Periodica Polytechnica
Civil Engineering

60(3), pp. 449–454, 2016
DOI: 10.3311/PPci.7277

RESEARCH ARTICLE

A Laboratory Experiment to Analyze Hydraulic Losses during Riverbank Filtration

Zsuzsanna Váradi

Received 19-01-2014, accepted 30-10-2015

Abstract

Hydraulic losses during riverbank filtration (RBF) can be an important factor when we try to calculate the ratio of discharge coming from the surface water and groundwater. A scaled-down laboratory experiment was carried out to help to better understand and demonstrate the hydraulic processes and their factors during RBF.

Keywords

Riverbank filtration · RBF · laboratory experiment · streambed loss · entrance head loss · clogging · Clogging-paradox

Zsuzsanna Váradi

Department of Hydraulic and Water Resources Engineering, Budapest University of Technology and Economics, Műegyetem rkp. 3, H-1111 Budapest, Hungary

e-mail: zsuzsvaradi@gmail.com

1 Introduction

The connection of surface water and groundwater becomes interesting for us when we want to produce drinking water from wells near natural water flows. This process is called riverbank filtration (RBF). There are two important factors of this process:

- We want to be as close to the surface water as it can be because that is where the water we need comes from

- We want to be far enough from the possibly polluted surface water so as it has time to get filtered while seeping through the soil

The contradiction between these two requirements is obvious so we need to find and optimal solution where both criteria are met. (Fig. 1)

The focus of my research is the hydraulics of riverbank filtration. I have been researching the connection between discharge and water level so that I can contribute to the clarification of numerous uncertainties or rather misunderstandings.

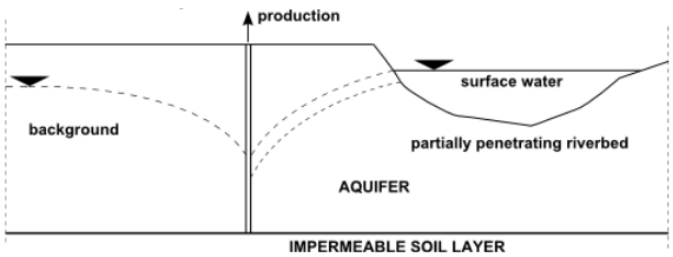


Fig. 1. Riverbank filtration

As it can be seen the properties of the connection between surface water and groundwater can be an important factor. For the surface water to connect with groundwater it has to overcome complicated hydraulic resistance.

This resistance of the surface water - ground water interface is currently neglected in practice and in the evaluation of production measurements. If we do so then in theory a huge part of the produced water comes from the surface water however in reality it can come from the background. The quality of the produced water often proves this as the quality is more like that of the background groundwater (especially the nitrate content) than that of the river.

In this article I would like to present a model experiment of the surface water - ground water interaction focusing on the hydraulic loss and its nature.

2 Hydraulic losses at the streambed

The head loss of surface water seeping into the ground is known as clogging in geohydrology although there are many uncertainties regarding its nature, size and importance. My experiment focuses on the hydraulic loss that comes from the water entering the soil. There is no adequate term for this phenomenon I will just call it *streambed loss* [7]. The term 'clogging' is used often but that covers only a part of this loss.

Let's see where these losses come from:

2.1 Quality of geological layer, formation

2.1.1 Riverbed material

The geological parameters of the riverbed are important factors. Riverbed filtration cannot develop in an impermeable riverbed.

2.1.2 Riverbed penetration

The thickness of the aquifer under the riverbed can also be an important factor. If the riverbed reaches an impermeable soil layer we call it a fully penetrating riverbed. If the riverbed cuts only partially into the aquifer we call it partially penetrating river. The problem with this is that the groundwater coming from the background through the aquifer under the river may have to overcome smaller resistance than the water coming from the river. Consequently we may end up producing water from unexpected sources like from the groundwater across the river [3].

2.2 Streambed loss

2.2.1 Clogging

Many factors contribute to this. The fine sedimentation which is present in the water can clog the riverbed thus a layer of poor permeability develops on the riverbed surface. The fine sediment deposits above the riverbed and a so-called bio-layer develops just under the surface [4]. If there is no such layer there will certainly be one after we start to produce water from the well. The micro-organisms settling in the bio-layer largely contribute to the cleansing of the water.

Different types of clogging are examined in greater detail in Reference [6]. According to that study riverbeds of gravel and more coarse grains clogged a lot faster and to a higher degree than riverbeds consisting of fine-grained sand. This is called the Clogging-paradox. The explanation is that the floating, colloidal sediment can get deeper into the coarse-grained streambed and thus eventually a thicker sedimentation layer builds up. On Fig. 2 the two types of clogging is shown. The left drawing shows the sediment developed on top of the riverbed and the right drawing shows the bio-layer just under the surface.

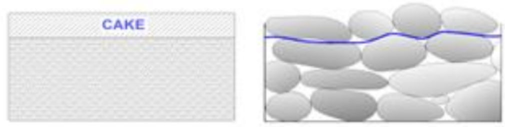


Fig. 2. Types of clogging

2.2.2 Entrance head loss

There is a loss even if we neglect clogging and the riverbed fully penetrates the aquifer. When the water enters the pores of the soil, the direction and magnitude of the water particles' velocity vector change. The energy required to change these vectors causes this head loss. Although this loss is always present, geohydrology does not take it into consideration. In the hydraulics of pipelines it is considered a significant factor [1, 5]. A similar phenomenon is the so-called well loss and it is not a surprise that the water level inside the well and outside of it is different.

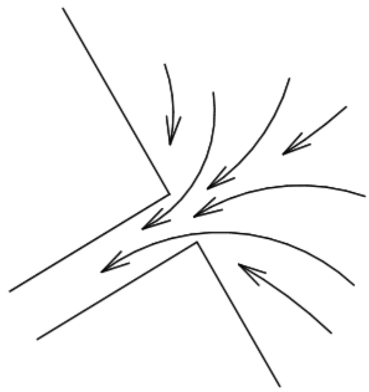


Fig. 3. Entrace head loss

To summarize: the streambed loss during riverbank filtration depends on many factors. The clogging of the riverbed creates a poorly pervious layer and causes a loss. If the river only partially intersects the aquifer the groundwater flow from the background has an impact on how the surface water enters the aquifer. It is possible that the groundwater coming from the background has to overcome a much smaller resistance and the effect of the pumping is wasted on the moving of groundwater from the background instead of forcing surface water to enter the aquifer. Finally the entrance head loss will be present even if the other circumstances are ideal.

3 The Experiment

With support from the Department of Hydraulic and Water Resources Engineering of the Budapest University of Technology and Economics I created a physical model to demonstrate the streambed loss during the surface water - ground water interaction.

In theory a complete model of a riverbank filtration well could have been created but the scaling laws prevent this [2].

Not even the geometric similarity could have been met considering the real-world examples I know of (i.e. real-world production on Primás-island, Esztergom, Hungary, or any of the test pumping during the diagnostics of underground water resources). In particular the scaling of the soil would lead to so fine grains in the artificial layer that the water could not seep through it at all. Kinematic and dynamic similarity would also pose a problem; the forces making the water move in the scale model would not be the same as in reality. Probably a fluid with a properly scaled viscosity could have been used instead of water but the budget of the project and the technical problems if would have had posed did not allow this.

Because of these problems my aim was to demonstrate the above-mentioned streambed loss which is neglected by many engineers however I consider it important.

Fig. 4 shows the model design. Basically it is a 200 cm long, 100 cm high and 20 cm wide water tank. The front panel is made of transparent plastic.

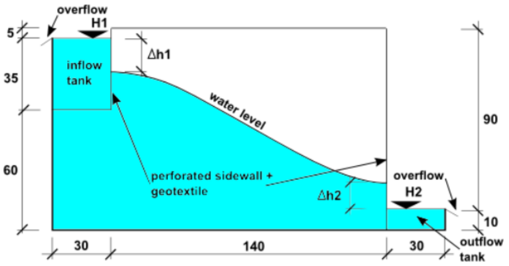


Fig. 4. Model schematic

Inside the tank the sidewalls (boundaries of the fill material) are made of perforated plastic with holes of 3-mm-diameter. These perforated sidewalls are covered with a screen and geotextile to prevent the fill material getting out of the holes.

During the experiments we continuously supply water to the inflow-tank in the upper left corner so that we can maintain level H1 utilizing an overflow as well. In the lower right corner we have the outflow-tank. During the experiment we always have to wait until level H2 is reached here before we do any evaluations.

The aim was to determine Δh1 streambed loss and Δh2 well loss. I expected to see a stabilized drawdown curve representing the groundwater table and be able to simply measure the Δh values. The measurements are supported by built-in piezometers (See Table 1 and 2, Fig. 5).

Tab. 1. Distance of piezometer from lower left corner

Piezom. number	1	2	3	4
Horizontal dist. (cm)	10.5	20	12	67
Vertical dist. (cm)	61.5	58.5	11.5	11.5

Tab. 2. Distance of piezometer from lower left corner

Piezom. number	5	6	7	8
Horizontal dist. (cm)	122.5	177.5	185	194.5
Vertical dist. (cm)	11.5	12	21.5	6.5

Fig. 5. Piezometers

3.1 Experiment 1

In case of the first experiment the fill material was plastic granule of 3-mm-diameter. Unfortunately as these were lighter than water they swam up and were compacted on the top and an empty channel developed on the bottom where the water could flow without any resistance. Thus the experiment did not show anything interesting because the water flow resembled more of a pipeline flow in this empty channel at the bottom. (Fig. 6)

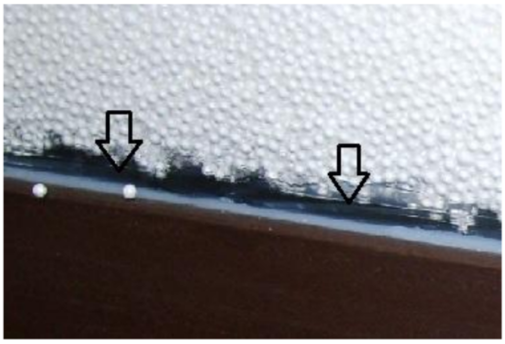


Fig. 6. The 'pipeline' at the bottom

3.2 Experiment 2

In the next experiment we replaced the fill material with gravelly sand. See the grain size curve on Fig. 7.

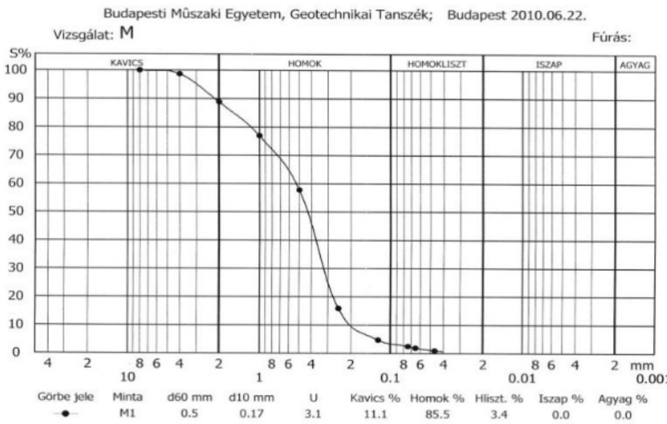


Fig. 7. Grain size curve experiment 2.

The problem in this case was the capillarity of the material as the whole soil body became wet and the water table could not be observed (Fig. 8). To be precise the boundary of the capillary zone was visible but the boundary between the 2-phase and 3-phase zones (i.e. the ground water level) was not. Once again this experiment was unable to demonstrate the streambed loss. The piezometers showed the right values but because of the capillarity the experiment could not give a clearly visible demonstration of the phenomenon.

Fig. 8. The boundary between the 2-phase and 3-phase zones (the water level could not be observed properly)

3.3 Experiment 3

Next we used gravel of 1 - 8 mm diameter. See Fig. 9 for the grain size curve.

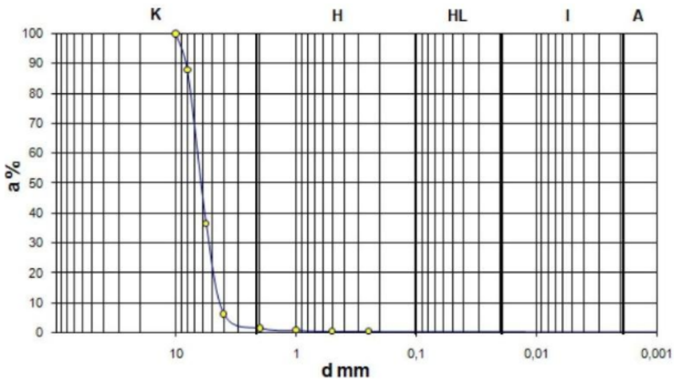


Fig. 9. Grain size curve experiment 3.

The dominant diameter was 5 - 6 mm (see Fig. 9) but fine fractions were present as well causing the same problem with capillarity again (and prevented the fill material to be able to dry out properly between experiments). See Fig. 10a.

Having the fill material dry out between experiments would have been important so that the experiments could have been done with different water levels. The wet stain ruined the demonstrative purposes of the photographs although the streambed loss phenomenon was successfully measured. After a permanent state was reached and the piezometer levels and discharge values was measured approximate calculations became possible despite of the not so good photographs.

The situation observable on Fig. 10b can be seen in the real world when the aquifer is very deep under the river and the ground water is deep beneath it. This is relatively rare as rivers and lakes are usually located in deep lines, points of the topology so they rather serve as a collector of ground waters around them as opposed to this situation when water from the river feeds the ground water underneath.

With riverbank filtered water production however, we can create a similar situation in real world as well, when we force a large seepage from the riverbed due to the pumping [8].

In the experiment the level distance between the two tanks represents the drawdown of a real world pumping.

The ideal experiment would be with gravel of 2-3-4 mm diameter and without of any finer fractions. Unfortunately this was not possible due to budget and time issues.

Nevertheless this last experiment demonstrated the streambed loss well. See Fig. 11 a, b, c.

After pouring fluorescence material into the water the groundwater table became clearly visible. The streambed loss is clearly visible too because the water level in the soil does not connect with the surface water level. The difference ΔH is much bigger than the well loss at the outflow-tank. The difference can be due to the denser geotextile in the inflow-tank which I used to represent the effect of the bio-layer in the clogged riverbed.

In the 2nd experiment the well loss was bigger compared to the streambed loss (or it was just not visible due to capillarity). During that experiment the separation of the water level of the well and the ground water just outside the well became clearly visible. It is a well-known phenomenon in wells or on the side of levees when the seeping water shows up on the side of the lower level. See Fig. 12. The water is well observable flowing down from the holes.

Using the piezometers' data, water levels and discharge we could also calculate the hydraulic conductivity of the system using Darcy's law.

$$Q = A \cdot k \cdot \Delta h / L \tag{1}$$

where,

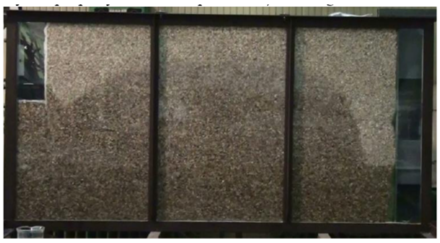
- Q volumetric flow rate (m^3/s),
- A flow area perpendicular to L (m^2),
- k hydraulic conductivity (m/s),
- L flow path length (m),
- h hydraulic head (m), and
- Δ denotes the change in h over the path L. [9]

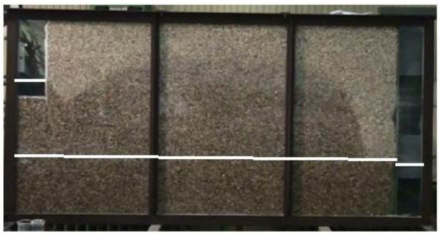
Using the data of piezometers 4 and 5 from experiment 2 we have the following values:

$Q = 1.37 \cdot 10^{-5}\,\mathrm{m^3/s}$, $A = 0.1251\,\mathrm{m^2}$ (canculated from water levels, width of the tank), $L = 0{,}555\,\mathrm{m}$ (distance of the piezometers) $\Delta h = 0{,}115\,\mathrm{m}$ (piezometer level difference), $k = \mathrm{Q}/(\mathrm{A} \cdot \Delta\mathrm{h/L})$ thus $\mathbf{k} = \mathbf{5{,}27 \cdot 10^{-4}\ m/s}$

Using the data of piezometers 2 and 4 from experiment 3 we have the following values: $Q = 1{,}05 \cdot 10^{-4}\,\mathrm{m^3/s}$ $A = 0{,}0894\,\mathrm{m^2}$ $L = 0{,}49\,\mathrm{m}$ $\Delta h = 0{,}222\,\mathrm{m}$, thus $\mathbf{k} = \mathbf{2{,}58 \cdot 10^{-3}\ m/s}$

In our model all of the water comes from the inflow-tank (i.e. the river) since there is no other inflow to the system. Even though we could demonstrate the streambed loss at the riverbed interface it is still very hard to predict the head loss in a real world situation since our model is significantly different from the real world.





(a) Wet gravel (b) Water level in the wet gravel

Fig. 10. The waterlevel is hard to observe due to capillarity

(a) (b)

(c)

Fig. 11. Infiltration of flouressenc into the aquifer at 3 different points in time

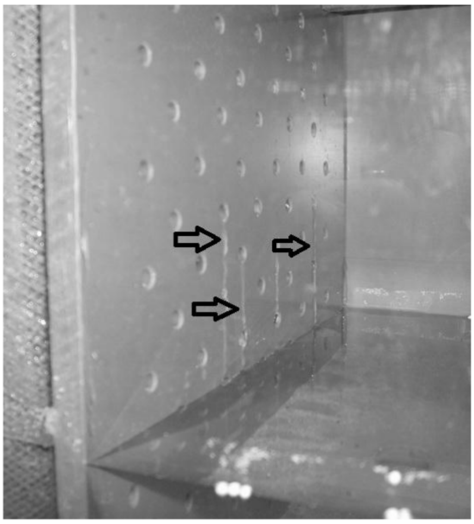


Fig. 12. Separation of the water level in the well and the ground water table

4 Conclusions

The laboratory experiment showed evidence of the streambed loss and the fact that it should not be neglected when the surface water - groundwater connection is calculated. This streambed loss is a loss of energy due to the work required to maintain the flow of surface water into the aquifer through the boundary of the two systems.

This streambed loss has more than one contributing factors. One is the fine-grained sedimentation on the surface of the riverbed which can be several meter thick. The other one is the so called clogging which develops underneath the surface when fine sediment enters and clogs the pores of the streambed. This is only a few centimeters thick however the chemical and biological processes of this layer contribute the most to filtering the surface water.

A third factor is the entrance head loss; this is the loss which comes from the change in the magnitude and direction of the water particles' velocity vector.

The laboratory experiments yielded a few useful hints for future experiments. The fill material should be heavier than water because although the polystyrene pearls would have been perfect considering the grain size and the grain size distribution they did not work well despite the load placed on the top. Even these could not prevent the swimming up of the pearls and a pipe-like empty zone developed at the bottom.

Capillarity can be also a problem is we could see in experiment 2 with gravelly sand filling material. Having fine grain fractions in the fill material can cause capillary movement making the whole soil body wet and making the surface of the water hard to see. The piezometers though presented some useful data that we could use for the calculations.

The gravel in experiment 3 worked out well although there were fine fractions present too so capillarity caused problems again. However the experiment showed the streambed loss as we expected. The piezometers give data for the hydraulic conductivity calculations too.

We could demonstrate water level separation at both the upstream and downstream - the result of streambed loss and well loss respectively. Despite this we could not deduct any numerical data that could be used when trying to predict the streambed loss in a real-world situation.

The fundamental problem with seepage tests in scale models is the difficulties to meet the scaling laws. It is very hard to calculate the scaled material properties not to mention of getting proper materials for the experiments. It is much simpler to calibrate and analyze real world data collected during test pumps using modeling software (i.e. ModFlow).

We could justify that the streambed loss should not be neglected as it can limit the water recharge from the surface water during riverbank filtered production.

References

1 **Burke JM, Smela E**, *A novel surface modification technique for forming porous polymer monoliths in poly(dimethylsiloxane)*, Biomicrofluidics, **6**(1), (2012), 16506–1650610, DOI 10.1063/1.3693589.

2 **Ivanics L**, *Hidromechanikai Modellkísérletek*, Műszaki Könyvkiadó; Budapest, 1968.

3 **Liu GD, Li JT**, *Seepage laws in aquifer near a partially penetrating river with an intensive extraction of ground water*, Science in China Series E: Technological Sciences, **40**(5), (1997), 489–496, DOI 10.1007/BF02917163.

4 **Mays DC, Hunt JR**, *Hydrodynamic Aspects of Particle Clogging in Porous Media*, Environmental Science & Technology, **39**(2), (2005), 577–584, DOI 10.1021/es049367k.

5 **Smela E, Martinez-Miranda LJ**, *Effect of substrate preparation on smectic liquid crystal alignment. II. Further results and modeling*, Journal of Applied Physics, **77**(5), (1995), 1923–1929, DOI 10.1063/1.358824.

6 **Stuyfanzd JP, Juhasz-Holterman MHA, de Lange WJ**, *Riverbank filtration in the Netherlands: well fields, clogging and geochemical reactions*, NATO Advanced Research Workshop on Riverbank Filtration Hydrology 2004 (Bratislava, Slovakia, 2004-09-07), In: Riverbank filtration hydrology: impacts on system capacity and water quality, NATO Science Series IV, Earth en Environmental Sciences 60, Springer, 2006, pp. 119–153.

7 **Varadi Zs**, *Calculation Methods of Riverbank Filtration*, News in Engineering, **1**(1), (2013), 4–11.

8 **Wett B, Jarosch H, Ingerle K**, *Flood induced infiltration affecting a bank filtrate well at the River Enns, Austria*, Journal of Hydrology, **266**(3-4), (2002), 222–234, DOI 10.1016/S0022-1694(02)00167-1.

9 **Brown G**, *Darcy's Law Basics and More, One-Dimensional Flow*, Oklahoma State University, 2002, `https://www.coursehero.com/file/10101566/biosystemsokstateedudarcylaloibasics/`.