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QUANTITATIVE EVALUATION OF CLOGGING PHENOMENA IN RIVER BEDS

by

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Summary:
Clogging phenomena in rivers are of extremely complex nature, and a development of a clogging layer depends on a large variety of influences. In this paper a quantitative approach for the evaluation of a defined hydrodynamic clogging parameter is presented.

This approach is based on the inverse use of type curves representing characteristics of the interaction between surface water bodies and the aquifer. The method is applied to field data of discharge measured in seepage ditches at levee protected sites. Since conventional approaches are limited to the assumption of quasi-steady-state flow, a stochastic method for the evaluation of time-variable hydrographs is also outlined.

1. INTRODUCTION

Clogging phenomena at stream or lake beds have been widely recognized as relevant to the interaction between surface and groundwater bodies. However, their quantitative evaluation still faces considerable difficulties due to the complexity of the underlying processes. Affecting a major component of the general groundwater balance, the development of a clogging layer is of interest in a number of hydrological and engineering problems concerning the evaluation of leakage from streams, canals or lakes. The design and operation of river bank filtration plants and of levee protected navigable waterways may be quoted as typical examples.

2. PREVIOUS APPROACHES AND PARAMETERIZATION

2.1 Filter column tests and practical estimates

In the past, a variety of different approaches has been applied in order to master the complexity of the clogging process: Since the clogging of a river bed may to some extent be explained by natural filtering, various investigators have tried to simulate the process in small laboratory filter columns under idealized conditions. Typical laboratory arrangements are characterized by the use of both, narrow filter grain size distributions and single turbit components. Commonly, biological and chemical processes are neglected in such experiments. A small number of column tests has been performed under more realistic conditions, applying polluted river water, however, disturbed filter samples /3/4/.

Already at an early stage, regional groundwater flow models faced the problem of taking a reduced exchange rate between surface and groundwater into account. Therefore, practical approaches often assume proportionality between the exchange flow rate and some arbitrarily defined head difference between the river stage and the groundwater surface. The factor of proportionality has to be estimated for individual sites as part of the model calibration. However, the physical significance of such factors is not transparent.

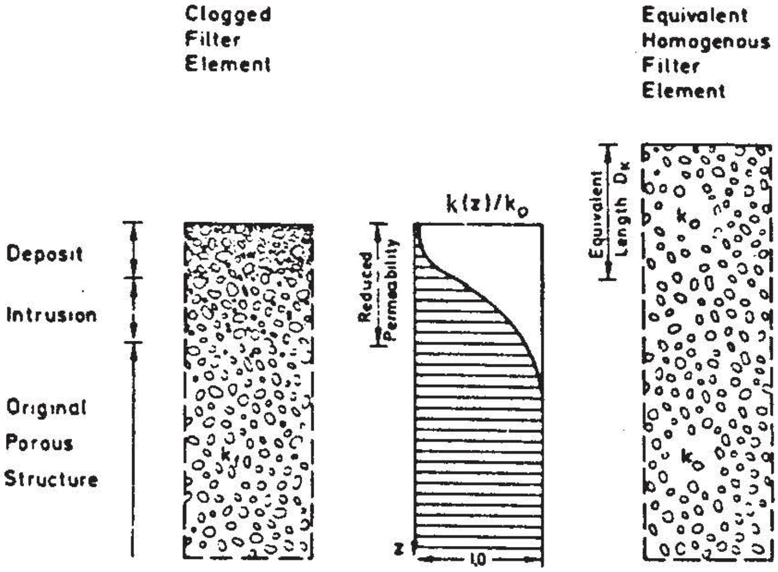


Figure 1: Definition of the bulk clogging parameter D_K

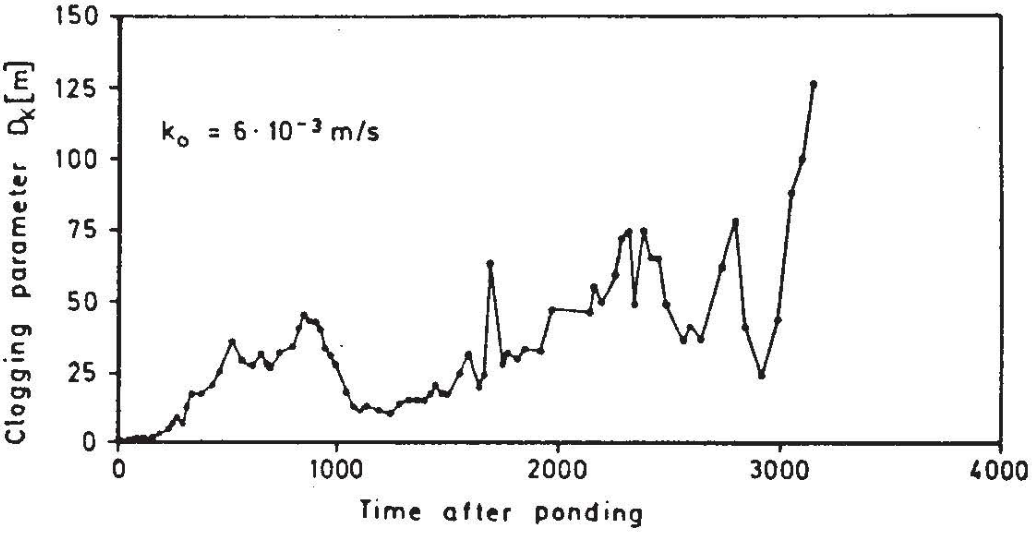


Figure 2: Measurement results of filter column test (polluted river water and gravel packing, column diameter 500 mm) /6/

2.2 Definition of a bulk clogging parameter

Experimental and empirical results have been presented in the form of many different parameters, such as the percentage of flow rate reduction or characteristic conductivity distributions with depth of a filter column. Frequently, clogging has been understood as a natural lining phenomenon, assuming a thin bottom layer of thickness d' and of the small conductivity k', which are both scarcely measurable, however.

In order to provide a universal and at the same time practicable parameter, the following bulk clogging parameter was defined in /6/:

$$D_K = k_0 \int_0^\infty \left(\frac{1}{k(z)} - \frac{1}{k_0} \right) dz \qquad (1)$$

in which $k(z)$ is an arbitrary vertical permeability distribution of a clogged filter element of the river bottom, and k_0 is the original permeability of the unclogged element. In Figure 1 the bulk clogging parameter D_K is visualized as the length of an equivalent homogeneous filter. In the given form the parameter represents the total increase in hydraulic resistance, which is produced in the river bottom element during the clogging process.

2.3 Comparison of available data

By use of the parametric definition Eq. (1), and application of a dimensional analysis, a comparison of available data from laboratory filter tests has revealed the following main aspects /6/ :

1. Due to strongly individual behavior of the constituents of the applied water, a valid universal relation could not be derived from the data, neither for a characteristic development in time nor for any major parameter of influence.

2. The scattering of the results, by far, exceeds commonly tolerable variations. Additionally, distinct build-up and tear-down phases of unknown reasons seem to characterize the development of a clogging layer (Figure 2).

3. A distinct long term behavior, as sometimes postulated in the literature, could not be verified from the available data, and an application of short term test results to field situations has failed due to the lack of quantitative similitude.

3. PARAMETER IDENTIFICATION BY NEAR-FIELD FUNCTIONS

3.1 A general strategy

An alternative method of evaluating clogging phenomena can be based on the inverse employment of flow calculation results. In a similar way as for many other hydrological parameter identification problems, such as pumping test evaluations, the present task implies a detailed flow analysis of the interaction between surface water bodies and the groundwater.

In order to establish a general inverse evaluation strategy, the part of an aquifer containing the surface water body and the exchange flow region, was conveniently defined as the "near-field" /6/ . Consistently, the remaining part of the aquifer may be called the "far-field". Substantiating a subsystem of the total aquifer, the definition of the near-field is not limited to any particular type of surface water nor of the aquifer. While groundwater flow in the far-field can practically always be treated by depth averaging approaches, near-field flow is, on the contrary, typically two- or three-dimensional.

On the basis of this definition it becomes possible to study the interaction between surface water and groundwater by a quantitative flow analysis of the parameterized near-field system. Analytical or numerical solutions may be used for this purpose. The general scope of a near-field flow analysis is to establish the near-field function, an explicit relation between a number of dependent and independent near-field parameters. The latter stand for the near-field's geometry, permeability distribution, boundary conditions and, in particular, an effective clogging parameter. Typical dependent parameters are characteristic head differences or fluxes.

Once the near-field function for a given system is known, its inversion may be used to evaluate the bulk clogging parameter from head or flux data measured in the field. This inversion is often best achieved by use of a graphical representation of the near-field function in the form of type-curves.

3.2 Example of a near-field analysis for a principal flow case

The evaluation of the near-field function (NF) is illustrated for the principal flow case in Figure 3. For this homogeneous aquifer the near-field function gains the dimensionless form:

$$\left.\begin{array}{c} \left(\dfrac{s_{c1,2}}{Q_{1,2}/k_f}\right) \\ \\ (Q_u/Q_2) \end{array}\right\} = \mathrm{NF}\left\{ \left(\frac{b_f}{D}\right), \left(\frac{Q_1}{Q_2}\right), \left(\frac{D_K}{D}\right) \right\} \tag{2}$$

in which are (see also Figure 3):

b_f/D	relative river width (geometry)
Q_1/Q_2	inflow-outflow ratio (boundary conditions)
D_K/D	dimensionless clogging parameter
$\dfrac{s_{c1}}{Q_1/k_f}$ $\dfrac{s_{c2}}{Q_2/k_f}$	dimensionless characteristic head-loss parameters on both sides of the river, defined in Figure (3a) as the difference between the river-stage and the extrapolated one-dimensional head-distribution
Q_u/Q_2	passage-flux ratio, characterizing the amount of volume rate of water passing under the river

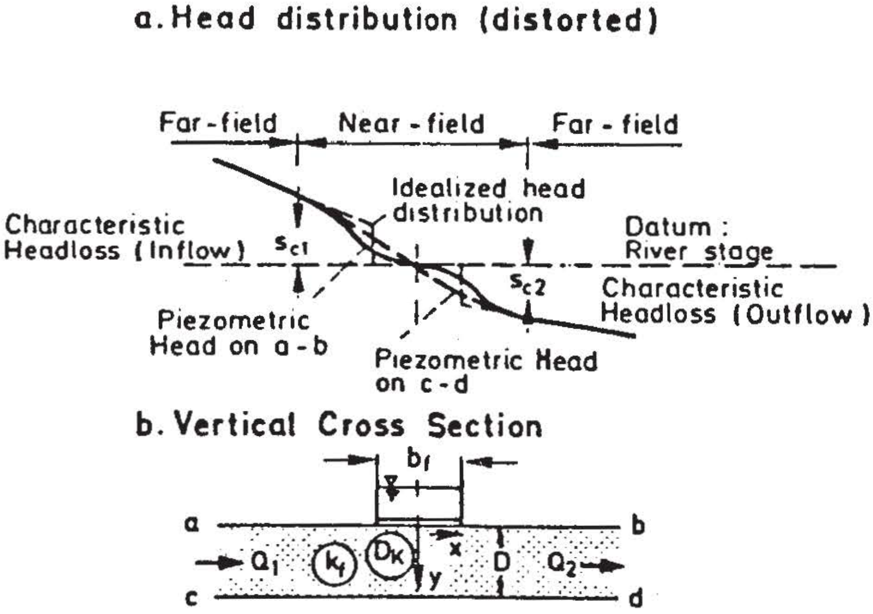


Figure 3: Principal near-field system with clogged river bed

b_f	river width	Q_1	inflow rate
D	aquifer thickness	Q_2	outflow rate
D_K	clogging parameter	s_{c1}	characteristic head losses
k_f	conductivity	s_{c2}	on either side of the river

Figure 4 presents an example of calculation results of the near-field function as obtained by a finite element scheme /4/ . An analytical solution is only available for an unclogged river bottom /1/6/ . From Figure 4a it is clearly recognized that for a wide range of near-field parameters a positive passage-flux underneath the river cannot be neglected. For a relative river width $b_f/D = 1.0$, the characteristic head-loss proves to be strictly dependent on the near-field's boundary conditions except for Q_1/Q_2 at the order of one.

Since the characteristic head loss may be obtained from an extrapolation of measured head data in the adjacent aquifer, the near-field-function can be used in the form of type-curves providing a way for an inverse determination of the clogging parameter. A more important application of the near-field function of this principal flow case, however, appears to be a more realistic consideration of clogging phenomena in two-dimensional regional groundwater flow models, replacing much less flexible approaches presently in use. First successes have already been achieved in /11/ . The values of the clogging parameter applied in such models can be evaluated from field head measurements by standard inverse calibration techniques.

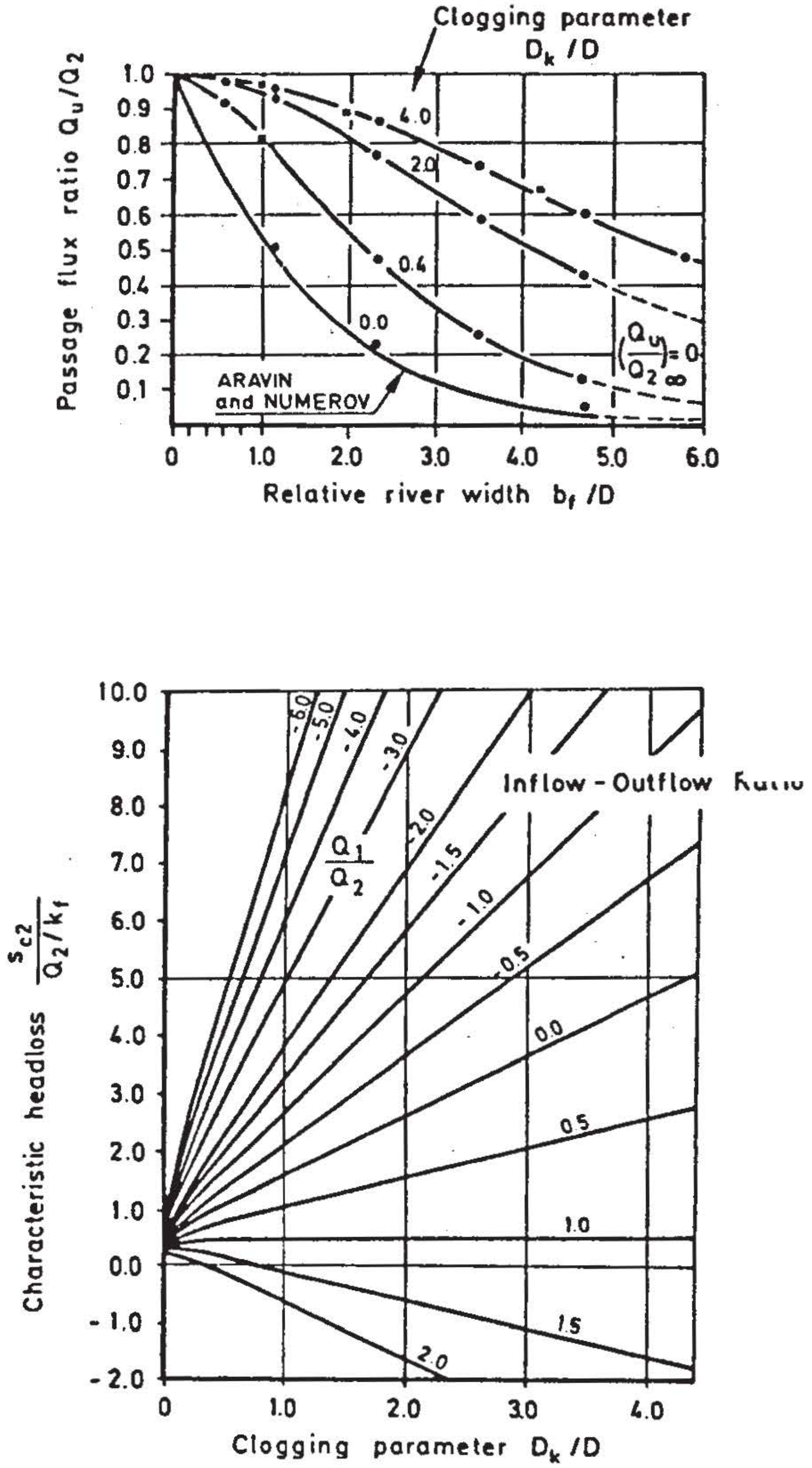


Figure 4: Near-field function for principal flow case

a) Passage flux ratio versus relative river width as function of dimensionless clogging parameter (inflow-outflow ratio $Q_1/Q_2 = 1.0$)

b) Characteristic head loss versus dimensionless clogging parameter as a function of boundary conditions (relative river width $b_f/D = 1.0$)

4. FIELD DATA EVALUATION FOR TWO LEVEE-PROTECTED SITES OF DAMMED-UP RIVERS

A considerably more detailed near-field flow analysis was performed for two levee-protected sites at the head water regime of two dammed-up rivers. Discharge measurements were available from drainage ditches at Altenwörth/Danube (Austria) and Gambsheim/Rhine (West Germany) for several years /6/7/

The evaluation procedure consisted of the following steps:

1. Model calculations
   to determine the near-field function in terms of a seepage rate from the river into the drainage ditch, including a comprehensive sensitivity analysis considering a variety of near-field parameters.

2. Reduction of the measured discharge data
   incorporating both, the evaluation of mean seepage rates per unit length of the drainage ditch, and corrections accounting for time varying influences such as water temperature or stage variations.

3. Evaluation
   of the clogging parameter by use of the model type-curve

The nomograph of Figure 5 presents the evaluation procedure: The reduced data of the seepage flow rate (per unit length of the ditch) are plotted versus time-after-ponding. Both, the data points and their regression curves are graphically "reflected" at the model type-curves to give the development of the clogging parameter versus time. (Type-curves and data points for one individual drainage ditch are marked by the same symbol.)

The results clearly show increasing trends of the clogging parameter, which deviate, however, from each other. In addition there is a considerable scattering of the resulting data points. In order to demonstrate the sensitivity of the evaluation method to possible errors due to estimated values of the conductivity and the anisotropy of the aquifer, correspondingly different type-curves were calculated in the model. Figure 6 illustrates the sensitivity of the results for data of Altenwörth drainage ditch No.3. The range of uncertainty covers the deviations among the results in the previous figure, so that the observed trend may be biassed to some unknown extent. Besides, the range of uncertainty increases with time, which illustrates the particular difficulties in measuring long-term clogging.

In Figure 7 the evaluation results for both, Altenwörth and Gambsheim are compared. Clearly considerable variations in time can be recognized. They cannot be explained by errors in the value estimated of any system parameter. Although, for Altenwörth some influence of the hydrological regime could not be thoroughly excluded due to the lack of additional data, for Gambsheim, groundwater table fluctuations were not at all sufficient to introduce the evaluated variance. It must rather be assumed that the fluctuations are indeed generation and degeneration phases of the development of the clogging layer. As could be shown by application of the same approach to more recent data from another site in the Rhine river valley, such phases may well have the character of distinct saisonal periodicities /10/ . Experience made so far gives rise to the speculation that biological processes are of major importance to the growth and decay of the clogging layer. Further investigations to find scientific evidence of the biological nature of the clogging layer are recommended by the authors.

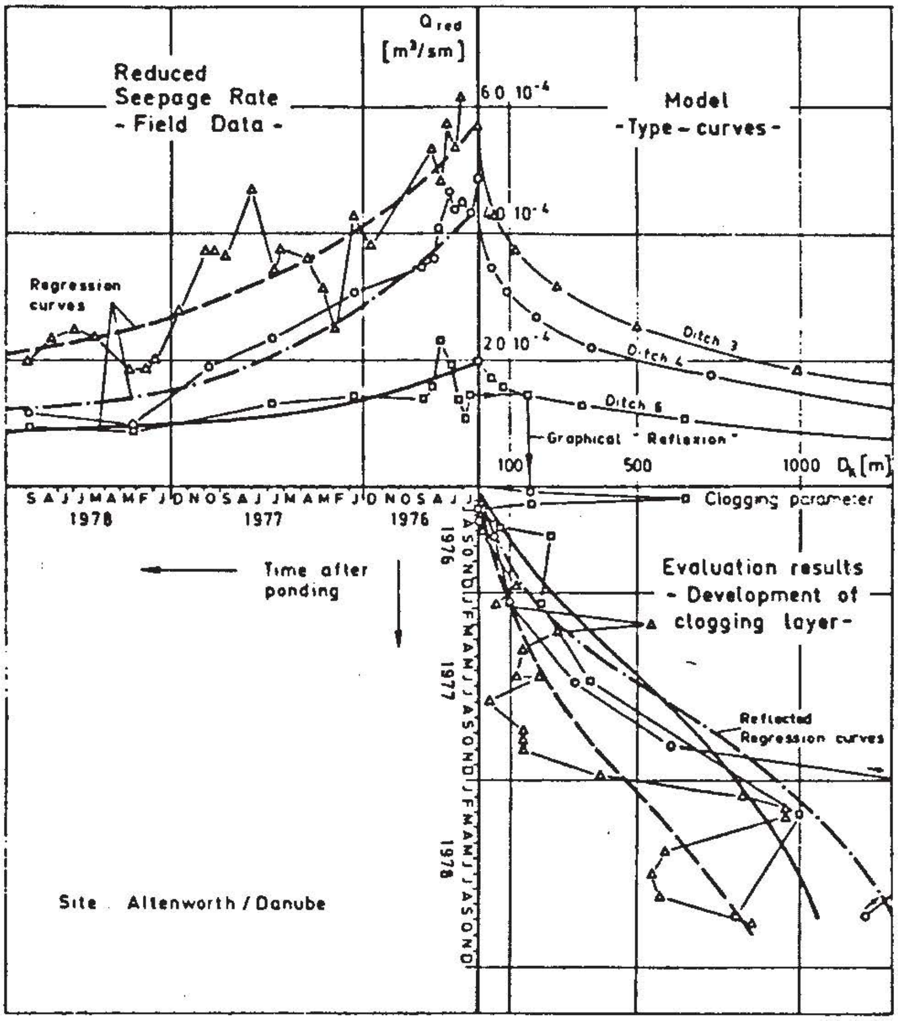


Figure 5: Inverse evaluation of the clogging parameter by use of model type-curves

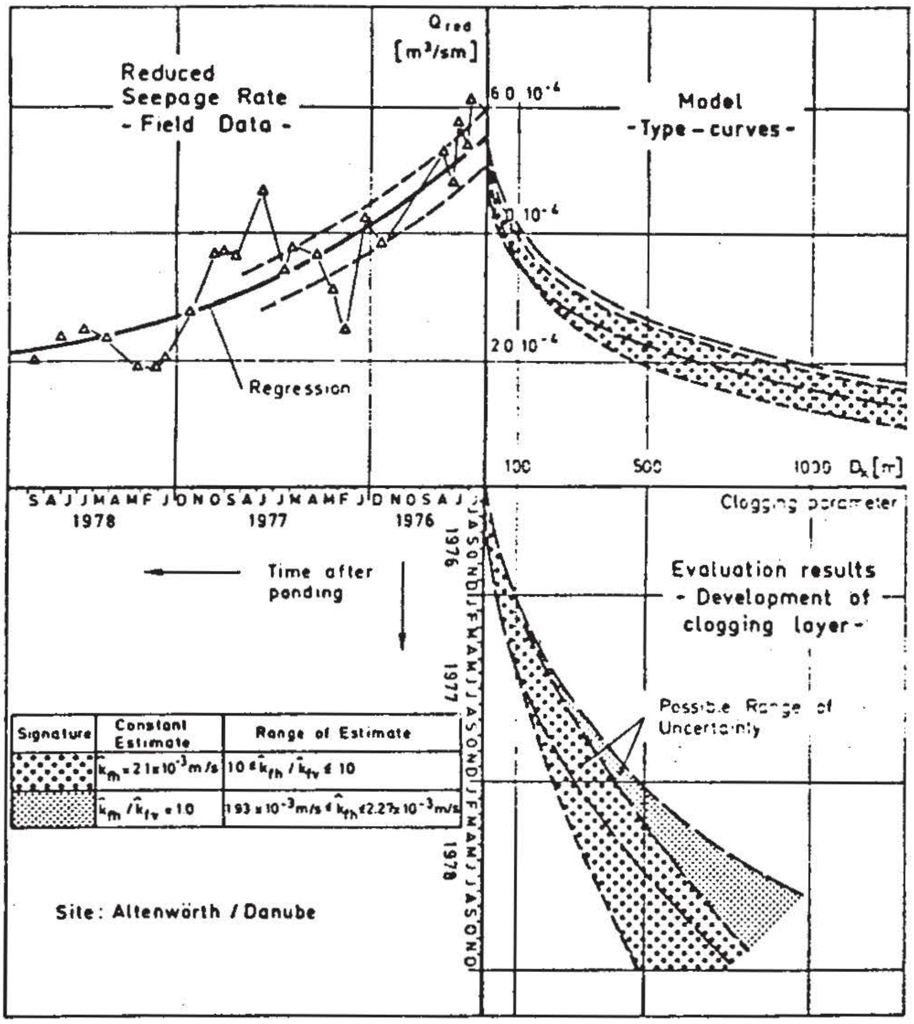
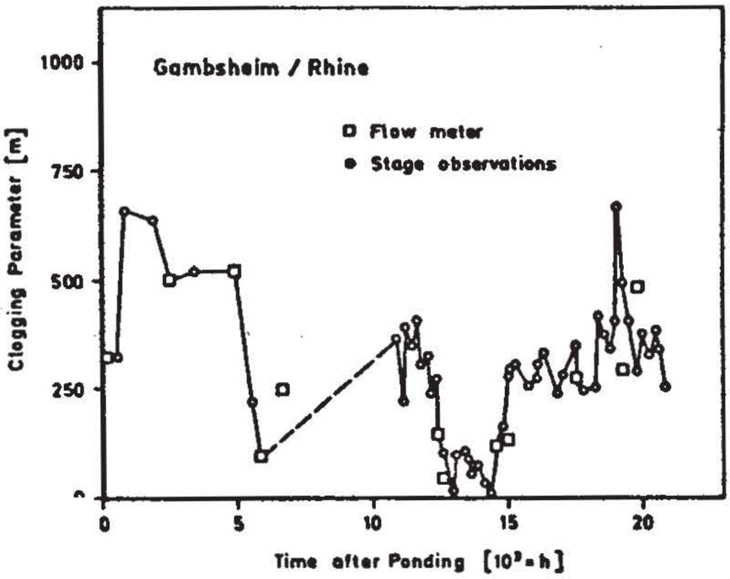


Figure 6: Sensitivity of evaluation results to possible estimation error in conductivity or anisotropy (data of drainage ditch No.3, Altenwörth/Danube)



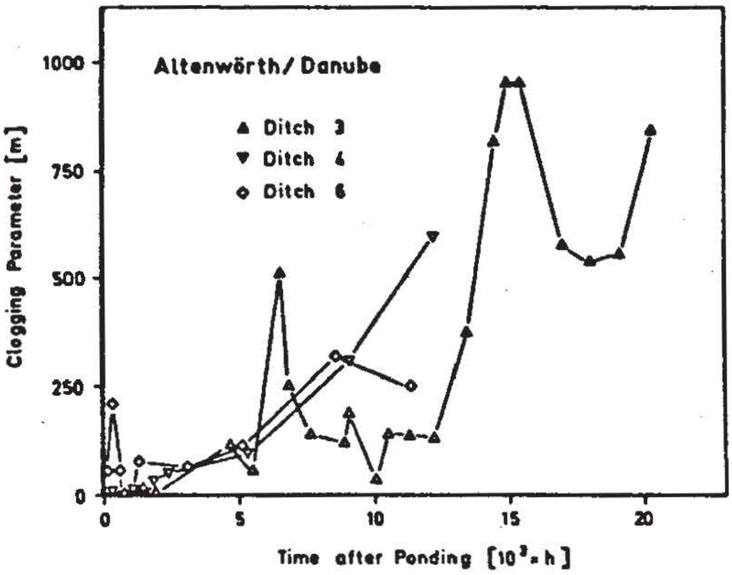


Figure 7: Field data evaluation results: the clogging parameter for dammed-up river

5. OUTLOOK ON A STOCHASTIC EVALUATION METHOD

5.1 The stochastic approach

Steady-state evaluation of the clogging parameter is limited to mean value considerations or to extremely slow changes in the hydraulic behavior of a flow system. In general, however, field data show considerable random fluctuations with time. To make use of the information comprised in such measured fluctuations, stochastic methods based on spectral solutions of the flow equations can be applied /9/5/ .

In doing so a linear flow system is described by a frequency dependent transfer function, which is commonly introduced as the Fourier transform of a statistical filter function, relating excitation and response time-processes. In the following the mathematically complex function transfer is only used in the form of the real-numbered square of its absolute, sometimes referred to as the "square of the amplitude of the transfer function". For a single excitation process the squared absolute of the transfer function becomes the ratio of the response and excitation spectra.

If river stage fluctuations are considered to be the excitation to an aquifer flow system, so that head fluctuations in the aquifer gain the role of a response time-process, the interaction between the river and the groundwater can well be described by a transfer function, now incorporating a number of near-field parameters. In a similar manner as for the steady-state approach, spectral type-curves representing the transfer function of a given system may consequently be used for an inverse evaluation of near-field parameters.

5.2 A first application example

For the principal flow case previously shown in Figure 3, the transfer function was analytically evaluated /4/5/ . A one-dimensional aquifer of finite length was assumed while the river width was approximately infinitely large. The far end of the aquifer was kept at a constant head. (A variety of different boundary conditions at the far end of the aquifer was treated in /5/ .)

In Figure 8 the analytical results are compared to spectral field data. The solid lines represent the analytical solutions of the transfer function in the general form:

$$|G|^2 = \text{fct} \quad \left(\frac{\omega x^2}{T/S}\right), \left(\frac{L}{x}\right), \left(\frac{x}{x_0}\right) \tag{3}$$

Herein are

$|G|^2$ squared absolute of the transfer function, also given by the ratio of the response and excitation spectra

$$|G|^2 = S_{hh} / S_{ff} \tag{4}$$

$\left(\frac{\omega x^2}{T/S}\right)$ a dimensionless frequency (ω circular frequency, x distance of an observation well from the river, T transmissivity, S storage coefficient)

(L/x)	relative length of the aquifer
(x_0/x)	a dimensionless leakage parameter defined in terms of the dimensionless characteristic head loss as (compare also /2/):

$$\frac{x_0}{x} = \left(\frac{s_c}{Q/k_f}\right) / \left(\frac{D}{x}\right) \tag{5}$$

The dimensionless leakage parameter x_0/x may be recognized to be dependent of the constant clogging parameter according to the near-field function given by Eq.(2).

Spectral analysis was performed for time-series of thirty years of weekly measurements of both, river stage and groundwater table from a cross-section of the Rhine aquifer south of the city of Karlsruhe (West Germany). For comparison with the analytical results, the ratio of the smoothed spectra was evaluated from the field data and also plotted in Figure 8. Best agreement between the data and a spectral type-curve was found for a leakage factor $x_0/x \simeq 0.5$.

Although the rather simple pattern of the underlying flow case would suggest some caution to a final application of the obtained value, the example may prove that also fluctuations of measured time-series can be used to determine an effective clogging of river beds. The sensitivity of the method gives rise to hope for a future successful application to more general flow cases /8/ .

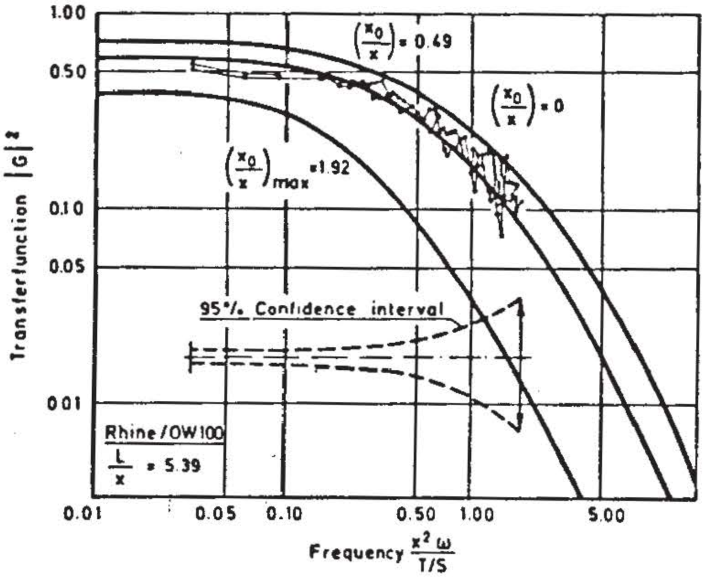


Figure 8: First stochastic evaluation results
(x_0/x = dimensionless leakage parameter acc. to Eq.(5))

6. CONCLUSIONS

The exchange flow rate between surface waters and the groundwater is doubtlessly an important component of the general groundwater balance. It is to a large extent dependent on a clogging layer at stream or lake beds.

First quantitative evaluation results seem to reveal a general clogging process that is characterized by an initial phase of increase (on the order of years). From rational reasoning it can be expected that the process will then stabilize to some degree. However, considerable fluctuations are superimposed to an average long-term value.

Since previous approaches have failed to provide applicable results, a strategy for the handling of the complexity of the clogging process may be outlined by the following programatic steps:

1. In practical engineering applicable values of the effective bulk clogging parameter are needed. The near-field function of relatively plain principle cases may be used to provide such values through conventional calibration of regional groundwater flow models.

2. A wide collection of field values of the bulk clogging parameter obtained by inverse calibration techniques may then serve as a basis for a statistical or correlative analysis of data and related experience.

3. At the same time, fundamental investigations should be promoted, particularly on the impact of biological processes on temporal variations of the clogging layer.

Steady-state and quasi-steady-state evaluation approaches, predominantly presented in this paper, may be applied to hydrological field data to determine trends and slow variations of the effective clogging parameter. The outlined stochastic approach may serve a twofold function: By analysis of time-dependent head or flux data a significant simplification and an increase in objectivity of conventional groundwater model calibration can be expected. The clogging parameter is still assumed a constant value in this approach. In a much wider sense, however, stochastic methods are capable of describing temporal and even spatial variability of the clogging layer.

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