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Notes

Exploring the influence of climate oscillations on groundwater: Review of observational studies

Explorando la influencia de oscilaciones climáticas en acuíferos: revisión de estudios observacionales

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Abstract

Groundwater is critical for society's adaptation to climate variability and change but simultaneously, is threatened by them. This paper reviews the linkages between climate oscillations and groundwater, focusing on studies reported in the Scopus database that use wavelet analysis. A total of 27 records published since 2009, covering North America, Europe, and Asia, have been analysed. El Niño Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), Arctic Oscillation, and the Pacific Decadal Oscillation (PDO) show important effects on groundwater levels in North America. In Europe, NAO is the most dominant, while in Asia, distinct climate indices impact groundwater levels at different periodicities. The hydrogeological features of the aquifers condition the magnitude of the response of groundwater to the climate signal and there is conflicting evidence concerning the effects of land-use change and human activities on detecting climate signals in aquifers. Further research must focus on understanding the effect of human activities in the climate signal perception in aquifers, unravelling the physical mechanisms underlying the propagation of climate signals through aquifers, developing predictive models to support water management decisions, and finding alternative methods to assess this influence in regions with limited observational data. The interaction between the atmosphere and groundwater is of critical relevance for the achievement of water security and this review contributes to synthesizing our current understanding of this relationship.

Keywords: Groundwater management, water resources management, climate oscillations, teleconnections, wavelet analysis.

Resumen

El agua subterránea es fundamental para la adaptación de la sociedad a la variabilidad y el cambio climáticos, pero, simultáneamente, está bajo amenaza. En este artículo se revisa la relación entre las oscilaciones climáticas y el agua subterránea, y se enfoca en estudios reportados en Scopus que utilizan análisis de ondeleta. Se analizaron 27 estudios publicados desde 2009, realizados en Norteamérica, Europa y Asia. El Niño Oscilación del Sur (ENSO), la Oscilación del Atlántico Norte (NAO), la Oscilación Ártica y la Oscilación Decadal del Pacífico (PDO) muestran efectos importantes en el agua subterránea de Norteamérica. En Europa, NAO es el factor dominante; mientras que en Asia, distintos índices climáticos afectan los niveles de agua subterránea en diferentes periodicidades. Las características hidrogeológicas de los acuíferos condicionan la magnitud de la respuesta a la señal climática, y la evidencia es contradictoria sobre los efectos del cambio de uso de suelo y las actividades humanas en la detección de señales climáticas en acuíferos. La investigación futura debe enfocarse en entender la influencia de la actividad humana en la percepción de la señal climática en acuíferos; identificar los mecanismos físicos de la propagación de las señales climáticas en acuíferos; desarrollar modelos predictivos para gestión del agua, y encontrar métodos alternativos para evaluar esta influencia en regiones con datos observacionales escasos. La interacción entre la atmósfera y el agua subterránea es crucial para alcanzar la seguridad hídrica, y esta revisión contribuye a sintetizar nuestra comprensión actual de esta relación.

Palabras clave: gestión de agua subterránea, gestión de recursos hídricos, oscilaciones climáticas, teleconexiones, análisis de ondeleta.

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Introduction

In the context of the ongoing water crisis, achieving water security must be the strategic objective of water management (Martínez-Austria, 2018). Despite its crucial role, groundwater often remains overlooked in water management. Globally, groundwater represents almost half of the freshwater supply, around 40 % of irrigation water, and around one-third of industrial water requirements (UN Water, 2018). Groundwater stress is a matter of concern in many of the world's largest aquifers (Kalu, Ndehedehe, Okwuashi, Eyoh and Ferreira, 2022). To address this challenge effectively, there is an imperative for the development and implementation of appropriate and integrated models for groundwater resources management (Roushangar, Dolatshahi, & Alizadeh, 2022).

Climate variability and change further exacerbate challenges to water security by increasing the frequency and severity of droughts (Martínez-Austria, 2020). Understanding groundwater variability is paramount for societal adaptation efforts (Rezaei, 2022) as groundwater can act as a buffer against hydrologic drought impacts (Malmgren, Neves, Gurdak, Costa, & Monteiro, 2022; Nygren, Barthel, Allen, & Giese, 2022). However, its resilience role decreases when drought conditions extend to groundwater (Kleine, Tetzlaff, Smith, Dubbert and Soulsby, 2021), highlighting its duality as a resilience factor and vulnerability to climate variability and change. Therefore, recognizing the influence of climate on groundwater is a crucial aspect of water resources planning and management (Balacco, Alfio, & Fidelibus, 2022).

Climate variability is driven by large atmospheric and oceanic circulation patterns known as climate oscillations (Malmgren *et al*., 2022). These oscillations, characterized by periodic anomalies of air temperature, sea surface temperature (SST), or atmospheric pressure that occur on different timescales, have far-reaching effects on regional climate named teleconnections (Misra, 2020). Understanding these teleconnections is valuable for supporting water management efforts, as they would provide insights into the linkage between climate variability and water storage (Scanlon *et al*., 2022).

In particular, links between climate variability and groundwater levels have been identified in several parts of the world (Malmgren *et al*., 2022). These teleconnection patterns influence recharge rates, which are further affected by land-use change and population migration, thereby affecting groundwater extraction and utilization (Kalu *et al*., 2022). Moreover, the analysis of climate indices to describe groundwater level variations proves useful, especially in data-scarce regions (Balacco *et al*., 2022), making it a convenient research endeavour for basic and applied research.

The objective of this review is to provide an overview of the influence of climate oscillations on groundwater. It aims to consolidate the growing body of evidence regarding the influence of climate oscillations on groundwater, tracking the evolution of methodologies and identifying key research areas for the future. The review delves into articles employing *in situ* data, rather than satellite-derived information [i.e., Gravity Recovery and Climate Experiment (GRACE)]. The focus is on methodologies evolving towards wavelet methods, given their widespread application in studying the interrelationships between climate and groundwater (Malmgren *et al*., 2022). While previous reviews have addressed wavelet methods in hydrology with a general approach (Sang, 2013), this paper specifically explores their historical development in examining the influence of climate oscillations on groundwater.

The questions addressed in this manuscript are. 1) What is the historical development of methodologies that have led us to apply wavelet analysis for understanding the influence of climate oscillations on groundwater?; 2) Which are the most studied climate indices and those that have more influence across countries?, and 3) What are the current research opportunities in this field that would have a theoretical and practical utility for groundwater science and management, respectively?

This paper begins with fundamental concepts of climate oscillations and their influence on groundwater. It continues with a chronological narrative to outline approaches used for this purpose, emphasizing the application of wavelet analysis. Subsequently, it presents an aggregated discussion of findings categorized by country, culminating with the identification of research opportunities.

Historical development and description of methods

Around the world, numerous climate oscillations have been identified and are commonly described using time series known as climate indices. A conceptual model explaining the physical mechanisms behind the influence of climate oscillations on groundwater was proposed by Rust, Holman, Corstanje, Bloomfield and Cuthbert (2018). Although this model was illustrated using the effect of NAO in Europe, conceptually, it can be extended to other areas and climate indices. Climate oscillations trigger hydroclimatic variability that can be modelled using climate signals. These climate signals are filtered and damped by surface processes in the hydrographic basin and further, in the vadose zone and saturated zone of aquifers before being reflected in groundwater proxies such as groundwater levels (GWL) or spring discharges. Tracing these climate signals is important for water management purposes.

El Niño Southern Oscillation (ENSO) is a coupled ocean-atmosphere phenomenon naturally occurring at the interannual time scale over the tropical Pacific and has a periodicity of 2-7 years (Christensen *et al*., 2013; Tremblay, Larocque, Anctil, & Rivard, 2011). It essentially refers to the large-scale weakening of the trade winds and warming of the sea surface temperature in the equatorial Pacific Ocean (Sangha, Lamba, & Kumar, 2020). The North Atlantic Oscillation (NAO) reflects pressure variations and the stability of the Icelandic Low and the Azores-Bermuda high-pressure cells and has a dominant quasiperiodic oscillation of 3-6 years with a less significant one of 8-10 years (Bridgman & Oliver, 2006;

Hurrell, Kushnir, Ottersen, & Visbeck, 2003). Pacific Decadal Oscillation (PDO) is a long-lived phenomenon defined by surface ocean temperatures in the northeast and tropical Pacific Ocean and has a periodicity of 20-30 years (Bridgman & Oliver, 2006; Perez-Valdivia, Sauchyn, & Vanstone, 2012). Atlantic Multidecadal Oscillation (AMO) is the SST anomaly observed in the North Atlantic with the highest intensity in the high latitudes and a quasi-periodicity of 70 years (Christensen *et al*., 2013; Cox, Meng, Khedun, & Quiring, 2009). Indian Ocean Dipole (IOD) Indian Ocean SST interannual variability with the largest amplitude in the eastern Indian Ocean off Indonesia, and weaker anomalies of the opposite polarity over the rest of the basin for 30 years (Christensen *et al*., 2013; Hochreuther *et al*., 2016). Finally, the AO is a fluctuation of atmospheric pressure, at polar and mid-latitude locations, between defined positive and negative phases (Bridgman & Oliver, 2006) and although its periodicity is unclear, its phase has been positive since 1960 (Thompson & Wallace, 1998).

The first evidence of the influence of climate oscillations on groundwater levels suggested that in Nevada, United States, high discharges were observed in the Spring months after winter El Niño events (Winograd, Riggs, & Coplen, 1998). Consistently, the phase of El Niño was positively correlated with recharge in south-eastern Arizona in the USA (Pool, 2005) while the opposite effect was observed in Barbados, with La Niña being positively correlated with recharge (Jones & Banner, 2003). The latter study used isotope analysis to support their conclusions while the former used statistical correlations between streamflow infiltration and climate indices. A linear model to forecast seasonal water table fluctuations, using the correlation between SST and rainfall as a predictor, was developed and applied to the region of La Pampa, Argentina (Tanco & Kruse, 2001). All these studies used statistical analysis to support their conclusions and were incipient before the application of other methodologies. With this same purpose, spectral analysis techniques have also been applied (Luque-Espinar, Chica-Olmo, Pardo-Igúzquiza, & García-Soldado, 2008; Venencio & García, 2011).

Previously, Vautard, Yiou, and Ghil (1992) developed an application of Singular Spectrum Analysis (SSA) for short and noisy time series, which was later implemented in a toolkit by Dettinger, Ghil, Strong, Weibel and Yiou (1995). Building on these methods, Hanson, Newhouse, and Dettinger (2004) developed a systematic method for the frequency analysis of hydrologic time series that provided a basis for comparing the lag correlation, phase and amplitude among data types or across frequencies and a mean to identify major forcings within hydrologic systems. This set the basis for further studies (Almanaseer & Sankarasubramanian, 2012; Gurdak *et al*., 2007; Hanson, Dettinger, & Newhouse, 2006; Velasco, Gurdak, Dickinson, Ferré, & Corona, 2017). Moreover, Ghanbari and Bravo (2011) used the estimation of squared coherency instead of correlations between time series arguing that significant coherence provided direct mathematical evidence of variability relationships. In parallel, Holman, Rivas-Casado, Howden, Bloomfield and Williams (2009) used univariate and bivariate spectral analysis to describe temporal dynamics for each record of GWL and estimate the correlation between GWL and climate indices, respectively.

On parallel, wavelet methods had already been developed by Torrence and Compo (1998), and implemented by Grinsted, Moore and Jevrejeva (2004). After Milly *et al*. (2008) suggested that stationarity should not be a central assumption in water management, these methods began to be used to assess the influence of climate oscillations on groundwater. Wavelet methods can analyze nonstationary hydrologic time series (Kuss & Gurdak, 2014), complementing spectral analysis (Grinsted *et al*., 2004). In addition, they have better performance than time series analysis, serial-correlation analysis, and Fourier transform (Sang, 2013). A diagram that illustrates the logical sequence of wavelet analysis is reported in Figure 1. The explanation of the techniques illustrated in this figure is addressed in the following section.

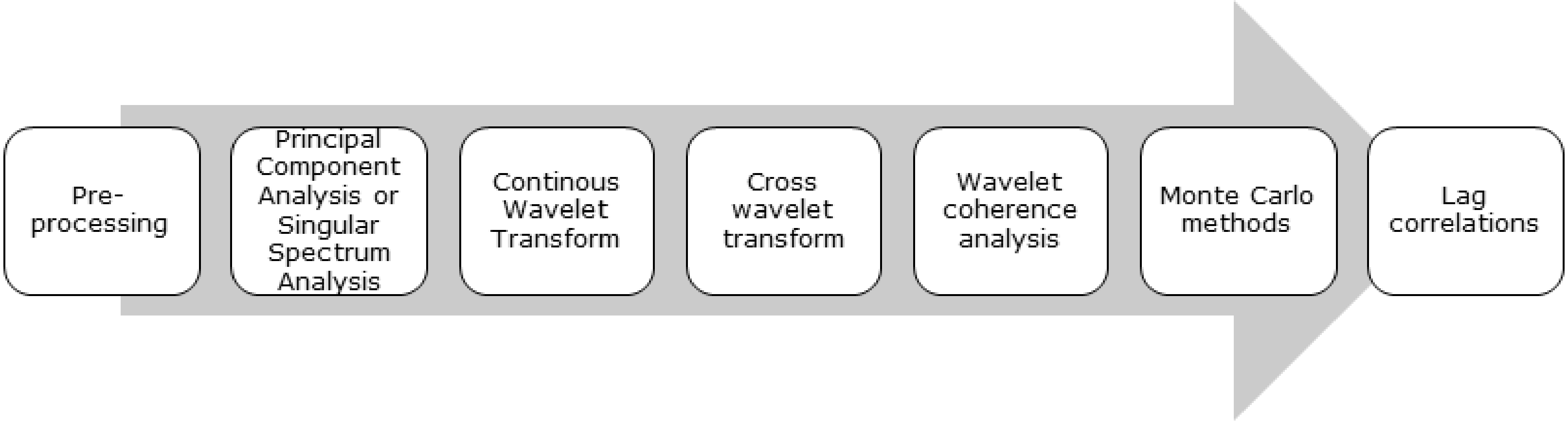

Figure 1. Logical sequence of steps usually used in wavelet analysis.

Finally, two recent advances are worth mentioning. First, the publication of the Hydrologic and Climatic Analysis Toolkit (HydroClimATe) by Dickinson, Hanson, and Predmore (2014), which was used for computing lag correlations between the time series of climate indices and GWL (Huo *et al*., 2016a; Kuss & Gurdak, 2014; Rezaei & Gurdak, 2020; Velasco *et al*., 2017). Lag correlations are useful when a system has a delayed response to some forcing (Kuss & Gurdak, 2014) and that is the case for climate indices and groundwater. Second, the development of WaveletComp, an open-source package to compute wavelet analysis (Rösch & Schmidbauer, 2014). These developments encourage the study of unstudied areas that are exposed to the influence of climate oscillations.

Discussion of methods

This section outlines the methodologies of this study. A search in Scopus database was conducted using the string (TITLE-ABS-KEY (groundwater OR aquifer) AND TITLE-ABS-KEY (wavelet) AND TITLE-ABS-KEY ((climate PRE/0 oscillation*) OR (teleconnection*) OR (climate PRE/0 ind*))). The latter element of the string was used to maximize the results that use distinct terminology to refer to similar phenomena. The search yielded 33 records. Initially, two were excluded because one was in an unknown language for the authors and another was a conference proceeding, which was not considered in the search protocol. In addition, after reading the records abstracts, three reports were decided to not be retrieved because the authors used GRACE data and, as it was mentioned previously, these studies were out of the extent of this review. The source includes all records published until 2022.

Under this criteria, 28 records (including one corrigendum) were considered in this review. These studies have used wavelet methods to assess the influence of climate indices in groundwater using some availability proxy. As shown in Figure 2, eight of them have been conducted in Europe (Table 1), six in North America (Table 2), one in

Japan, six in China (Table 3), one in Bangladesh, one in Pakistan and four in Iran (Table 4). One is a comparative study between Europe and North America and is reported in Table 1.

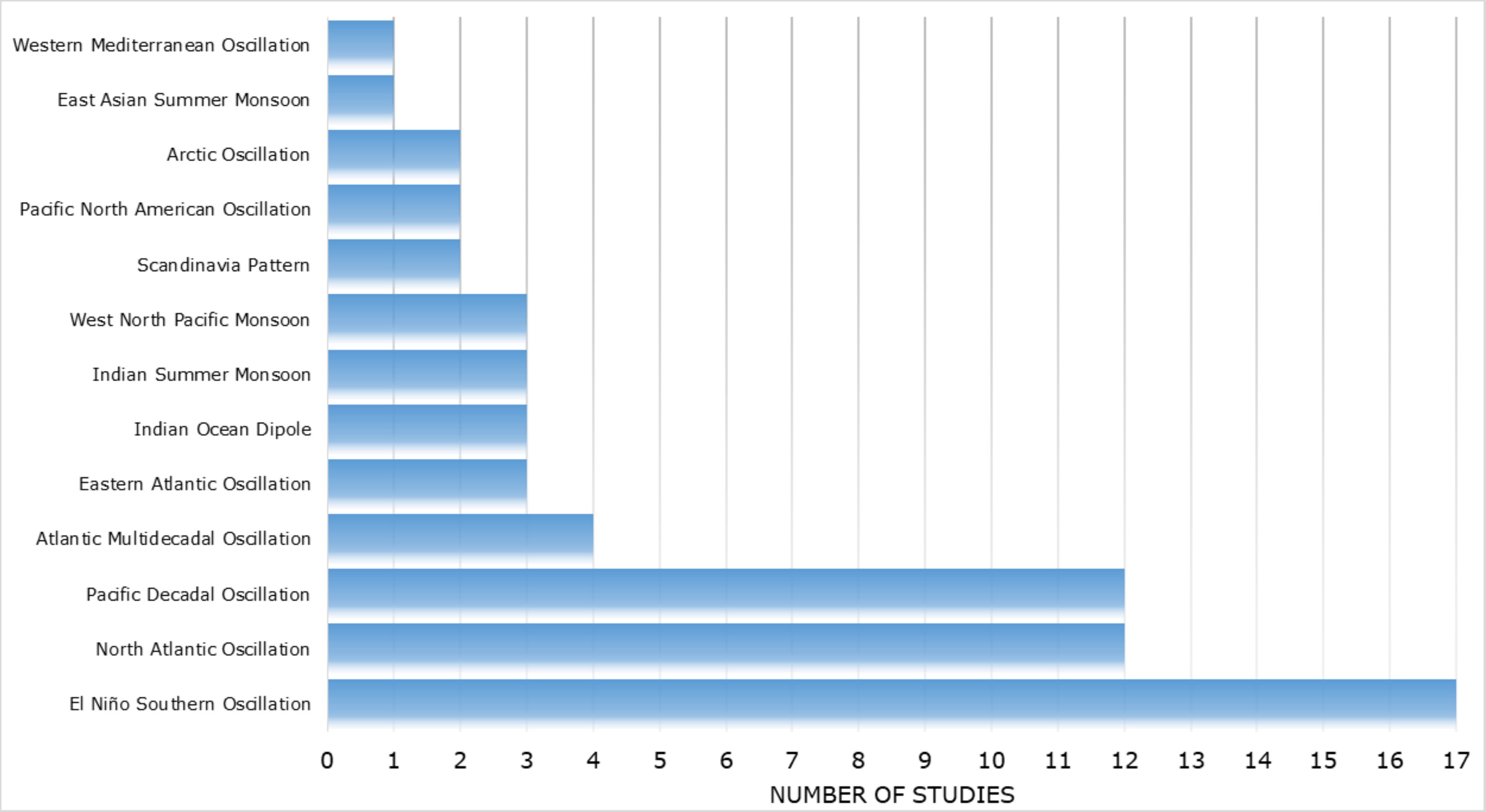

Figure 2. Number of studies of climate oscillations’ influence on groundwater.

Table 1. Available studies in Europe about the effect of climate oscillations on groundwater that use wavelet analysis.

Reference	**Study area**	**Climate indices**	**Data**	**Period**	**Aquifer features**
Slimani *et al*. (2009)	Upper Normandy Region, France	None	Daily GWL from 4 wells	1985-2005	Karstic
Holman, Rivas-Casado, Bloomfield and Gurdak (2011)	Yorkshire, England	NAO, EA, and Scandinavia Pattern	Monthly GWL from 3 wells	1960-2009	Jurassic Limestone and chalk
Neves, Costa, and Monteiro (2016)	Quarenca-Silver Aquifer, Portugal	None	GWL monthly precipitation	1985-2010	Karstic
Neves, Costa, Hugman and Monteiro (2019)	Coastal aquifers of Portugal	NAO and EA	Monthly GWL and monthly precipitation	1987-2016	Limestone
Liesch and Wunsch (2019)	Germany, Netherlands, and United Kingdom (UK)	NAO, AMO and ENSO	Monthly GWL and daily precipitation and temperature	1915-2016	Porous and karstic
Dountcheva, Gómez-Alday, Sanz, Cassiraga and Galabov (2020)	Mancha Oriental aquifer, Spain	NAO and WeMO	Daily precipitation and temperature. River aquifer interactions	1940-2010	Karstic region
Rust, Holman, Bloomfield, Cuthbert and Corstanje (2019)	United Kingdom	None	Monthly GWL, daily precipitation and monthly PET	1960-2015	Chalk, oolites, greensand, sandstone and limestone.
Malmgren *et al*. (2022)	Coastal aquifers in California and Portugal	ENSO, PDO, PNA, NAO, EA and Scandinavia Pattern	Observations from 8 wells in California and 8 in Portugal	1989-2019	Sand and gravel (California; Limestones, dolomites and marls (Portugal)

Table 2. Available studies in North America about the effect of climate oscillations on groundwater that use wavelet analysis.

Reference	Study area	Climate indices	Data	Period	Aquifer features
Cox *et al*. (2009)	Edwards Aquifer, Texas, United States	ENSO, PDO and AMO	Daily spring discharge Annual well pumping Daily pumping Monthly precipitation	1933-2007	Karstic Aquifer
Kuss and Gurdak (2014)	United States	ENSO (MEI), NAO, PDO, AMO	GWL levels, precipitation, simulated groundwater-pumping time series.	1930-2000	Overlapping discontinuous clay beds; alluvium-filled basin; and unconsolidated sand and gravel
Mitra, Srivastava, Singh and Yates (2014)	Apalachicola-Chattahoochee-Flint River Basin, US	ENSO	Daily GWL from 21 wells	1975-2010	Karstic aquifer
Perez-Valdivia and Sauchyn (2011)	Alberta, Canada	None	Five tree-ring chronologies Monthly GWL from two wells	1618-2003 (Well 1) 1589-2002 (Well 2)	Sandstone and sandy aquifer
Perez-Valdivia *et al*. (2012)	Canadian Prairies	ENSO and PDO	Monthly GWL, monthly precipitation and 3 tree-ring chronologies	1900-(Tree-rings) and 1970's (GWL) - 2000s	Mainly sandy aquifers
Tremblay *et al*. (2011), and Tremblay, Larocque, Anctil and Rivard (2012)	Canada	NAO, PNA, AO, ENSO	Monthly GWL, monthly temperature and precipitation	1974-2005	Sandstone; sand and gravel aquifer; and sand and silt aquifer.

Table 3. Available studies in East Asia about the effect of climate oscillations on groundwater that use wavelet analysis.

Reference	**Study area**	**Climate indices**	**Data**	**Period**	**Aquifer features**
Dong, Shimada, Kagabu and Fu (2015)	Kumamoto plain, Japan	ENSO	Sunspot number, monthly GWL	1990-2011	Quaternary deposits with high permeability
Fan, Chen, and Li (2014)	Aksu River, Northwestern China	None	Annual precipitation and streamflow	1956-2006	Alluvial deposits
Hao *et al*. (2016)	Xin'an springs complex, China	ISM, WNPM, ENSO and PDO	Monthly spring discharge data	1956-2012	Karstic aquifer
Cheng, Zhong and Wang (2021)	Heihe River Basin, China	ENSO, PDO, NAO, AO and AMO	Monthly runoff	2001-2015	Unspecified, the focus is on baseflow discharges
Huo *et al*. (2016b)	Niangziguan Springs Basin, China	ENSO, PDO, ISM and WNPM	Discharge data and monthly precipitation	1958-2011	Karstic aquifer
Huo *et al*. (2016a)	Niangziguan Springs Basin, China	AO, NAO, ENSO, PDO and IOD	Daily precipitation and 10-day discharge.	1958-2010	Karstic aquifer
Zhang *et al*. (2017)	Niangziguan spring Basin, China	ISM, WNPM, EASM, IOD, ENSO and PDO	Monthly discharge precipitation	1960-2010	Karstic aquifer

Table 4. Available studies in southwest Asia about the effect of climate oscillations on groundwater that use wavelet analysis

Reference	Study area	Climate indices	Data	Period	Aquifer features
Rezaei (2020)	Sarabkalan Spring, Iran	ENSO and PDO	Daily precipitation and discharge	1986-2019 and 2008-2019 in climate stations 2008-2019 for spring discharge	Karst aquifer
Rezaei and Gurdak (2020)	Lake Urmia watershed, Iran	ENSO, NAO and PDO	Monthly temperature, lake water level, and GWL	1980-2015	Variable
Rezaei (2022)	24 aquifers in Iran	AMO, PDO, NAO and ENSO	Monthly representative GWL time series	Variable	Variable
Roushangar *et al*. (2022)	Azarshahr Plain, Iran	ENSO and NAO	Streamflow, GWL and precipitation	1968-2015	Alluvial aquifer
Ali *et al*. (2022)	Irrigated Indus Basin Irrigation System, Pakistan	ENSO and PDO	398 GWL observations from 2003-2014 for validation	2003-2016	Alluvial aquifer
Salam, Islam and Islam (2020)	Bangladesh	IOD, ENSO, NAO, SST and SOI	Precipitation, temperature and GWL	1981-2017	Sandy semi-confined

The methodology usually used in wavelet analysis and, in particular, followed by Kuss and Gurdak (2014) encompasses the stages illustrated in Figure 1. The required input for this methodology is observational data from some groundwater proxy (spring discharges from a gauge station or GWL time series from boreholes).

Considering that some of these climate oscillations have long periodicities, the size of the time series determines the accuracy of the results. However, with a time series of 11 years, the influence of PDO and ENSO was detected in the spring of an aquifer (Rezaei, 2020). Hence, limited observational data should not discourage the study of climate oscillations in groundwater. Incomplete records of groundwater levels can be combined between adjacent wells to form temporal composite records (Hanson *et al*., 2004) or alternative sources of data can be explored. Interestingly, Ali *et al*. (2022) used satellite data validated with observational records to conduct their analysis, providing a possible alternative to address this issue.

The criteria for selecting the climate indices to be studied on a specific region is based on previous evidence of their effects on regional and local climates. The study of climate oscillations is growing, and hence, not all climate indices are studied with the same interest across regions. For example, the most studied climate index in the set of 27 studies reviewed in this manuscript was ENSO in 63 % of the studies, followed by NAO and PDO in 44 %, as shown in Figure 2. This is explained because these climate oscillations have proved to have global consequences worldwide (Gu & Gervais, 2022; Planton *et al*., 2021; Wei, Yan, & Li, 2021).

On the other hand, there are climate oscillations that have regional effects, such as the IOD, ISM, and the WNPM. While these oscillations have been addressed in studies in China, they have not been studied in other countries. The reason for this is that the effect of these oscillations has been previously studied in this country (Huo *et al*., 2016a; Zhang *et al*., 2017). It underscores the importance of assessing the effect of different climate indices on meteorological patterns in the watersheds.

The importance of conducting these studies is not to answer categorically if there is an influence of climate oscillations on groundwater, but to characterize it quantitatively. Usually, precipitation time series are characterized by observing their periodicity before being compared with climate oscillations. Afterwards, hydrogeological conditions determine the filtering of the climate signal and the periodical behavior of groundwater time series (Liesch & Wunsch, 2019). These studies are useful to forecast hydrological droughts (Ma *et al*., 2022), including their propagation to groundwater.

However, it is important to point out that groundwater data must also be spatially scattered to be representative of the aquifer where it was recorded, especially in regions that are sensitive to local conditions because of hydrogeologic differences or intensive water extraction.

The details of the methodology of the first two stages can be consulted in the work of Vautard *et al*. (1992) and Hanson *et al*. (2004). Much of the long-term, multidecadal anthropogenic signals in the GWL time series, such as long-term land-use change (Kuss & Gurdak, 2014) and pumping (Velasco *et al*., 2017), are removed during pre-processing. Roushangar *et al*. (2022) suggested pre-processing data using Maximal Overlap Discrete Wavelet Transform (MODWT) to denoise time series. This procedure isolates the effect of the climate index's in the groundwater proxy.

Subsequently, Principal Component Analysis (PCA) (Dong *et al*., 2015; Huo *et al*., 2016a; Zhang *et al*., 2017) or SSA (Kuss & Gurdak, 2014; Neves *et al*., 2019; Perez-Valdivia *et al*., 2012; Rezaei & Gurdak, 2020) are conducted. SSA is essentially a PCA applied to a time series along with its additional time-lagged copies (Hsieh & Wu, 2002). The PCA is used to extract the main components of precipitation (Huo *et al*., 2016a; Zhang *et al*., 2017) and GWL (Dong *et al*., 2015). Conversely, SSA is performed only in GWL (Neves *et al*., 2019); GWL, climate indices, precipitation, and pumping time series (Kuss & Gurdak, 2014); or GWL, precipitation, and tree-ring time series (Perez-Valdivia *et al*., 2012).

The following step in the methodology is that wavelet methods are used to obtain a time-frequency representation of the continuous hydroclimatic data (Holman *et al*., 2011). These methods encompass Continuous Wavelet Transformation (CWT), Cross Wavelet Transformation (XWT) and Wavelet Coherence (WTC). In summary, CWT transforms time series to the time-frequency space (Grinsted *et al*., 2004), XWT identifies the cross-wavelet power of two-time series (Holman *et al*., 2011), and WTC normalizes the cross-wavelet power and can be thought of as local correlations (Grinsted *et al*., 2004).

Finally, Monte Carlo methods are used to discard that the periodicity of the time series is explained by internal noise (Grinsted *et al*., 2004; Rust *et al*., 2019). According to these authors, a set of synthetic time series with the same lag-1 autocorrelation properties (AR1) coefficients as the original is used. The wavelet spectra maxima show the periodicities from these synthetic time series that arise from internal noise. Then, a comparison with the wavelet spectra of the original time series is made, and a confidence interval is established to verify the hypotheses.

In this regard and alternatively, Mitra *et al*. (2014) performed Mann-Whitney Tests to evaluate the impacts of ENSO phases on the medians of groundwater level anomalies. Finally, lag correlations may be computed according to the developments described in the previous sections (Huo *et al*., 2016a; Kuss & Gurdak, 2014; Rezaei & Gurdak, 2020).

Salam *et al*. (2020) conducted a different procedure that also yielded spatial variability of groundwater. Besides CWT, these authors used statistical tools (modified Mann-Kendall test, Sen's slope estimator, Pettitt's test, Pearson correlation matrix, cross-correlation analysis, and ARIMA modelling) to find evidence of the link between ENSO and groundwater levels, this phenomenon, but got distinct results, as it will be explained in the next section. Likewise, Cheng *et al*. (2021) performed the former two tests in their study.

Discussion of findings

The authors, study area, climate indices, data sources period, and general features of the aquifers are reported in Table 1, Table 2, Table 3, Table 4 and the countries that have conducted these studies are shown in Figure 3, aggregated by continent. What follows is a discussion of the findings of these studies, structured by climate index. It begins with discussing ENSO, followed by NAO, PDO and AMO. These are the four climate oscillations that are more studied in the documents included in this review.

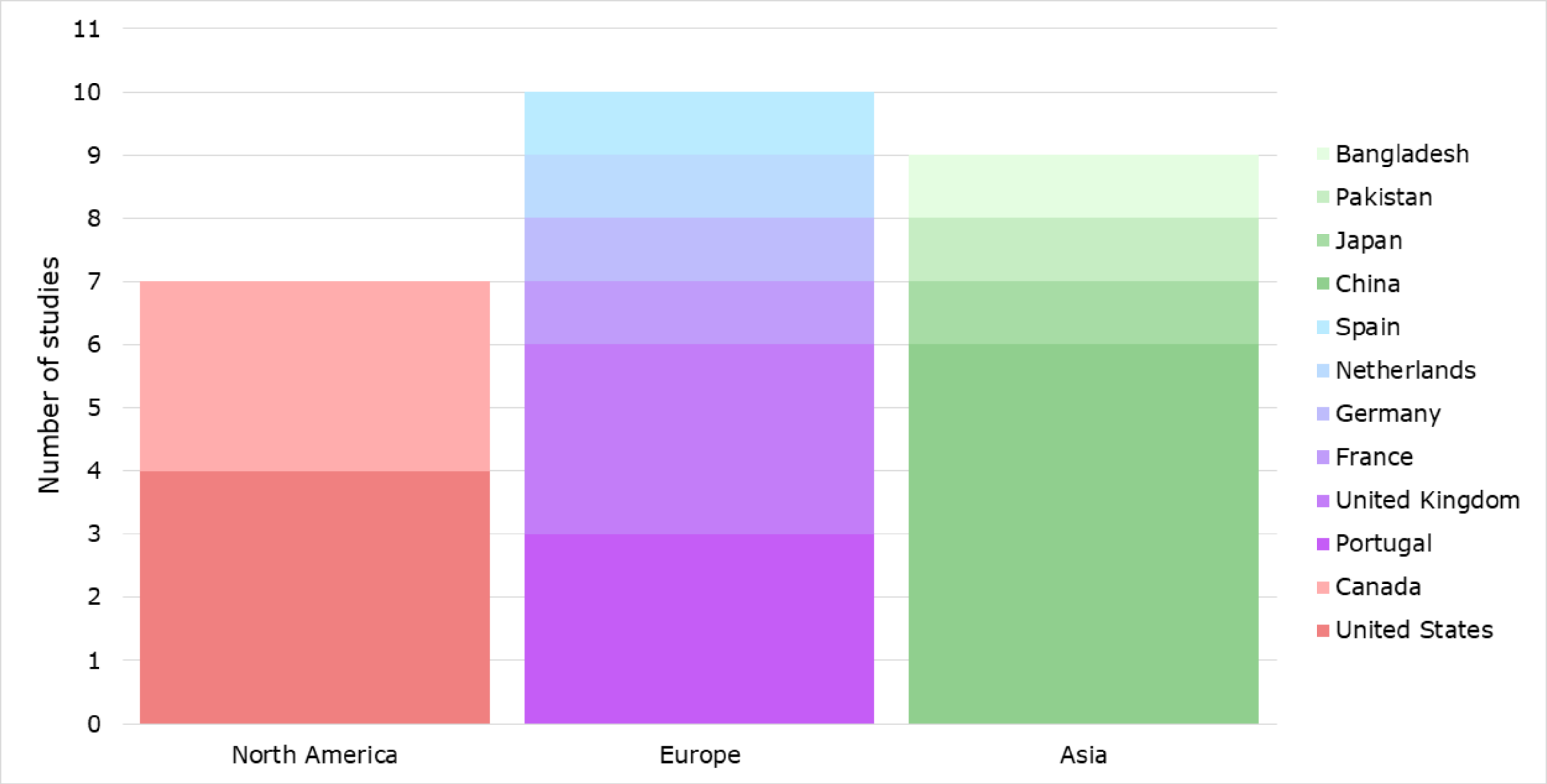

Figure 3. Countries that have assessed the influence of climate oscillations on groundwater, categorized by continent.

In the Edwards Aquifer, in the United States, ENSO produces 10 % anomalies in the discharge of the springs (Cox *et al*., 2009). Similarly, Kuss and Gurdak (2014) reported that three aquifer systems in the United States have moderate to strong (0.5-1.0) coherence with ENSO in the 3–7-year frequency. In the Lower Apalachicola-Chattahoochee-Flint River Basin, GWL anomalies were associated with ENSO. These anomalies were 2.5 times greater during recharge season than during the non-recharge season (Mitra *et al*., 2014). Finally, in California aquifers, ENSO coherence with GWLs occurs in the 2-4-year periodicity (Malmgren *et al*., 2022). In all these cases, the positive phase of ENSO (El Niño) produced positive anomalies while the negative phase (La Niña) produced negative anomalies in their respective groundwater availability proxy.

The relationship is inverse for aquifers in Canada, El Niño produces negative anomalies while La Niña results in positive anomalies. In that sense, The Vancouver Island aquifer GWL variability was influenced by ENSO (Tremblay *et al*., 2011). Perez-Valdivia *et al*. (2012) identified negative correlations between the Canadian Prairies' GWL and ENSO. The GWL of two wells in the Alberta province in Canada also showed coherence with ENSO (Perez-Valdivia & Sauchyn, 2011).

From the reviewed studies that focus on Europe, there is only one that considered ENSO. This is because there is further interest for NAO, which has shown to have stronger influence on Europe climate. Liesch and Wunsch (2019) informed that nine wells in Germany, the Netherlands, the United Kingdom, and Denmark exhibited significant relations with ENSO.

Dong *et al*. (2015) found that ENSO induced seasonal and annual fluctuations in the GWL of the Kumamoto Plain Aquifer, Japan. Similarly, ENSO has effects at intra-annual and interannual scale in the spring discharge of the Niangziguan Basin, China (Huo *et al*., 2016a; Huo *et al*., 2016b). ENSO has significant influence on groundwater of the Indus basin, Pakistan (Ali *et al*., 2022). This study focused on a groundwater drought index to disclose its relationship between teleconnection factors, rather than on sparse groundwater observations.

In a karst setting in Iran, Rezaei (2020) reported that seasonal periodicities in the spring discharge are largely controlled by ENSO.

However, in Bangladesh, ENSO has a weak correlation with GWL, presumably due to the hydrogeological and climatic setting in the study area (Salam *et al*., 2020). Similarly, ENSO does not have significant effects on the hydrological cycle in the Azarshahr Plain, Iran (Roushangar *et al*., 2022). These results are interesting because they are contradictory to the findings of the authors mentioned previously. The methodology conducted by Salam *et al*. (2020) is distinct from the other studies. Besides CWT, the authors used Sen's slope, Pettitt's test and Pearson correlation to describe teleconnections.

In this review, NAO turned out to be the most studied climate index in Europe. Liesch and Wunsch (2019) informed that NAO affected groundwater levels of nine wells in Germany, the Netherlands, the United Kingdom, and Denmark. Also, Dountcheva *et al*. (2020) reported that river-aquifer interactions in the Spanish aquifer of Mancha Oriental have significant correlations with NAO. Rust *et al*. (2019) documented that the strength of multi-annual behaviour aligns with NAO's principal periodicity of seven years. Holman *et al*. (2011) reported that in three wells in the United Kingdom, periodicities of 2.6 and 5.0 years are observed with the NAO. However, the timing of the statistically significant episodes of wavelet coherences differs between the wells due to geographical locations and hydrogeological features.

Portugal's share in European studies is 38 %. In the Ria Formosa coastal aquifers, NAO accounts for nearly 50 % of the total variance of groundwater levels, while EA emerges coupled to NAO and is mainly associated with oscillations in the 2-4-year band (Neves *et al*., 2019). Furthermore, the main mode of variability in the Quaranca-Silves Aquifer, corresponds to a period of 6.5 years, while other leading modes correspond to periods of 4.3, 3.2, and 2.6 years that may have a common climatic origin related to the NAO (Neves *et al*., 2016). Malmgren *et al*. (2022) suggest that this is a condition that can be observed across the entire country. There is wide recognition of the impact of NAO in groundwater levels in Europe, which is consistent with the consensus of the impact of NAO in weather patterns (Ibebuchi, 2024).

When comparing the share of variability attributed to climate oscillations, NAO was found to have the largest share in Portugal in comparison with California, which is mainly influenced by PDO (Malmgren *et al*., 2022). However, NAO does influence groundwater levels in North America. For instance, North Atlantic Coastal Plain has associations with NAO in the 3-to-7-year period (Kuss & Gurdak, 2014). Similarly, the Prince Edward Island and Vancouver Island aquifers GWL variability was influenced by NAO (Tremblay *et al*., 2011).

Spring discharges in the Niangziguan Basin, China, are correlated with NAO at the 1-year periodicity (Huo *et al*., 2016b). The Maragheh aquifer, in Iran, GWLs have strong coherence with NAO (Rezaei & Gurdak, 2020). Overall, the effect of NAO on Iranian aquifers is visible at annual and interdecadal frequency bands (Rezaei, 2022). In contrast, NAO does not have significant effects on the hydrological cycle in the Azarshahr Plain, Iran (Roushangar *et al*., 2022) and similarly, in Bangladesh there are weak negative correlations between GWL and NAO (Salam *et al*., 2020).

PDO triggers annual anomalies of 2.1 and -7.4 % in the positive and negative phase, respectively in the Comals Springs discharge, US (Cox *et al*., 2009). In addition, these anomalies are similar during the four weather seasons. The GWLs of the Central Valley, Basin Range and North

Atlantic Coastal Plain aquifers have coherence with PDO (Kuss & Gurdak, 2014). During winter in California, a strong positive phase of PDO coherence with a 4-8 period precedes drought events, El Niño coherence in this same period persists throughout major drought events, and their synchronization marks interaction between them and drought events (Malmgren *et al*., 2022). Finally, Perez-Valdivia *et al*. (2012) reported that negative correlations were identified between GWL and PDO indices in Canadian aquifers.

PDO also have effects in spring discharges at interannual and interdecadal scales in the Karst Niangziguan springs complex (Huo *et al*., 2016a; Huo *et al*., 2016b). However, these results are not consistent with those reported by Zhang *et al*. (2017), which suggests that PDO has weak impacts in the Niangziguan basin spring discharges. Conversely, in the Xin'an basin, PDO impacted spring discharges at intraannual time scales (Hao *et al*., 2016). However, after the development of the aquifer, the timescale becamse intraanual, annual and interannual. This underscores the affectation of human activities in the detection and magnitude of the climate signals in aquifers.

Annual periodicities (1-2 years) of Sarabkalan spring discharges are rather highly related to PDO (Rezaei, 2020). Similarly, in five aquifers of the southern Lake Urmia watershed, PDO is the first dominant mode of variability in the 2-4 years band and also, for the period greater than eight years (Rezaei & Gurdak, 2020). The effects of PDO on GWL were observed in decadal and interdecadal scales in iranian aquifers (Rezaei, 2022). Conversely, in Pakistan, the effect of PDO is weak (Ali *et al*., 2022).

AMO influences GWL in nine wells in Germany, the Netherlands, the United Kingdom, and Denmark (Liesch & Wunsch, 2019). In the Edwards

Aquifer, AMO causes mean annual spring discharges anomalies of -5.9 and 0.5 % in positive and negative phase, respectively, and they are enhanced during summer (Cox *et al*., 2009). AMO has lower impacts in groundwater levels in comparison with ENSO and PDO in four aquifers in the US (Kuss & Gurdak, 2014) and has significant effects at interdecadal and annual scales in iranian aquifers (Rezaei, 2022).

One of the takeaways from this review is the important role that hydrogeologic features have when modulating the influence of climate oscillations on groundwater. For instance, in a study in France, Slimani *et al*. (2009) found that downthrown compartments filter annual variability events in favour of multi-year variability events, while uplifted compartments show low filtering of annual fluctuations and reductions in the contribution of long-term climatic oscillations. This illustrates the effect of hydrogeological features in climate signal filtering.

Another point worth making is the importance of climate oscillations relies on its comparison with other factors of climate variability. For instance, in a study that disaggregated the period of analysis into pre-development and post-development of groundwater, Hao *et al*. (2016) found that monsoon signals at 1.0 and 0.5-year time scales can penetrate through the aquifer and also, be strengthened by human activity in the Xin'an Springs complex, China. At the intra-annual and annual scales, spring discharge was mainly affected by the monsoon. Later, it was found that in this watershed, spring discharge is more strongly affected by monsoons than by climate oscillations (Zhang *et al*., 2017). Conversely, it was found that meteorological factors rather than large-scale circulation indices can better explain the changes in baseflow in the Heihe River Basin in China (Cheng *et al*., 2021).

Given the diversity in the geography of study areas considered in this review, it cannot be indicated that climate oscillations only influence regions with specific hydrogeological, geological, or climatic conditions. However, the magnitude of the effect of climate oscillations on groundwater must guide us towards the anteposition of certain climate indices on concrete regions and specific kinds of aquifers in the research agenda. Based on this review, the most studied climate oscillation is ENSO.

To address this, the filtering and damping capacity of the vadose and unsaturated zone of the aquifers are worth studying to understand signal propagation and clarify distinctions in groundwater response to climate oscillations; the interrelationship between climate oscillations and groundwater extractions must be considered because the evidence in regions where withdrawals are notable is contradictory. Understanding this signal propagation is of relevance during the occurrence of droughts because groundwater represents the source of resilience against this phenomenon but at the same time, is threatened by it. Likewise, understanding hydrogeological mechanisms influencing the climate signal will allow us to detect the most resilient aquifers to support water supply during droughts without compromising their sustainability. Comparative studies should be conducted to deliver more clarity on the differentiated responses of aquifers to climate oscillations, following the example of Malmgren *et al*. (2022).

In addition, the state of climate indices should be considered when developing management strategies. A predictive approach for groundwater levels and other availability indicators of the hydrological cycle (i.e. runoff, spring discharges, baseflow) is necessary to support water management decisions. In some regions, specific climate indices can be used as proxies for precipitation and contribute to the formulation of preventive drought management measures that include the sustainable use of groundwater.

There are opportunities for research on the effect of simultaneous effect of two or more climate oscillations. Likewise, the interaction between climate change, climate oscillations, and anthropogenic influence must be studied. For instance, in a hydrologic drought scenario triggered by climate variability, groundwater withdrawals may be increased to supply water demand for distinct uses while at the same time, the recharge to the aquifer is compromised due to the same phenomena. The combined effect of climate change-variability and the proposal of alternatives of adaptation in water management represent interesting opportunities for research.

In addition, most of the other studies have been made in regions unaffected by withdrawals. One possibility is that anthropogenic influence may have offset the effects of climate oscillations, even at interannual and multidecadal timescales, given the extraordinary increase in groundwater extractions in past decades. However, this hypothesis needs to be studied further because there is incipient evidence that human activity enhances this correlation (Hao *et al*., 2016).

Finally, alternative methods for places where observational data is scarce must be developed to assess the control of climate oscillations in groundwater. It is interesting to note that the influence of climate oscillations on aquifers has been studied in Africa and Latin America using satellite data (Bolaños, Salazar, Betancur, & Werner, 2021; Kolusu *et al*., 2019). However, studies that use observational data in these regions were not found in this review. A possible explanation is that there is a need for more observational data (Bonsor, Shamsudduha, Marchant, MacDonald, & Taylor, 2018). Although they were outside the scope of this review, satellite data from GRACE and the use of citizen science may be both useful tools to perform this analysis and provide insights into the effect of climate oscillations in groundwater. Regions that are highly exposed to water scarcity and droughts should be more urged to understand these kinds of phenomena because of their reliance on groundwater.

Conclusion

Climate variability influences the hydrological cycle. Specifically, current evidence supports that climate oscillations affect groundwater availability. This article undertook a review of research regarding the influence of climate oscillations on groundwater using observational data. Studies of the influence of climate oscillations on groundwater have been conducted since 1998, but the use of wavelet analysis began in 2009. An overview of the current evidence on the influence of climate oscillation on groundwater follows. 27 studies were reviewed; 63 % of them considered ENSO, 44 % NAO and 41 % PDO. This is explained because they are the indices with the most important effects on precipitation in the countries where they have been studied.

The influence of climate oscillations in groundwater has been studied in North America. The aquifers in the US are most influenced by the presence of ENSO except for the EA, which is most influenced by AMO. It is interesting to note that aquifers emplaced in karstic, sandy, and alluvial deposits were studied. Conversely, in Canada, where the studied aquifers are sandy, the influence of climate oscillations on groundwater was different across the country. NAO and AO were the main influences for the PEI aquifer (Eastern Canada); MB showed no relationship with climate oscillations; AO and NAO and, to a lesser extent, MEI influenced GWL in British Columbia. In the provinces of Alberta, Saskatchewan and Manitoba, the influence of ENSO and PDO was documented.

The influence of climate oscillations in European aquifers has been documented in the United Kingdom, Portugal, Germany, Netherlands, and Spain. The most studied climate oscillation is NAO, and its impact is relevant in all the sites studied. However, other climate indices (ENSO, PDO for instance) should be studied to observe if their influence is significant in comparison with NAO.

Conversely, in Asia, more climate indices have been studied and all of them influence precipitation and groundwater at different periodicities apart from the Kumamoto Plain, where only ENSO was studied and the Aksu River, where periodicities were only detected but not correlated with climate indices. An interesting insight from these studies is that they have used other water availability proxies (baseflow discharges, spring discharges) that describe the effect on groundwater, proving their usefulness for computing these results.

Finally, there are research opportunities that would have a theoretical and practical utility for water management. Climate indices influences groundwater storage. However, their effect is differentiated based on hydrogeological, hydrological, and geographical features. To prioritize specific climate indices and aquifers, it is important to understand the mechanisms behind climate signal propagation through aquifers is important for quantifying the resilience of aquifers to droughts.

In addition, climate indices are useful for forecasting hydrological variables and therefore can inform water management strategies. Next, the interaction across climate oscillations and between them and climate change and their combined effect on groundwater must be understood as well. Finally, groundwater levels data scarcity must not discourage conducting these studies. However, considering the absence of these data, alternative methods for data-scarce regions must be developed. This is urgent especially in arid and semi-arid environments, where the water security of the people is most compromised.

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