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Key Points:

- A physically based framework was proposed to quantify effects of soil hydraulic properties on groundwater and climate interactions
- Saturated hydraulic conductivity and groundwater levels are crucial for assessing the coupling modes in the study area (Hamburg, Germany)
- Combined effects of climatic parameters, soil properties and shallow groundwater influence the mode of coupling in Hamburg, Germany

Supporting Information:

Supporting Information may be found in the online version of this article.

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An Analytical Framework to Investigate Groundwater-Atmosphere Interactions Influenced by Soil Properties

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Abstract The interaction between climate and groundwater forms a complex, coupled system that affects land-atmosphere feedback processes and thus local climatic parameters. We propose an analytical framework that integrates local groundwater information and soil hydrophysical characteristics to identify regions with bidirectional (two-way) coupling where groundwater is influenced by climatic factors (e.g., precipitation) and may affect local climate (e.g., through surface fluxes). The framework capitalizes on the concept of the evaporation characteristic length to quantify the hydraulic connection of groundwater to the soil surface. To evaluate the framework, we calculate the maximum depth of hydraulic connection (D_{max}) between groundwater and the soil surface in Hamburg, Germany. For regions with D_{max} exceeding the groundwater depth (d), a bidirectional mode of coupling is defined, while $D_{max} < d$ implies a unidirectional coupling mode. Our results indicate that climate driven evaporation changes potentially alter the coupling between groundwater and climate depending on soil texture. Moreover, soil hydraulic properties and shallow groundwater tables could play a crucial role in shifting land-atmosphere feedback processes by influencing the coupling mode. This research provides insights into the groundwater-climate interactions under various climatic conditions and soil textures which could contribute to sustainable land-use management practices, particularly in regions characterized by bidirectional coupling.

Plain Language Summary This study explores the hydraulic connection between climate and groundwater. We developed an analytical framework that combines local groundwater levels and soil hydrophysical characteristics to identify areas with potential two-way climate-groundwater interaction. In areas with bidirectional mode of coupling not only the groundwater is influenced by the climate (e.g., through precipitation), but also it may affect climatic parameters by influencing soil moisture and evapotranspiration. We employed the framework to calculate the maximum depth of hydraulic connection (D_{max}) linking groundwater and climate in Hamburg, Germany. Results identify bidirectional coupling zones, where climate and groundwater can mutually influence each other. We found that changes in soil properties, evaporation dynamics, and groundwater levels affect the climate-groundwater coupling thus shedding light on the impact of (shallow) groundwaters on land-athmosphere feedback processes.

1. Introduction

Quantifying the hydraulic interactions between groundwater and land surface and their mutual coupling plays a crucial role in soil moisture dynamics and thus variation of mass and energy exchanges with overlying atmosphere (Fan et al., 2007; Rihani et al., 2010). Climatic parameters can influence groundwater (primarily via precipitation and recharge). However, groundwater may also influence climate parameters through its effects on soil moisture and evapotranspiration contributing to variation of land-atmosphere feedback processes (Chen & Hu, 2004; Miguez-Macho & Fan, 2012; Seneviratne et al., 2010).

Regions with shallow water table depths (often <10 m) have shown strong connections between groundwater and land-surface processes (Alkhaier et al., 2012; Anyah et al., 2008; Kollet & Maxwell, 2008). In these regions, even small variations in groundwater tables can lead to significant changes in soil moisture availability (Fan et al., 2007; Ferguson & Maxwell, 2010). Soil drying can lead to a drier and warmer atmosphere, while increased soil moisture primarily enhances evaporative fluxes and thus cloud formation and precipitation (Aminzadeh et al., 2016; Sehler et al., 2019). Such local effects can exert significant impacts on extreme climatic events such as droughts, heatwaves, and floods (Hsu & Dirmeyer, 2023; Miralles et al., 2019; Vogel et al., 2018). Groundwater exhibits a buffer capacity to postpone or facilitate the onset of such events (Marchionni et al., 2020)

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highlighting the importance of groundwater-surface interactions in the local climate (Fan, 2015; Kollet & Maxwell, 2008; Rihani et al., 2010).

Various approaches have been proposed to classify the nature of groundwater-land surface interactions considering factors such as surface energy fluxes, water table depth, and topography (Cuthbert et al., 2019; Ferguson & Maxwell, 2010; Gleeson et al., 2011; Haitjema & Mitchell-Bruker, 2005; Salvucci & Entekhabi, 1995). Following earlier research (Kim et al., 1999; Salvucci & Entekhabi, 1995), Haitjema and Mitchell-Bruker (2005) introduced the Water Table Ratio to classify the mode of coupling between the groundwater table and land surface as being either topography- or recharge-controlled. This approach was further extended to characterize groundwater-climate interactions as either bi- or unidirectional for areas of topographic- or recharge-controlled water tables, respectively (Cuthbert et al., 2019; Gleeson et al., 2011). Results indicate a bidirectional interaction for regions with topographically controlled water table, correlating with shallow (below 10 m) water table depths (Cuthbert et al., 2019). Coupling mechanisms between groundwater and land surface have also been analyzed in the context of groundwater-ecosystem dynamics, especially in the potential change between carbon sinks to carbon sources due to groundwater abstractions and climate changes (Genereux et al., 2013; Ma et al., 2014).

While multiple parameters affect these groundwater-climate interactions, soil properties, particularly soil texture, have been identified as a key variable (Fernandez-Illescas et al., 2001; Vereecken et al., 2022; Yusefi et al., 2020). Existing approaches would benefit from a physically based analytical tool to spatially analyze groundwater-climate coupling mechanisms based on soil hydraulic properties and shallow water tables. Or and Lehmann (2019) invoked the concept of evaporative characteristic length (Lehmann et al., 2008) and developed the surface evaporation capacitance (SEC) model to estimate global surface evaporation. The characteristic length determines the extent of hydraulic coupling (via capillary connections) between the receding drying front within a drying porous medium and the vaporization plane at the surface during the so-called stage 1 evaporation (Shokri et al., 2012).

The present study aims to capitalize on the concept of evaporative characteristic length to offer a simple, yet physically based analytical framework in which local groundwater information and soil hydrophysical properties are employed to identify regions exhibiting bidirectional groundwater-atmosphere coupling on regional scales. To showcase the application of the general framework and the insights it provides, we apply it to Hamburg (Germany) which is characterized by the presence of shallow groundwater tables (influenced by the Elbe river). Within this context, we theoretically show how variations in groundwater table and soil hydrophysical parameters influence the groundwater-atmosphere interaction. For the verification of the framework's performance we used a locally available ground cooling capacity map. To the best of our knowledge there is no study providing such analytical framework for the estimation of groundwater-atmosphere coupling based on soil properties and comparing results to locally available ground cooling capacities. The findings of our analysis may have serious implications on how the projected climate variability may influence land-atmosphere interactions and hydrological processes. The application of this framework to an urban environment, such as Hamburg, with shallow water tables, can be used to explore the impacts of soil characteristics and climate parameters on the coupling mode. This allows us to identify connections of bidirectional coupling with land-atmosphere interactions (e.g., soil moisture-temperature and soil moisture-precipitation feedback mechanisms) and discuss further implications of the coupling mode for different climatic conditions and soil textures.

2. Theoretical Considerations

Identifying the mode of coupling relies on the extent of hydraulic connection (D_{max}) between the water table and the soil surface through capillary pathways supporting the upward water flow (due to evaporation). For the case of shallow groundwater tables (Figure 1a), we hypothesize a direct hydraulic link between groundwater and the soil surface through upward capillary pathways. Such hydraulically coupled system potentially influences the local climate parameters by supporting evaporation from the (shallow) groundwater table. For deep groundwater tables (relative to D_{max}), the hydraulic connection between water table and surface may get disrupted by the resistive gravity and viscous forces limiting upward capillary flows that supply vapourization plane at soil surface during stage 1 evaporation (Or et al., 2013). Hence, vapourization plane (the so-called primary drying front) eventually recedes below the surface (Shokri & Or, 2011) and the evaporation process is dominated by diffusive vapor fluxes marking the onset of stage 2 evaporation (Figure 1b) (Sadeghi et al., 2012; Shokri & Salvucci, 2011).

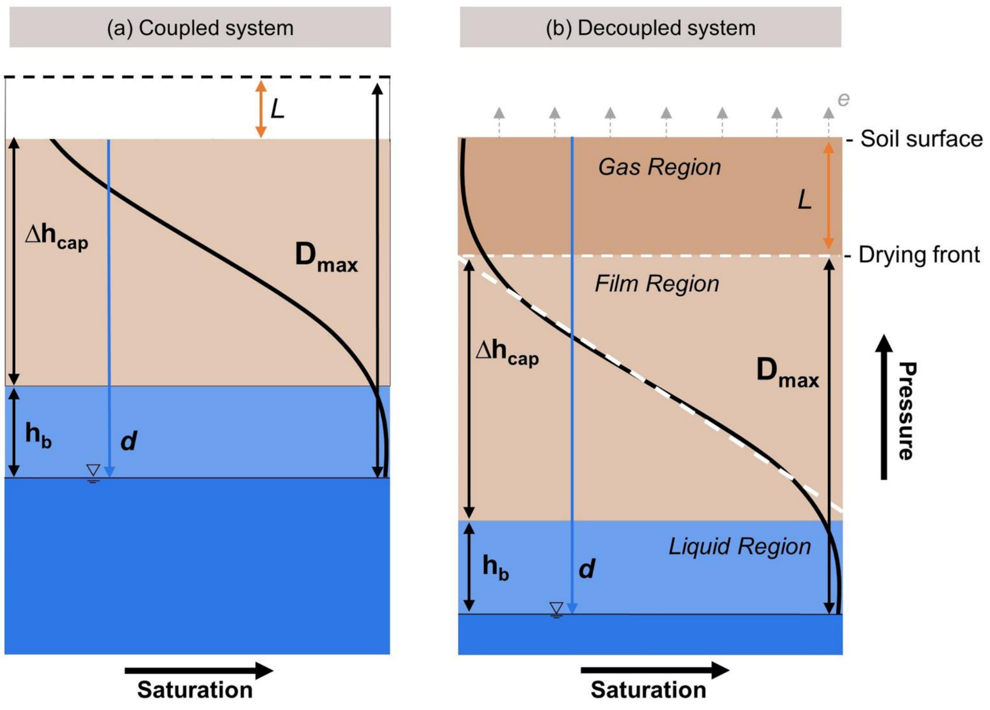

Figure 1. Schematic representation of upward capillary flows between water table and soil surface for (a) a coupled system (adapted from Sadeghi et al. (2012)); and (b) an uncoupled system. D_{max} represents the maximum depth of hydraulic connection between the water table and the soil surface, estimated from the height of the capillary fridge zone (h_b) and the capillary head gradient (Δh_{cap}). The parameter "d" depicts the depth to the water table while "L" represents the difference between the groundwater table and D_{max}. The black curves depict the water retention curves. Liquid region represents fully saturated pores, whereas pores in the gas region are filled with air.

The extent of the hydraulic connection (D_{max}) can be estimated based on the linearization of the water retention curve relating capillary pressure to the water content (Figure 1) outlined in Lehmann et al. (2008) and Shokri and Salvucci (2011) (see Equations 1–3 in Supporting Information S1 for details):

$$D_{max} = \frac{\Delta h_{cap}}{1 + \left(e/K_{eff}\right)} + h_b \tag{1}$$

where Δh_{cap} is the capillary head gradient resulting from the difference of the capillary pressure at the onset of the liquid discontinuity (h_{max}) and the upper boundary of the capillary fringe zone (h_b), e is the evaporation rate, and K_{eff} is the effective hydraulic conductivity that is expressed as a function of h_{max} (Haghighi et al., 2013; Or & Lehmann, 2019):

$$K_{eff} = 4K(h_{max}) = 4K_{sat}\sqrt{(1 + (\alpha * h_{max})^n)^{-m}}\left(1 - \left(1 - \frac{1}{1 + (\alpha * h_{max})^n}\right)^m\right)^2 \tag{2}$$

in which K_{sat} is the saturated hydraulic conductivity, and α and n are estimated by fitting the parametric model of van Genuchten on the measured data required to obtain the water retention curve (van Genuchten, 1980) (with $m = 1{-}1/n$).

To evaluate the mode of coupling being either bi- or unidirectional, the dimensionless factor C was derived from the relation between D_{max} and the depth to the water table (d) defined as:

$$C = \frac{d}{D_{max}} \tag{3}$$

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For values of $C \leq 1$, the maximum depth of hydraulic connection equals or exceeds the depth of the water table (Figure 1a), allowing a bidirectional connection to the surface. Values of $C > 1$ represent a decoupled system where the groundwater table depth exceeds the maximum depth of hydraulic connection (Figure 1b) leading to unidirectional mode of coupling.

In addition to quantifying the mode of coupling, we provide a simple method to estimate how susceptible each coupling mode is to change. To evaluate the transition, we estimate the difference between d and D_{max}, represented by L.

Given a bidirectional mode of coupling ($C \leq 1$), L is determined as the difference between D_{max} and the depth of the water table (d) and thus, normalized using the maximum height of hydraulic connection (Equation 4a):

$$\begin{gathered} C \leq 1 : L = D_{max} - d \\ \frac{L}{D_{max}} = 1 - \frac{\mathrm{d}}{D_{max}} \\ 0 < \frac{L}{D_{max}} \leq 1 \end{gathered} \tag{4a}$$

For the case of unidirectional coupling ($C > 1$), the length of L equals the height of the gas region normalized using the distance to the groundwater table (Equation 4b):

$$\begin{gathered} C > 1 : L = d - D_{max} \\ \frac{L}{d} = 1 - \frac{D_{max}}{d} \\ 0 < \frac{L}{d} < 1 \end{gathered} \tag{4b}$$

According to Equation 4, values of $\frac{L}{D_{max}}$ and $\frac{L}{d}$ closer to 0, for the respective bidirectional and unidirectional modes of coupling, indicate a higher susceptibility to change.

To further estimate the impact of soil characteristics and climate parameters on the mode of coupling, we define a dimensionless ratio, $r = \frac{e}{K_{sat}}$, representing the ratio of evaporation rate (e) to the saturated hydraulic conductivity (K_{sat}). For this purpose, we varied the evaporation rates three orders of magnitude (ranging from 0.01 to 10 mm/day). Saturated hydraulic conductivity values were also classified following the USDA classification of saturated hydraulic conductivity (U.S. Department of Agriculture, 2022) into three groups, that is, 1–10 μm/s, 10–20 μm/s and 20–30 μm/s (equivalent to 0.09–0.9, 0.9–1.7,1.7–2.6 m/day, respectively) representing finer to coarser soil textures within sandy soils.

3. The Proposed Framework to Identify Modes of Coupling

To determine D_{max}, we make use of soil water characteristic parameters based on the newly introduced Geo-Transfer functions (GTF) (Gupta et al., 2022) and an ancillary data set that describes the saturated hydraulic conductivity K_{sat} (Gupta et al., 2020). Using GTFs, local information on soil-forming processes are included by linking spatial information of soil hydraulic properties and vegetation, climate, and topography using a machine learning approach (Gupta et al., 2021). This provides valuable information and fills the gap of data availability for soil structure and site-dependent parameters (especially in urbanized regions). This approach reduces typical constraints associated with pedo-transfer functions, which mainly rely on soil texture, bulk density, and organic content, neglecting the incorporation of spatial covariates.

The data set of soil hydraulic properties contains information about the van Genuchten parameters (α and n) (Gupta et al., 2022). The second data set provides information about the saturated hydraulic conductivity (K_{sat}) (Gupta, et al., 2020). Both data sets are provided with spatial resolution of 1 km^2, defining the spatial scale of this analysis. Both data sets include soil information in depths of 0, 30, 60, and 100 cm below the surface. Statistical analysis of these parameters over depth in the study area (Hamburg) and comparison to a larger data extent (the

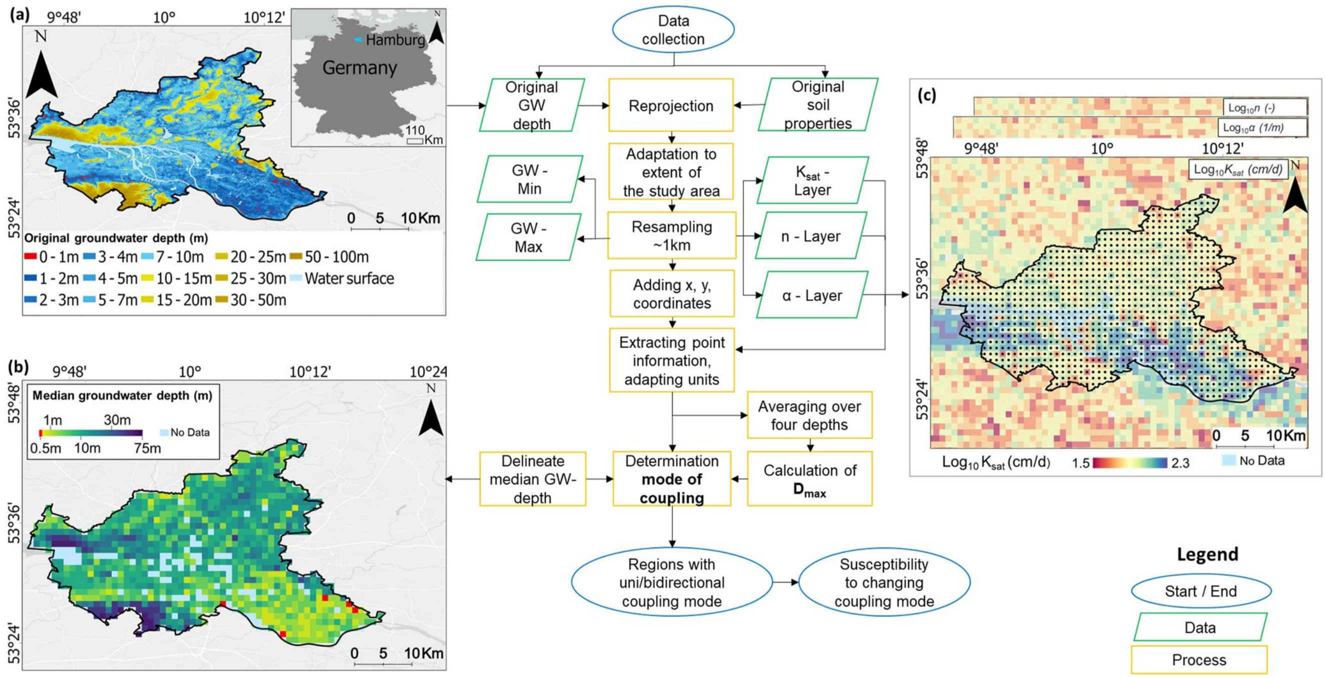

Figure 2. Proposed methodology for identifying the regions with bidirectional mode of coupling between the groundwater table and the soil surface. (a) The original groundwater depths ranging from 0 to 100 m (adapted from Free and Hanseatic City of Hamburg, Department of Environment, Climate, Energy and Agriculture, 2022). Blue indicate shallow water tables ($d < 10$ m), while yellow indicates deeper groundwater tables. (b) The adapted mean groundwater depths for each raster of 1 km^2, ranging from 0 to 75 m. Missing values belong to the surface water areas (the Elbe river). (c) The soil hydrophysical characteristic input layers: K_{sat}, n and α (adapted from Gupta et al., 2022, 2020).

entire Germany) reveal that depth variations of K_{sat}, α, and n remain neglegible (see details in Supporting Information S1). As a result, the depth-averaged values of these parameters were used in our calculation.

All data used to perform the analysis are publicly available and provided in the data availability statement. We used the geographical information system ArcGIS Pro and the statistical software R Studio version 4.1.3 (R Core Team, 2022) to adapt and calculate the data (see Figure 2). Both data sets were modified to a uniform coordinate system, using the common coordinate system WGS 1984. The developed framework was applied to Hamburg in Germany, covering an area of 755 km^2, to test its performance. We used available local groundwater table information (adapted from Free and Hanseatic City of Hamburg et al., 2022) for the hydrological year 2018 (Figures 2a and 2b). The hydrological year including the time period of November 2017–October 2018 represents the most current available data set at the time of analysis. It fully captures precipitation stored in the catchment area (DIN 4049–1, 1992). The original data set covers the depth of the groundwater table with a spatial resolution of 1 m. The groundwater tables were allocated to the raster size of 1 km using the nearest neighbor resampling technique. This method allocates the closest cell value to the output cell value. Hence, no new values are created, and original values are retained (Pacheco et al., 2018). The original data set provides a minimum and maximum range for groundwater depths from which an intermediate groundwater depth was calculated for each raster cell. The remaining data sets containing the soil properties were fitted to the study area, and the cell-centered information was extracted for each layer (smilar to the procedure of the groundwater data). The soil hydrophysical characteristics were then used to calculate D_{max} following Equations 1 and 2. Eventually, the mode of coupling and its susceptibility to change were estimated using Equation 3 and Equation 4, respectively.

4. Results and Discussion

4.1. The Extent of Hydraulic Connection (D_{max}) and Mode of Coupling

The extent of hydraulic connections between groundwater and surface (D_{max}) is calculated based on soil hydrophysical characteristics using Equation 1. As seen in Figure 3a, the estimated values of D_{max} in Hamburg

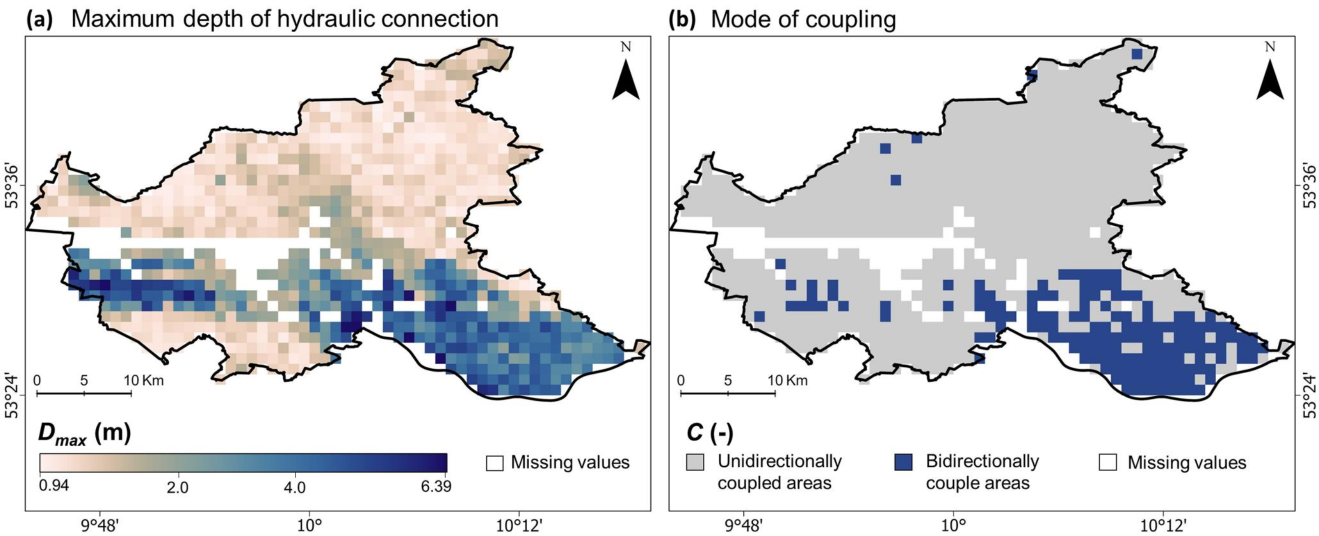

Figure 3. (a) Calculated maximum depth of hydraulic connection (D_{max}) for Hamburg assuming an average evaporation rate of 1 mm/day. (b) Areas with estimated bidirectional mode of coupling for Hamburg with blue and gray corresponding to the regions with bidirectional and unidirectional mode of coupling, respectively. White raster cells (within the border of Hamburg) represent missing values from the underlying data sets primarily corresponding to water surfaces.

range from 0.9 to 6.4 m for an assumed average evaporation rate of 1 mm/day. Higher values of D_{max} can be found south of the Elbe river, where lower values of n and α are found (indicating fine to medium-textured soils).

The averaged values for α, n, and K_{sat} in Hamburg range 0.63–2.87 1/m, 1.31–2 (−), and 0.34–3.47 m/day, respectively. The overall distribution of soil hydrophysical parameters for the case study of Hamburg is mainly homogenous in horizontal and vertical extents (see SI). To better understand the influence of individual input parameters on D_{max}, a Pearson correlation analysis was conducted and respective values of −0.88, −0.54, and 0.66 were obtained for α, n, and K_{sat} (see Figure 4 for details). The analysis indicate that higher values of α and n are associated with lower values of D_{max}, whereas K_{sat} within our sample range has an increasing effect on D_{max}.

The bidirectional mode of coupling (where D_{max} exceeds the depth of the water table) occurs in the southeast (SE) and southwest (SW) of Hamburg. In the southern part of the Elbe river, high values of D_{max} (4–6 m) and shallow local groundwater depths ($d < 5$ m SE, $d < 10$ m SW) support a bidirectional mode. In few locations in the north of Hamburg (Figure 3b), bidirectionally coupled regions are delineated, where D_{max} with values between 1.6 and 2 m is only slightly deeper than the groundwater table ($d < 1.5$ m). Assuming that the difference between D_{max} and the groundwater table is small, one can postulate a higher susceptibility for the change in the mode of unidirectional and bidirectional coupling (indicated by values closer to 0 for both modes in Figure 5).

According to Figure 5, most regions with unidirectional mode of coupling in northern and southern parts of Hamburg with susceptibility values more than 0.5 are not prone to transition. However, areas with susceptibility values smaller than 0.5 indicate a higher likelihood to change the current mode of coupling (especially in central areas). In the southwest of Hamburg, there is a higher susceptibility to a changing mode of coupling. In the southeast, there is a variation of both, with some areas indicating higher and others lower susceptibility to change, depending on the varying groundwater table depth and D_{max} (influenced by soil properties). In summary, the mode of coupling remains susceptible to change considering the variations in groundwater depth and soil properties. Therefore, in the next section, we analyzed how soil characteristics and the changes in climatic parameters could influence or change the mode of coupling between groundwater and climate.

4.2. Effect of Soil Characteristics and Climatic Parameters on the Mode of Coupling

As reflected in Equation 1, the change in climatic conditions (affecting evaporative flux) and soil properties is expected to change D_{max} and thus the mode of coupling. To quantify the extent of this dependency, we varied the ratio of evaporation rate to saturated hydraulic conductivity ($r = \frac{e}{K_{sat}}$) from 0.01 to 10 (dimensionless) and investigated how this variation influences the mode of coupling. Previous studies have shown the key role of evaporative fluxes in shaping and alternation of land-atmosphere feedback processes (Sehler et al., 2019;

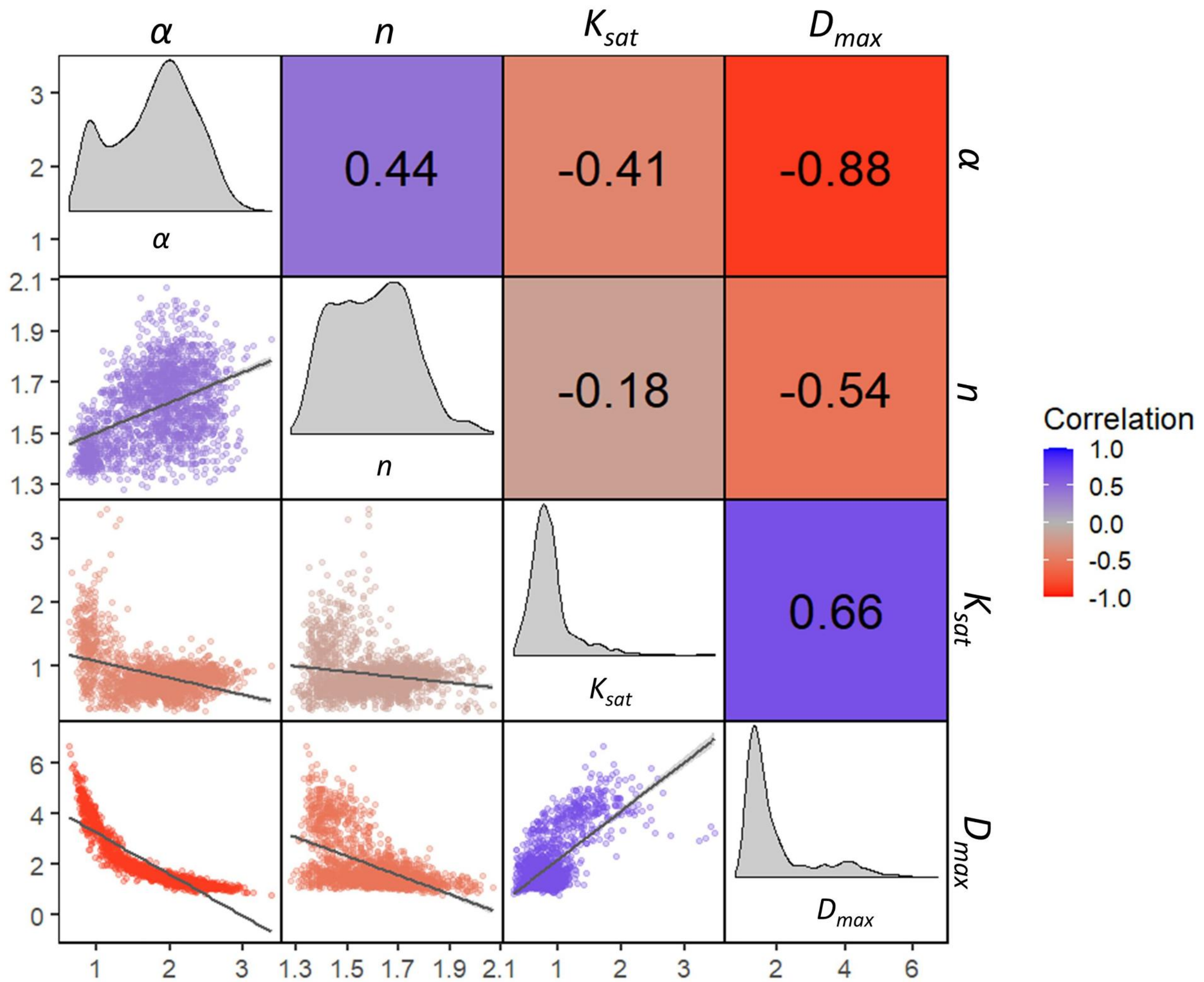

Figure 4. Summary statistics including Pearson's correlation coefficient for the input data used to calculate D_{max}. Scatter points show the raw data distribution averaged over the depth, indicating one average data point over the four-provided depths of 0, 30, 60, and 100 cm. Histograms depict the data distribution. Numbers indicate the Pearson-correlation-coefficient ranging between −1 and 1 for strong negative (−1) and positive (1) correlation.

Seneviratne et al., 2010). With increasing evaporation, the rate of upward flow increases, leading to increased viscous dissipations which in return, limit D_{max} and thus affect the mode of coupling. This can be also observed in our results, where D_{max} increases slightly for values of $r \leq 1$ and decreases significantly for values of $r > 1$ (see Table 1 in Supporting Information S1). The findings here highlight the role of climatic parameters (e.g., wind, radiation, and air temperature) affecting evaporation rates which in turn limit the extent of hydraulic coupling between groundwater and soil surface.

We use saturated hydraulic conductivity as a surrogate reflecting changes in soil characteristics (e.g., soil structure, texture, and pore size distribution) that explicitly affect soil water dynamics (Gupta et al., 2021; Lehmann et al., 2018; Usowicz & Lipiec, 2021). We analyzed the impact of K_{sat} on D_{max} for varying scenarios of r by classifying local values of K_{sat} in Hamburg into three groups corresponding to finer-to coarser-textured soil within the overall sandy soil present in the study area (with Group 1 to 3 with K_{sat} of 0.09–0.9, 0.9–1.7, 1.7–2.6 m/day, respectively). We then depicted the mode of coupling C ($= \frac{d}{D_{max}}$) for the three groups of K_{sat} and different values of r in Figure 6. The corresponding values are summarized in Table 3 in Supporting Information S1.

The results suggest a bidirectional mode of coupling ($C \leq 1$) for soils with higher K_{sat} (Group 3 in Figure 6) for the three scenarios of $r \leq 1$. Soils with lower K_{sat} (Groups 1 and two in Figure 6) tend to illustrate unidirectional coupling with values of $C > 1$, for all four scenarios. For $r = 10$, indicating $e > K_{sat}$, all three groups show a unidirectional mode of coupling. We further observed less susceptibility for changing the mode of coupling with

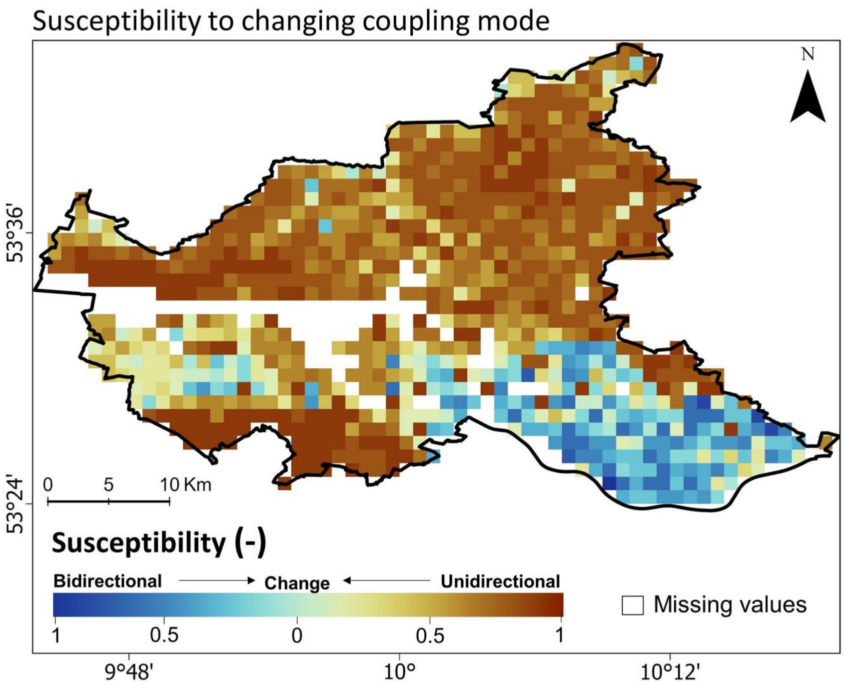

Figure 5. Estimated susceptibility to a change in coupling mode (bidirectional to unidirectional and vice versa) based on the distance between the calculated D_{max} and estimated groundwater depth.

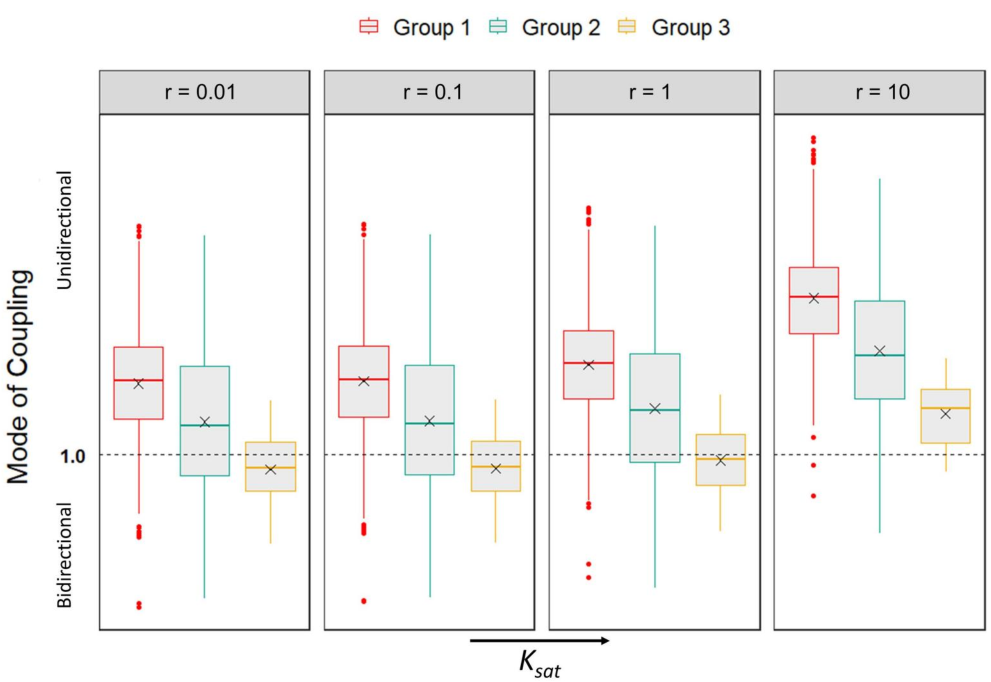

Figure 6. Mode of coupling (C) for each raster cell of 1 km^2 in Hamburg. The colors indicate the groups of K_{sat} (Group 1–3) and their classification of 1–10 μm/s, 10–20 μm/s and 20–30 μm/s (0.09–0.9, 0.9–1.7, 1.7–2.6 m/day, respectively). The cross sign (×) represents mean values. The dashed line represents the threshold of bi-to unidirectional mode of coupling.

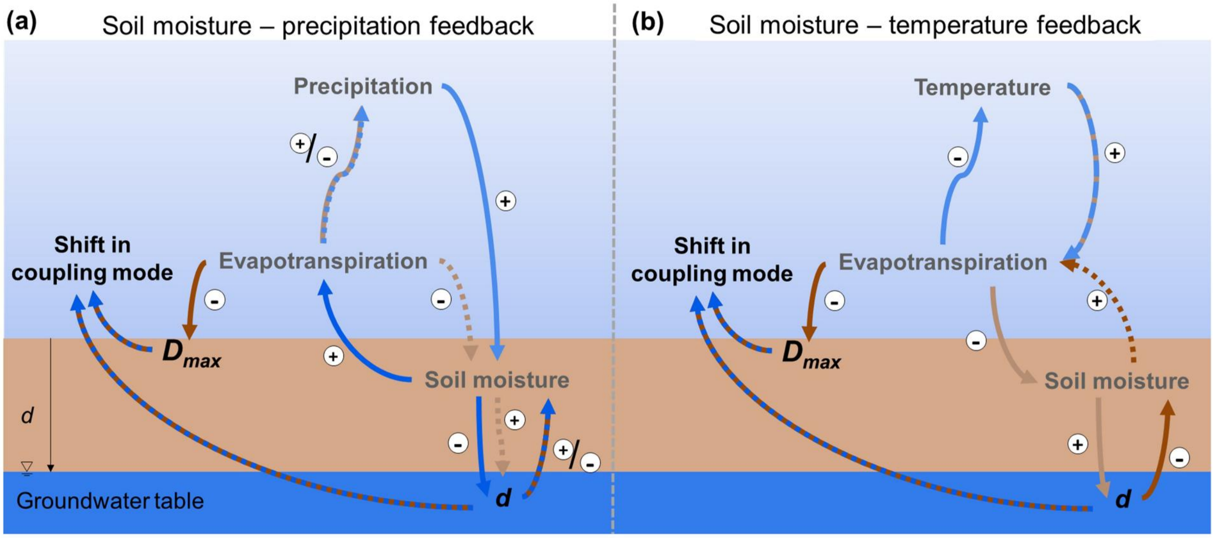

Figure 7. Soil moisture-precipitation (a) and soil moisture-temperature feedback (b) including possible effects of uni-and bidirectional mode of coupling as well as shifts in the groundwater table (*d*). Plus and minus signs indicate positive (supporting) or negative (contradicting) feedback. Blue (brown) arrows indicate cooling (warming) or wetting (drying) processes. Dashed arrows result from a feedback process.

increasing values of *r* (particularly in Groups 1 and 2). The increased distance from the threshold, which defines the onset of unidirectional coupling, suggests a more stable mode of coupling as the value of r increases. As one may generally expect higher capillary rise and thus the extent of hydraulic connection for fine-textured soils (possessing lower saturated hydraulic conductivities), shallow groundwater tables (as observed in Hamburg), have shown to be particularly influential in changing the mode of coupling in Hamburg. However, our results underline how combined effects of climatic parameters, soil properties (reflected in the value of *r*) and groundwater depth influence the mode of coupling. We have tacitly ignored the impact of the long term groundwater fluctuations and its lateral movement to retain applicability of the proposed framework in analyzing the coupling mode. Nonetheless, our calculations could be improved wherever such detailed information are available.

4.3. Implications of Mode of Coupling on Land Processes and Feedback

4.3.1. Land-Atmosphere Feedback Processes

The mode of coupling and its possible changes influence soil moisture (SM) and thus mass and energy exchanges between land and overlying atmosphere. Land-athmosphere feedback mechanisms and their associated sub-processes have already been well established (Hsu & Dirmeyer, 2023; Miralles et al., 2019; Seneviratne et al., 2010). We thus here focus on the contributions of the coupling modes on alterations of these feedback processes (Figure 7).

According to our analysis, in the case of a deeper groundwater table (i.e., d exceeding D_{max}), a (temporary) decoupling between the groundwater table and land surface could occur, affecting local precipitation via the change in surface soil moisture. On the other hand, elevated groundwater tables (with increased precipitation) can raise surface soil moisture content, thereby mitigating surface temperature and thus air temperature via enhanced latent heat cooling (Aminzadeh & Or, 2014; Seneviratne et al., 2010). Focusing on summer months in temperate climate zones with elevated temperatures, presence of shallow groundwaters offers a buffering capacity that primarily maintains surface soil moisture for longer periods (in a coupled system) and thus postpones formation of extreme events such as heatwaves and extreme surface temperature (Aminzadeh et al., 2021, 2023; Keune et al., 2016; Miralles et al., 2019; Zipper et al., 2019). These feedback mechanisms highlight the crucial role of groundwater-land surface coupling on temperature regulations and local climate.

For arid regions with less precipitation and often deeper groundwater tables, precipitation would need to overcome a certain threshold to contribute to the water table (Lehmann et al., 2019). These conditions would limit the bidirectional coupling and could further reinforce the groundwater-soil moisture-precipitation feedback.

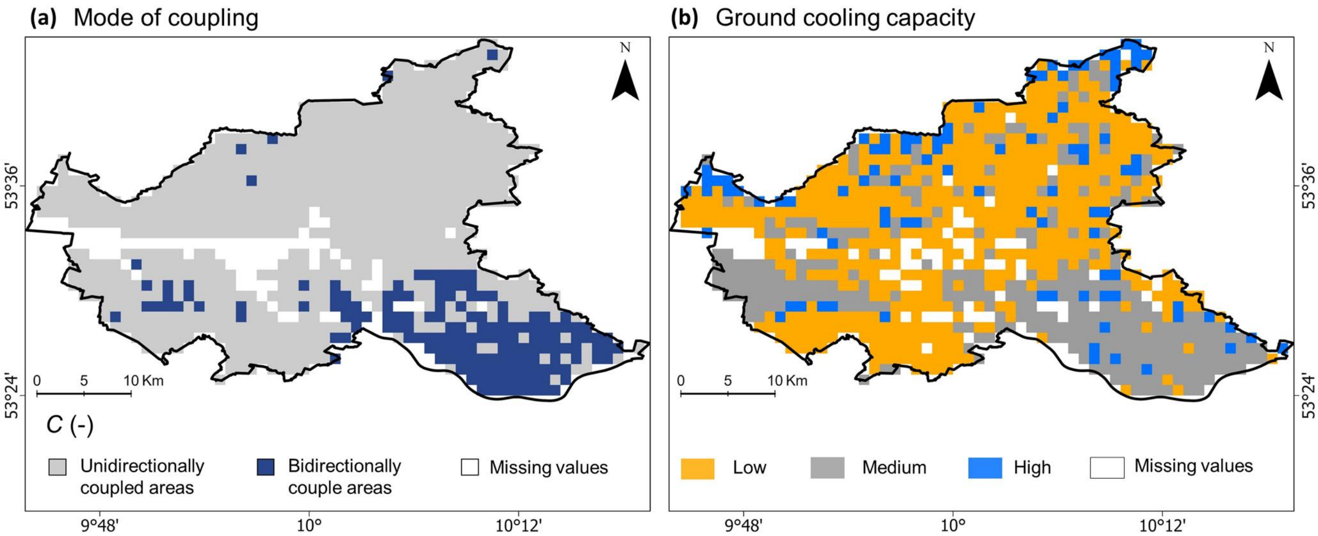

Figure 8. (a) Model predictions of areas with estimated bidirectional mode of coupling ($C = \frac{d}{D_{max}}$) in Hamburg. (b) Upscaled ground cooling capacity map in Hamburg based on Free and Hanseatic City of Hamburg, Department of Environment, Climate, Energy and Agriculture (2021).

In equatorial and boreal climate zones, with higher amounts of precipitation, bidirectional coupling could oocur for the cases where D_{max} exceeds d. These theoretical examples for different climate regions highlight the interrelations between groundwater table depth, soil characteristics and climatic variables (precipitation and evaporation), determining the depth of hydraulic connection and hence, the mode of coupling.

4.3.2. Identification of Ground Cooling Capacity

The ground cooling capacity describes the cooling potential of soil based on its evaporative characteristics, groundwater connection, and heat storage capacity (Domroese, 2021). Current approaches for identification of areas with high ground cooling properties rely on local land information, saturated hydraulic conductivity, and shallow groundwater tables. In a recent attempt (Domroese, 2021), a complex soil water budget model was invoked using daily timesteps for two decades to calculate the evaporation across diverse land covers in Hamburg. The results were superimposed with areas of shallow groundwater tables ($d < 1$ m) marking the final ground-cooling capacity hotspots. We made use of this information for comparison of bidirectional coupling with medium to high cooling potential within the present framework (Figure 8).

The comparison in Figure 8 shows that areas identified as bidirectionally coupled in the present study mostly correspond to areas with medium to high ground cooling capacity (Figure 8b). Differences can be seen in the southwest and some patches in the north due to very shallow groundwater tables ($d < 1$ m). This comparison illustrates the potential of the proposed framework as an effective analytical tool to offer insights regarding ground cooling capacities which is an important component to cope with projected global warming.

4.4. Model Limitations and Future Improvements

The proposed framework provides valuable insights about the hydraulic connection between the groundwater table and land surface and its possible influences on land-atmosphere feedback processes. However, there are a few challenges that could be addressed in future investigations.

The framework does not consider the role of lateral flows and temporal fluctuations (e.g., due to precipitation or drought events) in groundwater table. This simplification is closely bound to the availability of subsoil and hydrogeological data. For the application provided in this paper, the spatial resolution determining the performance of the framework was bound to the input data of soil hydrophysical parameters (Gupta et al., 2020, 2022). The choosen data sets provide state-of-the-art soil hydraulic characteristics on a global scale with 1 km^2 resolution. They preserve local information by combining soil properties with environmental covariates such as vegetation, climate and topography (Gupta et al., 2021). This can bridge the gap between small-scale soil

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properties and regional to landscape level issues. As the main objective of this work is to delineate bidirectionally coupled areas as a first estimate, this spatial extent was used providing a widely applicable framework. Nevertheless, simplifications should be expected on this scale. Such information could improve performance of the proposed framework with future availability and adaptation of current data sets to finer temporal- and spatial scales.

Additionally, we analyzed depth variation of soil hydrophysical characteristics in Hamburg over different depths (between the surface and 1 m) and compared it with a larger area (Germany) (see in Supporting Information S1). We concludeminor variations of saturated hydraulic conductivity along the depth (see in Supporting Information S1). Based on the definition of D_{max}, variations of saturated hydraulic conductivity would need to be considerable in order to change the outcome. In case of significant variations of soil hydrophysical characteristics over depth within the analyzed region, the framework can also be adapted to a several-layer system over heterogeneous terrains following Shokri et al. (2010). Although the applicability of the framework has been showcased for Hamburg, Germany, it can be widely implemented to study the effect of soil characteristics on the mode of coupling between the groundwater table and atmosphere. To do so, the presented information of soil hydraulic properties and saturated hydraulic conductivity, as well as the information on the groundwater table (locally available or large-scale model outputs) can be used to identify the mode of coupling (see data availability section).

Note that our analysis primarily focused on the role of soil hydrophysical characteristics, while future improvements of the model could investigate the role of vegetation on the interactions with the water and energy cycle. Including different land cover types and vegetation dynamics can provide insights into how changes in plant cover, root systems, and transpiration rates can alter the groundwater-atmosphere coupling (Fatichi et al., 2016), providing a more holistic perspective on land-atmosphere interactions.

5. Summary and Conclusions

We developed a physically based analytical framework that integrates first-order soil hydrophysical characteristics and groundwater information to estimate the mode of coupling between the groundwater table and atmosphere. Our findings highlighted the significance of soil characteristics on the mode of coupling and its sensitivity to climatic factors. Applying the framework to Hamburg (Germany) to showcase utility of the framework, we found that D_{max} (representing the extent of groundwater-surface hydraulic coupling) is affected by evaporation rate, soil hydraulic characteristics, and depth of the groundwater table. For an assumed evaporation rate of 1 mm/day, D_{max} in Hamburg varies between 0.9 and 6.4 m. Our results further demonstrated decreasing values of D_{max} for increasing values of e. Notably, higher values of D_{max} were prevalent south of the Elbe river, where soil exhibits lower values of n and α (indicating fine to medium-textured soils). For smaller values of n, fine-textured soils need to overcome higher viscous resistances limiting the extent of D_{max}. For coarse-textured soils, the length of hydraulic connection is limited by gravity and water holding capacity (Or & Lehmann, 2019). In southern regions of the Elbe River, we identified bidirectional coupling modes, characterized by high D_{max} values and shallow groundwater tables ($d < 5$ m). For areas in the north of Hamburg, we found that minor differences between d and D_{max} lead to bidirectional coupling in a few cases.

The framework enabled us to estimate the susceptibility of the coupling mode to change between bidirectional (coupled) and unidirectional (decoupled) systems, highlighting areas prone to change the coupling mode in the northern parts of Hamburg (with a small difference between d and D_{max}) and in the river valley, south of the Elbe River. Transitions in coupling mode could potentially intensify local climate sensitivity to groundwater-climate feedback in a changing climate. This emphasizes the importance of understanding unintended consequences stemming from land and water management practices leading to changes of the coupling mode. As further research and advancements are made in this field, it is crucial to consider the dynamic nature of groundwater-soil-climate interactions and their potential long-term consequences, paving the way for devising necessary action plans and practices prioritizing soil preservation and sustainable water resource management. These findings highlight the possible buffer capacities of soil during heatwave events and could contribute to mitigate urban heat effects during summer months (Keune et al., 2016; Zipper et al., 2019).

Conflict of Interest

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

Data Availability Statement

Local groundwater depth was used for the determination of the mode of coupling, provided by the authority for Environment, Climate, Energy and Agriculture (BUKEA), Free and Hanseatic City of Hamburg. The data set is publicy available under the data licence Germany–attribution–Version 2.0 on the Metadata Network (METAVER) (Object-ID: 4D740B4D-9184-450B-8B4E-896C7FF06BCE; https://metaver.de/trefferanzeige?cmd=doShowDocument&docuuid=4D740B4D-9184-450B-8B4E-896C7FF06BCE#detail_links). The geodataset on the ground cooling capacity was made available under the data licence Germany–attribution–Version 2.0 on METAVER and used for comparison of the results and possible implications on ground cooling capacity (Free and Hanseatic City of Hamburg, Department of Environment, Climate, Energy and Agriculture, 2021) (Object-ID: ED156485-55E0-4380-B5CB-2C681BE372BB, https://metaver.de/trefferanzeige?cmd=doShowDocument&docuuid=ED156485-55E0-4380-B5CB-2C681BE372BB). The soil hydraulic properties and saturated hydraulic conductivity data were used for the calculation of the maximum hydraulic depth (D_{max}) and for application of the framework. Global map of saturated hydraulic conductivity is available at https://doi.org/10.5281/zenodo.3935359 (Gupta et al., 2020). Global maps of soil water characteristics are available at https://doi.org/10.5281/zenodo.6348799 (Gupta et al., 2022). Figures were made using ArcGIS Pro Version 2.7.0 and the statistical software R Studio version 4.1.3. For the visualization of the correlation analysis, the “corrmorant” package was used (Link, 2020).

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