is also relatively large. The same tendency is found 278 for the other climate models. Hence, since the mean change in hydraulic head is 279 expected to depend on the changes in precipitation and evapotranspiration, the mean 280 standard deviation on heads from the different geological models are compared to the 281 change in the net precipitation (here represented by precipitation minus reference 282 evapotranspiration, P-ET_{ref}). The result (Fig. 5) reveals a clear linear tendency for

283 increasing uncertainty caused by geological model as the changes projected by the

284 climate model differs from the present climate, where the model was calibrated. Hence,

as the future climate moves away from the baseline, the more sensitive the results are
with respect to the conceptual geological model and the higher projection uncertainty
might be expected.

- 288
- 289 4.2 Uncertainty on stream discharge

290 Fig. 6a shows a box plot of the simulated mean summer stream discharge at the 291 downstream discharge station (st. 52.30, see Fig. 1). The projection of mean summer 292 discharge depends to a large degree on the geological model, with lower values for the 293 local models (L1 and L2) and higher values for the regional models (R1 and R2). The 294 uncertainty caused by climate model, represented by the length of the whiskers, is also 295 significant with a tendency for larger uncertainties for larger absolute mean summer 296 discharge. The ratio between the standard deviation and the median value is almost 297 constant for the six models. However, the geological model has the strongest impact, 298 resulting in a standard deviation of 0.21 m^3 /s compared to a value of 0.14 m^3 /s caused 299 by climate uncertainty (Table 4).

300

301 In Fig. 6b the box plot of the change in summer discharge from the reference period to 302 the future scenarios shows that the response in summer stream discharge from the 303 different geological models is similar when the median value is considered. On average, 304 the mean change in summer discharge is zero, see Table 4. The difference between 305 upper and lower whiskers indicates that the impact of climate models on the projection 306 of the change in summer stream discharge is significant, with changes from -0.3 to 0.3307 m^{3} /s. The standard deviations listed in Table 4 show that the uncertainty on the change in summer discharge caused by geology is 0.05 m^3 /s whereas the uncertainty caused by 308

309	climate model amounts to 0.14 m^3/s , i.e. the climate uncertainty is largest although the
310	contributions are in the same order of magnitude. With respect to annual mean
311	discharge (Q _a), see Table 4, climate uncertainty is much higher than geological
312	uncertainty, especially when the change in discharge is considered. This shows that the
313	uncertainty on annual mean stream discharge is much more sensitive to climate change
314	than to the geological model. Summer discharge, where groundwater-river interactions
315	are relatively more important, is much more affected by the uncertainty in geology.
316	

317 4.3 Uncertainty on travel time

318 The travel time of the groundwater abstracted at each of the six well fields in the focus 319 area has been quantified and listed in Table 4. The results obtained at the six wells fields 320 are similar, and therefore only results on travel times and changes in travel time are il-321 lustrated for one of the well fields, Lavringe, see Fig. 7.

322

323 The absolute travel times (Fig. 7a) depend strongly on the geological model. Median 324 travel times from less than 50 years to nearly 200 years are found for the different geo-325 logical models. Based on results from all six well fields, differences in median travel 326 time of up to a factor of 10 are found with a tendency for smaller travel times using the 327 geological model R2 and larger travel times using N1. Compared to the results for hy-328 draulic head and stream discharge, Figs. 3a and 6a, respectively, it is clear that the effect 329 of the geological model is crucial when travel times are considered. The standard devia-330 tions on geological models, in the order of 30-80 years (Table 4), are significantly high-331 er than the standard deviations on climate models, in the range of 2-6 years. Hence, 332 the climate model has limited impact on the absolute travel time predictions. This indi-

cates that climate changes do not notably change the flow pattern that controls the flow
paths and hereby the travel time of the groundwater from the surface to, e.g., an abstraction well.

336

337 If changes in travel time from the reference to future climate (Fig. 7b and Table 4) are 338 considered, it is seen that the role of the geological model on the change in travel time is 339 similar to the impact of climate change. The mean standard deviation on the change 340 caused by climate models and geological models are of the same magnitude with values 341 of approximately 2 years for Lavringe well field. At the other well fields comparative 342 results are also obtained with values in the range 2.5 to 7.1 years (Table 4). This is in 343 contrast to the results for hydraulic head and stream discharge where the climate signal 344 was the most important factor for the changes.

345

346 4.4 Uncertainty on capture zones

347 Fig. 8a shows results on capture zone area from Lavringe well field. Capture zone areas between 20 km² and 40 km² are found for the different geological models. If all six well 348 349 fields in the focus area (Fig. 1) are considered the capture zone area varies with a factor 350 of 2-3 using different geological models. In comparison, the effect of climate model on 351 the uncertainty is relatively small. For most models the change in capture zone area caused by climate change (Fig. 8b) amounts to less than 2 km² corresponding to less 352 353 than 10% of the reference area. Hence, the results with regard to the capture zone area 354 are very similar to those found for travel time (Fig. 7).

355

The impacts of climate model and conceptual geology on the capture zone locations are illustrated for Gevninge and Lavringe well fields in Fig. 9. At the left side the uncertainty of the capture zones using different geological models are illustrated. To the right the impact on using different climate models is shown. It is clear that relatively large differences between capture zone areas are found when multiple geological models are used whereas almost identical capture zones are predicted for the 11 climate models.

362

363 **5 Discussion**

364

In Table 4 the uncertainties caused by climate model and geological model are summarized, both with respect to the absolute level in the future situation and the change from the reference to the future situation. The results on the absolute values reflect the differences in model calibration which in turn affects the results in the future climate. It should be noted that no calibration has been carried out with respect to travel time and catchment area.

371

For projections of hydraulic head, the impact of geological model and climate model on the uncertainty on absolute heads is in the same order of magnitude with differences in standard deviations of about a factor of two. If the changes in hydraulic heads from reference to future climate are considered, the climate model is more important for the uncertainty than the geology (difference of a factor of five). Hence, in this case the choice of climate model is very important for the hydrological projection and on the uncertainty on the changes in future hydraulic head levels.

380 The results for summer stream discharge (Q_s) are somewhat similar. The uncertainty on 381 the absolute discharge is almost equally controlled by geological model and climate 382 model, which is comparable to the results for hydraulic head. If the change in summer 383 discharge is considered, the uncertainty caused by climate model is a factor of three 384 higher than geological uncertainty. Hence, climate model uncertainty is most important 385 but both sources of uncertainty are significant. With respect to annual mean discharge 386 (Q_a) the impact from climate model uncertainties on the absolute discharge is a factor of 387 four higher than the geological uncertainty. If the change from reference to future period 388 is considered, the results are even more clear. Almost all the uncertainty is caused by 389 the climate model whereas the geology has almost no impact on the results (standard deviations of 0.01 m^3 /s versus 0.32 m^3 /s). Therefore, the climate model projection is 390 391 extremely important for results on future annual mean stream discharge. The relatively 392 small impact of the geological model is probably explained by the clayey top soils in the 393 catchment that cause discharge to be dominated by shallow flow components such as 394 overland flow and drain flow, especially in the wet season (winter).

395

396 The uncertainty on absolute travel time (left two columns in Table 4) is dominated by 397 the geological model with standard deviations of up to about 80 years, whereas the un-398 certainties due to climate model only amount to a few years. Hence, in this case the geo-399 logical model uncertainty is by far the most important source of uncertainty and the im-400 pact of climate model uncertainty can almost be ignored. However, the uncertainties on 401 the changes (the column to the right) caused by geology is in the same order of magni-402 tude as the impact from climate model. The same type of results is obtained as for cap-403 ture zones (Fig. 8). The geological model dominates the uncertainty on the absolute

capture zone area while the uncertainties on geology and climate have a comparable,

405 and relatively small, effect on the change in capture zone location.

406

407 It should be noted that travel time and capture zone location were not included in the 408 model calibration where only observations on hydraulic head and stream discharge were 409 matched by the models. Hence, travel time and capture area were not constrained 410 against a common target and larger differences between the results from the six models 411 can therefore be expected. Additionally, only model parameters (e.g., hydraulic conduc-412 tivity) but not the geological structure were adjusted to fit the observations and possible 413 structural errors in the geological models are therefore, at least partially, compensated 414 by the estimated model parameters. Hence, larger differences are expected between 415 model predictions of travel time and capture zone, especially since the geological struc-416 ture has been shown to be crucial for variables as travel time and capture zone that de-417 pend on flow path (Seifert et al., 2008; He et al., 2013).

418

It was also found that when the models are used for simulating conditions beyond the calibration base, i.e., used to simulate situations or type of data, which they have not been calibrated against, the differences in the geological models become more important and significant differences in the model results should be expected. Hence, the uncertainty caused by the conceptual geological model increases as the climate moves away from the baseline conditions.

425

426 Our findings are based on results from a specific case study with specific geological427 conditions and hence the general applicability of our conclusions for other locations

428 needs to be considered with caution. As we are not aware of other studies that have re-429 ported results from comparison of climate model uncertainty and conceptual geological 430 model uncertainty we are not able to provide firm generic conclusions on this specific 431 aspect. However, our findings confirm the conclusions of previous studies that concep-432 tual geological uncertainty is an important source of uncertainty in groundwater model-433 ing (Neumann, 2003; Bredehoeft, 2005) and that it becomes more and more dominating 434 compared to other sources the further away model predictions are from the calibration 435 base (Refsgaard et al., 2012).

436

437 The fact that climate change uncertainty dominates over conceptual geological uncer-438 tainty for projections of groundwater heads and river discharge, while the opposite is 439 the case for projection of groundwater travel time and capture zones, clearly illustrates 440 the context dependency of uncertainty propagation (Refsgaard et al., 2013), i.e. that 441 climate uncertainty may be amplified and dominate in some cases but may be reduced 442 to negligible importance in other cases. Similar conclusions were drawn by Velazquez 443 et al. (2012) where several hydrological models with different structures were forced by 444 climate projections from several climate models. They found that the uncertainty on 445 climate change impacts on high flows were dominated by climate model uncertainty, 446 while hydrological model structure uncertainty contributed significantly for low flows. 447 Hence, our results on the travel times and capture zones are examples where climate 448 change uncertainty does not matter in practice (Refsgaard et al., 2013).

449

450 6 Conclusions

452 Based on hydrological model simulation using a combination of six geological models 453 and projections from 11 climate models the following conclusions are derived. (1) Cli-454 mate model uncertainty is important for projection of hydraulic head and stream dis-455 charge. Especially for stream discharge the uncertainty is dominated by the climate 456 model. (2) Geological model uncertainty is important for projection of hydraulic head 457 and the uncertainty becomes larger as the climate signal moves away from the baseline 458 conditions. (3) Geological model uncertainty has a relatively small effect on the projec-459 tions of stream discharge even though summer stream discharge is analyzed where 460 groundwater-river interactions controls a relatively high fraction of the total discharge. 461 (4) The uncertainty on travel times and capture zones to well fields is dominated by 462 geological model uncertainty. This uncertainty is controlled by the geological structure 463 which is not constrained during the calibration process. The impact and hence the 464 choice of climate model is relatively insignificant.

465

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Tables

Table 1. Geological models of the Langvad Stream catchment area. Calibration statistics are indicated by the mean error (ME_{TS}) and root mean square error of hydraulic head time series (RMS_{TS}), the Nash-Sutcliff coefficient (E) and the water balance (F_{bal}) for

579 str	eam discharge.
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Name	R1	R2	L1	L2	N1	N2
No. of hydro-	3	5	7	7	11	12
stratigraph. layers						
No. of numerical	3	5	7	7	9	10
layers in model						
	(Roskilde	(Roskilde	(Københavns	(Københavns	(Henriksen	(Højberg et
Reference	Amt, 2002)	Amt, 2003)	Energi,	Energi,	et al., 1998)	al., 2008)
			2005)	2005)		
ME _{TS} (m)	-1.41	-0.20	0.31	-0.16	1.38	-0.19
$RMS_{TS}(m)$	6.52	3.12	2.08	2.01	4.41	4.82
E (-)	0.58	0.58	0.17	-0.12	0.63	0.75
$F_{bal}(\%)$	-17	-8	-2	-2	-2	-2

- 582 Table 2. Matrix of ENSEMBLES climate models with GCM-RCM pairings used for the
- 583 climate models (GCM = Global Climate Model, RCM = Regional Climate Model).
- GCM HadCM3 ECHAM5 ARPEGE BCM2 RCM HadRM3 Х REMO Х RM5.1 Х HIRHAM5 Х Х Х CLM Х RACMO2 Х RegCM3 Х RCA3 Х Х 585 586 587 588 589 590 591 592 593 594 595 596 597
- 584 From Seaby et al. (2013).

Table 3. Simulated mean hydraulic head in the Limestone aquifer in the focus area for the reference scenario and the scenario climates. Changes in mean hydraulic head from reference to scenario climate are listed in brackets. "Mean geology" and "Std. dev. geology" are the average and the standard deviation of the results from the hydrological models for each climate scenario. "Mean climate" and "Std. dev. climate" the average and the standard deviation of the results from the different climate models used in each

	R1	R2	L1	L2	N1	N2	Mean geology	Std.dev. geology
h mean, m								
Reference Climate	21.0	20.7	20.0	20.4	18.5	19.1	19.9	1.0
ARPEGE-RM5.1	20.0	19.6	19.3	19.8	17.3	18.1	19.0	1.07
	(-1.01)	(-1.12)	(-0.73)	(-0.61)	(-1.16)	(-0.94)	(-0.93)	(0.22)
ARPEGE-HIRHAM5	20.0	19.6	19.3	19.8	17.4	18.2	19.1	1.04
	(-1.00)	(-1.07)	(-0.69)	(-0.59)	(-1.08)	(-0.88)	(-0.89)	(0.21)
BCM-HIRHAM5	21.2	20.9	20.1	20.5	18.6	19.2	20.1	1.00
	(0.17)	(0.19)	(0.11)	(0.08)	(0.14)	(0.12)	(0.13)	(0.04)
BCM-RCA3	21.5	21.2	20.3	20.7	18.8	19.4	20.3	1.02
	(0.47)	(0.52)	(0.31)	(0.25)	(0.40)	(0.33)	(0.38)	(0.10)
ECHAM-HIRHAM5	21.7	21.5	20.5	20.8	19.0	19.6	20.5	1.05
	(0.71)	(0.82)	(0.48)	(0.39)	(0.60)	(0.49)	(0.58)	(0.16)
ECHAM-RegCM3	21.2	20.9	20.1	20.5	18.6	19.2	20.1	1.02
	(0.23)	(0.23)	(0.13)	(0.09)	(0.14)	(0.11)	(0.15)	(0.06)
ECHAM-RACMO2	21.5	21.2	20.3	20.6	18.8	19.4	20.3	1.04
	(0.45)	(0.48)	(0.28)	(0.21)	(0.34)	(0.27)	(0.34)	(0.11)
ECHAM-REMO	21.2	20.9	20.1	20.5	18.6	19.2	20.1	1.01
	(0.21)	(0.21)	(0.13)	(0.10)	(0.15)	(0.12)	(0.15)	(0.05)
ECHAM-RCA3	21.5	21.2	20.3	20.7	18.8	19.4	20.3	1.03
	(0.50)	(0.55)	(0.33)	(0.25)	(0.40)	(0.32)	(0.39)	(0.11)
HADQ0-CLM	21.4	21.1	20.2	20.6	18.7	19.3	20.2	1.03
	(0.39)	(0.40)	(0.24)	(0.18)	(0.28)	(0.23)	(0.29)	(0.09)
HADQ0-HadRM3	20.6 (-0.39)	20.2 (-0.47)	19.7 (-0.32)	20.1 (-0.28)	18.0 (-0.47)	18.7 (-0.41)	19.6 (-0.39)	1.02 (0.08)
Mean climate	21.1 (0.07)	20.7 (0.07)	20.0 (0.02)	20.4 (0.01)	18.4 (-0.02)	19.1 (-0.02)	20.0 (0.02*)	1.03 (0.11**)
Std.dev. climate	0.60 (0.60)	0.66 (0.66)	0.42 (0.42)	0.34 (0.34)	0.60 (0.60)	0.49 (0.49)	0.52 (0.52***)	1.07 (0.51*)

604 hydrological model.

* Mean and standard deviation based on all the numbers in the matrix.

606 ** Mean of the standard deviations of geological models.

607 *** Mean of the standard deviations of climate models.

Table 4. Results of variance analysis with respect to climate models and geological models on (1) absolute mean values and (2) changes in mean values compared to results obtained using reference climate with respect to hydraulic head, discharge (annual and summer dis.), travel time and catchment area. All variance components (columns denoted "Geology" and "Climate") are presented as standard deviations. The column "Mean change" denotes the projected mean change.

		Absolute values		Change re	Change relative to reference cl		
	Location	Geology	Climate	Mean change	Geology	Climate	
Head, m	Focus area	1.03	0.52	0.02	0.11	0.52	
Annual dis., m ³ /s	St. 52.30	0.08	0.32	0.08	0.01	0.32	
Summer dis., m ³ /s	St. 52.30	0.21	0.14	0.00	0.05	0.14	
	Assermølle	30.7	6.4	-0.2	4.6	6.4	
	Gevninge	60.3	4.1	0.6	2.5	4.1	
Travel time,	Hule Mølle	36.4	4.9	1.6	7.1	4.9	
year	Kornerup	81.0	2.8	0.6	2.7	2.8	
	Lavringe	58.5	2.4	1.5	2.4	2.4	
	Ramsø	66.5	4.2	0.8	3.4	4.2	
	Assermølle	13.0	1.6	2.4	1.4	1.6	
	Gevninge	1.6	0.6	0.8	0.5	0.6	
Catchment	Hule Mølle	6.2	0.5	0.7	0.5	0.5	
area, km ²	Kornerup	15.9	1.0	2.9	1.6	1.0	
	Lavringe	6.7	0.3	0.9	0.4	0.3	
	Ramsø	10.5	0.4	1.0	0.5	0.4	

616 Figure captions

617 Figure 1. Model area of the Langvad Stream catchment area with land surface elevation,

618 streams, abstraction wells and location of the main well fields in the focus area (the619 clusters of wells along the streams).

620 Figure 2. Methodology for estimation of and change in capture zone area for a well field

Figure 3. Based on results where each of the six hydrological models are forced by 11

622 climate model projections: a) boxplot of the simulated mean hydraulic head, h, in

the limestone aquifer in the focus area and b) boxplot of the change in h from

624 reference to future scenarios.

Figure 4. Simulated change in mean hydraulic head of the Limestone aquifer in thefocus area using six geological models and 11 climate models.

627 Figure 5. Standard deviations of the change in hydraulic head from the geological

628 models, Table 3, compared with the change in the reference net precipitation (P-

 $629 ET_{ref}$).

630 Figure 6. a) Boxplot of the simulated mean summer stream discharge (Q_s) in a

downstream discharge station (st. 52.30) using input from 11 climate models, and
b) boxplot of the change in Q_s from reference to future scenarios.

633 Figure 7. a) Boxplot of the simulated median travel time to Lavringe well field, and b)

boxplot of the percentage change in median travel time from reference to futurescenarios.

Figure 8. a) Boxplot of the simulated capture zone area for Lavringe well fields and b)
boxplot of the percentage change in capture zone area from reference to future
scenarios.

- 639 Figure 9. Uncertainty of catchment areas for two well filelds using a) 6 geological
- 640 models with same climate model, and b) 11 climate models with the same
- 641 geological model.
- 642



Figure 1. Model area of the Langvad Stream catchment area with land surface elevation,
streams, abstraction wells and location of the main well fields in the focus area (the
clusters of wells along the streams).



- 649 Figure 2. Methodology for estimation of and change in capture zone area for a well
- 650 field.



Figure 3. Based on results where each of the six hydrological models are forced by 11
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limestone aquifer in the focus area and b) boxplot of the change in h from reference to
future scenarios.





659 Figure 4. Simulated change in mean hydraulic head of the Limestone aquifer in the





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666



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675 scenarios.

676



678 Figure 8. a) Boxplot of the simulated capture zone area for Lavringe well fields and b)

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- 685 model.