A Global Assessment of Groundwater Recharge Response to Infiltration Variability at Monthly to Decadal Timescales

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Abstract Predictions of groundwater fluctuations in space and time are important for sustainable water resource management. Infiltration variability on monthly to decadal timescales leads to fluctuations in the water tables and thus groundwater resources. However, connections between global-scale climate variability and infiltration patterns and groundwater are often poorly understood because the relationships between groundwater conditions and infiltration tend to be highly nonlinear. In addition, understanding is further hampered because many groundwater records are incomplete and groundwater tables are often anthropogenically influenced, which makes identifying the effects of infiltration variability difficult. Previous studies that have evaluated how infiltration variability controls groundwater are based on a limited number of point measurements. Here, we present a global assessment of how infiltration variability is expected to affect groundwater tables. We use an analytical solution derived from Richards' equation to model water level responses to idealized periodic infiltration variability with periods that range from months to decades, to approximate both the effects of short-term and long-term climate variability and thus infiltration patterns. Our global-scale assessment reveals why infiltration variability would lead to periodicity in groundwater recharge in particular regions. The vadose zone strongly dampens short-term (seasonal and shorter) variations in infiltration fluxes throughout most of Earth's land surface, while infiltration cycles exceeding 1 year would yield transient recharge, except in arid regions. Our results may help forecasting long-term groundwater tables and could support improving groundwater resource management.

Plain Language Summary Understanding how climate patterns affect groundwater is challenging because infiltration processes are complex and groundwater records are scarce and often incomplete. We use an analytical groundwater model to study the impact of infiltration variability on groundwater tables globally. Our analysis thereby quantifies how strongly groundwater recharge varies as the result of climate and infiltration variability at different timescales, ranging from seasonal fluctuations to multi-year climate phenomena with characteristic lengths similar to the El Niño/Southern oscillation and Pacific decadal oscillation. Our results show that periodic variations in climate and infiltration often have minimal influence on water tables in arid to semi-arid areas with deep groundwater tables, while, when wetter regions (and/or with shallower groundwater) have more strongly time-varying groundwater conditions. These findings may help to predict future groundwater tables and enhance the management of groundwater resources.

1. Introduction

Groundwater recharge is a crucial component of the global water cycle and provides an important basis for sustainable groundwater resource management. Recharge feeds groundwater storage, which is used to supply fresh water to large parts of the global population and irrigated agriculture, and provides base flow to rivers maintaining aquatic ecosystems during dry periods (Crosbie et al., 2013; Gleeson et al., 2012; Scanlon et al., 2023; Wada et al., 2010). However, in many regions, groundwater overuse has caused an imbalance between recharge and discharge, and groundwater depletion has become a global problem (Burri et al., 2019; Famiglietti, 2014; Sorensen et al., 2021).

Aside from human activities, such as managed aquifer recharge and land-use change, natural recharge can fluctuate in response to climatic patterns on various timescales (Dickinson et al., 2004; Gurdak et al., 2007; Hanson et al., 2006; Jasechko et al., 2014; Kuss & Gurdak, 2014; Perez-Valdivia et al., 2012). The amount of natural recharge to a given groundwater store is strongly related to the amount of precipitation and...
evapotranspiration (Berghuis et al., 2024). Therefore, these two processes are critical carriers of quasi-periodic signals between climatic systems and groundwater responses (Bloomfield & Marchant, 2013; Collenteur et al., 2023; Van Loon et al., 2016).

Local-to-global-scale climate patterns can have distinct and long-lasting effects on groundwater availability and sustainability (Gurdak, 2017; Rust et al., 2018). Thus, the ability to predict groundwater fluctuations in time and space is important to drought management (Rust et al., 2018). However, periodic controls of groundwater resources at (multi-)annual scales are rarely considered (Dickinson et al., 2004; Gurdak, 2017; Gurdak et al., 2009; Hanson et al., 2006; Liesch & Wunsch, 2019). To our knowledge, global hydrological models do consider these processes implicitly because they model recharge in response to climate, but they have not been used to quantify these connections explicitly.

The relationships between global-scale climate oscillations and groundwater remain poorly understood because the nonlinear relationships between vadose zone properties and infiltration (Cuthbert, 2010; Dickinson et al., 2014; Gurdak, 2017) can result in highly variable responses to climate and infiltration variability. In addition to the nonlinear relationships between vadose zone properties and infiltration, long-term observations of groundwater tables (Dickinson et al., 2004; Gurdak et al., 2007; Hanson et al., 2006; Holman et al., 2011) that could be used to analyze the effects of climate and infiltration variability on groundwater resources are lacking globally (Chilton & Foster, 2023; Fan et al., 2013; Gleeson et al., 2021). Moreover, time series analysis of groundwater can be complicated to analyze because water tables are often also affected by pumping and land use changes, which complicates interpreting the effects of periodic long-term climate and infiltration variability (Asoka et al., 2017).

Most previous studies on groundwater sensitivity to climate and infiltration controls have been based on point measurements (e.g., Neves et al., 2019; Rust et al., 2019; Rust et al., 2021; Tremblay et al., 2011; Velasco et al., 2017). Consequently, the spatial distribution of this sensitivity at larger scales remains unknown. Several studies have identified significant (multi-)annual periodic signals in long-term groundwater records (Anderson Jr & Emanuel, 2008; Corona et al., 2018; Gurdak et al., 2007; Holman et al., 2009, 2011; Huo et al., 2016; Kuss & Gurdak, 2014; Liesch & Wunsch, 2019; Malmgren et al., 2022; Neves et al., 2019; Taylor et al., 2013; Tremblay et al., 2011; Velasco et al., 2017; Zhang et al., 2017). While some studies have found evidence of the influence of such climatic oscillations within groundwater records, it remains mostly unquantified how quasi-periodic signals propagate from climate to groundwater (Rust et al., 2018). Thus, owing to the scarcity of field observations (Döll et al., 2011; Velasco et al., 2017), relationships between climate and infiltration cycles and groundwater tables have not been systematically investigated globally.

Here we combine an analytical solution to Richards' equation (Richards, 1931) with synthetic climate forcing, to assess how infiltration fluctuations with periods ranging from months to decades would affect dynamics of groundwater recharge and groundwater tables. We follow the methods of Dickinson et al. (2014) to understand how climate forcing is dampened at the depth of the water table. We use the output of the analytical solution to demonstrate how potential variability in fluxes at the land surface dampens with depth throughout the vadose zone. We assess this for short time scales such as monthly, seasonal, and annual periods of flux variations. These periods represent climatic and infiltration patterns with distinct wet and dry seasons or synoptic-scale meteorological climate systems. We also considered multi-annual and decadal periods of flux variations, which are in timescale generally consistent with the global-scale climate variabilities of the Pacific-North American oscillation (PNA), North Atlantic oscillation (NAO), El Niño/Southern Oscillation (ENSO), and Pacific decadal oscillation (PDO) (Corona et al., 2018; Kuss & Gurdak, 2014). Such climate oscillations can induce strong variations in recharge and lead to fluctuations in groundwater tables (Holman et al., 2011; Malmgren et al., 2022; Velasco et al., 2017). Our approach does not replicate teleconnections explicitly, but uses periodic infiltration variability described by sine curves with periods similar to that of teleconnections. This approach allows for a concise representation of temporal variability in climate and infiltration as well as groundwater tables. It is important to note that the relative dampening of an input is a function of its periodicity, but the damping is largely independent of the shape of the input function (for a given periodicity). Our analysis thereby studies the sensitivity of recharge to potential climate and infiltration fluctuations at various timescales, without the need that climate is sinusoidal or that variability at a particular timescale strongly occurs at that location. Note that reporting the sensitivity to a particular periodic infiltration does not mean the climate cycle at this length is important at this location, but it implies we assessed the relative dampening of potential climate-forcing variations at this timescale. We applied
the analytical calculation globally and provide insights into the relationships between infiltration cycles and groundwater recharge, and groundwater level fluctuations. The global-scale assessment explains why some periodic infiltration fluxes associated with climate variability would not be present in groundwater level fluctuations, while in other cases transient recharge would lead to dynamic groundwater tables.

2. Methods

Our assessment was based on an existing analytical solution to Richards’ equation (Bakker & Nieber, 2009). We used the approach by Dickinson et al. (2014) to understand how infiltration can be dampened at water table depths. We first present the analytical solution used for calculations and subsequently introduce the global input variables. The analytical solution to Richards’ equation for periodic vadose zone flow and periodic groundwater recharge is only briefly summarized here. Bakker and Nieber (2009) report a full derivation.

2.1. Analytical Solution for Periodic Groundwater Recharge

The analytical solution for hydraulic conductivity and soil moisture relies on the Gardner–Kozeny model (Mathias & Butler, 2006) and incorporates a linearization of the diffusive and advective terms within the governing differential equation (Bakker & Nieber, 2009; Dickinson et al., 2014). The one-dimensional Richards’ equation (Equation 1) governs the vertical downward flow:

\[
\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left( K \frac{\partial \theta}{\partial z} \right)
\]

Here, \( \theta \) represents the water content (\( \theta \)), \( \psi \) denotes the pressure head (L), \( K \) is the hydraulic conductivity as a function of the pressure head (LT\(^{-1}\)), \( t \) represents time (T), and \( z \) indicates depth (L). The vertical infiltration \( q_z \) (LT\(^{-1}\)) includes a constant component \( q_s \) (LT\(^{-1}\)) and a sinusoidal component with amplitude \( q_p \) (LT\(^{-1}\)) and period \( P \) (T) (Equation 2 and Figure 1a):

\[
q_z(z, t) = q_s + q_p \sin \omega t
\]

where \( \omega = 2\pi/P \) is the angular frequency and \( q_s \) the vertical flux at an infinite depth. Values for \( q_s \) typically are larger than those of \( q_p \) (Dickinson et al., 2014). The \( q \) component signifies the drainage flux beneath the root zone, embodying the net infiltration derived from the soil water balance (Corona et al., 2018). The \( q_s \) reflects a long-term mean infiltration flux (refer to Section 2.2) (Dickinson & Ferré, 2018a). The hydraulic conductivity function is approximated using the Gardner model (Equation 3):

\[
K(z) = K_s \exp \alpha (\psi - \psi_e) \quad \text{for } \psi < \psi_e
\]

where \( K_s \) (LT\(^{-1}\)) represents the saturated hydraulic conductivity, \( \psi_e \) (L) is the air entry pressure, and \( \alpha \) (L\(^{-1}\)) is a fitting parameter derived from pore size distribution (Dickinson et al., 2014). The water content, denoted as \( \theta \), is a function of the pressure head and is estimated using the Gardner-Kozeny model (Mathias & Butler, 2006) (Equation 4):

\[
\theta(z) = n_0 \exp \mu (\psi - \psi_e) \quad \text{for } \psi < \psi_e
\]

where \( n_0 \) is porosity (\( n \)) and \( \mu \) is a fitting parameter (L\(^{-1}\)).

In our study, the hydraulic soil properties for each grid cell were parameterized using the 12 soil textural classes from the U.S. Department of Agriculture, and the Gardner-Kozeny soil hydraulic models (Gardner, 1958; Mathias & Butler, 2006).

The analytical solution is obtained by writing Richards’ equation in terms of the Kirchhoff potential and through the aforementioned linearization of the resulting differential equation for vadose zone diffusivity \( D \) (L\(^2\)T\(^{-1}\)).

The resulting solution is as follows (Equation 5):
where $\delta$ is the damping factor and $k$ is the wave number. The damping factor increases with depth (Equation 6):

$$\delta \propto \exp \left( -\frac{z}{\lambda} \right)$$

where $\lambda$ (L) is (Equation 7):

$$\lambda \propto \frac{2}{\alpha + 1} \frac{s_a}{D_{50}} \frac{1}{\cos \frac{1}{2} \arctan \frac{s_a}{D_{50}}}$$

Damping in the system is governed by the Gardner soil parameter $\alpha$ and the non-dimensional term $\frac{s_a}{D_{50}}$, and is independent of the amplitude of the flux variation $q_p$ (Corona et al., 2018; Dickinson et al., 2014). The damping depth in this study is defined as the depth $z$ beneath the surface, where 5% of the applied variation is preserved, in accordance with the criterion established by Dickinson et al. (2014). The choice of a 5% damping threshold is integral to quantifying the exponential damping of the soil’s response to surface infiltration flux variations. The damping behavior in soil is exponential, implying a characteristic damping depth where the amplitude of the flux variation reaches $(1/e)$ or about 37% of its original value. This characteristic depth corresponds to damping length $\lambda$. When selecting a 5% threshold, this effectively means considering $e^{-0.5}$, which is $(1/e^0.5)$, thereby corresponding to a damping depth of $\lambda$0.5. This depth choice 5% $\lambda$ provides a measure for evaluating damping, useful for understanding deeper soil infiltration behavior beyond the immediate surface or root zone (Dickinson and Ferré, 2018a, 2018b). Figure 1 depicts the simulation of damping in the unsaturated zone for homogeneous sand, subjected to a periodic flux cycle below the root zone with $q_s$ and $q_v$ set at 0.001 (m d$^{-1}$) and a period of 90 days.

For a given period and mean flux, damping depths are larger in coarse soil textures (e.g., sand) than in finer soils (e.g., clay) (Figure 2). The damping of the periodic fluxes is a function of the soil type and depth, the period of the flux variations, and the mean recharge flux. The impacts of the surface and unsaturated zone parameters on the propagation of periodic signals can be explained as follows: the unsaturated zone acts as a damping mechanism for signals between infiltration from precipitation and recharge. The damping capacity of an unsaturated zone increases with depth and with lower hydraulic diffusivity (e.g., clayey soils) (Dickinson et al., 2014). Thicker unsaturated zones provide greater damping (and thus produce groundwater signals closer to a steady state), and increased damping results in a decreased amplitude in signals at the water table (Corona et al., 2018). The unsaturated zone does not stretch periodic signals, which means that the periodicity of recharge signals is preserved (Dickinson et al., 2014). Changing the value of the selected damping factor $\delta$ can affect whether a location is classified as steady state or transient (Figure 2).

2.2. Input Variables

To apply the analytical solution globally, we obtained global gridded input variables (Table 1). The general workflow (Figure 3) shows where the different gridded input variables are used in the analytical solution and that the simulated damping depth is compared to the depth to the water table to estimate if steady-state or transient conditions at the water table occur. This approach is carried out for every grid cell globally and repeated for different climatic conditions and idealized periods of flux variations. Soil texture classes (Figure 4) (Hengl et al., 2017; Hengl, 2018), groundwater recharge from five different sources (Berghuijs et al., 2022; de Graaf

Figure 1. (a) An example of periodic flux variation below the root zone for $q_s$ and $q_v$ of 0.001 (m d$^{-1}$) and a period of 90 days (b) Damping of these periodic flux variations as a function of depth, exemplified for sandy soil. The dashed red line shows the damping depth where the damping factor $\delta$ is 0.05. At this depth, only 5% of the surface flux variation is preserved. The figure structure was adapted from Bakker and Nieber (2009) and Dickinson et al. (2014).
et al., 2015, 2017, 2019; Herbert & Döll, 2019; Müller Schmied et al., 2020, 2021; de Graaf, 2022) (Figure 5), and their ensemble mean potential long-term recharge are used to calculate the damping depth for each grid cell.

Based on the soil texture classes (USDA system), the hydraulic soil properties for each grid cell were parameterized using the Gardner-Kozeny soil hydraulic models (Table 2). The calculated damping depth is where a constant recharge can be assumed (here defined as the depth below which 5% of the surface variation is preserved (see also Figure 1)). Here, we follow the suggestions of Dickinson et al. (2014), but this limit of 5% is arbitrary. Choosing a different threshold would change the determined damping depths (e.g., see Figure 2) but will not change the determined relative regional patterns and physical controls.

**Table 1**

Global Input Variables Used in the Analytical Solution and Analysis

<table>
<thead>
<tr>
<th>Variable</th>
<th>Dimension</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth to water table</td>
<td>L</td>
<td>Fan et al. (2013)</td>
</tr>
<tr>
<td>Long-term groundwater recharge</td>
<td>L/T</td>
<td>Berghuijs et al. (2022); Herbert and Döll (2019); Müller Schmied et al. (2021); de Graaf et al. (2015, 2019)</td>
</tr>
<tr>
<td>Soil texture class (USDA system)</td>
<td>-</td>
<td>Hengl (2018)</td>
</tr>
</tbody>
</table>
The considered periods of flux variations are monthly (30 days), seasonal (90 days), annual (365 days), multi-annual (730 and 2,557 days), and decadal (3,652 days). The longer periods of flux variations approximate natural climate variability and are generally consistent with the global-scale climate variability of the PNA (1–4 years cycle), NAO (3–6 years cycle), ENSO (2–7 years cycle), and PDO (15–30 years cycle) (Enfield et al., 2001; Holman et al., 2009; Kuss & Gurdak, 2014; Liesch & Wunsch, 2019; Liu & Alexander, 2007; Oñate-Valdivieso et al., 2020; Resende et al., 2019; Rust et al., 2021; Scanlon et al., 2022; Sulaiman et al., 2023; Wolter & Timlin, 2011). There is evidence that groundwater table responses vary at time scales resembling quasi-periodic climate variability (Kuss & Gurdak, 2014; Velasco et al., 2017 Liesch & Wunsch, 2019; Holman

Figure 3. Graphical workflow for the applied approach to quantify how soils affect infiltration rates to dampen recharge variations at water table depths.

Figure 4. Global soil texture distribution (Hengl et al., 2017; Hengl, 2018) for the soil texture classification of the U.S. Department of Agriculture (USDA).
et al., 2009; Holman et al., 2011; Neves et al., 2019, among many others). For instance, Rust et al. (2019) utilize a continuous wavelet transforms method to demonstrate the presence of repeating teleconnection-driven cycles, spanning 7 years and 16–32 years, across the majority of the UK’s major aquifers. This study reveals how these cycles systematically influence the recurrence of groundwater drought. Furthermore, they offer evidence to suggest that these periodic modes are driven by teleconnections. Their reconstructed common period domains, identified by the wavelet transform, indicate sinusoidal behavior. Liesch and Wunsch (2019) conducted a study in Germany, the Netherlands, the UK, and Denmark, with a variety of groundwater depths, aquifer types, and hydraulic conditions, and revealed significant correlations between climatic and infiltration periodicities and groundwater tables for the majority of the wells. Specifically, in phreatic porous aquifers, a damping effect was observed, which was attributed to the thickness of the unsaturated zone and decreasing permeabilities. The results from these studies show that periodic variability in the input data affects the system output (e.g., groundwater tables).

Subsequently, the calculated damping depth for each grid cell from the analytical solution was compared with the long-term water table depth, which was obtained from Fan et al. (2013). When the damping depth is above the groundwater table, steady-state recharge can be expected and groundwater table fluctuations remain mostly unaffected by climate variability (Figure 3). The use of sinusoidal curves is a simplification that allows for a concise representation of the largely cyclical behavior observed in climate data as well as groundwater tables, especially in the context of detecting and understanding long-term periodicity and its implications for hydrogeological extremes. This modeling approach provides valuable insights into the relationship between climate and infiltration patterns and groundwater behavior (see e.g., Fleming & Quilty, 2006; Holman et al., 2009; Tremblay et al., 2011). At annual timescales, most precipitation regimes globally are relatively accurately described by a sine curve (Berghuijs & Woods, 2016; Fleming & Quilty, 2006). Holman et al. (2009), Tremblay et al. (2011), and others, highlight the presence of long-term periodic cycles in groundwater tables globally. In our analysis, we excluded permafrost regions because permafrost soils may show entirely different infiltration patterns or are
frozen and prevent infiltration, so the methodology does not apply to these regions (Young et al., 2020). In addition, to the still largely unknown processes in the permafrost soils, groundwater recharge from five different sources (Berghuijs et al., 2022; de Graaf et al., 2015, 2019; Herbert & Döll, 2019; Müller Schmied et al., 2020) is likely rather inaccurate in these regions (Gädecke et al., 2020; Krysanova et al., 2018).

Moreover, Berghuijs et al. (2022) reported large differences between model simulations and a global synthesis of observed recharge estimates (Moeck et al., 2020) covering >5,000 sites. Biases between field data and hydrologic models arise from underestimations at both high and low recharge rates. Thus, instead of using only one recharge input, five global long-term potential recharge rates are used for the calculations to take uncertainty into account in this typically unknown and uncertain flux (Reinecke et al., 2021). However, it must be noted that there is a mixture of infiltration and groundwater recharge in these data. Infiltration is the process by which water enters the soil, and groundwater recharge is when this water further percolates to replenish groundwater (Nimmo et al., 2005). While these processes are distinct in specific studies or models, the distinction often blurs at a global scale (West et al., 2023), also in data sets that use different groundwater recharge estimation methods (von Freyberg et al., 2015). Global models used different concepts for soil infiltration and actual groundwater replenishment (Berghuijs et al., 2024). These models, as Vereecken et al. (2019) note, vary significantly in their infiltration modeling, frequently overlooking important soil effects. Similarly, indirect field estimation methods like the chloride method, which estimates groundwater recharge by comparing chloride concentrations in precipitation and soil pore water, do not directly measure recharge at the water table but offer a proxy (Allison & Hughes, 1978; Michelsen et al., 2024). Despite its limitations, these recharge data are the best available for providing insights into trends across diverse conditions.

Figure 5 shows the five global long-term potential recharge rates. The following analysis was carried out with the recharge from the five different models and with the calculated ensemble mean. In the following sections, the results from the ensemble mean are shown. Reiterating Section 2.1, the calculated damping depths are not affected by the amplitude of infiltration variability, and only depend on the long-term recharge rate, soil parameters, period of the flux variations, and depth to the water table.

3. Results

3.1. Global Recharge Behavior

The calculated damping depths of the variation in groundwater recharge in response to climate and infiltration variability are shown for monthly (30 days), seasonal (90 days), half-annual (180 days), and annual periods (365 days) of flux variations (Figure 6). The 30-day period is used to represent synoptic-scale meteorological
systems, while the 90-to-365-day periods represent climatic patterns with distinct wet and dry seasons (e.g., monsoonal or Mediterranean climates). We also considered multi-annual (730 and 2,557 days) and decadal long-term periodic cycles (3,652 days) of flux variations that are consistent with global-scale climate variability patterns. Damping depths tend to be relatively shallow for monthly and seasonal periods of flux variations, whereas damping depth often strongly increases when periods of flux variation increase. However, for arid to many semi-arid regions, low recharge rates make damping depths remain small even for longer periods of flux variations.

We compared damping depths with the water table depths, to expose regions of steady or transient recharge (Figure 7). The map indicates the shortest timescale at which the groundwater recharge rate at the groundwater table remains transient. This means, for example, that for large areas in Europe recharge and groundwater tables are sensitive to variations at monthly timescales, whereas in parts of Southern Africa, the US, and Australia, annual and multi-annual variation in recharge and groundwater tables can be expected. Most monthly and seasonal variations in infiltration fluxes will be damped in the vadose zone, creating steady-state behavior throughout most global land surface (approximately 75%, see also Table 3) (Figure 7) For these identified areas, groundwater recharge at the water table depth can still vary at longer than monthly or seasonal timescales. This indicates that these are not affected by short-term climate and infiltration fluctuations regions (> monthly and seasonal timescales) or that groundwater storage remains mostly unaffected by short-term near-surface fluctuations. This technically makes effective water resource planning more straightforward. However, in several cases, groundwater use is not sustainable in these regions (Scanlon et al., 2023). On the other hand, regions with transient conditions are significantly more sensitive to short- and long-term climate and infiltration variations and cycles, complicating forecasting and sustainable management of water resources. Overall, our results are in line with
Figure 7. The shortest timescale at which groundwater recharge behavior remains considered transient at the groundwater table. The determined groundwater recharge behavior is where recharge is either steady or transient as a function of computed damping depth (Figure 5) with the analytical solution and available global water table depth (Fan et al., 2013) (Figure 5). The periods of the flux variations are monthly (30 days), seasonal (90 days), half-annual (180 days), annual (365 days), multi-annual (730 days) and decadal (3,652 days). The approximate climate variability of 2,557 and 3,652 days on temporal scales are generally consistent with the NAO and ENSO and imitate distinct wet and dry seasons or synoptic-scale meteorological climate systems.

previous work that showed that groundwater fluxes in arid regions are less responsive to shorter-term climate variability than those in humid regions (Cuthbert et al., 2019).

Differences between damping depth and groundwater table are shown in Figure 8 for monthly, seasonal, half-annual, and annual, as well as multi-annual and decadal periods of flux variations. The differences were relatively small for monthly and seasonal periods of flux variations. For many regions of the globe, the water table is below the damping depth (blue colors), therefore, steady-state conditions apply. At half-annual and annual, the high recharge rates (e.g., the Amazon) paired with typically shallow groundwater tables lead to transient conditions (red color). However, for arid to many semi-arid regions damping depths remain smaller than water table depths even though the periods of flux variations increase.

The share of global land surface with transient recharge is limited (19% for monthly and 28% for seasonal), and these areas are mainly located in eastern Canada, northern South America, central Russia, and parts of equatorial Africa and Southeast Asia (Figure 7 and Table 3). Transient recharge occurs in these regions because of relatively high recharge rates (Berghuijs et al., 2022; de Graaf et al., 2015, 2019; Döll & Fiedler, 2008; Moeck et al., 2020; Müller Schmied et al., 2021) and relatively shallow water table depths (Fan et al., 2013). Flux variability longer than seasonal periods leads to an increasing percentage of global regions with transient recharge. The global percentage of areas with transient recharge is 49% (annual), 60% (multi-annual), 75% (ENSO), and 79% (decadal) for longer teleconnection (Figure 7 and Table 3). For the longer teleconnection cycles, transient recharge areas can be found almost everywhere except in arid regions and part of the semi-arid regions of the globe.

<table>
<thead>
<tr>
<th>Period of flux variation [days]</th>
<th>WaterGAP v2 (Herbert &amp; Döll, 2019)</th>
<th>WaterGAP v2.2 (Müller Schmied et al., 2021)</th>
<th>PCR-GLOB (de Graaf et al., 2015)</th>
<th>PCR-GLOB (de Graaf et al., 2019)</th>
<th>Sigmoid function (Berghuijs et al., 2022)</th>
<th>Ensemble mean</th>
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<tr>
<td>30</td>
<td>18.3</td>
<td>17.9</td>
<td>18.2</td>
<td>16.3</td>
<td>22.9</td>
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</tr>
<tr>
<td>90</td>
<td>26.1</td>
<td>24.9</td>
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<td>23.1</td>
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<tr>
<td>180</td>
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<td>730</td>
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<td>2,557</td>
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<td>3,652</td>
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<td>81.7</td>
<td>62.5</td>
<td>85.6</td>
<td>78.5</td>
</tr>
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</table>
3.2. Global Relationship Between Groundwater Recharge and Damping Depth

The relationship between the damping depth of water fluxes in the vadose zone and groundwater recharge on a global scale is summarized in Figure 9. As recharge rates and periods of flux variations increase, the damping depths also increase. Partly overlapping damping depths exist between the periods owing to differences in soil texture and geomorphological heterogeneity. In sandy soil, for example, a groundwater recharge rate of 10 mm per month can lead to a greater damping depth for the monthly period than in clay soil with the same recharge for the period seasonal. Periodic signal propagation is more damped in clayey soils than in sandy soils. Thus, soils with lower hydraulic diffusivity (e.g., clay soils) filter incoming signals more effectively than soils with greater diffusivity (e.g., sandy soils). Therefore overlapping damping depths exist under different periods. Figure 9 demonstrates positive relationships, indicating that the damping depth increases in direct proportion to both increasing recharge rates and longer periods, as well as with increases of soil texture coarseness.

Vadose zone soils with large sand content and large groundwater recharge are likely to obtain transient recharge fluxes, especially from multi-annual to decadal climate variability. For the arid regions with relatively small recharge, infiltration signals are preserved in the transient recharge flux when the depth to the water table is <10 m, which is rarely met for these regions. Therefore, the periodic infiltration signal at the groundwater table is not present. Transient recharge conditions only occur when focused or preferential recharge significantly increases the local rates due to, for instance, topographic depressions, irrigated return flow, river bank infiltration, or extreme rainfall events (MacDonald et al., 2021; Scanlon et al., 2006; Taylor et al., 2013). The depth to the water
The relationship between damping depth (m) and groundwater recharge (mm month⁻¹) obtained from every grid cell at the global scale. The figure structure is adapted from Corona et al. (2018). Both axes are shown in logarithmic scale. Each line within a color group represents a different soil texture.

Figure 9. Relationship between damping depth (m) and groundwater recharge (mm month⁻¹) obtained from every grid cell at the global scale. The figure structure is adapted from Corona et al. (2018). Both axes are shown in logarithmic scale. Each line within a color group represents a different soil texture.

Therefore, the relationships presented in Figure 9 indicate that the transient recharge associated with long-term infiltration variability (e.g., characteristic lengths similar to PNA, NAO, ENSO, and PDO) should be detectable at the water table depths in most aquifers worldwide.

3.3. Comparison to Local-Scale Field Studies

A comparison of Bakker and Nieber's (2009) analytical solution with field data from other studies (Figure 10) indicates that the model, in most cases, was consistent with the data. The analytical solution used was simplified and did not account for soil heterogeneity and layering or preferential flow. There is uncertainty in the input parameters and variables in every global analysis. However, the occurrence of quasi-periodic climate and infiltration variability at the groundwater table at four idealized periods aligns with the literature results compiled for this study (e.g., Anderson Jr & Emanuel, 2008; Dong et al., 2015; Fleming & Quilty, 2006; Holman et al., 2011; Huo et al., 2016; Kuss & Gurdak, 2014; Liesch & Wunsch, 2019; Neves et al., 2019; Perez-Valdivia et al., 2012; Rust et al., 2019; Velasco et al., 2017). This compilation of results, which are typically based on wavelet analysis of time series, provides field evidence of long-term climatic periodicities on groundwater tables (Figure 10, left panel). The occurrence of quasi-periodic climate and infiltration variability for four different periods at different locations (based on literature data) was mostly consistent with results of the analytical solution.

These local studies suggest good agreement between our calculations and independent local field studies, especially considering the wide range of input and resolution uncertainty for the global calculation, and assumptions in the analytical equations. For shorter periods, for example, 1-year (1a), we still only have a false percentage of 20%, which decreases with longer periods, such as 2,557-day and 7,300-day lengths. In this study, a false result of 6% was obtained, where 94% of the considered locations show good agreement between our analysis and the compiled literature data. This comparison with local-scale studies indicates that with increasing periodicity of climate and infiltration, subsurface heterogeneity (e.g., soil heterogeneity, uncertainty in the recharge rates and unsaturated zone thickness, fluctuations of the water table, etc.) becomes less crucial.

Certainly, the limited amount of local-scale data (Figure 10) does not provide a full image and a robust statistical validation, but shows that the obtained results are informative. Although more studies and results regarding long-
Figure 10. Global- and 98 field-scale evidence of climatic periodicities on groundwater water tables. The left panel shows the percentage for four periods (annual (1a), multi-annual (2a), 2,557 days, and 7,300 days where a match between global- and field-scale evidence of climatic periodicities was determined (TRUE) in light blue whereas the red color shows where field-scale evidence was found but not with the analytical solution. The right panel shows the compiled literature locations where field-scale climatic and infiltration periodicities on the groundwater table were evident. The background map is a global digital elevation model (Danielson & Gesch, 2011).

term periodic climate and infiltration variability are available (e.g., Rust et al., 2019), they often do not provide the latitude and longitude of study locations, which makes it difficult to compare with global model results. Therefore, we encourage the hydrological community to fill these gaps and provide the exact location and hydrogeologic information about the investigated well and piezometer and make these data publicly available.

4. Discussion

Understanding the physical processes that govern the replenishment of aquifers is key to predicting the effects of climate variability and climate change on recharge and groundwater tables. Our global application of the solution by Bakker and Nieber (2009), using the approach by Dickinson et al. (2014), determined the extent to which recharge (at the water table) is expected to be steady-state rather than dynamic. Moreover, we provide a new framework for understanding global water variability changes under climate and infiltration variability and highlight that climate adaption strategies should, in many regions, also consider long-term variations of groundwater conditions.

The vadose zone tends to dampen monthly and seasonal variations in infiltration fluxes throughout most regions globally (Figure 7). This indicates that infiltration from such short-term hydro-climatic variations can be widely treated as a steady-state recharge flux, which is consistent with Corona et al. (2018) who studied this across the continental United States. Flux variability at longer than seasonal timescales is associated with transient recharge at a substantial part (e.g., 60% for a period of 2 years; see Table 3 and Figure 7) of the Earth’s land surface. For the longer climate and infiltration cycles (>2,557 days), transient recharge areas occur almost everywhere, except in some arid landscapes. For arid regions with relatively low recharge rates, climate and infiltration variations tend to be strongly dampened and steady-state conditions exist. However, the projected increases in extreme rainfall events in future climates may significantly affect recharge conditions in these arid-to-semi-arid regions (Meixner et al., 2016; Moeck et al., 2016, 2020; Taylor et al., 2013; Zhang et al., 2016). The relationships of transient recharge associated with long-term periodic cycles (Figures 7 and 8) should be detectable in long-term water table variations across most aquifers worldwide. Consistent with Dickinson et al. (2014), shallow aquifers are anticipated to promptly reflect seasonal and annual climate fluctuations owing to recharge-related physical constraints, whereas deep aquifers exhibit heightened sensitivity to multi-annual and longer-term climate and infiltration variations.

Our results align with previous studies that have shown that shallow soil horizons filter finer-scaled variability from incoming infiltration signals (Baram et al., 2012) and that surface processes and landcover types tend to minimally impact the propagation of long-period signals (Bakker & Nieber, 2009; Dickinson et al., 2014). The results also show that soil type is an important characteristic in modulating the degree of signal damping (e.g., Figures 2 and 8). This is consistent with an earlier work (Dickinson et al., 2014) that describes periodic signal propagation as being more damped in clayey soils than in sandy soils. They concluded that soils with lower hydraulic diffusivity (e.g., clay soils) filter incoming signals more effectively than soils with greater diffusivity.
data (Figure 10). In cases where our results and field data do not align, such differences may be caused by the unaccounted variability of the water table depth due to missing data sets on the global scale. However, as the long-term climatic and infiltration periodicities on groundwater water tables tend to align with compiled literature variations of water table depths (including the capillary rise) are typically smaller than the damping depths under coarser world maps. From the first-order comparison with data, we can conclude that the simulated effects of overall findings appear robust. For example, the five global recharge data sources used in our study vary substantially from one another but lead to similar conclusions (Table 3). Through our analysis, we identified the causes and regions of when and where steady-state rather than transient recharge and water table fluctuations are expected. At small scales, climatic and physiographic gradients may lead to local conditions that differ from coarser world maps. From the first-order comparison with data, we can conclude that the simulated effects of long-term climatic and infiltration periodicities on groundwater water tables tend to align with compiled literature data (Figure 10). In cases where our results and field data do not align, such differences may be caused by the unaccounted variability of the water table depth due to missing data sets on the global scale. However, as the variations of water table depths (including the capillary rise) are typically smaller than the damping depths under various infiltration patterns (Fan et al., 2013), we conclude that the effects of simplification for the assessment of steady and transient recharge are mostly minimal.

Our approach does not consider structural changes in how hydraulic parameters vary with depth. Such soil heterogeneities (e.g., layering) can affect recharge and thus damping depths (Hartmann et al., 2017; Mocek et al., 2018). Although Dickinson and Ferré (2018a,b) and Dickinson et al. (2014) developed an improved version of the analytical solution that takes into account heterogeneity, global-scale information about soil heterogeneity and layering is still lacking (Hengl et al., 2017). However, Corona et al. (2018) found that the validity of the linear superposition assumption of damping depth in layered soil textures tends to increase as the period increases in the climate variability and this assumption was generally reasonable under a considerable range of subsurface layer properties and geometries. The finding implies that the damping depth of recharge flux variations in homogeneous soils can be used to reasonably estimate steady-state and transient recharge in more complex layered soil profiles that are representative of natural vadose zones.

The analytical solution we use is based on several approximations, such as using an exponential conductivity function, linearizing certain terms, and neglecting hysteresis. Previous work in sand and clay soils shows that calculated damping depths and flux variations of the analytical solution are very comparable to more complex numerical simulations, which accounts for variable diffusivity based on a nonlinear relation between diffusivity and water content (Dickinson et al., 2014). Moreover, Bakker and Nieber (2009) conducted a study using high-resolution finite-element models and compared the results to the analytical model. They found that the overall results of the analytical solution were similar to those of physically based finite-element models for the first two approximations. Dickinson et al. (2014) showed for different soil-water conditions that the analytical solution was most reliable when hydraulic diffusivity remained relatively constant. For fine soils with minimal variations in water content and flux, hydraulic diffusivity tends to remain steady. However, in coarse soils like sand, where water content and flux variability are higher, diffusivity can vary. In their examples, Dickinson et al. (2014) pointed out that regions with coarse soils in aquifers, where recharge is likely to be steady, could be mistakenly identified as having transient recharge. Regarding the neglected hysteresis, Lehmann et al. (1998) and Stauffer and Kinzelbach (2001) observed relatively small differences between numerical simulations and experimental data. The model with hysteresis exhibited greater damping of surface flux oscillation than did the model without hysteresis. It is speculated that a similar trend may occur within our calculations. The inclusion of hysteresis could potentially create a greater damping depth. Our relatively small damping factor of 5%, may compensate for the neglect of hysteresis and provides a more conservative estimate. Increasing the damping factor from 5% to, for example, 10% and 20% will lead to a change in damping depth from roughly 4.8 m to 4 and 3.8 m, respectively,
over a period of 90 days for sand with a $q_s$ of 0.001 mm per month (see Figure 2). Certainly, the definition of damping depth as the depth at which only 5% of the initial infiltration variability is preserved as percolation variability is uncertain but the chosen value of 5% is in line with previous studies that used the analytical solution (Bakker & Nieber, 2009; Corona et al., 2018; Dickinson et al., 2014; Dickinson & Ferré, 2018a).

Both uncertainties of the input variables and simplifications in the analytical solution (e.g., soil heterogeneity, macropores, and preferential flow) limit the accuracy of our global estimates. However, such problems persist with other approaches, and compared with physically based numerical models, the analytical solution provides similar but more conservative estimates of the damping depth, which avoids overestimating dampening (Bakker & Nieber, 2009; Corona et al., 2018; Dickinson et al., 2014). Moreover, the data used for the validation (Figure 10) indicate that the obtained results are plausible, but more extensive testing would be useful.

Although mostly consistent with a few field data and comparable to physically based models, integrated models such as Parflow (Maxwell et al., 2015), HydroGeoSphere (Therrien et al., 2006), or others could be used in our study. The analytical solution was chosen over a complex numerical model for several reasons. The analytical solution has demonstrated comparable accuracy to more complex numerical simulations in previous work, specifically in sand and clay soils, ensuring the necessary precision for our model's requirements (e.g., Bakker & Nieber, 2009; Corona et al., 2018; Dickinson et al., 2014). Since the analytical solution offers transparency and reproducibility, as all assumptions can be succinctly listed, and obtaining associated data and computational resources is straightforward. Integrated numerical models, though increasingly sophisticated and entail substantial computational demands, a critical consideration given the complexity and scale of our study. Alternatives, including global models (e.g., de Graaf et al., 2015, 2019; Herbert & Döll, 2019; Müller Schmied et al., 2021), do not inherently offer greater accuracy, as uncertainties and variations in parameters, such as recharge, persist among models (e.g., Berghuis et al., 2022; Reinecke et al., 2021). Moreover, we have to recognize that every modeling choice faces challenges in fully covering heterogeneity. We acknowledge the limitations of the choice of the analytical solution but emphasize that it strikes a balance between methodological rigor and practical considerations for the challenges posed by our research objective.

While we acknowledge the need for more extensive testing, our validation data indicate plausible results. Comparison of the analytical solution results with field data for some locations (Figure 10) suggests consistency in most cases, despite the model's simplified nature and approach that is more exploratory. The comparison with local-scale studies, though limited, demonstrates agreement in a significant percentage of cases. Although the analytical solution we employed cannot capture the intricate subsurface interactions and detailed relationships with surface and climatic forcing functions as comprehensively as an integrated distributed three-dimensional model, it remains robust in theory and is consistent with other extensive studies that used diverse model assumptions and data sets.

5. Summary and Conclusions

We demonstrate how oscillations associated with global-scale periodic infiltration variability can result in regionally varying degrees of transient groundwater recharge. Our global-scale assessment shows why some quasi-periodic infiltration fluxes associated with climate variability are absent in groundwater table fluctuations while others would result in transient recharge and dynamic groundwater tables. This quasi-periodic control of groundwater tables from oscillatory climatic systems could offer a valuable source of longer-term forecasting capability. This is especially relevant because controls on groundwater resources at very long scales are only rarely considered in water-availability and sustainability studies, which are typically based on average conditions and climatic values. We provide a new framework for understanding global water availability changes due to climate and infiltration variability and highlight that climate adaption strategies should also consider the long-term lag time of groundwater systems. This is especially important for assessing groundwater reliance and drought frequency.

Our analysis revealed that short-term variations (months-seasons) in infiltration fluxes are damped in the vadose zone throughout most arid-to-semi-arid regions of the globe, whereas recharge variability at longer than seasonal periods leads to an increasing amount of transient groundwater recharge. For longer climate cycles, transient recharge areas are expected to occur almost everywhere, except in the more arid regions. Moreover, our results show that soil and surface properties are important for short-term (seasonal and shorter) fluctuations, but only minimally influence recharge fluctuations for longer climate cycles. Despite model and data uncertainties, we
show that the simulated occurrence of long-term periodic climate and infiltration variability at the groundwater table compares well to compiled field data. Our results can help to detect regional variations in recharge conditions and support predictions of recharge globally.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

All data needed to evaluate the conclusions in the paper are present in the paper. The depth to water table is provided by Fan et al. (2013) and long-term groundwater recharge rates are from Berghuijs (2022); Herbert and Döll (2019); Müller Schmied et al. (2020); de Graaf et al. (2015, 2022). The soil texture data are from Hengl et al. (2018). The data compiled and used in this study is available at ERIC-Open (EAWAG Research Data Institutional Collection, https://opendata.eawag.ch/) (Moëck et al. (2024)).

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