TECHNISCHE UNIVERSITÄT DRESDEN

Fakultät Umweltwissenschaften

EXPERIMENTAL INVESTIGATION OF THE STABILITY OF THE COLMATION ZONE AROUND LEAKY SEWERS

By

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Academic dissertation submitted in accordance with the requirements for the degree of

Doktoringenieur (Dr.-Ing.)

Dissertation zur Erlangung des akademischen Grades Doktoringenieur (Dr.-Ing.)

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Dresden
2015

Abstract

Sewage exfiltration from a sanitary and combined sewer systems and its percolation into porous medium results in a clogged or colmation layer in the nearby soil. In order to develop a comprehensive understanding of raw sewage transport mechanisms in porous media, investigations were carried out on the micro-scale properties of the multiphase system. In our laboratory experiments, the role of surfactants as a major organic chemical compound in wastewater was evaluated by using a surfactant solution as an artificial wastewater percolating into a porous media, represented by using columns and Plexiglas model. We studied flows of water and surfactants solution in saturated porous medium to detect the dynamic effects by means of measuring pressure and permeability as well as by visualization of flow regions and consequence for porosity along interfaces between water and surfactants solution.

The tests revealed that mechanisms at interfaces between fluids and solids as well as between water and surfactants solution (i.e. wastewater) are significantly influencing the flow behavior. At the interfaces surfactant molecules are adsorbed or accumulate, respectively, and subsequently inducing electrical charges to those layers, altering the properties of fluids and these interfaces. Depending on the conditions, channels might be narrowed and thus decreasing the flow rate with a later erosion and increase of flow rates, or the flow and thus the erosive capacity might become intensified along the interface between surfactants solution and neighbouring water. In conclusion, the results of tests proved the surfactants to be an important controlling factor in the hydraulic properties of wastewater percolating into soil.

Acknowledgements

The author work was financially supported for three years (2010-2013) by Helmholtz Interdisciplinary Graduate School for Environmental Research (HIGRADE).

The author wish to thank the advisor, Prof. Dr. Peter Krebs, for his guidance and patience during this research. The author also wish to thank Dr. Detlef Lazik and Davood Toorchi Roodsari for their insights in soil-physics concepts and Jim Monroe for his valuable comments to the writing.

Table of Contents

Abstract.....I
Acknowledgements.....II

CHAPTER ONE

Introduction..... **1**
Background 1
Structure of the thesis..... 2

CHAPTER TWO

Sewer exfiltration and colmation process..... **4**
Abstract..... 4
Introduction 5
The clogging layer 6
Clogging and exfiltration assessment 8
Modeling of a colmation zone 11
The effects of soil clogging on hydraulic conductivity 14
The effects of surfactants on hydraulic properties of the soil..... 15
Conclusion 18
References 19

CHAPTER THREE

Water displacement by surfactant solution- an experimental study to represent wastewater loss from sewers to saturated soil **26**
Abstract..... 26
Introduction 27
Kinetic theory of surfactant monomers interfacial aggregation 28
Materials and methods 31
Results and discussion 34
Conclusion 38

References 39

CHAPTER FOUR

Permeability changes by surfactant solution- an experimental study to represent wastewater loss from sewers to saturated soil 42

Abstract 42

Introduction 43

Materials and methods 44

Results and discussion 46

Conclusion 53

References 54

CHAPTER FIVE

Visualization of surfactant solution transport in saturated soil – an experimental study to represent wastewater loss from sewers 58

Abstract 58

Introduction 59

Materials and methods 61

Results and discussion 63

Conclusion 69

References 70

CHAPTER SIX

Conclusions and outlook 74

Results summery 74

Outlook 76

I

CHAPTER ONE

Introduction

1 Introduction

1.1 Background

Sanitary systems are considered as one of the most important structures to support hygienic living conditions in urban areas. In the case of structural failure, raw sewage or combined wastewater eventually infiltrates into the soil and groundwater resources, known as exfiltration process from the sewers perspective. The task of accurate estimation of exfiltration rates is currently a main research topic of urban sanitation and urban hydrology. Exfiltration is frequently assumed to be a major cause for groundwater pollution, which can in turn have a serious impact on water supply with regard to process design, operation and eventually to public health, as well as on economic aspects due to rehabilitation efforts. During exfiltration, an important phenomenon is the formation of a colmation zone in the pipe's adjacent soil, which is to a large extent controlling the percolation flow and its variation.

There are currently two main hypotheses available that describe clogging and its influence on the exfiltration rate. Both discuss the Total Suspended Solids (TSS) and the biomass activity aggregation inside the void space of porous medium, which cause a reduction of the effective porosity and thus of the exfiltration rate. In this study, a third cause is added to the two above mentioned; surfactants aggregation at interfaces is hypothesized to influence the soil properties and as a result the exfiltration behaviour.

Surfactants are important organic compounds in various detergents, which are released in high quantities from households and industries into wastewater and sewer systems. The chemical nature of surfactants induces a surface-active behaviour and consequently their adsorption/accumulation at interfaces. This study focused on the investigation of anionic surfactant adsorption at fluid-fluid as well as at fluid-solid interfaces and their effect on the variability of two-phase flow in porous media.

In laboratory experiments, the surfactants effect on the hydraulic properties of fluids in the soil was investigated. This simplified system is a first step into evaluating the principle role of detergents for the exfiltration of wastewater from sewers. Therefore, the following laboratory experiments were carried out:

- In a column setup with glass beads, representing a porous medium, pressure and pressure changes induce through the passage of a water – surfactants solution interface were detected in order to conclude on the build-up of the expanding surfactant aggregation at fluid–fluid interface and how these are structured (Chapter 3).

- A column setup with micro-glass filters was loaded with surfactant solution to investigate permeability changes due to the sorption of surface-active agents at the solids surfaces in pores and thus reducing the flow capacity (Chapter 4).
- In an experiment, vertical parallel infiltration of water and surfactant solution into soil and the effect of the surfactants-solution – water interface on the soil structure were investigated by applying a dye-tracer and a 3D visualization approach (Chapter 5).

1.2 Structure of the thesis

After the introduction (Chapter 1), the thesis is divided into five chapters. Chapters 2 to 5 contain a manuscript and three papers and chapter 6 provides overall conclusions and an outlook.

- Chapter 2 is entitled "Sewer exfiltration and colmation process". This chapter is a literature review on the fundamentals of wastewater exfiltration, clogging development and modeling with special attention to the role of surfactants in the colmation process. Nikpay M., Ellis B. and Krebs P. (2015), Submitted Manuscript WR32845, *Water Research Journal*.
- In Chapter 3, entitled "Water displacement by surfactant solution – an experimental study to represent wastewater loss from sewers to saturated soil", an experimental study is described that detects the dynamic effect of the passage of the interface between water and surfactant solution (serving as a proxy for wastewater) through saturated porous media. The interpretation of the process of surfactant accumulation at the fluid-fluid interface is based on the dynamic pressure signals when the interface is passing the measurement horizons. Nikpay, M., D. Lazik, and P. Krebs (2014). Water displacement by surfactant solution: an experimental study to represent wastewater loss from sewers to saturated soil. *International Journal of Environmental Science and Technology*, 12.8, pp. 2447-2454.
- Chapter 4 entitled "Permeability changes by surfactant solution – an experimental study to represent wastewater loss from sewers to saturated soil" describes an experimental study that detects changes in the permeability of porous media for different surfactant concentrations during the infiltration and backwashing mode of the experimental column. The measurement of the outflow and its changes is used as a basis to conclude on the surfactant aggregation at the fluid-solid interface. Nikpay M., Lazik D. and Krebs P. (2015). *Environmental Earth Sciences*, 73.12, pp. 8443-8450.
- Chapter 5 entitled "Visualization of surfactant solution transport in saturated soil – an experimental study to represent wastewater loss from sewers" deals with an experimental study to visualize the behaviour of the interface between water and a surfactant solution parallelly infiltrating into soil and its effect on the soil structure. In this study, the surfactant concentration

was high, i.e. up to about 15 times of the critical micelle concentration (CMC). The flow and the soil structure was visualized by adding dye-tracer and by processing photographic images analysis. Nikpay M., Lazik D. and Krebs P. (2015). *Environmental Earth Sciences*, 74.9, pp. 6693-6701.

- Chapter 6 entitled “Conclusions and outlook” is a general wrap-up of the above-mentioned works with a recommendation for future studies.

II

CHAPTER TWO

Sewer exfiltration and colmation process

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Submitted Manuscript WR32845, Water Research Journal

Sewer exfiltration and colmation process

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Abstract

Wastewater is a significant source of pollution. Often after a failure, improper sealing or bad pipe connections cause raw sewage effluent to percolate through the adjacent soil. As a consequence, a colmation layer is developed, which regulates the exfiltration rate. Quantifying the wastewater clogging mechanism through intrinsic colmation processes in the enveloping soil matrix is a complex problem, which has not yet been described adequately. A survey of published literature in this field provides information highlighting influencing mechanisms and processes as well as new measuring techniques and data quantification. However, the lack of fundamental investigations on the hydro-physical properties of the colmation layer and clogging soil is noticeable. The purpose of this paper is to review and discuss the effects of exfiltration from leaky sewers on the clogging development and its stability, in addition to the impact of soil clogging on hydraulic properties of the colmation layer and a brief review of colmation zone modelling. Special attention is paid to the role of surfactants in the colmation process.

Keywords*: exfiltration, colmation layer, clogging, sewer systems*

1. Introduction

Sanitary systems are considered to be important structures for providing hygienic conditions in urban areas. In the case of structural failure and a groundwater level below the pipe base, raw sewage can conceivably be lost from the sewer to the soil and conveyed into underlying groundwater resources. This sewer loss process can be defined as exfiltration.

The problems associated with accurately defining sewer exfiltration rate data and the attendant control of groundwater pollution are two focal points of current research interest in urban sanitary systems in terms of both technical analysis and potential health risks (Ellis et al., 2009; Chisala, and Lerner, 2008; Selvakumar et al., 2004). Whilst new and innovative methods for determining sewage exfiltration rate are being continuously developed (Leschik et al., 2009; Fenz et al., 2005), the potential impact of such losses on groundwater resources are less known and understood (Schaider et al., 2014). Effects of exfiltration of untreated sewage are often identified following the detection of marker pollutants in groundwater which can be referred to wastewater constituents introduced by residential, commercial and industrial process discharges as well as from the release of pollutants from wastewater treatment system overflows (Re et al., 2010; Sercu et al., 2011; Yang et al., 2013).

All sewers are liable to leakage loss particularly in urban areas where the drainage system is ageing and subject to various pressures such as heavy traffic loadings or substantial groundwater rises (Ellis and Bertrand-Krajewski, 2010). Sewer exfiltration has become a priority concern in most metropolitan regions of Europe and North America, but surprisingly little work has been undertaken to investigate the properties of the clogging materials which are associated with the sewer fracture area and how such properties might influence the exfiltration rate.

This article is an investigative review of leaky sewers including the formation and cause of clogging in the colmation layer, triggering change in the hydraulic conductivity of the clogged zone and reviews conventional Darcian modeling approaches to exfiltration loss rates. Particular attention is paid to the potential role of wastewater surfactants in amending the hydraulic properties of the clogging layer and surrounding soil and in the development of preferential flow paths. The review is based on a collaborative examination of established works and current scientific knowledge in assessing exfiltration rates and recommendations to manage and direct future research and development initiatives.

2. The clogging layer

During exfiltration, an often described phenomenon is the formation of a clogged or colmation zone beneath and adjacent to the pipe base which results in the reduction of hydraulic conductivity and porosity (Fig.1) in the enveloping soil layer.

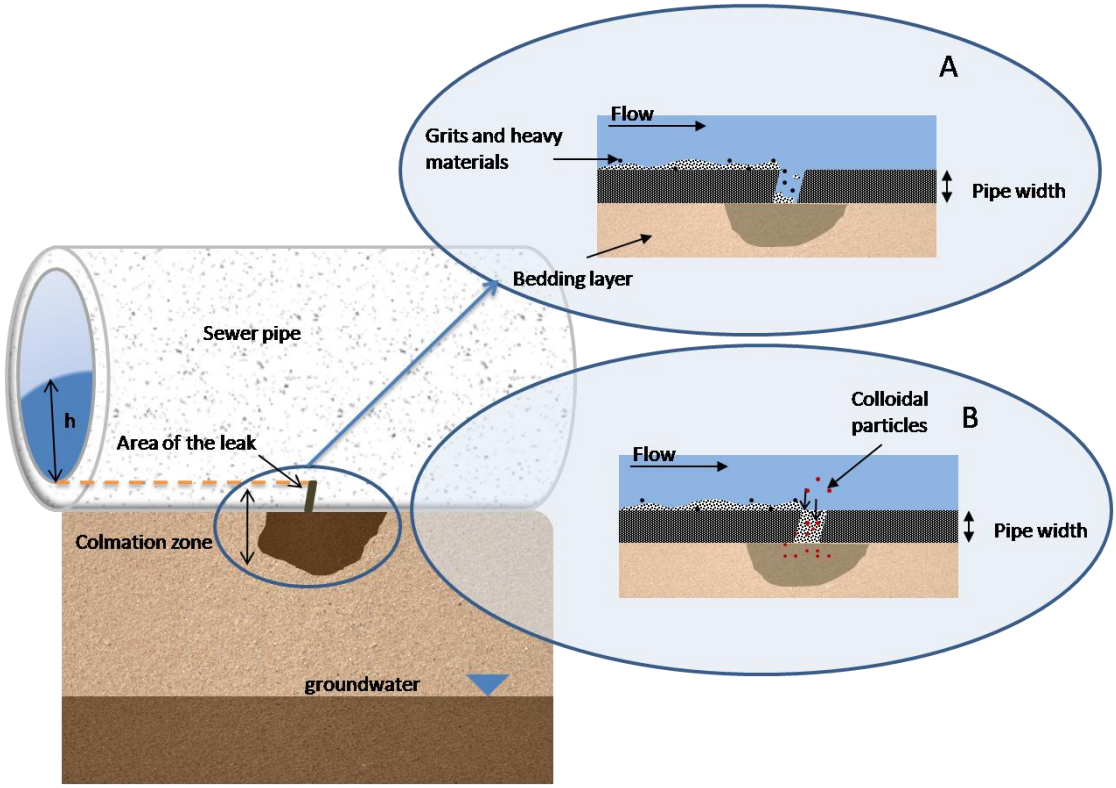

Figure1 Illustration of exfiltration from a leaky sewer pipe into an unsaturated sub-soil environment. The colmation layer includes the clogged layer at and below the pipe fracture. A and B show details of the clogging layer at the fracture area. First, the fault is filled with settable materials of wastewater until it reaches a quasi-equilibrium level. Next, the colloidal particles penetrate into the pore spaces. h is the hydrostatic height of wastewater.

Various studies have reported a decrease in exfiltration rate associated with the clogging process due to biodegradation-induced build-up of biomass or particle adsorption (McGauhey and Winneberger, 1964; Mitchell and Nevo, 1964). The clogging layer seems to be relatively thin with a typical vertical expansion of 10 to 50mm (Ellis et al., 2009). The reason that the clogged layer is maintained at such a minimal depth can be the result of physical clogging of the pores by wastewater constituents, thus reducing the hydraulic conductivity of the clogged layer. Subsequently, the process of infiltration deceases with depth while passing through a thin layer

with low permeability. The vertical build-up of the clogging layer is limited by the hydraulic action of the overlying wastewater flow which maintains a quasi-equilibrium sediment depth.

The flow rate through the clogged layer is driven by the pressure head difference between the inside (wastewater level in the sewer) and outside (groundwater level) pressure, but is also influenced by the type and degree of pipe deterioration and the structure of the clogging layer itself. Moreover, the clogging process is controlled by sewage quality, e.g. suspended particle size, the physical characteristic of the fault as well as the location of the fault in relation to the flow. The structure of the colmation layer consists of approximately 25% organic matter while the remainder comprises largely inert constituents. Formation of a mesh-like fabric occurs on the surface of the clogging layer to about 10 to 20 mm while the smaller particles penetrate into the inner sediment layers to a maximum of 14.7mm (Ellis et al.,2009; Karpf et al., 2009; Pholkern et al., 2015).

The clogging layer can occur in either saturated or unsaturated soil systems and is a function of the wastewater exfiltration rate and the sub-soil characteristics. From available information, there is insufficient quantifiable evidence on how such leakage is exactly controlled by the colmation layer, partly due to the complexity and nature of the sewage and its components. However, the development of the colmation layer is a prime relevant factor in reducing permeability through inherent physical, chemical or biological activities resulting from sewage-soil interactions.

The changes in hydro-physical properties of the sub-soil in such clogging layers have been attributed to variation in flow rate (Rajabzadeh, et al., 2015; de Camargo et al., 2013). However, laboratory tests and direct measurements from sewer leaks have shown that clogging in a model environment does not yield similar exfiltration results (Ellis et al., 2009; Karpf et al., 2009; Rutsch et al., 2008). Gray and Schrefler (2001) assert that the majority of investigations on sewage percolation into underlying sub-soil layers reveal a general lack of analysis of detailed hydro-physical properties especially on a micro-scale. For instance, the widespread use of detergents has generated relatively high concentrations of surfactants in wastewater. In 2013, the annual consumption of surfactants in Europe was estimated to be 2.98 Mt. of which 1.45 Mt was non-ionic and 1.19 Mt was anionic according to the data reported by the European Committee of Organic Surfactants and their Intermediates (CESIO, 2013). Such surfactants are known to have potential to change or modify soil properties such as soil-hydrophobicity (Travis et al., 2010). It is also well known that surfactants can affect metal lability and algal toxicity with the detergent

complexation modifying the soil adsorption properties (Morrison and Florence, 1988). Thus, a hypothesis relating surfactants to soil property changes, such as percolation behaviour, can be developed. This theoretical approach is discussed in the final section of this article along with the discussion of our own research investigations on the effect of surfactants on the dynamics of the wastewater exfiltration process into sub-soil.

3. Clogging and Exfiltration assessment

Two principal hypotheses can be put forward to explain the decrease mechanisms in exfiltration rate which have been noted to occur in both experimental and field studies. According to the first, organic and inorganic wastewater micro-particles accumulate in the void space of the porous colmation medium causing a decrease in its effective porosity (Rice, 1974; Rauch and Stegner, 1994; Karpf et al., 2009). Thus, the total suspended solids (TSS) smaller than 0.47 μm, which impact micro and meso-pores, would be the main contributing factor in the loss of percolation capacity within the clogged layer. However, the colloidal phase including organic and inorganic particles, also plays a crucial role in the self-sealing of the clogging layer (Auset and Keller, 2006). Mcdowell-Boyer et al., (1986), argued that there was an initial accumulation of fine solids at the surface of the porous media with particles larger than pore sizes. This shrouding particle layer would then control the internal clogging potential of the porous medium (Platzer and Mauch, 1997).

The second hypothesis suggests that heterotrophic biomass growth, taking place within the pore spaces comprises the main reason for clogging. Flowing effluent is enriched with nutrients and aerobic organic substrates which enable the biomass to flourish. The availability of a readily biodegradable benthic substrate is conducive to maximize yield and growth rates (Vollertsen and Hvitved-Jacobsen, 1998). Sakrabani et al (2009) have demonstrated the importance of oxygen uptake rates (OURs) as a crucial biochemical factor in controlling biomass biodegradability. Degradation kinetics for organic carbon are much more dynamic during dry weather, low flow conditions when total biomass and bacterial growth increase substantially over extended residence times (Sakrabani et al., 2009). Experimental results, however, show that clogging along with the associated percolation reduction is a rather quick process (Fig.2) with rapid development of surface mats while biomass clogging becomes more significant in later phases. Zhao et al. (2009) argued that the contribution of organic particle accumulation to the process of clogging is

higher than biofilm growth, as especially for porous media with a small pore size, TSS would reduce the pore spaces more rapidly than the biofilm growth rate.

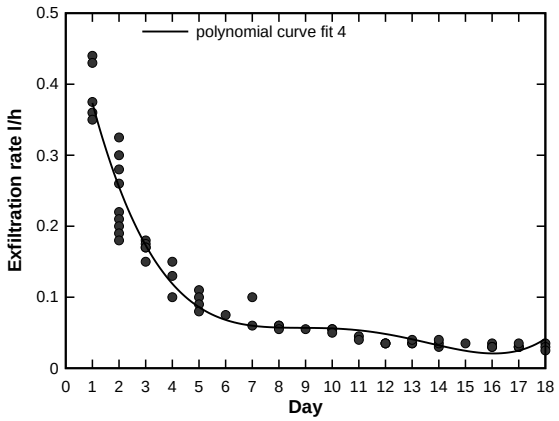

Figure2 Time series of sewage exfiltration rate originating from a concrete pipe with a crack of 4 mm width, installed in a sand bedding (data adapted from Dohmann et al., 1995).

VanGulck and Rowe (2004) stated that the development of a clogging layer at the surface of the porous medium is supportive to the growth of biomass, since it provides a protective and nutrient rich environment for microbial growth. In turn, the constituent flocs can significantly reduce the potential for mobilization of sessile microorganisms (Davey and O'toole, 2000). In a nutrient-rich environment with or without dissolved oxygen, both heterotrophic and autotrophic microorganisms are able to flourish as indicated by various studies (Okubo and Matsumoto, 1983; Wood and Bassett, 1975). The conditions in a colmation layer provide such a nutrient-rich environment (Sierra et al., 1995).

In the uppermost zones, obligate aerobic bacteria prevail, resulting in degradation of the organic substrate (Langergraber et al., 2003). In addition to both facultative aerobic and anaerobic bacteria, the presence of fungi in the enveloping transition zone soil around the sewer leak will enhance the clogging process (Dizer and Hagendorf, 1991). In the work of Kristiansen (1981), reviewed by Baveye et al. (1998), the underlying sand bed to the sewer pipe was examined following infiltration with wastewater. The results indicated that the top few centimetres contained $3 \cdot 10^{10}$ cells g^{-1}, equivalent to 1.4% of the total void volume of the sand layer. Francisca and Glatstein (2010) reported the reduction of hydraulic conductivity of soil due to microbial activity, to reach up to two orders of magnitude. Mattison et al. (2002) in their sand-filled column experiments using Pseudomonas sp. (strain PS^{+}) bacteria in an air-saturated artificial groundwater

through which a glucose solution was percolating, showed the permeability to decrease by a factor of 26 as compared to the initial condition.

In other investigations, clogging has been attributed to the larger scale infiltration of particle-laden or to the organics-rich substrate infiltrate. Houston et al. (1999) reported the development of microbial clogging by infiltration of surface waters in artificial recharge facilities. Basal clogging induced by the infiltration of landfill leachate has also been observed along with biofilm formation and the reduction of pore space (Fleming and Rowe, 2004; Paksy et al., 1998).

The above-cited publications give a good overall picture of the basic mechanisms of particle and biomass-growth induced soil clogging by percolating wastewater, causing interior and exterior blockage to sewer leaks that significantly reduces hydraulic conductivity of the porous media. However, it is difficult to obtain clear information on particle size distribution of the transitional zone, underlying soil or of the percolate that can be related to the degree of clogging. Commonly, fine sand is used for sewer pipe bedding with grain size distribution ranging between 0.06 to 2 mm according to the AASHTO soil classification system (Das and Sobhan, 2013).

Referring to particle sizes, Baumann (2007) stated that the contribution of colloidal particles with a diameter between 1nm to 1 µm to be self-sealing. Thus there appears to be some contention as to the relative significance of particle deposition against biomass growth as the primary influence in the development of the colmation structure. It is probable however, that both processes contribute to the formation and growth of the colmation zone with local circumstances and conditions controlling which process dominates temporally or spatially within the sewer system.

The clogging layer does not seem to be stable over the long term, because of hydrostatic pressure variations inside the pipe. Ellis et al (2009) have shown how small-scale diurnal kinematic waves in the sewage flow can lead to equilibrium breakthrough of the colmation layer even under very low hydrostatic pressure and shear stress conditions (> 1.5 N m^2). Rapid elevation in groundwater levels can also destabilise the clogging layer as reported by Karpf and Krebs (2005) during the 2002 flooding events in Dresden, Germany. The leading investigations on sewer clogging processes have been essentially concerned to date with biochemical degradability and the relationship between pressure head and leakage rate (Vollertsen and Jacobsen, 2003; Blackwood et al., 2005b; Rauch and Stegner, 1994). Ellis et al. (2008) have categorized various investigation approaches to the estimation of exfiltration rate suggesting that the minimum average daily rate

under controlled experimental conditions for a standardized leak area ranges from 0.02 to 9.0 l d^{-1} cm^{-2} for sewer lengths between 0.0002 and 2.0 l s^{-1} km^{-1}. However, the data indicate that the range between minimum and maximum exfiltration rate is large and that experimental test rig results are difficult to transfer to field conditions. There is a distinct lack of such direct field observations of colmation processes which are needed to evaluate the validity of the experimental and theoretical approaches (Wolf et al., 2007).

4. Modelling of a colmation zone

Empirical models based on the use of pipe structure and sewer deterioration data or from sewer leakage rates, can be correlated with sewer damage format as well as exfiltration rates modeled on the application of the Darcy theory (Rutsch et al., 2008). The latter approach is also essentially an empirical approach which is scaled in a similar manner as the empirical models.

According to Darcy's equation the steady-state flow rate (Q ; m^3 s^{-1}) can be related to the porous medium as characterized by its hydraulic conductivity (K; m s^{-1}) and the hydraulic gradient ($\Delta h/l$):

$$Q = KA\frac{\Delta h}{l}\ , \qquad \text{Eq.1}$$

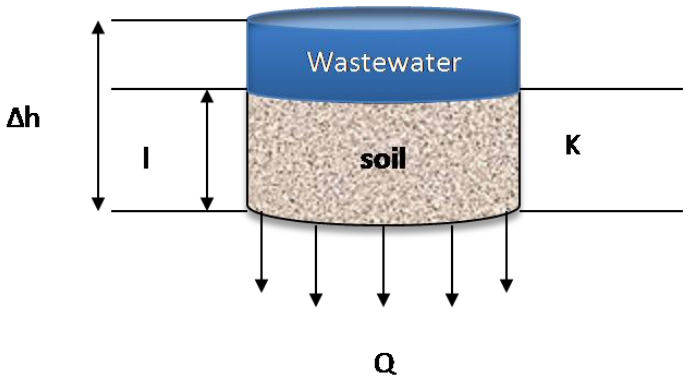

Figure3 Sketch of wastewater-soil interaction at the area of the leak and components of Darcy's law.

where A is the area of the leakage flow (m^2) (Fig.3). The conductivity K considers physical properties of the porous media on the one hand and the characteristics of the flow on the other hand. To measure permeability k (m^2) as a solid property of porous media rather than that as a fluid, k can be expressed as:

$$k = K\frac{\mu}{\rho g} \qquad \text{Eq.2}$$

where μ is the viscosity of the fluid (Pa.s), ρ is the density of the fluid (Kg m^{-3}) and g is the gravitational acceleration (m s^{-2}). Rauch and Stegner (1994) defined the k_f value as the permeability coefficient of the clogged zone (m s^{-1}). Hence, the k_f factor is an estimation of the permeability and can be determined based on void geometry and pore channel distribution as defined by the grain size.

The outcome of the work of Rauch and Stegner (1994) is an application of Darcy's law for a leakage approach. With Q_{ex} as the exfiltration flow rate (m^3 s^{-1}), A_{leak} as the leakage area of the pipe (m^2), Δh as the water pressure on the leak (m) and L_{leak} as the leakage factor (s^{-1}), Eq.1 can be rewritten as

$$Q_{ex} = A_{leak}\Delta h L_{leak} \qquad \text{Eq.3}$$

where the leakage factor L_{leak} follows as (Rauch and Stegner, 1994):

$$L_{leak} = \frac{k_f}{\Delta l} = \frac{Q_{ex}}{A_{leak}\Delta h} \qquad \text{Eq.4}$$

with Δl being the thickness of the clogging zone (m). A crucial term in this equation is the matrix potential (Δh), which considers the soil and water content of the total colmation zone. This matrix potential will increase with increasing saturation and particle cohesion within the colmation and underlying transition zones and this will vary temporally. Summarized results of various laboratory tests for estimating the leakage factor can be found in Table 1 based on Rutsch et al., (2008).

The Darcian equation however, can really only be valid if the hydraulic conductivity of the clogging layer is in fact the controlling factor for exfiltration loss rather than the result of the properties and age of the clogging layer itself. The full limitations for the application of Darcy's law have been discussed in various papers (e.g. Bear, 1972; Hassanizadeh and Gray, 1993; Mavko et al., 2009; Ellis et al., 2009). The principal issues identified in these analyses include:

1) Applications for macroscopic scale behaviour in porous media, where the volume is substantially larger than the pore volume
2) Application for low fluid velocity such that inertial forces can be neglected. This occurs with laminar flow at low Reynolds number **Re** $\leq$ 1. However, such laminar flow conditions are likely to occur infrequently under normal sewer conditions.
3) For low pressure gradient induced flow in fine-grained soil, non-Newtonian fluid behaviour may develop due to clay-water interaction leading to an immobile adsorbed water boundary layer.
4) Gas molecules larger than pore space could result in a greater permeability for gas than for liquid and significantly influence flow behaviour.

Table1 Results of experimental investigations on exfiltration rates (After Rutsch et al., 2008)

Experiment	Initial soil condition	Charging time	Thickness of the colmation layer (mm)	Exfiltration rate ($ld^{-1}cm^{-2}$)	Leakage factor ($ms^{-1}cm^{-2}$)
Rauch and Stegner (1994)	Coarse sand gravel	20-50 minutes	10 50	0.87-5.2	0.01-0.001
Dohmann et al.(1999)	Silty sand Medium/ Coarse	12 weeks 12 weeks 3 weeks	20-40 100 20	0 0.48-5.52 0.96-6 0.02-0.06	0.001-0.54
Vollertsen and Hvitved-Jacobsen(2003)	Loamy sand	9 days to 7 weeks	10-20 (assumed)	0.02-0.06	1.4×10^{-4}
Blackwood et al.(2005b)	Gravel	60-90 minutes	-	8.6-86	0.83

The multiphase flow is represented by the concept of volume fraction of the pore space occupied by the each fluid phase and the degree of saturation. The function of the multiphase flow in a clogged layer is even more complex, since physicochemical and biological processes are influencing the properties of the pore areas. Nevertheless, the fluid saturation does not provide information about boundary-effects, wettability or adsorption of compounds at the solid surfaces as a consequence of the characteristic composition of the fluids. In this regard, several authors

have discussed the need for an increased knowledge on the micro-scale properties of such multiphase systems (Gray and Miller, 2010; Hassanizadeh and Gray, 1993).

5. The effects of soil clogging on hydraulic conductivity

The main characteristic of the colmation layer is a combination of fine particulate, the co-development of cohesive properties and bacterial biodegradation of the biomass substrate. It is these parameters which lead to the accumulation and persistence of the clogging material and associated structural composition.

The effect of untreated wastewater on the reduction of hydraulic conductivity under saturated conditions (K_s) is induced by dynamic reactions between cohesive organic and inorganic particulate and biological activity. K_s is a quantitative expression of the soil's capability for water movement as well as infiltration under saturated condition which is a function of the porosity.
Baveye et al. (1998) classified clogging effects in K_s reduction into three categories; physical, chemical and biological. Later Rinck-Pfeiffer (2000) used the term mechanical clogging to describe the trapped gas inside of the pore spaces. The gas bubbles in saturated porous media may be produced by biological activities, fluctuations in the water table or changes in fluid pressure.

Infiltration of fluid with high concentrations of suspended solids leads to the physical clogging of porous media (Velickovic, 2005). In this process, the suspended solids particles with a size less than the porous medium particles successfully penetrate inside the soil layer. The suspended solids with a size near the porous medium or larger are observed accumulating at the surface forming a mesh base layer thus reducing the hydraulic conductivity of the medium (Herzig et al., 1970). Other physical processes leading to *Ks* reduction include the migration of fines (Kanti Sen and Khilar, 2006).

Infiltration of nutrient-rich wastewater into the soil increases microbial activity and biomass aggregation. Okubo and Matsumoto, (1983) have shown that the biological clogging of porous medium consists of three phases; the initial decrease in K_s through aerobic microbial growth, the slight increase in K_s because of a decrease in microbial accumulation and a decrease in K_s through anaerobic microbial growth. The bio-clogging can cause changes in the flow regime or transport pattern (Seifert and Engesgaard, 2007). The subject of clogging through a chemical process, however, is generally agreed by the scientific community. The three mechanisms of advection,

dispersion and deposition are suggested as a means of controlling the clogging of porous media (Grolimund et al., 1998), and has been visualized and reviewed by Auset and Keller (2006).

Viviani and lovino (2004) surveyed the effects of various municipal wastewater TSS concentrations on soil using a constant head permeameter revealing a decrease in K_s values, especially in the upper layer of the embedding soil. Vandevivere and Baveye (1992) made a distinction between K_s reduction induced by the formation of nutrient-rich bacterial mats and that resulting from *TSS* concentrations. The reduction of permeability was observed in the region close to the point of nutrient injection. The authors also indicated the important role of aerobic bacteria for K_s reduction as they exhibit a higher growth rate on a given substrate than that exerted by anaerobic bacteria.

Baveye et al. (1998) described how the distribution pattern of bacterial clusters inside the porous medium is an important influencing factor for clogging. This conglomerate formation of bacterial cells which are attached to the substratum, form vertical and horizontal voids thus enabling the transportation of products and oxygen inside the colony which results in their stability through the occupation of the conduits (de Beer at al.,1994). Seki and Miyazaki, (2001) found that the initial reduction in K_s value associated with clogging of the uppermost soil layer was supportive to microbial activity, thus resulting in an exponential decrease in the hydraulic conductivity (Mays and Hunt, 2005). They attributed a second cause of clogging to the methane gas production by anaerobic bacteria which leads to a sealing of the pores by the CH_4 generation as indentified in the work of Seki et al (1996).

6. The effect of surfactants on hydraulic properties of the soil

Studies on greywater (domestic non-toilet effluent) irrigation to soil have suggested that direct infiltration can increase the inherent soil repellency properties (Thwaites et al., 2006), principally due to penetration by substances such as chloride, boron and surfactants (Gross et al., 2005). Misra and Sivongxay (2009) confirmed such hydrophobicity resulting from infiltration of laundry detergents, whilst Travis et al (2010) demonstrated the same effect from infiltration irrigation of surfactants and edible oils.

A decrease in the capillary rise of greywater-irrigated soil has been measured by Shafran et al. (2005) which supports this argument for increased soil hydrophobicity and has been explained by the adsorption of surfactant molecules at the soil particle surfaces. Using three types of surfactants on two different soil types (silty loam and sandy loam), Abu-Zreig et al. (2003) found that anionic surfactants strongly affected the hydraulic properties of both soil types. Recent experimental studies (Nikpay et al., 2014) have used a liquid detergent containing anionic surfactants loaded onto a laboratory column packed with water-saturated glass beads to investigate the influence of surfactants on the infiltration behaviour of wastewater from leaky sewers into the soil beneath the pipe. This work indicated that controlling factors such as the electrostatic properties of the porous media, interfacial characteristics of the percolating fluids, and the adsorption of surfactants at the interfaces affect the flow behaviour. The results of this experiment showed that during the dynamic process of water displaced by a surfactants solution, a stable interface between the fluids, if formed, locally increases the pressure and temporarily increases the flow rate through the colmation layer. However, due to the stable interface, mixing is largely inhibited and thus the surfactants solution, i.e. the wastewater exfiltrating from sewer leaks, is hardly diluted by either the surrounding water or groundwater.

In another experiment by Nikpay et al. (2015a), a column setup with micro-glass filters was loaded with different surfactant concentrations in order to investigate permeability changes due to the adsorption of surface-active agents at the solids surfaces in the pores. This was accomplished by measuring the outflow and its changes which resulted in the discovery of surfactant aggregation at the fluid-solid interface. Nikpay et al. (2015a) assert that the adsorption of anionic surfactants at solid substrate surfaces causes a decrease in permeability and that the extent of the permeability reduction is stronger with the increase of surfactant concentration. Therefore, it can be concluded that surfactants are involved in a self-sealing mechanism of porous media, which in turn is the controlling factor for the exfiltration rate. Additionally, flushing experiments showed that the permeability reduction induced by surfactants is persistent, so that after each period of washing, the permeability returned to the level before the start of the washing. Eventually, surfactant adsorption at the solids can modify their original surface characteristics.

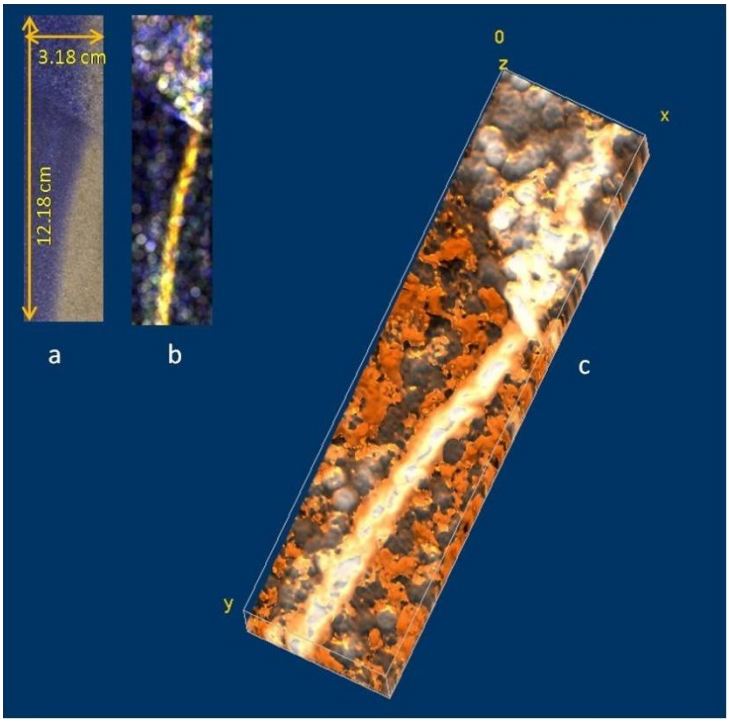

Figure 4 The 3D volumetric view of the surfactant solution and water interface where the soil structure was non-homogeneous. (a) is a selected section of original image and (b) is a filtered image using software ImageJ (Abramoff et al. 2004). The inhomogeneous soil structure is influencing the pattern of the interface and of the flow (a). An increased dye concentration at the interface indicates a pronounced interfacial flow (b, c).

Further information on the infiltration process was produced by a 3D visualization based on dye-tracer tests (Nikpay et al., 2015b). In this test, water and surfactant solution were vertically loaded into the soil column. By studying the region of fluid interface, the development of soil erosion along the interface was observed. The visualization showed a preferential pathway developing along the vertical interface between the two fluids, enabling solutes to be transported more efficiently towards the groundwater (Fig.4). This opens up the potential for transport of fines and pollutants along the interface between exfiltrated wastewater and neighbouring groundwater, possibly even through the colmation layer.

The investigation confirmed the formation of a colmation layer by clogging in the core part of the percolating wastewater, which was even magnified by the effect of surfactants. Similarly, the results of these tests confirmed that wastewater particles and microbial growth are not the only controlling factors for the infiltration and clogging process in the sub-soil and that the kinetic process and interactions are highly complex in nature.

7. Conclusion

The mechanism and structural composition of soil clogging in porous media is an important process for wastewater exfiltration from sewers into the underlying soil. Whilst many studies of exfiltration, infiltration and pollution transfer by leaky sewers have been carried out over the last decade, several key areas in the clogging process still require improved description and explanation. These areas include:

- identification and dynamics of microbial groups involved in clogging,
- the role of organic chemicals and surfactants in the clogging phenomenon,
- adequate prediction of potential clogging based on sewage and soil information,
- modeling of flow and sewage constituent transport inside the porous media.

The apparent uncertainty in the results of direct and indirect measurements as well as modeling approaches, suggests that serious difficulties arise with the description of wastewater flow in porous media, due to the complexity of wastewater composition and the kinetic interactions with soil and with groundwater. In particular, the micro-scale controls and features of bacterial biodegradation in both benthic sewer substrates and colmation layer need further consideration to improve the understanding and prediction of exfiltration mechanisms and rates.

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III

CHAPTER THREE

Water displacement by surfactant solution- an experimental study to represent wastewater loss from sewers to saturated soil

Mitra Nikpay, Detlef Lazik, Peter Krebs

International Journal of Environmental Science and Technology, 12.8 (2014), pp. 2447-2454.

Water displacement by surfactant solution- an experimental study to represent wastewater loss from sewers to saturated soil

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Abstract

Leakage of wastewater from sewer lines may result in contamination of soil and groundwater. Our investigation dealt with the effects of surfactant as one of the constituents of wastewater on the infiltration process of wastewater through soil. To that aim, in a laboratory experiment a column was uniformly packed with glass beads of 0.25 to 0.50 mm diameter and equipped with sensors to measure local fluid pressure at 3 observation points along the direction of flow. The artificial laboratory wastewater was created by adding a commercially available detergent to degassed tap water producing surfactant concentrations between 8 mgl^{-1} and 16 mgl^{-1}. The displacement process of degassed tap water by such a particle-free artificial wastewater was studied by loading the surfactant solution into the saturated glass beads column. Short term pressure changes were observed while the interface between water and surfactant solution passed the observation points within the column. The pressure peaks increased for higher surfactant concentrations. The theory of growing interface between surfactant solution and clean water by aggregation of monomers to a double layer could be supported by the column experiments.

Keywords*: wastewater exfiltration, interface, sewer, interfacial tension*

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IV

CHAPTER FOUR

Permeability changes by surfactant solution- an experimental study to represent wastewater loss from sewers to saturated soil

Mitra Nikpay, Detlef Lazik, Peter Krebs

Environmental Earth Sciences, 73.12 (2015), pp. 8443-8450.

Permeability changes by surfactant solution- an experimental study to represent wastewater loss from sewers to saturated soil

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Abstract

Leakage of wastewater from sewer lines may result in contamination of soil and groundwater. The widespread use of detergents is causing relatively high concentrations of surfactants in wastewater. We studied the effects of surfactants on the infiltration process of wastewater through soil. To that aim, in a laboratory experiment three micro-pore glass filters were installed. A laboratory wastewater substitute was created by adding a commercially available detergent to degassed tap water producing surfactant concentrations of 100 mgl^{-1}, 200 mgl^{-1} and 400 mgl^{-1}. Rapid changes in permeability after using the surfactant solution were detected. These were further examined during a process of washing the glass filters with water. The experimental results indicated that changes in permeability were induced by significant adsorption of surfactant molecules on the solids surfaces and thus reducing the size of the pores. Higher levels of permeability changes were detected for higher surfactants concentrations. Additionally, the efficiency of washing process of an adsorbed surfactant molecular layer at the pores surfaces was greater that before the critical micelle concentration (CMC).

Keywords*: exfiltration, interface, sewer, permeability, surfactant*

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V

CHAPTER FIVE

Visualization of surfactant solution transport in saturated soil – an experimental study to represent wastewater loss from sewers

Mitra Nikpay, Detlef Lazik, Peter Krebs

Environmental Earth Sciences, 74.9 (2015), pp. 6693-6701.

Visualization of surfactant solution transport in saturated soil – an experimental study to represent wastewater loss from sewers

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Abstract

Surfactants are the main active agents in detergents products. Our investigation dealt with the effects of surfactants as a wastewater constituent on the infiltration process of wastewater through saturated soil. In order to more closely observe the flow's interaction, in a laboratory experiment, a 2D Plexiglas model was filled with fine-grained soil and saturated with degassed water. The particle-free artificial laboratory wastewater was created by adding a commercially available detergent to degassed tap water producing a surfactant concentration with the strength equivalent of up to about 15 times of its critical micelle concentration (CMC). The visualization of flow was improved by adding a brilliant blue dye tracer enhancing the color contrast. Photographs were taken from the 2D model using conventional imaging equipment and were processed by image analysis to distinguish the dynamic flow interface between dyed and non-dyed areas. Primarily, the images of vertical flows were analyzed after reducing the contrast range. Next, utilizing an image analysis method, 2D images were re-constructed into 3D visualization models. Three dimensional and cross-sectional images of the fluid-fluid-soil boundary layer revealed a rapid solute transport prevailing at the dynamic interfaces. This was confirmed with image analysis showing geometric irregularities on the soil surface.

Keywords*: exfiltration, interface, sewer, dye tracer, surfactant*

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VI

CHAPTER SIX

Conclusion and outlook

6 Conclusion and outlook

6.1 Results summary

The purpose of the work described in this thesis was to advance scientific understanding of the processes associated with wastewater exfiltration from sewers and subsequent percolation through soil. There are various challenges that must be addressed in order to advance our understanding in this area of study. One key challenge is measuring the physicochemical properties of fluids in soil system within the clogged zone. The properties of the clogging layer and thus the flow characteristics are highly heterogeneous in space and time. Hence, the work introduced here aimed to improve the understanding on the clogging process and the interacting percolation in soil by developing measurement and interpretation approaches. The focus of the investigation was on the influence of surfactants, which are present in significant concentrations in wastewater and affecting namely the interfaces between fluids and between fluids and solids surfaces. Therefore, the permeability of porous medium and the percolation process within that medium are significantly influenced by the presence of surfactants and their effects.

The literature review presented in chapter 2 of the work indicated that the exfiltration rate estimation and measurement methods still need development to become a reliable tool for quantification. Recent studies of exfiltration from sewers have involved the monitoring of solutes and pollutants transport, the effect of microbial processes, clogging modeling and measurement as well as groundwater pollution. The investigations described in this thesis focused on the effects of clogging and contaminant mobilization processes in soil induced by surfactants. While the current major hypothesis regarding changes in hydraulic properties of porous media, i.e. of the clogging process, are focusing on colmation by particles or bio-mass growth within the pores, it could be shown by means of experiments that clogging is also influenced by surfactants, according to the below summarized tests results.

Laboratory-scale studies were designed to investigate the interaction between surfactants solution, water and a porous medium, serving as proxies of wastewater, groundwater and soil, respectively. In all experiments, degassed water was used to achieve full saturation and to omit side effects from entrapped air. Special attention was paid to the development of a clogging layer and the associated flow behavior as well as to reasons for potential development of preferential flow paths through the colmation layer.

In chapter 3, this question was addressed through studying the propagation of a fluid-fluid interface induced by displacement of water by a surfactant solution through porous medium. The pressure dynamics induced by the passage of the interface was interpreted with regard to the character of the

interface. Based on reviewed theories and the experiments, it was concluded that the pressure increase at the interface between the fluids is caused by the aggregation of surfactant molecules. This generated local increase of pressure, i.e. a pressure gradient, at the interface of water and surfactant solution can increase the displacement capacity of water by surfactants solution, i.e. of groundwater by wastewater, through the clogged zone. This test result indicates the importance of surfactants and their effects in affecting the flow behavior in the colmation layer.

Processes at the solid-fluid interface between surfactant solution and porous medium have a direct impact on permeability and on surface interaction properties of porous media, which is crucial or the clogging process. With characteristics monitoring of the interface, our understanding of processes in the clogged layer could be improved. In chapter 4, the clogging potential by surfactants, causing changes in the permeability of porous media, was tested for different surfactant concentrations above and below the critical micelle concentration (CMC). The results showed a significant decrease in the permeability by the aggregation of surfactants on hydrophilic solid surfaces due to the surface accumulation of surfactant molecules. Therefore, it can be concluded that surfactants are involved in a self-sealing mechanism of porous media, which in turn is the controlling factor for the exfiltration rate. Also, the potential of water flow cleaning efficiency on porous media was relevant with the way of molecular aggregation at surfaces. Flushing experiments showed that the permeability reduction induced by surfactants is persistent, so that after each period of washing, the permeability turned back to the level before the start of the washing. Eventually, surfactants adsorption at solids can modify the original surface characteristics of solids.

In chapter 5, a visualization technique was applied with which the interface between the fluids water and surfactant solution in soil, was investigated. The two fluids were vertically loaded onto the soil column, parallel in immediate neighborhood. The variance method is used as an edge-detector filter, visualized sharp boundaries between a dark and bright regions over the selected images. By studying the region of fluid interface, the development of soil erosion along the interface was observed. This information could be interpreted as an indicator for local permeability, exhibiting preferential pathways. These preferential pathways were created along the interface between the two fluids, induced by increased flow intensity. This opens up the potential for transport of fines and pollutants along the interface between exfiltrated wastewater and neighboring groundwater, possibly even through the colmation layer. Also, the approach for visualization showed the potential of low-cost techniques to improve the understanding of complex mechanisms.

All over, the investigation confirmed the formation of a colmation layer by clogging in the core part of the percolating wastewater, even magnified by the effect of surfactants. On the other hand, from the

investigations it must be hypothesized that – under saturated conditions – along the interface between the percolating wastewater and the adjacent groundwater, matter transport may be intensified despite the existence of a colmation layer.

6.2 Outlook

The apparent lack of hypothetical/experimental information regarding the interaction between wastewater, groundwater and soil, should be a motivation for further investigations in this field. I suggest three main research areas: physical and chemical sorption, fluid dynamics and biological effects. After performing further well-designed experiments, set-up of a pilot-plant for conducting long-term studies may improve the findings and their reliability for real systems.

Step by step, the experimental system should become more real towards the percolation of real wastewater in soil. Only the step-by-step procedure will allow to identify cause-effect relationships between the complex wastewater matrix and the soil. Along with increasing complexity, also the measuring and visualization techniques will have to be further developed.

Since the conditions of the experiments carried out for this PhD study were rather restricting, I suggest the following future studies to investigate details which are still unclear up to now:

- In this study, anionic surfactants were investigated. Thus, in further research, cationic and a mixture of surfactants should be investigated to evaluate whether effect are synergetic or antagonistic.
- We need further analysis to understand and quantify how surfactants influence organic and inorganic wastewater constituents in the clogging process in a porous medium.
- Adverse and positive effects of gases in wastewater, in groundwater and in the unsaturated soil should be examined.
- The effect of grease and oil in combination with surfactants in wastewater should be studied for the percolation process.
- A further development of image analysis techniques and subsequent interpretation algorithms to improve the information content gained from the experiments is needed.
- We need further investigation regarding the transport of dissolved and particulate compounds through the clogged layer, where the particulates are expected to adsorb various pollutants. In that respect, the questions whether or not micro-pollutants can reach the groundwater and what their fate is become crucial.

Last, model development should go beyond a simplistic view. The available descriptions of biological processes and their effects on clogging in the colmation layer are rather vague so far. In view of the development of a fluid-fluid and biological model, the processes of degradation of organic substances as well as of the associated biomass growth should be quantified and integrated into a flow model.