Internat. Rev. Hydrobiol.	**88**	2003	3–4	397–413

Alfred Paul Blaschke[1], Karl-Heinz Steiner[1], Roland Schmalfuss[2],
Dieter Gutknecht[1] and Dieter Sengschmitt[1]

[1]Institute of Hydraulics, Hydrology and Water Resources Management, 1040 Vienna, Austria;
email: blaschke@hydro.tuwien.ac.at
[2]Chartered Engineering Consultant for Civil Engineering, Oswaldgasse 27–31, 1120 Vienna, Austria

Clogging Processes in Hyporheic Interstices of an Impounded River, the Danube at Vienna, Austria

key words: riverbed clogging, hyporheic interstices, hydraulic conductivity

Abstract

Stream-aquifer interactions are influenced significantly by riverbed clogging processes. Detailed field observations have been made in the "Freudenau reservoir" of the Danube at Vienna. Different types of clogged layers have been observed. Multi-level-piezometers below the riverbed indicate that the overall clogging process consists of several clogging cycles of a few weeks each initiated by floods until a stable state is reached. Minor flood events cause a temporary increase in the leakage coefficient followed by a new decrease approaching the original level after a few weeks. Major flood events tended to add a sediment layer which re-initiated the clogging process leading over to a lower level of the leakage coefficient. The computation of the water balance of the two reservoirs of the New Danube indicated a reduction of the seepage rate by about 40% to 60% over a period of 4.5 years. Undisturbed riverbed sediment samples taken by an innovative freeze-panel-sampling method demonstrate that the depth of the clogged layer is about 2 cm for two of the clogging types (external clogging and armour layer clogging). Video techniques were used to identify the different types of clogged layers and their variability in time and space. Additionally, this technique facilitated observations of macrozoobenthos organism activities in the hyporheic interstices.

1. Introduction

A main objective in the study of alluvial aquifers is the quantification of stream-aquifer interactions. Such interactions affect the dynamics of the adjacent aquifer especially due to flood events in the stream. In addition they are of fundamental importance to the study of natural groundwater recharge (Mitchell-Bruker *et al.*, 1996; Serrano *et al.*, 1998) as well as to design irrigation and drainage systems or wells near streams (Hantush, 1965). Furthermore, the exchange of contaminants between rivers and aquifers is a problem closely related to the hydraulics of the stream-aquifer system.

1.1. Controlling Factors

The variables affecting hydraulic exchange include aquifer geometry, stream-groundwater pressure differences and hydraulic properties such as the hydraulic conductivity of the riverbed. Settling and straining of suspended and bedload sediments on the riverbed may cause a substantial reduction of the conductivity of the outermost layer of the riverbed material. These processes are usually referred to as clogging (Lisle, 1989; Joppen *et al.*, 1992; Schälchli, 1996). Clogging may be of advantage for the water management of reservoirs and irrigation channels as it reduces the loss of water. However, in artificial recharge facilities

 1434-2944/03/3-407-0397 $ 17.50+.50/0

and wells near streams the clogging process, often, is considered a disadvantage in a management context due to the possible reduction in the seepage rate. INGERLE (1991) showed that, as a consequence of the impoundment of the Danube River by the "Altenwörth" hydropower dam, a semi-pervious bed with a hydraulic conductivity 100 000 times lower than that of the adjacent aquifer was created. Laboratory studies (CUNNINGHAM *et al.*, 1987; SCHÄLCHLI, 1993) generally show that the clogging process depends on a number of variables, particularly grain size distribution of the riverbed material, suspended sediment concentration, flow velocity and the hydraulic gradient. These laboratory results, however, have never been verified by field measurements in a large river. Studies performed in small streams have identified two types of riverbed clogging (e.g. LISLE, 1989; SCHÄLCHLI, 1993; BRUNKE, 1999). The first type is termed internal clogging which relates to an increase of fine material in the existing top centimetres or decimetres of the river bed (i.e. the filter layer). This process results in a decrease of hydraulic conductivity in that layer. The second type is termed external clogging which relates to a build up of an additional fine sediment layer on the stream bed. The additional layer usually has a much lower hydraulic conductivity than the original river bed.

A summary of the main controls of these two types of riverbed clogging is given in GELDNER (1981), SCHÄLCHLI (1993), PATSCHEIDER (1994), GUTKNECHT *et al.* (1998), BRUNKE (1999) und BLASCHKE *et al.* (2002).

1.2. Objectives

The aim of this paper is to quantify the effect of clogging processes on the hydraulic characteristics of the hyporheic zone in a river impoundment setting. The boundary conditions of the study site and the piezometer measurements underneath the river bottom allow a clear analysis of the development of the hydraulic conductivity of the river bottom over time. The specific objectives of this study were a) to analyse the clogging processes over time and space, b) to examine the effect of the clogging process on the water balance, c) to classify riverbed clogging types, d) to estimate the thickness of the clogged layer, and e) to identify the presence of biological activity influencing the clogging process.

2. Study Site, Measurement and Methods

The Danube river at Vienna is impounded by the "Freudenau" hydro power plant (river km 1921.05). It has a heavily modified channel with a mean width of 270 m and a mean longitudinal bed-slope of 0.4 ‰. The long-term mean discharge at this site is about 1700 $m^3\ s^{-1}$. A partial impoundment in March 1996 increased the water level by 6 m (phase 1) at the hydro power plant site. An additional impoundment in November 1997 caused a further increase by 2.3 m (phase 2).

The left bank of the "Danube" is separated from an attendant channel called "New Danube" by an artificial, 21 km long and 250 m wide island, the "Donauinsel". The "New Danube" is impounded by two weirs (Fig. 1). The weirs are only opened during floods. The impoundment in March 1996 resulted in water levels of the Danube that were higher than those of the New Danube which produced continuous groundwater flow from the Danube through the island to the New Danube. The groundwater flow decreased significantly over the months following the impoundment as expected. In the right embankment impermeable diaphragm walls were established to block groundwater flow between the reservoir and the surrounding city districts.

The aquifer underlying the Danube and the Donauinsel consists of sandy gravels with a hydraulic conductivity of about $6 \cdot 10^{-3}$ m s^{-1}. It is based on an impermeable layer of silty clays and has an average thickness of about 5 m below the channels (see Fig. 2).

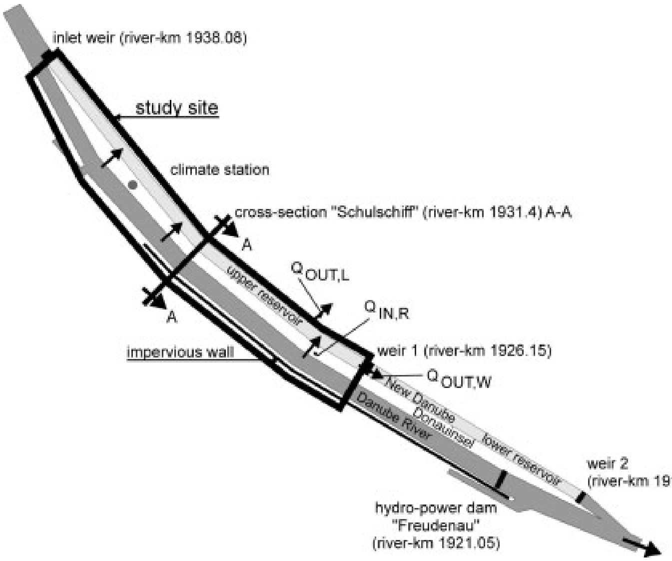


Figure 1. The study site near Vienna, Austria (48°11′N, 16°29′E).
$Q_{IN,R}$ = groundwater inflow at the right bank
$Q_{OUT,L}$ = outflow at the left bank
$Q_{OUT,W}$ = outflow at the weir 1

2.1. *The "Schulschiff" Study Site and the Multi-Level-Piezometer Measurements*

At the "Schulschiff" cross-section (river km 1931.4, Fig. 2) measuring equipment was installed in 1996 for analysing the local clogging effects on groundwater recharge. To this end, a special arrangement of multi-level-piezometers was developed and deployed. Two pipes, each 1.7 m long and 5 cm in diameter and laterally slotted at depths of 0.5, 1.0 and 1.5 m, were rammed into the ground (pipe 1 and pipe 2 in Figure 2). They were situated 220.0 m (pipe 1) and 238.6 m (pipe 2) from the right embankment and

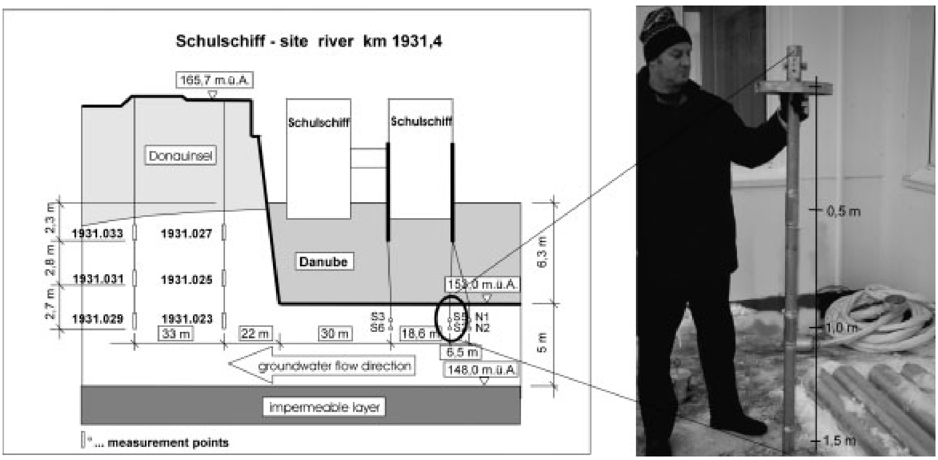


Figure 2. The "Schulschiff" test site at river km 1931.4 (left) and multi-level-piezometer (right).

enabled the measurement of the hydraulic pressure heads at two different points and three different depths. With additional measurements of the stream water level, which is equivalent to the pressure head at the river bottom, it was possible to estimate the leakage coefficient of the aquifer (see chapter 3.1.).

2.2. *Sediment Sampling – Freeze-Panel-Method (FPS)*

To improve riverbed sampling, a freeze-panel-sampling (FPS) method was developed (NIEDERREITER and STEINER, 1999; STEINER and NIEDERREITER, 1999, Fig. 3). It is a modification of the freeze-core-sampling method introduced by HUMPESCH and NIEDERREITER (1993). It allows to take nearly undisturbed 20 cm riverbed sediment samples down to a water depth of about 10 m, as was the case in this study. Organisms (crustaceans, bivalves, annelides, etc.) and vestiges of plants (leaves, twigs) found on the surface of the samples, as well as the possibility to analyse the grain-size distribution based on thin layers of the sample demonstrate the new capabilities of this innovative sampling method.

Figure 3. Freeze-panel-sampling (FPS) (NIEDERREITER and STEINER, 1999)

2.3. *Video Recording*

In co-operation with UWITEC, an innovative video unit was developed to take digital photographs and video sequences at a distance of 25 cm from the river bottom. The video unit was used for a continuous documentation of the measurement sites as well as for vessel-based mobile use to analyse the regional distribution and the development of clogged layers (Fig. 4). The river bed between km 1933.2 and km 1922.2 was mapped at 11 cross sections, six times during the study period (Feb. 11, 1997; Aug. 26, 1997; Sep. 1, 1998; Feb. 16, 1999; Sep. 7, 1999; July 4, 2000).

2.4. *Quantitative Modelling*

2.4.1. Local Seepage-Rate through the Riverbed at the "Schulschiff" Site Based on Piezometer Readings

The modelling approach is based on a one-dimensional analytic groundwater model that is supported by the pressure measurements along the two pipe sections and equivalent to that used by RAUCH (1993). With the measured pressure head differences at the two multi-level-piezometers $s(x = 220\ \mathrm{m}) = s(\text{pipe 1})$ and $s(x = 238.6\ \mathrm{m}) = s(\text{pipe 2})$ the leakage coefficient λ_T^c can be calculated iteratively from Equation 1:

$$\frac{s(\text{pipe1})}{s(\text{pipe2})} = \frac{\cosh\left(238.6 \cdot \sqrt{\lambda_T^c/(K_T \cdot D)}\right)}{\cosh\left(220 \cdot \sqrt{\lambda_T^c/(K_T \cdot D)}\right)} \tag{1}$$

Figure 4. Vessel-based mobile use of video unit.

where
s(pipe1) = measured pressure head in pipe 1 (m)
s(pipe2) = measured pressure head in pipe 2 (m)
λ_T^c = leakage coefficient (s^{-1})
K_T = hydraulic conductivity of the aquifer (m/s)
D = thickness of the aquifer (m)

The seepage-rate $q_v(x)$ through the clogged riverbed can be estimated by applying Darcy's law

$$q_v(x) = K_T^c \cdot i_v(x) = K_T^c \cdot s(x)/D^c = \lambda_T^c \cdot s(x) \tag{2}$$

where
$i_v(x)$ = hydraulic gradient (–)

Replacing λ_T^c by its 10 °C value λ_{10}^c and taking viscosity ν_T at temperature T, the seepage-rate through the clogged riverbed can be expressed as:

$$q_v(x) = \lambda_T^c \cdot \frac{s(\text{pipe2}) \cdot \cosh(a \cdot x)}{\cosh(a \cdot 238.6)} = \lambda_{10^\circ}^c \cdot \frac{\nu_{10^\circ}}{\nu_T} \cdot \frac{s(\text{pipe2})}{\cosh(a \cdot 238.6)} \cdot \cosh(a \cdot x) \tag{3}$$

where
ν_{10° = the kinematic viscosity at 10 °C (m^2/s)
ν_T = the kinematic viscosity for the actual temperature (m^2/s)
$a = \sqrt{K_T^c / (K_T \cdot D \cdot D^c)}$
K_T^c = hydraulic conductivity of the clogged layer (m/s)
D^c = thickness of the clogged layer (m)

2.4.2. Regional Seepage-Rate through the Riverbed Based on the Water Balance

The seepage-rates through the "Donauinsel" to the two reservoirs of the New Danube ($Q_{IN,R}$) have been calculated from a water balance of the reservoirs (SCHMALFUSS *et al.*, 1999; SENGSCHMITT *et al.*, 1998). Equation 4 states that the change of the storage of the reservoir (ΔV_{RES}) is equal to the groundwater inflow at the right bank ($Q_{IN,R}$) plus the difference of precipitation (P) and evaporation (E) multiplied

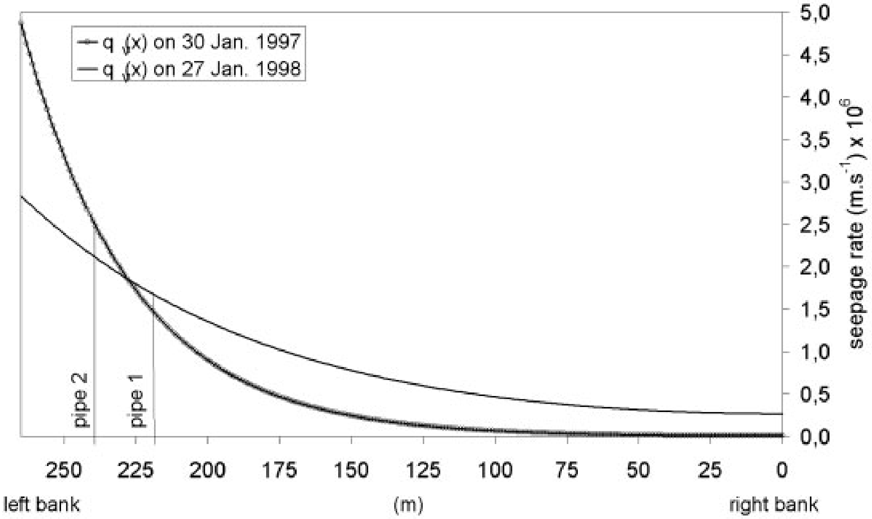


Figure 5. Spatial distribution of the seepage rate q_v along the Danube riverbed on 30 January 1997 (phase 1) and 27 January 1998 (phase 2).

by the reservoir surface area (A_R), minus the outflow at the left bank ($Q_{OUT,L}$) and at weir 1 ($Q_{OUT,W}$):

$$\Delta V_{RES} = Q_{IN,R} + (P - E) \cdot A_R - Q_{OUT,L} - Q_{OUT,W} \tag{4}$$

The weirs are usually closed during the night (5:00 p.m. to 7:00 a.m.), rendering the outflow $Q_{OUT,W}$ during this period to zero. The outflow at the left bank, $Q_{OUT,L}$, could be estimated by a groundwater flow model (GRUPPE WASSER, 1997). Precipitation (P) and evaporation (E) have been measured at a meteorological station situated at the Donauinsel (see Fig. 1). Evaporation is relatively small during the night, so estimation errors in evaporation are unlikely to affect the accuracy of the results. Putting this information into Equation 4 the water balances during the night can be simplified as:

$$\Delta V_{RES} = Q_{IN,R} + (P - E) \cdot A_R - Q_{OUT,L} \cdot \Delta t \tag{5}$$

ΔV_{RES} can be calculated from the water levels measured at weir 1 (upper reservoir) and weir 2 (lower reservoir) after closing the weirs (W_C) and before opening them the next day (W_O), as

$$\Delta V_{RES} = (W_O - W_C) \cdot A_R \tag{6}$$

The infiltration term $Q_{IN,R}$ expressed in $m^3\ s^{-1}$ can now be estimated by combining Equations 5 and 6 and dividing the result by the time the weirs are closed (Δt):

$$Q_{IN,R} = \frac{(W_O - W_C) \cdot A_R - (P - E) \cdot A_R}{\Delta t} - Q_{OUT,L} \tag{7}$$

Equation 7 allows the estimation of the seepage rates into each of the two reservoirs.

3. Results

3.1. Analysis of Clogging Processes in Time and Space

3.1.1. Local Results at the Schulschiff Site Based on the Multi-Level Piezometers

Figure 5 shows the results of the analysis based on the multi-level piezometers. The seepage rates are flows from the Danube into the New Danube moving through the island of the "Donauinsel". They are largest near the left bank adjacent to the "Donauinsel" island. Figure 5 suggests that the seepage-rate was unevenly distributed across the cross-section. The main contributing sections of the riverbed change over time as the riverbed clogging proceeds. The seepage-rate q_v calculated (Eq. 3) for 30 January, 1997 (phase 1) was $4.9 \cdot 10^{-6}$ m s^{-1} at the left bank, declining sharply towards the centre of the river. At the stream centre ($x = 100$ to 125 m) the seepage rate was zero. One year later, on 27 January 1998, the seepage-rates were much smaller on the left bank ($2.8 \cdot 10^{-6}$ m s^{-1}) but had increased in most of the stream cross section ($0.3 \cdot 10^{-6}$ m s^{-1} at the right bank). These changes are associated with leakage values being 6 times lower and pressure head differences between the water level in the Danube and the New Danube being 2 times higher in 1998 as compared to 1997. The shift of the seepage rates away from the left bank is a result of the clogging being most intensive near the left bank.

Figure 6 gives the time series of the leakage coefficients for the Schulschiff site based on the multi-level piezometer readings. Figure 6 suggests that in December 1997 the additional impoundment (moving from phase I to phase II) results in a reduction of the leakage coefficients from $1 \cdot 10^{-5}$ to about $3 \cdot 10^{-6}$ s^{-1}. The whole clogging process starting in March 1996 leads to a total decrease in the leakage coefficients of two orders of magnitude and appears

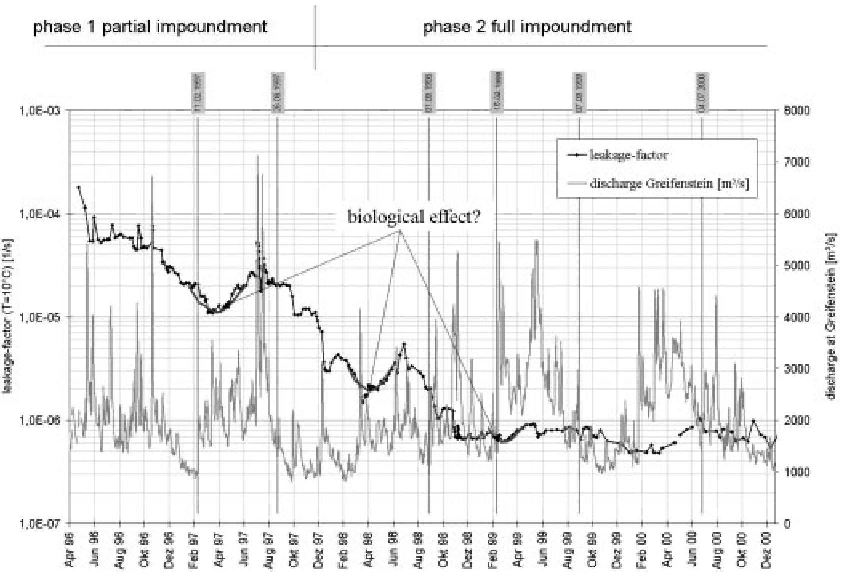


Figure 6. Time series of the leakage coefficient at the "Schulschiff" site (river km 1931.4) calculated by the one-dimensional analytic groundwater model (Eq. 1) making use of the piezometer data. Also shown is the stream discharge of the Danube at the Greifenstein gauge. Top shows the dates of the video surveys.

to level out at a quasi-steady state. It is interesting that Figure 6 shows a number of episodes with slightly increasing leakage coefficients during the spring periods (February to June) in three years (1997, 1998 and 1999) (labelled "biological effect?" in Fig. 6). This increase could not be accounted for by abiotic variables that influence the sedimentary clogging process. It is therefore likely that these increases are due to biological processes (SENGSCHMITT and BATTIN, 1999).

The time series of the leakage coefficient (Fig. 6) shows the existence of quasi stable states and also the effect of flood events on the temporal development of clogging processes. Minor flood events cause an increase in the leakage coefficient which quickly fades away. On the other hand, major flood events lead to a re-initialisation of the clogging processes due to sedimentation leading to a decrease of the leakage factor over a few weeks. These results suggest that the overall clogging process consists of a series of clogging cycles related to floods, each taking a few weeks to reach a quasi stable state.

3.1.2. Impact of the Clogging Process on the Water Balance

Figure 7 shows the seepage rates into the upper and lower reservoirs of the New Danube calculated from the water balance. In December 1997 the seepage increased dramatically as a consequence of the full impoundment. During 1998 and 2001 the seepage-rate decreased to about 50% due to clogging effects. The annual fluctuations in Figure 7 are partly a temperature effect. Groundwater temperatures differ between 2 °C in winter and 20 °C in summer. A simple analysis of the viscosities suggests that 50% of the amplitudes in seepage rates shown in Figure 7 can be accounted for by the differences in viscosities between winter and summer (SCHMALFUSS, 1998).

It is of interest to compare the (regional) seepage rates estimated from the water balance with the local estimates based on the piezometer data. To this end the local estimates at the Schulschiff site (chapter 3.1.1) were upscaled to the Upper New Danube reservoir. The upscaling was done by first multiplying the local (per unit length) "Schulschiff" seepage rates

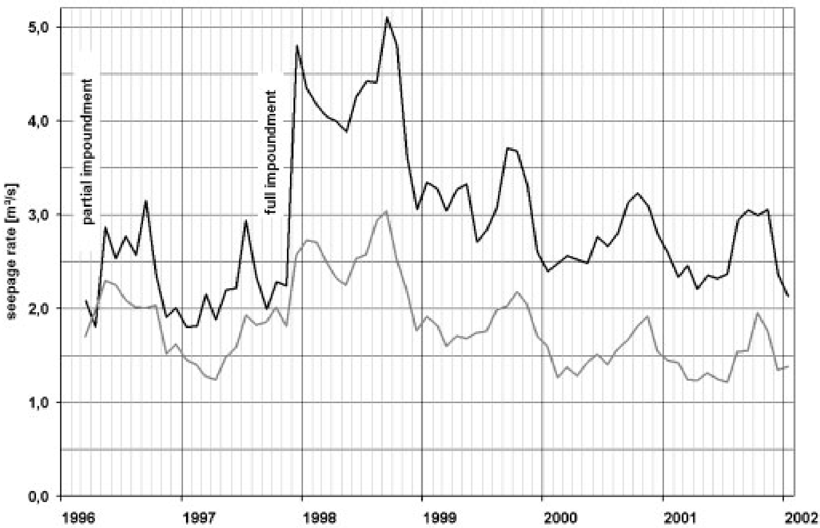


Figure 7. Seepage-rate into the New Danube reservoirs calculated from the water balance. Black line: Upper New Danube reservoir. Grey line: Lower New Danube reservoir.

q_v by the length of the upper reservoir $L = 11930$ m. The "Schulschiff" site does not represent the mean hydrological and geological conditions of the Upper reservoir, so one would expect differences between the so obtained estimates and the seepage rates from the water balance. A calibration factor c was therefore introduced that takes into account the spatial variability of the seepage rates.

$$c = \frac{Q_{IN,R}}{q_v \cdot L}. \tag{8}$$

where $Q_{IN,R}$ is the seepage rates estimated from the water balance. The calibration factor was found to be $c = 0.81$ using data from Mai to June 1996. For July 1996 to September 1998 (the verification period) the upscaled seepage rates were then calculated as

$$Q^{*}_{IN,R} = c \cdot q_v \cdot L \tag{9}$$

These upscaled values are shown in Figure 7 along with the estimates from the regional water balance. Figure 8 shows a good correspondence between the seepage rates at the two scales for phase 1. The short time variation in the seepage rates (#1, #2, #4, #5, #6, #7) can be found in both estimates, often with the same magnitude. One exception in the peak in September 1996 (#3) which appears in the regional scale estimates but not in the local scale estimates. The seasonal variability with high seepage rates during summer and low seepage rates during winter is apparent in both the local and the regional scale estimates which suggests that, for phase 1, a linear upscaling from the location "Schulschiff" site to the whole length of the upper reservoir is possible.

However, at the beginning of the full impoundment (phase 2) in November 1997, the upscaled seepage rates differ by 1 $m^3 s^{-1}$ from the regional water balance estimates. After five months (at the end of April) the two estimates become almost identical again. The reason for this discrepancy most likely is an underestimation of the regional seepage rates at the "Schulschiff" site during the first five months. The assumption of an impervious left bank

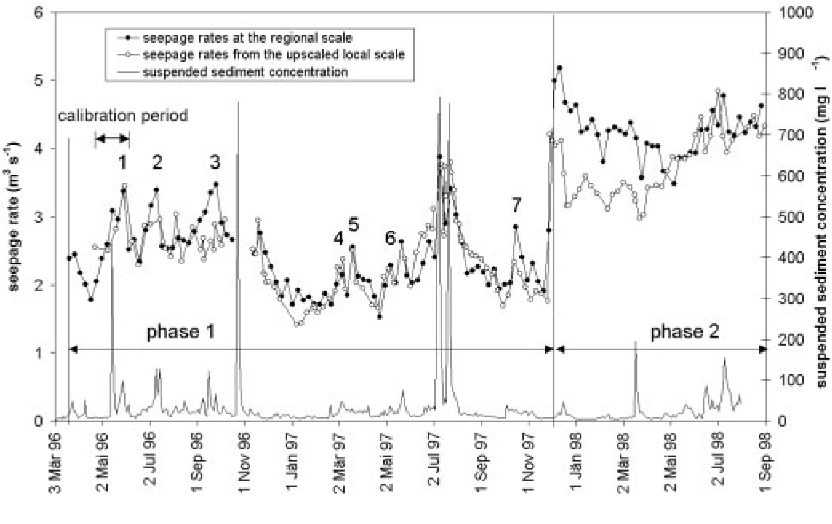


Figure 8. Seepage rate into the upper New Danube reservoir estimated by two methods. Full circles: regional scale estimates from water balance calculations. Open circles: local scale estimates from upscaling the results of the piezometer readings.

which was used in the analytical model was not satisfied after the additional impounding in November 1997 (begin of phase 2). The water level in the Danube was raised by about 2 m. This caused additional bank area not yet clogged to be flooded which significantly contributed to the seepage. The clogging of this additional bank area proceeded very slowly due to low suspended sediment concentrations (about 10 mg l^{-1}) in winter. It is believed that the flood event in late April 1998 advanced the clogging of these additional bank areas quickly as the suspended sediment concentrations were about 200 mg l^{-1}. Hence, after this flood event, the seepage rates calculated from the local and the regional scales were back at a good correspondence.

3.1.3. Video Analyses

The video analyses provided extremely interesting insights into the space-time behaviour of the clogging processes. The general result is that there is no evidence of fining in the reservoir. While one would generally expect a clear boundary between fine sediments (near the impoundment) and coarse sediments (far from the impoundment), the video images did not show any clear trend of grain size along the longitudinal section. In a setting such as in the Freudenau reservoir (length of the reservoir about 17 km, water depth about 10 m, flow velocities from 0.5 to 2 m s^{-1}) the local flow conditions are by far more important for the settling of sediments than the longitudinal trend. It is therefore likely that the type of clogging (internal vs. external clogging) will also be controlled by the local flow conditions.

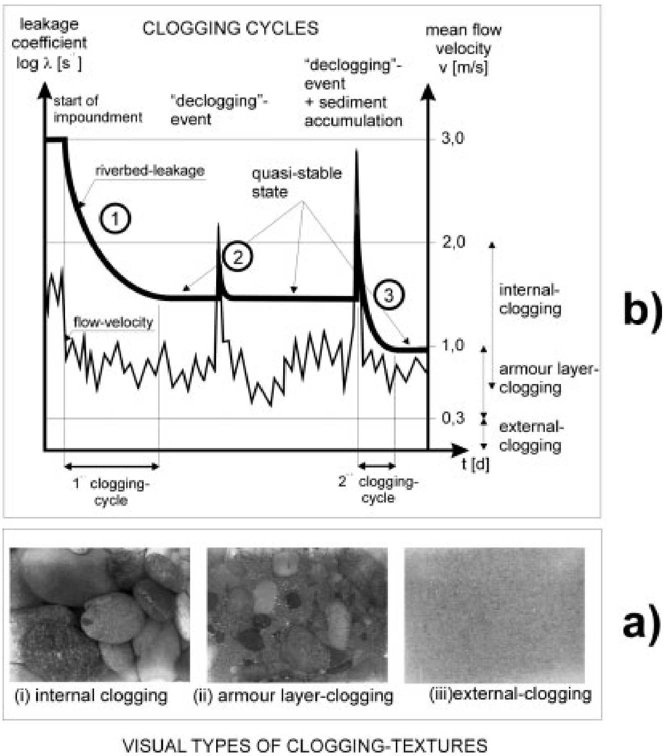


Figure 9. Texture of the three clogging types and clogging cycles.

The other important result of the video analysis was an assessment of the presence of clogging types. The video images clearly showed that both types of clogging (internal and external clogging) described in the literature were present in the Freudenau reservoir. Locations of the river bed with internal clogging exhibited grain sizes in the order of centimetres or more while locations with external clogging showed grain sizes in the order of millimetres or less. This interpretation is consistent with the results of the freeze panel sampling discussed later in this paper. The video analysis (and the attendant freeze panel sampling) also showed that in the Freudenau reservoir large areas exhibited an intermediate clogging

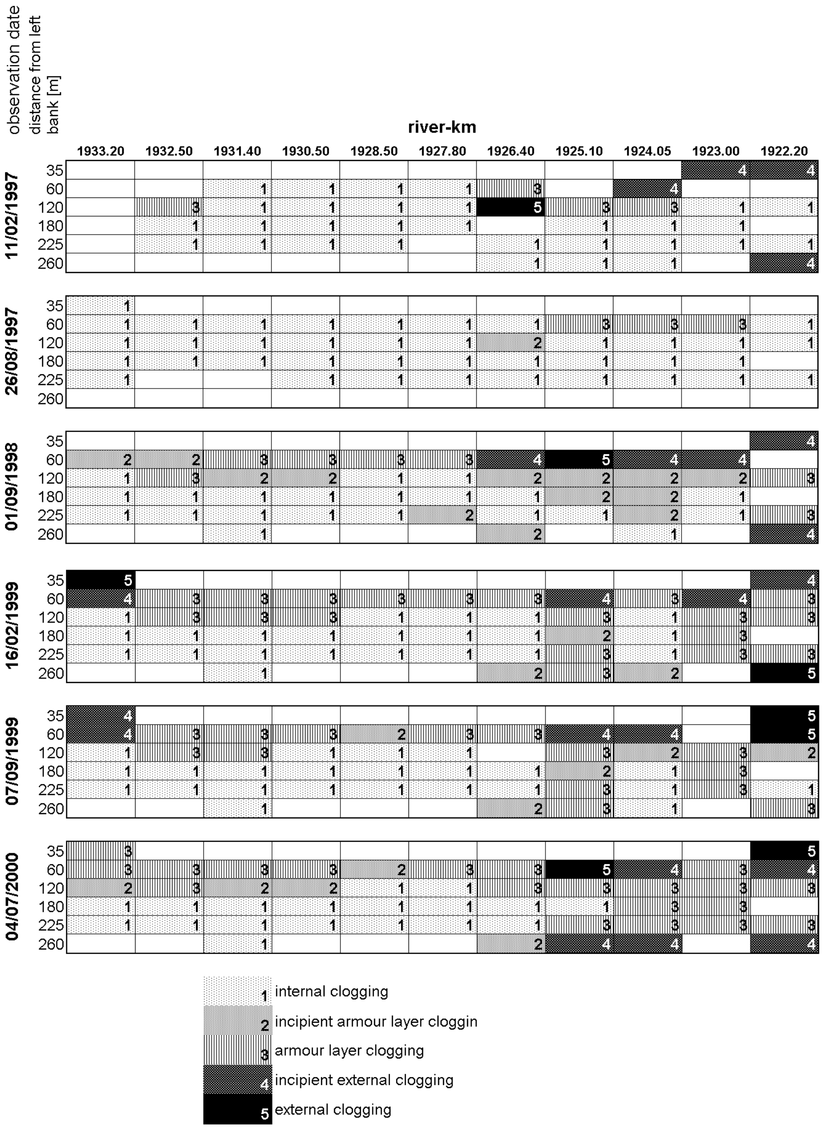


Figure 10. Space-time patters of the clogging types as identified by the video photographs (Feb. 11, 1997 to July 4, 2000).

type. This intermediate type is termed “armour layer clogging” in this paper. In this type, the fine sediments fill the voids of the armour layer rendering it very compact. Figure 9a shows the texture of these three clogging types from the video images. It should be noted that the internally clogged layer has the same visual appearance as an unclogged layer.

A comparison of the occurrence of the three clogging types based on the video analyses with the flow velocities in the Danube allows an assessment of which flow velocities are conducive to the development of a particular clogging type. At the lower end of flow velocities (less than 0.3 m s^{-1}) external clogging appears to develop. At intermediate flow velocities (between 0.3 and 1 m s^{-1}) armour layer clogging develops. At larger flow velocities (larger than 1 m s^{-1}) internal clogging may still develop. At very large flow velocities around 2 m s^{-1} (particularly during flood events) declogging tends to occur, when the armour layer is removed as a result of exceedingly large shear stresses. A schematic pattern of the clogging cycles and associated clogging types is shown in Figure 9b.

The space-time patterns of clogging types interpreted from the mobile video mapping are shown in Figure 10. In addition to the three main types mentioned above two intermediate types (incipient armour layer clogging and incipient external clogging) have been identified. For each of the six surveys (Feb. 11, 1997 to July 4, 2000) 11 cross sections are shown. Figure 10 suggests, that external clogging starts in the vicinity of the impoundment (right hand side of Fig. 10). This is clearly due to the lower flow velocities near the impoundment which allow the settling of fine suspended sediments. However this general longitudinal trend is superimposed by local effects. External clogging and armour layer clogging tends to occur along the left bank over most of the reservoir. These types of clogging start at a relatively short time after the impoundment and appear to move from the left bank towards the centre of the stream as the clogging proceeds.

3.2. Conductivities of the Clogging Types

The multilevel piezometer readings at the Schulschiff site and an additional site downstream (Ostbahnbrücke, Fig. 1) were used to obtain quantitative estimates of the hydraulic conductivities for each of the clogging types identified above. This was done by estimating the conductivities of the clogged layers as the product of the leakage coefficients (from the multilevel piezometer readings) and the thicknesses of the clogged layer (from the freeze panel analyses, see below) (Blaschke *et al.*, 2002). Comparisons of these conductivities with the clogging types from the video documentation, taking into account the temporal variability at each of the sites, allowed an approximate assessment of the conductivities of each clogging type. The approximate values of the conductivities are given in Figure 11 along with typical photographs of the stream bed for each of the types. Note that the conductivities vary by more than five orders of magnitude between the different clogging types.

3.3. Thickness of Clogged Layer

During the period September 1998 to November 1999 four surveys were conducted during which a total of 16 Freeze Panel samples were collected in the vicinity of the Schulschiff (river km 1931.4) and the Ostbahnbrücke (river km 1925.1) sites. From each sample the grain size distributions were analysed as a function of depth. These grain size distributions provided clear information on the thickness of the clogged layer. The finest median grain sizes were found close to the stream bed and the sizes were generally found to increase with depth. To illustrate the changes of the grain sizes with depth in the interstices, the Hazen (1892) formula was used to calculate the hydraulic conductivities from the portion of grain sizes <2 mm. Figure 12 shows the results for the freeze panel samples, stratified by clogg-

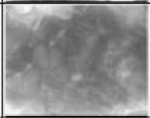
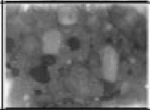
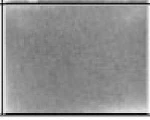
clogging type		conductivity [m/s] using a thickness of the layer of 10 cm
internal clogging		$1 \cdot 10^{-3} - 1 \cdot 10^{-4}$
incipient armour layer clogging		$1 \cdot 10^{-5} - 5 \cdot 10^{-6}$
armour layer clogging		$1 \cdot 10^{-7} - 5 \cdot 10^{-7}$
incipient external clogging		$5 \cdot 10^{-8} - 1 \cdot 10^{-7}$
external clogging		$< 1 \cdot 10^{-8}$

Figure 11. Assessment of the hydraulic conductivities for each of the clogging types examined.

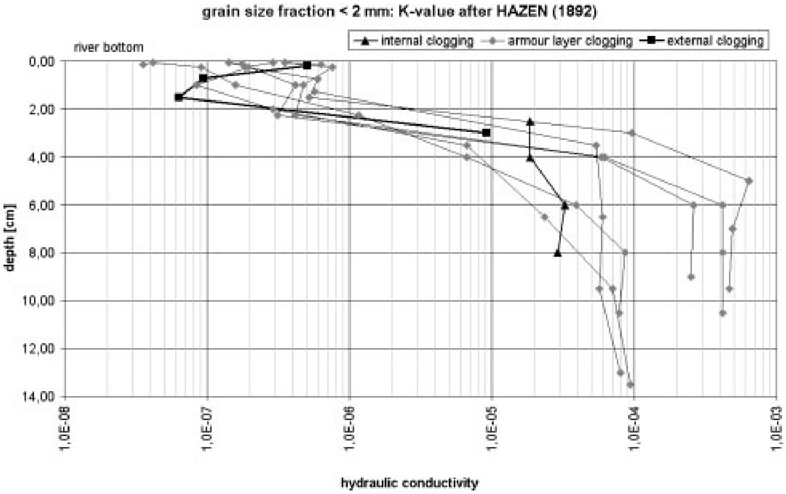


Figure 12. Hydraulic conductivities estimated from the Freeze panel sample grain sizes using the HAZEN (1892) formula $K = 0{,}0116 \cdot d_{10}^2 \cdot (0.7 + 0.03\ T)$ where K is the hydraulic conductivity (m/s), d_{10} is a representative grain diameter (10% of the sediment mass are smaller than d_{10}), and T is the water temperature which has been set to 10 °C.

ing type. For external clogging and armour layer clogging, the conductivities are very small in the top 2 cm of the interstices (about 10^{-6}–10^{-7} m/s^{-1}). The conductivities increase drastically with depth to reach a stable value at a depth of about 6 cm. These are conductivities that are representative of the river bed before clogging had commenced. Given these data it can be concluded that the thickness of the clogged layer for these two clogging types is in the order of 2 cm. For the third clogging type (internal clogging, triangles in Fig. 12) the surface layer is very coarse, so no conductivity can be calculated from the HAZEN (1892) formula. The conductivities at the depth of 6 cm or more are similar to those of the other clogging types.

3.4. Identification of Biological Activity

The video recordings were also used to visually examine the presence of biological activity on the stream bed. Photos taken in the winter (February) of 1997 showed masses of macrophytic algae covering the river bottom (Figs. 13 and 14) regardless of water depth and type of substrate (blocks, gravel, sand) in widespread areas extending from the river banks up to a distance of about 40 m from the river banks. Scuba divers reported an extraordinarily high visibility (more than 5 m in horizontal distance) during this period.

In addition to the vessel-based video documentation a stationary time-lapse videocamera was installed in the top layer of the riverbed at the Schulschiff study-site. Two thirds of the visual field of this camera was buried in the sediment. The camera was oriented across the flow direction of the river. Designed initially to observe the sediment transport at the study-site at higher discharges, the camera also supplied a wealth of unique sequences of activities of organisms. Crustaceans, gastropods, annelids and nematodes were observed creating new and using existing macropores when digging and moving through the uppermost 10 cm layer of the sediment. These activities most likely affect the hydraulic conductivities of the clogged layer. It is believed that the changes in leakage coefficients found from the piezometer analyses during moderate and low flows in late winter (marked as "biological effects?" in Fig. 6) can be attributed to activities such as those observed by the video photos. However, it is difficult to derive quantitative estimates of these effects in terms of hydraulic conductivities.

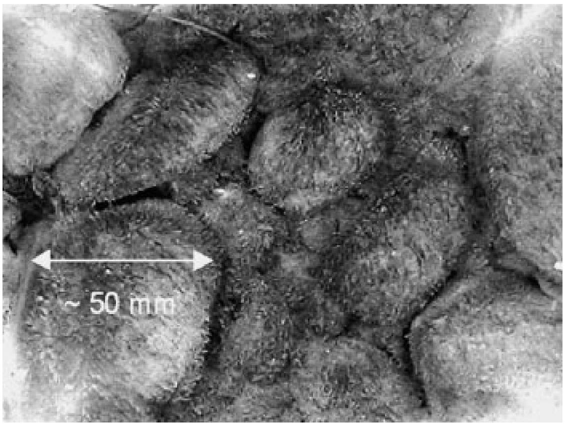


Figure 13. Macrophytic algae settling on gravel (water depth 8.0 m; scale bar 50 mm).

Figure 14. Freeze-panel sample with *Dreissena polymorpha* located on sandy spaces between gravels (armour layer clogging; water depth 9.5 m; view size 9×13 cm).

4. Discussion and Conclusions

The main strength of this paper has been to quantify the hydraulic characteristics of stream-aquifer interactions by a number of complimentary methods. The results suggest that the clogging processes in a setting such as the Freudenau reservoir consist of a series of clogging cycles and declogging episodes. Each clogging cycle is initiated by a flood event. After flood recession, a new clogging episode commences leading to a stepwise reduction of the leakage coefficient which is due to an additional sedimentation on the surface of the clogged layer and a subsequent clogging of the new sediment layer. It is likely that this effect will continue in the future and a further decline of the leakage coefficient is expected until a stable state in the sedimentation process is reached within the reservoir. We are unaware of any previous studies reporting the cyclic behaviour of clogging. Most other studies have either been laboratory studies (such as SCHÄLCHLI, 1993) or indirect methods analysing seepages rates (INGERLE, 1991) that have not examined the cyclic behaviour of clogging.

The duration of an individual clogging cycle to reach a quasi-stable state is only a few weeks. This is consistent with laboratory results (CUNNINGHAM *et al.*, 1987; SCHÄLCHLI, 1993). There has been an apparent inconsistency between these laboratory results and large scale field observations such as INGERLE (1991) and JOPPEN *et al.* (1992) who found a final stable state in the clogging process after 3 to 4 years for their reservoirs. The findings of this paper allow us to reconcile these apparently conflicting results. It appears that the laboratory analyses examined a single clogging cycle only, so the scale of a few weeks relates to a single clogging cycle. On the other hand the long term observations in the field have likely shown the cumulative effect of a number of clogging cycles. These cycles then give rise to the long term trends extending over several years observed by INGERLE (1991) and JOPPEN *et al.* (1992).

Another important result of this study refers to the thickness of a single clogged layer and it is interesting to put this result into the context of the existing literature. For two of the clogging types (external clogging and armour layer clogging) the freeze panel analyses indicate that the proportion of fines in the top 2 cm was very large and much lower below that depth. This suggests that the clogged layer is only 2 cm. For internal clogging the freeze panels are not deep enough but the piezometric analyses indicate that the clogged layer is not deeper than 50 cm. Freeze core analyses of BRUNKE (1999) suggest that there existed a maximum of fines at a depth of 45 cm at the Töss River which they attributed to internal clogging. For the study site of this paper a number of freeze cores have been taken (GUTKNECHT, 1998) but the problem with the freeze core method is that it is unable to capture fines in the top 5 cm due to the impact of ramming the core into the sediment, so the results may be biased.

Our combined approach also allowed us to spatially map the clogging types (internal clogging, amour layer clogging, external clogging) and to associate each type with typical values of the hydraulic conductivity. These spatial maps indicate that the spatial heterogeneity of the clogging types can be enormous in the same reservoir. The spatial heterogeneity is to some degree related to flow velocities but there are apparently other controls that cannot be fully resolved. Taking single profiles of the hyporheic zone to examine its hydraulic behaviour can therefore be associated with considerable uncertainty. The spatial patterns of conductivity derived here from the mapping along with the large scale spatial averages derived from the water balance analyses provide an unique methodology for obtaining more reliable estimates of the hydraulic behaviour of the hyporheic zone.

While this study has shed considerable light on the space-time variability of the hydraulic effects of clogging processes there are a number of aspects of the temporal variability that cannot be fully explained by abiotic controls. Results from the video monitoring and the sediment analysis of this study point to a potentially significant effect of biological activities on the clogging processes. While a number of authors have emphasised the importance of biologic effects for the hydraulic properties of the hyporheic zone (e.g. SENGSCHMITT and BATTIN, 1999), difficulties with accurate measurements have so far defied a rigid quantitative analysis. It is believed that interdisciplinary research involving both biologists and hydraulic engineers will be necessary if headway is to be made in quantifying the biological effects on the clogging processes. Such research may address topics such as the seasonality of metabolism and physiological conditions (light-, substrate-, food parameters) as well as the effect of biocenoses on the stability and the hydraulic conductivity of the substrate. From a hydraulic point of view, some of the most relevant questions to be addressed by biologists are:

- Which biocenoses appear in which zones (depths of the sediment)?
- In which way and to which extent do they influence hydraulic conductivity?
- What are their favourite metabolic conditions?
- What is known about their sensitivity to and resistance against mechanical-, chemical-, hydraulic- and other stress factors?
- How long does it take to establish fully functioning and stable biocenoses after disruptions such as flood events under given boundary conditions?
- Do seasonal or other cyclic deviations exist?

5. Acknowledgements

The Forschung des Verbund and the Vienna City Council provided generous financial and in kind support of the research reported in this paper over a period of five years. This support is gratefully acknowledged by the authors. We thank Prof. G. BLÖSCHL for his valuable comments on the manuscript.

6. References

BLASCHKE, A. P., R. BRAUNSHOFER, H. FEREGYHAZY, D. GUTKNECHT, H. HABERSACK, CH. KARNER, P. MAYR, R. SCHMALFUSS, S. SCHOBER, D. SENGSCHMITT and K.-H. STEINER, 2002: Kolmationsprozesse am Beispiel des Stauraumes Freudenau. Phase II. Schriftenreihe der Forschung im Verbund. Band 75.

BRUNKE, M., 1999: Colmation and Depth Filtration within Streambeds: Retention of Particles in Hyporheic Interstices. – Internat. Rev. Hydrobiol. **84**: 99–117.

CUNNINGHAM, A. B., C. J. ANDERSON and H. BOUWER, 1987: Effects of Sediment Laden Flow on Channel Bed Clogging. – J. of. Irrigation and Drainage Eng., ASCE. Vol. **113**: 106–118.

GELDNER, P., 1981: Deterministische und stochastische Methoden zur Bestimmung der Selbstdichtung von Gewässern. – Institut für Wasserbau, Universität Stuttgart, Heft 49.

GRUPPE WASSER, 1997: Kraftwerk Freudenau. Beweissicherung Neue Donau. Jahresbericht 1996. Wasserbilanzen und Grundwasserschichtenpläne (Beilage 3). Magistrat der Stadt Wien – Magistratsabteilung 45.

GUTKNECHT, D., A. P. BLASCHKE, D. SENGSCHMITT and K.-H. STEINER, 1998: Kolmationsvorgänge in Flußstauräumen – Konzeptionen und Beobachtungen. – Österreichische Ingenieur- und Architekten – Zeitschrift. **143**: 21–32.

HANTUSH, M. S., 1965: Wells near Streams with Semipervious Beds. – J. of Geophysical Research, Vol. **70**, No. 12, 2829–2838.

HAZEN, A., 1892: Some physical properties of sands and gravels with special reference to their use in filtration. – Twenty-fourth annual report state board of health Mass.: p. 541–556. Boston, Mass.

HUMPESCH, U. H. and R. NIEDERREITER, 1993: Freeze-core method for sampling the vertical distribution of the macrozoobenthos in the main channel of a large deep river, the River Danube at kilometre 1889. – Short commun.: Arch. Hydrobiol. Suppl. **101**: 87–90.

INGERLE, K., 1991: Über die Flußbettdurchlässigkeit und die Sauerstoffzehrung des Uferfiltrates im Staubereich von Donaukraftwerken. – Wasserwirtschaft, **81**. Jg.: 415–422.

JOPPEN, M., P. SULSER, P. BLASER and A. KOHLER, 1992: Einfluß der Stauregelung auf Grundwasser. Wasserbau München–Obernach, Mitteilung Nr. **73**: 365–375.

LILSE, T. E., 1989: Sediment Transport and Resulting Deposition in Spawning Gravels, North Coastal California. – Water Resour. Res., Vol. **25**: 1303–1319.

MITCHELLL-BRUKER, S. and H. M. HAITJEMA, 1996: Modeling steady state conjuctive groundwater and surface water flow with analytic elements. – Water Resour. Res. **32**: 2725–2732.

NIEDERREITER, R. and K.-H. STEINER, 1999: Der Freeze-Panel-Sampler (Frost-Platten-Sam-mler; FPS) – Ein neues korngrößenunabhängiges Verfahren zur Entnahme gefügeintakter oberflächennaher Urproben aus wassergesättigten Lockersedimenten. – Hydrologie und Wasserbewirtschaftung **43**: 30–32.

PATSCHEIDER, R., 1994: Selbstdichtung von Gewässern, Ursachen und Einflußfaktoren. Diplomarbeit Techn. Univ. Wien.

RAUCH, W., 1993: Über die hydraulische Wechselwirkung von Oberflächengewässern und Grundwasserkörpern. – Die Wasserwirtschaft **83**: 14–18.

SCHÄLCHLI, U., 1993: Die Kolmation von Fließgewässersohlen: Prozesse und Berechnungsgrundlagen. – Technischen Hochschule Zürich (VAW). Nr. 124.

SCHÄLCHLI, U., 1996: Feinstoffeinlagerung in Deckschichten. Schriftenreihe des österreichischen Wasser- und Abfallwirtschaftsverbandes (ÖWAV), H. **105**: 77–89.

SCHMALFUSS, R., 1998: Der Einfluß der Grundwassertemperatur auf den Wasserhaushalt am Beispiel der Neuen Donau. – Wiener Mitteilungen, Wasser-Abwasser-Gewässer. **148**: 373–392.

SENGSCHMITT, D. and T. J. BATTIN, 1999: Linking Sediment Biofilms, Hydrodynamics, and River Bed Clogging: Evidence from a Large River. – Microb. Ecol. **37**: 185–196.

SERRANO, S. E. and S. R. WORKMAN, 1998: Modeling transient stream/aquifer interaction with the non-linear Boussinesq equation and its analytical solution. – J. of Hydrology **206**: 245–255.

STEINER, K.-H. and R. NIEDERREITER, 1999: Frost-Platten-Sammler (FPS) zur Entnahme ungestörter wassergesättigter Sedimentproben. – DVWK-Schrift "Methoden zur Erkundung, Untersuchung und Bewertung von Sedimentablagerungen und Schwebstoffen in Gewässern" **128**: 139–143.