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Key Points:

- First experimental data set focusing on redox processes in aquifers affected by hydropeaking
- Water stable isotopes indicate that surface water-groundwater interaction is not leading to significant water mixing
- Hydropeaking-driven groundwater level fluctuations enhance highly transient redox reactions

Supporting Information:

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

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Hydropeaking Catalyzes Redox Reactions in Impacted Aquifers: A First Field Evidence

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Abstract Hydropeaking indicates the sudden and frequent fluctuation of river stage caused by the operation of hydropower plants. This river alteration affects numerous physical, chemical, biological, and ecohydrological processes in surface water bodies. The impact of hydropeaking on groundwater hydraulics has been investigated only recently through modeling and experimental studies at multiple spatial scales. This study presents new hydrological and geochemical surface water and groundwater data providing the first evidence of the impact of hydropeaking on groundwater hydrogeochemistry. To interpret these observations, we propose a conceptual model where the rapid vertical oscillation of the groundwater table acts as a pressure-driven “geochemical pump” impacting redox conditions in the aquifer. This work has important implications for better understanding of groundwater biogeochemistry as well as for nutrient and carbon cycles.

Plain Language Summary Fluctuations in energy demand and supply lead to fast and frequent changes in the water level of the rivers, a phenomenon called hydropeaking. While the effects of hydropeaking have been widely studied in surface ecohydrology, a research gap exists concerning its impact on groundwater systems. In this work, we provide experimental evidence that the fluctuations in the river influence the groundwater table and hence mass exchange between dissolved chemical species in the soil and groundwater. Accounting for this process has important implications for the turnover of several chemical species and geochemical processes. We expect that our results can enhance further research investigating the impact of hydropeaking on groundwater ecosystems.

1. Introduction

Hydropeaking occurs in river reaches due to intermittent water release from hydropower plants connected to storage dams (Bipa et al., 2024). The period (on the order of less than one day up to 1 week), amplitude (with water level changes on the order of decimeters to meters), and rate of change (on the order of meters per hour) of such human-related fluctuations clearly differentiate hydropeaking from natural drivers such as snow and glacier melting, or precipitation (Ashraf et al., 2018; Déry et al., 2021). Increasing demand for renewable energy sources and the need to stabilize the energy grid with flexible energy production lead to irregular and variable patterns of hydropeaking worldwide (Jones, 2014; Olivares et al., 2021; Pérez Ciria et al., 2019).

Hayes et al. (2023) identified 100 urgent research questions in hydropeaking research and clustered them according to nine different interdisciplinary fields. The impacts of hydropeaking on surface water affect riverine ecosystems (Bejarano et al., 2018; Greimel et al., 2018; Maddock et al., 2013; Tonolla et al., 2017), heat fluxes (Feng et al., 2018; Toffolon et al., 2010; Zolezzi et al., 2011), biogeochemical fluxes (Calamita et al., 2021; Dolcetti et al., 2025), aeration (Pulg et al., 2016), underwater soundscapes (Kowal et al., 2023; Lumsdon et al., 2018) and sediment transport (Batalla et al., 2021; Béjar et al., 2017; Nguyen et al., 2025; Vericat et al., 2020).

Some studies on the influence of hydropeaking on riparian zones exist in the Rhone River (Fette, 2005), the Ain River (Judes et al., 2023), the Colorado River (Abernethy et al., 2021; Francis et al., 2010; Hucks Sawyer et al., 2009), the Cockburn River (McCallum & Shanafield, 2016; Welch et al., 2013), the Deerfield River (Boutt & Fleming, 2009; Yellen & Boutt, 2015) and the Danube River (Derx et al., 2010; Pander et al., 2023). These

investigations mostly addressed questions of hydrological and geochemical interactions between surface water and the hyporheic zone or its proximity (e.g., Schmadel et al., 2016; Welch et al., 2013). While attention to the impacts of hydropeaking on rivers has increased in recent years, hydrochemical effects on connected aquifers remain largely unknown. Moreover, further-reaching investigations of the specific consequences on hydro-geochemical processes beyond the hyporheic zone (saturated and unsaturated zones up to a scale of tens of meters distance from the river) are still missing.

The laboratory experiments of Basilio Hazas et al. (2023), Basilio Hazas, et al. (2022b), and Ziliotto et al. (2021), considered a vertical cross-section of a homogenous aquifer in hydraulic contact with two rivers affected by sub-daily riverstage fluctuations driven by hydropeaking. The investigation led to identifying the impacts of river fluctuations on flow topology (e.g., regions dominated by strain or rotation identified through the Okubo-Weiss parameter (de Barros et al., 2012)), solute transport and dilution as achieved by metrics such as the dilution index (Kitanidis, 1994). Merchan-Rivera et al. (2022) showed that the shape of the hydropeaking wave can modify groundwater flow topology and plume deformation. Derx et al. (2010) and Boutt and Fleming (2009) documented potential enhanced transport mechanisms in high-frequency surface water fluctuations caused by anthropogenic flow regulation and indicated the effects of river stage fluctuations on dilution of a conservative tracer. Rizzo et al. (2020) modeled the impact of seasonal and high-frequency fluctuations on solute transport in the river corridor, which includes the river channel, the riparian zone and the hyporheic zone. However, possible geochemical effects of the pressure-wave propagation from the river to the aquifer remain unresolved because they require high-frequency monitoring.

In other hydrological contexts, including coastal aquifers, storm events or snowmelt, similar groundwater level fluctuations have been found to shape the geochemistry of related groundwater (Machado-Silva et al., 2024; Roumelis et al., 2025; Wallace et al., 2019; Wei et al., 2024; Zachara et al., 2016). Such natural fluctuations differ, however, from hydropeaking in terms of frequency and intensity. Nonetheless, these comparisons raise expectations that proper assessment of impacts caused by propagation of pressure hydropeaking waves on hydro-geochemical reactions should include both the saturated and unsaturated zones. It seems plausible that rapid hydraulic alterations also cause enhanced hydrogeochemical changes in river-connected aquifers. These changes may persist even if mass exchange between river and aquifer water remains limited to the hyporheic zone. For instance, pressure waves can enhance reactive transport in a fluctuating unsaturated zone.

In this work, we will address the limited understanding of how hydropeaking influences river hydrochemistry and hydrogeochemical reactions in the aquifer beyond the hyporheic zone. We present a unique hydrochemical and isotope data set (field parameters, $\delta^{18}\text{O}/\delta^2\text{H}$ -water, major ions and trace elements) that indicates how hydropeaking may influence groundwater redox conditions.

With these parameters, we aim to establish a novel conceptual model to illustrate flow and transport mechanisms in the saturated and unsaturated zones. The affected region covers a distance of up to tens of meters from the river channel, where we still expect hydrochemical reactions triggered by hydropeaking.

2. Materials and Methods

Our experimental data set focuses on the Noce aquifer system in North-East Italy (Basilio Hazas, et al., 2022a; Castagna et al., 2015; Chiogna et al., 2018) (Figure 1).

The Noce River is connected to the Adige Valley aquifer, which lies in the northeast of Italy, and is surrounded by carbonate massifs extending mostly to the east and west (Figure 1a). The underlying unconfined aquifer has a thickness of approximately 40 m (Castagna et al., 2015). The Noce River is a well-documented case of severe and broad hydropeaking impacts (Bruno et al., 2023; Toffolon et al., 2010). Here, the natural river water-level variability is masked by fluctuations of up to one meter at sub-hourly frequencies, driven by water releases from the Mezzocorona hydropower plant, located approximately 4 km upstream of the study area. The degree of stress in the aquifer close to the Noce River at the studied locations was classified as between moderately and highly affected by hydropeaking (Basilio Hazas et al., 2024). A groundwater model of the aquifer connected to the Noce showed that the wavelet coherence between river and groundwater fluctuations is high (Basilio Hazas, et al., 2022a).

For this work, we carried out a comprehensive 24-hr-long sampling campaign on 26 August 2025 (Chiogna et al., 2026). No precipitation occurred during the sampling period. Water level, temperature and electrical conductivity

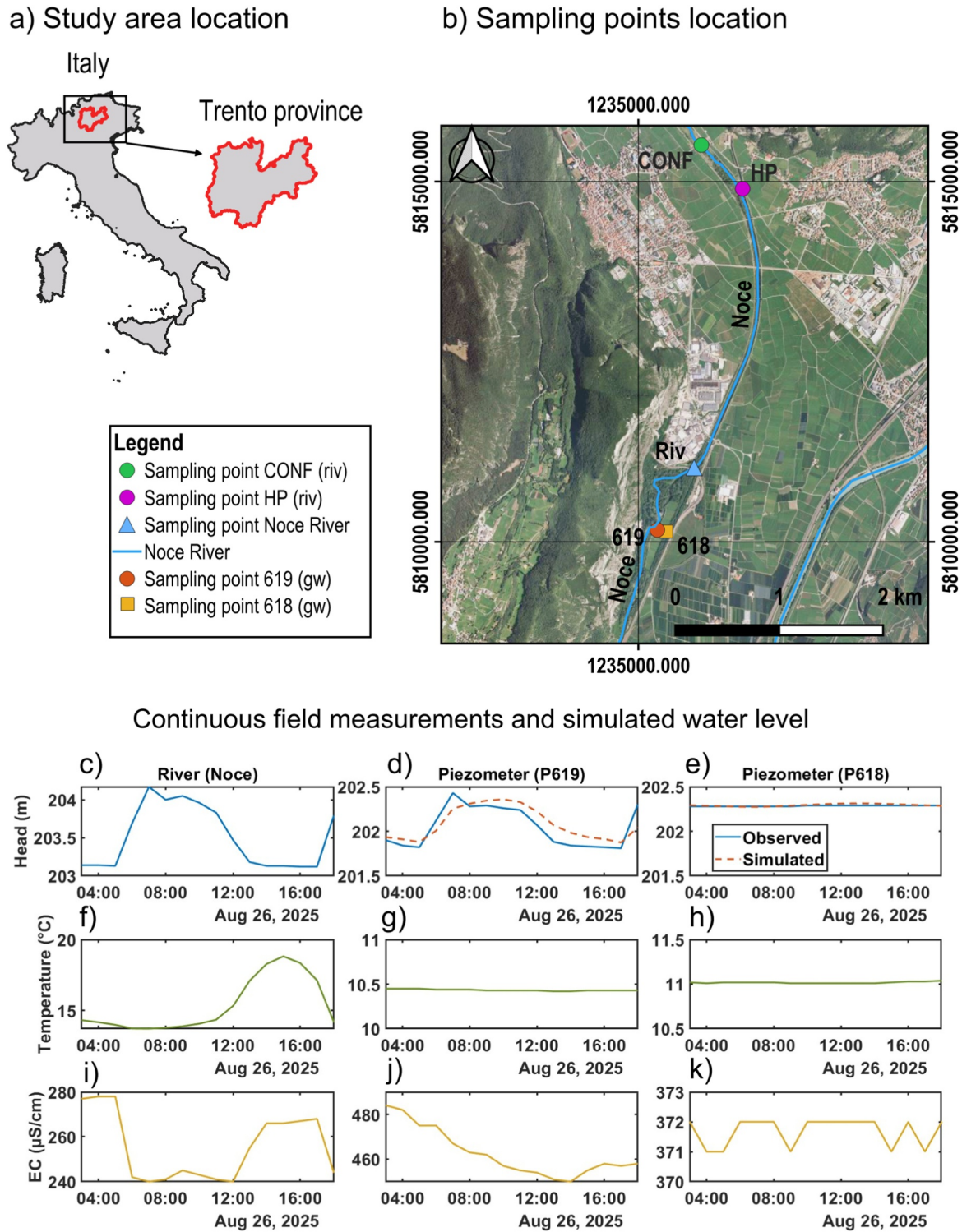


Figure 1. Study site and variables with continuous observations in the river and the two piezometers. (a) Study area location. (b) Sampling points location. CONF indicates the sampling point located upstream the hydropower plant where the river is not affected by hydropeaking and HP indicates the sampling point at the outlet of the hydropower plant. Sampling points 619 and 618 are located in the aquifer at different distances from the Noce river. (c–e) (modeled) Water level in m a.s.l., (f–h) (measured) temperature and (i–k) (measured) electrical conductivity for the Noce River and piezometer P619 and P618 during the observation period.

loggers (OTT-CTD, Germany) provided hourly measurements for the Noce River and groundwater measurements at P618 and P619 (Figure 1b), at 123 and 39 m from the river center, respectively (Figures 1c–1k).

We collected 19 water samples at the Noce River near the biotope La Rupe (GN-LRu), two at the outlet of the hydropower plant and two upstream of the hydropower plant release, as well as at the two piezometers P618 and P619 (three and 19 samples, respectively). We filtered the samples directly in the field via 0.45 μm syringe disk filters (Minisart HighFlow PES, Sartorius AG, Germany). Samples for major ions (Ca^{2+} , Mg^{2+} , Na^+ , K^+ , Cl^- , SO_4^{2-} , NO_3^- , PO_4^{3-}) and trace elements (Si, Li, B, Al, Ti, V, Cr, Mn, Fe, Co Ni, Cu, Zn, As, Se, Rb, Mo, Ag Cd, Sn, Sb, Ba, La, Ce, Ti, Pb, U) were filled into 15 mL polypropylene vials. For oxygen and hydrogen stable isotopes of water ($\delta^2\text{H}$ and $\delta^{18}\text{O}$) samples were collected in 12-mL glass bottles without headspace. All sample containers were tightly sealed and stored in the dark at 4°C. We measured CaCO_3 by titration in the field and was computed considering the available pH measurements.

In the laboratory, samples were analyzed for $\delta^2\text{H}$ and $\delta^{18}\text{O}$ by an isotope ratio infrared spectroscopy (IRIS) analyzer, based on wavelength-scanned cavity ring-down spectroscopy (L 1102-i WS-CRDS, Picarro). All values are reported in the standard δ -notation in per mille (‰) versus a standard known as Vienna Standard Mean Ocean Water (VSMOW) according to

$$\delta = (R_{\text{sample}}/R_{\text{reference}} - 1) \quad (1)$$

where R is the molar ratio heavy to light isotopes (e.g., $n(^{18}\text{O})/n(^{16}\text{O})$) (Coplen, 2011). These values are multiplied by 1000 to express them in permille (‰).

The data sets were corrected for instrumental drift during the run. External reproducibility based on repeat analyses of controls was better than 0.1 and 1‰ (± 1 sigma) for $\delta^{18}\text{O}$ and $\delta^2\text{H}$. For a detailed description of the analysis procedure, refer to Van Geldern and Barth (2012).

Major anions were determined by ion chromatography (930 Compact IC Flex, Metrohm). The limit of quantification (LOQ) for major anions was 0.1 mg L^{-1} with a 1-sigma precision of <5%. Major cations and trace elements were analyzed with an iCAP Qc inductively coupled plasma-mass spectrometer (ICP-MS, Thermo Fisher Scientific). Before measurement, the samples were stabilized with two drops of 65% HNO_3 Suprapur. These samples were measured in triplicates with a typical RSD < 1%. For most trace elements, the practical quantification limit was determined with 0.1 $\mu\text{g L}^{-1}$.

High-resolution time series of major ion concentrations were computed following Richieri et al. (2023) and Benettin and Van Breukelen (2017). This method enables evaluations of solute concentrations at times without direct solute observation, starting from EC measurements and previous knowledge on individual contributions by each ion to the total EC. For each ion i , a time-dependent weight factor $f_i(t)$ is defined as the ratio of $\text{EC}_i(t)$ to $\text{EC}(t)$, where $\text{EC}_i(t)$ is the contribution of the specific ion i to the total $\text{EC}(t)$ as computed by PHREEQC (Parkhurst & Appelo, 2013). This approach enabled to infer solute concentrations from weight factors and observed patterns of EC values (Richieri et al., 2023).

3. Results and Discussion

3.1. Hydraulic Signal, Temperature and Electrical Conductivity

As it is evident from Figures 1c and 1d, the Noce River impacts groundwater levels in the connected aquifer. Figure 1c shows the river level fluctuations as computed by a HEC-RAS one-dimensional model (Basilio-Hazas et al., 2022a) calibrated at the official gauging station Noce Ponte Rupe one Km upstream the sampling point (Figure S1 in Supporting Information S1). In this work, we focus only on short-term fluctuations during a single hydropeaking event. The square wave in the water-level signal appeared dampened and halved in amplitude in P619 compared to the river level. In contrast, groundwater level fluctuations were not observed in P618. We observed complex spatial and temporal variabilities of groundwater levels. In particular, although the river acts as a losing stream, potential flow reversal can occur between the two piezometers. In fact, while the head in P618 is generally higher than in P619, P619 values occasionally exceed the ones in P618 during the peak event (e.g., at 07:00). This reversal in the groundwater head gradient impacts both the magnitude of the groundwater flow

velocity and the groundwater flow direction according to Darcy's law. Consequently, this process may impact both advective and dispersive transport of dissolved species in the saturated zone. Effective diffusivities within the aquifer were estimated as 30,000 m²/h (for P619) and 1000 m²/h (for P618) by applying the analytical solution of Singh (2004) separately to each piezometer. This analytical solution assumes homogeneity and isotropy within a confined aquifer with infinite extent and with a streambed resistance of 300 m to account for impervious beds and banks. The difference in effective diffusivity between the two piezometers shows the heterogeneity of the aquifer, and even though the analytical solution assumes a confined aquifer, it is common to apply it in unconfined systems where the fluctuations are small in comparison to the aquifer thickness (Hucks Sawyer et al., 2009). The high diffusivities enable rapid propagation of pressure signals even at sub-daily frequencies. The distance of P618 is, however, long enough to dissipate such fluctuations. Figures 1c–1e show a good match between simulated and observed groundwater levels.

The river temperature varies with a seasonal and diel cycle due to sun radiation and heat exchange with the atmosphere, and on a sub-diel scale due to the release of water with a different temperature from the reservoir during hydropeaking (so-called thermopeaking, Zolezzi et al., 2011). In summertime, at the measurement site, thermopeaking causes a reduction in water temperature comparable to diel fluctuations (Dolcetti et al., 2025). Measured temperature fluctuations driven by thermopeaking, sun radiation and atmospheric exchange during the observation period were approximately 5°C in the river (Figure 1f). However, temperatures in both aquifers remained approximately constant in time (Figures 1g and 1h). Similarly to the pressure signal, the aquifer acted as a low-pass filter for temperature fluctuations. This was likely due to the short time scales of these fluctuations relative to diffusive processes, and potentially to heat exchange with the porous aquifer material. A temperature gradient of 0.5°C between the two piezometers likely represented the delayed propagation of slow seasonal-scale heat fluxes between the river and the aquifer.

Electrical conductivity changes in the river were strongly affected by dissolved inorganic carbon (DIC) fluxes, carbonate speciation, and alkalinity (Figure S2 in Supporting Information S1). EC in the river varied between 240 μS/cm during hydropeaking and 280 μS/cm during ecological minimum flow conditions (Figures 1i–1k). DIC fluxes at the measurement sites reflect the superposition of multiple drivers interacting on a range of scales: ecosystem metabolism, CO₂ exchange with the atmosphere, carbonate buffering, and carbopeaking, that is, supply of CO₂-rich and low-pH water from the reservoir during hydropeaking (Dolcetti et al., 2025). Upstream of the hydropower release, CO₂ fluctuated daily below and above equilibrium due to primary production, while in the hydropeaking-affected reach, CO₂ levels also increased during carbopeaking (Figure S2a in Supporting Information S1). CO₂ variations were partly counteracted by a shift of the carbonate equilibrium, evidenced by the large variation in pH. The complexity of DIC drivers and dynamics hampers the use of EC for end-member mixing analysis. In the aquifer, CO₂ remained significantly supersaturated during the whole measurement period and pH and DIC dynamics seemed to be decoupled from those in the river (Figure S2 in Supporting Information S1). We observed a noticeable change in EC at P619 (values between 485 and 450 μS/cm), but not at P618 (values between 372 and 371 μS/cm). However, the temporal pattern of the EC signal in P619 was not correlated with the changes in water level ($R^2 = 0.003$).

3.2. Water Stable Isotopes as Conservative Tracers

Water stable isotopes in the Noce River decreased with increasing contributions of reservoir water (Figure 2a), which stems from a higher elevation (Chiogna et al., 2016). An endmember mixing analysis revealed that 75%–97% of the river discharge came from the hydropower plant ($\delta^{18}\text{O} = -11.83$ ‰, $\delta\text{D} = -82.4$ ‰) during energy generation periods. This leaves between 25% and 3% contributions from baseflow ($\delta^{18}\text{O} = -11.38$ ‰, $\delta\text{D} = -78.7$ ‰) during the peak event. The calculation is consistent with the official discharge data measured at the gauging station Ponte Rupe and available at (www.floods.it). The isotope values of groundwater collected in P619 and P618 do not strongly correlate with changes observed in the river during the hydropeaking event ($R^2 = 0.38$ for both $\delta^{18}\text{O}$ and δD), ruling out rapid mass transfer from the river to the aquifer during the observed peaking event. More importantly, the isotopic signature of the river water and the water in P619 indicates only a limited amount of mixing between surface water and groundwater (Figure 2b). Propagation of lower-frequency signals and mixing between the river and the aquifer at longer temporal scales (e.g., weekly or seasonal) cannot be excluded as we can observe for P618 ($\delta^{18}\text{O} = -11.32$ ‰, $\delta\text{D} = -78.3$ ‰). Overall, water isotopes, as the best possible conservative tracers, suggest that hydrochemical changes at high frequencies observed in the aquifer would not result from a direct interaction (mass-flux exchange) with the river.

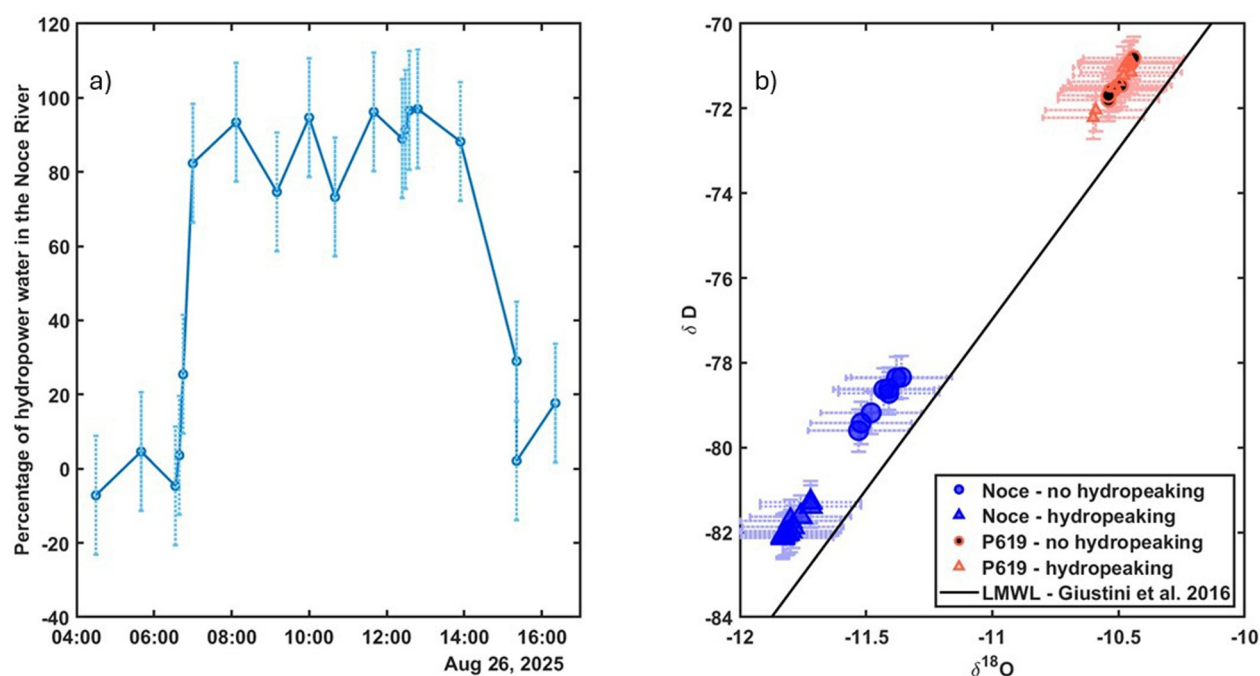


Figure 2. (a) Percentage of water in the Nocer River from the hydropower plant using end-member mixing analysis based on δD and $\delta^{18}O$, error bars are computed by error propagation as in Cano-Paoli et al., 2019 and (b) Comparison between the local meteoric water line on Giustini et al., 2016 (black line) and the water stable isotopes of the Noce River (blue full symbols) and of the piezometer P619 (red and black full symbols). Circles represent samples collected outside the hydropeaking event, triangles are taken during the hydropeaking event.

3.3. Major Ions

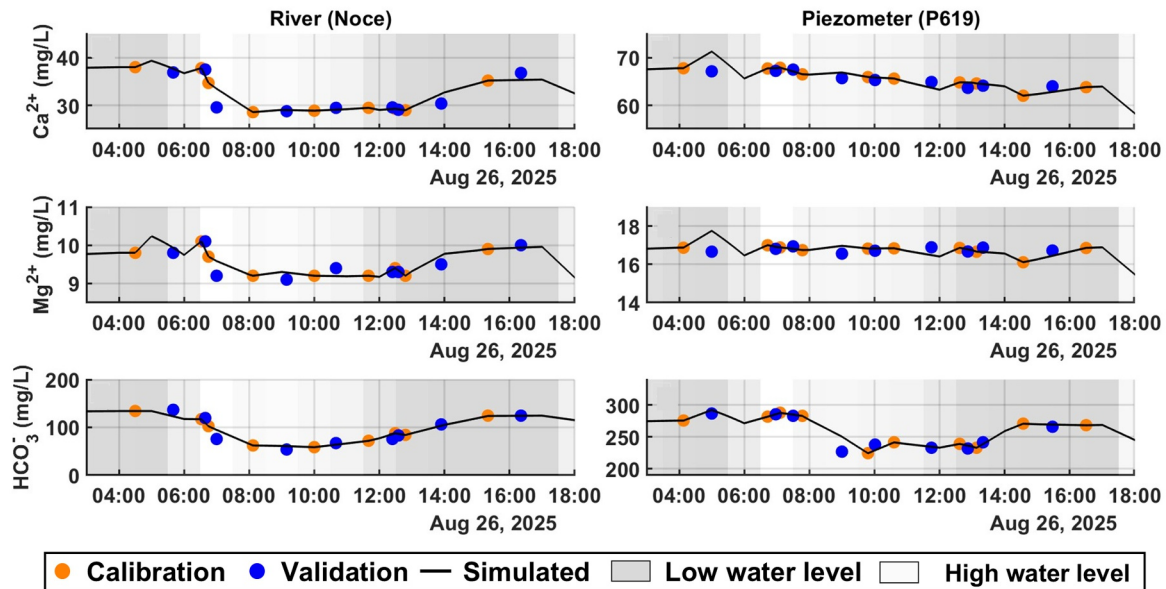
To increase the temporal resolution of the major ions data, we reconstructed hourly time series by calibrating a relationship with the electrical conductivity. As shown in Figure 3a, the EC-based fitting and reconstruction of the data performed well both for the Noce River data and the P619 data. However, in P618, the variability in the ionic content and EC values was too small for an accurate fitting. As already observed in other studies (Richieri et al., 2023), the method works more accurately for ions that contribute most to EC. In the case of this study, these were Ca^{2+} , Mg^{2+} , and HCO_3^- (Figure 3a). In the Noce River, we were able to identify the variability in the ionic composition of water depending on its source (minimum flow vs. water derived from the hydropower plant). Nevertheless, the temporal variability in the major ion composition at P619 was small, and limited to HCO_3^- where its variability anticorrelated with groundwater level fluctuations ($r = -0.72$) with a temporal delay of 2 hrs.

3.4. Redox Species

The analysis of reactive species O_2 , SO_4^{2-} , Mn, and Fe (Figure 3b) reveals a different and complementary picture of the system. Dissolved oxygen concentrations in the river were slightly undersaturated ($>90\%$) during the night and during the hydropeaking event, when primary production was limited (Figure S3 in Supporting Information S1). Oxygen saturation increased up to 120% after the end of hydropeaking due to the larger relative effects of productivity during baseflow (Figure S3a in Supporting Information S1). O_2 concentrations in the aquifer remained undersaturated and displayed a significant variability (Figure 3b): at night, before the hydropeaking event, P619 displayed low oxygen concentration (1.7–2.11 mg/L), but oxygen levels increased with the groundwater levels during hydropeaking (between 06:00 and 12:00), reaching a maximum twice as high as the minimum (3.4 mg/L). The fluctuations correlated with the groundwater fluctuations ($r = 0.7$) suggesting that oxygen entered groundwater where it was eventually consumed.

Fe and Mn had low concentrations in the river. In contrast, their concentrations in the aquifer were about 10 times larger, and variations of Fe and Mn in the aquifer were stronger in amplitude than those of O_2 , and also correlated with the water table fluctuations ($r = 0.88$). The positive correlation of Fe and Mn with the water table fluctuations

a) EC-based reconstruction



b) Field measurements

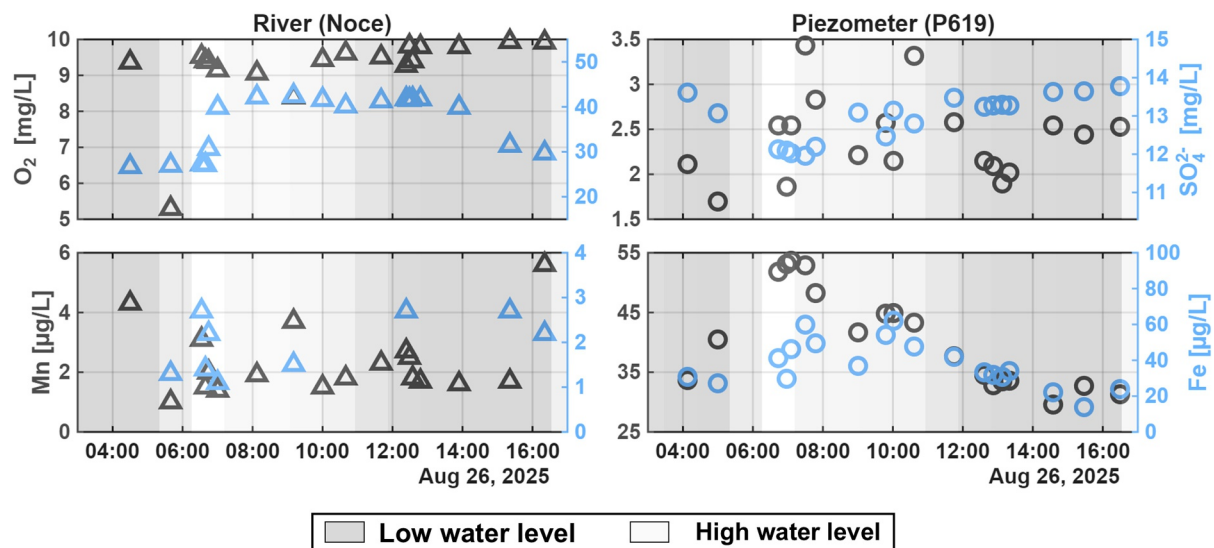


Figure 3. (a) Variability in Ca^{2+} , Mg^{2+} , and HCO_3^- in the Noce River and in Piezometer P619. Orange dots are observed values used for calibrating the model of Richieri et al. (2023), blue dots are observed values used to validate the model, and the continuous line represents the high-frequency values reconstructed with the EC signal. (b) O_2 , SO_4^{2-} , Mn, and Fe variability in the Noce and P619 during the observation period. The background color of the figures qualitatively indicates the water level: from gray indicating a low water level to white indicating a high water level.

suggests a mobilization from the capillary fringe. The rapid saturation of the previously unsaturated pores likely triggers a transient release of reduced species before the newly introduced oxygen can promote their precipitation.

SO_4^{2-} negatively correlated with groundwater table fluctuations ($r = -0.8$). This trend either suggests a dilution effect or a mixing with sulfate-poor pore water residing in the unsaturated zone. Note that the transient oxygenation occurs on a timescale of minutes to hours that would likely be too short to trigger possible secondary production of sulfate from sulfide oxidation if present at all. This temporal overlap of time scales highlights the complexity and the non-equilibrium nature of the system.

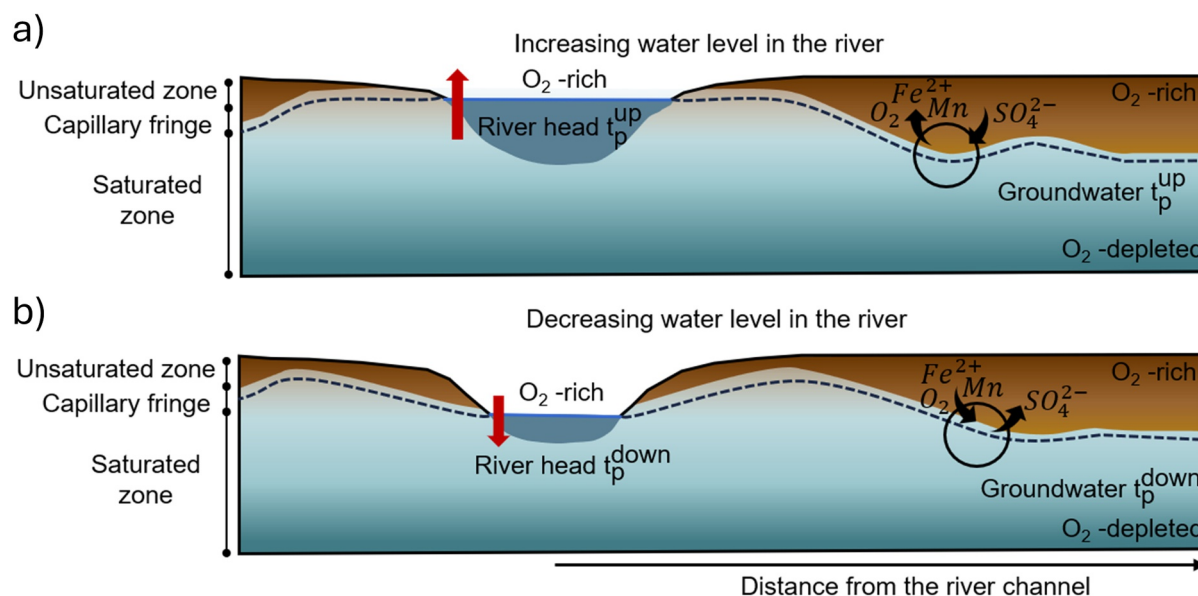


Figure 4. Conceptual representation of the interaction between surface water and groundwater during hydropeaking, with focus on the hydrogeochemical conditions at the interface between saturated and unsaturated zones. (a) t_p^{up} indicates the time of the highest water level and (b) t_p^{down} the lowest water level.

3.5. Conceptual Model

Our data set suggests that hydropeaking effects propagate beyond the hyporheic zone and impact hydrogeochemical conditions in the aquifer. The lack of a clear link between temperature and isotope signals in the river and in the aquifer suggests that these effects are not driven by mass exchange between the river and groundwater but rather by vertical movement of the groundwater itself. To interpret these observations, we propose a conceptual model where the rapid vertical oscillation of the water table acts as a pressure-driven “geochemical pump.” This pump weakly affects hydrogeochemical processes that are mostly related to mixing between groundwater and river water. The geochemical pump in the alluvial aquifer is triggered by variable groundwater levels that enhance mixing processes between the oxygen-poor aquifer and the more oxygen-enriched unsaturated zone (Figure 4), supplying elements to support redox reactions. Our findings suggest that such effects can be of broad importance for groundwater ecosystem services related to carbon and nutrient cycling as well as reactive transport in the unsaturated zone (Farhat et al., 2026).

4. Conclusions

Our work provides the first evidence on previously unknown interactions between the saturated and unsaturated zone caused by hydropeaking-related groundwater table fluctuations. We identified a geochemical pump, activated by the propagation of the hydropeaking wave from the river in the alluvial aquifer. This pump enhances mixing processes between the oxygen-poor aquifer and the more oxygen-enriched unsaturated zone. This new conceptual model indicates that geochemical activity is primarily caused by vertical fluctuations rather than lateral mass transport. Specifically, our data exclude rapid infiltration of surface water in the aquifer as a cause for the fluctuations in dissolved O₂, Fe, Mn, and SO₄²⁻. This was corroborated by the fact that water stable isotopes did not change significantly in the aquifer before, during, and after a peak event. In contrast, these conservative isotope tracers showed clear responses in the river during a hydropeaking event.

In our study, the aquifer has a high hydraulic diffusivity, allowing for a rapid propagation of the pressure wave and strong oscillation of the groundwater level. Resulting changes in groundwater chemistry can plausibly be explained by dynamic interaction between the aquifer and the unsaturated zone. Such findings may be relevant for other sites along hydropeaking rivers with similar dynamic conditions. These are likely in many alluvial aquifers that largely consist of gravel and sand.

The duration of the measurement was limited by the considerable practical challenges in organizing and conducting a high-frequency sampling campaign of this extent in the field. Multiple processes occurring on large time

scales, such as variations in precipitation patterns, hydropower operation, and ecosystem metabolism, can modify water levels and biogeochemical processes in the river and in the aquifer, affecting the scale and magnitude of the groundwater response to hydropeaking. Future studies should address these potential additional drivers through repeated sampling campaigns across longer periods of time.

Temporal variations in groundwater chemistry caused by hydropeaking are currently not monitored or accounted for. Our findings help to quantify the impacts of hydropeaking on reactive solute transport as well as on alterations of the groundwater ecosystem. Our data offer the potential to develop hydrogeochemical indicators, which have been scarcely applied to date, to assess the quality of the groundwater ecosystem. With hydropeaking being a global phenomenon, our results suggest that its impacts on related groundwater quality in combination with the unsaturated zone need to receive more attention in future studies about the ecological consequences of hydro-power generation.

Conflict of Interest

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

Availability Statement

The data sets supporting the findings of this study (continuous hydrological and water quality data for the Noce River and piezometers P618 and P619) are publicly available in the HydroShare repository (Chiogna et al., 2026) at: <http://www.hydroshare.org/resource/68b59c3ab8da44c89dd11a99ce7d3085>. The data set is openly accessible under the Creative Commons Attribution 4.0 International (CC BY 4.0) license.

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