Article

Assessment of Riverbed Clogging in Reservoirs by Analysis of Periodic Oscillation of Reservoir Level and Groundwater Level

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Abstract: In the area of the the Krško alluvial field, the Brežice hydroelectric power plant (BHPP), with its surface water reservoir, was completed in 2017. The new BHPP reservoir dam is located approximately 7 km air distance downstream of the old Krško nuclear power plant (NEK) reservoir dam. The NEK dam was built in the 1970s. The primary purpose of the NEK reservoir is to provide fresh water for cooling the NEK nuclear reactor. To assess the impact of the newly built surface water reservoir on groundwater, we performed a series of data analyses prior to its construction. One part of the analysis relating to data from the monitoring facility of the NEK showed an interesting correspondence between the water level oscillation in the NEK reservoir and the groundwater oscillation in the nearby observation well. Based on measurements taken in 2000, we sought to estimate the clogging of the Sava riverbed sediments in the area of the old NEK surface water reservoir. To determine the permeability of the riverbed sediments, we applied geometry similar to that chosen by Hantush for his pumping test method. Using Fourier analysis, we determined the dominant frequencies from the hydrograph records of the NEK surface water reservoir and from the pressure probe in the nearby observation well. Based on the determination of the dominant frequency, we used the wave equation to compare the influence of different values of the hydraulic transmissivity of the clogged part of the NEK surface water reservoir on the transfer of its water oscillations to the groundwater in the observation well. For the hydraulic values of the non-clogged part of the aquifer (T, S), we assumed the values from the pumping experiments performed in the alluvial aquifer of Krško polje. We also assumed that the aquifer is homogeneous and isotropic, as Hantush had assumed in his method for the determination of semipervious river beds. The results obtained indicated the potential for estimation of the thickness of the clogging layer which, by analogy from applied geophysics, can be called the apparent thickness. This meant that the thickness could be determined on the basis of the default conceptual model rather than on real measurements. The presented method shows the potential for using the analysis of periodic oscillations in river reservoir level and nearby piezometers, as a method of monitoring riverbed clogging, in cases where periodical oscillations in reservoir level occur and observation wells are near enough to detect the oscillations.

Keywords: riverbed clogging; alluvial aquifer recharge; time series; analytical modelling

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1. Introduction

The relation between the surface water and the groundwater in shallow, unconfined aquifers is of utmost importance for maintaining the good quantitative and chemical status of groundwater [1,2]. There are three possible hydraulic cases of surface water–groundwater interaction. The river can either recharge or drain groundwater, or it can simply cross the surface of a shallow aquifer without connection to the groundwater [1,2]. Knowledge of the hydrodynamic relation between surface water and groundwater is thus of great importance in planning structures that change the regime of surface water [3]. The

change is greatest in large artificial reservoirs, created by damming of the river. These structures cause a decrease in river flow velocity, leading to a decrease in the river material's transport power [3–6]. The sedimentation of fine particles starts, with the silt-clay fraction predominant, by silting the banks and bottom of the river reservoir. In the case of long-period sedimentation, the hydraulic connection between the surface water and groundwater significantly decreases [3–6]. When there is no cleaning of the reservoir bed, its state deteriorates, leading to disruption of the hydraulic connection between surface water and groundwater. There are several hydrodynamic and/or geophysical methods to determine or assess the quantity of recharge from the river into the aquifer [7–9]. What they all have in common is defining the coefficient of hydraulic conductivity, with varying accuracy, in the zone of an unconfined aquifer close to the riverbed. Among the most well-known methods is that developed by Hantush [10,11], based on a pumping test, which takes into account recharge from the adjacent river. However, this method is relatively expensive.

In 2017, the construction of the dam of the BHEPP was completed in this area. The dam is located approximately 7 km downstream from the existing NEK dam. In relation to the assessment of the impacts of the new building on the surface water accumulation on the groundwater of the alluvial aquifer, several studies have been performed in the last few years [12–14].

When reviewing slightly older data and reports, relating to the monitoring facility of the NEK, we came across data from 2000 that showed an interesting correspondence between the water level oscillation in the NEK reservoir and the groundwater oscillation in the nearby observation well [15].

Previously between 1998 and 2000, in pursuit of a better solution, we performed a series of test measurements to define the state of reservoir-bed clogging of the Sava river, in the area of the Krško nuclear power plant (Figure 1). Based on these measurements, it was shown that riverbed clogging could be defined by analysis of the surface water level—groundwater level interaction.

Figure 1. Layout of monitoring sites by the Sava River.

During the planning phase of the Krško nuclear power plant (NEK), it was intended [16] to determine the initial state of the River Sava silting, upstream of the dam site, and later, after the dam completion, to monitor the progress of the riverbed clogging,

intervening by technical measures if needed to avoid clogging. These tasks however were not carried out at that time. However, the NEK monitoring network of piezometers was established in 1976 [16], in such a manner (Figure 1) that, by including the already existing piezometers, proper monitoring could be established. Previously, in 1965, Hantush [10] had developed a hydraulic method of determining riverbed clogging using pumping tests.

This approach was followed in the planning of the NEK monitoring network. Unfortunately, this approach requires periodic repetition of pumping tests at monitoring sites, thus making it rather expensive.

Field inspection, to assess the working hypothesis of the anticipated monitoring network as a part of the already existing NEK network, showed that the measuring devices, by the River Sava and at one of two piezometers, were fitted with new sensors, produced by the German company OTT, for measuring water level and water temperature. Pressure probes had a measuring accuracy of water level ± 0.01 m and a resolution of 0.001 m. Temperature sensors had an accuracy of water temperature measurements ± 0.3 °C and resolution of 0.1 °C [15]. The second planned piezometer, which was older and of simpler technical design, and for these reasons has not been included in the NEK monitoring network, was destroyed after 1976 and could not be found and included in our network [16]. Therefore, another piezometer was included further away from the Sava, but also as part of the NEK monitoring network, with the same previously described OTT instrumentation.

Unfortunately, NEK at that time did not allow us to interfere in any way with the piezometers themselves or their instrumentation. Therefore, we were not able to carry out pumping and slug tests [15]. The hydrogeological cross-section across the monitoring network is shown in Figure 2.

Figure 2. Schematic cross-section of the Sava reservoir.

2. Materials and Methods

Although the theory of sinusoidal pressure wave propagation into an aquifer is long-established [1,17], the study of references in 2000 showed that a hydraulic method had not so far been developed that could define any increase in riverbed clogging by the change in propagation of the pressure wave from the river [15].

Recently, a number of methods have been developed to evaluate the hydraulic conductivity of clogging riverbed sediments. Gianni, et al. [18] proposed a method which requires

transience in the surface water and, if the river geometry is not changing significantly, riverbed conductance can be evaluated. An integrated modelling approach to solve the surface–groundwater physical interface was proposed in 2017 by Partington et al. [19]. The main purpose of the presented modelling approach was to take into account the dynamics of erosion, transport, and deposition of sediments, and their impact on the surface elevation and hydraulic conductivity of the streambeds. The impact of river flooding on riverbed sediment hydraulic parameters was presented in 2018, where Tang et al. [20] used unnamed aerial-vehicle-based observations of riverbed topography transience, together with data assimilation techniques based on the Kalman filter, for the improvement of forecasted heads.

Thus, in the course of research on the basis of data from 2000, a primary challenge appeared to be the need to define riverbed clogging based on the monitoring of periodic pressure disturbance propagation from the river into an aquifer.

Previous research has indicated [1,17,21] that, in the course of propagation of a sinusoidal pressure disturbance from a line source into an aquifer, there is a progressive damping [17,18] and phase shift. The method used was developed for other typical sinusoidal pressure disturbances, such as sea tides [1,17,21]. For the success of the chosen method, contact between the water in the river and the aquifer is of vital importance. The occurrence of an unsaturated zone between the riverbed and the groundwater level can lead to an erroneous result [22]. However, knowing from previous studies [12–14] that this was not the case, an attempt was made to use the method in the propagation of non-classical sinusoidal cyclic disturbances, such as the oscillation of river level. The amplitude of the pressure disturbance in the river and aquifer could be represented by the amplitude of water level change, the damping and phase shift as a function of the observed point distance in the aquifer from the line source of the disturbance, and as a function of the hydrodynamic parameters of the aquifer. The phenomenon described in the riparian zone of the aquifer could be represented mathematically by solving an equation for wave progress through space in the case where the latter is spreading as a wave. The well-known solution can be written in the following form [20,21,23]:

$$h(x, t) = B(\omega)e^{-\gamma x}e^{i(\omega t - \gamma x)} \quad (1)$$

If in Equation (1) only the real form is taken into account, this yields Equation (2):

$$h(x, t) = B(\omega)e^{-\gamma x} \cos(\omega t - \gamma x) \quad (2)$$

where $B(\omega)$ is the amplitude of the dominant frequency of the Fourier spectrum of the water oscillation in the river or water reservoir. Equation (2) may be supplemented by the following symbols:

- $h(x, t)$ —amplitude of water level oscillation in the aquifer of chosen frequency,
- $B(\omega)$ —amplitude of chosen frequency water level oscillation in the river or water reservoir,
- x —distance of water level observation point in the aquifer from the river bank,
- t_o —period of water level oscillation in the river for chosen frequency,
- S —coefficient of aquifer elastic storativity (in the case of unconfined aquifers in direct contact with the river or reservoir, parameter S should be replaced by effective porosity n_e , or by “specific yield” S_y , but in this case this transformation was not carried out (in order to simplify the form of equation writing),
- γ —damping coefficient,
- T —transmissivity of aquifer,
- t —time from the pressure disturbance start that causes groundwater level change in the aquifer.

From the theory of waves [7,21,23], it is known that parameter γ enables calculation of the so-called characteristic distance of damping (the distance before the waves are damped at $1/e$ of the initial value of the wave amplitude). In solving the diffusive Equation (1), that

represents propagation of the hydraulic pressure disturbance in space, the coefficient could be written in the following form [21,23]:

$$\gamma = \sqrt{\frac{\omega S}{2T}} \quad (3)$$

By complementing Equation (2) with the previously shown symbols, one arrives at the following equation [1,20–22]:

$$h(x, t) = B(\omega) \exp \left[-\sqrt{\frac{\pi x^2 S}{t_0 T}} \right] \sin \left[\frac{2\pi t}{t_0} - \sqrt{\frac{\pi x^2 S}{t_0 T}} \right] \quad (4)$$

Inspection of Equation (4) shows that in the case of large aquifer transmissivity, periodic disturbance travels very far (damping is low). A large storativity coefficient means the reverse—that a wave in the aquifer is quickly absorbed. Precisely this relation enables an assessment of riverbed clogging. If the clogging of the riverbed is changing, so too is the characteristic distance of wave damping. The coefficient of elastic storativity and hydraulic transmissivity describes the hydraulic characteristics of the porous medium, through which the pressure disturbance travels, caused by oscillation of the water level in the river. To calculate the characteristic distance of periodic wave damping it is necessary to know the value of the damping coefficient γ , defined in Equation (3). As can be seen, this value is dependent on the dominant frequency of the spectrum, the hydraulic transmissivity, and the storativity coefficient. It is the last two parameters that describe the hydraulic characteristics of the porous medium, through which the pressure disturbance travels, caused by oscillation of the water level in the river. This analysis is based both on the observation of the longer time series of oscillation of groundwater levels and levels of the water in the Sava river reservoir (Figure 3), as well as on the determination of the dominant frequency of this phenomenon by spectral analysis and detrending.

Figure 3. Oscillation of groundwater levels and levels of the NEK river reservoir.

The data shown in Figure 3 are not suitable for Fourier analysis since they exhibit a trend. Therefore, it was necessary to perform detrending. The results of time se-

ries detrending, shown in Figure 3, together with the relevant equations, are presented in Figures 4 and 5. Following trend removal, the time series were analysed by Fourier analysis. Fourier analysis was performed by the program tool Statistica 6.0. The results of Fourier analysis in the form of a periodogram, detrended time series water level oscillation of the Sava, and of groundwater oscillation in piezometer V-2/77, are presented in Figures 6 and 7. Upon close inspection of the periodogram graphs, it was observed that long-wave oscillations of the River Sava reservoir levels are less damped than short-wave oscillations. Therefore, the ratio between long-wave oscillation and short-wave oscillation of the groundwater level also shifted to the former, as would be expected according to Equation (4).

Figure 4. Detrended water level oscillation of the Sava in centimetres.

Figure 5. Detrended groundwater level oscillation of V-2/77 in metres.

Figure 6. Fourier analysis of water level oscillation of the Sava.

Figure 7. Fourier analysis of groundwater oscillation in piezometer V-2/77.

3. Results

An analysis to determine riverbed clogging of the Sava in the NEK reservoir was performed, as shown in the flow-chart in Figure 8. As shown in the flow-chart, the time window of the river level oscillation in the first step was chosen in such a way that the time series had as many regular sinusoidal oscillations as possible. After time series selection, detrending of data was performed, then Fourier processing of the river oscillation and the groundwater oscillation in the nearby piezometer, together with determination of the dominant frequency. When the dominant frequency of river oscillation was determined, dominant frequencies were examined for groundwater oscillation. If the piezometer was within the influential range of the river with contact to the groundwater, then oscillations in the groundwater would be predicted as well. This case is shown in Figures 4 and 5, as well as in Tables 1 and 2. In this analysis, the strongest dominant frequency of the river reservoir was 48.5 of sampling time, which for measurements at $\frac{1}{2}$ hour intervals means

an approximate frequency of 1 per day. Analysis of times of groundwater oscillations in piezometer V-2/77 shows that there is a dominant frequency of the spectrum long wave oscillation for a length of 48.5 days^{-1} (Figure 6 and Table 2). The amplification is due to travelling of the waves of hydraulic disturbances through the porous medium, where short-wave oscillations are more intensely damped than long-wave oscillations.

Figure 8. Flow-chart of analysis of riverbed clogging by analysis of river reservoir oscillation and groundwater oscillation in the piezometer close enough to the reservoir.

Table 1. First 10 frequencies of NEK Sava river reservoir levels.

Frequency	Period	Cosine Coefficient	Sine Coefficient	Spectral Density
0.020619	48.5000	−6.05677	0.972169	4991.965
0.001718	582.0000	−2.63198	−0.054160	989.187
0.041237	24.2500	−2.25252	0.376709	782.725
0.027491	36.3750	1.13149	−0.312111	207.183
0.042955	23.2800	0.92477	−0.644434	537.569
0.022337	44.7692	0.90685	−0.551341	2795.761
0.037801	26.4545	−0.06771	−0.879216	164.862
0.012027	83.1429	−0.05883	0.775411	99.271
0.049828	20.0690	0.59839	0.199939	79.811
0.008591	116.4000	−0.17651	0.589065	76.016

Table 2. First 10 frequencies of measured groundwater oscillations in piezometer V-2/77.

Frequency	Period	Cosine Coefficient	Sine Coefficient	Spectral Density
0.001718	582.000	−0.019012	−0.007736	0.063140
0.020619	48.5000	−0.008066	−0.017220	0.049131
0.005155	194.000	0.007233	0.006049	0.021079
0.003436	291.000	0.006506	0.001407	0.041810
0.022337	44.7692	0.002772	0.004448	0.029079
0.008591	116.400	−0.001650	0.004817	0.006734
0.006873	145.500	0.000777	0.004968	0.011863
0.012027	83.1429	−0.002210	0.004306	0.004377
0.027491	36.3750	0.001575	0.004498	0.003992
0.017182	58.2000	−0.000710	0.003894	0.006053

After spectral analysis construction of synthetic records by Fourier analysis of oscillations in the river reservoir and groundwater, comparison of the records to determine silted thickness of the riverbed was needed. The frequency was chosen so that it is representatively present both in the reservoir and in the groundwater. For the chosen frequency, oscillations are drawn both for the levels of the reservoir and for the groundwater (Figures 9 and 10).

Figure 9. Synthetic record of the Sava oscillation with the period 24.5 h.

Figure 10. Synthetic record of groundwater oscillation in piezometer V-2/77 with period of 24.5 h.

If the analysis was correct, the records should be similar, differing in amplitude and phase. The riverbed clogging lead to substantial changes in the hydraulic permeability and to the associated T , while S was decreased to the magnitude of n_e (effective porosity) characteristic of fine-grained materials. The result of such changes is shown in Figure 11, which illustrates the influence of the grain thickness of the fine material that clogs pores of the river reservoir bed on the changed values of T and S . As seen from Figure 11, already the 0.25 cm thick clay layer has a considerable influence on the oscillation wave in groundwater with an approximate period of 1 day. Since in our case the piezometer V-2/77 was 21 m away from the Sava, it was necessary firstly to compute groundwater oscillation by equation (4), and then to compare it to the synthetic record constructed by Fourier analysis (Figure 10). For the first calculation, hydrodynamic data from pumping tests at Krško polje were used [12–16]. From the data for the pumping tests, T could be ascertained in a range from 10^{-1} to 10^{-3} m^2/s ; the value of S has been assessed as 0.10, being the usual value of effective porosity n_e of sediments in alluvial aquifers [24]. The whole procedure is shown in Figure 12. The calculated values in Figure 13 were predicted, in the case of the absence of fine material at the NEK reservoir bed, on the basis of graphs representing groundwater oscillation, to be within the range from $T = 10^{-1}$ m^2/s to $T = 10^{-3}$ m^2/s . Since this was not the case, it is presumed that this effect was caused by the silted bed of the NEK river reservoir.

Figure 11. Influence of reservoir bed clogging for different values of T , computed by Equation (4).

To assess clogging of the NEK reservoir bed, in the calculations, pressure disturbances that cause waves were considered to propagate through two different parts of the aquifer; firstly, those with poor hydraulic characteristics, and according to calculations shown in Figure 11 with no great thickness, and, secondly, those with good hydraulic characteristics, which are characteristic of Quaternary sediments.

Thus, the assessment of clogging was made by dividing the area between the riverbed and the observation well into two zones (Figure 12). The first zone, which is usually very thin compared to the whole conceptual model and represents the clogging area, and the second zone, which is the area between the clogging zone and the observation well. We used the values of k and S , which were available to us from previous research [12–16] and the literature [24], to approximate the values for the clogging zone. We proceeded similarly to determine the values of k and S of the aquifer between the clogging zone and the observation well.

Figure 12. Simplified conceptual model of pressure disturbance transmission from river reservoir into groundwater.

As can be seen from Figure 12, we assumed, in the conceptual model for each zone, that the values were the same over the entire range and do not change. This means that we have assumed that each zone was homogeneous; the values of each zone were determined as average values from previous pumping tests [12–16], or the literature [24]. The average thickness of the aquifer [12–16] was also determined on the basis of boreholes and electrical sounding performed in previous research in the near area and was the same throughout the model area.

In practice, the analysis was performed first by computation of the influence of the clogged zone on the amplitude and phase delay using Equation (1). These recalculated amplitude and phase shifts, characteristic for the clogged zone, were taken into account for the aspect of the analysis that treated the part of the aquifer that was unaffected by clogging, which was again recalculated with Equation (1). For the described procedure, the best way is to tabulate calculations, where, by changing the values of S , T and x_1 , the

calculated wave is adapted to the wave determined by Fourier analysis. In the equation, the following values have been introduced from Table 3.

Table 3. Input data for analysis carried out by the hydraulic method, and thickness at which there is best fitting.

Layer Type	Amplitude [cm]	T	S	Thickness [m]
River reservoir	6.05677			
Aquifer		$T = 10^{-2} \text{ m}^2/\text{s}$	$S = 10^{-1}$	20.88
Clogged zone		$T = 10^{-8} \text{ m}^2/\text{s}$	$S = 10^{-2}$	0.12 [apparent thicknes]

Figure 13. Best fitting of calculated values from data in Table 3 to values computed by Fourier analysis.

The calculated values based on the parameters shown in Table 3 are shown in Figure 13. It should be noted that we used values for silty clay sediments from the previous field research and literature to determine the clogging area T and S [1,2,4,24], as was performed for the aquifer component.

We should mention that the calculated thickness does not represent the true thickness but an apparent thickness resulting from the default model and the T and S parameters used [12–16].

4. Discussion

The presented method allows us to estimate clogging on river reservoirs where periodic oscillations occur. The clogging issue can be very problematic as it reduces surface water inflows from river reservoirs to groundwater and vice versa. Hantush [10] developed a method for addressing this problem that works on the principle of a pump test. Our method is based on the principle of analysis of periodic oscillations of water levels in the river reservoir and nearby piezometers. For the method to be successful, it is necessary to have a piezometer or piezometers that are within the impact zone of the accumulation. The impact zone of the accumulation decreases over the years due to the deposition of fine

material [3–6,25–27]. The intensity of the reduction strongly depends on the sedimentation of the silty clay fractions in the accumulation.

Given the observed damping of groundwater oscillation in the observation wells, it is of great importance that observation wells are drilled in the impact zone of the reservoir in order to apply the presented method. The impact zone can be determined if the frequency of oscillations in the future reservoir and the hydraulic parameters of alluvial backfill are known, using Equation (4). The resolution of the level probe must be taken into account when determining the maximum distance of piezometers from the reservoir.

It should be noted that the determination of the thickness of the clogging zone was performed on the basis of knowledge of the permeability values obtained from pumping experiments in the area of alluvial backfill of the NEK river accumulation [12–16], and that the values for the clogging zone were provided by data from previous research [12–16], and by the literature [24].

The specified thickness of the clogging area is not real, but is apparent. In fact, it is the result of the selected model and the T and S parameters used. The concept of apparent thickness is similar to the concept of apparent specific resistance derived from geo-electrical sounding [7].

The presented method faces the problem of a multiplicity of solutions, which is typical for inverse geophysical [7] and hydrological [28] models. Therefore, when using the method shown, parameter constraints should be set for parameters S , α_1 and T , which should be derived from the literature or, where possible, from analyzed field samples. We also know from the methods of applied geophysics [7] that the determination of the physical parameters and geometry of the problem is greatly improved if the research is carried out with a combination of several geophysical methods. The same can be expected in this case.

In addition to the river reservoir bed clogging determination, the presented method also allows us to analyze the future impact of river reservoirs of hydropower and other facilities on groundwater oscillations in alluvial backfill. Frequently, before constructing a reservoir for the needs of a hydroelectric power plant, an analysis of the impact of groundwater uplift in the surrounding alluvial backfill is performed; the method shown can show the impact of oscillations and uplift. The effect of oscillations without an artificially low permeable injection layer, and with an injection low permeable layer, can be estimated using the presented method.

The method shown has some limitations related to the conceptual model on which the method is based. In sediments that are very strongly heterogeneous, the method shown will not give sufficiently good results; in such cases other methods based on numerical clogging modeling should be used [29]. An unsaturated zone, which can occur between a river and groundwater, is also a problem [22]. In the case of large changes in the thickness of the wetted aquifer layer, its reliability will be questionable, since we assume that T is constant, which is not the case in alluvial aquifers. In addition, as already noted, for its successful use, we need periodic oscillation of the surface water level in the reservoir, which must be long enough to satisfy the Nyquist—Shannon sampling theorem.

5. Conclusions

The described alternative method of determining the clogging of riverbeds and of reservoir beds by comparative analysis of groundwater level oscillation and reservoir level oscillation requires only one piezometer and no pumping tests. From the case study at Krško polje it could be concluded that the method is sufficiently sensitive for clogging detection and an assessment of average apparent thickness of the clogged zone. The method is applicable for determination of the clogged zone, as long as there is communication between the groundwater and water in the river reservoir, with periodical oscillations present. There are additional requirements for the successful application of the method, as sediments must be as homogeneous as possible, changes in groundwater levels must

be small compared to the thickness of the aquifer, and there must be no unsaturated zone between the surface water and the groundwater in the aquifer.

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