Impact of clogging layer disruption on riverbed sediment permeability: An experimental study on the Torysa River, eastern Slovakias

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Abstract: In areas heavily influenced by water extraction, the interaction between river water and groundwater is crucial for maintaining hydrological balance. This study examines the effects of mechanically disrupting the clogging layer in the Torysa River's riverbed on water infiltration into an adjacent aquifer. Using a tractor-mounted plough to break up the clogging layer, an unconventional method in this field, we observed the changes in water levels to determine alterations in hydraulic connectivity. The intervention led to a notable rise in groundwater levels, with an increase of over one meter in six days, suggesting enhanced river-aquifer interaction. A 2D hydrological model quantified the changes in the riverbed's hydraulic conductivity before and after the intervention. Although the results confirm the variable nature of riverbed sediment permeability and its importance in water management, the practicality of employing tractors for such purposes is limited. The study advocates for future research to investigate less conventional methods to sustain or improve the natural functionality of riverbeds, contributing to the development of sustainable water extraction practices and a deeper understanding of the interplay between human activity and hydrological systems.

Key words: riverbed sediment clogging, induced river-aquifer flow, groundwater level response, sustainable water management, hydrological modelling

1. INTRODUCTION

The dynamic interplay between surface water and groundwater is a cornerstone of the hydrological cycle and has significant implications for water resource management, ecological balance, and environmental policy. In regions characterised by intensive groundwater extraction, such as the Brezovica water source by the Torysa River in eastern Slovakia, understanding the interaction between rivers and adjacent aquifers becomes crucial because it profoundly influences the hydrological equilibrium. This study investigates the effects of mechanical disruption of the clogging layer on the permeability of riverbed sediments, focusing specifically on the Torysa River in eastern Slovakia. By offering insights into the potential enhancement of river-aquifer interactions, this research is of global relevance, while also highlighting the specific importance of the Torysa River as a case study.

Surface water and groundwater are in a dynamic state of interaction, where almost all surface water characteristics, including streams, rivers, lakes, reservoirs, and wetlands, along with rainwater, are linked to the water located beneath the surface. This connection occurs in the hyporheic zone below the water body's bottom, where surface and groundwater mix. This interrelationship between surface and groundwater can alter the quantitative and qualitative characteristics of water. For example, in areas where linear arrays of wells are present near rivers, excessive water extraction from the aquifer can significantly impact the volume of water flowing in the surface stream, potentially leading to complete drying up of the surface flow (Némethy, 1986). On the contrary, processes such as bank filtration and those that occur in the riparian zone can positively influence water quality by purifying contaminated surface water by filtration of water through sediments, subsequently enabling the extraction of clean groundwater from wells.

Research into the interaction between surface and groundwater has garnered significant attention from numerous authors in recent decades, leading to a wealth of scientific articles. The focal points of these works revolve primarily around reviewing and developing analytical solutions for surface and groundwater interactions (Zlotnik & Huang, 1999; Hunt et al., 2001; Kollet & Zlotnik, 2003; Dubuis & De Cesare, 2023), establishing theoretical foundations, and exploring practical applications through numerical models that simulate the flow of groundwater, surface water, and water in the unsaturated zone (Sophocleous et al., 1995; Anderson, 2005). A review of 18 programs that address the interaction between surface water and groundwater can be found in (Spanoudaki et al., 2009). Qualitative aspects related to substance transport processes in the riparian zone, clogging issues, the relationship between riverbed morphology and water infiltration, and utilization of natural tracers like heat and isotopes of various elements to monitor water exchange dynamics between rivers and aquifers, among others, have also been addressed (Woessner 2000; Sophocleous, 2002; Fleckenstein et al., 2010).

The direction and magnitude of the interaction between surface and groundwater are influenced by various factors, including geomorphology, hydrology, climate, and groundwater flow (Sophocleous, 2002). Although a straightforward definition of water flow in this system considers the amount of water flowing

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between the river and the aquifer (leakage) as a function of the difference in water levels, it is important to note that this assumption of linear dependency is overly simplistic. In cases where the groundwater level is below the riverbed, the flow of water depends on multiple factors, such as the hydraulic properties of the unsaturated zone, free storage available, the geometry of the river channel, the wet perimeter, the level of water in the river, the moisture content of the unsaturated zone and the temperature of the water. The morphology of the river bed plays a vital role in the locations where water infiltrates the aquifer or exits it. Certain organisms that inhabit surface streams depend on areas where groundwater infiltrates the surface stream. Furthermore, the surface topography of the riverbed itself influences water exchange processes, whereby even in situations where the surface stream extensively drains the aquifer, surface water infiltration can occur in rough or obstructed areas of the riverbed. Temperature differentials can also influence surface water infiltration, with warmer surface water exhibiting lower density and potentially flowing into the aquifer due to convection (Woessner, 2000; Fleckenstein et al., 2010).

Previous research has established a solid foundation for understanding the dynamics and consequences of riverbed clogging. However, there is a notable research gap in the development of effective and practical methods to disrupt clogging layers and restore the permeability of the riverbed, which is essential to promote the health of aquatic ecosystems and effectively manage water resources. Although mechanical disturbance has been proposed as a potential solution, its practicality and long-term effectiveness require thorough evaluation (Blaschke et al., 2003). Furthermore, the integration of hydrological models with ecological and biogeochemical data presents ample opportunities for advancement, as highlighted by Jones & Holmes (1996). This integration is critical to improving our understanding of the complex interactions within the hyporheic zone and informing the implementation of sustainable water management practices.

Research activities continue to concentrate on the interaction between river and groundwater due to the ongoing relevance and complexity of understanding these critical hydrological connections, particularly in the context of managing water resources in arid and semi-arid regions amid escalating climate change concerns. In addressing the complexities of surface water-groundwater interactions within arid environments, recent studies have significantly advanced our understanding and modelling capabilities. P. Vasilevskiy et al. (2022) have made notable progress in simulating river/lake-groundwater exchanges in such regions, emphasizing the importance of incorporating remote sensing data on lake surface area dynamics and evapotranspiration to reduce uncertainties in hydrological models. Their work, focused on the Ejina Basin of the Heihe River Basin, demonstrates how leveraging these additional data sources can enhance model accuracy in areas where traditional observations are limited. Complementing this, Cui et al. (2022) explored the potential for aquifer exploitation at a riverbank filtration site, revealing how spatiotemporal variations in riverbed hydraulic conductivity, influenced by factors such as sediment clogging, play a critical role in water infiltration processes. Furthermore, Vasilevskiy et al. (2019) provided field validation for a modified Hvorslev formula that accounts for streambed clogging, offering a more accurate method for estimating hydraulic conductivity in arid regions. These studies collectively underscore the intricate dynamics of water exchange processes in arid zones and highlight the evolving methodologies aimed at improving our understanding and management of these critical resources.

Incorporating the pioneering work of Zlotnik et al. (2021) and Min et al. (2020) into the current discourse on surface water-groundwater interactions and riverbed hydraulic conductivity (RHC) significantly enriches our understanding of these complex systems. Zlotnik et al. (2021) introduced innovative shape factors for the application of large-footprint open-bottom permeameters, a development that promises to enhance the precision of groundwater flow measurements in various hydrogeological settings. This advancement is particularly relevant for accurately assessing the permeability of riverbeds, which is a critical factor in the dynamics of river infiltration and groundwater recharge processes.

On the other hand, Min et al. (2020) focused on the effects of anthropogenic activities on river-groundwater interactions, providing insights into how land use changes and water management practices influence the hydrological balance and RHC in riparian zones. Their work likely complements the findings of Cui et al. (2022) and Vasilevskiy et al. (2022) by offering a broader perspective on the factors that affect RHC and, consequently, the efficiency of riverbank filtration systems. Together, these studies underscore the multifaceted nature of water exchange processes and the importance of integrating various methodological approaches – from field measurements to modelling and remote sensing—to accurately characterise and manage the interactions between surface water and groundwater. This holistic view is crucial for developing sustainable water resource management strategies, particularly in regions facing the dual challenges of water scarcity and environmental degradation.

In conclusion, this study addresses a critical research gap by investigating the effects of mechanically disrupting the clogging layer on riverbed sediment permeability. The Torysa River in eastern Slovakia serves as an ideal case study, providing valuable information on the potential improvement of river-aquifer interactions. By offering empirical evidence on the efficacy of mechanical disruption and using a 2D hydrological model calibrated with field data, this research will contribute to the existing body of knowledge. Furthermore, the findings have implications beyond the Torysa River, suggesting broader strategies for sustainable water resource management and ecological conservation efforts.

MATERIALS AND METHODS

Study Site and Water Extraction: The Brezovica I water resource site (Fig. 1), characterised by an average water extraction of 60 l/s, experiences water scarcity during the summer months (July – September). The research objective was to evaluate the possibility of increasing the extraction rate to 130 l/s. This increase was proposed to be achieved by enhancing surface water infiltration from the Torysa River through artificial disruption of the riverbed's clogging layer. Two lines of observation wells (Profile 1 and 2 in Fig. 1) perpendicular to the river were available on-site to monitor groundwater levels. One of these lines included the pumping well NT-3, where a pumping test was conducted concurrently with the disruption of the riverbed's clogging layer to demonstrate increased replenishment of groundwater reserves during minimal river flows. Previous investigations (Némethy 1986) have shown that during dry periods, characterised by minimal water levels in both the river and aquifer, about 10 litres per second of water flowed from the Torysa River into the aquifer. Additionally, approximately 45 litres per second entered the aquifer from adjacent slopes as groundwater flowed through sediments from the north and south, while around 20 litres per second exited the system as subsurface runoff, flowing out of the study area to the east.

Clogging Assessment and Measurement: In August 1984, an initial assessment was conducted to estimate the extent of clogging affecting the riverbed. This was achieved through a pumping test, which provided a calculated hydraulic conductivity of the riverbed sediments (k_0/b_0, where k_0 = riverbed conductivity and b_0 = riverbed thickness) at 4×10^{-6} (s^{-1}). The pumping test allowed for the estimation of the clogging without the need for sediment sampling, thereby preserving the integrity of the riverbed structure. Our field investigations confirmed the presence of a clogging layer approximately 2 cm thick. The groundwater level was measured in the line of observation wells located perpendicular to the river (Fig. 1). The groundwater level was measured four times a day (at 8, 12, 16 and 20 hours). At the same time, the water level in the river was measured. The pumping test also calculated the hydraulic conductivity of the aquifer, which ranged between $4.8\times10_{-4}$ and 1.65×10^{-3} $m.s^{-1}$, and a storativity coefficient (S) of 0.174.

Mechanical Removal of Clogging Layer: Subsequently, on November 29, 1984, a mechanical intervention was carried out to disrupt and remove the cell layer from the riverbed. This process involved the use of specialised equipment (a tractor-mounted plough) designed to physically break up clogged sediments, thereby restoring the natural permeability of the riverbed and improving groundwater recharge. Unfortunately, there is scant information available about the ploughing process. Available details indicate that the riverbed along the Brezovica water source area was ploughed, and multiple furrows were created to encompass the wetted area of the riverbed (Némethy, 1997).

Post-Intervention Monitoring: Following the mechanical removal of the clogging layer, a series of measurements were taken to monitor the changes in water levels. This included continuous observation of groundwater levels in nearby wells and surface water levels in the river to quantify the increase in groundwater recharge. The measurements were made for 9 days until December 8, 1984. The monitoring following the mechanical disruption

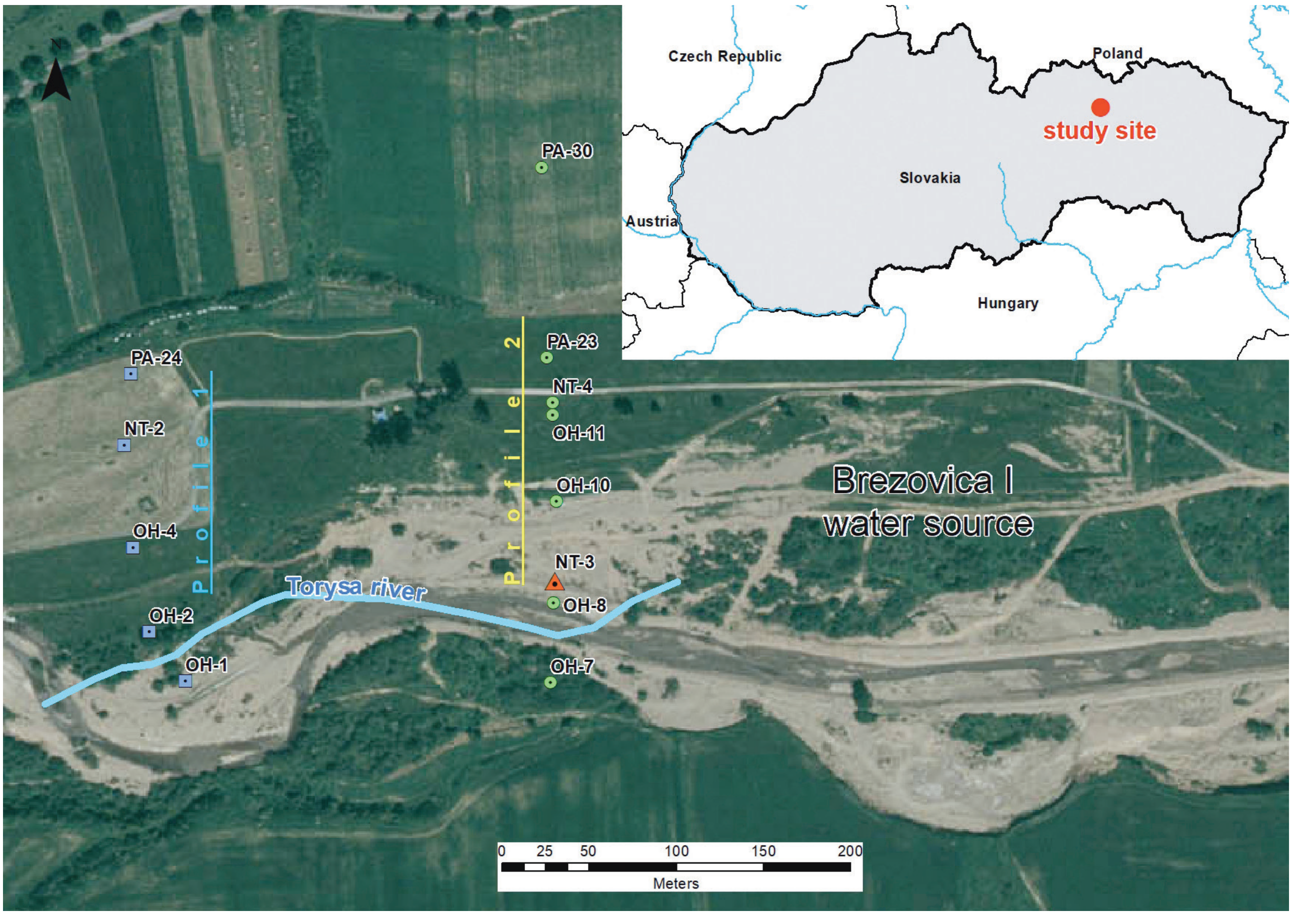

Fig. 1: Study site with observation wells (The course of the river in 1984, indicated by the blue line, does not correspond to the current situation shown in the orthophoto)

of the clogging layer involved systematic measurements of water levels in the two lines of wells perpendicular to the river (OH-1 - PA-24 and OH-7 - PA-30). In the line OH-7 - PA-30, the pumping well NT-3 was included. From the well 23.8 l/s of water was extracted starting from the beginning of the riverbed clogging layer disruption.

Data Analysis: The collected data were analysed using a one-dimensional (1D) cross-sectional model created in Microsoft Excel, which was set up to simulate an unconfined aquifer with a RIVER boundary condition (according to MODFLOW terminology, McDonald & Harbaugh (1988)). The steady flow equation was solved using the Gauss-Seidel iterative method with a relaxation factor, as described by (Kinzelbach Wolfgang, 1986). For the entire model, a constant value of the hydraulic conductivity k was used, and thus equation 1 for calculating the groundwater level in a given cell could be simplified to the following form:

$$h_i^n = ((h_i^{n-1} + h_{i-1}^n) \times h_{i-1}^n + (h_i^{n-1} + h_{i+1}^{n-1}) \times h_{i+1}^{n-1} + \frac{2 \times \sum q_i}{k}) / (2 \times h_i^{n-1} + h_{i-1}^n + h_{i+1}^{n-1}) \quad (1)$$

where h (m) represents the groundwater level, the lower index i denotes the cell number, the upper index (n^{-1}) denotes the previous iteration (or initial state), and the upper index n denotes the current iteration. q (m^3/s) indicates the inflow or outflow of water into/from (+/–) the cell (e.g., water inflow from the river or pumping/drainage from a well), and k (m/s) represents the hydraulic conductivity of the aquifer layer. At the river location, q is calculated from the relationship (equation 2):

$$q = \left(\frac{k_{riv}}{b_{riv}} \times A\right) \times (h_{riv} - h_i^{n-1}) \quad (2)$$

where k_{riv} (m/s) is the hydraulic conductivity of the riverbed sediments, b_{riv}(m) is the thickness of the riverbed sediments, A (m^2) is the area of the riverbed at the cell location, and h_{riv} (m) is the water level in the river. The above relationship assumes that $h_i^{n-1} > h_{bottom}$ where (m) is the riverbed level, where this condition is met in our model.

This model was calibrated by adjusting the hydraulic conductivity of the river-bed sediments before and after the clogging layer removal to match the calculated groundwater heads with the measured heads observed before and after the clogging layer removal. The agreement between the model's output and the observed data validated the effectiveness of the clogging removal and provided insights into the hydraulic behaviour of the aquifer-river system.

Justification of the Methodology: The methodology adopted in this research was strategically chosen for its comprehensive capacity to quantify the effects of clogging on groundwater recharge processes. Our initial step involved a carefully executed pumping test, which was instrumental in providing a minimally invasive assessment of the hydraulic properties of the riverbed. This preliminary measure was critical, as it established a reliable baseline while preserving the natural state of the riverbed, thus ensuring the integrity of subsequent interventions.

The next phase of our methodology centred on the mechanical removal of the clogging layer. This technique was selected for its ability to offer a direct and immediate restoration of the permeability of the riverbed. By physically removing the impediments to water flow, we were able to observe and measure the changes in infiltration rates in real-time. This hands-on approach was crucial to determining the practicality and effectiveness of mechanical interventions to improve groundwater recharge.

To complement the empirical fieldwork, we incorporated an Excel-based hydrological model to analyse the collected data. This model was designed to be robust in its computational capabilities and accessible for widespread use, allowing for simulation of the groundwater system response to the intervention. The model played a crucial role in capturing the dynamic interactions between the river and the aquifer, providing a framework for interpreting the observed data.

3. RESULTS

The results of our study, as detailed in Tabs. 1 and 2, provide a comprehensive account of the groundwater and river water level observations. The initial measurements, recorded on November 29, 1984, at 8:00 AM, established the baseline for our analysis. Each profile included a well on the southern bank of the river (OH-1 and OH-7), with additional wells, including the pumping well NT-3, situated on the northern bank. The data revealed that the groundwater levels rose most significantly in the wells closest to the river, specifically in wells OH-1 and OH-2, as well as OH-7 and OH-8, which are paired wells located on opposite banks of the river. The southern bank wells provided a means to evaluate if the effects of pumping were perceptible across the river. In Profile 1, the peak groundwater levels were observed on December 5, 1984, at 4:00 PM, six days following the intervention (Tabs. 1 and 3). Post-peak, the groundwater levels began to stabilise, displaying fluctuations that corresponded with the river water levels, indicative of a direct hydraulic connection between the river and the aquifer. In Profile 2, the groundwater levels had not yet stabilised six days after the intervention and continued to show a gradual increase (Tabs. 2 and 4). For wells positioned further from the river, the groundwater levels continued to rise beyond the eight-day mark, suggesting a delayed response to the intervention. This trend was evident in the measurements from Profile 1 and inferred from Profile 2. Unfortunately, the duration of the measurement period did not allow for the observation of stabilization in these more distant wells. The most substantial rise in groundwater levels was recorded in OH-1 and OH-2 wells, with an increase of 1.14 meters, and in OH-7 well, with an increase of 0.76 meters (Tabs. 3 and 4). In Profile 1, the change in groundwater level decreased with increasing distance from the river, with the smallest change of 0.48 meters noted in well PA-24, located 161.5 meters from the river (Tab. 1). The river level remained relatively constant throughout the observation period, with a minor decrease of 13 centimetres observed during the last three days. In Profile 2, the data revealed the impact of groundwater extraction from well NT-3, which was pumping at a rate of 23.8 l/s. At well OH-7, the groundwater level rose by 0.76 meters (Tab. 4), which was 0.38 meters less than the increase observed in wells OH-1 and OH-2. This suggests that the disruption of the clogging layer facilitated an increased inflow of water

Tab. 1: Groundwater heads from observation wells and water levels in the Torysa River during the experiment, Profile 1.

	OH-1	river	OH-2	OH-4	NT-2	PA-24
distance from river:	*-23.90*	*0.00*	*11.87*	*61.38*	*120.44*	*161.51*
25.11.84 12:00	480.95	480.84	480.50	480.18	479.75	482.06
26.11.84 12:00	480.94	480.82	480.49	480.16	479.75	482.03
27.11.84 12:00	480.93	480.80	480.46	480.14	479.72	482.03
28.11.84 12:00	480.88	480.74	480.41	480.10	479.69	482.00
29.11.84 08:00	480.83	481.99	480.70	480.38	480.07	479.67
29.11.84 12:00	481.08	481.99	480.99	480.44	480.07	479.67
29.11.84 16:00	481.30	481.99	481.20	480.59	480.08	479.69
29.11.84 20:00	481.50	481.99	481.31	480.64	480.12	479.71
30.11.84 08:00	481.56	481.98	481.41	480.80	480.21	479.73
30.11.84 12:00	481.60	481.98	481.51	480.84	480.24	479.76
30.11.84 16:00	481.63	481.98	481.51	480.90	480.27	479.78
30.11.84 20:00	481.67	481.98	481.55	480.91	480.32	479.81
1.12.84 08:00	481.73	481.98	481.61	481.03	480.38	479.86
1.12.84 12:00	481.76	481.98	481.64	481.07	480.41	479.89
1.12.84 16:00	481.78	481.98	481.66	481.09	480.43	479.91
1.12.84 20:00	481.79	481.98	481.67	481.11	480.45	479.93
2.12.84 08:00	481.81	481.97	481.69	481.14	480.49	479.95
2.12.84 12:00	481.82	481.97	481.71	481.17	480.52	479.97
2.12.84 16:00	481.83	481.97	481.71	481.18	480.53	479.98
2.12.84 20:00	481.84	481.96	481.72	481.19	480.54	480.00
3.12.84 08:00	481.86	481.96	481.74	481.21	480.57	480.02
3.12.84 12:00	481.86	481.95	481.74	481.23	480.58	480.03
3.12.84 16:00	481.86	481.95	481.74	481.24	480.58	480.03
3.12.84 20:00	481.87	481.96	481.75	481.24	480.59	480.05
4.12.84 08:00	481.90	481.97	481.77	481.27	480.62	480.08
4.12.84 12:00	481.92	481.98	481.78	481.28	480.63	480.08
4.12.84 16:00	481.93	481.98	481.79	481.29	480.64	480.08
4.12.84 20:00	481.94	481.98	481.80	481.30	480.64	480.09
5.12.84 08:00	481.95	481.99	481.81	481.31	480.67	480.14
5.12.84 12:00	481.95	482.00	481.82	481.32	480.68	480.14
5.12.84 16:00	481.97	482.00	481.84	481.34	480.69	480.15
5.12.84 20:00	481.95	481.97	481.82	481.34	480.69	480.16
6.12.84 08:00	481.92	481.90	481.78	481.33	480.71	480.18
6.12.84 12:00	481.90	481.88	481.78	481.32	480.71	480.19
6.12.84 16:00	481.89	481.87	481.77	481.31	480.71	480.18
6.12.84 20:00	481.87	481.87	481.76	481.30	480.70	480.17
7.12.84 08:00	481.88	481.88	481.76	481.30	480.71	480.17
7.12.84 12:00	481.90	481.89	481.75	481.31	480.74	480.19
7.12.84 16:00	481.92	481.90	481.78	481.32	480.72	480.21
7.12.84 20:00	481.94	481.91	481.81	481.35	480.78	480.23

Tab. 2: Groundwater heads from observation wells and water levels in the Torysa River during the experiment, Profile 2

	OH-7	river	OH-8	NT-3	OH-10	PA-30
distance from river:	-28.20	0.00	17.86	30.03	76.32	268.41
29.11.1984 08:00	478.02	478.83	477.58	477.46	477.08	476.54
29.11.1984 20:00	478.17	478.83	476.88	473.03	476.79	476.55
3.12.1984 12:00	478.57	478.83	477.13	473.13	476.92	476.55
5.12.1984 16:00	478.78	478.83	477.37	473.41	477.14	476.61

Tab. 3: Change in heads in Profile 1.

	OH-1	river	OH-2	OH-4	NT-2	PA-24
H 29.11.84	480.83	481.99	480.70	480.38	480.07	479.67
H 05.12.84	481.97	482.00	481.84	481.34	480.69	480.15
dH	1.14	0.01	1.14	0.96	0.62	0.48

Tab. 4: Change in heads in Profile 2.

	OH-7	river	OH-8	NT-3	OH-10	PA-30
H 29.1184	478.02	478.83	477.58	477.46	477.08	476.54
H 05.12.84	478.78	478.83	477.37	473.41	477.14	476.61
dH	0.76	0.00	-0.21	-4.05	0.06	0.07

from the river, thereby mitigating the effects of pumping on the opposite bank. Conversely, well OH-8 experienced a decrease in groundwater level of 0.21 meters due to pumping, although this reduction would likely have been more pronounced had the clogging layer remained intact. The temporal variations captured in Figs. 2 and 3, alongside the data from Tabs. 1 and 2, illustrate the dynamic response of groundwater levels to the intervention. These findings provide critical insights into the spatial and temporal dynamics of groundwater response and are instrumental in validating our methodology. They also inform future strategies for enhancing groundwater recharge, particularly in hydrogeological settings like those studied here. The results underscore the effectiveness of mechanical clogging layer removal in improving hydraulic connectivity and groundwater recharge, which has significant implications for sustainable water resource management.

The hydrological modelling conducted as a part of this study provided a detailed analysis of the groundwater system's response to the intervention. The 1D cross-sectional model was meticulously calibrated for two specific scenarios: the pre-intervention state on November 29, 1984, and the post-intervention state on December 5, 1984, for both Profile 1 and Profile 2 (Figs. 4 and 5, note that the profiles in the Figures are rotated, which means that the wells shown on the right side of the river in the image are on the northern bank of the river). This dual-phase modelling approach allowed for a comparative assessment of the hydraulic conductivity changes in the riverbed sediments. The initial model calibration, reflecting the pre-intervention conditions, was based on a hydraulic conductivity of 4.10^{-6} $m.s^{-1}$, as determined from the pumping test data. This phase also involved estimating the unknown outflow from the aquifer, which was crucial for setting the boundary conditions accurately. The model incorporated a constant head boundary condition on the left side, at a distance of –180 meters from the river (the minus sign indicates the right side of the river), to ensure that the boundary was not affected by the changes in riverbed sediment permeability. A RIVER boundary condition was applied at 20 meters (in the model – Fig. 4, the distance 'zero' is located at the position of well OH-1) for Profile 1 and 30 meters for Profile 2 (in the model – Fig. 5, the distance 'zero' is located at the position of well OH-7). On the right side of the model, a constant flow boundary condition represented the outflow from the system, with the exact value determined during the calibration process. The pumping well in Profile 2 was modelled with a constant rate of 23.8 l/s to simulate the

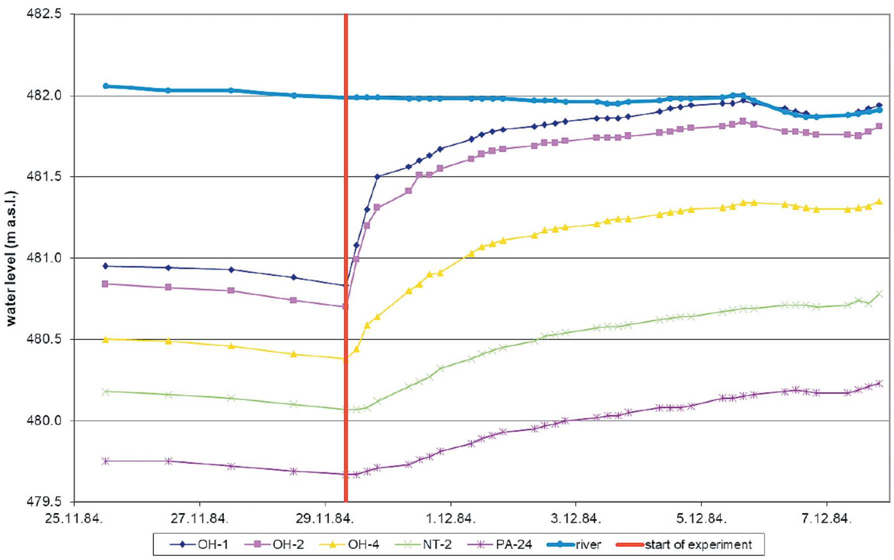

Fig. 2: Temporal variation of water levels throughout the experiment in observation wells in Profile 1 and the Torysa River.

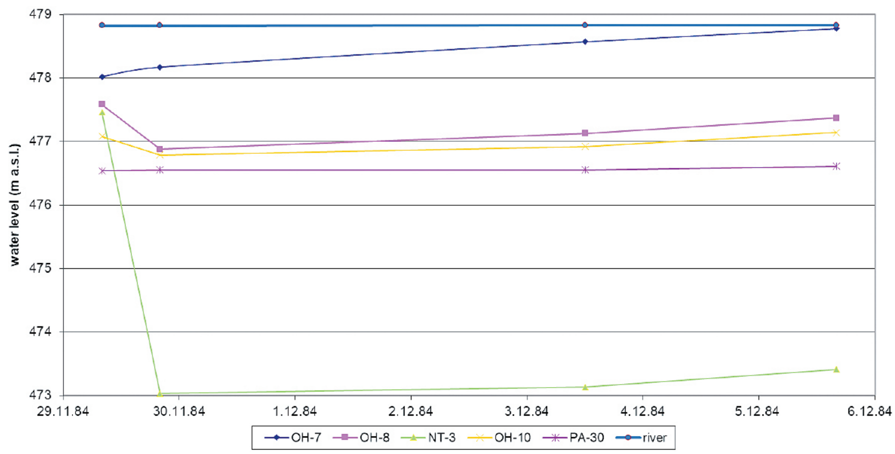

Fig. 3: Temporal variation of water levels throughout the experiment in observation wells in Profile 2 and the Torysa River.

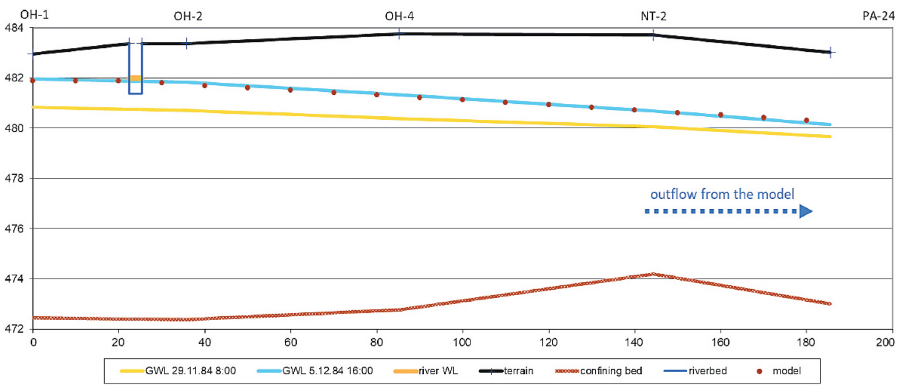

Fig. 4: Model setup of Profile 1 in Excel.

extraction of groundwater. Following the intervention, the recalibration of the model was necessary to align with the observed post-intervention groundwater heads. This recalibration revealed a dramatic increase in the hydraulic conductivity of the riverbed sediments to 4.10^{-3} m/s, indicating a significant enhancement in the riverbed's permeability. The specific flow from the river into the aquifer increased by a factor of 167, as evidenced by the recalibrated model, which reflects a substantial improvement in the rate of water infiltration from the river due to the clogging layer removal. Figs. 4 and 5 display the model results for Profiles 1 and 2, respectively, and demonstrate the good fit between the modelled and measured heads. This close alignment validates the model's accuracy in simulating the groundwater system's behaviour and supports the reliability of the findings.

4. DISCUSSION

The results of our experimental study on the Torysa River in Eastern Slovakia have demonstrated a significant increase in groundwater levels following the mechanical disruption of the riverbed's clogging layer. Specifically, the intervention led to a rise in groundwater levels of over one meter within six days, with the most substantial increases observed in wells closest to the river. The hydraulic conductivity of the riverbed sediments increased by three orders of magnitude, from 4.10^{-6} $m.s^{-1}$ to 4.10^{-3} $m.s^{-1}$, post-intervention, indicating a marked improvement in the river-aquifer hydraulic connection.

Using this model, we gained an understanding of the changes in hydraulic connectivity that occurred as a result of our intervention. The analysis revealed a significant improvement in groundwater recharge, as evidenced by the observed increase in water levels in the aquifer following the mechanical disruption of the clogging layer.

Modelling adds to the understanding the effectiveness of the intervention and for evaluating the potential of mechanical removal techniques in enhancing groundwater recharge. The extended period of rising groundwater levels in wells further from the river, as observed in the field data, suggests a delayed response to the intervention, which the model helped to contextualise. Although the measurement period was not sufficient to capture the full stabilization of groundwater levels in these wells, the model provided valuable insights into the long-term effects of the intervention. In summary, the hydrological model served as a useful tool for quantifying the infiltration from the river and for understanding the broader implications of the intervention on the river-aquifer system. The substantial increase in infiltration capacity has significant implications for water resource management, particularly in enhancing the sustainability of groundwater extraction practices. The study's findings highlight the importance of considering mechanical interventions as part of an integrated approach to managing and restoring hydrological systems.

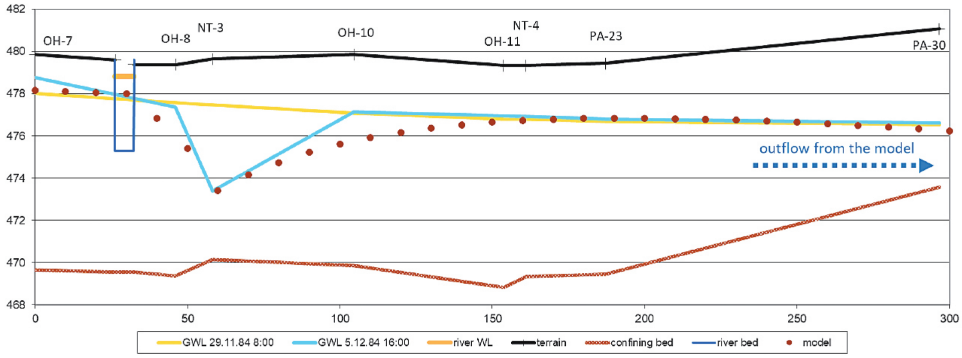

Fig. 5: Model setup of Profile 2 in Excel.

These findings have implications for the field of water resource management, especially considering the challenges posed by water scarcity in various regions. The clear demonstration of improved groundwater recharge after intervention underscores the potential of mechanical methods as a strategic approach to water management. It suggests that such interventions can effectively maintain or enhance the natural functionality of riverbeds, thus supporting the development of sustainable water extraction practices.

Furthermore, the study provides a scientific basis for understanding the complex relationship between human-induced activities and the hydrological systems they impact. By clarifying the benefits of mechanical interventions, this research contributes to the broader discourse on how to balance the needs of human water consumption with the preservation of ecological systems. It advocates for the continued exploration of innovative techniques that can sustainably manage and protect our vital water resources.

Our findings are in line with the dynamic nature of riverbed sediment clogging and its variability with river flow conditions, as highlighted by (Blaschke et al., 2003). This study challenges the common assumption in hydrological modelling that sediment conductivity is constant, providing empirical evidence of the significant alterations in riverbed sediment permeability that can be achieved through targeted interventions. The importance of incorporating temporal changes in sediment permeability into hydrological models is underscored for more accurate predictions of GW-SW interactions.

While the 1D model used in our study was effective for capturing the essential dynamics of the river-aquifer interactions, it is important to note that this approach may have oversimplified the complex interplay of factors influencing groundwater recharge. Future research should aim to employ more sophisticated 2D or 3D hydrological models, which could provide a more comprehensive representation of the system, particularly for unsteady flow conditions. These models would allow for a more accurate determination of the clogging coefficient of riverbed sediments and the calculation of the volume of water infiltrating from the river into the aquifer.

The type of clogging observed in the Torysa River before our intervention was identified as armour layer clogging (Blaschke et al., 2003), which is consistent with the findings of (Blaschke et al., 2003). While the natural removal of clogging layers, such as those occurring during flood events, offers a potential solution for maintaining riverbed permeability, their unpredictability makes them unreliable for consistent water management. Alternative methods, such as suction dredging (Provost et al., 2021), could provide a more controlled and potentially less invasive approach to the removal of the clogging layer. These methods may offer a more sustainable and long-term solution compared to the labour-intensive and potentially ecologically disruptive mechanical disruption utilised in this study.

The implications of our research are significant for regions where water extraction activities are prevalent, and the sustainability of water resources is a concern. Our study contributes to the body of knowledge by providing empirical evidence of the efficacy of mechanical disruption in enhancing river-aquifer interactions. It also highlights the necessity of incorporating the temporal variability of sediment permeability into hydrological models for more accurate simulations of natural systems and informs the development of water management policies that can adapt to these dynamic conditions.

5. CONCLUSIONS

This study aimed to assess the impact of mechanically removing the clogging layer on the permeability of the riverbed and the subsequent effects on groundwater recharge in the Torysa River. Our results indicated a significant, albeit temporary, increase in groundwater levels and hydraulic conductivity, confirming the potential of such interventions to enhance river-aquifer connectivity. The initial rise in groundwater levels and the threefold increase in hydraulic conductivity post-intervention are promising, yet the reformation of the clogging layer within approximately 40 days, as noted by (Némethy, 1986), suggests the need for ongoing management strategies.

The practical implications of our findings indicate that while mechanical disruption using a plough is an effective emergency response to improve groundwater recharge, the effectiveness of this method diminishes over time as the riverbed tends to rapidly clog again. In drought conditions, utilizing surface water directly could be an alternative; however, this approach is less favourable due to the need for extensive treatment and the higher costs associated—approximately 3.5 times more than treating groundwater – as well as the inherent quality differences between surface and groundwater.

We acknowledge that a limitation of our study is the use of a simplified 1D model, which, while useful for demonstrating the immediate effects of declogging, does not capture the full complexity of the system. Future research should focus on the development of more sophisticated 2D or 3D models that can provide a better and more precise representation, particularly for unsteady flow conditions. These models would enable a more accurate determination of the clogging coefficient of riverbed sediments and the calculation of the volume of water infiltrating from the river into the aquifer.

Our study highlights the importance of finding new ways to balance human water needs with the preservation of natural hydrological processes. Future research should focus on the development of long-term, ecologically sound declogging methods, the creation of predictive models that can accommodate the dynamic behaviour of sediment permeability, and the exploration of sediment resilience to clogging. Collaborative efforts across disciplines, including ecology and engineering, could lead to the development of interdisciplinary approaches to managing riverbed permeability. Investigating these areas will be crucial for devising effective and sustainable strategies to ensure the health of aquatic ecosystems and the longevity of water resources for future generations.

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