

Impact of precipitation trends and the North Atlantic Oscillation on phreatic water levels in Low Belgium

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ABSTRACT. A set of 10 representative multi-decade long time series of piezometric levels of phreatic aquifers were selected in different parts of Low Belgium to investigate correlations between groundwater levels, precipitation rates and the North Atlantic Oscillation (NAO) index. Correlations between piezometric levels and precipitation rates are always high and significant at the 5% level for all series. A direct relation between groundwater levels and the NAO is only possible if there is a correlation with aquifer recharge, which in north Belgium is limited to the winter period. Correlation between monthly precipitation and monthly NAO indices are highly temporal, with two distinct periods during which the correlation is significant at the 5% level. In summer (July and August) there is a negative correlation, in winter time (December and January) a positive one. As in summer aquifer recharge is negligible, only the winter NAO index can have an impact on groundwater levels. Of the ten investigated series, only two have a significant correlation at the 5% level, between piezometric levels and the December-January NAO values. Both wells lie in the same region, in the upper part of the lithologically heterogeneous Campine Complex. The local hydrogeological conditions here seem to increase sensitivity to winter NAO modus.

KEYWORDS: groundwater, piezometric levels, time series, aquifer recharge, correlation, winter NAO modus

1. Introduction

Fluctuations in piezometric levels of phreatic aquifers usually reflect variations in overall meteorological conditions. Precipitation and evapotranspiration rates determine the recharge and discharge periods of these aquifers and cause cyclic seasonal alternations of high and low levels. The occurrence of dry or wet years is the main factor for interannual variability and a sequence of successive years with more or less than average recharge or discharge can introduce longer multi-year periods with elevated or lowered water table levels. This can have implications in the hydro-ecological domain and agriculture as vegetation heavily depends on the depth to the water table for water uptake by the root system. Besides the aspect of (over)exploitation, the long-term hydrodynamic evolution of many phreatic aquifers must be seen in terms of the future groundwater recharge. Many factors affect future groundwater recharge including changed precipitation and temperature regimes, coastal flooding, urbanisation, woodland establishment and changes in cropping and rotations (Holman, 2006). Variations in the meteorological conditions must be seen in the context of variations in the general atmospheric circulation patterns which determine precipitations and temperature (and hence evapotranspiration) trends. A close link between phreatic level fluctuations and weather systems is then obvious.

Attempts have been made to link piezometric levels directly to general atmospheric circulation indicators. Fleming & Quilty (2006) investigated the possible impact of the El Niño-Southern Oscillation (ENSO) on groundwater levels in Southwest British Columbia and found that composite annual hyetographs suggest that ENSO precipitation impacts are largely limited to winter and spring, with higher rainfall occurring under cold phase episodes. A simple model was developed by Tanco & Kruse (2001) to predict water table fluctuations in Argentina. It is based on the relationship between sea surface temperature (SST) in the Pacific Ocean and seasonal rainfall, which shows a high correlation between August-September SST and the rainfall of December till February. The rainfall forecast was then used to estimate seasonal fluctuations of the water table for three seasons.

In West-Europe the variability in the weather system is strongly influenced by the North-Atlantic Oscillation (NAO) which is dependent on the pressure difference between the Icelandic low and the height around the Azores, and can be expressed in the NAO-index. A link between NAO and precipitation patterns should also imply a link between the NAO and aquifer hydrodynamics. Tanase (2006) found some numeric evidences for a teleconnection between phreatic levels and the NAO variability mode in Romania, such as serial correlations between the NAO index of the positive phase and the phreatic levels during the cold season, the increasing depth of the phreatic

levels and the presence of a 7-8 year peak in the winter phreatic spectra. On the Iberian peninsula both influences from the ENSO and the NAO were recognized. Analysis of data from seventeen rainfall stations in the Iberian Peninsula, Balearic Islands and Northern Africa has revealed significant ENSO signals in Europe. Both NAO and Southern Oscillation (SO) exert an influence on Iberian climate, but at different temporal and spatial scales (Rodo et al., 1997). The influence of the NAO can possibly reach even the Middle East. Inter-annual to decadal variations in Middle Eastern temperature, precipitation and stream-flow reflect the far-field influence of the NAO (Cullen et al., 2002).

Studies have suggested that SST is an important source of variability of the NAO (Paeth et al, 2003). Efforts have been made to predict NAO index values from north Atlantic SST. Saunders & Qian (2002) were able to predict the winter NAO (December-January-February) from North Atlantic SST anomalies averaged over several prior months. The link is strongest for the 5 months period from June to October, but also the 3 months August-October period was usable. The relationship between interdecadal variations of tropical SST in the last 120 years and circulation anomalies related to the NAO was investigated using an atmospheric general circulation model (AGCM) (Kucharski et al., 2006). They confirmed observational evidence that variations in the SST gradient in the western tropical Pacific are related to the NAO anomalies on decadal timescale, and may be contributing to the shift towards the positive NAO phase observed in the late 20th century.

With the expected global warming and corresponding change in weather patterns an impact on groundwater levels will be logical. Changes in precipitation patterns form a direct link with aquifer recharge. The warmer future climate also leads to an

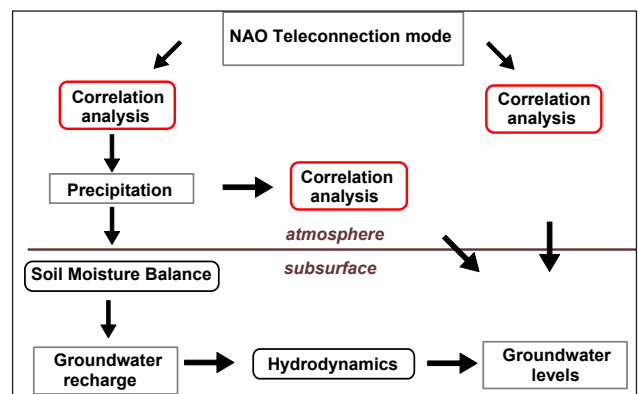


Figure 1. Schematic representation of the investigated correlations

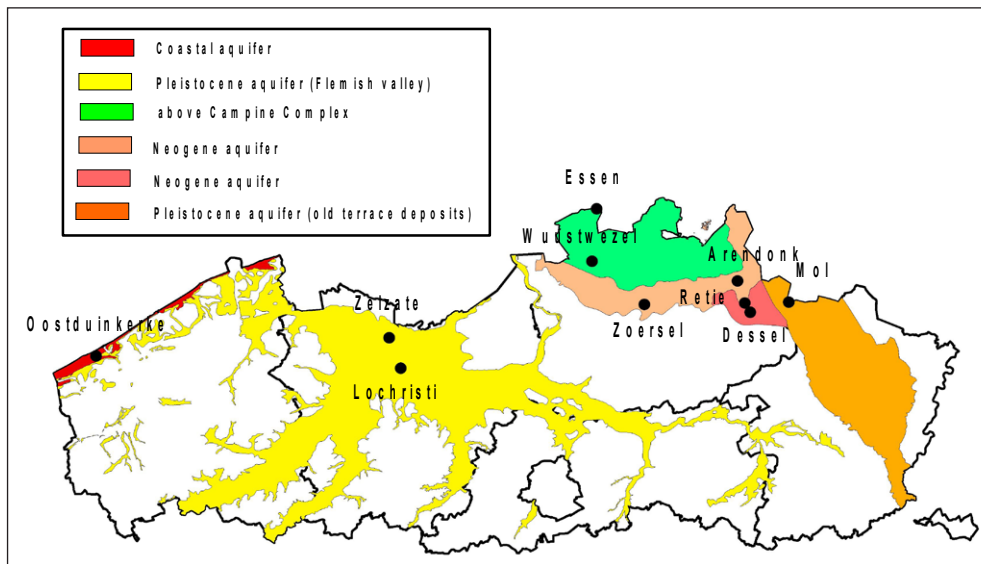


Figure 2. Location of the 10 selected piezometric series

increase in the length of the growing season, so that the region's soil returns to field capacity later in the autumn and starts drying out sooner in the spring. This leads to a reduction in the length of the recharge period (Holman, 2006). Previous studies have shown that the continuing rise in anthropogenic emissions is likely to cause European summers to become substantially drier over the coming century. This would result in a decline in soil moisture (Rowell & Jones, 2006). At the other side, Schmith (2001) analysed 40 precipitation series in Northwestern Europe covering the period 1900-1990 and found a positive trend of the observed winter precipitation totals (October to March) in nearly all of the 40 stations.

As phreatic piezometric levels are mainly dependent on the aquifer recharge which originates from precipitation, and as large scale precipitation is coupled to general atmospheric circulation, a direct correlation between groundwater levels and atmospheric circulation can be expected. The obvious plausibility of such effects does not eliminate the need to demonstrate their existence in a statistically rigorous matter (Fleming & Quilty, 2006).

Recently the relation between atmospheric circulation patterns and extreme rainfall and subsequent flood events was investigated (Jacobeit et al., 2006). The authors recognized that the most important pattern sequence for prominent recharge events in wintertime in large parts of Central Europe is not a pure westerly flow according to the positive mode of the NAO, but a strong cyclonic centre above northern Europe inducing repeatedly northwestern components above Central Europe.

In this study three correlation analyses are performed (Fig. 1) to investigate to which degree phreatic groundwater levels are directly linked to the NAO. The first analysis tests how monthly precipitation totals depend on the monthly averaged NAO indices. The second analysis quantifies how well the piezometric levels are related to the precipitation amounts. The third analysis investigates the direct correlation between the groundwater levels and the NAO index, taking into account the results of the previous analyses.

2. Data

2.1. Piezometric data

Ten piezometric series were selected (Table 1) based on the length of the series, measuring frequency, the apparent absence of anthropogenic influences (pumping) and the regularity of their fluctuations. All selected wells have well screens in the water table aquifer, although the screens may be positioned some meters below it. The location of the wells is indicated in Fig. 2.

2.2. Hydrogeological setting

The observation well in Oostduinkerke is situated in the coastal dune belt and is installed in the Quaternary aquifer system. This system consists of around 30 m of sands resting upon a thick clay sequence. As the dunes form the recharge area of the aquifer system, the well is located in a flow cycle that drains water from the dunes towards a local brook.

The observation wells in Zelzate and Lochristi are situated in a region where a Pleistocene valley was eroded in Tertiary sediments and was filled up during the ice ages to form a 20 to 30 m thick sequence, consisting of two sand members separated by a more silty layer. The piezometer is installed in the upper sandy layer which can be considered as an unconfined aquifer.

The observation wells in Essen and Wuustwezel are situated in the lithologically heterogeneous formation of the Campine Complex, built up by a 30 m thick alternating sequence of more sandy and more silty layers of variable thickness, that are of Pleistocene age. Water table fluctuations propagate into this sequence through the more sandy horizons and piezometric variations can be detected into the underlying sand formation. This well is installed in the upper part of the heterogeneous formation and clearly follows water table fluctuations.

The wells in Arendonk, Dessel, Retie and Zoersel lie within the outcrop of the Neogene aquifer. Here the phreatic aquifer is very thick, as both the Quaternary sand cover and underlying Neogene system form a single aquifer.

Location	Well id	Length series (years)	Measuring frequency (yr ⁻¹)	Hydrogeological zone
Oostduinkerke	SB21	13	47.3	Coastal aquifer
Zelzate	BXV-F2	21	11.34	Pleistocene
Dessel	1-0500	27	17.8	Neogene
Wuustwezel	1-0391	27	26.27	Campine Complex
Mol	1-0501	26	12.87	Pleistocene
Arendonk	1-0402	27	18.69	Neogene
Essen	1-0145	31	14.23	Campine Complex
Retie	1-0389	27	15.92	Neogene
Zoersel	1-1084	31	15.15	Neogene
Lochristi	4-0085	16	12.22	Pleistocene

Table 1. Selected piezometric time series

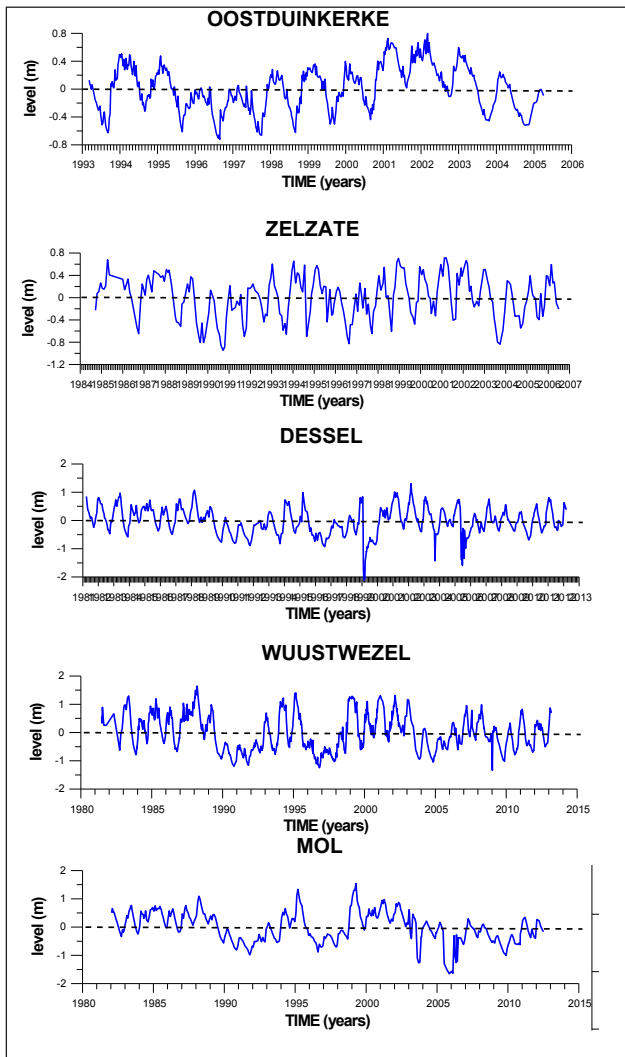


Figure 3. Time-graphs of the selected piezometric series

The well in Mol lies on the Campine plateau, a topographic higher region (elevation up to +70 masl) that consists of coarse Pleistocene terrace deposits. This region is the main recharge area for the Neogene aquifer that outcrops to the west of the plateau. All wells are placed in sand layers, not in less permeable silt- or loam containing deposits.

For each observation well the piezometric levels were recalculated to levels above/below average (Fig. 3). Visual

inspection of the series reveals their most important characteristics. Two cyclic components can be recognized in the graphs:

a) Seasonal fluctuations have a period of around a year and are the most typical feature of phreatic aquifer series. They can be used to distinguish different hydrological years which consist of a recharge and a discharge period. The seasonal fluctuations have amplitudes between 0.5 and 1 meter. Their size depends on the recharge intensity and the specific yield of the sediment in which the water table is located. This can be dependent on the depth of the water table if the aquifer is vertically heterogeneous. Lowest levels are usually reached at the end of summer (August - October), the highest ones in springtime (March-April).

b) Interannual variations are caused by a succession of wetter or dryer than average years. In most series the interannual variation is of the same size as the seasonal fluctuations. In some series (Wuustwezel, Mol) they are the main component. During wet years summer levels can be higher than winter levels in dry years. Sequences of successive wet or dry years can trigger a prolonged increasing or decreasing trend in levels.

2.3. Precipitation data

Historical precipitation data were obtained from the Global Historical Climatology Network version 2 dataset (Vose et al., 1992, Peterson & Vose, 1997). This is a comprehensive global surface baseline climate data set designed for monitoring and detecting climate change. It includes surface station observations of temperature and precipitation on a monthly basis. The data were obtained from <http://www.ncdc.noaa.gov>. The longest and most recently updated series for Belgium is available for the Ukkel station and was used in this study.

2.4. NAO index of the North Atlantic Oscillation

The NAO is the dominant mode of winter climate variability in the North Atlantic region ranging from central North America to Europe and much into Northern Asia. The NAO is a large scale seesaw in atmospheric mass between the subtropical high and the polar low. The corresponding index varies from year to year, but also exhibits a tendency to remain in one phase for longer time intervals.

The positive NAO index phase shows a stronger than usual subtropical high pressure center and a deeper than normal Icelandic low. The increased pressure difference results in more and stronger winter storms crossing the Atlantic Ocean on a more northerly track. This leads to warm and wet winters in Europe.

The negative NAO index phase shows a weak subtropical high and a weak Icelandic low. The reduced pressure gradient results in fewer and weaker winter storms crossing on a more west-east pathway. They bring moist air into the Mediterranean and cold air to northern Europe.

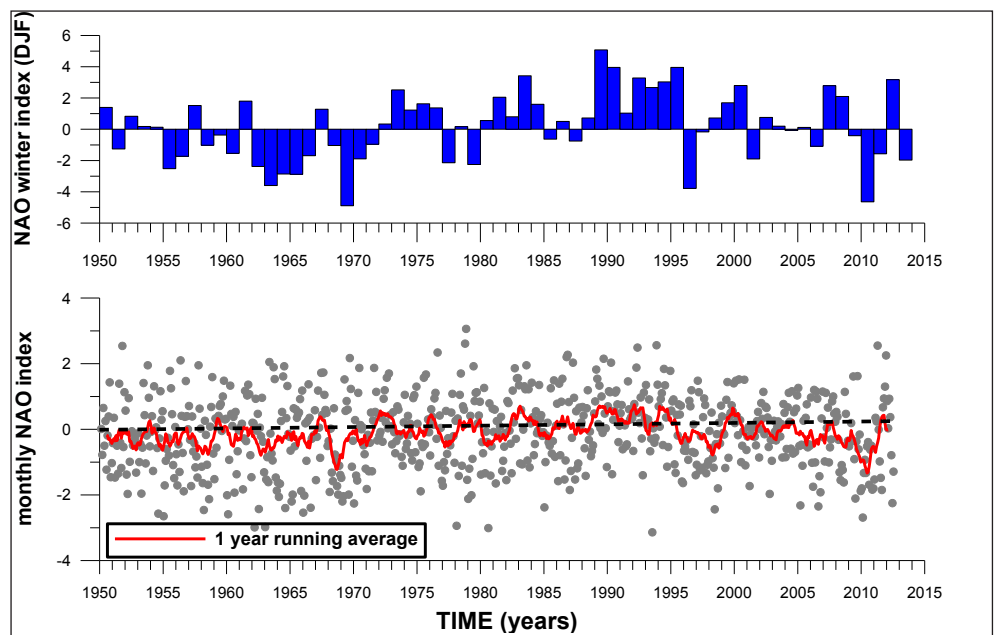


Figure 4. Evolution of NAO winter index (1950-2013)

Monthly values of the NAO index are plotted in Fig. 4. The one-year running average shows that the last fifteen years the average index has been mainly negative. Between 1990 and 1995 the index was positive.

Because Belgium lies in between Northern Europe and the Mediterranean, the relation between the NAO and the weather pattern is less obvious. As the main recharge period for phreatic aquifers is winter time, it can be expected that the NAO winter index is more important, rather than the year averaged value. The winter NAO index, defined as the average of December, January and February (Saunders & Qian, 2002), is separately plotted in Fig. 4.

2.5 Recharge of phreatic aquifers in Low Belgium

Time series of phreatic aquifers are typically characterized by cyclic variations. The first and more easily recognizable are seasonal fluctuations with high levels during recharge periods of the aquifer system and low levels during discharge periods. In Low Belgium and West-Europe in general these coincide with winter and summer respectively. This cycle has a length of a hydrological year and lasts around one calendar year. A second cyclic component has a longer period, usually spanning several years, and originates from the succession of several wetter or dryer years caused by the large inter-annual variations of precipitation, mainly in winter time. Amplitude of this signal can be equal or even exceed the one of the normal seasonal variations. For this reason summer levels in wet years can be higher than winter levels in dry years. It is obvious that the size of these fluctuations is important for the eco-hydrological aspects of the related biotopes and thus also for agriculture.

Other points to consider are the response time of aquifers (time it requires to detect an impact after boundary conditions have changed) and the “hydrogeological memory”. Response time is the time required after a meteorological extreme event (wet or dry period) to produce a signal in the piezometric time series. The hydrogeological memory is the time it requires before the produced impact on the piezometry has faded away. Both depend on the hydraulic properties of the aquifer, mainly the storage coefficient; it seems that in some aquifers the “memory” can last for several years. This means it may take several years before the impact of an extremely dry or wet year has disappeared from the aquifer.

Phreatic aquifers in natural conditions are directly recharged by meteoric precipitation and discharge into surface water like rivers and streams. Coastal aquifers can, at least partly, discharge directly into the sea. Interaction with underlying deeper aquifers can also contribute recharging and discharging fluxes. Imbalance between recharge and discharge of an aquifer system will cause the piezometric levels and hence water table position to change with time. For a limited interval of time Δt a mass balance equation can be written:

$$\text{RECH} - \text{DISCH} + \Delta S = 0 \quad (1)$$

where:

RECH = recharge of aquifer

DISCH = discharge of aquifer

ΔS = change in storage

The change in storage defines the rate of change of the piezometric levels:

$$\Delta S = S_y \frac{dh}{dt} \quad (2)$$

where:

S_y = specific yield of a phreatic aquifer

h = piezometric level

The net recharge from precipitation depends both on precipitation and evapotranspiration rates. Time variations of these parameters can alter the recharge of an aquifer and hence the piezometric levels. Temporal trends of these parameters are dependent on climatological and meteorological conditions of the considered region.

In Low Belgium precipitation is distributed quite equally over the year (usually 50-70 mm/month, Fig. 5), but shows large inter-annual variations. Potential evapotranspiration rates show strong seasonal variations (< 20 mm/month in winter time, > 100 mm/month in summer time), but a small interannual change.

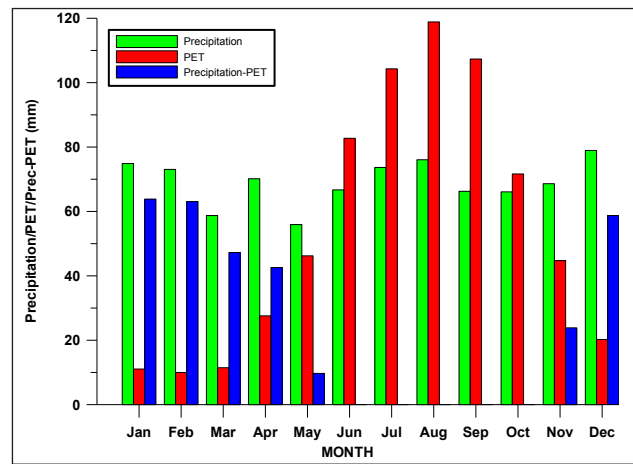


Figure 5. Monthly average precipitation and PET values (1970-2005) in Ukkel

The difference between both is a simple indication of aquifer recharge. It shows that phreatic aquifers are, under normal conditions, recharged in winter time when PET is low while during summer period there is only aquifer discharge. Of course, during winter time the aquifer is also discharging, but recharge exceeds discharge and piezometric levels will rise. Observations indicate that only during exceptionally wet summer months (often in August in the last decennium) temporary recharge periods may also be found in summer time, causing an unusual peak in water table levels.

A methodology for calculating aquifer recharge can be based on a water balance approach as proposed by Thornthwaite & Mather (1955 and 1957) and can easily be implemented (Willmott, 1977; Steenhuis & Van der Molen, 1996). The Thornthwaite & Mather water budget is a simple and frequently applicable tool to estimate surpluses of water, which are not stored in the soil profile (Zimmerman, 2006). In this approach the unsaturated zone is characterized by the plant available water (PAW), the water content between field capacity and the permanent wilting point, and represents the water that can be withdrawn by plants. Calculated aquifer rates depend on the chosen value of PAW, which depends on the local situation, including land use and vegetation, root depth and soil characteristics. The SMB method has been applied for three different values of PAW (resp 50, 100 and 150 mm) and monthly precipitation and temperature data (to estimate PET) of the Ukkel meteorological station for the period 1970-2005. The calculated monthly recharge rates were averaged over the period and recalculated to their contribution (in %) to the total yearly recharge. These values are visualized in Fig. 6. From the graph, the recharge period for phreatic aquifers in Low Belgium can be derived. Most recharge occurs from January to

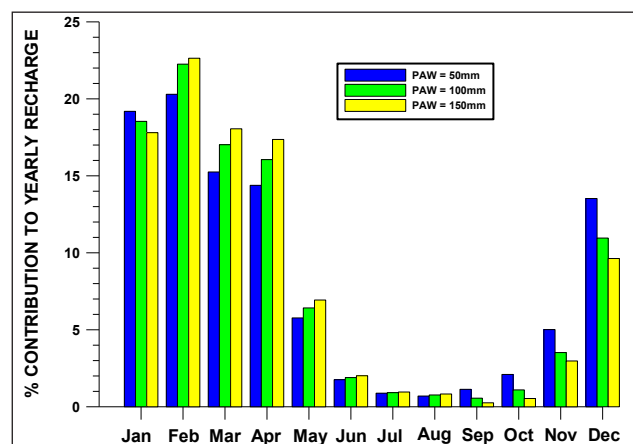


Figure 6. Monthly relative contribution (in %) to the yearly recharge of the water table, calculated with a SMB model for 3 different values of the PAW (50, 100 and 150 mm respectively)

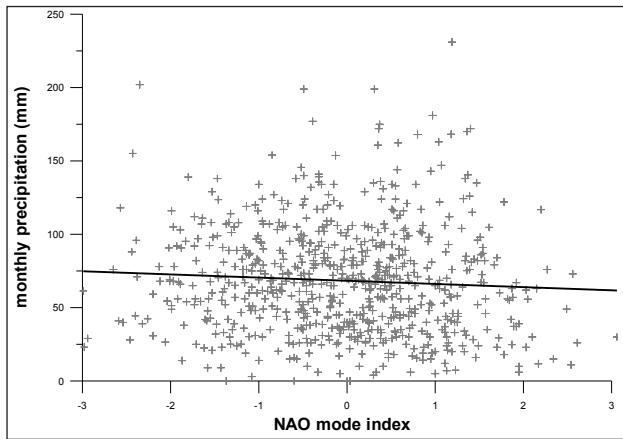


Figure 7. Cross-plot of monthly precipitation amounts versus monthly NAO index (1950-2007) and linear correlation

April, with each month contributing between 15 and 20% of the yearly total. February contributes most (more than 20%), despite the fact that this is the shortest month. The months June to October deliver no more than ca 2% each to the total recharge. The next recharge period sets off in November, while December has about 10% contribution. The difference between the 3 considered PAW values is no more than 2%. All mentioned values are averages and actual recharge rates may be considerably different as interannual variation of precipitation rates is high.

3. Results and discussion

3.1. Correlation between NAO and precipitation

A regression analysis based upon monthly values from the period 1950-2007 does, with $r=0.066$ and $p=0.084$, not indicate a correlation significant at the 5% level (Fig. 7). However, if the monthly values are classified into 4 groups according to their NAO index (< -1 , -1 to 0 , 0 to 1 and > 1), and the group averages are used, a significant relation ($r= 0.998$, $p=0.0015$) is found, with a decreasing precipitation trend with increasing NAO index values (Fig. 8).

The relation NAO – precipitation seems strongly seasonal. Regression analysis for each month separately, whereby each dataset consists of the 28 values of the specific month from 1950 to 2007, shows significant correlations in winter time and summer period, but not in the periods in between. The results of the regression analysis are visualized in Fig. 9, where for each month both the correlation coefficient r (left axis) and the p -value (right axis) are plotted as a function of the slope coefficient. Small slope coefficients indicate an absence of relation and significant correlations are only found for the highest positive (December and January) and lowest negative (July and August) months.

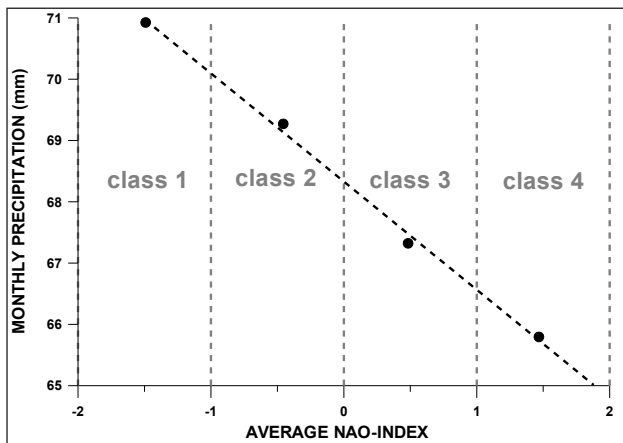


Figure 8. Cross-plot of average monthly precipitation amounts versus classified monthly NAO index (4 classes)

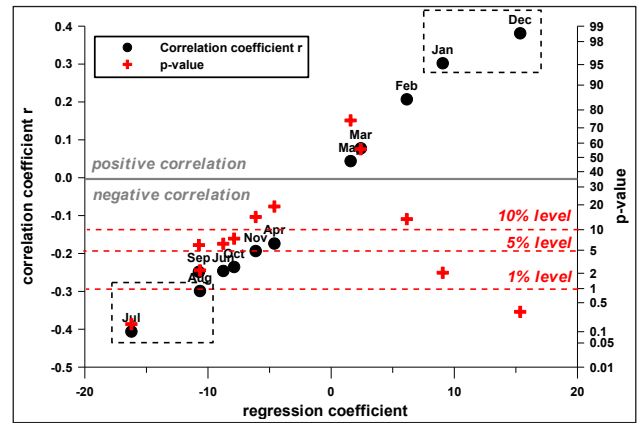


Figure 9. Correlation between monthly NAO index and precipitation (1950-2007)

These represent a positive correlation in winter time and a negative correlation in summer period. This opposite relationship explains why no significant correlation is found when using all monthly values together.

As aquifer recharge is restricted to winter period, only the winter correlation can possibly influence groundwater levels by altering winter precipitation rates. Both months have slope coefficients between 10 and 20, defining a sensitivity of the precipitation with 10 to 20 mm/month if the average NAO index changes by a unit. This could represent a change of 15 to 30% in the average monthly precipitation totals (Fig. 10).

3.2. Correlation between precipitation and groundwater levels

The dependence of groundwater levels on precipitation is quantified using yearly averaged piezometric levels and yearly totals of precipitation. The number of data points in the analysis depends on the length of the time series and their sampling frequency (Table 1). Some years were omitted from some series as they contained too few measurements. The result of the correlation analysis for each of the 10 series is visualized in Fig. 11, where the correlation coefficient r (left axis) and p -value (right axis) are plotted versus the slope coefficient, which is a measure for the sensitivity. All series show high correlation coefficients in the range between ca 0.4 and ca 0.8 and are all significant at the 5% level, 5 series even at the 1% level. The best correlation was found in the series from the coastal aquifer in the dune area. The slope coefficients are in the range between 0.6 and 1.9. These numbers will depend on the hydraulic characteristics

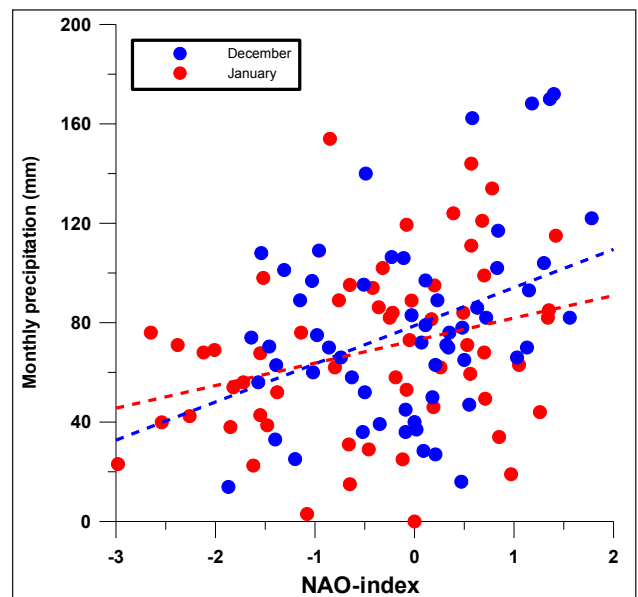


Figure 10. Relation between NAO and precipitation in December and January

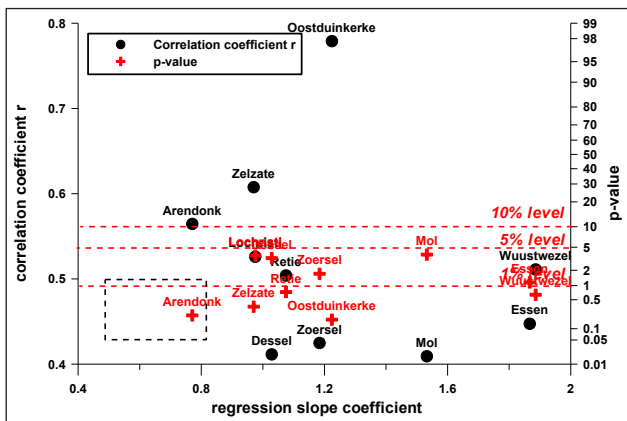


Figure 11. Correlation between yearly averaged piezometric levels and yearly precipitation totals

of the phreatic layer, mainly the specific yield where lower values will increase the slope coefficient, and the aquifer recharge, which on its turn will depend on local vegetation and land use. The slope coefficients give a direct indication of the sensitivity for changes in precipitation rates. The highest sensitivities are found in the series in Wuuwstwezel and Essen, above 1.8. Both are located in the northern Campine region and have a comparable hydrogeological typology. The well screens are positioned in the lithologically heterogeneous Campine Formation unit. It should be noted that these more sensitive locations do not show the best correlation and their r value is between 0.45 and 0.50, compared to the 0.80 found in the coastal aquifer.

3.3. Correlation between NAO and groundwater levels

Based on the fact that there is only a significant correlation between NAO and precipitation in the winter months December and January that can contribute to aquifer recharge, only the NAO index of these months was used in the analysis, and the two-month average was calculated. The index values in the other months were not included, as they could mask the winter correlation. The two-month index was correlated with yearly average groundwater levels for each series. The results are visualized in Fig. 12. Slope coefficients range between 0.02 and 0.23 and correlation coefficients are always below 0.40, with 5 series above 0.30. Of these, only the series in Wuuwstwezel and Essen have a correlation significant at the 5% level, with slope coefficients above 0.20. Both series lie in the northern Campine region in the same hydrogeological typology, with their wells positioned in the heterogeneous Campine Formation. These two series are more sensitive to changes in precipitation with a ratio of about 1.8 for the ratio between changes in groundwater level to changes in precipitation rate. This seems to be a threshold value for promoting a significant NAO signal (at the 5% level) directly into the groundwater level series.

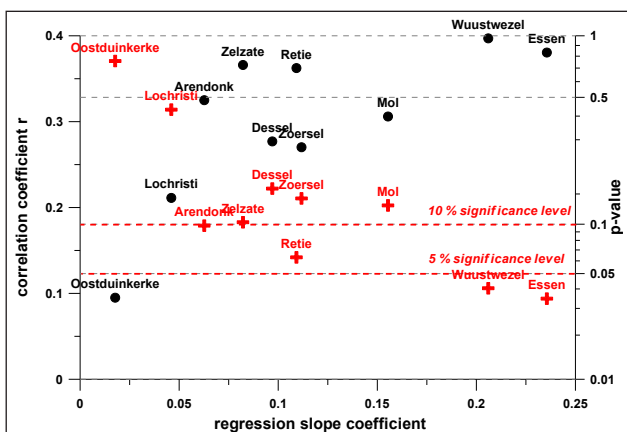


Figure 12. Correlation between the NAO index and groundwater levels

4. Conclusions

Using 10 long multi-decadal time-series (20 to 30 years) of piezometric levels in phreatic aquifers in north Belgium (Flanders), the presence of a signal related to fluctuations in the North Atlantic Oscillation (NAO) was investigated by correlation with meteorological parameters. The NAO is correlated with precipitation rates in Flanders, but only in the months of December and January in winter time (positive correlation at the 5% level) and July and August in summer period (negative correlation at the 5% level). As aquifer recharge in northern Belgium is restricted to winter period, the negative summer correlation is not important for controlling groundwater levels. All 10 investigated series show a strong correlation ($r = 0.4$ to 0.8) between yearly averaged piezometric levels and yearly precipitation at the 5% and even 1% (5 series) significance level. A direct correlation with the NAO, using the average NAO index of the months December and January, was only found in 2 of the 10 series. Both series are located in the northern Campine region and have the same hydrogeological typology. The two locations have a high sensitivity for changes in precipitation rates with a ratio of 1.8 for changes in groundwater level to changes in precipitation rate. This seems to be a threshold value for promoting the NAO signal into the piezometric time series, caused by the dependence of the December-January precipitation on the NAO index.

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