VARIABILITY OF WATER FLOW IN THE HYPORHEIC CORRIDOR: A CASE STUDY OF THE WARTA VALLEY IN POZNAŃ

Monika Okońska, Filip Wolny

Institute of Physical Geography and Environmental Planning, Adam Mickiewicz University in Poznań, Poznań, Poland

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Abstract: The relationship between surface water (SW) and groundwater (GW) is most evident in river valleys, where GW typically lies at shallow depths beneath the surface. The nature of this relationship can change dynamically over time, depending on various factors such as water levels, landform features, meteorological and hydrogeological conditions and the initial retention capacity of the catchment area. Additionally, in meandering rivers, GW may flow through the alluvium of the meander along the river channel within a hyporheic corridor, following the hydraulic gradient and thus shortening the flow path. This study presents the results of observations of river and GW levels conducted at the hydrological station of Adam Mickiewicz University (AMU), located in the Warta Valley in Poznań. The main objective was to determine the position of the GW table relative to the river water level and to analyse the variability of GW flow in the study area. The findings confirmed the functioning of the hyporheic corridor in the studied meander of the Warta River.

Keywords: hyporheic zone, meander, gaining stream, losing stream

Corresponding author: Monika Okońska; okonska@amu.edu.pl

Introduction

The relationship between surface water (SW) and groundwater (GW) is crucial for understanding the water cycle. This connection is most evident in river valleys, where GW typically lies at shallow depths beneath the surface. Despite its significance in shaping water resources, the interaction between these two systems remains poorly understood in many river basins. When analysing the interaction between hydraulically connected SWs and GW in river valleys in humid climates, where catchment retention is low, it is often assumed that GW feeds SW (Fig. 1). Valley sediments, particularly those of large lowland rivers, are typically rich in GW. Aquifers sustain river flow for much of the year during dry periods, especially during low-flow conditions and hydrological droughts (Staśko, Olichwer 2005, Van Loon 2015). During flood events, when water levels are high, rivers are generally believed to lose water through seepage into the underlying aquifer (Fig. 1).

A river can alternately gain GW (effluent stream) and lose water (influent stream), with its behaviour varying over time and along its course (Winter et al. 1998, Bajkiewicz-Grabowska 2020). In wide alluvial valleys, there are instances where the GW table matches the river water level. In such scenarios, the river neither gains

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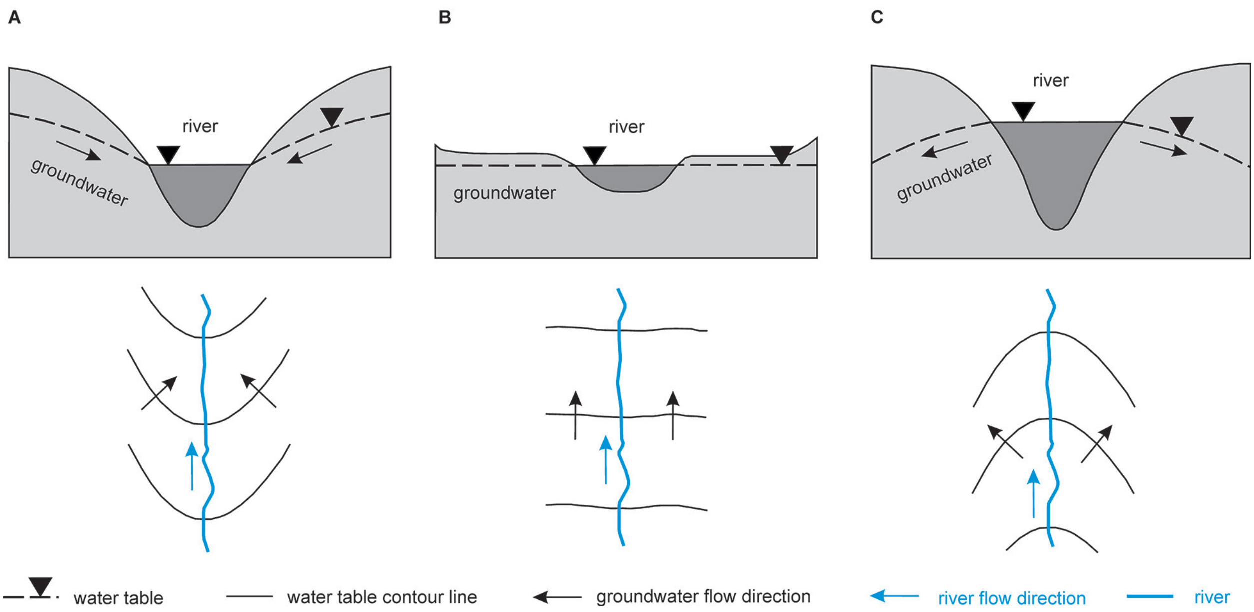

Fig. 1. Groundwater flow directions in a river valley for a straight section of the stream: gaining stream – A, equilibrium conditions – B and losing stream – C (based on Bajkiewicz-Grabowska 2020).

nor recharges to GW. Instead, GW flows across the entire valley width, following the slope of the valley (Bajkiewicz-Grabowska 2020) (Fig. 1).

In the case of meandering rivers, the sinuosity of the river can influence the direction of GW flow in the near-stream areas. The literature introduces the concept of the *river corridor* (Williams 1986, Harvey, Gooseff 2015) which refers to the area adjacent to the river where river erosion, channel evolution and the migration of meanders downstream are most likely to occur. The width of the river corridor is defined by the extent of the river meanders (the width of the meander belt), which is determined by the topography of the river valley, surface geology and the length and slope of the river (Fig. 2).

In the case of meandering rivers and relatively flat valley floors, conditions may arise in the inner part of the meander that allows for lateral GW recharge from river water into the near-stream zone, known as the *hyporheic zone* (Orghidan 1959, Winter et al. 1998, Marciniak et al. 2022). The hyporheic zone is understood in the literature as a zone of porous sediments beneath and along the riverbed, where shallow GW and river water mix and where a series of important hydrological processes occurs, including hydrodynamic (upwelling and downwelling), hydrochemical and hydrobiological processes (Naegeli, Uehlinger 1997, Boulton et al. 1998, Lerner et al. 2009, Krause et al. 2011, Stegen et al. 2018, Lewandowski et al. 2019, Jekatierynczuk-Rudczyk et al. 2021, Wen et al. 2024). This study defines the hyporheic zone as shallow sub-surface sediments through which SW enters, flows and eventually returns to the main river channel (Stegen et al. 2018). It is assumed that water in hyporheic corridors flows through fine-grained alluvium along the riverbed, with the meander apex limiting hyporheic flow (Boulton et al. 1998, Alley et al. 2002, Smith 2005, Cardenas 2009). The concept of the hyporheic zone, hyporheic flow and hyporheic corridor is schematically presented in Figure 2.

Hyporheic zones are widely considered interfaces between GW and SW in river corridors. This

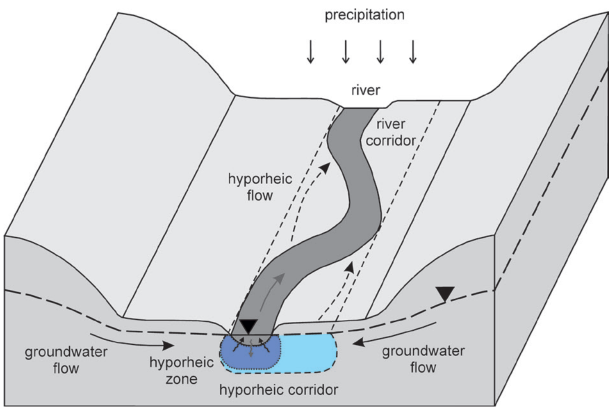

Fig. 2. Concept of the hyporheic zone and hyporheic flow in the corridor of a meandering river valley (modified scheme based on Williams (1986), Winter et al. (1998), and Alley et al. (2002).

exchange zone is assumed to be ubiquitous and relatively stable over time and space. According to modelling studies conducted by Wu et al. (2024), hyporheic exchange is intermittent and restricted to a narrow range of hydrological conditions, characterised by small differences between the levels of river water and GW.

Stanford and Ward (1993) proposed the *hyporheic corridor concept*, which is particularly applicable to large meandering rivers with wide floodplains. This concept, describing the continuous and dynamic interactions between the stream water and water in the adjacent sediments of the river's floodplain, helps better explain the distinction between the hyporheic zone and GW. According to the researchers, these connections are vertical, lateral, longitudinal and temporal (Dahl et al. 2007, Smith et al. 2008, Pacioglu 2010). The sub-surface zone forming the hyporheic corridor extends to alluvial aquifers several kilometres from the main river channel (up to 3 km), connecting riverine zones, side channels, paleochannels and floodplain aquifers (Stanford, Ward 1993, Boulton et al. 1998). The functioning of the corridor, its temporal variability and the pathways of alluvial flow depend on the hydrology and ecology of the alluvial sediments, linked to their degree of connectivity and the river's flow regime. According to Smith et al. (2008), the concept of the hyporheic corridor, as proposed by Stanford and Ward (1993), still needs to be thoroughly tested and validated.

The aim of the research was to investigate the seasonal variability of the GW table in relation to the river water level in a selected section of the Warta Valley, as well as to analyse the dynamics of changes in the direction of GW flow in the study area, with the goal of confirming the functioning of the hyporheic corridor in the Warta meander.

SW and GW interactions play a key role in shaping water quantity and water quality. Any alterations in these interactions can directly impact both surface and GW availability and affect their quality due to the exchange of contaminants and nutrients between surface and GW. Moreover, GW discharge can stabilise river temperatures, alter the chemical composition of water and affect pH, mineral content and dissolved oxygen levels, which are crucial for aquatic ecosystems. Conversely, SW infiltration can introduce cooler or warmer water into aquifers, affecting microbial and chemical reactions. In areas where it is possible, proper management of these interactions is crucial for ecosystem health and sustainable water resources.

Because of the importance of SW and GW interactions in relation to water quantity and quality, the European Union (EU) has introduced several directives and policies on this topic. For example, the Water Framework Directive (WFD) (2000/60/EC) requires monitoring of SW and GW interactions to prevent water-quality deterioration and improve water quantity. The Groundwater Directive (GWD) (2006/118/EC) establishes quality standards for GW to prevent contamination from SW pollutants and ensures that GW recharge does not compromise water quality through sustainable abstraction limits. The Nitrates Directive (91/676/EEC) regulates nitrate levels in SW and GW, addressing nutrient transport caused by hydrological interactions. An in-depth analysis of these interactions also aligns with the objectives of the EU Biodiversity Strategy for 2030, which aims to improve water resource management as part of climate resilience and ecosystem protection.

Study area and research methods

The study area, i.e. the hydrological station of Adam Mickiewicz University in Poznań, is located in the northern part of the city (Fig. 3), on the left bank of the Warta River, a tributary of the Oder. According to the physico-geographical division by Richling et al. (2021), it is situated in the macroregion of the Greater Poland Lakeland (315.5) and the mesoregion of the Poznań Warta River Gorge (315.52). Geomorphologically, the area (i.e. the Warta River valley) consists of flood terraces formed as a result of the erosion of Neogene clays (Fig. 4), on which sediments – mainly in the form of fine and medium sands – were deposited during the North Polish Glaciation and the Holocene. The study area, which is part of the Warta River meander, is characterised by a gentle slope of approximately 1‰. The terrain descends from the direction of the railway viaduct in the western part towards the east, i.e. towards the Warta River bed.

The presence of impermeable clays at a relatively shallow depth below the ground surface

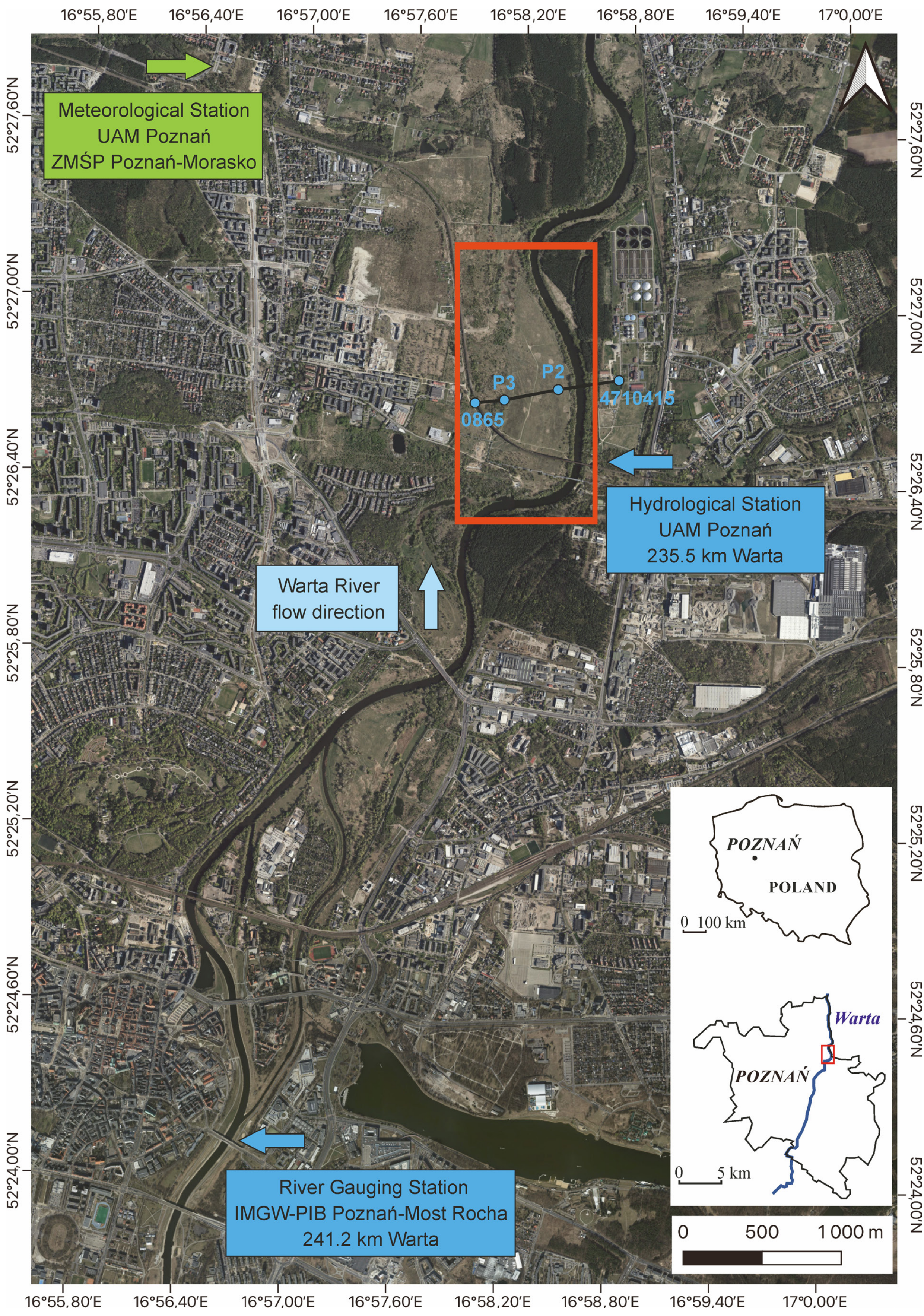

Fig. 3. Location of the study area (based on an orthophotomap from www.geoportal.gov.pl).

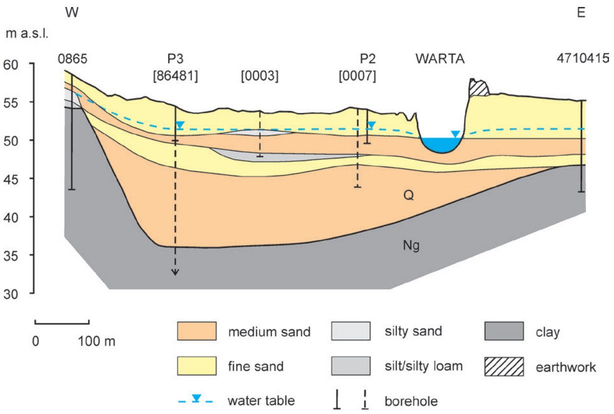

Fig. 4. Hydrogeological cross-section through the sediments of the Warta River meander. Dashed lines indicate profiles (borehole number in parentheses) that are located near the cross-sectional line and were used to interpret the geological structure.

prevents deep water circulation within the meander. The analysis of the sediments in terms of grain size distribution and hydraulic properties is presented in Table 1. The values of hydraulic conductivity were determined using the empirical United States Bureau of Reclamation (USBR) formula based on the grain size distribution:

$$k = 0.36d_{20}^{2.3}\ [\mathrm{cm \cdot s^{-1}}] \quad (1)$$

and grain uniformity index U according to the formula:

$$U = d_{60} / d_{10}\ [-] \quad (2)$$

where d_{10}, d_{20} and d_{60} [mm] represent effective sizes of grains corresponding to 10%, 20% and 60% finer in the grain size distribution graph, respectively. The conducted grain size analyses indicate a low variability in sediment grain size in the zone of GW table fluctuations (U = 1.53–2.79, U < 5). The calculated hydraulic conductivity values are k = 0.65–1.65 m · h^{-1} for fine sands and k = 1.91–5.85 m · h^{-1} for medium sands, which correspond very well with the results of *in situ* studies conducted in the Warta Valley by Marciniak (1999).

The Warta River in the analysed section has a moderately developed nival regime, which means it is fed by melting snow. This type of river regime is characterised by an average spring flow (March–April) ranging from 130% to 180% of the average annual flow (Wrzesiński, Perz 2016), which is 106.95 m^3 · s^{-1} at the Poznań profile (Choiński 2019). The studied meander of the Warta is located approximately 5.7 km downstream from the Poznań-Most Rocha gauging station (Fig. 3). A strong hydraulic connection between GW and river water was observed in the study area (Okońska, Brzezińska 2024).

According to the recommendations of Obidziński (2018), the local direction of GW flow in a selected section of the river valley was determined based on measurements of the GW table depth in observation wells arranged in a triangular pattern and measurements of the water level in the Warta River at the 235.5 km point. The

Table 1. Granulometric and hydraulic characteristics of meander sediments.

No.	Depth	Grain uniformity index U	Hydraulic conductivity k	Clay + Silt (<0.063 mm)	Sand (0.063–2 mm)			Gravel (2–63 mm)	Type*	
					Fine sand	Medium sand	Coarse sand		PN-EN ISO 14688	PN-B-02480
	[m]	[–]	[m · h^{-1}]	[%]					[–]	
P1										
P1/4	2.2	1.78	0.81	1.5	81.1	17.0	0.4	0.0	FSa	SiSa
P1/5	3.0	2.11	0.99	1.7	58.7	27.5	12.1	0.0	FSa	FSa
P1/7	4.3	1.53	0.65	2.4	93.8	3.6	0.2	0.0	FSa	SiSa
P2										
P2/2	1.6	1.64	1.91	0.4	39.9	59.3	0.4	0.0	MSa	FSa
P2/3	3.0	1.54	1.65	0.6	59.1	39.6	0.7	0.0	FSa	FSa
P2/4	3.7	2.00	5.85	0.2	8.9	83.2	7.3	0.4	MSa	MSa
P3										
P3/3	2.0	2.18	1.19	1.4	47.0	43.8	7.8	0.0	FSa/MSa	FSa
P3/5	2.7	2.00	1.41	1.0	45.7	45.1	8.2	0.0	FSa/MSa	FSa
P3/8	3.4	2.00	0.99	1.6	59.1	25.6	12.8	0.9	FSa	FSa
P3/10	4.1	2.79	1.91	0.4	32.4	55.4	10.9	0.9	MSa	MSa
P3/12	4.5	2.00	3.98	0.6	14.8	76.7	7.4	0.5	MSa	MSa

* FSa, fine sand, MSa, medium sand, SiSa, silty sand.

observation wells were manually drilled using the rotary method. Plastic pipes were used in the boreholes, allowing water to enter through the bottom. The water inflow depths are 3.70 m below ground level for observation well OW1, and for wells P1, P2 and P3, they are 4.60 m, 4.20 m and 4.40 m below ground level, respectively.

The measurement points forming the hydrological station were levelled, with the levelling tied to the national geodetic height reference system (the mean error in the adjustment of geodetic traverses was ±0.74 mm). Water table measurements were performed with an accuracy of ±1.0 cm using a hydrogeological whistle and a measuring tape at weekly intervals. Additionally, data from the IMGW-PIB Poznań-Most Rocha gauging station (daily data from 2022 to 2023 and hourly data from 2024) and daily precipitation data from the ZMŚP Poznań-Morasko meteorological station (2022–2024) were used for analysis. Maps of the water table were generated using Surfer v.13 software, with kriging interpolation used to draw contour lines. Due to the limited number of wells, the visualisation in the southern part of the meander should be considered approximate.

In 2022–2023, water table observations could only be conducted for half of the year during average and high Warta River levels, when the water in well OW1 was above the bottom of the well, i.e. above the elevation of 50.40 m.a.s.l. The periods of high, medium and low Warta River levels at the study site were approximated based on measurements from the IMGW-PIB Poznań-Most Rocha gauging station (Hydrological Yearbook 2023). In the 2024 hydrological year, after expanding the network of observation wells with wells P1–P3 at greater depths (well bottom elevation around 49.8 m.a.s.l.), measurements were also taken during periods of low Warta River levels.

To determine the water level difference between the local hydrological station of Adam Mickiewicz University on the Warta River and the IMGW-PIB Poznań-Most Rocha gauging station, a longitudinal profile of the water level gradient along the Warta River was created. The profile was based on data from the Digital Elevation Model (with a vertical accuracy of ±5.0 cm) available on the www.geoportal.gov.pl platform, covering the section from the northern side of the Św. Rocha Bridge (241.2 km of the Warta River) to the northern side of the Naramowicki Bridge (235.5 km of the Warta River), i.e. the railway viaduct. A difference of 1.08 m in the river water level between the study points was obtained, which was additionally confirmed by field measurements carried out in 2024. The obtained value, when related to the length of the analysed section, gave a river water level gradient of 0.19‰. A similar longitudinal profile was created for the studied river meander between the 235 km and 236.5 km section, where a water level difference of 0.29 m was observed over approximately 1550 m, resulting in a similar gradient of 0.19‰.

Results

First, the difference in the river water level at the beginning and end of the studied meander (approximately 235–236.5 km along the Warta River) was analysed. The visualisation of the water level in metres above sea level, without accounting for the inflow of GW from surrounding areas, is presented in Figure 5. The observed

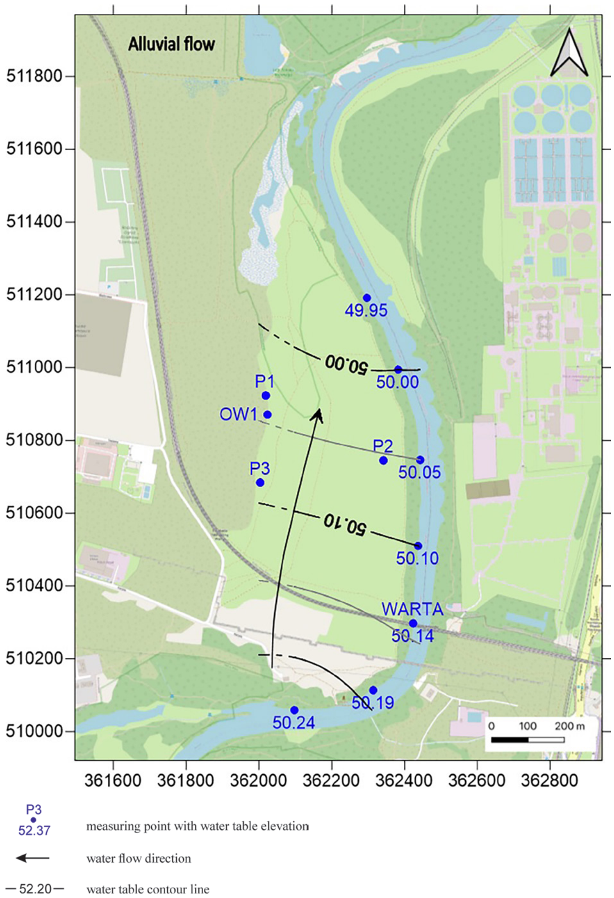

Fig. 5. Water flow in the hyporheic corridor within the meander bend.

hydraulic gradient, estimated at 0.25‰, forces some river water to infiltrate into the alluvial sediments and flow through the hyporheic corridor. Due to the mixing of river water and GW, it can be assumed that a *hyporheic corridor* zone is formed in the subsurface formation of the meander bend (see Fig. 2).

The direction of water flow – from S to N – in the hyporheic corridor is overlapped by water flow in the W–E or E–W direction, depending on the SW level relative to the GW level, which is hydraulically connected. This periodically alters the functioning of the hyporheic corridor. Observations of the relative position of the river water table to the GW table in the study area during the hydrological years 2022–2024 identified periods of river water infiltration, GW discharge into the river and moments of equilibrium between the two (Fig. 6). These instances were associated with changes in the direction of water flow within the Warta River meander (Fig. 7).

The field studies indicate that automatically categorising a river as a gaining or losing stream based solely on specific water levels is an oversimplification. The river's behaviour depends on various factors, including water levels, terrain morphology, meteorological and hydrogeological conditions and the initial retention capacity of the catchment area. During the study, it was observed that in the analysed hyporheic corridor, the hydrodynamic behaviour of the Warta River was closely associated with periods of rising or falling water levels in the river (Fig. 6).

The losing stream character of the Warta River in the studied section was observed during the first part of the hydrological year, specifically from November to March and in October. During this time, the river water level rises from a low to a high state. The flow direction is distinctly oriented from the river towards the alluvial sediments of the meander (Fig. 7A), resulting in the recharge of GW by river water and its mixing within the hyporheic corridor.

The transition from the losing stream (influent) period to the gaining stream (effluent) period is brief. The shift in the river's hydrodynamic behaviour occurs over a period of several days (Fig. 6). During this transition, similar water table elevations were recorded in the river and the observation wells, with GW flowing through the hyporheic corridor along the river channel. This state, referred to as equilibrium, was documented during field measurements on 12 March 2024 (Fig. 7B). The arrangement of water table contour lines in Figure 7B illustrates the transition from the losing stream period to the gaining stream period of the Warta River.

Spring months (April–May) are characterised by a rapid decline in the river water level due to lower precipitation and higher air temperatures. A significantly slower decrease in the GW table is observed, marking a period of pronounced GW discharge into the river (Fig. 7C). During the summer months (June–September), low river water levels persist, and GW discharge remains the dominant process. However, during this time, rapid but short-lived rises in river water levels are occasionally observed, caused by heavy rainfall events (Fig. 6, year 2024). As a result, the hyporheic corridor is recharged with river water, temporarily altering the local direction of GW flow (Fig. 8). During these periods, changes in the direction of flow occur within the river's hyporheic corridor, with the flow potentially covering different sections.

The transformation of hydrological conditions and the shift in the river's hydrodynamic behaviour from a gaining stream to a losing stream happens very quickly, within a few days or less, in the second half of September, when a steady change in the river water level relative to GW is observed, marking the beginning of another period of infiltration in the Warta River. Figure 6 indicates that, in the observed section of the river, the Warta can exhibit either losing or gaining character, both at medium and high water levels. A correlation can be observed between the river's behaviour and periods of rising or falling water tables.

The flow of water in the area of the studied hyporheic corridor results from meteorological factors, including precipitation amount and duration, air temperature, humidity and associated evaporation rates, as well as hydrogeological factors, such as the lithological composition of the soil, terrain morphology and the depth of the GW table. These conditions are linked to the effective infiltration index, which represents the ratio of infiltrating water reaching the saturation zone to the average annual precipitation amount in a given area (Dowgiałło et al. 2002). According to Pazdro's classification (Kowalski

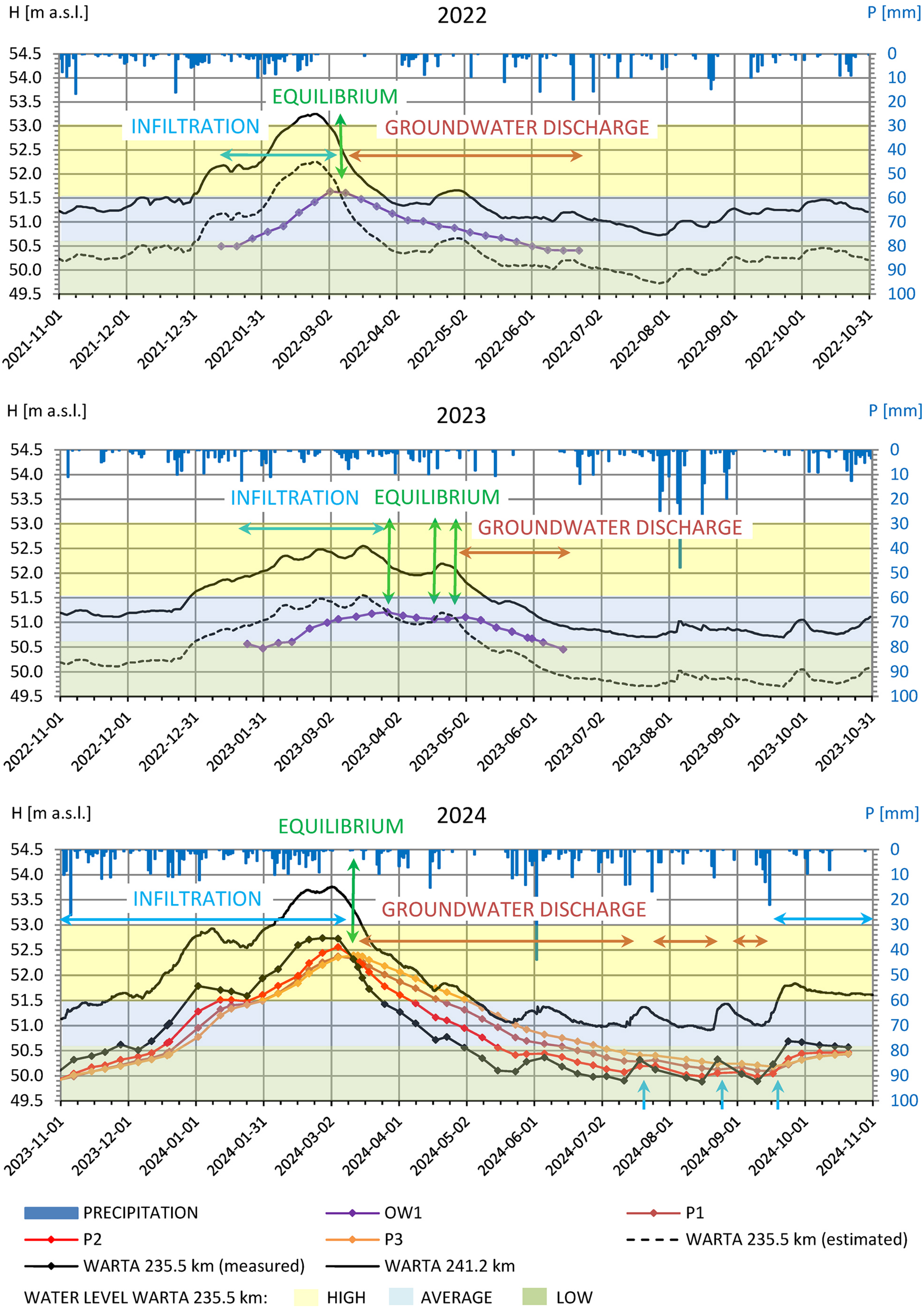

Fig. 6. River and groundwater levels (H) in the hydrological years 2022–2024 against the background of precipitation (P).

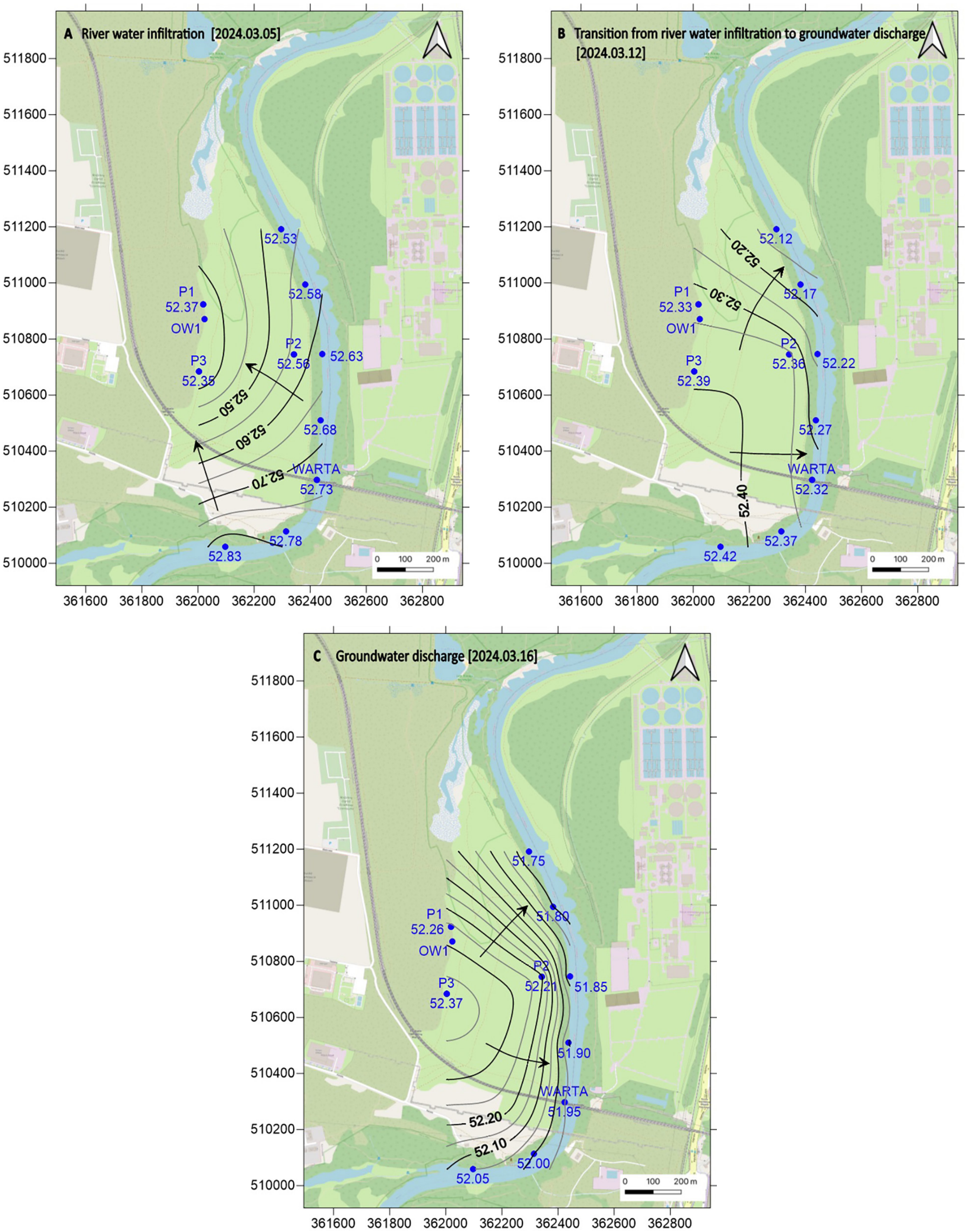

Fig. 7. Direction of groundwater flow in the hyporheic corridor of the Warta River during losing stream conditions – A, the transition from losing stream to gaining stream conditions – B and gaining stream conditions – C.

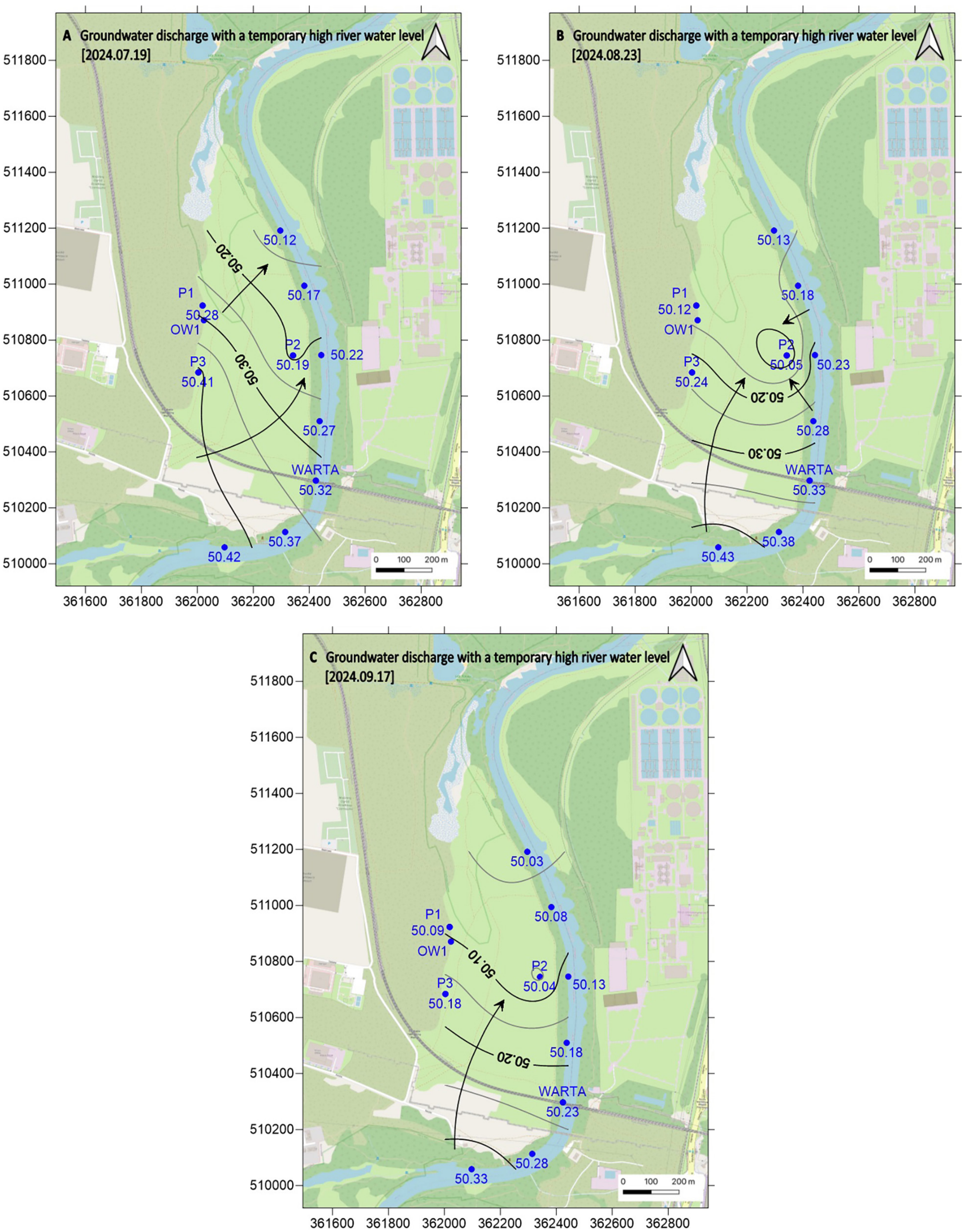

Fig. 8. Direction of groundwater flow in the hyporheic corridor of the Warta River during a rise in river water levels due to precipitation.

Table 2. Changes in the position of the water table/ river water level in the study area in 2024.

Object	Distance from river	Depth to the water table		Amplitude
		Min	Max	
	[m]			
Warta	–	–	–	2.86
P1	400	1.96	4.43	2.47
P2	100	1.45	4.11	2.66
P3	400	1.88	4.38	2.50

1998), alluvial deposits fall into class III, indicating average infiltration conditions with an effective infiltration index around 0.20. Effective infiltration occurs more rapidly when the water table of the uppermost aquifer is shallower, with GW responding to precipitation more quickly. During observations in the study area of the Warta River, fluctuations in the GW table in observation wells were noted, ranging from 1.45–1.96 m below the surface (March) to 4.11–4.43 m below the surface (September–October), with an amplitude of 2.47–2.66 m (Table 2). In 2024, the Warta River water level fluctuated within a range of 2.86 m, with the highest level recorded at the end of February and March and the lowest in mid-August.

Summary

This study presents the results of observations on SW and GW levels conducted between 2022 and 2024 at the hydrological station of Adam Mickiewicz University, located in the Warta River valley in the northern part of Poznań. The installation of three observation wells and a gauging station on the Warta River, along with the levelling of measurement points relative to the national geodetic height reference system, enabled the identification of relationships between river water and GW in the studied Warta River meander. It was found that the flow of GW in the hyporheic corridor of the Warta River was conditioned by:

1. The flow of infiltrating river water due to the difference in water levels at the beginning and end of the studied section of the Warta River,
2. Infiltration of SW and discharge of GW depending on the difference in water levels between the river and the alluvial deposits of the meander,
3. Meteorological and hydrogeological conditions, such as precipitation amounts and the depth to the GW table, which generate variable effective infiltration of precipitation during different periods of the hydrological year.

Fluctuations in the first GW level were recorded in the study area, averaging 2.5 m over the course of the hydrological year. The infiltrating character of the Warta River was observed in the hyporheic corridor for approximately 6 months of the hydrological year (from November to March and in October). During the spring and summer months (April–August and September), however, GW was primarily discharged into the Warta. The river's character changed very rapidly within a few days. It should be noted that the influent or effluent character of a meandering river that depends on the difference in water levels between the Warta and the valley's alluvium does not depend solely on the river water level and cannot be automatically correlated with it. The water level in the river responds much more quickly to changing meteorological conditions than the GW table. This is particularly evident in the spring months when the Warta water levels fluctuate from high to medium and then to low, while the GW table in the alluvium declines more slowly.

The obtained results document the dynamics of surface and GW exchange in the hyporheic corridor of the Warta River. The conducted studies may inspire further observations of the functioning of the hyporheic corridor, especially regarding hydrochemical and hydrobiological processes. Understanding the interactions between SW and GW is crucial in the context of preventing their pollution and ensuring their protection. In this regard, the authors' research aligns with studies conducted in all EU member states on assessing impacts within the GW–SW interface zone.

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Authors' Contribution

MO: conceptualisation, methodology, project administration, data curation, investigation, visualisation, writing – original draft, writing – review, editing and correspondence with editor. FW: conceptualisation, data curation, visualisation, writing – original draft and writing – review and editing. The authors declare no conflict of interest in this study. Both authors have read and agreed to the published version of the manuscript.

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