How does daily groundwater table drawdown affect the diel rhythm of hyporheic exchange?

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Abstract. Groundwater table dynamics extensively modify the volume of the hyporheic zone and the rate of hyporheic exchange processes. Understanding the effects of daily groundwater table fluctuations on the tightly coupled flow and heat transport within hyporheic zones is crucial for water resources management. With this aim in mind, a physically based model is used to explore hyporheic responses to varying groundwater table fluctuation scenarios. Effects of different timing and amplitude of groundwater table daily drawdowns under gaining and losing conditions are explored in hyporheic zones influenced by natural flood events and diel river temperature fluctuations. We find that both diel river temperature fluctuations and daily groundwater table drawdowns play important roles in determining the spatiotemporal variability of hyporheic exchange rates, temperature of exfiltrating hyporheic fluxes, mean residence times, and hyporheic denitrification potentials. Groundwater table dynamics present substantially distinct impacts on hyporheic exchange under gaining or losing conditions. The timing of groundwater withdrawal has a direct influence on hyporheic exchange rates and hyporheic buffering capacity on thermal disturbances. Consequently, the selection of aquifer pumping regimes has significant impacts on the dispersal of pollutants in the aquifer and thermal heterogeneity in the sediment.

1 Introduction

Hyporheic zones, as transitional areas between surface water and groundwater environments, often exhibit marked physical,
15 chemical and biological gradients that drive the exchanges of water flow, energy, solute and microorganisms between surface
and subsurface regions (Boano et al., 2014). Although the hyporheic zone is a small veneer, it has disproportionately significant
effects on nutrient cycling and river ecological functioning (Malcolm et al., 2002; Krause et al., 2009; Gomez-Velez et al.,
2015). Understanding the spatiotemporal variability of hyporheic exchange processes is key to water resources management
and ecosystem restoration.

20 The hydrological drivers and modulators of time-varying hyporheic exchange processes have been extensively studied in the
last decade. Hydraulic gradient change along the sediment-water interface, as the main driver, determines the spatiotemporal
variability of hyporheic zone extent and characteristic time scales of hyporheic exchange processes (Boano et al., 2013; Ward
et al., 2017; Gomez-Velez et al., 2017). Factors influence the hydraulic gradient change at the sediment-water interface include
channel flow conditions (Trauth and Fleckenstein, 2017; Grant et al., 2018; Broecker et al., 2018), geomorphological settings
25 (Tonina and Buffington, 2011; Schmadel et al., 2016; Singh et al., 2019), and regional groundwater flow (Nützmann et al., 2014;
Malzone et al., 2016; Wu et al., 2018). Sediment and fluid properties, even though do not directly drive hyporheic exchange,
substantially modulate hyporheic exchange processes. Sediment heterogeneity can alter hyporheic flow paths and residence
time distributions, creating hot spots for biogeochemical transformations (Sawyer and Cardenas, 2009; Gomez-Velez et al.,
2014; Pescimoro et al., 2019). Effects of fluid properties, i.e., density and viscosity, also play an indispensable role. As functions
30 of temperature, fluid density and viscosity directly influence the hydraulic conductivity which governs the flow transport
in the sediment. Consequently, river temperature variability (i.e., diel and seasonal river temperature fluctuations) induces
significant changes in the hydraulic conductivity and subsequently the changes in hyporheic exchange processes (Cardenas
and Wilson, 2007a). The spatiotemporal variability of the drivers and modulators eventually results in dynamic hyporheic
exchange processes. Among these drivers and modulators, the combined effects of groundwater flow and river temperature on
35 dynamic hyporheic exchanges are comparably understudied.

Depending on the direction of net groundwater flow, the river can be gaining when groundwater discharges into the river,
or losing when river recharges the aquifer (Winter et al., 1998) (Fig. 1a). Different directions of groundwater flow result in
substantially different flow fields (Fig. 1b and 1c). Large groundwater upwelling and downwelling may compress hyporheic
zone's spatial extent and reduce the hyporheic exchange flow rate. Nevertheless, most of the previous numerical modeling
40 studies about the impact of groundwater direction on hyporheic exchanges are either limited to steady hydrological conditions,
and/or a uniform groundwater flow conditions (Cardenas and Wilson, 2006, 2007b; Boano et al., 2008; Trauth et al., 2013;
Marzadri et al., 2016; Wu et al., 2018). Although there are recent field investigations on the role of transient groundwater table
fluctuations in hyporheic exchange processes (Malcolm et al., 2006; Ward et al., 2013; Zimmer and Lautz, 2014), they usually
lack a quantification of the impact of groundwater table dynamics on hyporheic exchange processes (Malzone et al., 2016).
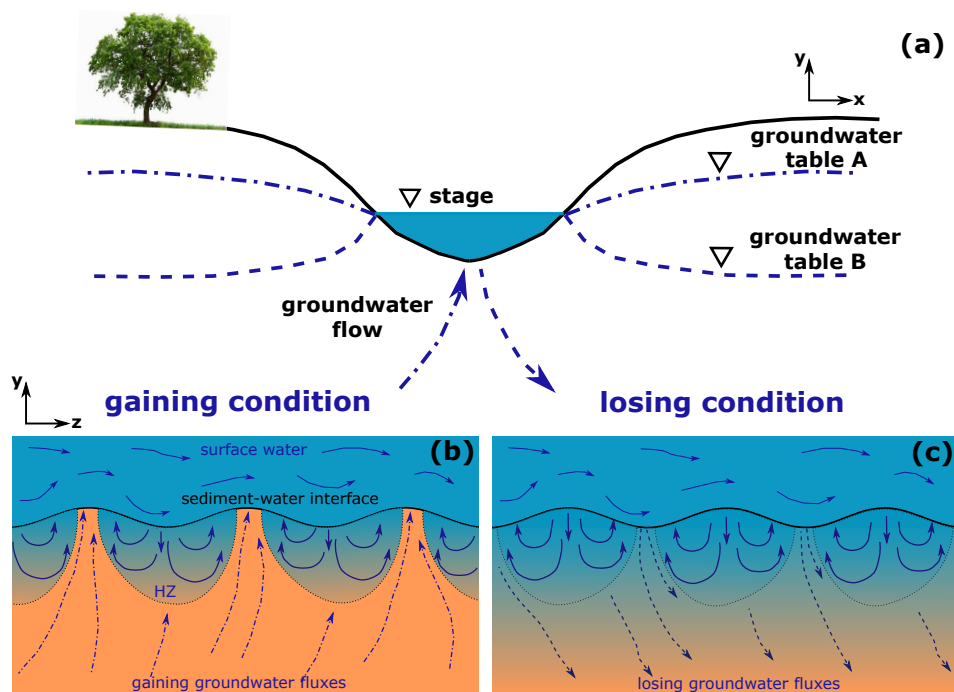
Figure 1. Schematic description of (a) gaining and losing groundwater systems and bedform-induced hyporheic exchanges under (b) gaining and (c) losing conditions. The river can be gaining when groundwater discharges into the river (scenario of groundwater table A), or losing when river recharges the aquifer (scenario of groundwater table B). Different directions of groundwater flow result in substantially different flow field, location and geometry of hyporheic zones.

45   Groundwater table fluctuations are observed across multiple temporal scales. On seasonal scales, rainfall and irrigation pumping following well-defined seasonal cycles cause groundwater table fluctuations; on daily scales, phreatophytes (long-rooted plants that take up water from the saturated zone) induced water-use and anthropogenic pumping activities are the main causes for groundwater table fluctuations; on event-scales, groundwater tables fluctuate in response to storm events (Todd and Mays, 2005; Butler Jr et al., 2007; Malzone et al., 2016). Both numerical modeling studies and field observation

50   indicate that groundwater table fluctuations have a significant control on the hydraulic gradient change at the sediment-water interfaces, which is the main driver of transient hyporheic responses (Malcolm et al., 2006; Voltz et al., 2013; Malzone et al., 2016). However, these studies are usually focused on seasonal and event-scale groundwater table fluctuations. The role of daily groundwater table fluctuations for hyporheic exchange processes requires more attention.

    The daily groundwater table fluctuation is of particular interest for understanding the transient hyporheic exchange not only

55   because it is ubiquitous due to evapotranspiration and pumping activities, but also because it induces additional daily hydraulic gradient changes besides the diel rhythm of hyporheic exchanges. Hyporheic exchanges often exhibit diel fluctuation pattern in response to diel river temperature fluctuations. This diel rhythm of hyporheic exchange results from the temperature-dependent

hydraulic conductivity that governs the flow transport in the sediment. Wu et al. (2020) observe that hyporheic exchange fluxes inherit the daily-scale spectral signatures from river temperature fluctuations, and noticeably, however, these signatures are absent in river discharge of the studied site. This observation evidently indicates a direct control of diel river temperature fluctuations on hyporheic exchange processes. Therefore, understanding the two players, namely daily groundwater hydraulic gradient change (as a result of daily groundwater table fluctuations) and diel hydraulic conductivity change (as a result of diel river temperature fluctuation), is important to characterize dynamic hyporheic exchange processes.

Groundwater level fluctuations in daily scales are often associated with activities that support important human needs, such as irrigation, residential and industrial water uses. Regulating reservoirs with enough storage capacities allow planning of pumping schedules independent of user demand (Reca et al., 2014). The selection of pumping regimes has a clear influence on the spreading and mixing of pollutants (Moore, 1999; Libera et al., 2017). Consequently, a poorly designed pumping regime is detrimental to the biological and ecological functioning of the fluvial systems (Bredehoeft and Kendy, 2008). Therefore, understanding the impact of daily groundwater withdrawal on hyporheic exchange processes is also beneficial for water management agencies to optimize pumping regimes, and thus minimize the environmental footprint of the withdrawal process.

In the present study, we aim to disentangle the interactions between impacts of groundwater withdrawal and river temperature on dynamic hyporheic exchange processes on daily scales. Hyporheic potential for denitrification and capacity for buffering thermal changes are explored. With these aims in mind, different groundwater scenarios corresponding to different timings of groundwater withdrawal under gaining and losing conditions are applied in a physically based hyporheic flow and heat transport model. Our findings for the first time provide insights into the dynamic hyporheic responses to impacts of daily groundwater withdrawal and river temperature fluctuations, allowing for a better mechanistic understanding on hyporheic exchange processes and hence an improved pumping operational scheme.

2 Methods

2.1 Model Domain

To explore the interactions among hyporheic exchange, river discharge, temperature and groundwater table fluctuations, a two-dimensional conceptualization is proposed based on Wu et al. (2018) and Wu et al. (2020) (Fig. 2a). The sediment is assumed homogeneous and isotropic with a sinusoidal sediment-water interface of wavelength λ and amplitude Δ, representing periodic bedforms. Bedforms are assumed stationary and fully saturated. Transport of flow and heat is simulated by using COMSOL Multiphysics with finite element method. The simulations are mesh-independent.
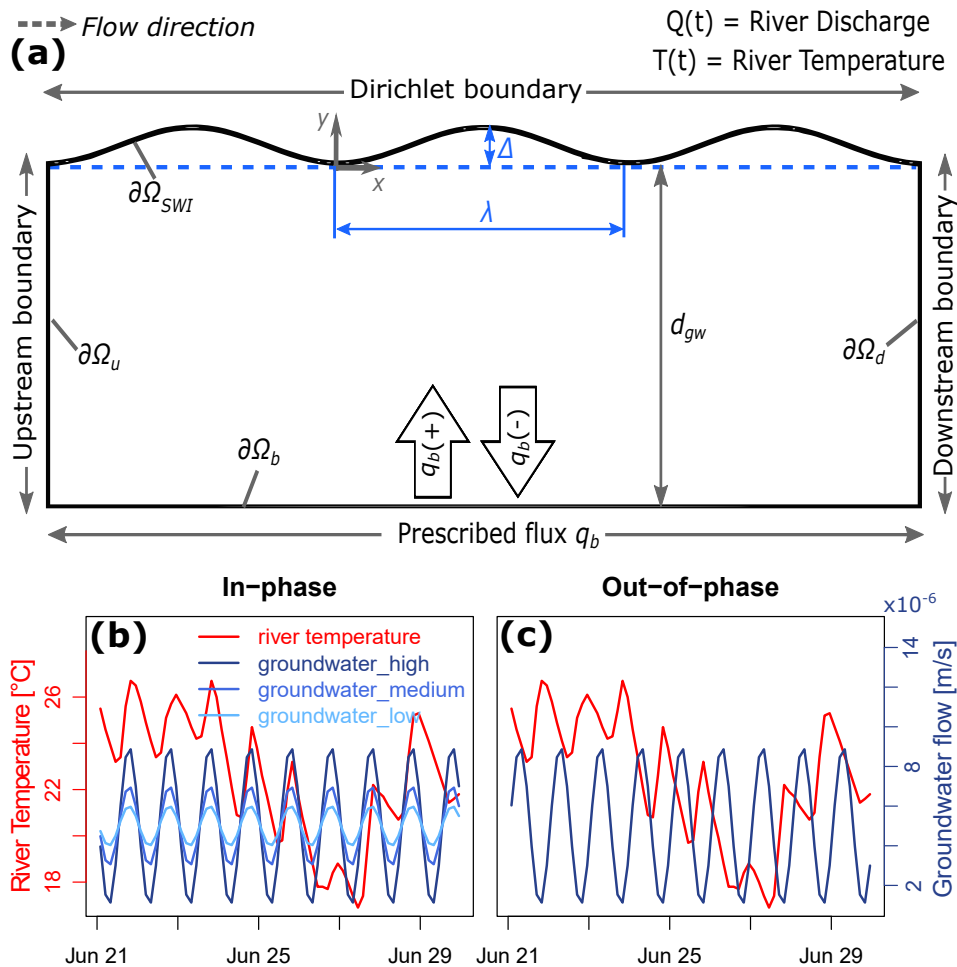
Figure 2. Model geometry and scenarios. (a) Schematic representation of the sediment domain. The top boundary is sinusoidal with amplitude Δ and wavelength λ. Lateral boundaries are periodic, representing an infinite domain in the longitudinal direction. Groundwater enters (gaining condition, $q_b(+)$) or leaves (losing condition, $q_b(-)$) the domain through the bottom boundary. (b) In-phase groundwater conditions with three amplitudes of groundwater level fluctuations. In-phase condition means that the strongest groundwater fluxes occur around the same time of the day as the highest river temperature. (c) Out-of-phase groundwater condition, i.e. strongest groundwater fluxes occur almost simultaneously to lowest river temperatures.

2.2 Model for Coupled Flow and Heat Transport

2.2.1 Model for Groundwater Flow

Groundwater flow is described using Darcy's law in a non-deformable porous media (Bear, 1972). The top boundary is a Dirichlet boundary. Lateral boundaries are periodic boundaries, representing an infinite domain in the longitudinal direction. The bottom boundary is either prescribed inflow for groundwater gaining condition ($q_b(+)$) or outflow for groundwater losing condition ($q_b(-)$).

$$\theta \frac{\partial \rho}{\partial t} = \nabla \cdot \left[\rho \frac{\kappa}{\mu} (\nabla p + \rho g \nabla h) \right] \tag{1a}$$

$$p(x, y = Z_{bed}(x), t) = \rho g \, h_{SWI}(x, t) \text{ for } \partial\Omega_{SWI} \tag{1b}$$

$$p(x = -\lambda, y, t) = p(x = 2\lambda, y, t) + \rho g [h_{SWI}(x = -\lambda, t) + h_{SWI}(x = 2\lambda, t)] \text{ for } \partial\Omega_u \text{ and } \partial\Omega_d \tag{1c}$$

$$\mathbf{n} \cdot \left[-\frac{\kappa}{\mu} (\nabla p + \rho g \nabla z) \right] = -q_b \text{ for } \partial\Omega_b \tag{1d}$$

where t is time [T], θ is porosity [-], $p(\mathbf{x}, t)$ is pressure [$ML^{-1}T^{-2}$], g is gravitational acceleration [LT^{-2}], κ is permeability [L^2], ρ is fluid density [ML^{-3}], μ is fluid dynamic viscosity [$ML^{-1}T^{-1}$], Darcy velocity is $\mathbf{q} = -\frac{\kappa}{\mu} (\nabla p + \rho g \nabla h))$ [LT^{-1}], $Z_{bed}(x) = (\Delta/2) \sin(2\pi x/\lambda)$ is the elevation of the water-sediment interface [L], $\mathbf{n}$ is an outward vector normal to the boundary [-], q_b is groundwater flux [LT^{-1}].

Prescribed head distributions are applied at the sediment-water interface (Wörman et al., 2006)

$$h_{SWI}(x, t) = H_s(t) - Z_{bed}(x) + \frac{2 \, h_d(t)}{\Delta} Z_{bed}\left(x + \frac{\lambda}{4}\right) \tag{2}$$

where $H_s(t)$ [L] is the transient river stage, and $h_d(t)$ is the dynamic head fluctuations (Fehlman, 1985; Elliott and Brooks, 1997)

$$h_d(t) = 0.28 \frac{U_s(t)^2}{2g} \begin{cases} \left(\dfrac{\Delta}{0.34 \, H_s(t)} \right)^{3/8} & \text{for } \dfrac{\Delta}{H_s(t)} \leqslant 0.34 \\[3mm] \left(\dfrac{\Delta}{0.34 \, H_s(t)} \right)^{3/2} & \text{for } \dfrac{\Delta}{H_s(t)} > 0.34 \end{cases} \tag{3}$$

with the mean velocity $U_s(t) = M^{-1} H_s(t)^{2/3} S^{1/2}$ estimated with the Chezy equation for a rectangular channel with slope S [-] and Manning coefficient M [$L^{-1/3}T$] (Dingman, 2009).

In the present study, an aspect ratio (the ratio between amplitude and wavelength Δ/λ) of 0.1 and slope of 0.01 are used to describe the geomorphological setting. A Manning coefficient of 0.05 is chosen. Although this two-dimensional conceptualization is simple in nature, it allows us to capture the hydrodynamic effects on hyporheic exchange based on empirical

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approaches. A comprehensive discussion on the effect of local morphology (i.e., aspect ratios), channel slope, and sediment heterogeneity on the transient hydraulic pressure propagation within hyporheic zones can be found in Wu et al. (2018).

105 ### 2.2.2 Model for Heat Transport

Transport of heat in porous media is described by using the heat transport equation (Bejan, 1993; Nield and Bejan, 2013)

$$\frac{\partial T}{\partial t} = \nabla \cdot (\mathbf{D_T} \nabla T) - \nabla \cdot (\mathbf{v_T} T) \tag{4a}$$

$$T(x,t) = T_s \text{ for } \partial\Omega_{in,SWI} \tag{4b}$$

$$\mathbf{n} \cdot (\mathbf{D_T}\nabla T) = 0 \text{ for } \partial\Omega_{out,SWI} \tag{4c}$$

$$T(x=-L,y) = T(x=2L,y) \text{ for } \partial\Omega_u \text{ and } \partial\Omega_d \tag{4d}$$

$$T(x,t) = T_b \text{ for } \partial\Omega_b \text{ under gaining condition} \tag{4e}$$

$$\mathbf{n} \cdot (\mathbf{D_T}\nabla T) = 0 \text{ for } \partial\Omega_b \text{ under losing condition} \tag{4f}$$

where T is temperature [Θ], $\mathbf{v_T} = (\rho_f c_f)/(\rho c)\mathbf{q}$ is the thermal front velocity [LT^{-1}], $\mathbf{D_T}$ is the hydrodynamic thermal dispersion tensor [L^2T^{-1}], and $\rho c = \theta \rho_f c_f + (1-\theta) \rho_s c_s$, is the specific volumetric heat capacity of the fluid-grains media [$ML^{-1}T^{-2}\Theta^{-1}$], $\rho_f c_f$ is the specific volumetric heat capacity of the fluid [$ML^{-1}T^{-2}\Theta^{-1}$], and $\rho_s c_s$ is the specific volumetric

110 heat capacity of the solids [$ML^{-1}T^{-2}\Theta^{-1}$], T_s is the temperature of the water column [Θ], which is the measured river temperature time series. $\partial\Omega_{in,SWI}$ and $\partial\Omega_{out,SWI}$ represent the boundaries where surface water flows into and out of the sediment at the sediment-water interface, respectively. A mixed Dirichlet and Neumann boundary is used for heat transport along the sediment-water interface. Temperature at the bottom boundary is prescribed under gaining conditions. In this case, seasonal variations in groundwater temperature (T_b) are assumed sinusoidal with the mean of 10 °C and the amplitude of 3 °C.

115 T_b is higher than T_s in winter and lower than T_s in summer. Under losing conditions, the bottom boundary is represented by a pure convection of heat boundary.

2.2.3 Coupling Groundwater Flow and Heat Transport

Transport of flow and heat in porous media is coupled by the equations of state for density and viscosity (Furbish, 1996)

$$\mu(T) = m_5 T^5 + m_4 T^4 + m_3 T^3 + m_2 T^2 + m_1 T + m_0 \tag{5a}$$

$$\rho(T) = \rho_0 - \rho_0 \alpha (T - T_0) \tag{5b}$$

where viscosity is in Pa·s, temperature is in °C and $m_5 = -3.916 \times 10^{-13}$, $m_4 = 1.300 \times 10^{-10}$, $m_3 = -1.756 \times 10^{-8}$, $m_2 =$

120 1.286×10^{-6}, $m_1 = -5.895 \times 10^{-5}$, and $m_0 = 1.786 \times 10^{-3}$. The reference density and temperature are $\rho_0 = 1000 \text{ kg/m}^3$ and $T_0 = 20$ °C, respectively, and the thermal expansion coefficient is $\alpha = 2.067 \times 10^{-4}$ °C^{-1}.

2.3 Model for Mean Residence Time

We use the mean residence time to describe the time that water is exposed to biogeochemical reactive sediments (Gomez and Wilson, 2013)

$$\theta \frac{\partial a_1}{\partial t} = \nabla \cdot (\mathbf{D}\nabla a_1) - \nabla \cdot (\mathbf{q}a_1) + \theta a_0 \tag{6a}$$

$$a_1(\mathbf{x},t) = 0 \quad \text{for } \partial\Omega_{in,SWI} \tag{6b}$$

$$\mathbf{n} \cdot (\mathbf{D}\nabla a_1) = 0 \quad \text{for } \partial\Omega_{out,SWI} \tag{6c}$$

$$a_1(x_u,y,t) = a_1(x_d,y,t) \text{ for } \partial\Omega_u \text{ and } \partial\Omega_d \tag{6d}$$

$$a_1(\mathbf{x},t) = a_{1b} \quad \text{on } \partial\Omega_b \text{ under gaining condition} \tag{6e}$$

$$\mathbf{n} \cdot (\mathbf{D}\nabla a_1) = 0 \quad \text{on } \partial\Omega_b \text{ under losing condition} \tag{6f}$$

125 where $a_1(\mathbf{x},t)$ is the mean of the residence time distribution [T], t is time [T], $\mathbf{x} = (x,y)$ is the spatial location vector, $\mathbf{q}$ is the Darcy flux [LT^{-1}], and $\mathbf{D}$ is the dispersion-diffusion tensor defined by (Bear, 1972), a_{1b} is the mean residence time of the groundwater fluid [T^{-1}]. a_{1b} is prescribed, similar to Gomez-Velez et al. (2014), and a value of 10 years is assumed based on Mcguire and Mcdonnell (2006).

2.4 Defining Hyporheic Zones

130 In the present study, the hyporheic zone is defined as the sediment area containing at least 90% of the surface water (Triska et al., 1989; Gooseff, 2010). Numerical tracer is simulated with advection-dispersion equation to define the boundary of hyporheic zones

$$\theta \frac{\partial C}{\partial t} = \nabla \cdot (\mathbf{D}\nabla C) - \nabla \cdot (\mathbf{q}C) \tag{7}$$

where C is the concentration of the non-reactive tracer[ML^{-3}], $\mathbf{q}$ is the Darcy flux [LT^{-1}], and $\mathbf{D} = \{D_{ij}\}$ is the dispersion-
135 diffusion tensor defined as Bear (1972). The concentration of tracer in the surface water column is assumed as C_s. Therefore, the hyporheic zone is defined when $C \geq 0.9C_s$ in the sediment.

2.5 Study Scenarios

To better focus on the effect of river temperature and groundwater table dynamics on hyporheic exchange, we use the observed river discharge and temperature measurements from USGS gauging station (ID: 06893970). Spectral analysis, presented
140 in a previous study, shows that river temperature of this site has a clear daily fluctuation pattern; whereas the river discharge exhibits no daily fluctuations (the "reference site" in Fig. 5 presented in Wu et al. (2020)). Therefore, this site is an ideal site to explore the interactions of groundwater table dynamics and river temperature fluctuations in daily scale without the additional influence of daily river stage changes.

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Daily groundwater table drawdown due to phreatophytes induced water-uptake mainly takes place in the afternoon when transpiration processes are strongest due to high air and river temperature; while agricultural, residential or industrial water-supply may cause water table drawdown at any time during the day. Since the objective of the present study is to explore the impacts of daily groundwater table drawdowns and diel river temperature fluctuations, the study focuses on two special cases: *in-phase* and *out-of-phase* conditions. In the in-phase condition, the highest hydraulic gradient between surface water and groundwater table (also means strongest groundwater flux) occurs around the same time of the day as the occurrence of the highest river temperature; in the out-of-phase condition, the highest hydraulic gradient between surface water and groundwater (also means strongest groundwater flux) occurs around the same time of the day as the occurrence of the lowest river temperature (Fig. 2b and 2c). Even though the timing of groundwater table drawdown depends on multiple factors, i.e. hydrological conditions and aquifer properties for plant water-use; pumping capacity and electricity tariff for anthropocentric pumping activities, the two special cases, namely in-phase and out-of-phase groundwater conditions, can capture the representative dynamic hyporheic responses to different timing of daily groundwater withdrawal under corresponding river temperature conditions.

Groundwater flow fluctuations, as a response to daily groundwater table drawdown, are conceptualized as sinusoidal curves with varying amplitudes and phases. Different phases reflect different timing of daily groundwater withdrawal, represented by the in-phase and out-of-phase groundwater flow conditions as described above. Different amplitudes represent different intensities of groundwater table drawdowns. For gaining system, three degrees of groundwater table fluctuation amplitudes are investigated. The highest fluctuation amplitude is two times higher than the scenario with medium amplitude, and four times higher than the scenario with low amplitude. With the highest amplitude, the daily groundwater table drawdown is $2mm$ in the aquifer adjacent to the river for gaining condition (calculation based on Boano et al. (2008)). This value is within a reasonable range for groundwater table fluctuations induced by plant water-use (Butler Jr et al., 2007). For simplicity, the same values of groundwater fluxes are also applied to losing systems.

No matter for plant's water-uptakes or anthropogenic activities (i.e., irrigation, municipal, or industrial water-supply), seasonal variations of groundwater fluxes cannot be neglected. For instance, a gradual transition of phreatophyte's dormancy in fall often induces a progressive diminishing in diurnal fluctuations and changes in the multi-day trend in groundwater tables (Butler Jr et al., 2007). Irrigation activities also follow the different seasonal water demand of agricultural plants. However, these seasonal changes are hard to generalize because groundwater flux variability depends on a variety of factors such as plant types, water availability and local climate conditions. Understanding the effect of seasonal groundwater variability is beyond the scope of the present study. Therefore, uniform fluctuation amplitude of groundwater fluxes in the studied period is used.

3 Results

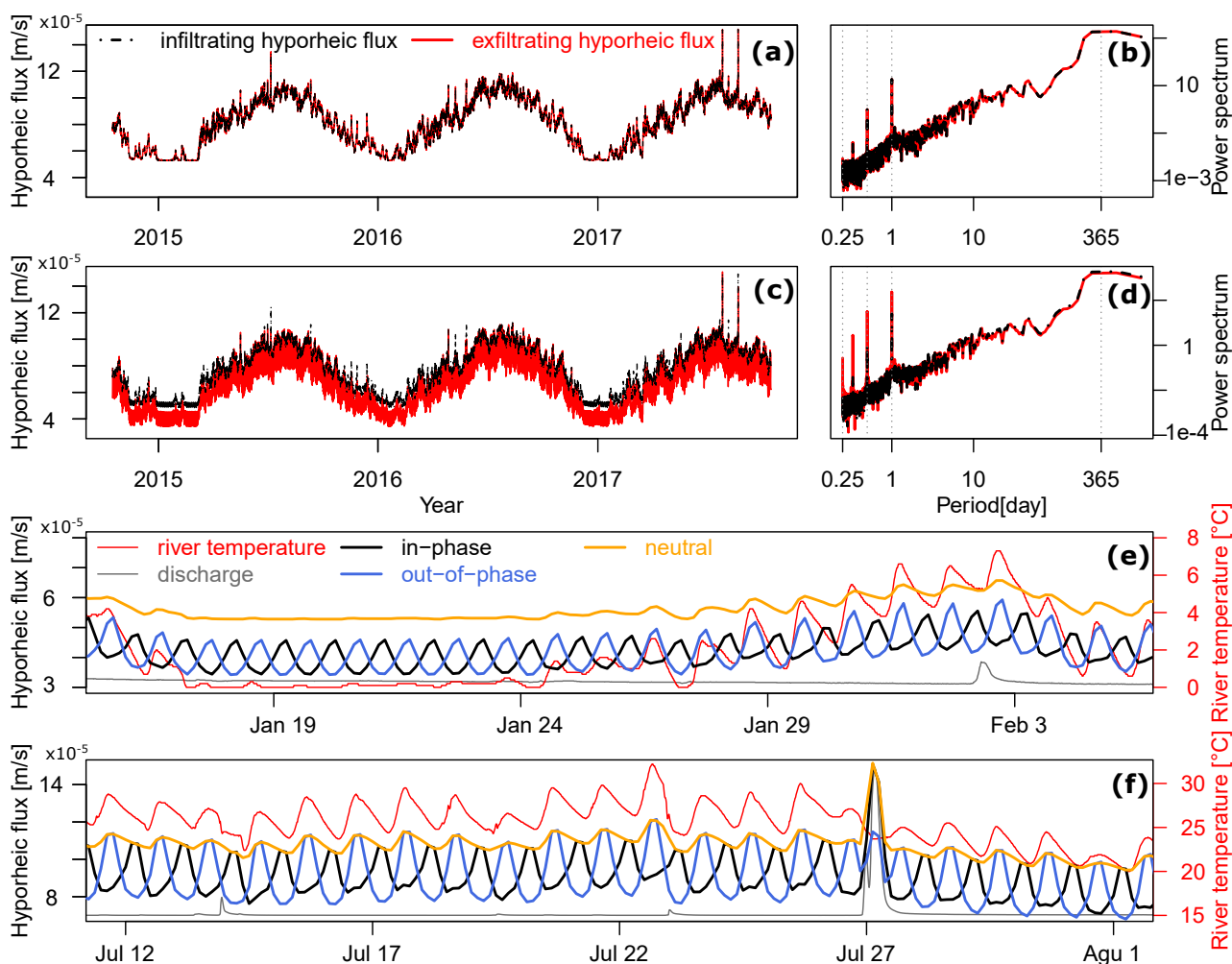### 3.1 Hyporheic Fluxes

3.1.1 under Gaining Conditions

175   Compared to neutral condition, groundwater upwelling increases the daily fluctuations of exfiltrating hyporheic fluxes. Under neutral condition, exfiltrating hyporheic fluxes (the red solid line in Fig. 3a) present similar temporal variations as infiltrating hyporheic fluxes (the black dotdash line in Fig. 3a). Under gaining condition, exfiltrating hyporheic fluxes (the red solid line in Fig. 3c) present larger daily amplitude variations than infiltrating hyporheic fluxes (the black dotdash line in Fig. 3c). These observations are reflected in the frequency domain using power spectrum. For neutral conditions, infiltrating and exfiltrating

180   hyporheic fluxes show similar spectral power on both annual and daily scales (Fig. 3b); whereas for gaining conditions, the spectral power of exfiltrating hyporheic fluxes (the red solid line in Fig. 3d) at daily scales are markedly higher than the spectral power of infiltrating hyporheic fluxes (the black dotdash line in Fig. 3d).

Under neutral conditions, the diel fluctuations of exfiltrating hyporheic fluxes (the orange solid line in Fig. 3e and 3f) follow the diel river temperature fluctuations (the red solid line in Fig. 3e and 3f). In winter, when the river temperature (the red solid

185   line in Fig. 3e) is relatively stable (around Jan 20), the exfiltrating hyporheic fluxes also have negligible daily fluctuations; when temperature gets higher, the exfiltrating hyporheic fluxes start to fluctuate following the diel fluctuations of river temperature.

However, with gaining groundwater fluxes, the fluctuation pattern of hyporheic fluxes changes substantially. Even with negligible diel fluctuations of river temperature (around Jan 20), the exfiltrating hyporheic fluxes still present clear daily fluctuations following the groundwater drawdown as indicated by the opposite fluctuating patterns between the exfiltrating hyporheic

190   fluxes under in-phase (the black line in Fig. 3e and 3f) and out-of-phase (the blue line in Fig. 3e and 3f) groundwater scenarios. When temperature gets higher, the groundwater table-drawdown induced hyporheic fluctuations are maintained. The exfiltrating hyporheic fluxes under in-phase scenario have an opposite fluctuation pattern with the exfiltrating hyporheic fluxes under out-of-phase scenario, river temperature and the exfiltrating hyporheic fluxes under neutral condition; the exfiltrating hyporheic fluxes under the out-of-phase scenario fluctuate following river temperature. It's worth noticing that the peaks of exfiltrating

195   hyporheic fluxes under out-of-phase scenario are slightly higher than the peaks of exfiltrating hyporheic fluxes under in-phase scenario at a warm temperature (Fig. 3f).

On Jul 27, under the same flood event, which causes a discharge increase from 2 to 1500 m^3/s (the gray solid line in Fig. 3f), exfiltrating hyporheic fluxes increase much more under in-phase scenario (the black solid line) than under out-of-phase scenario (the blue solid line). The increase of exfiltrating hyporheic fluxes under in-phase scenario is nearly two times as high

200   as the increase of hyporheic fluxes under out-of-phase scenario.

To explore the impact of groundwater table fluctuation amplitudes on dynamic hyporheic responses, groundwater table fluctuations with three different amplitudes are applied to simulate hyporheic exchange processes under in-phase scenarios

Figure 3. Effect of diel river temperature fluctuations and daily groundwater table drawdowns on hyporheic fluxes under gaining condition. Infiltrating and exfiltrating hyporheic fluxes under (a) neutral and (c) gaining conditions. Power spectrum of infiltrating and exfiltrating hyporheic fluxes under (b) neutral and (d) gaining conditions. Exfiltrating hyporheic fluxes under neutral conditions and under gaining conditions with in-phase and out-of-phase groundwater drawdown scenarios in (e) winter and (f) summer. For figure clarity, discharge is not labeled in e and f. The flood event on Jul 27 causes a discharge increase from 2 to 1500 m^3/s

(as the groundwater scenarios plotted in Fig. 2b). With the reduced groundwater upwelling amplitudes, the amplitudes of exfiltrating hyporheic flux fluctuations are also reduced (Fig. 4a). More than the amplitude reduction of exfiltrating hyporheic

205   fluxes, with decreasing groundwater upwelling amplitude, the peaks of exfiltrating hyporheic fluxes (the black dash line, blue solid line and red solid line in Fig. 4b) are shifted towards the patterns which are more coinciding with diel river temperature fluctuations (the dash line in Fig. 4b) and hyporheic fluxes under neutral conditions (gray solid line). In other words, with decreasing groundwater table fluctuation amplitude, river temperatures exhibit stronger controls on the phase of hyporheic flux diel fluctuations.

210   Effects of groundwater table fluctuation amplitudes on dynamic hyporheic responses are only explored under in-phase scenarios, because under out-of-phase scenarios, fluctuations of exfiltrating hyporheic fluxes are almost always in the same phase with the diel river temperature fluctuations. Therefore, unlike in-phase scenarios, the phase shifts due to reduced amplitudes in groundwater table fluctuation are not observed. Reduced amplitudes in groundwater table fluctuation under out-of-phase scenarios only contribute to reduced amplitudes in exfiltrating hyporheic flux fluctuations. For simplicity, only results in in-phase

215   scenarios are presented.

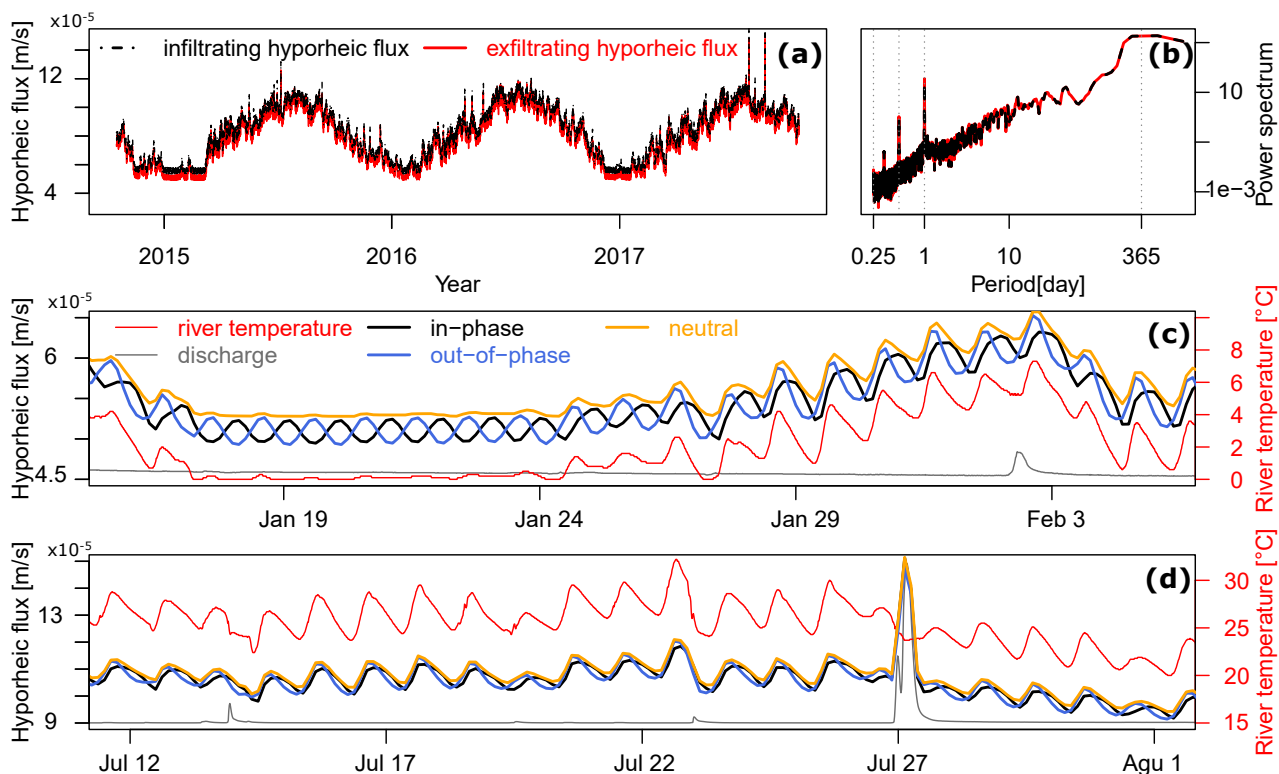### 3.1.2   under Losing Conditions

Differing from the gaining conditions, under losing conditions, the fluctuation amplitudes of exfiltrating hyporheic fluxes have not substantially increased compared with infiltrating hyporheic fluxes (Fig. 5a). This is also revealed in the frequency domain where the spectral power is similar between infiltrating and exfiltrating hyporheic fluxes across all temporal scales

220   (Fig. 5b).

The river temperature also demonstrates different impacts under losing conditions. In winter, when the river temperature (the red solid line in Fig. 5c) is relatively stable (around Jan 20), the exfiltrating hyporheic fluxes under in-phase and out-of-phase groundwater drawdown conditions exhibit an opposite fluctuation pattern resulting from the different timing of groundwater table drawdown (black and blue solid lines). This observation is the same with gaining conditions (Fig. 3e). However, when

225   the river temperature gradually increases, the phase differences between the diel fluctuations of exfiltrating hyporheic fluxes under in-phase and out-of-phase scenarios are diminishing. In summer, when river temperature is relatively high, exfiltrating hyporheic fluxes under in-phase and out-of-phase conditions are fluctuating with almost the same phase with the river temperature (Fig. 5d). This observation is in great contrast to the gaining condition where the opposite fluctuation patterns between exfiltrating hyporheic fluxes under in-phase and out-of-phase conditions are kept from winter to summer (Fig. 3f).

230   Unlike gaining conditions, on Jul 27 under the same flood event (the gray solid line in Fig. 5d), the increases of exfiltrating hyporheic fluxes under in-phase and out-of-phase scenarios are similar. These distinctions indicate a vastly different coupled flow and heat transport pattern between gaining and losing systems.
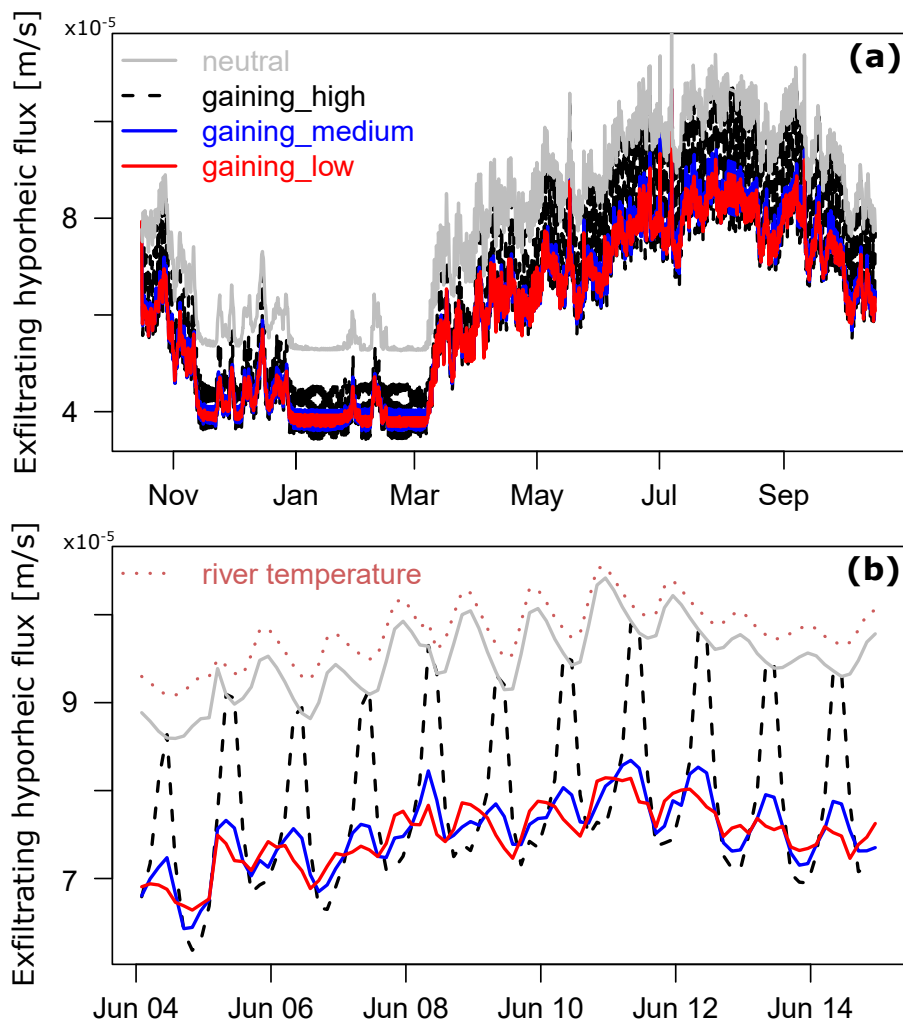
Figure 4. Effect of amplitudes in groundwater level fluctuations on hyporheic fluxes. (a) Exfiltrating hyporheic fluxes under neutral and gaining groundwater fluxes with three different amplitudes. (b) Comparisons of daily fluctuation phases among river temperature and exfiltrating hyporheic fluxes under neutral and gaining groundwater fluxes with three different amplitudes.

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Figure 5. Effect of diel river temperature fluctuations and daily groundwater table drawdowns on hyporheic fluxes under losing condition. (a) Infiltrating and exfiltrating hyporheic fluxes under losing conditions and (b) corresponding power spectrum. Exfiltrating hyporheic fluxes under neutral conditions and under losing conditions with in-phase and out-of-phase groundwater drawdown scenarios in (c) winter and (d) summer. For figure clarity, discharge is not labeled in c and d. The flood event on Jul 27 causes a discharge increase from 2 to 1500 m^3/s

3.2 Heat Transport in Hyporheic Zones

Snapshots of temperature distributions in the sediment demonstrate noticeable differences of the heat transport under differ-
235 ent groundwater conditions (Fig. 6). Under gaining conditions, both river and groundwater temperature play important roles
in determining the temperature of the sediment; whereas under losing conditions, only the river temperature affects the tem-
perature distributions in the sediment. At the moment of the snapshots (2017-07-22 17:00), the river temperature peaks, the
groundwater fluxes of in-phase scenarios also peak; while the groundwater fluxes of out-of-phase scenarios are around the
daily trough. Consequently, with the reduced upwards-directed groundwater gradient, more surface water penetrate into the
240 sediment under gaining out-of-phase scenarios than under gaining in-phase scenarios. Therefore, areas affected by warm sur-
face water are larger under gaining out-of-phase condition than under gaining in-phase conditions (Fig. 6a and 6b). Under
losing conditions, the differences of temperature distributions between in-phase and out-of-phase scenarios are not as clear as
under gaining conditions (Fig. 6c and 6d).

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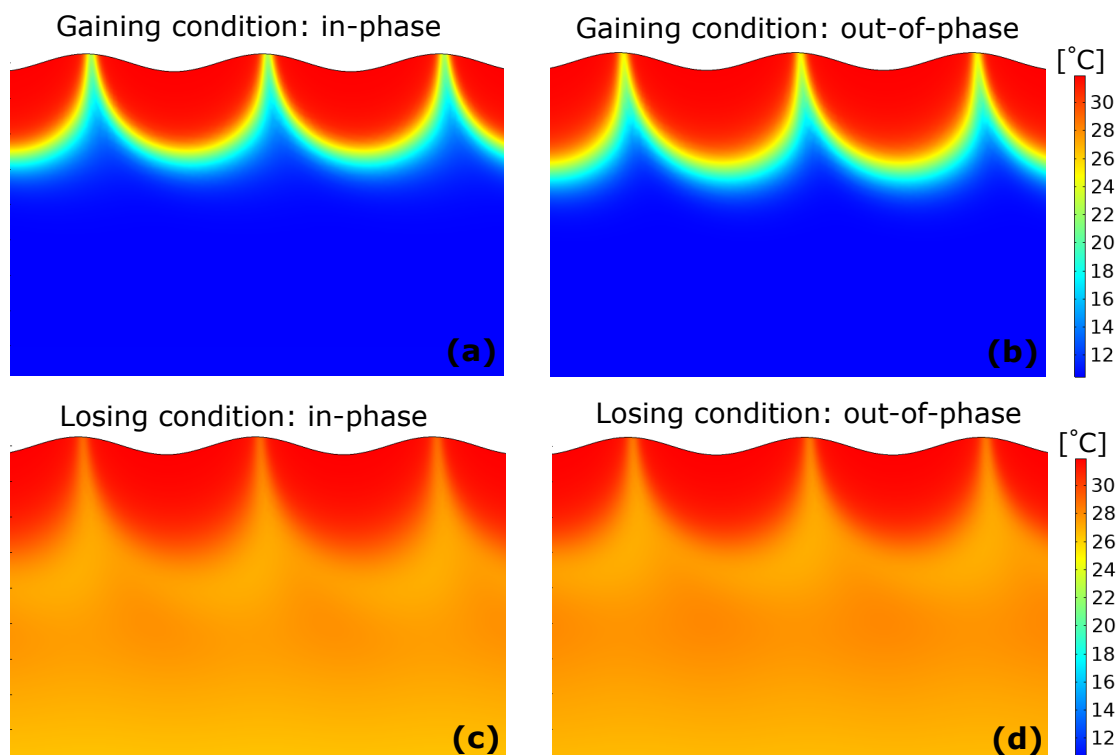
Figure 6. Snapshots of 2D-temperature distributions in the sediment on 2017-07-22 17:00 for different scenarios, i.e. (a,b) gaining and (c,d) losing, (a,c) in-phase and (b,d) out-of-phase fluctuations of diel river temperature and daily groundwater table drawdown.

Temperature differences between river and exfiltrating hyporheic fluxes are explored for both gaining and losing, in-phase and out-of-phase conditions (Fig.7). Positive values indicate a higher river temperature than the temperature of exfiltrating hyporheic fluxes; negative values indicate a higher temperature of exfiltrating hyporheic fluxes. Under gaining conditions, seasonal variations are observed for both in-phase and out-of-phase conditions. In winter, the exfiltrating hyporheic fluxes are generally warmer than the river; in summer, the river is generally warmer than the exfiltrating hyporheic fluxes. These seasonal variations are more prominent under out-of-phase conditions (the gray solid line in Fig. 7a) than under in-phase conditions (the blue dashed line in Fig. 7a). In summer, the exfiltrating hyporheic fluxes under out-of-phase conditions are much cooler than river water compared to the in-phase conditions. Under losing conditions, the differences between in-phase and out-of-phase conditions are not as significant as under gaining conditions (Fig. 7b).

3.3 Reaction Significance Factor

Denitrification potential in hyporheic zones can be quantified using the reaction significance factor (RSF). The RSF is calculated as the ratio between hyporheic mean residence time and a characteristic time scale for denitrification, and then
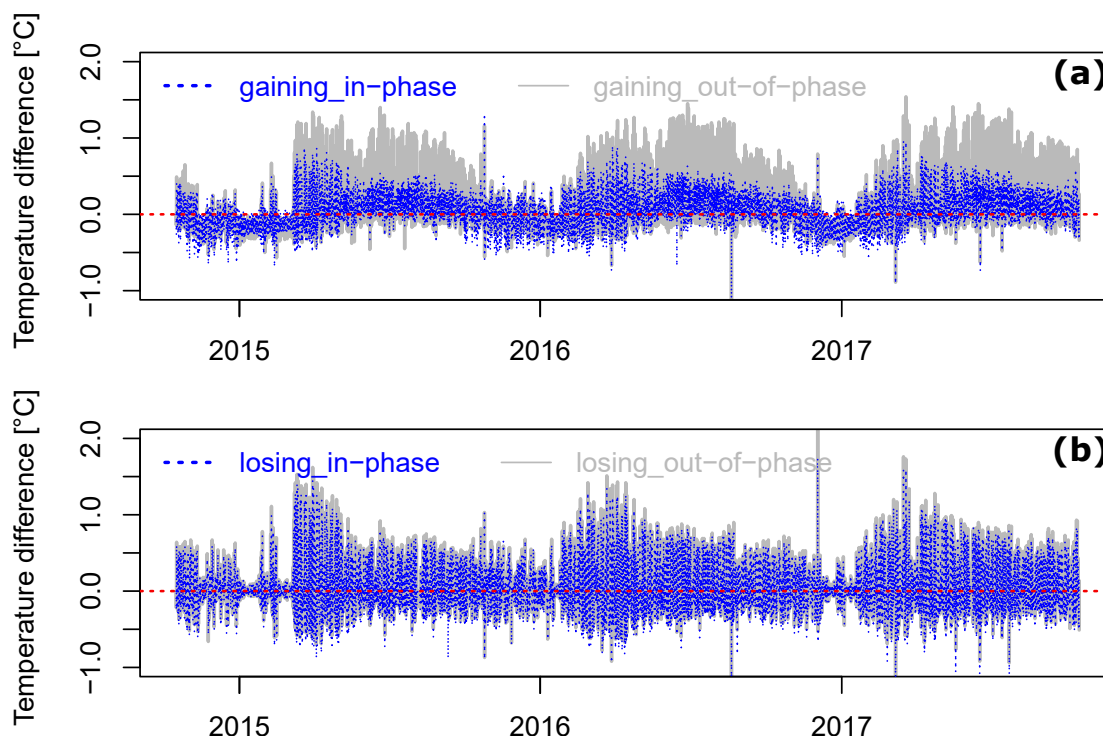
Figure 7. Temperature differences between river and exfiltrating hyporheic fluxes under (a) gaining and (b) losing in-phase and out-of-phase fluctuations of diel river temperature and daily groundwater table drawdown.

scaled by the proportion of the river discharge passing the hyporheic zone (Harvey et al., 2013). In the present study, we use the RSF calculated as the value per unit bedform area (denoted by the subscript "a")

$$\text{RSF}_a = \frac{q_{HZ}}{Q} \cdot \frac{\tau_{HZ}}{\tau_{dn}} \tag{8}$$

where q_{HZ} is the exfiltrating hyporheic fluxes [LT^{-1}], Q is the river discharge [L^{3}T^{-1}], τ_{HZ} is the hyporheic zone mean residence time [T], τ_{dn} is the characteristic time scale for denitrification [T]. Typical time scales of denitrification in hyporheic

260 zones are reported by Gomez-Velez and Harvey (2014); Gomez-Velez et al. (2015) and the quantiles are used in the calculation.

Under gaining conditions, RSF$_a$ displays opposite diel variations between in-phase and out-of-phase scenarios. Significant drops occur during flood events. Under losing conditions, RSF$_a$ is around 3.5 orders of magnitude lower than under gaining conditions. Daily-scale variations between in-phase and out-of-phase scenarios under losing conditions are less significant than under gaining conditions.
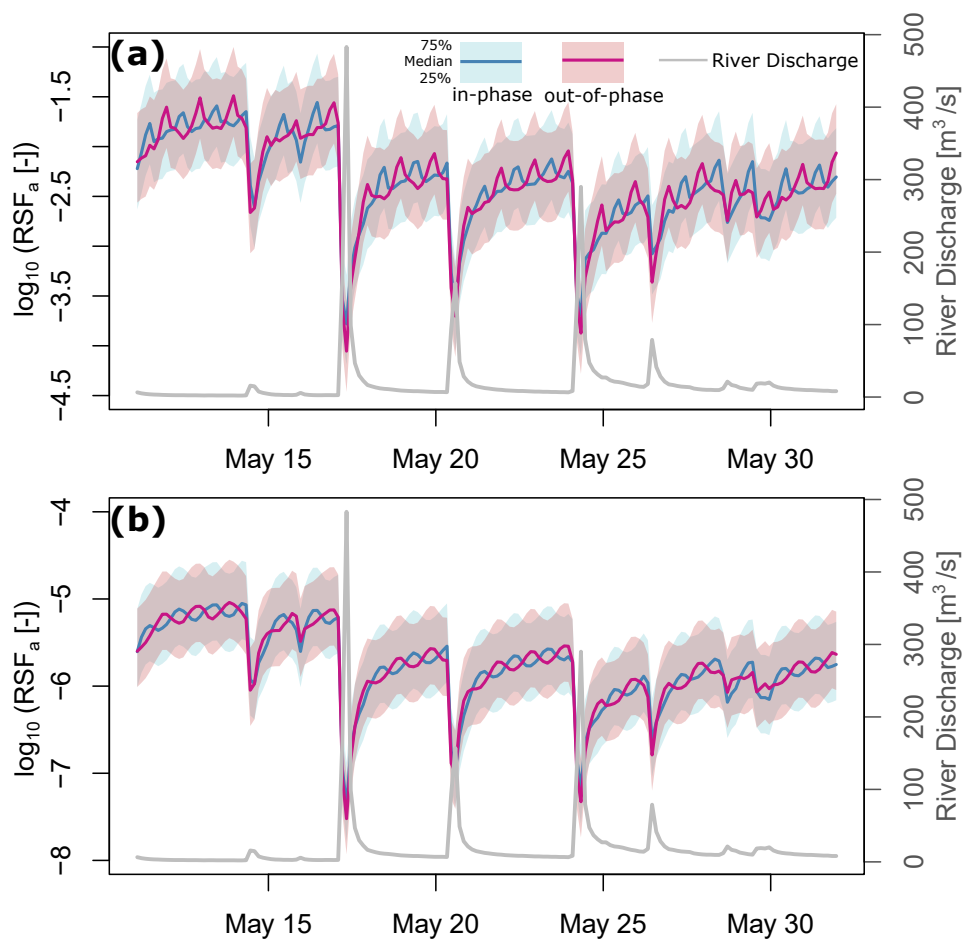
Figure 8. Reaction significance factors per unit area (RSF_a) for denitrification potentials. (a) RSF_a under gaining condition. (b) RSF_a under losing condition.

4   Discussion

4.1   Groundwater Modifies the Variability of Hyporheic Exchange Rates

With daily groundwater table drawdowns, additional hydraulic gradient changes in a daily scale contribute to enhanced diel fluctuations of exfiltrating hyporheic fluxes. Under neutral condition, similar diel fluctuations patterns in both infiltrating and exfiltrating hyporheic fluxes (Fig. 3a and 3b) are mainly due to the change of hydraulic conductivity which is a function of the diel temperature fluctuations. Differing from the neutral conditions, daily groundwater table fluctuations induce additional hydraulic gradients on daily scales, which result in higher daily fluctuation amplitudes of exfiltrating hyporheic fluxes than infiltrating hyporheic fluxes (Fig. 3c, 3d, 5a, and 5b).

17

The timing of groundwater table drawdown also affects hyporheic exchange rates. For instance, under the same flood event on July 27 (the gray solid line in Fig. 3f), the exfiltrating hyporheic flux under in-phase gaining conditions (the black solid

275   line) increases more than the exfiltrating hyporheic flux under out-of-phase conditions (the blue solid line). This is because the groundwater gaining flux under in-phase scenario is lowest in the course of the day when the flood arrives; whereas it is highest under out-of-phase scenario. As a result of higher groundwater upward pressure, higher groundwater upwelling flow under out-of-phase scenario compresses the hyporheic zone extension during the flood event. Consequently, exfiltrating hyporheic fluxes under in-phase conditions increase twice as much as exfiltrating hyporheic fluxes under out-of-phase conditions. In contrast,

280   the differences of exfiltrating hyporheic fluxes between in-phase and out-of-phase scenarios are marginal in response to the same flood event under losing conditions (Fig. 5d). Reasons will be explored in the following section.

This observation has potential implications on optimizing aquifer pumping schedule. Hypothetically, if the rising discharge is from an untreated wastewater discharge source, the timing of the groundwater table drawdown will significantly affect the spreading and mixing of pollutants in the sediment. At the moment of flood events, more pollutants will be carried into the

285   sediment with a higher hyporheic exchange rate under a relatively low upwards-directed pressure of the groundwater than under a relatively high upwards-directed pressure. Therefore, the timing of the aquifer pumping can potentially amplify or reduce the dispersal of pollutants in the aquifer.

4.2   Different Impacts of Groundwater on Hyporheic Exchange Under Gaining and Losing Systems

The timing of groundwater table drawdown has substantially different impacts on hyporheic exchange processes under gain-

290   ing and losing conditions in different seasons. More specifically, under gaining conditions, the opposite phases of groundwater table fluctuations in in-phase and out-of-phase conditions induce an opposite fluctuation pattern of exfiltrating hyporheic fluxes in both winter and summer (the black and blue solid lines in Fig. 3e and 3f). However, under losing conditions the opposite fluctuation patterns of exfiltrating hyporheic fluxes under in-phase and out-of-phase conditions gradually disappear with increasing river temperatures from winter to summer (the black and blue solid lines in Fig. 5c and 5d). Differing from gaining

295   conditions, under losing conditions, exfiltrating hyporheic fluxes in both in-phase and out-of-phase scenarios present an almost synchronized fluctuation pattern following the diel river temperature fluctuations in summer. These results indicate that under losing conditions, even though both river temperature and timing of groundwater table drawdown affect the phase of exfiltrating hyporheic flux fluctuations in winter when river temperatures are relatively low, river temperature, however, plays a more dominant role in determining the phase of the hyporheic flux fluctuations in summer when river temperatures are relatively

300   high.

To better understand the causes of different hyporheic responses under gaining and losing conditions in relatively high river temperatures (i.e. in summer), snapshots of sediment temperature distributions on a summer afternoon are presented (Fig. 6). Under gaining conditions, areas affected by the river temperature are closely dependent on the hyporheic exchange processes (Fig. 6a and 6b). When hyporheic exchange rate is low, the river temperature has a negligible effect on the sediment hydraulic

305   conductivity because the heat advection of upwelling groundwater is dominant. When hyporheic exchange rates are relatively

high, hyporheic zones will extend deeper and wider in the sediment and river bank (Gomez-Velez et al., 2017; Wu et al., 2018). As a consequence, river temperature will have a larger impact on the sediment hydraulic conductivity. Under losing conditions, however, the sediment hydraulic conductivity is predominantly affected by the surface water heat advection and conduction (Fig. 6c and 6d).

310   With the temperature variation approximately from 0 °C to 30 °C, viscosity decreases by 45% and hydraulic conductivity increases by 220% (Wu et al., 2020). Therefore, in summer when river temperature is relatively high, the hydraulic conductivity is enhanced and becomes the main modulator for hyporheic exchange rate under losing condition. Compared with hydraulic conductivity, the effect of daily fluctuations of groundwater gradients becomes less important in determining the variability of hyporheic exchange processes. Therefore, the differences of exfiltrating hyporheic fluxes between in-phase and out-of-phase
315   losing conditions disappear in summer.

This also explains the different effects of the timing of groundwater table drawdowns during the same flood event on Jul 27 under gaining (Fig. 3f) and losing conditions (Fig. 5d). Unlike gaining conditions, under losing condition, the differences between flood-induced increases of exfiltrating hyporheic fluxes in in-phase and out-of-phase scenarios are negligible, because river temperatures have a more dominant role in determining the variability of hyporheic exchange fluxes under losing systems.

320   It is noteworthy that when river temperature is relatively high, the exfiltrating hyporheic fluxes under out-of-phase gaining condition fluctuate with a higher amplitude (Fig. 3f). This is because under gaining out-of-phase scenario, a lower groundwater table (also means lower groundwater upwelling fluxes) occurs in the afternoon when river temperature is relatively high. Both a low groundwater upward gradient and a high river temperature promote hyporheic exchange. Consequently, the exfiltrating hyporheic fluxes fluctuate with a higher amplitude under out-of-phase gaining conditions than under in-phase conditions.

325   When gradually reducing the groundwater fluctuation amplitudes, the crests of exfiltrating hyporheic fluxes under in-phase gaining groundwater scenario shift from the timing of river temperature troughs to river temperature peaks (Fig. 4b). This is another clear evidence that both diel river temperatures and groundwater daily fluctuations regulate the phases and amplitudes of hyporheic exchange fluxes: when the groundwater fluxes are small, the diel rhythm of hyporheic flux fluctuations is following the diel fluctuations of river temperature; whereas when the groundwater fluxes increase, the diel rhythm of hyporheic flux
330   fluctuations is following the timing of groundwater level daily drawdown.

4.3   Groundwater Modifies Hyporheic Buffering Effects on Temperature

Temperature differences between river and exfiltrating hyporheic fluxes also demonstrate distinct patterns between gaining and losing, in-phase and out-of-phase conditions. Under gaining conditions, the temperature differences display negative values in winter periods and positive values in summer periods due to the mixing between surface water and groundwater (Fig. 7a).
335   In winter, the groundwater is often warmer than surface water; while in summer, the groundwater is often colder than surface water. Therefore, temperature differences under gaining conditions demonstrate a clear seasonal fluctuations around zero.

Unlike gaining conditions, temperature differences under losing conditions have no clear seasonal fluctuations around the value zero due to the limited mixing between regional groundwater and surface water.

The temperature differences between exfiltrating hyporheic fluxes between in-phase and out-of-phase gaining conditions are
340 directly related to the temporal variability of hyporheic exchange fluxes (Fig. 3e and 3f) and sediment temperature distribution (Fig. 6a and 6b). As discussed above, the hyporheic exchange rate is higher under out-of-phase conditions than under in-phase conditions when river temperatures are relatively high. As a result, the hyporheic zone has a larger extension and surface water can infiltrate deeper into the sediment. Therefore, hyporheic zones have a larger cooling effect during high river temperature under out-of-phase gaining conditions than under in-phase conditions.

345 Spatial variability in river and sediment temperature may provide localized refugia against extreme thermal disturbances for aquatic communities (Berman and Quinn, 1991). Loss of these refugia increases the risk for organisms living under undesirable temperatures associated with diel temperature fluctuations and anthropogenic activities (Poole and Berman, 2001). In the present study, we observe that the timing of daily groundwater table drawdown (i.e. in-phase or out-of-phase scenarios) potentially affects the ability of hyporheic zones to act as temperature buffers that can sustain vital activities (i.e., survival, growth
350 and reproduction) for aquatic communities. Therefore, cares must be taken in scheduling the pumping activities in order to protect thermal heterogeneity across multiple spatial scales.

4.4 Groundwater Modifies Hyporheic Potential for Biogeochemical Reactions

Hyporheic potential for denitrification varies between gaining and losing, in-phase and out-of-phase conditions (Fig. 8). RSF_a displays substantial drops during flood events. This is because flood-induced hydraulic gradient increases at the sediment-
355 water interface drive more surface water into the sediment, and consequently accelerate hyporheic exchange rates. Increased hyporheic exchange rates lead to a substantial decrease of the residence time in the hyporheic zone, creating conditions less suitable for denitrification. Similarly, RSF_a under gaining conditions is around three orders of magnitude higher than under losing conditions due to the significantly longer residence time resulting from mixing between surface water and groundwater under gaining conditions.

360 With groundwater gaining conditions, RSF_a peaks at different time during a day under in-phase and out-of-phase scenarios, indicating hyporheic denitrification potential can be regulated by adjusting the timing of daily groundwater table drawdowns. With groundwater losing conditions, even though RSF_a display peaks at different times during a day on a logarithmic scale under in-phase and out-of-phase scenarios, the actual differences of RSF_a (in the scale of 10 to the power of -5) between in-phase and out-of-phase conditions are insignificant compared to gaining conditions (Fig. 8a and 8b). In conclusion, the timing
365 of groundwater table drawdown is more important under gaining conditions than under losing conditions for denitrification reactions.

It's worth mentioning that the observations of RSF_a are not limited to denitrification processes. For a different biogeochemical reaction, another characteristic time scale is applied instead of τ_{dn}. Results presented in Fig. 8 will only be scaled by

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a different biogeochemical time scale for the reaction of interest. The relative variations of RSF_a remain the same for other

370   biogeochemical reactions.

4.5   Study limitations

The aim of the present study is not to simulate hyporheic exchange processes with perfect details, but rather to gain mechanistic understanding of hyporheic responses to varying groundwater table fluctuation patterns. Therefore, simplifications are made to allow for an efficient and reasonably correct representation of hyporheic exchange processes. Detailed simplifications

375   and limitations on model dimensionality, geomorphological settings, and boundary conditions are critically reviewed in previous studies on which the development of current method is based (Wu et al., 2018, 2020). In the following, only simplifications that are most relevant to the present study are discussed.

Groundwater fluxes are simplified as prescribed upward or downward fluxes. Daily groundwater table drawdowns are represented by sinusoidal curves with different phases and amplitudes representing different timing of groundwater table draw-

380   downs and strength of groundwater upwelling or downwelling, respectively (Fig. 2). However, the direction and magnitude of groundwater flow is a response to the head difference between river stage and riparian water table elevation, as well as sediment properties. An important process that cannot be represented by using prescribed groundwater fluxes is the impact of river temperature as a major factor contributing to reduced afternoon river discharge. High river temperature in the afternoon results in a high hydraulic conductivity which contribute to increased losing fluxes and consequently a reduced afternoon river discharge

385   (Constantz et al., 1994). However, increasing of losing fluxes due to higher river temperature in the afternoon cannot be captured using a prescribed groundwater flux time series. Apart from changing sediment hydraulic conductivity, there are a myriad of other factors affecting groundwater table fluctuations. For instance, a flood event may change the head difference between river stage and riparian water table elevation, and eventually leads to changes in the direction and magnitude of groundwater flow (Todd and Mays, 2005; Lewandowski et al., 2009). The head difference may change from negative to positive, resulting

390   in a switch of groundwater gaining to losing condition. However, these changes cannot be represented by using a prescribed groundwater flux time series. Groundwater table as a direct response to the head difference between the adjacent aquifer and the river stage is hence suggested for future hyporheic modeling in order to account for the hyporheic dynamics introduced by natural groundwater table fluctuations.

5   Conclusions

395   Groundwater table dynamics substantially modulate hyporheic exchange processes. Daily groundwater withdrawal causes additional variability of hyporheic exchange besides the variability induced by the diel river temperature changes. However, the variability induced by daily groundwater table drawdown is not necessarily an addition to the fluctuations induced by the diel river temperature changes. More specifically, groundwater flow fluctuations that are out-of-phase to diel river temperature fluctuations are likely to promote hyporheic exchange to a larger extent than groundwater flow fluctuations that are in-phase

400   to diel river temperature fluctuations. Even though both groundwater table fluctuations and diel river temperature fluctuations

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affect hyporheic exchange dynamics, under the same discharge condition, river temperature has a more dominant role in determining hyporheic exchange variability under losing conditions than under gaining conditions.

The timing of groundwater table drawdown modifies the rates of hyporheic exchange, and as a result the mixing and spreading of pollutants in the aquifer. Additionally, it also affect the hyporheic zone's ability to act as a temperature buffer that protects
405　aquatic communities from thermal extremes. Although not as significant as the effect of flood events, hyporheic denitrification potential (and potentially for other biogeochemical reactions) is also changing following the groundwater table drawdown. Therefore, it goes without saying that careful considerations must be taken when planning aquifer pumping schedules in order to minimize negative environmental impacts.

Data availability. All data required to reproduce the figures in this paper is available on the database of Leibniz-Institute of Freshwater
410　Ecology and Inland Fisheries (https://www.igb-berlin.de/freshwater-research-and-environmental-database)

Author contributions. LW, JGV, and JL designed the study layout with the feedback from SK, AW, TS, and GN. LW performed simulations, analyzed the data, and prepared the manuscript with the contributions from JGV, AW, TS, and JL. The manuscript was reviewed by JGV, SK, AW, TS, GN, and JL.

Competing interests. The authors declare that they have no conflict of interest.

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