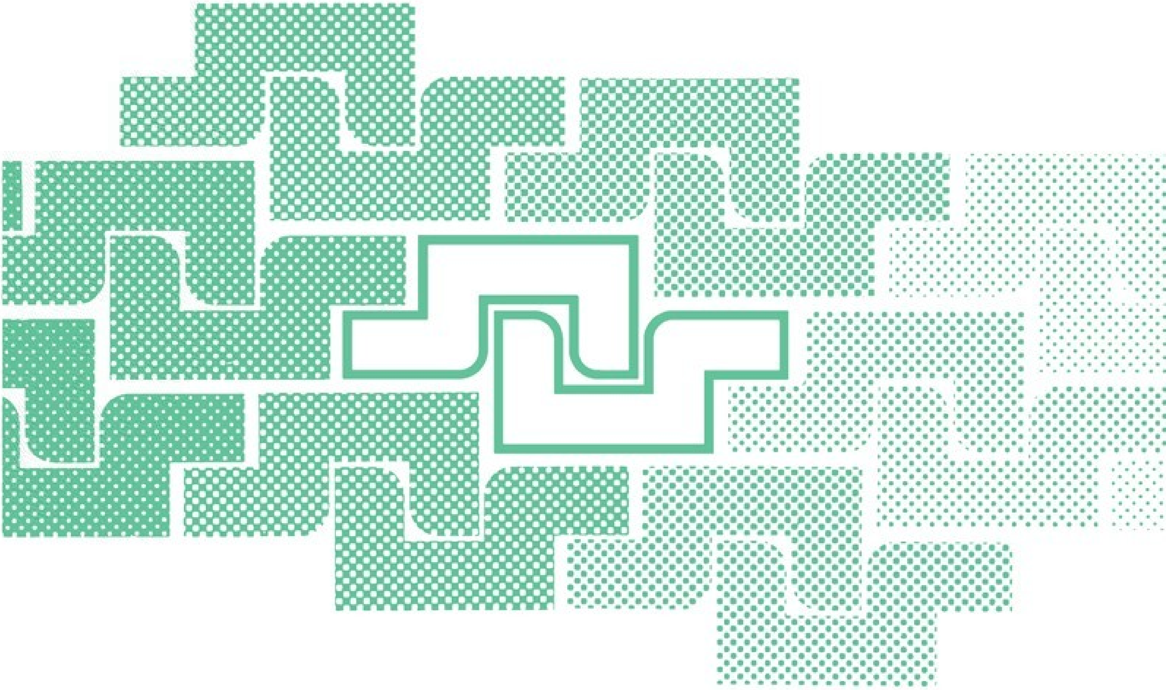

Riverbank Filtration Hydrology

Impacts on System Capacity and Water Quality

Edited by

Stephen A. Hubbs

NATO Science Series

IV. Earth and Environmental Sciences – Vol. 60

Riverbank Filtration Hydrology

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Riverbank Filtration Hydrology

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Dedication

This book is dedicated to our
meeting hosts in Bratislava,
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warm hospitality and excellent
facilities for this workshop.

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The workshop and the compilation of this book was funded by the Public Diplomacy Division NATO's Collaborative Programs Section. The participants benefited not only from the scientific exchange, but also from the opportunity to establish friendships across cultural barriers.

Preface

The workshop from which this book is taken was held to share knowledge from the US and Europe on the science of riverbank filtration hydrology. Participants at the workshop represented all known elements of science that impact the hydrology of riverbank filtration: surface water hydrology, particle filtration, biological processes, and geochemical processes.

Those unfamiliar with the science of Riverbank Filtration might want to start with Chapter Fourteen, which includes some of the basic concepts of riverbank filtration hydrology. This chapter was written with the RBF novice in mind. It also includes extensive site data from RBF facilities in Europe and the US.

The first four chapters cover the basic hydrology of riverbank filtration, with a focus on those factors impacting system capacity and water quality through the clogging processes. Chapters Five and Six evaluate the impacts of biological and geochemical processes, and their impacts on flow and water quality. Chapters Seven and Eight provide examples of how modelling is used to predict yield and water quality in RBF facilities.

Chapters Nine through Thirteen document case studies from RBF facilities in Europe and the US. Chapter Six also contains extensive data on the many RBF sites located in the Netherlands. These chapters provide valuable practical experience from managers and scientists of RBF facilities across Europe and the US which should be helpful to those considering RBF as a water supply.

Chapter Fourteen was written after the workshop, and provides a listing of key measures developed during the workshop to be considered when designing RBF facilities. This chapter was written to provide a compilation of data from successful RBF sites to gain better insight into future sites being considered for RBF facilities. Data from many Riverbank Filtration sites are provided for these key measures.

Discussion from this workshop indicated that further research is needed into the impact of gas bubble formation on the flow through riverbeds, and through porous media in general. Several of the workshop participants had observed the formation of gas in laboratory settings, and outgassing has been observed in at least two field sites. This is an area warranting further work.

SIGNIFICANCE OF HYDROLOGIC ASPECTS ON RBF PERFORMANCE

Everything is linked to everything else

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Abstract: Clogging of the riverbed is still an important factor causing uncertainness in the planning stage of riverbank filtration plants. Several attempts have been made to develop tools, which are suitable to predict this process. But up till now, these tools are only a slight help for the engineering of riverbank filtration plants. On the other hand there exists a lot of experience about clogging from the operation of riverbank filtration plants. But to utilize this experience for a new plant, the hydrological and morphological aspects of the river and the aquifer have to be analyzed carefully to create a basis for the transfer of available knowledge. This paper deals with the relevant properties of rivers, concerning riverbank filtration: the runoff regime and the runoff dynamics, the river-aquifer interactions, the stream processes – erosion, transport and deposition – and the progress of the clogging process itself.

Key words: Characteristics of rivers concerning RBF: runoff regime and runoff dynamics, river morphology, erosion, bed load transport, deposition, structure of the riverbed, river-aquifer interaction, the clogging process.

1. INTRODUCTION

Clogging is caused by the continual percolation of water, which contains suspended matter. This process will appear in impounded basins, artificial groundwater recharge and riverbank filtration (RBF). Clogging in impounded basins is sometimes a desired process to reduce water losses. The upper layer in basins for artificial groundwater recharge is removed and cleaned at regular intervals. A first lesson to be learned from artificial

Stephen A. Hubbs (ed.), Riverbank Filtration Hydrology, 1–20.

groundwater recharge is that the so-called “Schmutzdecke” is essential for the purification of the percolated water.

Mechanical clogging of parts of the riverbed during long-term operation of RBF wells is principally unavoidable. The main task during the planning of RBF plants is to choose a suitable site for the plant near the river and to determine the type and the site arrangement of the wells.

The planning process of a groundwater plant is opened with a careful and very detailed site catchment area analysis, based on the geologic situation, the properties of the aquifer, the regional hydrology and the existing as well as possible future risks for contamination. The results of this investigation are used to determine type, size and location of the wells, to estimate long-term quantity and quality of the abstracted ground water and to check the necessity of protective measures for sustainable groundwater quality.

The step from planning groundwater plants to riverbank filtration (RBF) plants involves a significant expansion of the total catchment area, usually including the whole upstream drainage basin of the river and in detail the regions of the river upstream and downstream the location of the wells. Of particular importance for sustainable yield of the RBF wells is the unavoidable clogging process in the infiltration area. The decrease of the hydraulic conductivity of the riverbed by clogging will emerge in several steps and finally be balanced out between the position and shape of the cone of depression of the wells and the self-cleaning power of the river.

Based on a detailed site catchment area analysis, completed by pumping tests, all tools are available to predict the long-term behavior of groundwater wells very precisely. This is quite different with RBF wells due to the difficult assessment of the clogging process. Several attempts have been made to overcome this problem by theoretical and experimental means (Riesen, 1975). But the clogging process as a result of the dynamic river-aquifer interaction is rather complex and, up till now, this process cannot be calculated in advance employing some formula.

RBF is employed since more than 130 years along European rivers and a lot of experience on RBF well arrangement and operation is available (Hunt et al., 2002). This experience may be linked to relevant characteristics of the river to utilize it as a tool not only for the estimation of the clogging process but also for the optimal arrangement of RBF wells. This chapter will focus the attention on river characteristics and the mechanical clogging process.

1.1 Safe Drinking Water – A Reason to Utilize RBF

The legal definition of drinking water quality is a negative definition worldwide: Threshold limit values are limits for substances and microorganisms found in water. Values based on toxicological data have been derived to safeguard health on the basis of lifelong consumption. When looking at carcinogenesis and mutagenesis as non-threshold phenomena, other principles are applied in addition: Threshold limit values defined by precautionary aspects for preventing adverse affects of a general nature. Threshold limit values for aesthetic parameters are provided to prevent unpleasant changes, such as in taste, color and odor. Any water, which complies with these threshold limit values, can be classified and supplied as drinking water (WHO, 2004).

But the definition of a high quality drinking water is a quite different matter. The hydrologic cycle is an approved method of nature to provide high quality drinking water. A positive definition of a high quality drinking water is therefore based on pure groundwater without any contamination with reference to the hydrologic cycle. Such a definition can be found for example in DIN 2000, a Technical Standard in Germany (DIN 2000, 2000).

The preference of groundwater for water supply or, if not available, of a natural (riverbank filtration) or artificial (infiltration, groundwater recharge) subsoil passage of river water is a result of the conclusions drawn from the early outbreak of epidemic cholera in Hamburg, Germany (1892), caused by drinking water drawn from the Elbe River. This preference is now reflected in the concept of the DIN 2000.

To focus the attention on water quality aspects, it is expedient to vary the virtual point of raw water extraction. There are two important purification steps in the hydrologic cycle of nature. One step is evaporation, which separates H_2O from natural substances, chiefly salts, and all impurities. This step needs too much energy to be employed in urban water supply and this step creates totally demineralized water, which is not convenient for water supply. A second more interesting purification step is infiltration and subsoil passage of water. This step incorporates the physicochemical and biological processes to treat water and to balance out the physical (e.g. temperature), chemical (e.g. carbonate balance), and biological (e.g. low assimilable organic carbon concentration (AOC)) properties of the water.

The most advantageous water supply is to extract raw water after infiltration and subsoil passage from suitable aquifers (groundwater) regarding water quality aspects. The next most advantageous water supply is riverbank filtered water and replenished groundwater. Both types of raw water utilize the benefits of the powerful natural purification step:

- Removal of particles and turbidity
- Removal of bacteria, viruses, parasites
- Biodegradation of micro-pollutants, NOM, THM-precursors
- Reduction of mutagenic activity
- Smoothing out variations in temperature and concentration
- Compensation for peaks and shock loads.

The quality of surface water depends on several influences, e.g. contamination by sewage water, by fertilizers and pesticides from agriculture, by industrial chemicals in the case of accidents, from traffic on the surface water, etc. Usually the source water quality decreases from lakes over reservoirs to rivers. While surface water from lakes and reservoirs may be extracted by direct intake with only low risks, the direct intake from river water is always accompanied with higher risks (e.g. parasites, micro-pollutants) regarding the aim to produce safe drinking water. Therefore the potential of the natural purification steps of infiltration and subsoil passage should be utilized where possible.

2. CHARACTERISTICS OF THE RIVER

2.1 The Runoff Regime

The aerial extent, structural diversity, and altitudes in the headwater regions of the drainage basin associated with the regional and seasonal distribution of precipitation create the runoff regime of natural rivers. The runoff regime is characterized by amount, frequency, length, time and rate of change of runoff conditions. Runoff dynamics and runoff volumes are important factors when looking at the river and channel morphology, the transport of solids, the modification of the riverbed and the interactions with the groundwater (Leibundgut and Hildebrand, 1999).

Human impact on streams – e.g. for flood control, hydropower generation and improved navigation – changes the natural runoff regime. Dams dramatically alter the flow characteristics of rivers; particularly, the transport and deposition of solids, the erosion of the riverbed, and the interactions with the groundwater may be severely affected by dams.

The runoff regime of a river may initially be characterized by the average monthly discharge, developed from daily data over several decades. Figure 1, as an example, shows the result for the Rhine River at Lobith (near the German/Netherlands border) and Basel (near the Switzerland/German border), the Aare River (one of the headwaters) and the Mosel River (one of the tributaries). Compared to other European rivers, the Rhine River with a drainage basin of approximately 224.000 km^2 and a total length of 1320 km is not among the largest rivers. But the Rhine River is one of the most important European rivers and one of the busiest waterways due to its abundance of water and balanced runoff regime.

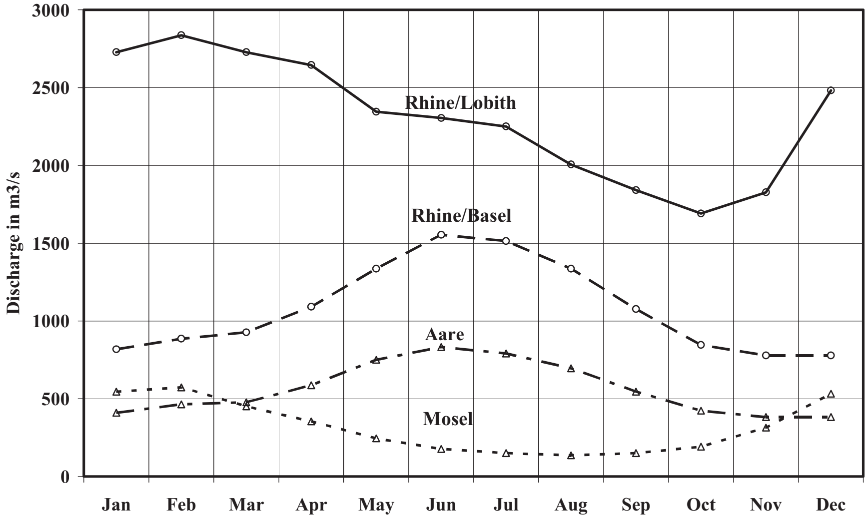

Figure 1. Average monthly discharge of the Rhine River at Lobith and at Basel, the Aare and the Mosel River.

The main sources of the Rhine River are the snow and glacier regions in the Swiss Alps with an average annual precipitation up to more than 2,500 mm. The headwater region is drained by the rivers Aare and the Alpine Rhine. Both rivers show the typical characteristics of high mountain range rivers with maximum runoff in the thawing season between May and July. The smoothing effects by lakes near the fringe of the mountain range (Lac Leman and Lake of Constance) are included in the runoff regime of both rivers. The rivers Aare and Alpine Rhine contribute approximately 50 % to the total runoff of the Rhine River.

The Mosel River is a typical low mountain range river with low runoff in the summer season and high runoff during the rainy season between November and March, and is typical of most of the other tributaries of the Rhine River The average annual precipitation in the drainage basin of the Mosel River and likewise in the regions of the other low mountain range rivers is approximately 800 mm.

Averaging discharge or level data is helpful to understand the basic properties of the runoff regime. But only unaltered original data give insight into the runoff dynamics of a river. Figure 2 shows a clip-out (500 days) of the stage hydrograph of the Rhine River near Düsseldorf (River km 744.2). Though the Rhine River with its dams in the Upper Rhine region is not spared from human impacts, the runoff dynamics in the downstream region approach to the properties of a natural river.

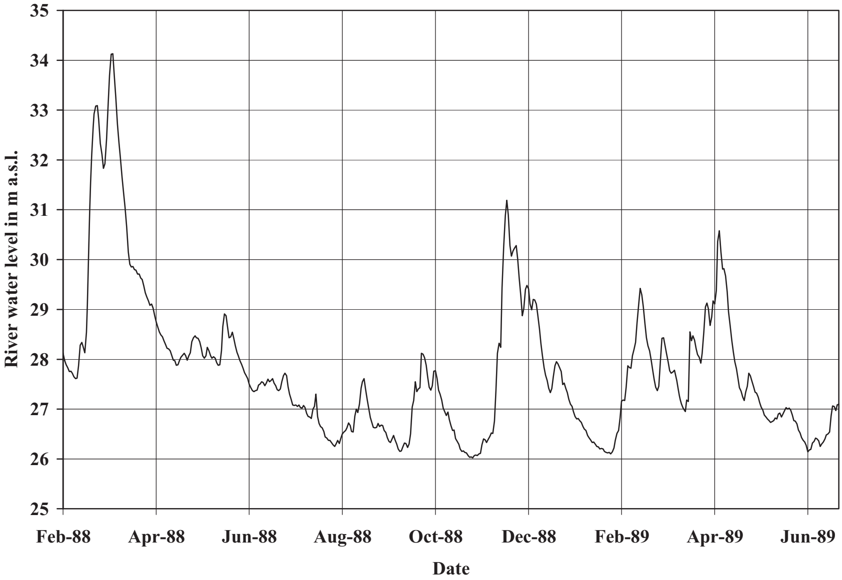

Figure 2. Stage hydrograph of the Rhine River near Düsseldorf (km 744.2).

This is quite different at the dam-regulated Ohio River. Figure 3 shows a clip-out (600 days) of the stage hydrograph of the Ohio River near Louisville, KY, indicating greatly dampened runoff dynamics.

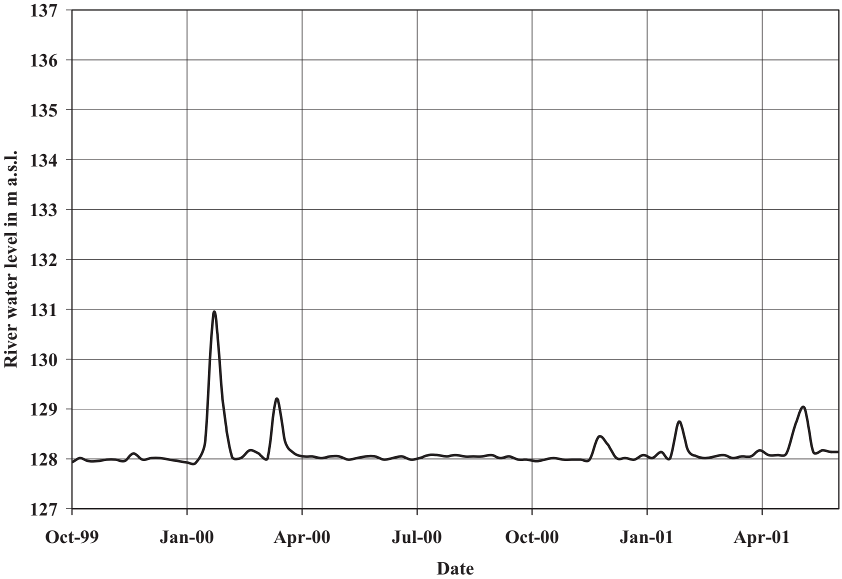

Figure 3. Stage hydrograph of the Ohio River near Louisville (Hubbs, 2003).

2.2 Bank Storage

The stage hydrograph represents the runoff dynamics of the river and controls natural river-aquifer interactions. Typical river-aquifer interactions during a flood wave were investigated in the Neuwieder Becken, a section of the Middle Rhine region near Koblenz, Germany (Ubell, 1987a,b). The adjacent aquifer, composed of fluvial sediments based on tertiary layer, is characterized by a hydraulic conductivity between $2*10^{-2}$ and $4*10^{-3}$ m/s, a porosity of 0.2 and a thickness of 10 to 15 m.

The aim of the investigation was to understand and to quantify the bank storage process, which occurs by the passage of a flood wave: groundwater runoff into the river is interrupted and bank filtrate is temporarily stored in the adjacent aquifer. A gallery of seven monitoring wells (U01 – U07) was installed perpendicular to the 300 m wide river at river km 602.4 to collect data of the groundwater level. Based on the gauge observations – including the river level and relevant data of the aquifer – a time series of the specific volume of bank storage and infiltration/exfiltration rates was determined.

Figure 4 shows the level of the Rhine River during a flood wave with a rise of about 5 m at river km 602.4.

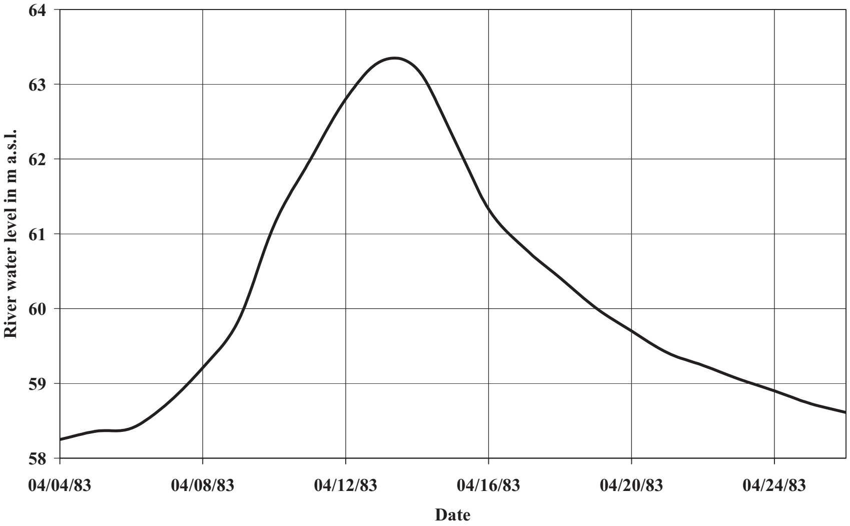

Figure 4. River level of the Rhine River at river km 602.4 during a flood wave.

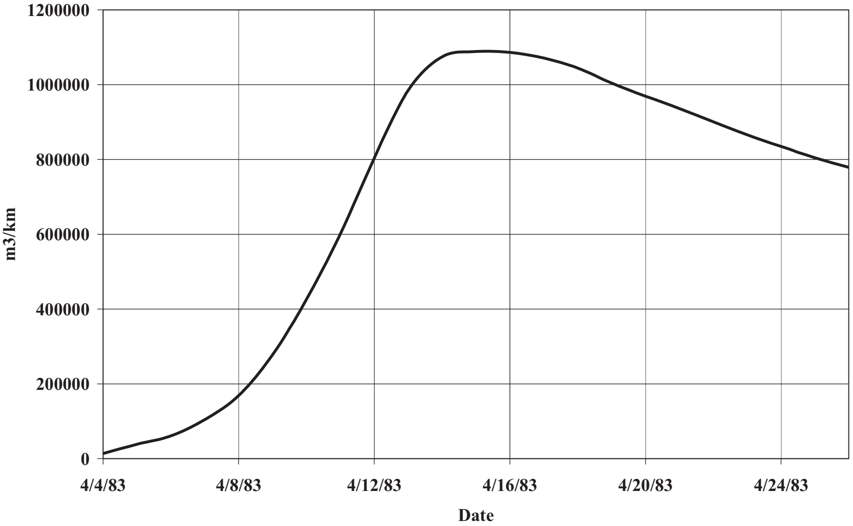

Figure 5. Changes in volume of bank storage during the passage of a flood wave.

The cumulative specific volume of bank storage during the flood event is shown in Figure 5. More than 1 million cubic meters of bank-filtered water entered the left side part of the aquifer in a few days along a riverbed length of 1 km!

Figure 6 shows the quantitative part of the river-aquifer interaction by the rates of infiltration and exfiltration. The maximum infiltration rate into the aquifer of approximately 2,400 l/s km is about three to five times higher than the infiltration rates of existing RBF plants! The flow direction at the river-aquifer border changes about four days after the maximum infiltration rate of bank-filtered water to exfiltration of bank filtered water and groundwater into the river. A significant amount of bank-filtered water is stored in the aquifer for weeks or months (see Fig. 5). Bank-filtered water penetrated about 300 m into the adjacent aquifer during this event. Even smaller flood events significantly increase the volume of bank storage and the depth of penetration.

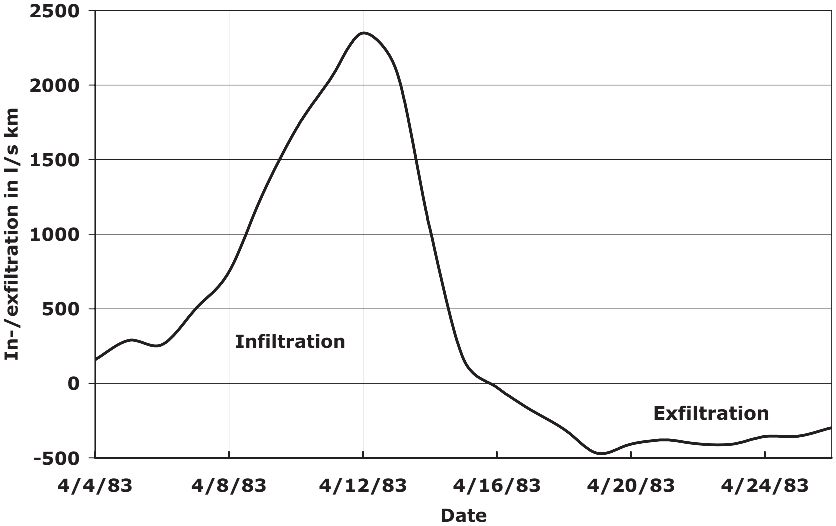

Figure 6. Infiltration and exfiltration rates during a flood wave.

One aspect concerning the clogging process should be mentioned in advance, based on the investigations of the bank storage effect of a flood wave. In the gallery of the seven monitoring wells along the cross section at river km 602.4 monitoring well U01 is situated close to the bank of the river. This allows, the estimation of possible variations of the hydraulic conductivity of the infiltration area due to clogging when combined with the infiltration rates. These data indicate that during this short time of infiltration (about 12 days) no significant decrease of the hydraulic conductivity could be found. This result corresponds with experience and may by supported by a later discussion of the sequences of the clogging process during the early stage of RBF operation.

2.3 Runoff Dynamics and Transport of Suspended Matter

Flood waves cause an increase in the transport of suspended matter and bed load. The increase of suspended matter originates from the coincidence of matter from soils washed up by heavy rainfall, direct runoff from sewage water treatment plants (overflow), erosion of the riverbed and banks, and re-suspension of suspended matter e.g. upstream of dams. This load of suspended matter rises nearly exponentially with the discharge of the river up to a maximum and relapses quickly as the discharge begins to decrease. In the infiltration area of RBF plants high concentrations of suspended matter decrease the hydraulic conductivity of the riverbed significantly and may protect the silt layer against erosion in clogged areas by increased differential pressure into the riverbed.

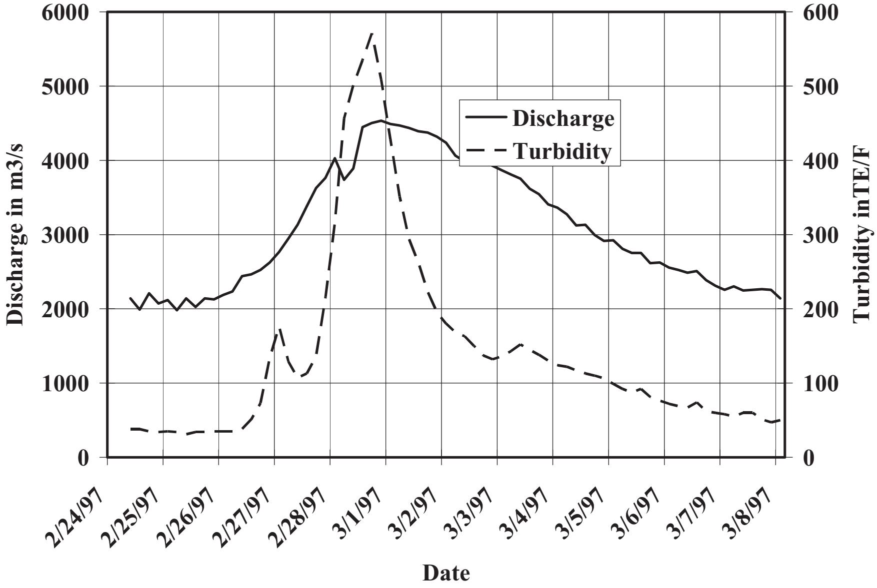

Figure 7. Turbidity during a flood event in 1997 in the Rhine River at Koblenz.

Figure 7 shows the regime of suspended matter during a flood wave (Breitung, 1999). The concentration of suspended matter is represented by Formacine turbidity units (TE/F), which tend to underestimate the influence of coarser particles (sand and gravel). The maximum concentration of suspended matter (340 g/m^3 corresponding with 575 TE/F) is reached just before the maximum runoff (4.610 m^3/s) occurs. The turbidity during steady state conditions is in the range of 40 TE/F.

2.4 Stream Processes

The runoff regime alters the profile and the bed of a river by erosion, transport of sediments, and deposition and in the long run creates landforms. The critical erosion velocity varies with the size of particles. Fundamental research in the field of the critical velocities for erosion, transport, and sedimentation over a spectrum of grain sizes between clay and stone has been carried out and published by Hjulström (Hjulström, 1935).

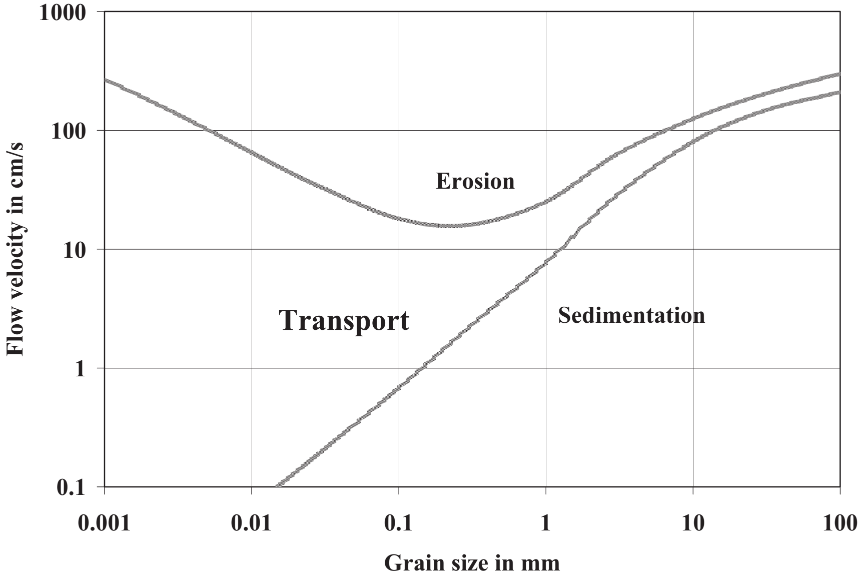

Figure 8. Hjulström diagram: Conditions for erosion, transport and sedimentation.

Figure 8 shows the slightly modified Hjulström diagram, which in this form is valid for uniform grain size only. The critical velocity for the beginning of erosion has a minimum at the grain size of fine sand, which confirms the common experience with stream processes. For clay and for stones the critical erosion velocity is about ten times higher! If the grain size is mixed, the tendency for bed material to be moved will increase.

Of particular importance for bed load transport are temporary water rolls (vortex) with horizontal axes, which occur prevalently during rising river water level. Due to the vertical distribution of the flow velocity in a river channel ground rolls are created, rotating contrary to the flow direction along the riverbed (Wundt, 1953). Those ground rolls contribute in loosening the sediments at the riverbed and feed the transport. These rolls create forceful transport effects that result in sediment transport greater than that, which would be expected from the increase in flow rate and stream velocity alone.

Regarding the energy transformation between two adjacent cross sections of a river with approximately the same shape and area during steady state conditions, the discharge and the average flow velocity don't change. That means, that the kinetic energy of the river flow will be conserved. Only the potential energy, depending on the hydraulic gradient of the river, is completely consumed by internal friction (turbulence, vortex) and friction along the riverbed (Louis, 1961). During the rise of the river level (unsteady state conditions), caused by a flood wave, there occurs a temporary increase in the hydraulic gradient and a temporary difference in discharge between two adjacent cross sections. This means that additional potential and kinetic energy is available during the passage of the front of even smaller flood waves to be transformed into friction. Figure 7 may be interpreted as an image of this process. This supports observations that the runoff dynamics are an essential factor for the self-cleaning potential of a river.

2.5 The Profile of a River

The profile of a river is permanently exposed to the stream processes. Erosion is the dominating process in the headwater regions. Sediments are transported downstream and are deposited when the stream velocity falls below their settling velocities. In the mid-reach section of a river deposition and erosion may be regarded as alternating processes due to the runoff dynamics. Where a river approaches base level, water slows and deposition is the dominating process, which creates depositional landforms, such as deltas.

The general shape of the profile of a river shows a high gradient in the headwater region, a gradually waning gradient in the mid-reaches and a small gradient approaching base level (e.g. the mouth of the river). Figure 9 shows the profile of the Rhine River as an example. Altogether three base levels characterize the profile of the Rhine River. The Lake of Constance accumulates the coarse sediments from the Alpine Rhine River. After this first base level the gradient starts with a steep rise again and reaches low values at the hard rocks of the Nackenheimer Schwelle, which forms the second base level. The third base level is the mouth of the river into the North Sea.

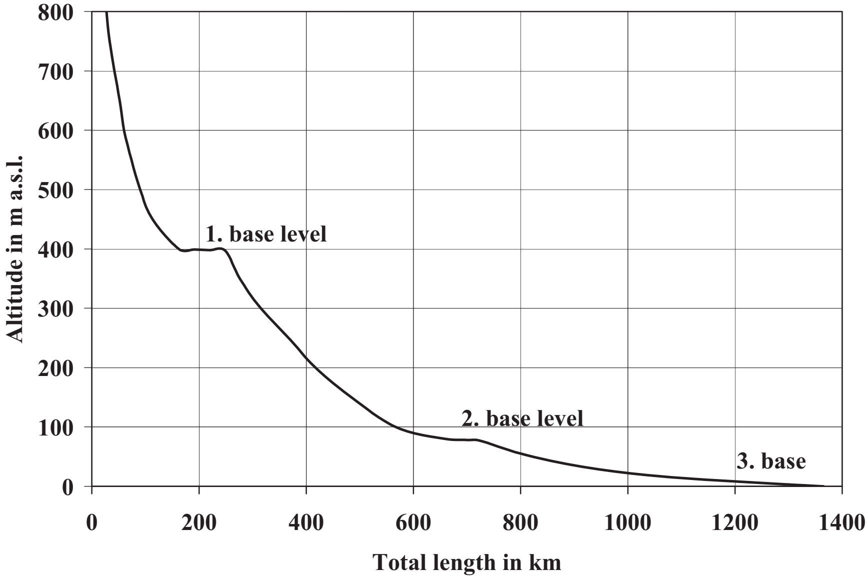

Figure 9. Profile of the Rhine River.

RBF along the Rhine River is not employed upstream of the first base level due to the coarse material in the adjacent aquifers. Between the first and second base level there can only be found a few RBF plants. RBF would be possible but is not typical for this region because the depth of several 100 m and the width of the alluvial deposits are more suitable for groundwater extraction.

An agglomeration of RBF plants exists in the alluvial deposits of the Lower Rhine region between the second and third base level of the river (Schubert, 2002). It may be helpful to consider the characteristic data of this region between Rhine-km 660 and Rhine-km 789 concerning RBF (Der Bundesminister für Verkehr, 1987):

Average hydraulic gradient	0.21 – 0.18 m/km
Average flow velocity	1.4 – 1.0 m/s
Average shear stress on the riverbed (MQ)	Approximately 10 N/m^2
Mean grain size diameter of the bed load	13 mm at km 660 8 mm at km 780
Mean grain size diameter in the riverbed	33 mm at km 640 26 mm at km 730 10 mm at km 860
Hydraulic conductivity of the adjacent aquifer	$k_f = 2.2 \times 10^{-2}$ to 3.3×10^{-3} m/s.

These conditions have supported RBF operation for more than 130 years.

When the slope of the river and the flow velocity decreases, the channel begins to meander. The development of meanders is a natural phenomenon of river channels caused by the inertia of the flow. In meanders or bends the maximum flow velocity occurs towards the outside of the bend. This outside border is washed out by erosion and the riverbed is deepened, creating an asymmetric cross section of the riverbed (Schubert, 2002). In this dynamic process the larger fraction of the riverbed material that resists erosion – e.g. stones – accumulate and may cause a paved bed along the outside bend. The resulting riverbed is immobile even during the passage of flood waves. In regions near the inside border of the bend the flow velocity is low and deposition occurs; the riverbed material remains movable.

Meanders of the river channel are preferred sites for RBF plants; inside the loop of a meander the natural cross flow between the upstream and the downstream side of the loop augments the proportion of bank-filtered water in the extracted well water. An additional advantage is the movable riverbed along the inside border of the river channel, which supports the self-cleaning process of clogged areas.

3. THE CLOGGING PROCESS

River-aquifer interactions are governed by the fluctuating water level of the river. The resulting gradients between the quickly changing river level and the gradual adaptation of the groundwater table in the adjacent aquifer control flow and transport of the infiltrated river water. The runoff dynamics are not only relevant for clogging processes and flow velocities in the subsoil, but can also affect the water quality of the well water by fluctuating removal efficiency, e.g. due to varying residence times.

Infiltration of river water to an aquifer is a natural phenomenon at the upstream side of river bends, due to the hydraulic gradient of the river, and during rising river levels, without any wells near the riverbank (natural bank storage). These natural infiltration processes don’t cause clogging because they are temporary and are over and over interrupted by groundwater exfiltration into the river. This natural variation of the flow direction prevents clogging of the riverbed.

Clogging is caused by the continuous infiltration of river water due to well pumpage. Clogging of parts of the riverbed during long-term operation of RBF wells is principally unavoidable.

The progress of the clogging process from the beginning of pump operation shows some important details. During the first phase of clogging two competing processes are involved:

- Clogging of the riverbed: Correlative to the distribution of the infiltration rate a spatially different clogged layer will be formed in the region of the cone of depression of the wells. Within the infiltration area a permanent equalization between regions of different permeability leads gradually to an adaptation of different specific infiltration rates. The distribution of infiltration rates is more uniform at the end of the first phase without significant reduction of the permeability of the riverbed.
- Suffosion in the pore channels of the adjacent aquifer: Suffosion means a hydro-mechanical deformation phenomenon of natural aquifers caused by the motion of water through a porous medium. With the operation of RBF wells the natural variations of the flow direction between the wells and the river are stopped. Governed by the uniform flow direction the transport and displacement of fine fractions in the pores of the aquifer gets started. The skeleton of the non-uniform grain structure is not altered during this process, but the pore channels are smoothed with a positive effect on the hydraulic conductivity. This type of inside suffosion is a temporary process. Once the fine particles are displaced due to the flow conditions, the process runs out.

Both processes together in the early stage of RBF operation, which may reach for several months, are generically characterized by small fluctuations, but no significant decrease of the water yield! Therefore predictions on the long-term behavior of the system cannot be drawn from the data of the first phase.

The second phase of the clogging process is characterized by a significant reduction of permeability in the whole infiltration area and a reduction of the water yield. The self-regulating system tries to find the balance between the ongoing clogging process and the self-cleaning processes of the river, chiefly governed by the runoff dynamics. Compensation by intensification of the depression cone, to stabilize the water yield, may introduce a third phase of the clogging process.

The third phase of the clogging process is characterized by the spread out of an unsaturated zone beyond the riverbed. The zone where the direct contact between the aquifer and the riverbed will be interrupted spreads out. At the same time, caused by deepening of the depression cone, additional infiltration areas will be developed with lower driving head and may be in regions of the riverbed with higher flow velocities. The reduction of permeability in the infiltration area and the reduction of water yield are going on, but on a lower level.

A forth and final phase of the clogging process is characterized by the total interruption between the cone of depression and the riverbed near the well site. This situation often means the end of RBF operation.

Based on the data of the Louisville RBF well at the Ohio River (Hubbs, 2003) phase one to three of the clogging process may be visualized. Figure 10 shows the original data of the river water level, the well water level, and the pumping rate from the beginning of RBF operation over a period of nearly 200 weeks.

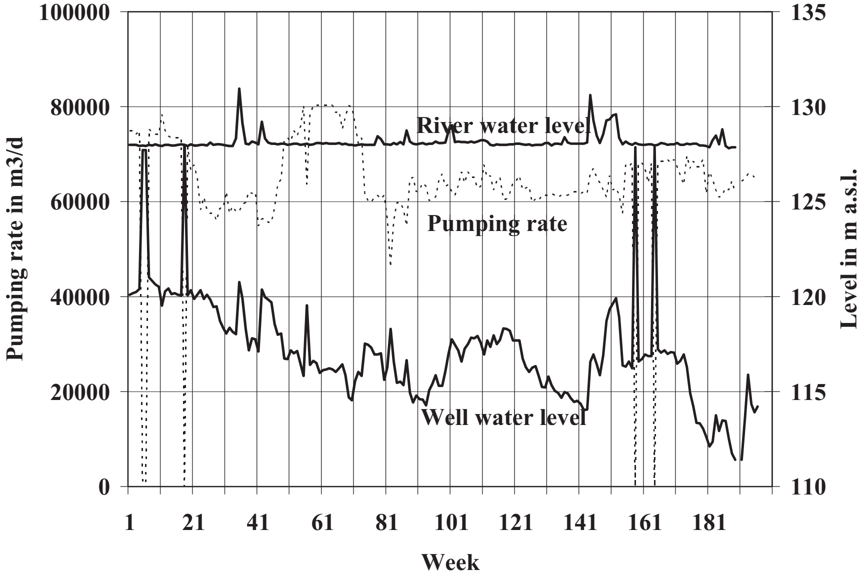

Figure 10. Pumping results of the RBF facility on the bank of Ohio River at River Mile 592 (Louisville Water Company).

From the beginning of pump operation to about week 20 the driving head is less then 8 m during an average pumping rate of about 74,000 m^3/d. A driving head of about 12 m is reached in week 60 during a pumping rate of about 80.000 m^3/d. At the end of the observation period (week 188) the driving head is about 16 m during an average pumping rate of 64,000 m^3/d. This sequence indicates severe clogging. But to quantify the clogging process, also the influence of the water temperature and respectively the viscosity of the water on the yield have to be considered. Figure 11 shows the temperature of the river water and the well water.

The seasonal fluctuation of the river water temperature is between 30 degree Celsius and 2 degree Celsius. The water temperature of the well water is smoothed by riverbank filtration and fluctuates between 26 and 11 degree Celsius. The resulting viscosity varies significantly from 0.8 to 1.66 m^2/s in the river water and 0.88 to 1.27 m^2/s in the well water.

To normalize the data of the pumping rate from the influence of varying water temperatures, a representative water temperature has to be determined. For this purpose a fictitious water temperature in the aquifer has been introduced as an average value between the river water temperature and the well water temperature regarding the time lag of four till five weeks between both temperatures.

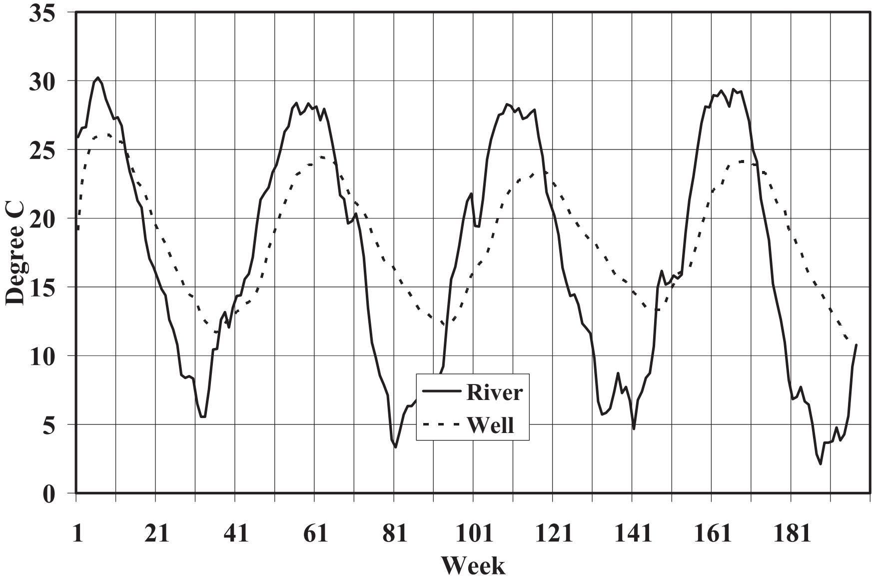

Figure 11. Water temperature of the river water and the well water.

Two different approaches have been employed, to visualize the pattern of the clogging process and its interrelation with the flow dynamics of the river. One approach is the time series of the specific capacity. The specific capacity is based on the temperature-corrected pumping rate Q’ in m^3/s and the driving head in m. The other approach is based on the analytical methods for groundwater flow towards a ditch and towards a well. Both approaches lead to corresponding results due to the simplified analytical methods and allow acceptable insight into the general pattern of the clogging process. Figure 12 shows the result with the specific capacity $m^3/s/m$.

Three different segments can be extracted from the sequence of the specific capacity:

- First phase of the clogging process: Between the beginning of pump operation and about week 23 are smaller variations but no decrease of the specific capacity.

- Second phase of the clogging process: A significant drop of the specific capacity occurs between week 23 and week 61.
- Third phase of the clogging process: Between week 61 and the end of the observation period in week 188 the decrease of the specific capacity proceeds slowly.

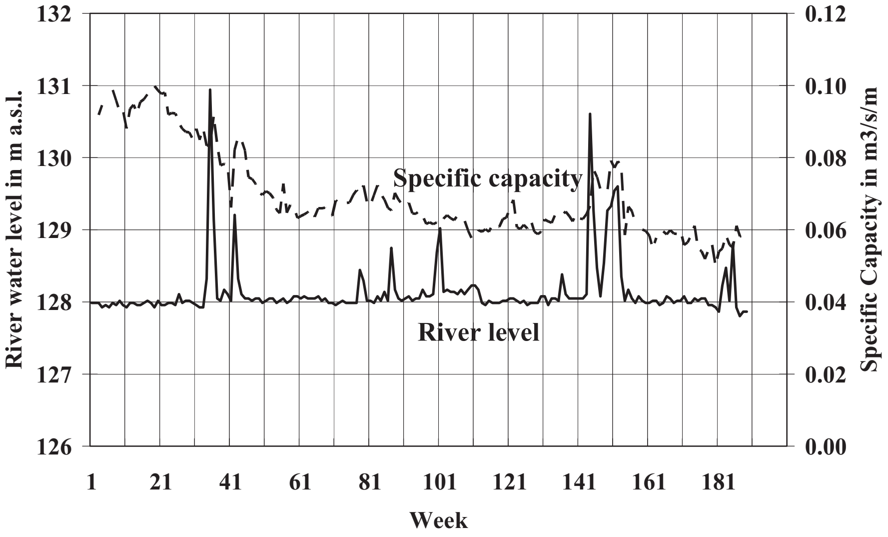

Figure 12. Pattern of the clogging process.

Even minor variations in the river level of less than 1 m (in week 78, 87, 101 and 136) are able to cause temporary improvements of the specific capacity. A real jump is caused by a flood wave with an amplitude of 2.6 m in week 144 and two flood waves during phase two (3 m in week 35 and 1.2 m in week 42). But the time series of the specific capacity through week 185 also show that the position and size of the cone of depression is not yet balanced out with the self-cleaning potential of the river.

4. CONCLUSIONS

The runoff regime, characterized by amount, frequency, length, time and rate of change of runoff conditions, determines the self-cleaning potential of a river. As this is the main process limiting clogging of the riverbed during RBF operation, the properties of the river must be considered when