Study of historical groundwater level changes in two Belgian chalk aquifers in the context of climate change impacts 3

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12 Abstract

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13 In Southern Belgium, 23% of abstracted groundwater volumes are from chalk aquifers which represent strategic resources for the region. Due to their specific nature, these chalk aquifers 14 15 often exhibit singular behaviour and require specific analysis. The quantitative evolution of these groundwater resources is analysed for the Mons Basin and Hesbaye chalk aquifers as a 16 17 function of past evolution, in the short and long terms. Groundwater level time series exhibit decreases when analysed over different periods. This is particularly visible for the Hesbaye 18 chalk aquifer when comparing the 1960-1990 and 1990-2020 periods. Such decreases are 19 20 associated to observed temperature increase and a precipitation decrease, inducing a decrease of aquifer recharge, and a probable increase of groundwater abstraction in the adjacent 21 22 catchment. Past evolution is also discussed considering recent winter and summer drought 23 events. The aquifers exhibit long delays in response to recharge events, particularly where the thickness of the partially saturated zone plays a crucial role in observed delays. Regarding 24 25 future evolution, simulations of the impact of climate changes using medium-high emission 26 scenarios indicate a probable decrease of the groundwater levels over the Hesbaye chalk 27 aquifer.

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29 Introduction

30 In Southern Belgium (Wallonia), 23% of abstracted groundwater volumes are from chalk

31 aquifers (SPW 2020). These chalk geological formations thus represent strategic aquifers for

- 32 drinking water supply in the region.
- 33 Due to their specific hydraulic properties, chalk aquifers often exhibit singular behaviours
- 34 where the large matrix porosity enables storage of large quantities of groundwater and the
- 35 fractures and fissures allow drainage and fast preferential groundwater flow. This duality in
- 36 terms of permeability and porosity induces challenges related to aquifer characterization and
- 37 particularities regarding the evolution of groundwater levels (Brouyère *et al.* 2004,
- 38 Goderniaux et al. 2015, Goderniaux et al. 2018), solute transport (Orban et al. 2010, Hakoun
- *et al.* 2017, Hoffmann *et al.* 2020) or even with regards to more recent applications such as
- 40 energy storage. Because of their strategic importance and because climate is currently
- 41 changing, studying the resilience of chalk aquifers during drought periods is crucial. It allows
- 42 the implementation of efficient management strategies to perpetuate effective and robust43 water supply in the future.
- 44 In this paper, an overview of chalk aquifers from Southern Belgium, the Mons Basin and the
- 45 Hesbaye aquifers is undertaken, focussing on groundwater quantity. In particular, the
- 46 quantitative evolution of these groundwater resources is analysed as a function of past and

- 47 future climate conditions, in the short and long terms. Impacts are also discussed in light of
- 48 the 2016-2019 period characterized by winter and summer drought events in Belgium.
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50 Hydrogeological context of chalk aquifers in Southern Belgium

- 51 The chalk aquifers in Belgium have been described by Dassargues & Monjoie (1993), Hallet
- 52 (1998), Rorive and Goderniaux (2014), Orban et al. (2014). Various types of chalks are
- 53 represented in Belgium, those from Turonian to Maastrichtian ages can be found in the Mons
- 54 Basin and in the Tournai area, and Campanian to Maastrichtian chalks are found in north-
- 55 eastern Belgium, in the region of Herve, in the Hesbaye region near Liège, in Northern
- 56 Brabant and in the Kampen.
- 57

58 The chalk aquifer of the Mons sedimentary Basin (or Haine valley)

- 59 The chalk aquifer of the Mons Basin is located in South-Western Belgium (Figure 1A) within
- 60 Cretaceous strata accumulated due to the subsidence of the sedimentary basin. The extent of
- 61 the aquifer (403 km²) corresponds approximately to the catchment of the Haine River, which
- 62 is mainly oriented along an East-West direction.
- 63 The chalk aquifer is composed of different geological formations, mainly chalk *sensu stricto*
- 64 but also some calcarenite and tuffeau layers. The geological formations form a 10 to 15 km
- 65 wide syncline-shape structure oriented East-West. The total thickness of the aquifer may
- 66 reach more than 300 m in the central part of the sedimentary basin.
- 67 The base of the aquifer consists of marl layers. The aquifer is considered as unconfined in the
- 68 Northern, Southern and Eastern parts of the basin. It is considered as confined or semi-
- 69 confined in the central part, along the Haine River, where the chalk layers are covered by
- 70 some Cenozoic clay and sand deposits (168 km²).
- 71 From a hydrogeological perspective, the different chalk geological layers are usually grouped
- 72 in thicker hydrogeological units, characterized by similar hydraulic properties. The mean
- hydraulic conductivity of those aquifer units ranges from 10^{-6} to 10^{-4} m/s, mainly depending
- on the level of fracturation of the chalk rocks. From a general and regional perspective,
- 75 groundwater flows from the Northern and Southern limits of the aquifer to the Haine River in
- the center of the basin (Figure 1A and Figure 2A) (Rorive & Goderniaux 2014). The average
- direct and indirect recharge of the aquifer is estimated to be 81×10^6 m³/year for the period
- 78 1970-1982. Groundwater resources are intensely exploited, mostly for drinking water
- 79 production. Abstracted volumes correspond to about 60% of the annual recharge (Rorive,
- 80 1983). A significant part of the abstracted groundwater is exported to supply other regions
- 81 with drinking water, in particular the city of Brussels.
- 82

83 The Hesbaye chalk aquifer

- 84 The Hesbaye chalk aquifer is located in eastern Belgium (Figure $1B 596 \text{ km}^2$) to the north-
- 85 west of the city of Liège within Cretaceous chalk strata. The 'smectite de Herve' which is a
- 86 calcareous clay layer of 2 to 10 m thick is considered as the aquifer low permeability base
- 87 above Palaeozoic strata. From bottom to the top, the chalk sequence consists of 20 to 40 m of
- compact Campanian chalk locally fractured, a thin (about 1 m) hardened layer of Campanian
- 89 chalk (called the Froidmont Hardground), and 10 to 15 m of weathered and fractured
- 90 Maastrichtian chalk. Above the chalk, a 2 to 9 m thick residual conglomerate is found,
- 91 overlaid by 2 to 20 m of Cenozoic sands and Quaternary loess. In the Geer valley located in
- 92 the North of the Hesbaye region, up to 5 m of recent alluvial and colluvial deposits, are
- observed. The extent of the unconfined part of the aquifer corresponds more or less to the

- 94 Geer river basin. Due to a slight dip of the geological strata to the North, the aquifer becomes
- 95 confined to the North of the Geer basin under clayey Cenozoic sediments.
- 96 In the Geer basin, the chalk is covered by a thick layer of loess that plays a key role in the
- 97 infiltration of water and pollutants to the aquifer (Batlle-Aguilar *et al.* 2007).
- 98 From a regional perspective, groundwater flows mainly from the South to the North.
- However, in the eastern part of the Geer basin, groundwater flows towards the Geer river
- 100 (Figure 2B) (Orban *et al.* 2014). About 25×10^6 m³ of groundwater production is recorded by
- drainage in 45 km of galleries (red lines in Fig. 1B) and by pumping in water wells (red
- 102 squares in Fig. 1B). This amount represents about 10% of the mean annual rainfall and about $102 = 20 \pm 50\%$ of the active to be 102 = 10%
- 103 30 to 50% of the estimated recharge. Different groundwater modelling works have been used
- 104 for the groundwater quantity and quality management of this aquifer (Dassargues *et al.* 1988, 105 Della et al. 1988, Other 2010) and for the analysis of l_{10}^{10} and l_{10} and for the analysis of l_{10}^{10} and l_{10} an
- Bolly *et al.* 1988, Orban, 2010) and for the evaluation of different climate change scenarios
- 106 (Brouyère et al. 2004, Goderniaux et al. 2015)
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108 Analysis of long-term groundwater level time series

- 109 Groundwater levels have been monitored over the two aquifers for several decades. Figure 2A
- and B shows maps of groundwater monitoring stations along with the calculated ranges of
- 111 groundwater variations (difference between maximum and minimum values) over the period
- 112 1990 2020. The intervals of groundwater head variations logically increase with the distance
- 113 to the main draining rivers.
- Figure 2C and Figure 2D show two examples of evolutions of groundwater levels in recharge
- 115 zones of both aquifers. The locations of the two related piezometers are indicated in yellow in
- Figure 1. Time series are provided along with estimated annual recharge rates calculated
- using the Thornthwaite algorithm, using data from the meteorological stations 'La Hestre' and
- 118 'Bierset' for the Mons Basin and Hesbaye aquifer, respectively. Recharge values
- 119 consequently corresponds to recharge rates just below the evaporation and root zones. Runoff
- 120 is neglected in those quite flat and infiltrative areas. This may lead to overestimation of
- 121 recharge, especially during summers when extreme stormy rainfall events are frequently
- 122 observed. Over the period 1990-2020, the mean annual recharge is equal to 217 mm/year and
- 123 117 mm/year in the Mons Basin and Hesbaye aquifers, respectively.
- 124 In the chalk aquifer of the Mons Basin, clear seasonal and multi-annual variations are visible.
- 125 Groundwater levels are generally correlated with recharge rates with a very short time delay.
- 126 A maximum delay of 3 months is observed in the South-East area of the aquifer, where the
- 127 partially saturated zone become thicker, with a maximum thickness of 40 m.
- 128 In the Hesbaye aquifer, the evolution of groundwater levels is different. Due the thick layer of
- 129 loess and the thick unsaturated zone, the delay observed between precipitations and variations
- 130 in groundwater levels can be long, ranging from a few weeks to one year and a half.
- 131 Fluctuations of groundwater levels do not show seasonal variations and clearly allow
- 132 distinguishing contrasted periods of high and low groundwater levels such as those existing in
- 133 1983-1984 and 1991-1992. On the other hand, a general decrease in groundwater levels can
- be observed in Figure 2D between 1983 and nowadays, as illustrated by the mean
- 135 groundwater level that is shifted downwards for the period 1990-2020 compared to the period
- 136 1960-1990 (Figure 2F). This decrease is generally observed throughout the basin although the 137 intensity may vary according to the local context or the proximity of specific hydrogeological
- 138 limits.

140For the Hesbaye aquifer, the comparison is performed for the two 30-year non-overlapping1411960-1990 and 1990-2020 intervals. Those 30-year time periods aim to discriminate the142impact of climate change to that of meteorological conditions. For the Mons Basin aquifer,143intervals are shorter and partly superimposed (1986-2005 and 2000-2020), due the lack of144continuous meteorological time series. Figure 2E and Figure 2F show monthly mean147recharge rates for all calendar months. A seasonal behaviour is visible in Figure 2E148(Mons Basin), showing a slightly delayed increase in groundwater levels compared to the149recharge period. In Figure 2F (Hesbaye), the seasonab behaviour is almost imperceptible, in140accordance with the piezometric evolution presented previously.150A clear groundwater level decrease of about 6 m is observed for the Hesbaye aquifer (Figure1512F). Several reasons may explain such decreases. Figure 2G and Figure 2H show precipitation152an temperature monthly statistics for the investigated periods. For the Hesbaye chalk aquifer,153an increase of temperature is observed for all months of the calendar, with a maximum value154of about +2°C T in summer. Decrease of precipitation rates are also observed, especially at the154end of winter. These changes clearly impact meduction in the recharge rate has155a direct influence on groundwater perlse. Di addition, the Hesbaye chalk units are continuous156to 207 mm/year, and for the period 1960-1990, groundwater recharge157is estimated to 207 mm/year, and for the period 1960	139	Figure 2E and Figure 2F compare groundwater level and recharge over different time periods.		
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	182	Unfortunately, no recent calculation of the water balance is available. However, over the		

- 183 investigated time period, groundwater production has been relatively constant in the Geer
- 184 basin, while an increase of water production by pumping has been observed in the confined
- 185 part of the chalk aquifer outside the Geer basin and especially in the south of the Limburg
- 186 province of Belgium (VMM, 2019). This increase of groundwater production was recently
- 187 further reenforced by the addition of new pumping wells in the neighbouring area of the Geer basin (Six, 2017).
- 188
- 189
- 190 For the Mons Basin aquifer, decrease of groundwater levels and increase of temperatures are
- 191 also observed for all calendar months. The impact of climate change on recharge and
- 192 groundwater levels is also possible. Conclusions are nevertheless difficult to draw because the
- 193 comparison is based on shorter and partly overlapping time intervals.
- 194

195 Analysis of short-term groundwater level time series in the context of droughts 196

- 197 Since October 2016, groundwater recharge rates have been characterized by low values,
- 198 compared to the mean value calculated over the period 1990-2020 (Figure 2C and Figure 2D).
- 199 Such lower recharge rates are mainly explained by lower precipitations during the recharge
- 200 periods. Hot and dry summers were also observed but they theoretically do not impact directly
- 201 recharge. They can however contribute to increase the water demand during summers. These
- 202 lower recharge rates have induced significant decreases in groundwater levels in the two chalk
- 203 aquifers, and generally in Southern Belgium. This decrease is particularly visible during the 204 hydrological year 2016-2017 for the Mons Basin aquifer, and with a delay of a few months
- 205 for the Hesbaye aquifer. During this period and in many places, groundwater levels have been 206 close to their lowest levels measured anytime in the past.
- 207 During winter 2019-2020, a higher recharge and partial recovery of groundwater levels was 208 generally observed in most aquifers. In the two studied chalk aquifers, this recovery is
- 209 heterogeneous, depending on the aquifer hydrogeological context and the thickness of the
- 210 partially saturated zone, which controls infiltrations from the ground surface to the
- 211 groundwater table. Figure 3 shows the state of groundwater levels in May 2020, compared to
- 212 all months of May within the period 1990-2020. The month of May is considered for the
- 213 comparison because it approximately corresponds to the end of the recharge period. The
- 214 indicator shown in Figure 3 is calculated as the difference between the groundwater level in
- 215 May 2020 and the mean groundwater level among all months of May within 1990-2020, normalized by the min-max interval (Equation 2). A negative value of the indicator,
- 216 217 corresponding to reddish colours, means that the groundwater level in May 2020 is below
- 218 average.
- 219
- 220

$$Indicator = \frac{H_{May \, 2020} - \bar{H}_{May}|_{1990-2020}}{[Max(H_{May}) - Min(H_{May})]|_{1990-2020}}$$
(2)

- 221 222 with
- 223 • H_{Mav 2020} Groundwater level in May 2020 • $\overline{H}_{May}|_{1990-2020}$ • $Max(H_{May})|_{1990-2020}$ 224 Mean groundwater level in May for the period 1990-2020 225 Max groundwater level in May for the period 1990-2020 • $Min(H_{May})|_{1990-2020}$ 226 Min groundwater level in May for the period 1990-2020

- 227
- 228 The values and spatial distribution of the indicator are different in the two studied aquifers. In
- the Mons Basin aquifer, about two-third of the values are positive or close to zero, except in
- the areas with a thicker partially saturated zone (South-East). Groundwater levels generally
- benefited from normal recharge rates during winter 2019-2020. In the Hesbaye chalk aquifer,
- values are strongly negative in most of the locations, indicating that groundwater levels still
- remain low, demonstrating a stronger inertia in this aquifer and probably a different behaviour
- due to the increase of groundwater production from the chalk aquifer in the northern areaoutside the Geer basin (see above).
- 235

237 Climate change impact on groundwater resources

238 239 Previous sections presented the evolution and specific behavior of groundwater levels in the 240 two chalk aguifers, in relation to past climate and weather. Nevertheless, the climate has been 241 changing and it is expected to change further in the next decades. According to Blenkinsop et 242 al. (2013) and Goderniaux et al. (2009), and based on Regional Climate Model (RCM) output 243 from the FP5 PRUDENCE project (Christensen et al., 2007), temperatures in the Hesbave 244 region are generally expected to increase throughout the year, with hotter and dryer summers, 245 and increased precipitations during winter months. This configuration is not easy to capture as 246 the recharge period is affected by a simultaneous increase of precipitation and 247 evapotranspiration, which are concurrent processes regarding groundwater recharge generation. 248 As groundwater is strategic for drinking water distribution in Southern Belgium and Brussels 249 city, it is crucial for water managers to know how groundwater resources may evolve in the 250 future, including in the chalk aquifers of the Mons Basin and Hesbaye.

- 251 To answer this question and project climate change impact on groundwater resources, 252 Goderniaux et al. (2009) developed a 3D spatially-distributed, physically-based numerical 253 model of the Hesbaye chalk aquifer. The model was developed with the simulator 254 HydroGeoSphere (Therrien et al. 2005) which integrates the calculation of surface flow, 255 groundwater flows in the partially and fully saturated zones, and the actual evapotranspiration. 256 Water exchanges between the different compartments are calculated at each time step. The 257 integration of all processes in a unique model allows more robust and realistic simulations, with 258 possible feedbacks between the different compartments.
- The model was coupled with climate change scenarios (Blenkinsop et al. 2013) statistically downscaled from six different Regional Climate Models (RCMs) using projections corresponding to the SRES A2 emissions (medium–high) scenario (Nakicenovic et al., 2000). Equiprobable scenarios corresponding to the time interval 2010-2100 were generated for each RCM and used as input of the hydrological model.
- 264 Results generally show decreasing trends of the average simulated groundwater levels, 265 calculated over all equiprobable scenarios. Figure 4 shows examples for 30 scenarios generated 266 from the RCM ARPEGE. Figure 4A shows the projected changes in temperature and precipitation by the end of the century. Figure 4B presents the corresponding simulated 267 268 groundwater levels at the piezometer highlighted in yellow in Figure 1. The decreasing trend 269 of the mean simulated groundwater levels is explained by climate change. The uncertainty 270 related to the natural variability of the weather is illustrated by all equiprobable scenarios 271 displayed around the average behavior. This uncertainty looks higher at the end of the period. 272 This is mainly explained by the influence of the partially saturated zone whose thickness and 273 control on infiltrations from the ground surface to the groundwater table increase as

274 groundwater levels decrease. Beside the natural variability of the weather, simulated results 275 are also affected by other sources of uncertainty, including the climate models, and the 276 implementation and calibration of the hydrological model. Despite these uncertainties, which 277 make difficult the accurate impact quantification, Goderniaux et al. (2015) showed that it 278 remains likely that groundwater levels will decrease by the end of the century.

279

280 Conclusions

281

282 On a middle to long-term basis, observations over the 1960-1990 and 1990-2020 periods show 283 precipitation and temperature changes, with a negative impact on calculated recharge rates for 284 the Hesbaye aquifer. This recharge change contributes to explain the mean groundwater level 285 decrease observed over the two periods, although the evolution and impact of groundwater 286 abstraction rates at a regional scale must also be considered and assessed carefully. Previous simulations on the impact of climate changes have predicted a probable decrease of the 287 288 groundwater levels. New simulations with the most recent climate models and emission 289 scenarios are being started. They will be useful for possible changes in the structural long-term 290 water management policies.

- 291 On a short-term basis, chalk aquifers in South Belgium involve large volumes of groundwater,
- characterized by long delays in reaction to recharge and groundwater exploitation changes. This
 is particularly true in Hesbaye (Geer basin). As a consequence, the two studied aquifers
- represent important resources, which can probably be used as buffers to compensate temporary difficulties, such as a higher water demand during a particular summer drought, or a recharge
- deficit during a specific winter. The question nevertheless arises about the aquifer resilience if
- successive difficulties are occurring. In any case, short-term events and long-term trends should
- 298 not be confused because they require different management responses.
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- 368 Figures



Figure 1. (A) Chalk aquifer of the Mons sedimentary Basin. (B) Chalk aquifer of Hesbaye. Legend is provided only for the hydrogeological units present within the aquifer limits. The yellow points correspond to the two piezometers discussed in Figure 2.

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Figure 2. (A) Piezometric contours and range of groundwater variations (Max-Min) in the Mons Basin aquifer. (*B*) Piezometric contours and range of groundwater variations (Max-Min) in the Hesbaye aquifer. (*C*) Example of groundwater level evolution in the Mons Basin aquifer (PZ Villers – Figure 1A) with annual recharge values. The dotted horizontal line represents the mean annual recharge calculated over the shown period. (*D*) Example of groundwater level evolution in the Hesbaye aquifer (PZ Villers – Figure 1B) with annual recharge values. (*E*) Monthly piezometric and recharge statistics in the Mons Basin aquifer (PZ Villers). (*F*) Monthly piezometric and recharge statistics in the Hesbaye aquifer (PZ Villers).



Figure 3. Spatial distribution of an indicator value showing the state of groundwater levels in May 2020, compared to all months of May within the period 1990-2020, in (A) the Mons Basin aquifer and (B) the Hesbaye aquifer. The indicator is calculated using Equation 2.

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Figure 4. (A) Monthly precipitation and temperature changes from the RCM ARPEGE for the time slice 2071-2100 and corresponding to the SRES A2 emissions (medium-high) scenario. (B) Corresponding simulated groundwater levels in the Hesbaye aquifer at the level of the piezometer highlighted in Figure 1.

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404 **Figure captions**

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408 Figure 2. (A) Piezometric curves and range of groundwater variations in the Mons Basin 409 aquifer. (A) Piezometric curves and range of groundwater variations in the Hesbaye aquifer. 410 (C) Example of groundwater level evolution in the Mons Basin aquifer (PZ Villers – Figure 411 1A) with annual recharge values. The dotted horizontal line represents the mean annual 412 recharge calculated over the shown period. (D) Example of groundwater level evolution in the 413 Hesbaye aquifer (PZ Viemme – Figure 1B) with annual recharge values. (E) Monthly piezometric statistics in the Mons Basin aquifer (PZ Villers). (F) Monthly piezometric statistics 414 415 in the Hesbaye aquifer (PZ Viemme). (G) Monthly precipitation and temperature statistics in 416 the Mons Basin ("La Hestre" meteo station). (H) Monthly precipitation and temperature statistics in Hesbaye ("Bierset" meteo station). 417

418 Figure 3. Spatial distribution of an indicator value showing the state of groundwater levels in

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