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Estimation of future groundwater recharge using climatic analogues and Hydrus-1D

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Abstract

The impact of climate change on groundwater recharge is simulated using climatic analogue stations, i.e. stations presently under climatic conditions corresponding to a given climate state. The study was conducted in the context of a safety assessment of a future near-surface disposal facility for low and intermediate level short-lived radioactive waste in Belgium; this includes estimating groundwater recharge for the next millennia. Groundwater recharge was simulated using the Richard's based soil water balance model Hydrus-1D and meteorological time series from analogue stations. Water balance calculations showed that transition from a temperate oceanic to a warmer subtropical climate without rainfall seasonality is expected to yield a decrease in groundwater recharge (−12 % for the chosen representative analogue station of Gijon, Northern Spain). Based on a time series of 24 yr of daily climate data, the long-term average annual recharge decreased from 314 to 276 mm, although total rainfall was higher (947 mm) in the warmer climate compared to the current temperate climate (899 mm). This is due to a higher soil evaporation (233 mm versus 206 mm) and higher plant transpiration (350 versus 285 mm) under the warmer climate.

1 Introduction

In the context of disposal of low and intermediate level short-lived radioactive waste (LILW-SL), the Belgian Agency for Radioactive Waste and Enriched Fissile Materials (ONDRAF/NIRAS) aims at developing a disposal facility in Dessel, North-East Belgium. Demonstrating safety of the repository requires investigating the short and long-term impact of the evolution of environmental conditions on the performance of the facility. In this context, it is important to characterise future groundwater recharge, because radionuclide dispersion and dilution would eventually depend on groundwater flow conditions. The time scale of interest is several millennia (Van Geet et al., 2012).

Future groundwater recharge depends heavily on future climate conditions. However, studies of the impact of climate change on groundwater recharge are usually restricted to time scales of several tens to hundreds of years (e.g. Goderniaux et al., 2009; van Roosmalen et al., 2009). This is because climate scenarios of such studies are often based on predictions of general climate models (GCMs) used in IPCC assessment reports (the latest of which is IPCC, 2007). These predictions extend until AD 2100 or AD 2300 for some models (IPCC, 2007). Other studies do not include a specific time scale and focus more on a sensitivity analysis regarding the response of the groundwater recharge to a given change in climatic inputs (e.g. Wilkinson and Cooper, 1993).

Different approaches have been developed to generate meteorological time series characterising different climate states in terms of average annual temperatures and precipitation:

a. use of GCM outputs, often after downscaling of the results. Dynamical downscaling uses a regional climate model (RCM) to create higher resolution time series; while statistical downscaling includes methods of varying complexity, from (delta) perturbation approach to stochastic weather generators conditioned on site-specific or hypothetical weather statistics (Fowler et al., 2007; Holman et al., 2009).

b. Use of actual meteorological data from instrumental analogue stations taking account of local conditions that influence hydroclimatological conditions such as similarities and differences in latitude/longitude effects on insolation and oceanic/continental influences.

Using analogue stations represents an easy and transparent way of deriving climate state bounds for the climate classes of interest. It also has some weaknesses: analogues are restricted to sites with instrumental data; time series of 30 or 50 yr are assumed to be representative of an entire climate state; and analogue stations may not be optimal in terms of environmental conditions of the site.

The approach based on GCMs can make use of more site-specific information and probably provides a better paramerisation of temperature and precipitation in the near future. However, on a longer time scale as in the present study, validation and robustness of this approach remains very uncertain.

Therefore, the approach using analogue stations was chosen for the present study in order to describe future climate states at the Dessel site with current observations from appropriate climate zones. This approach was previously used in several safety assessment studies (Palutikof and Goodess, 1991; Bechtel SAIC Company, 2004).

The objective of the present study is to estimate future groundwater recharge in the vicinity of the Dessel site on a time scale of up to a few thousand years. An estimate of current groundwater recharge is provided and the potential impact of a warmer climate is investigated using climatic analogue stations. Because of the long time scales (Van Geet et al., 2012), colder climates cannot be excluded and their impact on recharge is assessed.

2 Material and methods

2.1 Present-day and future climate in Belgium

The present-day climate of Belgium is defined as a temperate oceanic climate – "DO" following the classification of Trewartha et al. (1968). Climate data collected for the period 1985–2009 in the Dessel area (Campine Region, northern of Belgium) indicate a mean temperature of 10.4 °C and mean precipitation of 899 mm yr^{-1}. The atmospheric circulation is dominated by western winds which bring humidity from the Atlantic Ocean. Based on different scenarios of greenhouse gas emissions, IPCC models for the region of Northern Europe predict a warming of 2.3 to 5.3 °C (median 3.2 °C) by AD 2100. Annual precipitation is very likely to increase in most of Northern Europe, and extremes of daily precipitation are also likely to increase (IPCC, 2007).

On the longer term, important driving forces of climate evolution include of variations of insolation (astronomical and solar forcings), and in greenhouse gas and aerosol concentrations in the atmosphere (natural and anthropogenic sources). These variations are forced by changes in the Earth's orbit and spin and by other forcing agents such as volcanism, the evolution of life and the movement of tectonic plates and ocean currents. The BIOCLIM (2003) project studied possible future climate states for the long term accounting for atmospheric CO_2, solar and astronomical forcings. Over the period of 10 000 yr AP chosen for the present study, BIOCLIM results suggest that North-Eastern Belgium will be characterised by a climate moderately warmer than present, with a similar degree of water availability through the year, but with drier summers and wetter winters ("Cs" climate in Trewartha's classification – subtropical climate with winter rain). The subtropical climate class with no rainfall seasonality is denoted as "Cr". No colder climate is foreseen in the next 10 000 yr AP on the basis of BIOCLIM (2003) scenarios. However for illustrative purposes the present study also investigates the consequences of a tundra climate (with permafrost) designated by "FT" in Trewartha's classification to have a more comprehensive evaluation of the water balance sensitivity at the Dessel site.

2.2 Climatic analogue stations

Climate analogue stations were selected based on following criteria: (i) fulfilling Trewartha's classification criteria based on temperature and precipitation, (ii) sufficiently long time series (>20 yr) of key meteorological variables (temperature, precipitation, wind speed, relative humidity, solar radiation) and (iii) similarity with respect to latitude/longitude effects on insolation and oceanic/continental influences compared to the Dessel site. Pertinent criteria for the latter were defined as follows:

a. Elevation: the analogue stations must have an elevation of less than 150 m a.s.l. This criterion is chosen to avoid the inclusion of stations displaying too important orographic rainfall effects, as the Dessel site is at approximately 20 m a.s.l.

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b. Maritime influence: the distance to the nearest source of moisture (shoreline) has to be maximum 120 km taking dominant wind direction into account (Dessel site is about 120 km from the coast).

c. Atmospheric circulation system: analogue stations located in the Atlantic circulation system (Northern Hemisphere) are preferred. Besides, analogue stations should not be located on a small island (as in Burgess et al., 2002).

Among the potential weather stations in a given climate class (Cs/Cr, FT), the two displaying the smallest rank deviation from the class annual average temperature and precipitation were arbitrarily selected for model simulation. Besides the latter two stations, the stations with the highest and lowest precipitation regimes were also selected to represent bounding cases. This allowed assessing the influence of variability in precipitation, temperature and other climatic parameters within a climate class on groundwater recharge. Table 1 lists the selected climatic analogue stations for simulating the warmer (Cs/Cr) and colder (FT) climate classes.

2.3 Groundwater recharge modelling

Time series of meteorological observations were used to derive daily potential evapotranspiration (ET) using Penman-Monteith approach (Allen et al., 1998). Then, the interception, throughfall, evaporation of intercepted water, potential evaporation and potential transpiration were calculated in a canopy water balance model implemented in Excel (see Appendix A) and were used later as input variables for Hydrus-1D (Šimůnek et al., 2005). The main outputs calculated with Hydrus-1D include daily values of the soil actual evaporation, actual transpiration and groundwater recharge (discharge at the profile bottom). From these daily values, annual values were calculated.

Simulations were performed on sandy soils (podzol) characteristic of the study area, with a uniform grass cover. Three-meter deep soil profiles of Zcg (Belgian classification for sand, moderately drained, B horizon with obvious accumulation of organic matter and/or iron; FAO: Haplic Podzol, USDA: Aquic Haplorthod) and Zeg (sand, poorly drained, B horizon with obvious accumulation of organic matter and/or iron; FAO: Gleyic Podzol, USDA: Typic Haplaquod) soil series were used (Seuntjens et al., 2001). The most typical horizon sequence of these series and related texture and organic matter content properties were looked up in the Aardewerk soil information system (Van Orshoven et al., 1988). Grass rooting depth was set at 30 cm. Table 2 gives the parameterisation of the two soil profiles for the Mualem-van Genuchten model (van Genuchten, 1980). The pedotransfer functions of Schaap et al. (1999) were used to derive soil hydraulic parameters for the Zcg and Zeg profiles (respectively 6 and 5 horizons).

In the Dessel area, the actual groundwater table is around 1.5 m deep on average (Beerten et al., 2010). Using this average groundwater table depth as the bottom boundary condition for the calculations make sense for current climate conditions (DO class) but would not necessarily match future groundwater table conditions under other climates. For example, simulations for the warmer Cs/Cr climate showed that a constant groundwater table at 1.5 m led to a negative annual drainage (i.e. upward flow from groundwater) under a precipitation deficit (i.e. difference between precipitation and potential ET) because groundwater then acted as a supplier for actual ET (results not shown). A consequence of the high ET demand would be a drop in groundwater level, which cannot happen with the constant head boundary condition. As an alternative, the "deep drainage" bottom boundary condition implemented in Hydrus-1D was used, for which the discharge rate $q(n)$ at the bottom of the soil profile at node n is defined as function of the position of the groundwater table (Hopmans and Stricker, 1989):

$$q(n) = q(h) = A_{qh} \exp(B_{qh} \times |h - \mathrm{GWL0L}|) \tag{1}$$

where $q(h)$ (cm day^{-1}) is the discharge rate, h (cm) is the pressure head at the bottom of the soil profile, A_{qh} (cm day^{-1}) and B_{qh} (cm^{-1}) are empirical parameters and GWL0L (cm) is the reference (initial) groundwater depth. In this case vertical drainage across the lower boundary of the soil profile is approximated by a flux which depends on the position of the groundwater level (Hopmans and Stricker, 1989). Parameters for Eq. (1) were obtained from a series of measured groundwater levels in the Dessel area (1990–2009) and corresponding calculated fluxes (Leterme et al., 2012). An average parameter B_{qh} ($= -0.0083\,\text{cm}^{-1}$) was fitted for the 12 selected piezometers. A_{qh} ($= -0.667\,\text{cm}\,\text{day}^{-1}$) was calculated following Hopmans and Stricker (1989) and GWL0L was set to 300 cm (= depth of the simulation domain). This bottom boundary condition was used for all climate states.

3 Results and discussion

3.1 Inter-annual variability

Table 3 shows the detailed long-term arithmetic average water budget of the climatic analogue stations for a grass cover. In the current climate (Dessel, DO), simulated groundwater recharge is $314\,\text{mm}\,\text{yr}^{-1}$ on average. Actual ET (ET_a) is 96 % of potential ET (ET_0) and 55 % of total rainfall.

Simulations for the warmer climate class (Cs/Cr) show a decrease of groundwater recharge for all analogue stations. For Huelva and Cádiz, the main reason is a precipitation deficit ($\text{ET}_0 \gg P$), which leaves little water available for groundwater recharge. Results show a decrease of groundwater recharge for Gijon, despite more precipitation compared to Dessel and precipitation surplus on an annual basis ($P > \text{ET}_0$). As a consequence of decreasing recharge, groundwater table is deeper on average in Gijon (2.8 m) than in Dessel (2.6 m) simulations.

It is important to note that groundwater table depth is in a critical interval of values where ET can be considered to be "groundwater controlled" (Maxwell and Kollet, 2008). This means that the ET_a (and groundwater recharge) response to a given increase in temperature and/or precipitation strongly depends on groundwater table depth. Shallow groundwater tables (<1 m) would ensure a constant ET_a response for any change in ET_0 (i.e. surface fluxes are not water limited). Deep groundwater tables (>7–8 m) would cause precipitation and land-surface processes to be the drivers of groundwater recharge (i.e. groundwater is disconnected from surface processes; Fig. 2 in Maxwell and Kollet, 2008). Therefore, a deeper groundwater table under warmer Gijon climate means that the influence of precipitation and land-surface processes on ET increases.

As mentioned above, the actual groundwater table in the Dessel area is approximately 1.5 m deep. The difference between the simulations and field observations is partly due to the use of the "deep drainage" boundary condition which would not be optimal for the present case, but other factors affecting groundwater table depth were not accounted for (e.g. rivers, topography). Further work will address this issue, for example by coupling the unsaturated zone model with a local hydrogeological model.

Analogue stations of the colder FT class show two contrasting types of water budget. Ilulissat and Sisimiut have a very low precipitation record and hence very small groundwater recharge despite limited ET_0 and ET_a compared to present-day climate class. Nuuk and Paamiut have a precipitation record similar to present-day Dessel climate, but groundwater recharge increases due to low ET. The snow hydrology module of Hydrus-1D (snow fall and melting) was tested for the FT and DO classes (results not shown) but did not show any significant impact due to a low runoff potential (high infiltration capacity of Zcg and Zeg profiles) and to the use of daily time steps. However, soil freezing and thawing were not simulated in the present study and these would probably reduce groundwater recharge for analogue stations of the FT class.

Figure 1a depicts the cumulative distribution functions of annual groundwater recharge simulated for the climatic analogues of the Cs/Cr class and comparison with the simulation for Dessel. In the upper percentiles, Gijon shows lower groundwater recharge than Dessel despite having higher precipitation (i.e. supplementary available water in wetter years is primarily used to satisfy high ET demand).

Figure 1b depicts the cumulative distribution functions of annual groundwater recharge simulated for the climatic analogues of the FT class and comparison with the simulation for Dessel. The contrast mentioned above between Ilulissat and Sisimiut on the one hand, and Nuuk and Paamiut on the other hand, is clearly visible. The former stations have a very low precipitation record and small groundwater recharge,

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while the latter show higher groundwater recharge than Dessel despite lower precipitation records (Table 3). Note that calculations did not account for snow evaporation; therefore calculated recharge may be overestimated.

3.2 Representative analogue stations

Although simulating groundwater recharge with several analogue stations gives a good representation of the variability within a climate class, one may need to choose a representative analogue among the different stations for management applications or to try reducing the uncertainty on possible future groundwater recharge. Ancillary information on probable future climate conditions can help to assess the representativeness of the climatic analogue stations.

In the case of Cs/Cr climate class, for example, Gijon is considered as the best representative analogue given its resemblance in temperature and precipitation characteristics with projected climate evolution in the near future at Dessel. The seasonal distribution and magnitude of temperature and precipitation increases for Gijon are consistent with GCM scenarios of IPCC 2007. Indeed, the latter projects a median annual precipitation increase for Northern Europe of 9 % and a temperature increase of 3.2 °C. For Gijon, precipitation and temperature are, respectively, by 5 % and 3.4 °C higher compared to Dessel. Although Gijon is classified as a subtropical climate with no rainfall seasonality, summers are drier and winters are wetter than in Dessel (see Fig. 2), which is in accordance with BIOCLIM projections of future climate for the next 10 000 yr (Sect. 2.1).

Concerning the colder climate (FT class), Sisimiut is considered as the best representative analogue based on inference from geological records of the last glacial period indicating that the coldest periods were very dry in the Dessel area. This is supported in the region of the Belgian-Dutch border by evidence such as deflation horizons indicating strong wind erosion, abundant aeolian deposition, (near) absence of fluvial activity in the valleys (Vandenberghe, 1985, 1993). It is reasonable to assume that precipitation during colder periods has been much lower than today. For instance, Wemaere et al.

(1999) examined future climate scenarios based on a definition of climate intervals characterised by paleo-reconstruction starting from 126 000 yr BP. Boreal, periglacial, and glacial climate states were found to display very low infiltration rates (at least two orders of magnitude lower compared to present-day values for moderate conditions).

3.3 Intra-annual variability

For the three representative analogue stations (Dessel, Gijon and Sisimiut), Fig. 2 shows the intra-annual variability of ET_a and groundwater recharge. Even though Gijon is classified as a subtropical station with no rainfall seasonality, summer is somewhat drier and this is reflected in a slight decrease of ET_a in the summer months compared to Dessel. Seasonality of groundwater recharge is similar between Dessel and Gijon. The bottom boundary condition (Eq. 1) prevents a net negative bottom flux (water supply from the aquifer), but allows groundwater table to fluctuate and hence to be shallow enough for use by the vegetation.

Sisimiut is characterised by low annual precipitation and groundwater recharge shows almost no seasonality. Average groundwater depth of the numerical simulations is 4.5 m.

4 Conclusions

Climatic analogue stations were used to assess average groundwater recharge under different climate states. Although no optimal choice of analogue stations may exist due to different weather circulation systems, this approach allows including observed variations of all meteorological parameters in a transparent and straightforward way.

This study demonstrated that transition to a warmer, subtropical climate is expected to yield a decrease in groundwater recharge in the vicinity of the Dessel disposal site (typical podzol with a grass cover). Using Gijon as representative analogue station for the next 10 000 yr, a decrease of long-term average groundwater recharge by 12 %

was simulated compared to present-day climate conditions. Although no colder climate is foreseen in the next 10 000 yr, the approach was also tested with analogue stations for a colder climate state. Groundwater recharge simulated for the representative analogue Sisimiut showed a decrease by 69 %.

A deep drainage bottom boundary condition was used but may not be optimal for the problem examined. Further developments will focus on coupling the unsaturated zone model with a local hydrogeological model (Seo et al., 2007; Gedeon and Mallants, 2010). For colder climate states, it is also necessary to investigate the effect of freeze-thaw cycles and snow evaporation on groundwater recharge.

On the time scale considered, other factors than climate change may have an important influence on groundwater recharge. Land use change and the dependency between climate and land use are being investigated. Some vegetation parameters of a given land use may depend on climate variables, such as stomatal behaviour under increased CO_2 concentration. Furthermore, soil development may also have an impact, because soil evolution studies in the vicinity of the Dessel site have shown that cemented podzols may develop in several thousands of years (Beerten et al., 2012).

Appendix A

Canopy water balance model

In this model described by Jacques et al. (2011), the canopy water balance per unit area, for day d, is written as:

$$\Delta S = P_d - (E_{\mathrm{i},d} + Tr_d) \tag{A1}$$

where ΔS (mm day^{-1}) is the variation of canopy storage over one day, P (mm day^{-1}) is precipitation, E_i (mm day^{-1}) is evaporation of intercepted water and Tr_d (mm day^{-1}) is throughfall. The maximum amount of water left on the canopy at start of the day is defined by the interception capacity, w_c (mm). On a daily basis (start of the day), the throughfall is calculated as:

$$Tr_d = \begin{cases} S_{d-1} + P_d - w_\mathrm{c} & \text{if } S_{d-1} + P_d > w_\mathrm{c} \\ 0 & \text{if } S_{d-1} + P_d \le w_\mathrm{c} \end{cases} \tag{A2}$$

and an intermediate value of canopy storage, $S_{d,i}$ (mm), is calculated as:

$$S_{d,i} = \begin{cases} w_\mathrm{c} & \text{if } S_{d-1} + P_d > w_\mathrm{c} \\ S_{d-1} + P_d & \text{if } S_{d-1} + P_d \le w_\mathrm{c} \end{cases} \tag{A3}$$

Then, the storage is corrected for evaporation of water from the leaf surface. The latter is obtained by splitting the daily potential crop evapotranspiration $\mathrm{ET}_{c,d}$ (mm day^{-1}) (calculated using Penman-Monteith equation) into daily potential soil evaporation $E_{p,d}$ (mm day^{-1}), daily potential transpiration $T_{p,d}$ (mm day^{-1}) and $E_{\mathrm{i},d}$:

$$E_{\mathrm{i},d} + T_{p,d} = \mathrm{ET}_{c,d} - E_{p,d} \tag{A4}$$

Assuming that the net radiation inside the canopy decreases according to an exponential function and that soil heat flux can be neglected, $E_{p,d}$ is calculated as (Goudriaan, 1977; Belmans et al., 1983; Kroes et al., 2008):

$$E_{p,d} = \mathrm{ET}_{c,d}\ \exp(-k\mathrm{LAI}_d) \tag{A5}$$

where k (–) is the light extinction coefficient and LAI (–) is the leaf area index. $E_{\mathrm{i},d}$ depends on the canopy storage. If $S_{d,i} > \mathrm{ET}_{c,d} - E_{p,d}$, the following applies:

$$\begin{array}{l} T_{p,d} = 0 \\ S_d = S_{d,i} - (\mathrm{ET}_{c,d} + E_{p,d}) \end{array}. \tag{A6}$$

In case $S_{d,i} \le \mathrm{ET}_{c,d} - E_{p,d}$, the following applies:

$$\begin{array}{l} T_{p,d} = (\mathrm{ET}_{c,d} + E_{p,d}) - S_{d,i} \\ S_d = 0 \end{array}. \tag{A7}$$

S_d is then used as a starting value for storage to calculate the boundary water balance terms for the next day.

Concerning vegetation parameters, the interception capacity for grass was fixed at 55 mm (giving on average 15 % of precipitation intercepted), a constant LAI of 2 was used and the light extinction coefficient was 0.5 (Jacques et al., 2011).

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Table 1. Characteristics of selected analogue stations for different climate classes (DO = temperate oceanic, Cs/Cr = subtropical with/without rainfall seasonality, FT = tundra – with permafrost). The Dessel site is the reference station for current climate. Cádiz is the station with the smallest rank deviation from Cs class average temperature (16.8 °C) and precipitation (607 mm). Ourense and Huelva were selected as bounding cases for the precipitation. For the Cr class, sufficient input data were found only for Gijon. Sisimiut and Nuuk are the stations with the smallest rank deviations from FT class average temperature (–2.0 °C) and precipitation (571 mm). Paamiut and Ilulissat were selected as bounding cases for the precipitation.

Climate class	Station	Latitude and longitude	Mean annual temperature (°C)	Mean annual precipitation (mm yr^{-1})	Altitude (m)	Distance (km) from humidity source (shoreline)
DO	Dessel, Belgium	51° 13′ N, 05° 06′ E	10.3	899	20	120
Cs	Ourense, Spain	42° 20′ N, 07° 52′ W	14.5	807	143	90
Cs	Cádiz, Spain	36° 45′ N, 06° 04′ W	17.7	536	27	0
Cs	Huelva, Spain	37° 17′ N, 06° 55′ W	18.1	479	19	0
Cr	Gijon, Spain	43° 32′ N, 05° 39′ W	13.8	947	3	0
FT	Nuuk, Greenland	64° 10′ N, 51° 45′ W	−1.4	740	54/80	0
FT	Ilulissat, Greenland	69° 13′ N, 51° 03′ W	−5.0	268	39	0
FT	Sisimiut, Greenland	66° 55′ N, 53° 40′ W	−3.9	319	12	0
FT	Paamiut, Greenland	62° 00′ N, 49° 43′ W	−0.8	794	15	0

Table 2. Parameters of the Mualem-van Genuchten model for the Zcg and Zeg soil profiles.

Soil profile	Horizon	Depth (cm)	θ_r ($\mathrm{m^3\,m^{-3}}$)	θ_s ($\mathrm{m^3\,m^{-3}}$)	α ($\mathrm{m^{-1}}$)	n (–)	K_s ($\mathrm{m\,s^{-1}}$)	l (–)
Zcg	A1	0–5	0.06	0.47	1.3	1.68	2.3×10^{-5}	0.5
	A2	5–8	0.03	0.40	1.6	1.75	2.3×10^{-5}	0.5
	Bh	8–10	0.05	0.45	1.4	1.62	4.5×10^{-6}	0.5
	Bi	10–13	0.03	0.40	1.6	1.75	4.5×10^{-6}	0.5
	BC	13–17	0.02	0.38	1.5	1.71	1.3×10^{-4}	0.5
	C	17–100/300	0.02	0.38	1.6	1.75	1.3×10^{-4}	0.5
Zeg	A1	0–9	0.06	0.46	1.3	1.63	4.7×10^{-5}	0.5
	A2	9–15	0.02	0.38	1.7	1.86	4.7×10^{-5}	0.5
	Bh	15–21	0.03	0.41	1.5	1.68	6.1×10^{-6}	0.5
	Bi	21–43	0.03	0.40	1.6	1.73	6.1×10^{-6}	0.5
	BC	43–100/300	0.02	0.39	1.5	1.71	1.6×10^{-5}	0.5

Table 3. Average annual precipitation (P), potential evapotranspiration (ET_0), actual evapotranspiration (ET_a), evaporation of intercepted water (E_i), soil evaporation (E_a), transpiration (T_a) and groundwater recharge, in $\mathrm{mm\,yr}^{-1}$ for Dessel and the 8 analogue stations. In parenthesis the percentage of precipitation is given for some variables.

Station	P	ET_0	ET_a	E_i	E_a	T_a	Recharge
Dessel (DO)	899	596	572	81 (9 %)	206 (23 %)	285 (32 %)	314 (35 %)
Huelva (Cs)	518	1265	458	33 (6 %)	132 (25 %)	293 (57 %)	61 (12 %)
Cádiz (Cs)	524	1140	467	33 (6 %)	128 (25 %)	306 (58 %)	60 (12 %)
Ourense (Cs)	863	874	644	63 (7 %)	195 (23 %)	386 (45 %)	175 (20 %)
Gijon (Cr)	947	704	658	75 (8 %)	233 (25 %)	350 (37 %)	276 (29 %)
Ilulissat (FT)	282	313	234	34 (12 %)	76 (27 %)	124 (44 %)	39 (14 %)
Sisimiut (FT)[1]	306	284	225	30 (10 %)	77 (25 %)	118 (39 %)	96 (32 %)
Nuuk (FT)	747	329	329	57 (8 %)	121 (16 %)	151 (20 %)	403 (54 %)
Paamiut (FT)	774	298	298	47 (6 %)	110 (14 %)	141 (18 %)	481 (62 %)

[1] The sum of ET_a and recharge is higher than P. This is due to a strong decrease of soil water content (about −400 mm per unit area in the 3 m soil profile) between the start (wetter) and end (drier) of the 24 yr simulation period, resulting in a recharge increase.

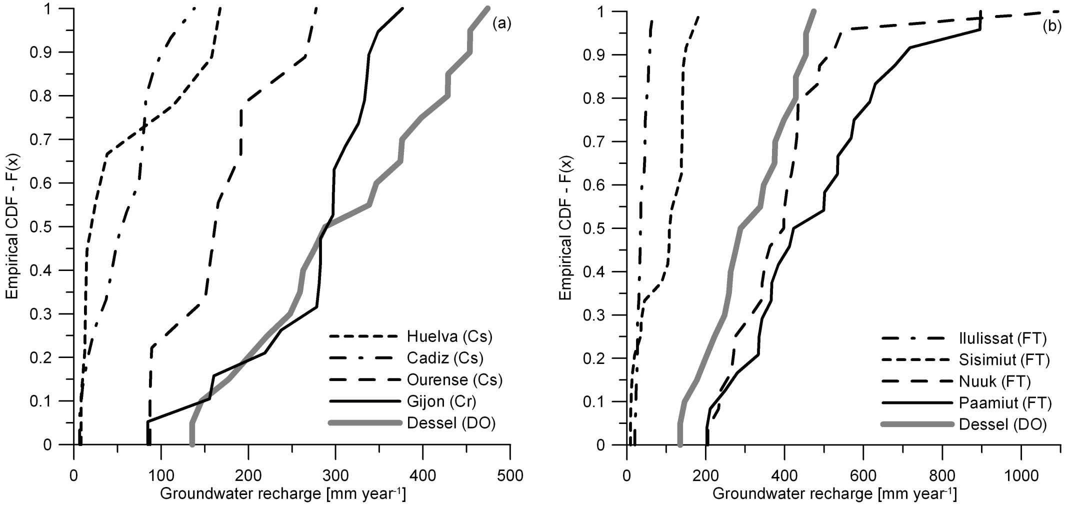
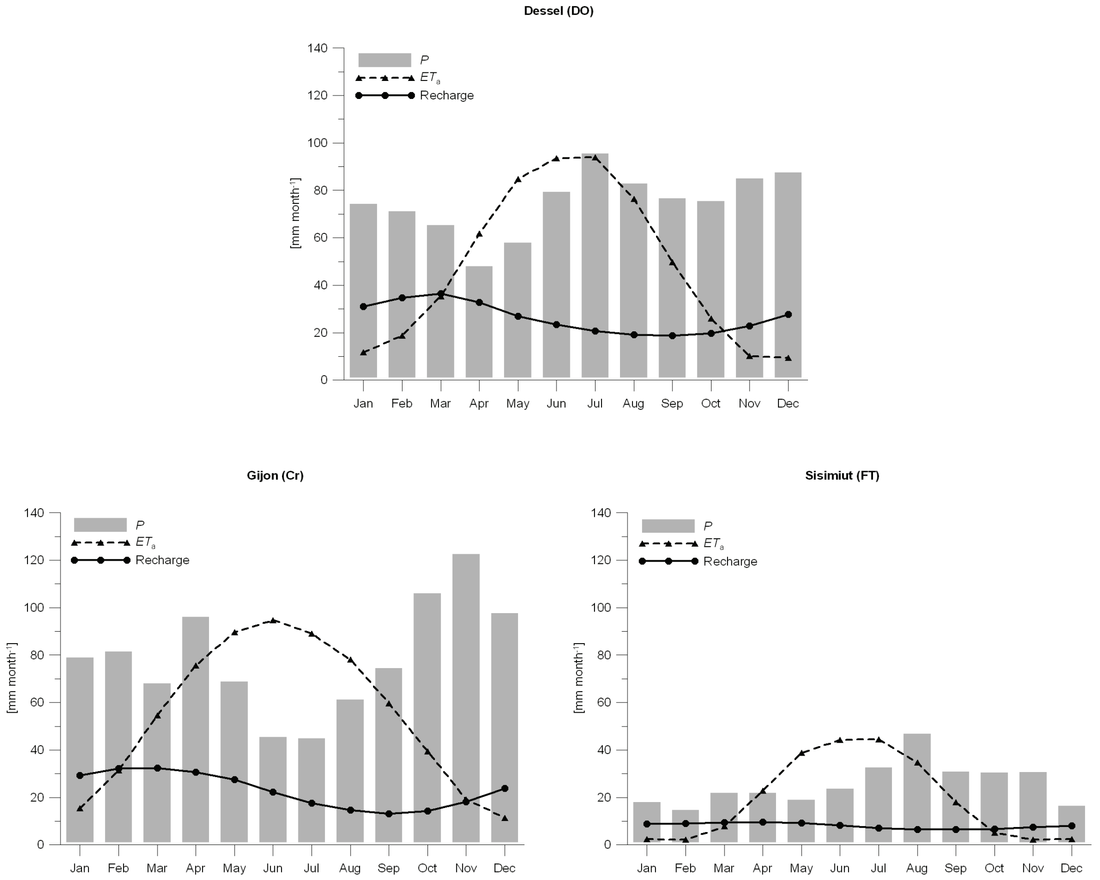


Fig. 1. Cumulative distribution functions of annual groundwater recharge simulated for **(a)** Cs and Cr and **(b)** FT analogue stations. The DO reference simulation of the Dessel site is included for comparison.



Dessel (DO)

Gijon (Cr)

Sisimiut (FT)

Fig. 2. Monthly average precipitation (P), actual evapotranspiration ($\mathrm{ET_a}$) and groundwater recharge for the analogue stations of Dessel (DO, top panel), Gijon (Cr, bottom left panel) and Sisimiut (FT, bottom right panel).

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