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Climate and land-use change impacts on groundwater recharge

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Abstract We show the effects of both climate and land-use changes on long-term groundwater recharge. The study was conducted in the context of a safety assessment of a near-surface disposal facility for low and intermediate level waste; this includes estimating groundwater recharge for the next millenia. Climate change impact on groundwater recharge was simulated using HYDRUS-1D and weather time series from so-called analogue stations. Results showed that transition to a warmer climate is expected to yield a decrease in groundwater recharge. For land-use change impact on groundwater recharge in the Nete catchment, conversion to crop (maize) and coniferous forest resulted in the highest positive (recharge increase by 30%) and negative (recharge decrease by 41%) sensitivities, respectively. Further improvements of the method may consider correlation and feedback between combined land-use change and climate change.

Key words groundwater recharge; climate change; land-use change; Nete catchment, Belgium

INTRODUCTION

The Belgian Agency for Radioactive Waste and Enriched Fissile Materials (ONDRAF/NIRAS) aims to develop a surface disposal facility for low and intermediate level waste (L/ILW) in Dessel (northeastern Belgium). In the context of long-term safety assessment of the facility, groundwater recharge is a key factor determining the dispersion and dilution of radionuclides in the environment. Climate change may lead to modifications of groundwater recharge or groundwater level, thus affecting the dispersion and dilution of radionuclides outside of the L/ILW facility. Land-use conversions may affect the atmosphere-vegetation-soil water balance in the vicinity of the site, thus changing the amount of groundwater recharge and possibly the magnitude of dispersion/dilution.

The objective of this study is to provide estimates for the next few millennia of groundwater recharge in the vicinity of the Dessel site, characterized currently by a maritime temperate climate that will gradually evolve to a warmer subtropical climate, possibly combined with climate-driven land-use changes. In this respect, the relative importance of climate and land-use changes on the regional groundwater recharge needs to be assessed.

MATERIAL AND METHODS

Study area

The study area is the Nete catchment (1673 km^2), in the northeast of Belgium. The topography is relatively flat (from 2 m.a.s.l. in the west to 67 m.a.s.l. in the east). Dominant land-uses, as visible in Fig. 1, are cropland (37%), grassland (22%), coniferous (12%) and deciduous (9%) forests and built areas (16%). The present study considered the first four of these, thus representing 80% of the study area. Maize is the dominant crop in the area (Mestbank, 2011) and was taken as the representative cover for cropland (crop rotation schemes were not considered).

Within the Nete catchment boundaries, the groundwater flow originates mostly from the atmospheric infiltration and to a lesser extent from external sources (navigation canals across the catchment boundaries). Infiltrated water travels towards groundwater sinks, i.e. mainly drains and rivers. The influence of two rivers, the (northern) Kleine Nete and the (southern) Grote Nete, reaches down to the Boom Clay aquitard. The latter is considered the bottom boundary of the catchment groundwater system (outcropping in the southwest to ~270 m below surface in the northeast, and even deeper east of the boundary of the *Rur graben* (Beerten *et al.*, 2010).

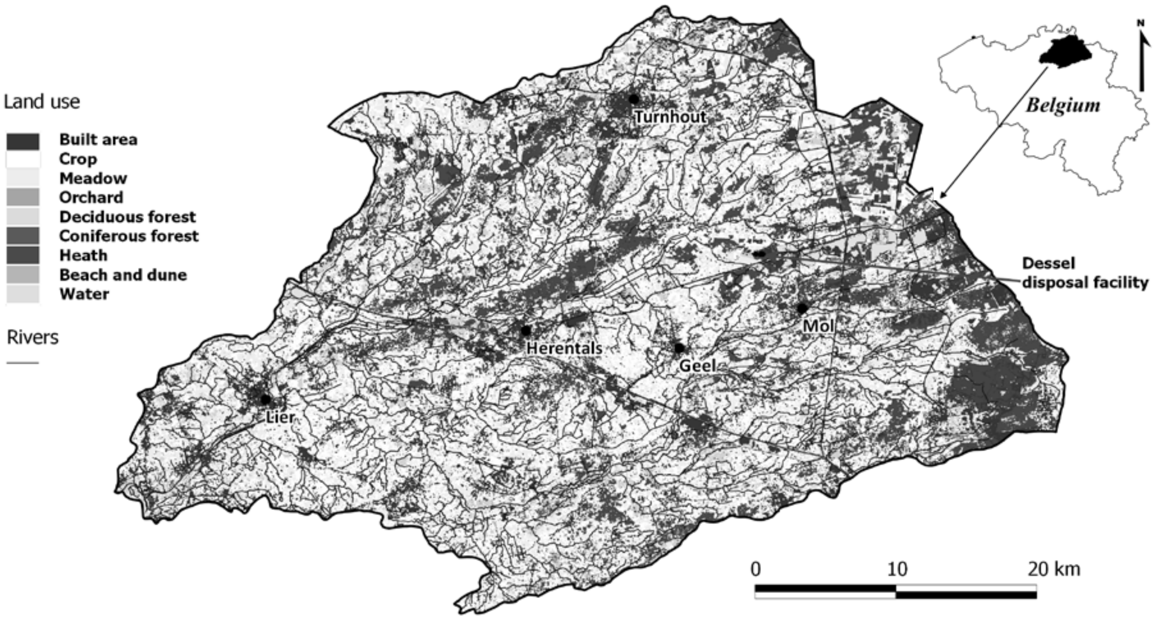

Fig. 1 Land-use in the Nete catchment (source: Landsat 2001 supervised classification; AGIV, 2011).

Climate change

The following climate states (Trewartha, 1968) are considered in the evaluation of the evolution of climate for the Dessel site: DO (maritime temperate, present-day climate in Dessel), Cs/Cr (subtropical with dry summers/no rainfall seasonality), EO (cold without permafrost) and FT (cold with permafrost). The reference evolution of climate adopted here (assuming a scenario of high anthropogenic CO_2 increase; BIOCLIM, 2003) foresees a Cs/Cr climate for the next ~150 000 years. In alternative sequences of climate states, a colder climate state EO or FT will not occur before ~50 000 AP (Leterme *et al*., 2011).

Different approaches exist to generate weather time series of future climate conditions. A widely used approach consists of applying dynamical or statistical downscaling to the output of global climate model simulations. Similarly, time series can be created using weather generators conditioned on site-specific weather statistics. An alternative approach, already used in several long-term performance assessment studies (Palutikof & Goodess, 1991; Bechtel, 2004), implies the use of so-called analogue stations. In this approach, time series are obtained from meteorological data of analogue stations selected to minimize differences due to latitude/longitude effects on insolation and oceanic/continental influences compared to the reference site.

Criteria for the selection of analogue stations included elevation (<150 m.a.s.l.) and the distance to the nearest source of moisture or shoreline (<120 km taking dominant wind direction into account). Analogue stations located in the Atlantic circulation system (Northern Hemisphere) were preferred. Potential analogue stations were ranked based on their deviation from the annual average temperature and precipitation. The two stations with the smallest deviation from the annual averages were selected as reference stations. The two stations with the highest and lowest precipitation regimes were also selected to represent bounding cases. This allowed us to investigate as much as possible the existing variability in precipitation, temperature and other climate parameters within a climate class and its influence on soil infiltration and groundwater recharge.

In this paper, only the results of Dessel (DO), Gijon (Cr) and Sisimiut (FT) analogue stations will be presented. For the Cs/Cr climate state, Gijon was chosen as the most appropriate to estimate future groundwater recharge rate, because its precipitation record (about +5% compared to Dessel) is more in accordance with the predicted increase for the near future (median +9% on annual total; IPCC, 2007). Sisimiut was chosen to be the representative analogue of both EO and FT colder climate states, for being drier (geological records of the last glacial period suggest that precipitation was much lower than today) but not the most extreme case in the FT climate class; and because the EO class shows a too large variability in groundwater recharge rates to allow a defensible designation of any representative EO station (Leterme *et al.*, 2011). Climatographs for the three analogue stations selected are presented in Fig. 2.

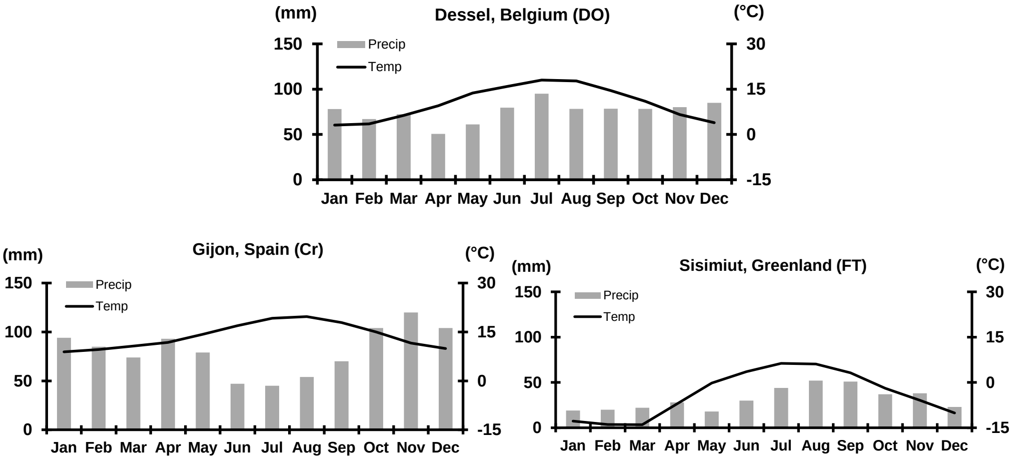

Fig. 2 Climatographs of Dessel (DO), Gijon (Cr) and Sisimiut (FT) analogue stations.

Land-use change

The sensitivity of groundwater recharge to land-use change was estimated by arbitrarily converting the whole study area to a given land-use. No detailed (more realistic) scenarios of land-use change were assessed. Such scenarios are discussed for example in Dams *et al.* (2008) in the Kleine Nete catchment (approximately the northern half of the Nete catchment) but were limited to the next 20 years. The four scenarios of land-use change in the latter study all predict a decrease in agricultural land-use (from –8 to –18% between 2000 and 2020) and a significant increase in urban land-use (+14 to +58%). The present study aimed to assess the impact of more drastic changes in the long term and therefore only the sensitivity to a complete conversion of land-use was assessed as a sensitivity measure. This indicator was also calculated by Dams *et al.* (2008).

Potential evapotranspiration and throughfall

Time series (between 20 and 30 years depending on data availability) of daily meteorological observations were used to derive potential evapotranspiration (ET) for the climate analogue stations. Potential ET was calculated using Penman-Monteith equation (as outlined in the guidelines of Allen *et al.*, 1998) implemented in the REF-ET software.

Then, the daily interception, throughfall, evaporation of intercepted water, potential evaporation and potential transpiration are calculated in an Excel worksheet (see description in Jacques *et al.*, 2011). The daily variability of vegetation parameters is shown in Fig. 3.

Groundwater recharge modelling

Regional groundwater recharge is calculated by coupling the HYDRUS-1D model (Šimůnek *et al.*, 2005) with a Geographical Information System (GIS). Climate-dependent time series of throughfall and potential evapotranspiration are used as the top boundary condition. Soil hydraulic properties are combined with root depth parameters for a given land use (cropland, meadow, coniferous and deciduous forests) and the net downward flow is taken as model output for groundwater recharge. Maximum root depth over time is shown in Fig. 3. Root distributions for the different vegetation types were: linear for maize and grass, derived from observations (Vincke & Thiry (2008) for coniferous forest, and derived from the function $Y = 1 - \beta^d$ (d is the depth in cm) with $\beta = 0.966$ (Jackson *et al.*, 1996) for deciduous forest.

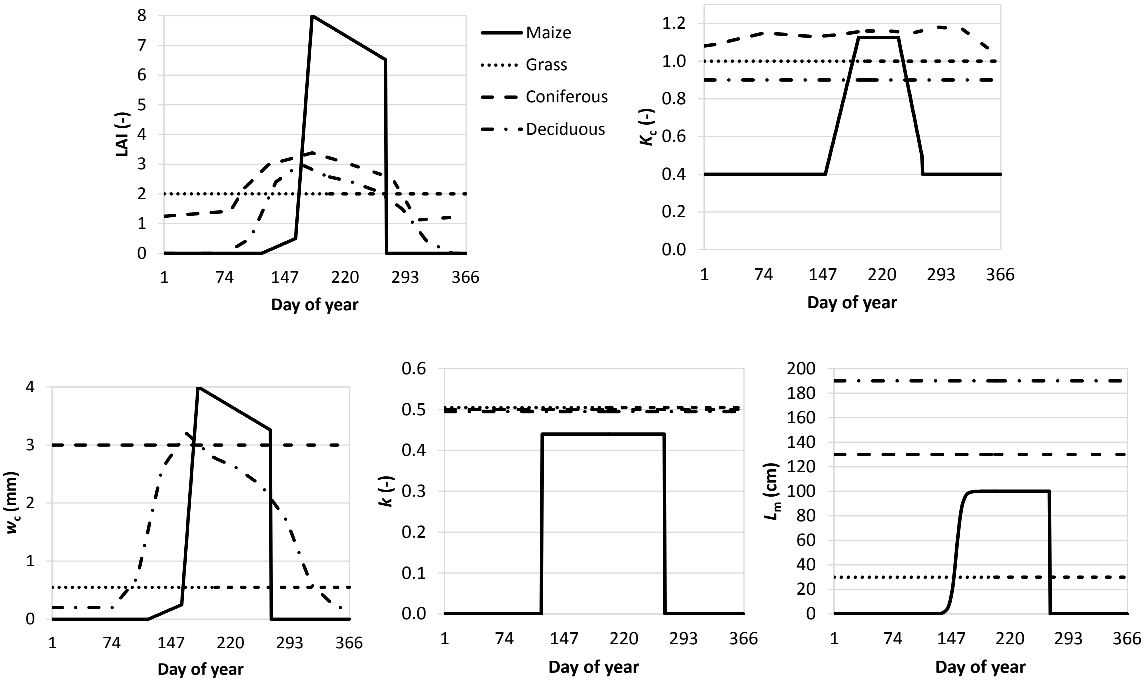

Fig. 3 Daily variability of vegetation parameters used for the modelling of potential evapotranspiration and groundwater recharge. LAI: leaf area index (grass: Jacques *et al.* (2011), coniferous: Vincke & Thiry (2008), deciduous: Lawrence (pers.comm.) based on Lawrence & Slingo (2004)); K_c: crop coefficient (maize: Allen *et al.* (1998), coniferous: Meiresonne *et al.* (2003) based on Gellens-Meulenberghs & Gellens (1992), deciduous: City of Riverside Planning Department (1994) cited in Amador *et al.* (2007)); w_c: interception capacity (maize: w_c (mm) = LAI×0.5 so that mean interception fraction (f_{int}) is equal to 0.10, grass: w_c = 0.55 mm so that f_{int} = 0.15 (Meyus *et al.*, 2004), coniferous: Breuer *et al.* (2003), deciduous: w_c (mm) = LAI+0.2 so that mean f_{int} = 0.15 (Breuer *et al.*, 2003)); k: light extinction coefficient (maize: Flénet *et al.* (1996), grass: Jacques *et al.* (2011), coniferous and deciduous: Granier *et al.* (1999); L_m: maximum root depth (grass: Jacques *et al.* (2011), coniferous: Vincke & Thiry (2008), deciduous: Breuer *et al.* (2003)).

Simulations were performed on sandy soils (podzol) characteristic of the study area. Three-metre deep soil profiles of the Zcg (six horizons) and Zeg soil series (five horizons) were used. A constant 1-m deep groundwater table was taken as bottom BC for the calculations under current climate conditions. Observations under a pine forest stand in the Dessel area (Vincke & Thiry, 2008) and simulations indicate that the aquifer can supply considerable water for ET. However, the validity of a constant 1-m deep water table as bottom BC is highly questionable under different climate conditions. Simulations for the warmer Cs/Cr climate showed that a groundwater table at 1 m led to negative annual drainage (i.e. upward flow from groundwater) under a precipitation deficit (compared to potential ET) because groundwater then acted as a supplier for ET. A consequence of the high ET demand would be a drop in groundwater level. However, with the constant BC this will never happen.

An alternative is to use the deep drainage BC implemented in HYDRUS-1D, for which discharge rate $q(n)$ at the bottom of the soil profile at node n is defined as:

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

where $q(h)$ is the discharge rate (L.T^{-1}), h (L) is the pressure head at the bottom of the soil profile, A_{qh} (L.T^{-1}) and B_{qh} (L^{-1}) are empirical parameters and $GWL0L$ (L) is the reference (initial) groundwater depth (L). 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 & Stricker, 1989). Parameters for equation (1) were obtained from a series of measured groundwater levels and corresponding calculated fluxes (Leterme *et al.*, 2011).

RESULTS AND DISCUSSION

Sensitivity to climate change

Table 1 shows the simulation results for Dessel (DO), Gijon (Cs/Cr) and Sisimiut (EO/FT) analogue stations. Current groundwater recharge in the Nete catchment calculated for Dessel conditions gives a mean annual value of 391 mm. A decrease of groundwater recharge is simulated under (warmer) Gijon climate, due to higher potential ET combined with the presence of groundwater at a depth of 3 m (on average for Gijon) allowing limited water supply to plant transpiration.

Sensitivity to land-use change

Using the results from Table 1, the sensitivity of groundwater recharge to the conversion of the whole Nete catchment into a single land-use can easily be estimated. Table 2 shows that conversion of the entire catchment to crop (maize) land-use would increase groundwater recharge, while conversion to other land-uses would decrease it. Although crop (maize) is the dominant land-use in the study area, groundwater recharge sensitivity is high for this land-use. The main reason is the absence of a vegetation cover in winter (i.e. during relatively high precipitation and low ET_0 period), which results in a higher recharge.

Table 1 Mean annual groundwater recharge (mm) per land-use and percentage of annual precipitation.

	Dessel (current DO) P = 899 mm	Gijon (warmer Cs/Cr) P = 947 mm	Sisimiut (colder EO/FT) P = 306 mm
Crop (maize)	495 (55%)	463 (49%)	128 (42%)
Meadow (grass)	307 (34%)	276 (29%)	96 (31%)
Coniferous forest	239 (27%)	211 (22%)	73 (24%)
Deciduous forest	375 (42%)	315 (33%)	104 (34%)
Nete catchment	391	357	108

Table 2 Sensitivity of groundwater recharge to land-use change in the Nete catchment. The sensitivity, given in parenthesis as a percentage, is calculated by assuming a complete conversion of the Nete catchment to one land-use for a given climate state.

	Mean annual groundwater recharge in Nete catchment (mm)				
Climate state	Current land-use	Crop (maize)	Meadow (grass)	Coniferous forest	Deciduous forest
Dessel (DO)	391	495 (+26%)	307 (–21%)	239 (–39%)	375 (–4%)
Gijon (Cs/Cr)	357	463 (+30%)	276 (–23%)	211 (–41%)	315 (–12%)
Sisimiut (EO/FT)	108	128 (+18%)	96 (–11%)	73 (–33%)	104 (–4%)

Conversion to coniferous forest would result in the strongest decrease of groundwater recharge under all climate states.

Using the same indicator, Dams *et al.* (2008) found the following sensitivity values: +12% for deciduous forest, +9% for wet meadow +5% for meadow and agriculture 5%, and +1% for coniferous forest. The sensitivity was negative for industry (–19%) and urban (–24%) land uses. These values are given only as an indication and not for comparison because Dams *et al.* (2008) considered different land-use categories and different modelling assumptions than in the present study.

In the present study, not taking built areas into account has the consequence that groundwater recharge is probably overestimated at the catchment scale. Therefore the absolute sensitivity of the conversion to a given land use maybe biased, but qualitatively the relative sensitivity of the land uses analysed here would not change.

CONCLUSION

Climatic analogues provided robust estimations of future (long term) climatological parameters needed for groundwater recharge estimation, even though considerable uncertainty is unavoidable given the time scale considered. Although no optimal choice of analogue stations may exist due to different weather circulation systems (e.g. Gijon *vs* Dessel), this approach allows us to include variations of all meteorological parameters in a transparent and simple way. This study suggested that transition to a warmer climate by AD 2100 (IPCC projection) is expected to yield a decrease in groundwater recharge (–9%) in the Nete catchment.

Land-use changes can also significantly affect the regional balance. A diminution of agricultural areas (as in the scenarios analysed by Dams *et al.*, 2008) could further reduce recharge. Among the four land-use classes included in the present analysis, crop (maize) and coniferous forest provided the highest positive (recharge increase) and negative (recharge decrease) sensitivities, respectively.

On the time scale considered, it is important to take into account the dependency between climate and land use. Furthermore, it is expected that climate change will have a significant impact on land use. Also, some combinations of land use and climate are unrealistic or will not occupy large areas of land and some vegetation parameters of a given land use may depend on climate variables. Therefore, effective approaches to estimate long-term regional groundwater recharge need to consider both climate and land-use changes while accounting for such dependencies.

Finally, coupling HYDRUS-1D model with the available groundwater model (Gedeon *et al.*, 2012) instead of using the deep drainage boundary condition could better describe the interactions between the unsaturated zone and groundwater.

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REFERENCES

AGIV (2011) Agentschap voor Geografische Informatie Vlaanderen, available on www.agiv.be/gis (accessed 25 August 2011).

Allen, R. G., Pereira, L. S., Raes, D. & Smith, M. (1998) Crop evapotranspiration: Guidelines for computing crop water requirements. In: *Irrigation and Drainage Paper, no. 56, Food and Agriculture Organization of the United Nations, Rome*.

Amador, J. A., Hull, R. J., Patenaude, E. L., Bushoven, J. T. & Görres, J. H. (2007) Potential nitrate leaching under common Landscaping plants. *Water Air Soil Pollut.* 185, 323–333.

Bechtel SAIC Company (2004) Future Climate Analysis. *Document ANL-NBS-GS-000008 REV 01.*

Beerten, K., Wemaere, I., Gedeon, M., Labat, S., Rogiers, B., Mallants, D. & Salah, S. (2010) Geological, hydrogeological and hydrological data for the Dessel disposal site. *Report NIROND-TR 2009-05E V1, SCK•CEN, Mol, Belgium.*

BIOCLIM (2003) Modelling Sequential Biosphere Systems under Climate change for Radioactive Waste Disposal. *Final Report EC-contract FIKW-CT-2000-00024*, http://www.andra.fr/bioclim.

Breuer, L., Eckhardt, K. & Frede, H.-G. (2003) Plant paramater values for models in temperate climates. *Ecologic. Model.* 169, 237–293.

City of Riverside Planning Department (1994) Water efficient landscaping and irrigation ordinance. *Summary and Design Manual*, 2nd edn.

Dams, J., Woldeamlak, S. T. & Batelaan, O. (2008) Predicting land-use change and its impact on the groundwater system of the Kleine Nete catchment, Belgium. *Hydrol. Earth Syst. Sci.* 12, 1369–1385.

Flénet, F., Kiniry, J. R., Board, J. E., Westgate, M. E. & Reicosky, D. C. (1996) Row spacing effects on light extinction coefficients of corn, sorghum, soybean, and sunflower. *Agronomy J.* 88(2), 185–190.

Gedeon, M., Mallants, D., Vandersteen, K. & Rogiers, B. (2012) Hydrogeological modelling of the Dessel site. Overview report. *Report NIROND-TR 2008-15E V2, SCK•CEN, Mol, Belgium.*

Gellens-Meulenberghs, F. & Gellens, D. (1992) L’évapotranspiration potentielle en Belgique: variabilité spatiale et temporelle. *Institut Royal Météorologique de Belgique, Publications, Série A 130.*

Granier, A., Bréda, N., Biron, P. & Villette, S. (1999) A lumped water balance model to evaluate duration and intensity of drought constraints in forest stands. *Ecological Modelling* 116, 269–283.

Hopmans, J. W. & Stricker, J. N. M. (1989) Stochastic analysis of soil water regime in a watershed. *J. Hydrol.* 105, 57–84.

Intergovernmental Panel on Climate Change (2007) Climate Change 2007: The Physical Science Basis. In: *Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (ed. by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor & H. L. Miller). Cambridge University Press, Cambridge, UK and NY, USA, 996 pp.

Jackson, R. B., Canadell, J., Ehleringer, J. R., Mooney, H. A., Sala, O. E. & Schulze, E. D. (1996) A global analysis of root distributions for terrestrial biomes. *Oecologia* 108, 389–411.

Jacques, D., Mallants, D. & Leterme, B. (2011) Modelling potential and actual evapotranspiration and drainage at the nuclear zone Mol-Dessel. *Report NIROND-TR 2008-25E V2, SCK•CEN, Mol, Belgium*.

Lawrence, D. M. & Slingo, J. M. (2004) An annual cycle of vegetation in a GCM. Part I: Implementation and impact on evaporation. *Climate Dynamics* 22, 87–105.

Leterme, B., Jacques, D., Mallants, D., Hooker, P., De Craen, M. & Van den Hoof, C. (2011) Long-term climate change and effects on disposal facility, geosphere and biosphere. *Report NIROND-TR 2009-07E V2, SCK•CEN, Mol, Belgium.*

Meiresonne, L., Sampson, D. A., Kowalski, A.S., Janssens, I. A., Nadezhdina, N., Cermák, J., Van Slycken, J. & Ceulemans, R. (2003) Water flux estimates from a Belgian Scots pine stand: a comparison of different approaches. *J. Hydrol.* 270, 230–252.

Mestbank (2011) available on www.vlm.be (accessed 25 August 2011).

Meyus, Y., Adyns, D., Woldeamlak, S., Batalaan, O. & De Smedt, F. (2004) Opbouw van een Vlaams Grondwatervoedingsmodel. Deelrapport 2: Totaal VGM-karteergebied en Vlaanderen. Vrij Universiteit Brussel, Brussels, België (in Dutch).

Palutikof, J. P. & Goodess, C. M. (1991) Analogue scenarios of future climates of the UK. In: *Future Climate Change and Radioactive Waste Disposal* (ed. by C. M. Goodess & J. P. Palutikof), 225–244. Proceedings of the International Workshop, University of East Anglia, 1–3 November 1989. Nirex Report NSS/R257.

REF-ET, reference Evapotranspiration Calculator, version 2.01.17 for support of ASCE Manual 70 (1990) and 2001 ASCE Standardizations and FAO Irrigation and Drainage Paper no. 56; *University of Idaho, Research and Extension Center, Kimberly, Idaho*, http://www.kimberly.uidaho.edu/ref-et/.

Šimůnek, J., Sejna, M. & van Genuchten, M. Th. (2005) HYDRUS-1D, version 4.14, code for simulating the one-dimensional movement of water, heat, and multiple solutes in variably saturated porous media.

Trewartha, G. T. (1968) *Fundamentals of Physical Geography*. McGraw-Hill Co.

Vincke, C. & Thiry, Y. (2008) Water table is a relevant source for water uptake by a Scots pine (*Pinus sylvestris L.*) stand: Evidences from continuous evapotranspiration and water table monitoring. *Agric. For. Met.* 148(10), 1419–1432.