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Determining the groundwater movement velocity using cross-correlation analysis: Velika Morava alluvium case study

Milan Kresojević[1], Vesna Ristić Vakanjac[2], Dušan Polomčić[2], Boris Vakanjac[3], Dragan Trifković[1], Jugoslav Nikolić[4]

[1] University of Defence in Belgrade, Military Academy, Veljka Lukića Kurjaka 33, 11042 Belgrade, Serbia;
E-mails: milan.kresojevic@va.mod.gov.rs; dragan.trifkovic@va.mod.gov.rs
[2] University of Belgrade, Faculty of Mining and Geology, Djusina 7, 11000 Belgrade, Serbia;
E-mails: vesna.ristic@rgf.bg.ac.rs; dusan.polomcic@rgf.bg.ac.rs
[3] Republic Hydrometeorological Service of Serbia, Kneza Višeslava 66, 11030 Belgrade, Serbia;
E-mail: jugoslav.nikolic@hidmet.gov.rs

Определяне на скоростта на движение на подземните води с помощта на крос-корелационен анализ: примерно изследване на алувиалния хоризонт на Велика Морава

Милан Кресоевич[1], Весна Ристич Ваканяц[2], Душан Поломчич[2], Борис Ваканяц[3], Драган Трифкович[1], Югослав Николич[4]

Abstract. Monitoring of water levels and flow rates of the Velika Morava River, due to its significance for the Republic of Serbia, was established over 100 years ago at the profiles of Ljubičevski Most and Ćuprija. This was followed a year later by the activation of the Varvarin monitoring station, then in 1935 by the Žabarski Most, and in 1952 by the Bagrdan station. Groundwater monitoring started in 1977 with 12 piezometers and the network was gradually expanded to include 92 piezometers in 2002. This study presents a comparative analysis of the water level elevations of the Velika Morava River and associated piezometers arranged along and normal to the river flow. Cross-correlation analysis was applied to evaluate the existing hydraulic connectivity between the Velika Morava River and the groundwater, with results used to calculate the average groundwater flow velocities within this section of the Velika Morava basin.

Keywords: surface and groundwater regime, cross-correlation analysis, groundwater flow velocity, the Velika Morava River.

Introduction

The Velika Morava River is considered the main drainage basin of the Republic of Serbia because its watershed covers approximately 42% of its territory (37 444 km²). A relatively small portion of the Velika Morava watershed also belongs to the Republic of Bulgaria (1237 km²) and North Macedonia (44 km²). This river originates near Stalać, where it is formed by the confluence of the West Morava (15 849 km²) and the South Morava (15 469 km²). At Smederevo, with an average flow rate of 300 m³/s, it flows into the Danube River. The alluvial plain of the Velika Morava is also the most densely populated area of central Serbia. However, due to frequent flooding of this river and inundation of the surrounding areas, all settlements, except for Ćuprija, are located at a certain distance from the riverbank (Kresojević et

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al., 2023). Aside from Ćuprija, other significant settlements include Paraćin, Jagodina, Batočina, Lapovo, Svilajnac, Velika Plana, Požarevac, and Smederevo. The high population density is a result of the presence of significant reserves of groundwater found within the alluvium of the Morava River and fertile soil. Since the groundwater is hydraulically connected to the Velika Morava, these groundwater reserves are replenished relatively quickly, and they are primarily used for the water supply of the population and industry, as well as for irrigation (Kresojević et al., 2023). Due to the significance of this river, monitoring of quantitative parameters on the Velika Morava River (water level and flow rate) was established very early on by official agencies (now the Republic Hydrometeorological Service of Serbia). In 1923, monitoring started at the profiles of Ćuprija and Ljubičevski Most, followed a year later by the initiation of monitoring water level and flow rate at the Varvarin profile, and in 1935, at the Žabarski Most. After World War II, specifically in 1952, the Bagrdan water measurement profile was also included in the monitoring network of the Velika Morava. Water level observations are conducted at all water measurement profiles, while flow rate measurements are carried out at the Ljubičevski Most, Bagrdan, and Varvarin profiles. After World War II, but somewhat later, monitoring of groundwater in the alluvium of the Velika Morava began. Between 1977 and 1978, groundwater levels were measured at 12 piezometers. Then, from 1987 to 1988, 8 more piezometers were added to the monitoring network, and in 1997, one more was added (for a total of 21 monitoring points). In the first half of 2002, an additional 71 piezometers became part of the monitoring network, which tracks changes in groundwater levels in the alluvium of the Velika Morava. The piezometers are positioned in such a way that they can be arranged in linear profiles normal to the Velika Morava or parallel to the river flow, or they can be placed separately (Kresojević, 2024, https://www.hidmet.gov.rs/ciril/hidrologija/podzemne/o_profili.php).

Methodology

Correlation functions were established to determine the hydraulic connection between the water level of Velika Morava and the groundwater levels recorded at the analyzed profiles. These time series analyses are used in cases where the surface water levels condition the time-dependent random variable (in this case, groundwater levels). In these analyses, the relationship between the time-dependent random variable (absolute groundwater levels observed in the piezometers) and the independent random variable (absolute water level of the Velika Morava) is quantified by calculating cross-correlation coefficients for different time lags (Krešić, Stevanović, 2010; Ristić Vakanjac 2015). To apply cross-correlation analyses to determine the strength of the connections between groundwater and surface water, the water measurement profiles of Ljubičevski Most and Žabarski Most, were selected, along with the accompanying piezometers arranged linearly, both perpendicular and parallel to the river. The profiles, from the most upstream to the most downstream, are as follows: The Dubravica-Lipe profile with three piezometers on the right valley side (NPPD121 (1.58 km), NPPD122 (1.57 km), and NPPD123 (1.59 km)) and one on the left (NPPL123 (3.39 km)); The Ljubičevski Most profile with four piezometers on the right (NP973 (0.03 km), NP908A (1.16 km), NP909A (2.01 km), and NP910A (2.83 km)) and three piezometers on the left valley side (NP904A (0.91 km), NP974A (1.54 km), and NP901A (0.2 km from the Jezava River, approximately 5.5 km from the Velika Morava)); The V. Plana-Žabari profile with three piezometers on the right (NPPD143 (2.52 km), NPPD144 (3.77 km), NPPD145 (6.26 km)) and two on the left (NPPL141 (0.63 km) and NPPL142 (1.31 km)); The Markovac-Svilajnac profile with two piezometers on the right (NPPD152 (1.44 km) and NPPD153 (1.45 km)) and two piezometers on the left valley side of the Velika Morava (NPPL151 (0.05 km) and NPPL152 (0.25 km)). Note: The values in parentheses next to the piezometer designations represent their distance from the Velika Morava, expressed in kilometers. The spatial position of the analyzed piezometers is shown in Figure 1a.

Results

The results of the conducted cross-correlation analyses for each profile are presented in the correlograms, specifically in Figure 1b for the Dubravice-Lipe profile, Figure 1c for the Ljubičevski Most profile, Figure 1d the V. Plana-Žabari profile, and Figure 1e for the Markovac-Svilajnac profile.

Discussion and conclusion

The lowest values of the cross-correlation coefficients were obtained from the analysis of the influence of the Velika Morava River on groundwater levels in the Dubravice-Lipe area (the highest correlation coefficient value is $r = 0.1$). The reason for these low correlation coefficient values is that the piezometers are located in an area where oxbow lakes are present, as well as the influence of the Danube and Dunavac, which are at similar distances from the piezometers as the Velika Morava. From Figure 1c, it can be clearly seen that the values of

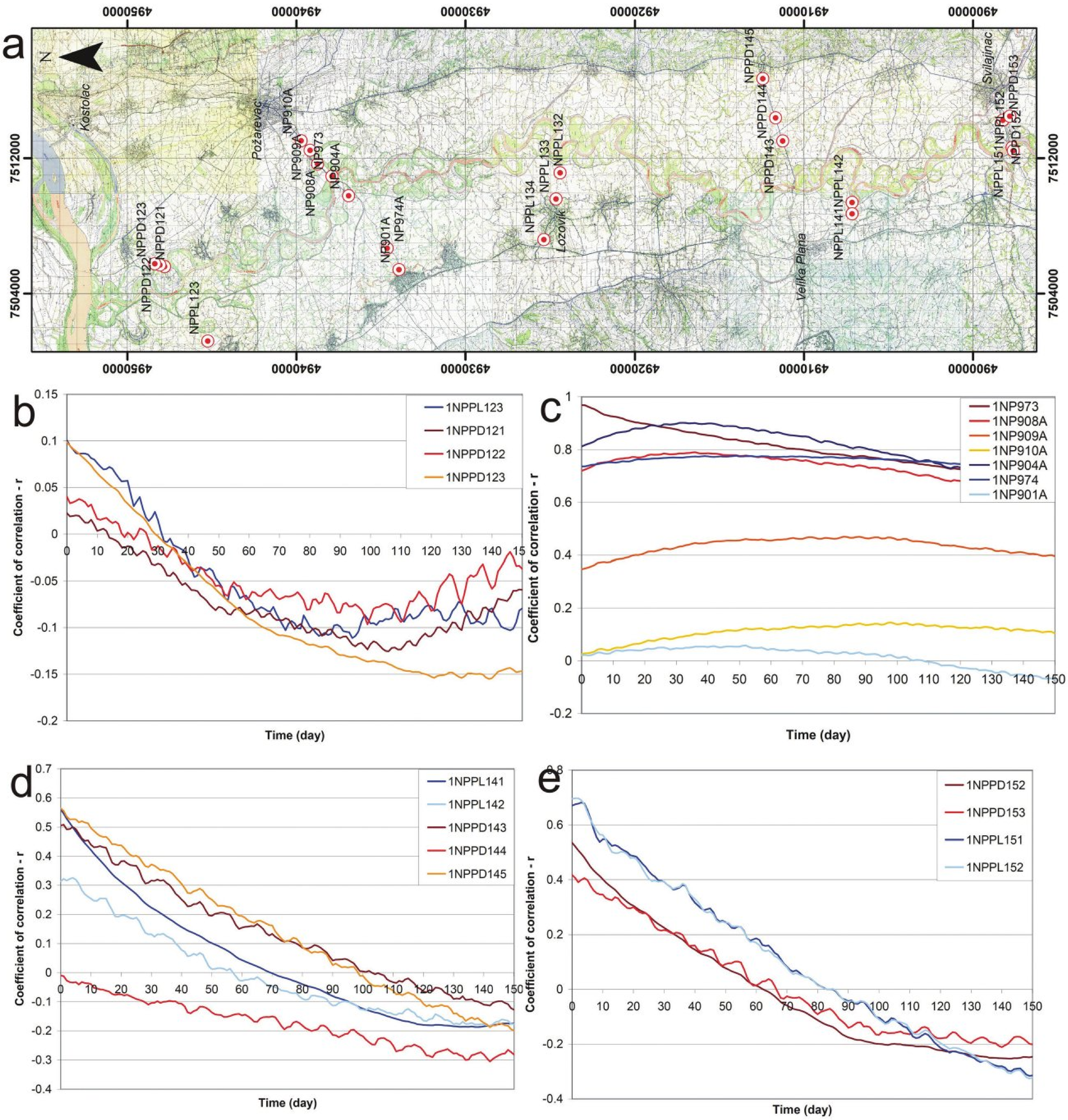

Fig. 1: *a*, position of the analyzed piezometers plotted on topographic maps at a scale of 1:25 000 (second edition, printed 1969); *b*, cross-correlogram of the piezometers installed at the Dubravice-Lipe profile; *c*, cross-correlogram of the piezometers installed at the Ljubičevski Most profile; *d*, cross-correlogram of the piezometers installed at the V. Plana-Žabari, *e*, cross-correlogram of the piezometers installed at the Markovac-Svilajnac profile

the cross-correlation coefficient decrease with the distance of the piezometer from the riverbed. If we look at the left bank in the Ljubičevski Most profile, the strongest connection between the surface waters of Velika Morava and the underground waters is at piezometer 1NP904A. The reason is certainly the fact that it is located closest to the river, at a distance of less than 1 km (910 m), so that here after 32 days the correlation coefficient has the highest value (0.902). Observing the right bank on the same diagram, it is clearly seen that the highest values of the correlation coefficient were obtained at the piezometer 1NP973, which is only 30 m away, and the highest value was obtained for the shift of 0 days. At a distance of 1160 meters, there is the next piezometer 1NP908A where the correlation coefficient values range from 0.615 (for a time step of 150 days) to 0.790 (for a time step of 49 days). For the remaining two analyzed profiles, similar cross-correlograms are obtained. Here we note that the lithological column of the piezometers located on the right side of Markovac consists of sands and gravely sands. In the profile Ljubičevski Most, surface clay layer exist but, water level of Velika Morava and groundwater level is below the clay layer (Mladenović et al., 2023a) In contrast to them, on the other profiles, at the surface exist layer of clay and sandy clay with a thickness of 4 m (Lipa profile) and up to over 12 m near Žabarski Most, where on the left side their thickness reaches over 25 m (Mladenović et al., 2023b). The presence of the clay component certainly affects the hydraulic connection of surface and underground water and the velocity of movement of underground water. For example, the highest values of correlation coefficients (*r*) were obtained in the case of the Ljubičevski Most (Fig. 1c) and Markovac (Fig. 1e) at the piezometers on the right side. As the thickness of the surface clay layer increases, the correlation coefficients are lower.

In order to calculate the velocity of groundwater movement in the intergranular medium of the Velika Morava alluvium, the distances of the piezometers from the river were taken as the distance traveled, and the time was defined as the moment when the highest value of the correlation coefficient was obtained (time expressed in days). The velocity of movement of groundwater was calculated using a simple equation for calculating the speed $v = s/t$, where v represents the mean velocity of movement of underground water, s represents the distance traveled, which in this particular case is the distance between the piezometer and the river Velika Morava, and t represents time for which the maximum value of the correlation coefficient was obtained for each piezometer. For example, for places where surface clay layer does not exist, for piezometer NP904A (Ljubičevski Most profile), the maximum value of the correlation coefficient on the cross-correlogram (Fig. 1c) was recorded at 32 days, and the distance of this piezometer from the river is 910 m, so the speed of groundwater movement is 3.3×10^{-4} m/s. Piezometer NPPL151 (Fig. 1e) is located at a distance of only 50 m from the river, and on the fourth day, the maximum r value was recorded on the cross-correlogram, so the velocity of groundwater in this part is 1.45×10^{-4} m/s.

As a conclusion, cross-correlation analysis has considerable application in hydrology and karst hydrogeology. The paper presents the application of this method as the example of determining the groundwater movement velocity in an alluvial outcrop. The obtained results indicate the possibility of applying this method for the stated purpose, whereby the obtained values are very close to the results obtained by creating a regional hydrodynamic model.

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