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Inconsistent hydrological trends do not necessarily imply spatially heterogeneous drivers

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ABSTRACT

Trend analyses are widely used to check for climate change effects on hydrological systems. However, often inconsistent patterns have been found, that is, non-significant as well as significant but opposing trends in the same data set. These inconsistencies have often been ascribed to local, mostly anthropogenic effects like wetland draining or land use change. In this study local effects were subtracted from time series of lake water level and groundwater head covering a 28 years period in Northeast Germany. But this did hardly affect the observed inconsistent trends. In contrast, the apparent inconsistent behavior could be ascribed to different degrees of low-pass filtering of the groundwater recharge signal. Due to successively increasing attenuation of high frequency oscillations during the passage through the vadose zone minor long-term oscillations in the input signal became increasingly more visible, resulting in apparent monotonic trends for the 28 year period. There is strong evidence that this phenomenon could be ascribed to frequency-dependent damping of the input signal which has been found for a wide range of natural processes, including hydrological systems.

1. Introduction

Direct anthropogenic effects as well as long-term climate change are expected to cause major shifts in long-term climate and hydrological time series (Milly et al., 2008). Correspondingly, trend analysis of respective state variables is very common in order to check for these effects (Hamed, 2008; Lins, 2005). For Northeast Germany a long-term decrease of water availability has been predicted (Holsten et al., 2009; Huang et al., 2010; Wegehenkel and Kersebaum, 2009). In fact, significantly decreasing trends of groundwater head and lake water level have been observed during the last three decades (Germer et al., 2011; Heinrich et al., 2018; Kaiser et al., 2014a). Climate change effects might have been even amplified by direct anthropogenic effects (Åkesson et al., 2016; Germer et al., 2011; Merz and Pekdeger, 2011; Natkhin et al., 2012).

However, opposing trends have been observed in this region as well (Kaiser et al., 2014a). The same applies to lake water level studied in 32 lakes in an adjacent region in North Poland (Wrzesiński and Ptak, 2016). These have often been interpreted as deviations from a general regional trend due to local natural or anthropogenic effects (Germer et al., 2011; Wrzesiński and Ptak, 2016). Similar inconsistent trends for observation wells close to each other have been reported recently from other regions (e.g., Ayers et al., 2019; Haas and Birk, 2017; Lorenzo-Lacruz et al., 2017; Qiao et al., 2019), and for other climatological and hydrological observables (Hamed, 2008; Lins, 2005; Pilon and Yue, 2002; and references therein). Thus any identification of clear cause-effect relationships seems to be a tedious task (Åkesson et al., 2016).

In contrast, it has been argued that apparent linear trends might rather be part of low-frequency oscillations that are characteristic for climatological and hydrological time series as a consequence of frequency-dependent damping of input signals. It has often been related to the "Hurst phenomenon", "persistence", "scaling behavior" etc. (Hurst, 1951; Koutsoyiannis and Montanari, 2007; Mandelbrot and van Ness, 1968) although the latter is not a necessary prerequisite for the

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former. It could result in apparently arbitrary monotonic trends even for longer periods irrespective of any clear trend in driving variables (Koutsoyiannis, 2006). In fact, numerous studies have found low-frequency oscillations of runoff, groundwater head and lake water with a period length of some decades (Gudmundsson et al., 2011; García Molinos et al., 2015; Neves et al., 2016; Shun and Duffy, 1999) that could be confused with montonic trends at shorter time scales. In addition, low frequency oscillations can differ substantially between adjacent sites (García Molinos et al., 2015). It is felt that the implications of these effects are still strongly underestimated in environmental and geo-sciences as well as in water resources management (Koutsoyiannis, 2006, 2013).

To study this in real-world data sets local effects need to be systematically factored out. This was done by applying a principal component analysis to a set of time series of lake water level and groundwater head in Northeast Germany, covering a 28 years period, and partly exhibiting significant trends but with differing signs. Local effects were subtracted from the observations following the approach by Lischeid et al. (2010) and Hohenbrink et al. (2016). The residuals were then analyzed with respect to consistent long-term trends, compared to that of precipitation and potential evapotranspiration.

2. Data

Time series of lake water level and groundwater head were provided from the environmental authorities of the federal states of Mecklenburg-Vorpommern and Brandenburg and by the Leibniz Institute of Freshwater Ecology and Inland Fisheries for a region rich in lakes that formed during the last (Weichselian) glaciation (Kaiser et al., 2012). It extends along a 180 km distance from Lake Müritz, about 110 km Northwest of Berlin, to Lake Schwielochsee, 75 km southeast of Berlin (Fig. 1). Only data from sites without any clear direct anthropogenic impact have been considered, except for Lake Schwielochsee (Fig. 1). In total, time series from 23 lakes and 17 groundwater wells for a 40 year period (November 1985 to October 2013) were analyzed.

In this region, repeated advances and retreats of inland glaciers during the Pleistocene resulted in a complex setting of unconsolidated sediments with high textural heterogeneity, mostly of 100–200 m thickness. Here complex stacked aquifer systems developed, partly confined, but usually of unknown number and extent of single aquifers (e.g., Pöschke et al., 2018) where groundwater flow direction can differ between various storeys. In addition, groundwater flow direction in single aquifers can vary between dry and wet years (Holzbecher, 2001). Thus any delineation of watersheds or capture zones is prone to substantial uncertainties. Correspondingly, land use effects can only tentatively be assessed by that of the immediate surroundings (Table 1).

Lakes are partly topographically isolated (endorheic lakes), partly interlinked by streams (exorheic lakes). The stream network has been substantially extended by man during the last millennium and exhibits numerous weirs (Kaiser et al., 2018). Flow velocity in the streams usually is very low due to low relief intensity. Occasional desiccation has been observed in many streams but has rarely been monitored systematically.

Long-term time series of meteorological data at daily intervals were used from five sites in the study region, operated by the German Weather Service (Fig. 1). The region is located in the transition zone between oceanic climate in the northwest and more continental climate in the southeast. Annual mean temperature is about 9 °C. Annual mean precipitation is between 520 and 550 mm yr^{-1} and tends to decrease towards southeast.

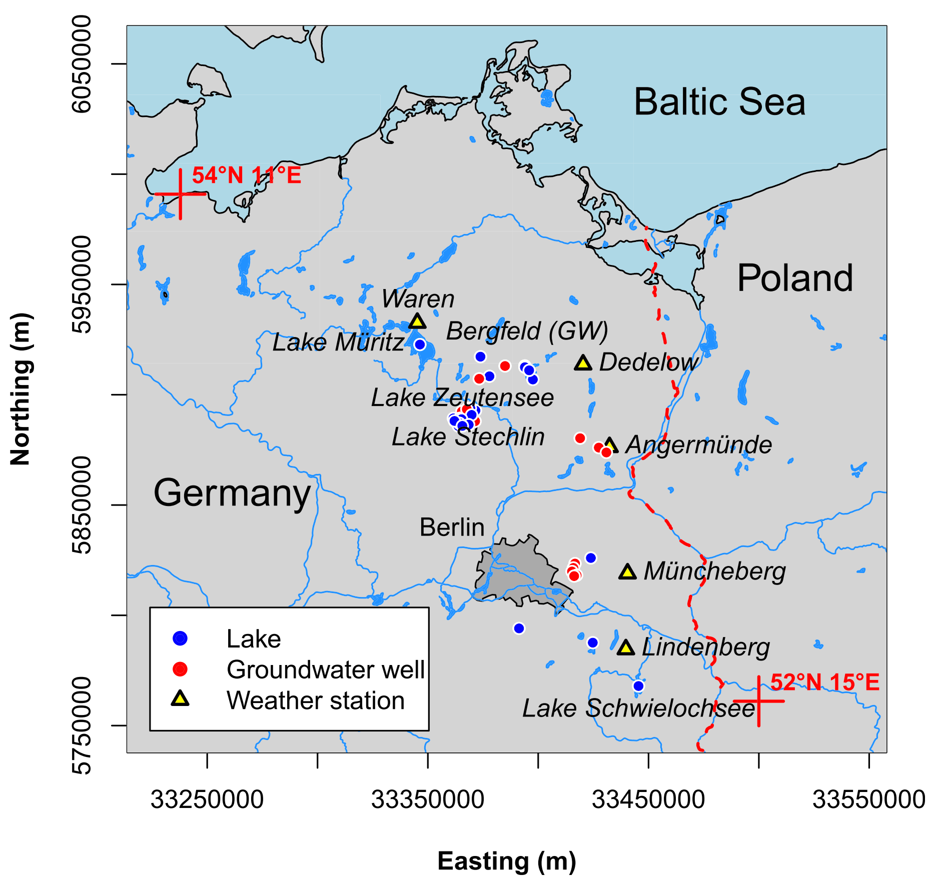

Fig. 1. Map of measurement sites in Northeast Germany. Only major streams and lakes are indicated explicitly. Measurement sites referred to in the text are indicated in italics.

Table 1
List of sites from which time series of groundwater head (type “GW”) or lake water table were analyzed, ordered roughly along a northwest-southeast transect. “Land use” refers to the immediate surroundings of the respective site, differentiating between settlement, arable field, grassland and forest. “Altitude” means mean lake water level or ground level of groundwater wells, respectively. “Inflow” and “outflow” refers to streams discharging into the lakes or draining the lakes.

Name	Type	Spatial cluster	Land use				Altitude (m a.s.l.)	Lake area (km^2)	Inflow	Outflow
			Settlem.	Arable f.	Grassl.	Forest				
Müritz	Lake			x	x	x	62.2	112.60	yes	yes
Langer See Weisdin	Lake	Feldberg		x		x		0.42	yes	yes
Bergfeld	GW	Feldberg		x	x	x	87.2			
Klein Trebbow	GW	Feldberg				x	69.3			
Fürstenseer See	Lake	Feldberg				x	63.6	2.12	yes	yes
Sprockfitz	Lake	Feldberg			x	x		0.10	yes	no
Hechtsee	Lake	Feldberg			x			0.06	no	no
Feldberger Haussee	Lake	Feldberg	x		x	x	84.3	1.31	yes	yes
Carwitzer See	Lake	Feldberg		x	x	x	83.7	7.22	yes	yes
Krummer See	Lake	Stechlin				x		0.08	no	no
Wittwesee	Lake	Stechlin				x	60.8	1.42	yes	yes
Glabatzsee	Lake	Stechlin				x		0.02	no	no
Plötzensee	Lake	Stechlin				x		0.08	no	no
Kleiner Tietzensee	Lake	Stechlin		x	x	x		0.11	no	no
Nehmitzsee	Lake	Stechlin				x	59.6	1.64	yes	yes
Peetschsee	Lake	Stechlin				x	59.1	0.89	no	no
Zeutensee	Lake	Stechlin				x	59.1	1.36	yes	yes
P12	GW	Stechlin				x	81.3			
P26	GW	Stechlin				x	60.9			
P10	GW	Stechlin				x	80.5			
Grosser Glietzensee	Lake	Stechlin				x	58.7	0.20	no	no
P15	GW	Stechlin				x	75.2			
Stechlin	Lake	Stechlin				x	59.6	4.13	yes	yes
Dagowsee	Lake	Stechlin	x			x	60.2	0.20	yes	yes
Roofensee	Lake	Stechlin	x			x	59.2	0.56	yes	yes
P42	GW	Stechlin		x	x	x	82.9			
Poratz	GW	Schorfheide		x		x	67.6			
Wolletz	GW	Schorfheide		x		x	54.2			
Sternfelde	GW	Schorfheide		x		x	55.4			
Bruchmühle 34	GW	Bruchmühle	x			x	58.3			
Bruchmühle 35	GW	Bruchmühle	x			x	58.3			
Bruchmühle 36	GW	Bruchmühle	x			x	58.3			
Fredersdorf 32	GW	Bruchmühle	x				53.8			
Fredersdorf 66	GW	Bruchmühle	x				51.1			
Petershagen 60	GW	Bruchmühle		x	x	x	50.7			
Vogelsdorf	GW	Bruchmühle	x		x		50.3			
Straussee	Lake	Bruchmühle	x			x	65.3	1.38	yes	yes
Rangsdorfer See	Lake		x	x	x	x	36.1	2.14	yes	yes
Groß Schauener See	Lake		x	x	x		35.7	1.48	yes	yes
Schwielochsee	Lake		x	x	x	x	40.8	10.40	yes	yes

3. Methods

For statistical analyses and graphs the R software version 3.1.0 (R Core Team, 2014) was used.

3.1. Preprocessing of data

Application of the principal component analysis to time series of lake water level and groundwater head required synchronous and gap-free data sets. Temporal resolution was once per month at least with mid-month readings mostly, but not strictly synchronously at different sites. Thus measured data were linearly interpolated to the 15th day of each month defined as support points. This is justified by the pronounced autocorrelation of groundwater head and lake water level data (Lischeid et al., 2010). Selection of sites and period aimed at a maximum number of sites and a maximum length with a minimum of data gaps. Gaps were defined as cases were no observation data were available within a 28 days interval around the mid-month support points. Gap-less time series were available for 31 sites. Seven sites exhibited up to four gaps. At three sites major gaps of 11 or 12 months were encountered, i.e., for groundwater well Fredersdorf_32 (between 15 May 2010 and 01 June 2011), well Bergfeld (between 15 October 1987 and 15 November 1988) and for lake Sprockfitz (between 15 October 1985 and 15 November 1986). Weekly or daily data were available from some sites. These data were synchronized to weekly data as well to be used for power spectrum analysis.

Gaps in meterological time series were filled by regression with data from adjacent sites. Precipitation was corrected to account for the wind and evaporation error after Richter (1995). Potential evapotranspiration was assessed as reference crop evapotranspiration according to Allen et al. (1998) based on air temperature and duration of sunshine data or global radiation, modified by Wendling (1991). Daily climatic water balance was calculated as the difference between precipitation and reference crop evapotranspiration.

3.2. Significance tests

A $p < 0.05$ level of significance was used throughout for significance testing. Differences between two groups of sampling sites with respect to loadings on principal components were tested using the Mann-Whitney test (routine “wilcox.test”, R Core Team, 2014). The Kendall rank correlation (package “Kendall”; McLeod, 2011) was used to test for monotonic relationships between metrically scaled variables. This test gives rather exact assessments of p values for ties. None of the two tests requires any specific distribution of the data or homoscedasticity.

Time series were tested for significance of monotonic trends using the Mann-Kendall test (Kendall, 1975) with correction for serial correlation according to Yue et al. (2002). The magnitude of significant trends was assessed using the approach presented by Sen (1968). The analysis was performed using the "zyp" package (Bronaugh and Werner, 2009). In contrast to lake water level and groundwater head, trend analysis of the meteorological data was performed for daily rather than monthly data for the November 1985 to October 2013 period due to larger statistical power.

3.3. Principal component analysis

Principal component analysis (PCA) performs an eigenvalue decomposition of a covariance matrix of a multivariate data set in order to identify orthogonal principal components, defined by the eigenvectors. Applications of PCA on time series of observables that have been measured synchronously at different locations is a common approach in climatology and meteorology where it has been termed the "Empirical Orthogonal Functions" (EOF) approach (Jolliffe, 2002; Vereecken et al., 2016). When time series are inputted into the principal component analysis (PCA), the resulting principal components can be regarded as archetypal time series. Single observed time series can then be represented by linear regression to the principal components (PC). Longuevergne et al. (2007), Lischeid et al. (2010) and Lehr et al. (2015) give some examples for application on groundwater head data, Gottschalk (1985) and Thomas et al. (2012) on discharge data, and Jawson and Niemann (2007) and Hohenbrink et al. (2016) on soil moisture data. In this study the "prcomp" routine was used (R Core Team, 2014).

Loadings of time series on selected PC (l_{PC1}, l_{PC2}, etc.), that is, the Pearson correlation coefficient for comparison of single observed time series with selected PC, can be used as a quantitative assessment of the respective effect size at single sites (Jolliffe, 2002). Due to normalization of the observed time series to unit variance, principal components with an eigenvalue exceeding unity reflect effects that necessarily concern more than just a single time series. In contrast, local effects restricted to single sites are depicted by principal components with much smaller eigenvalues. Thus to factor out local effects from the observed time series they are projected onto the principal components with eigenvalues exceeding unity. Projection is performed by multivariate linear regression of the time series with those of the respective principal components. Details of that approach are given by Lehr and Lischeid (2020).

3.4. Spectrum analysis and low-pass filtering

Any discrete time series can be decomposed into a set of sine and cosine functions of different frequencies without any loss of information (Fourier transformation). The sum of squared coefficients of the respective sine and cosine function, that is, the power, is then proportional to the fraction of variance explained by oscillation of the respective frequency. Plotting power versus frequencies yields a graph of power spectrum density. It provides information, e.g., about the weighting of low versus high frequency patterns in the respective time series.

The Fourier transformation is often applied to the autocorrelation function of the time series rather than directly to the genuine time series. Power spectrum analysis was performed by subjecting the results of autocorrelation analysis (routine "acf", R Core Team, 2014) to the routine "spectrum" (R Core Team, 2014). In order to achieve sufficient frequency resolution it was applied only to data with weekly resolution at least. This applied to time series of groundwater head at six sites. For the sake of comparability with the groundwater head data, readings of the same weekly dates from daily meteorological data and daily data of Lake Stechlin water level were used for that analysis.

For the weather station Lindenberg (Fig. 1) daily meteorological data for the 01 April 1906 to 31 October 2013 period were used to compile a long-term time series of climatic water balance as a proxy of groundwater recharge. This time series was subjected to low-pass filtering to mimic the proposed low-pass filtering of the groundwater recharge signal. In a first step, a Fourier analysis of the time series of n data points $x(t_i)$ at dates t_i, normalized to zero mean, was performed, yielding a set of coefficients a_k for different frequencies:

$$a_k = \frac{2}{n}\sum_{i=1}^{n} x(t_i)\cdot e^{-2\pi i\cdot\frac{k}{n}\cdot t_i} \quad for \quad k = -\frac{n}{2}+1,\ \ldots,\ \frac{n}{2} \tag{1}$$

Low-pass filtering was then applied by the inverse Fourier transform

$$x(t_i) = \sum_{k=-\frac{n}{2}+1} \mathbf{ERROR!!}\frac{n}{2} e^{-2i\cdot\frac{k}{n}\cdot\widehat{a}_k} \tag{2}$$

where

$$\widehat{a}_k = a_k\cdot\left(\frac{a_k}{\frac{n}{2}}\right)^b$$

The degree of low-pass filtering is adjusted by the coefficient b, where b = 0 denotes no filtering at all, and $b \gg 0$ denotes strong low-pass filtering.

4. Results

4.1. Factoring out local effects by principal component analysis

Principal component analysis aimed at decomposing the time series of lake water level and groundwater head into a general, that is, regional, and a more specific local part each. In a rather conservative approach the general part was assessed via principal components with eigenvalues exceeding unity. This holds for the first four principal components that explained 88% (53%, 25%, 7% and 3%) of the variance of the data set. Except for Lake Schwielochsee (28% of the variance), between 68% and 98% of the variance was explained for each of the remaining sites, and more than 80% for 35 out of 40 sites. Thus local effects, including direct anthropogenic effects like groundwater extraction obviously played only a minor role for most of the investigated sites. In addition, the effect of filling data gaps by linear interpolation seemed to be negligible, as the respective sites (groundwater wells Fredersdorf_32 and Bergdorf, and Lake Sprockfitz) did not stand out in regard to explained variance (0.93, 0.94, and 0.86, respectively).

Fig. 2a shows the loadings of all 40 time series on the 1st and 2nd principal component (PC). These first two principal components depict 78% of the variance of the data set. Symbols close to the outer unit circle (dashed line) indicate time series where most of the variance is depicted by the first two PC, like for Lake Stechlin (89% of variance).

Corresponding to findings in other studies where PCA was applied to a set of hydrological time series (Gottschalk, 1985; Hohenbrink and Lischeid, 2015; Lehr and Lischeid, 2020), the 1st PC was similar to a time series of spatial averages of normalized values at all 40 sites for each date of the time series. Thus it reflected the mean behavior averaged of all sites. The second PC has often been found to reflect the degree of transformation of the hydrological input signal in the vadose zone (Hohenbrink and Lischeid, 2015; Lischeid et al., 2010; Lehr and Lischeid, 2020), that is, the degree of damping and delaying compared to the precipitation signal. In fact this holds for this study as well, although with inversed sign: Time series exhibiting very responsive behavior like water level at Lake Zeutensee exhibited strong positive correlation with the second PC (Fig. 2). The opposite is true for very smooth time series like groundwater head at well Bergfeld (Fig. 2).

This degree of transformation can be quantified by a "damping coefficient" D based on the loadings l_{PC1}, l_{PC2} on the first and second PC (Lischeid et al., 2010), thus factoring out all other effects:

$$D = arctan\frac{l_{PC2}}{l_{PC1}} \tag{4}$$

Here, low (negative) values denote weak transformation, and high (positive) values strong transformation. Among all 40 time series, that of

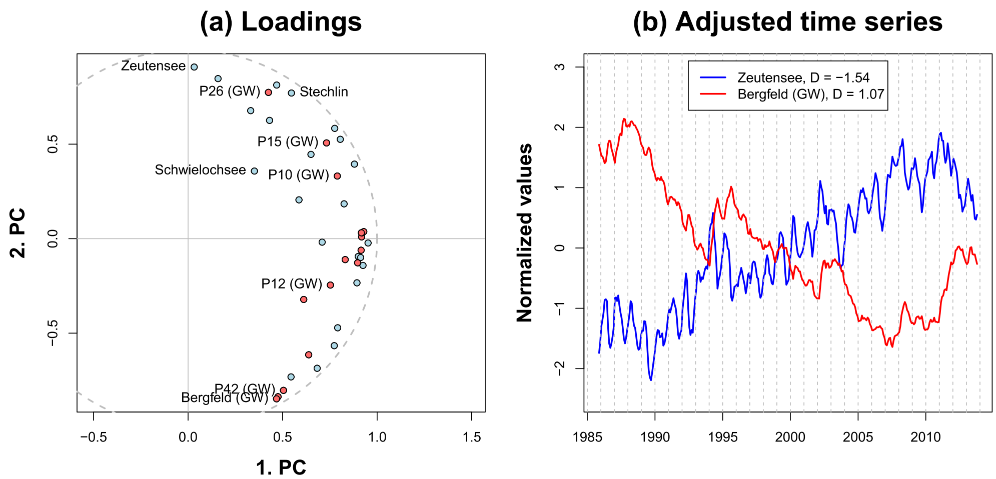

Fig. 2. Loadings of time series (blue: lake water level; red: groundwater head) on 1st and 2nd PC (a; selected sites labelled) and adjusted time series of the two sites with extreme D values (b). Please see Fig. 1 for location of the specified sites.

water level at Lake Zeutensee exhibited a minimum damping coefficient of D = −1.54, and that of groundwater well Bergfeld (GW) a maximum of +1.07 (Fig. 2). For these sites time series are given (Fig. 2b) where the effects of additional PCs have been subtracted. In general, time series with high positive damping coefficients exhibit a more smooth shape. Correspondingly, autocorrelation for lag 1 month is highly significantly correlated with the damping coefficient ($p < 0.001$). In addition, time series with positive damping coefficients lag behind those with negative damping coefficients, accounting for up to three months for single time series compared to that of the lowest damping coefficient (Fig. 2b).

This study focuses on analysis of inconsistent trends rather than at ascribing principal components to various processes of physical factors. Thus the third and fourth component are only shortly described here. Loadings of the time series on the third PC differed significantly ($p < 0.001$) between sites with pure forest land cover in up to 1 km distance compared to those of mixed land use. Exorheic and endorheic lakes differed with respect to loadings on the first and third principal component, although on the edge of insignificance ($p = 0.047$ in both cases). Time series of lake water level and groundwater head differed significantly from each other ($p < 0.002$) with respect to the fourth component only which comprised 3% of the total variance. In addition, loadings on that component were significantly correlated with the northings. Please note that the share of lakes tended to increase towards the north (Fig. 1), although not significantly ($p = 0.08$). No significant correlations were found for the first four principal components with respect to eastings, altitude of groundwater head or lake water level, mean depth to groundwater, mean or maximum water depth, lake area, or lake volume (not shown).

4.2. Trend analysis

Time series of lake water level and groundwater head were tested for significant monotonic trends for the whole 1985–2013 period. On the one hand the genuine time series were directly subjected to the trend analysis. On the other hand, possible local and direct anthropogenic effects were subtracted, thus reducing the variance by 12% on average. The latter differed from the unmodified data with respect to the significance of the trend at three out of eleven single sites, but hardly in regard to trend size ($r^2 = 0.998$). In either case 11 out of 40 time series (27.5% of all time series) exhibited significant trends (Fig. 3). Both for the genuine time series as well as for the time series adjusted for local effects significantly increasing trends were found only for time series with low damping coefficients, and significantly decreasing trends only for those with high damping coefficients.

In addition, time series of daily precipitation, potential evapotranspiration, and the climatic water balance as the difference of the two,

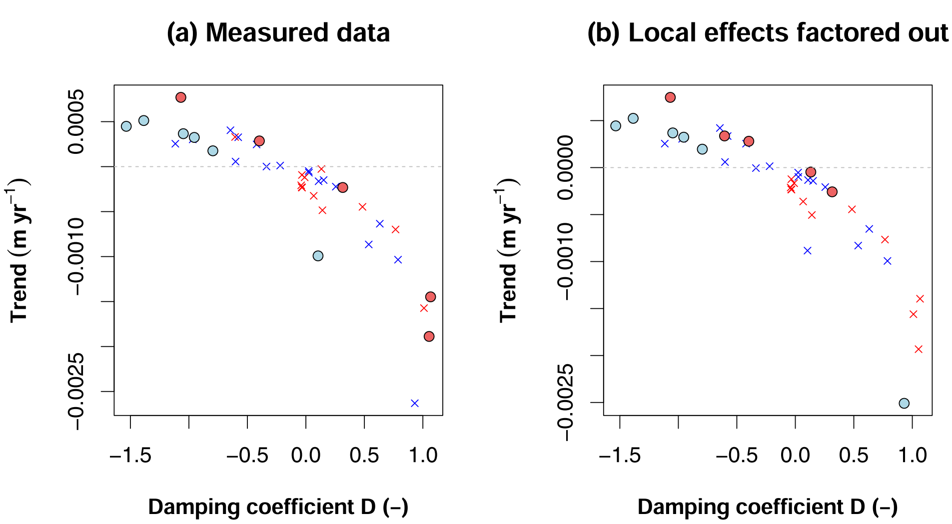

Fig. 3. Size of significant (filled symbols) and insignificant (crosses) trends in time series of lake water level (blue symbols) and groundwater head (red symbols) versus damping coefficient for unmodified observations (a) and time series adjusted for local effects (b).

were tested for significant monotonic trends for the same period. A significant increase was found only for potential evapotranspiration at one out of five sites, and a significant decrease of the climatic water balance at three out of five sites. Precipitation did not exhibit a significant trend at any of the five weather stations (Fig. 4). However, for none of these observables the size of the trend exceeded 0.02 mm yr^{-1}, that is, 0.54 mm for the whole 28 year period. This is about two orders of magnitude smaller than those of the strongest trends found in lake water level and groundwater head data (Fig. 3).

4.3. Relating trends to low-pass filtering

To elucidate the interplay between signal transformation in the vadose zone, quantified by the damping coefficient, on the one side and monotonic trends on the other side, Fig. 5 presents time series of Lake Stechlin water level and groundwater head from various observation wells, all at <3.5 km distance from the lake. Land use is forest exclusively for the whole Stechlin region (Table 1), except for some minor settlements, and has been so for decades. The higher the damping coefficient, the more the seasonal pattern was damped and the more low-frequency patterns became clear. This effect was related to mean depth to groundwater, that is, the thickness of the vadose zone. In addition, long-term trends inverse: All time series in the upper row of panels of Fig. 5(a–d) with $D < 0$ exhibited a significant increase, and the two time series in the lower panel (e-f) with $D > 0$ a significant decrease during the 1985–2013 period. The set of time series clearly reflects a successive transformation with increasing damping coefficient rather than systematic differences between time series with increasing or decreasing trend, respectively.

It has been argued that damping of the hydrological signal in the soil can be described as a low-pass filtering process. Then the slope of the power spectrum can be used as a measure to quantify the latter. The slope of the power spectrum of time series of precipitation is close to zero, indicating approximately the same share of variance in the high frequency range compared to the low frequency range (Fig. 6). In contrast, the power spectrum of potential evapotranspiration decreases towards the higher frequencies (right side of the bottom right graph), indicating less variance in the high frequency range. The slope of the power spectrum of the time series of the climatic water balance as the difference between these two variables exhibits an intermediate slope. In contrast, the power spectrum of lake water level and groundwater head (Fig. 6) shows a much stronger decline towards the high frequencies.

This is equivalent to the frequency-dependent damping of sound in air or in solid materials: Attenuation of high frequencies is much stronger compared to that of low frequencies. Consequently, sound becomes duller during transmission through air (Harris, 1966; International Organization for Standardization, 1993) or through a concrete wall. The same applies to hydrological signals that propagate as pressure waves in the subsurface.

To check whether the observed trends on groundwater head and lake water level could be ascribed to low-pass filtering of a climate signal without any clear trend, a long-time series of climatic water balance data was subjected to different degrees of low-pass filtering. The time series of climatic water balance was calculated for daily meteorological data of the Lindenberg weather station (Fig. 1), covering the 01 April 1906 to 31 October 2013 period. A high degree of low-pass filtering did not only yield very smooth time series, but also a clear negative trend during the last decades as part of a low-frequency pattern (Fig. 7), similar to that observed at some groundwater wells with high damping coefficient (cf., Fig. 5, lower row). However, the increasing trend observed at other sites (cf., Fig. 5, upper row) could not be reproduced (not shown).

5. Discussion

This study aims at testing two competing hypotheses to explain inconsistent trends observed in 28 year time series of lake water level and groundwater head in Northeast Germany. The first hypothesis ascribes inconsistent trends to local, that is, presumably anthropogenic, effects at single sites. To that end, local effects were factored out using principal component analysis. The second hypothesis states that low-frequency patterns in meteorological driver variables are masked by high-frequency patterns. The latter are increasingly stripped off during passage of the hydrological signal through the vadose zone. Consequently, low-frequency patterns become increasingly more clear. When the period length of prevailing frequencies is at least roughly double the length of the study period, the visible range of that pattern might be mistaken as a continuous trend.

5.1. Inconsistent trends

Trend analysis is easy to perform, and thus has often been used to check for climate change effects or anthropogenic effects in environmental data. The term “trend analysis” usually is used in a rather narrow sense for testing for a linear or monotonic trend of the mean value of a time series. The basic assumption is often that significant trends at the

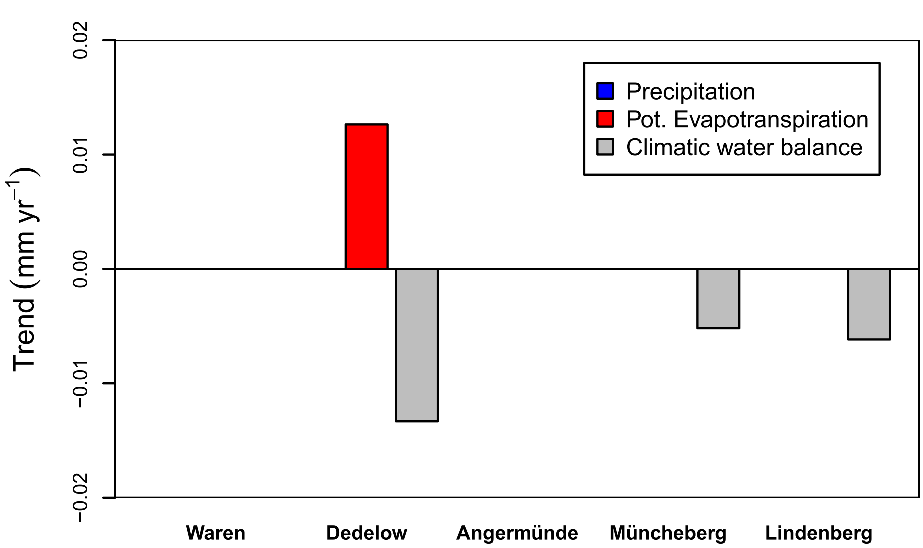

Fig. 4. Magnitude of significant trends for meteorological variables at five weather stations 1985–2013. Non-significant trends were set equal to zero. See Fig. 1 for location of the weather stations.

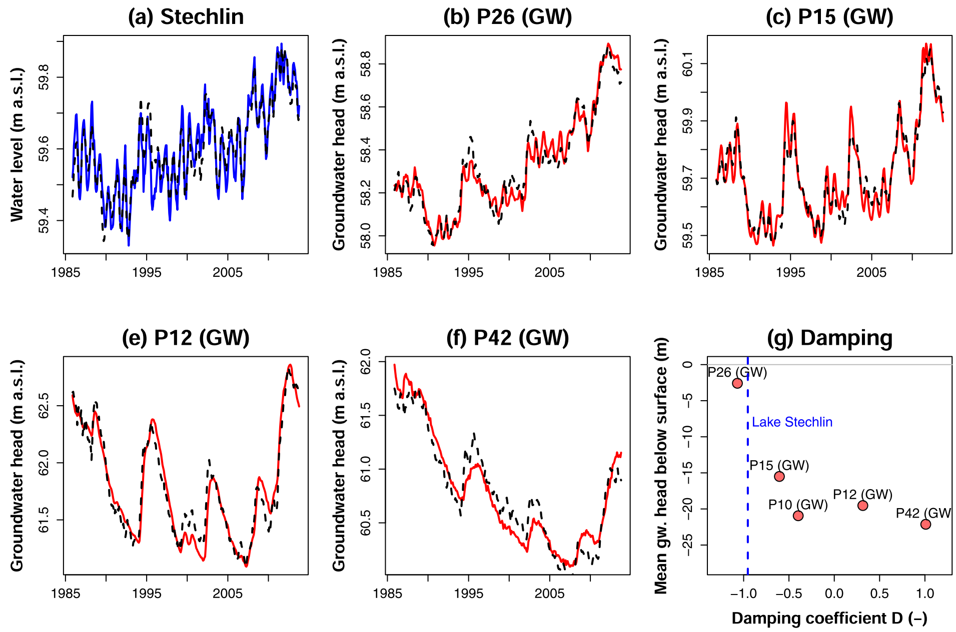

Fig. 5. Observed time series of Lake Stechlin water level (a; blue) and groundwater head of wells close to Lake Stechlin (b-f; red). Dashed black lines indicate the same time series but with local effects factored out. (g): Damping coefficient of Lake Stechlin (blue dashed line) and mean groundwater head below surface versus damping coefficient D (red symbols).

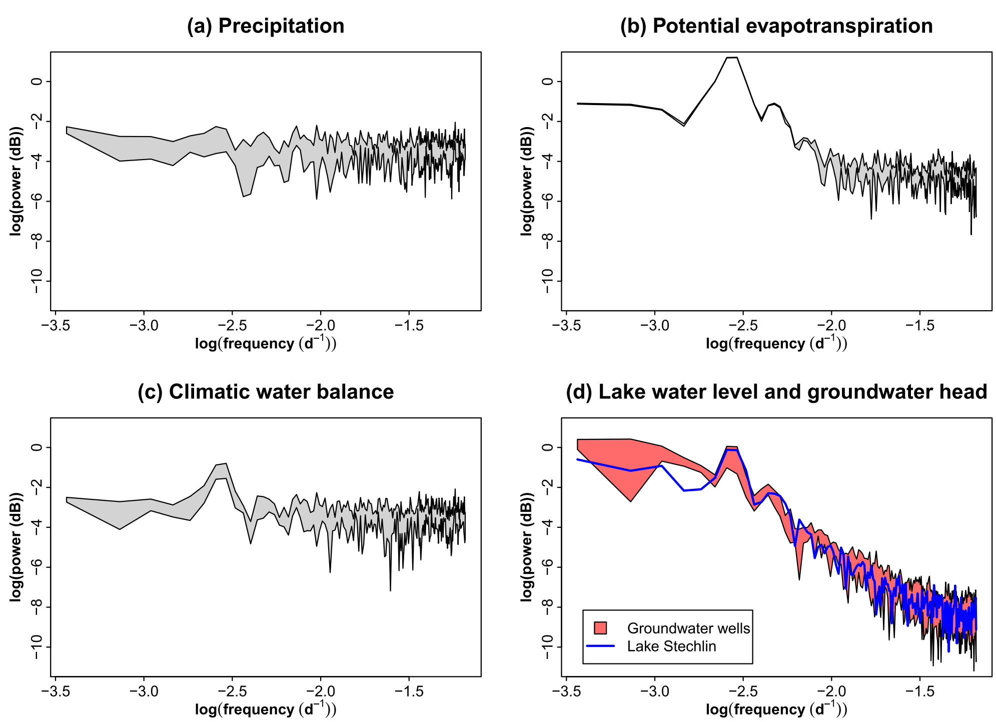

Fig. 6. Power spectra of meteorological observations (a-c), groundwater head and Lake Stechlin water level (d). Filled areas denote the range spanned by data from five meteorological stations (precipitation, potential evapotranspiration and climatic water balance; a-c) or six groundwater observation wells (d), respectively.

scale of years or decades would indicate major changes. Previous work in the study region gave clear evidence for substantial oscillations of lake water level at the scale of decades (Kaiser et al., 2015) up to millennia (Dietze et al., 2016; Kaiser et al., 2014b). Corresponding results have been reported from a similar region in Poland by Starkel et al. (1996), from southern central Europe by Magny (2004), and from Ireland by García Molinos et al. (2015). Likewise, Todhunter and Fietzek-DeVries (2016) found evidence for substantial multi-decadal and centennial oscillations of the water level of the Devils Lake (North Dakota, USA) during the last 4000 years that they ascribed to the dynamics of hydroclimatic forcing, including the catastrophic flooding during the last two decades. Gudmundsson et al. (2011) describe low-frequency patterns for runoff data from numerous catchments all over Europe, and Clarke (2007) for South America. Thus results of the analysis of linear or monotonic trends are necessarily restricted to limited time periods.

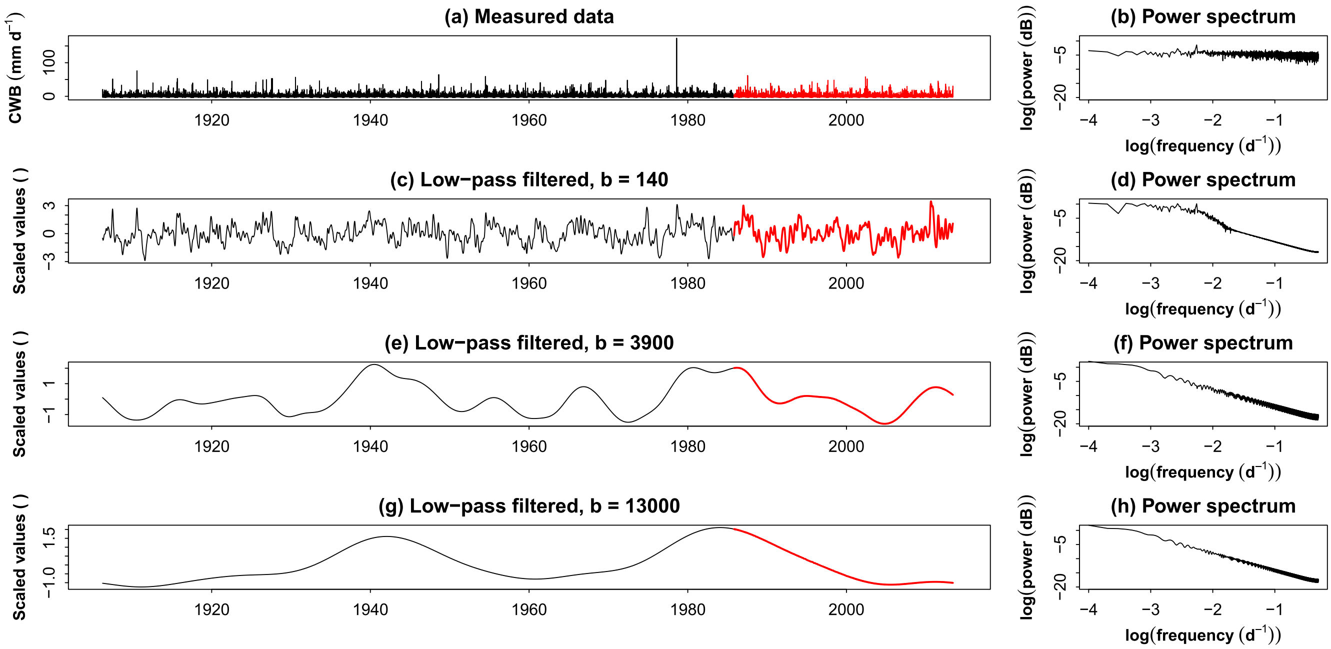

Fig. 7. Time series of climatic water balance at Lindenberg 1906–2013 (a), low-pass filtering applied to this time series with increasing degree of filtering from top to bottom (c, e, g) and respective power spectra (b, d, f, h). The red segments of the time series indicate the 1985–2013 period for which groundwater head and lake water level data had been analyzed.

However, that does not explain why trends of the same observable but at different sites usually differ not only in strength but even in sign. Not only monotonic trends but even the degree of low-frequency oscillations can differ substantially between adjacent sites at the scale of decades (García Molinos et al., 2015) or of centuries to millennia, as indicated by rather poor correlation between palaeo-records of lake water level within a small region (Starkel et al., 1996).

5.2. First hypothesis: Inconsistent trends are due to local peculiarities

Trends of lake water level and groundwater head were not closely related to those of climatological variables. Firstly, trends in the driving meteorological variables, as far as they were significant, were very small and unlikely to result in the observed major differences between sites (Fig. 4). Secondly, these trends could not explain trends of lake water level and groundwater head with opposing signs within a few km distance (Fig. 3). Thirdly, the maximum time shift between corresponding peaks in time series exhibiting different damping coefficients was three months (Fig. 2). A temporal delay that short could not explain the observed inconsistent trends, e.g., groundwater head at some sites responding to climatological input of preceding decades, and others to more recent input. Please note that this holds for the pressure signal only and must not be mismatched with groundwater age dating data.

Principal components exceeding an eigenvalue of one were considered indicative for non-local effects on lake water level and groundwater head. Thus more than two third of the variance at all sites could be ascribed to regional rather than local effects, except for Lake Schwielochsee (Fig. 2). Here up to 75% of the variance had to be ascribed to local effects. The River Spree runs through the lake which discharges a region with massive open-cast mining and corresponding extensive dewatering (Grünewald, 2001; Schoenheinz et al., 2011). However, even at this site natural processes added onto the observed dynamics rather than substituting them. The principal component analysis allowed extracting the respective pieces of information that were related to natural processes (cf., Hohenbrink et al., 2016; Lehr and Lischeid, 2020).

For the remaining sites possible local effects were substantially smaller but could not fully be ruled out. In contrast to common assumptions, however, neither direct anthropogenic effects nor land use or systematic differences between groundwater head and lake water level, or between exorheic and endorheic lakes seemed to have played a major role in this data set. Factoring out local effects had only minor effects on sign and strength of monotonic trends (Figs. 3 and 5). Even more important, the correlation between trends and damping effects was hardly modified (Fig. 5). Thus inconsistent trends of lake water level and groundwater head could not be ascribed to local effects.

Instead, there was a systematic shift from time series with low damping coefficient, often exhibiting a significant long-term increase, to time series with high damping coefficient, partly exhibiting a significant decrease. Similar observations are reported from other studies, although without establishing a causal connection. Van der Maaten et al. (2015) found significantly decreasing lake water levels in two out of three studied lakes in this region for the 1988–2010 period. The third lake did not exhibit any trend but a much more pronounced seasonal pattern, pointing to much less damping of the input signal. Pathak and Dodamani (2019) investigated groundwater level trends in 59 wells in the Ghataprabha river basin in Southwest India. The data set was divided into three clusters that reflected different degrees of short-term oscillations. Decreasing trends were detected in 81% of the wells in the cluster of least fluctuating groundwater heads, but substantially less in the other two clusters with more responsive time series. In addition, some wells even exhibited opposing trends in the latter two clusters.

Dong et al. (2019) report on "slight rising trends" in shallow groundwater in contrast to "distinctive declining trends" in deep groundwater in a set of 575 wells in the Mid-Atlantic region of the United States. They ascribe these differences to the delayed response of the deep groundwater to changes of precipitation. In our study, though, maximal delay time between different wells did not exceed three months which could not explain opposing trends in our 28 year data set (cf., Fig. 5).

5.3. Second hypothesis: Inconsistent trends result from a misconception of low-pass filtering processes

It has been argued that frequency-dependent damping of input signals could explain patterns of inconsistent trends in hydrological time series. According to that, apparent long-term monotonic trends can evolve from very low-frequency oscillations with period lengths of decades, centuries or even longer (Cohn and Lins, 2005; Hamed, 2008; Lins and Cohn, 2011).

Low-frequency oscillations are already part of the meteorological input signal (Bordi et al., 2009) but are masked by much stronger high-frequency patterns and become visible only when the latter are increasingly more attenuated. This so-called low-pass filtering is a typical feature of dissipative processes like heat dispersion in water bodies (Cyr and Cyr, 2003), seepage fluxes (Gudmundsson et al., 2011; Katul et al., 2007; Shun and Duffy, 1999), and solute transport (Gall et al., 2013; Kirchner et al., 2010) in the vadose zone, and water transport (Kleidon et al., 2013) in catchments. In either case the energy of the input signal dissipates, resulting in a delay and in a damping of amplitudes. With increasing strength of damping, that is, increasing attenuation of high frequency patterns, even more lower frequency patterns become visible (Katul et al., 2007). In this study, it was by chance only that different trends with opposing signs showed up for different degrees of damping. In general, probability of a significant trend increases systematically with increasing smoothness of the time series, that is, at sites with high damping factors.

Often the slope of the power spectrum has been used to quantify the degree of damping of the input signal in the vadose zone (Katul et al., 2007; Kirchner et al., 2010; Neves et al., 2016) like in this study. Other measures have been used as well (e.g., Gall et al., 2013). Hohenbrink and Lischeid (2015) showed that the damping behavior could be described by the first two components of a principal component analysis of the respective set of time series of soil moisture. In fact the differing degrees of damping of the input signal observed in time series of groundwater head can be traced back to vadose zone processes (Lischeid et al., 2017a, 2017b). This is confirmed, e.g., by Shun and Duffy (1999) who studied low-frequency oscillations in precipitation, temperature, and runoff at various sites within a mountainous catchment along an elevation gradient. They found increasingly more pronounced low-frequency oscillations at lower elevation that they ascribe to decreasing suppression of high-frequency patterns that prevail in the meteorological input data. Correspondingly, increasing persistence in hydrological time series has been related recently to properties which likely reflect a higher degree of damping of the hydrological input signal, e.g., catchment size (Dey and Mujumdar, 2018; Markonis et al., 2018), the ratio of pervious over impervious areas in the catchment (Jovanovic et al., 2018), or higher persistence in speleothem compared to tree ring based paleoclimatic records (Iliopoulou et al., 2018).

In order to check whether the observed low-frequency patterns of groundwater head dynamics could be ascribed to low-pass filtering of a climate signal, the climatic water balance was taken as a proxy for groundwater recharge. The time series of the climatic water balance did neither exhibit a significant trend nor any dominant frequency (Fig. 7). In spite of that, pronounced low-pass filtering of that signal resulted in a low-frequency pattern that resembled that observed in some of the groundwater observation wells with high damping coefficients (Fig. 7, cf. Fig. 5), thus supporting the hypothesis. Correspondingly, e.g., Boutt (2016) reported on significant (either positive or negative) 40-years trends in 12% of the studied precipitation stations and stream gauges, but in 60% of the observation wells in the same region in New England (USA) with 75, 73 and 83 spatial replicates each. To summarize, climate and hydrological time series exhibit random fluctuation at different scales (National Research Council, 1991; Koutsoyiannis, 2002) which should not be confused with instationarity of the underlying processes (Montanari and Koutsoyiannis, 2014; Koutsoyiannis and Montanari, 2015). Trend analysis is sensitive to low-frequency patterns that become visible only when the high-frequency part is stripped off.

The low-pass filtering applied in this study does not consider time lags, thus the low-pass filtered time series run ahead of the actually observed time series of groundwater head. More severely, long-term trends observed at other wells with less strong damping could not be reproduced. This might be due to various reasons. First of all, the climatic water balance is only a crude approximation of the true groundwater recharge. It does neither consider higher evapotranspiration of larger plants compared to short-cut grass, nor reduction of evapotranspiration after crop harvesting, grassland harvesting or grazing, or due to limited water availability, e.g., at the end of the growing season. Secondly, the power spectrum of measured groundwater head and lake water level (Fig. 6) exhibits more scatter compared to those of the low-pass filtering exercise (Fig. 7). Both effects likely play a major role especially in the higher frequency range, that is, for less strongly damped time series. Consequently, the behavior effects could not be mimicked for these sites.

The resulting phenomenon of significant trends arising apparently out of nothing is closely related to the concept of stochastic resonance. It means that in non-linear systems a noisy input pattern might amplify system-inherent weak periodicities, thus exceeding a crucial threshold and pushing the system to a new state. Nicolis (1982) and Benzi et al. (1982) introduced the concept of stochastic resonance as a potential trigger mechanism for the glaciation cycles during the Pleistocene. The concept has since then been extended and has been applied to numerous non-linear systems in various scientific disciplines, including, e.g., neurophysiology or quantum physics (Gammaitoni et al., 1998).

However, the notion of "noise" needs to be reconsidered in environmental sciences. This term is often used according to the concept in radio technology, where the signal is provided by the low-frequency part of an electromagnetic wave, and high frequency noise adds to that due to technological imperfections. Correspondingly, environmental scientists tend to consider the low frequency part the "signal" to be separated from high frequency "noise". However, in case of hydrological processes meteorological variables impose a high frequency signal from which low-frequency patterns at greater depth evolve due to progressive attenuation of the high frequency part of the input signal. Thus the role of high frequency and low frequency patterns is rather inverse to the common perception in environmental sciences.

6. Conclusions

Inconsistent trends were found in 28 year time series of lake water level and groundwater head at 40 sites in Northeast Germany, even when local effects had been factored out. Instead, we found strong evidence for the decisive role of low-pass filtering of hydrological input signals in this regard.

We observed that during passage of infiltrated water through the vadose zone the hydrological input signal became increasingly more damped. In addition to a certain time delay, damping occured as a low-pass filtering of the input signal. Thus minor high-frequency oscillations in the climatological time series became increasingly more attenuated, and the inherent low-frequency patterns became increasingly more clear, resulting in apparent monotonic trends for limited time periods. Strength and sign of these trends was closely related to the degree of low-pass filtering of the hydrological input signal in the vadose zone which differed substantially even between adjacent sites.

Oscillations occuring at all time scales have often been observed in climatological and hydrological time series and have been ascribed to persistence (Bordi et al., 2009; García Molinos et al., 2015; Koutsoyiannis, 2006; Lins and Cohn, 2011). However, diagnosis of persistence in practice often yields unstable results due to restricted length of the available time series (Bordi et al., 2009; Hodgkins et al., 2017; Koutsoyiannis, 2013). But, persistence is not a necessary prerequisite for frequency-dependent damping of input signals. This study has shown that the latter clearly needs to be taken into account in trend analysis studies.

For scenario analyses of long-term changes, usually clear trends or stepwise changes are imposed on model input data to study the system's response. Inversely, it is often argued that hydrological response cannot exhibit any clear trend without a corresponding clear trend of the driving data. This study provides some examples that this does not necessarily hold true. Hydrological modelling as well as many field studies rarely account for frequency-dependent damping in spite of clear theoretical evidence (Koutsoyiannis, 2013). Whereas this might be reasonable for short-term dynamics it obviously falls short when long-term trends are studied.

We conclude that trend analysis turns out to be anything but easy to apply and easy to understand. Rather, identifying major changes in a world of permanent changes remains a major scientific challenge: Presence or absence of clear trends in groundwater head or lake water level time series does not necessarily confirm or disprove a major system shift. Correspondingly, our results do neither imply that climate change does not occur nor that climate change would not affect hydrological processes. Rather, they point to the fact that climate change or direct anthropogenic effects are much more difficult to identify in real-world data sets than widely presumed (cf., Natkhin et al., 2012). Correspondingly, the recommendation using trend analysis to test for possible direct anthropogenic effects on groundwater quantity in regards to the European Water Framework Directive clearly is at odds with some fundamental features of hydrological systems' behavior.

CRediT authorship contribution statement

Gunnar Lischeid: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Visualization, Project administration. **Ralf Dannowski:** Software, Formal analysis, Investigation, Data curation, Writing - review & editing. **Knut Kaiser:** Investigation, Data curation, Writing - review & editing, Funding acquisition. **Gunnar Nützmann:** Investigation, Data curation, Writing - review & editing. **Jörg Steidl:** Investigation, Data curation, Writing - review & editing. **Peter Stüve:** Investigation, Data curation, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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