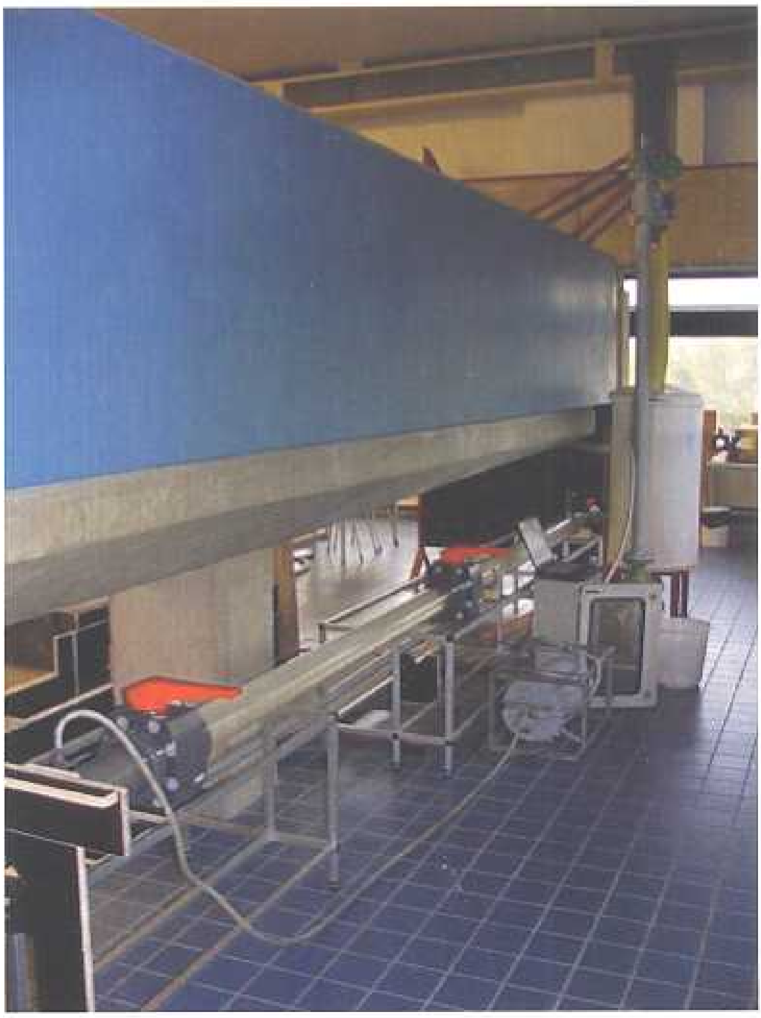
2005_002

Hydraulic behaviour of particles in a drinking water distribution system

Design and first operation of a test rig

January 2005



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Faculty of Civil Engineering and Geosciences

Delft University of Technology

January, 2005

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Colophon

Title
Hydraulic behaviour of particles in a drinking water distribution system
Design and first operation of a test rig

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Preface

This report is the result of my Master Thesis study at the Faculty of Civil Engineering and Geosciences of the Technical University of Delft. The study was carried out at the Section of Sanitary Engineering of the Department of Water Management (TU Delft) and supported by Kiwa Water Research, the Dutch research and knowledge institute for water and associated ecological and environmental questions.

I would like to thank all participants of the monthly Q21-meetings for their comments and advise. Special thanks go to the section of Fluid Mechanics of the Department of Hydraulic and Geotechnical Engineering for their support with the build up of the test rig. Special thanks also go to Jan Vreeburg for his insight and his help during this project.

Summary

Project framework
Drinking water companies want to preserve the consumers trust. One of the challenges to meet the high expectations of modern costumers is to prevent deterioration of water quality during transport and distribution. Within the framework of the Q21 concept, developed by water companies together with Kiwa and TU Delft, research is done to the underlying mechanisms of water quality deterioration in networks.

Due to hydraulic effects and biological or chemical processes, the water quality may be subject to changes while being distributed. To study these phenomena the concept of a mass balance in a distribution system is followed. Different processes like settling, resuspension, corrosion, and biofilm formation contribute to this mass balance.
In this study the effect of particles in the incoming water on the accumulation of mass in a test rig is studied. Aim is to get a better understanding of the settling process.
Theoretically, the amount of sedimentary deposits can be calculated by measuring the differences in the ingoing and outgoing sediment load of the water. However, in practice the differences in the particle concentration of the ingoing and outgoing water are too small to calculate the amount of sedimentary deposits. Also, biological and chemical processes inside the distribution system may result in the production of particles, adding to the mass balance. With the test rig the actual layer development is studied by charging the test pipe during a longer time and analysing the layer itself.

Experimental setup
To study the effect of sediment layer development a multiple pipe test rig with identical parallel pipes has been designed. With this multiple pipe test rig it would be possible to determine layer development by removing one pipe at a time and measuring the amount of sediment. As every pipe would show the same layer generation process, analysing multiple pipes at different times would give an image of the development of a sediment layer in time.

To study the feasibility of a test rig to determine the development of a layer of sediment, a single pipe test rig has been build. The main question is whether it is possible to see any significant layer development within a reasonable time. This test rig was used for a number of experiments, researching the influence of flow velocity and sediment source on the sedimentation process. For most experiments iron chloride or kaolinite has been used as particle source. Dosing iron chloride results in the formation of iron flocks with a relative low density of approximately 1200 kg/m^3. Kaolinite is a clay mineral with a density of 2600 kg/m^3. One experiment has been done with collected sediment from the drinking water distribution system of the city of Leusden (Utrecht).

Based on settling according to Stokes' Law and the assumption that resuspension of particles occurs depending on particle size and weight, a hypothesis was formed. This hypothesis shows settling of particles as a function of the particle concentration and resuspension of a certain part of the settled particles. As the amount of settling particles decreases and the amount of resuspending particles increases, equilibrium will develop between both processes.

Results
From the experiments it can be concluded that the test rig can be used to investigate the sedimentation process in a distribution pipe. The first results show a number of interesting phenomena like different forms of the sediment bed developed at different flow velocities and with different sediment sources.

The results of the experiments show an influence of the flow velocity on the sedimentation process. For example bed load transport of iron flocks is visible at a flow velocity of 0.06 m/s and not at 0.14 m/s. At 0.06 m/s only the bottom half of the pipe shows layer development when using iron flocks, while at 0.14 m/s the entire pipe wall shows layer development. Experiments with kaolinite show layer development in the bottom half of the pipe at 0.06 m/s as well as 0.14 m/s.
It also shows that a sediment layer is easier to remobilize when the layer has developed at a lower flow velocity. Apparently, a sediment bed is more cohesive when developed at a higher flow velocity.

Comparison of the different sediment sources show that iron flocks have a lower sedimentation rate than kaolinite particles at the same flow velocity. It also shows that the sediment sample taken from a real network in Leusden is more similar to kaolinite than to iron flocks.

With regard to the hypothesis the experiments did show that equilibrium is reached, although the value of the 'steady state' turbidity was quite low for most experiments. Also, adding more particles did not show an increase of the 'steady state' turbidity. This was not expected as, according to the hypothesis, dosing more particles to the system would lead to a higher number of resuspending particles resulting in a higher steady state turbidity. Calculating the settling of particles with Stokes' Law and resuspension with different 'resuspension factors' (percentage of sedimentary deposits per unit of time) show that only a low number of settled particles resuspend.

The most important recommendations relate to additional experiments and further development of the test rig. For example, experiments with a particle counter in addition to using a turbidity meter would give more insight in changes in the particle size distribution during experiments.
When designing the multiple pipe test rig and scaling down the pipe diameter, it is preferred to use shear stress as design parameter instead of turbulence. Shear stress is chosen as it is of importance for the resuspension of particles and the cohesion of the sediment layer.
The results of experiments with the test rig could be used for verification and development of computer models like PODDS and PSM.

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1 Introduction

With the introduction of new water treatment techniques like membrane filtration, the particle load of the produced drinking water decreases. As the particle load of the water introduced to the distribution system decreases, questions arise about the influence of the distribution system on the water quality during distribution. It might be possible that, although the water delivered at the pumping station is of very high quality, the water quality might be subject to changes in the distribution system.

To ensure a high quality of the drinking water at the customers tap in the future, the Q21 research program is formulated by the Dutch drinking water companies. Research is performed by Kiwa Water Research and TU Delft. This program focuses on the possibilities of reaching an even better water quality at the consumers tap, by introducing new water treatment techniques and investigating the influence of the distribution system on the water quality.

Although the water originating from a treatment plant may be of very high quality, there will always be a certain amount of particles in the water. Due to hydraulic processes in the distribution system, these particles will settle in the pipes and layers of sediment will develop. Together with other processes like corrosion and biofilm formation sediment could be formed in distribution pipes.

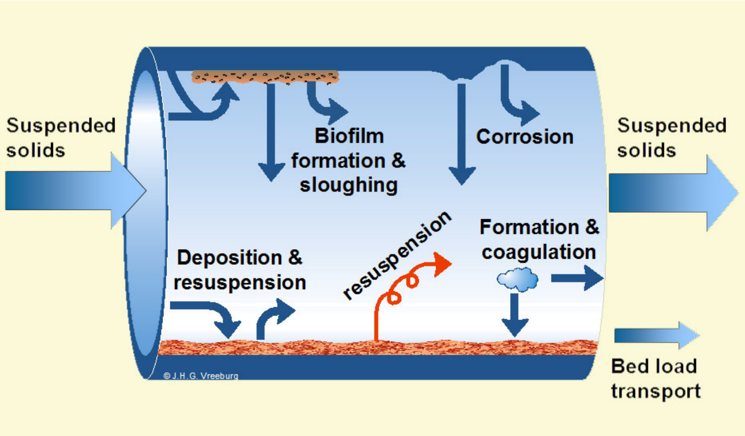

figure 1.1 Various processes contributing to the mass balance

A mass balance of a distribution pipe can be used as a framework to study various processes. By measuring the ingoing and outgoing particle concentration the sediment load can be calculated. As processes like corrosion and biofilm formation add to the particle load of the water it is difficult to calculate the development of sedimentary deposits in the distribution network from the ingoing and outgoing particle concentration.

Because it is difficult to study layer development in practice, a test rig can be used to analyse the process of particle deposition. By measuring the actual layer development, results with a test rig could be used to calculate layer development for a distribution pipe. A first design was made of a multiple pipe setup. However, problems were expected when scaling down to a smaller pipe diameter. To avoid problems with downsizing and to be able to do experiments with a relative short duration, a single pipe test rig was build operated in a circulation setup. This test rig was used to study the sedimentation processes in a distribution pipe at different flow velocities and for different sources of sediment.

The main goal of this thesis project was to determine the feasibility of a test rig to study the effect of the sediment load of drinking water on the mass balance in a drinking water distribution system.

In this report a comprehensive description will be given of relevant literature (chapter 2) followed by a description of the theory in chapter 3. Chapter 4 gives a problem analysis resulting in a more detailed goal of this project. The design of the test rig is described in chapter 5 followed by a description of the experiments in chapter 6. Chapter 7 describes a model which was used to compare the theoretical sedimentation process with the experimental data. The results of the experiments are discussed in chapter 8 resulting in conclusions and recommendations in chapters 9 and 10.

2 Literature

2.1 Literature study

A literature study has been conducted prior to starting the design of the test rig. In the recent history different kind of test rigs, including pipe rigs, have been used for different studies. For example, the 'Torus' experimental pipe rig developed by Thames Water Utilities Ltd was used to study biofilms, nitrite formation, particle entrainment and corrosion of cast iron pipes (Smith et.al., 1999).
A study by Horn et.al. (2002) focuses on the growth and detachment of biofilms in a pipe rig using primary waste water. The results show a homogeneous initial growth of the biofilm switching to a steady-state situation when the biofilm reaches a certain thickness. It was also shown that an increase in shear stress resulted in detachment of the biofilm.
Beuken and Schaap (2002) did research on the remobilisation of sediment in distribution pipes. The results show that at a flow velocity of 0.35 m/s all of the used sediment types are moving near the bottom of the pipe.

However, reviewing literature, it appears that very little research has been done to the actual development of sediment layers in a drinking water distribution system. Some information is available about sedimentation of particles in test rigs, but most of these studies focus on particles with a diameter larger than 100 µm (Kiger and Pan, 2001), while most particles in distribution systems have a diameter smaller than 20 µm (figure 6.1). It is expected that these smaller dimensions of particles are of influence on the behaviour of the particles.

2.2 Sediment modelling

Two studies, carried out by the University of Sheffield (UK) and the Cooperative Research Centre (CRC) for water quality and treatment (Australia), aim on a better understanding of sedimentation and resuspension processes creating a discolouration risk. This is similar to the goal of the Q21 project. In Sheffield a test rig called the 'Prediction Of Discolouration events in Distribution Systems regeneration rig' (PODDS) is being build, which will be used to better understand the changes of parameters used in the PODDS model, a computer model which is used to predict discolouration events. In Australia a test rig has been used to research the mechanisms of particle build up in pipes.

2.2.1 PODDS regeneration rig

In this paragraph a description is given of the PODDS model and PODDS regeneration rig, developed by the University of Sheffield. The text is based on the article 'Cohesive Layer Generation and Erosion in Water Distribution Systems using Simulated Hydraulic Conditions' by Husband,S. Saul,A. and Boxall,J.

The PODDS (Prediction Of Discolouration events in Distribution Systems) model, developed at the University of Sheffield, is used to predict discolouration risks in pipe networks. The model is based on erosion of sediment layers as a function of the shear stress. The parameters used in the model are determined by field measurements and observations of sediment layer regeneration in drinking water distribution systems.
To gain a better understanding of these parameters a test rig has been build. This rig is called the PODDS Regeneration Rig.

figure 2.1 PODDS Regeneration Rig

When developing the PODDS model it was hypothesised that discoloration of drinking water originates from cohesive layers on the pipe walls. Based on visual observations from fieldwork and excavations it is assumed that these cohesive layers are formed around the entire pipe circumference and not only on the bottom of the pipe. The model is based on the principle that material is held in stable cohesive layers which are conditioned by the daily hydraulic regime. The strength of a layer is dictated by the maximum shear stress at the maximum daily flow velocity. Discolouration may occur as the shear stress becomes higher than this maximum value.

The objective of the experiments with the regeneration rig is to monitor the growth, erosion and mobilisation of cohesive layers and subsequent regeneration. PODDS model parameters will be evaluated and compared with values obtained from fieldwork. Results will be used to enhance the PODDS model.

2.2.2 Particle Sediment Modelling

In this paragraph a description is given of the Particle Sediment Model, developed by the Cooperative Research Centre for Water Quality and Treatment in Australia. The text is based upon the articles 'Particles in Water distribution system – 5th progress report. Part I: Settling, Re-suspension and transport' (Grainger et.al., 2003) and 'Particles in Water Distribution System –

6th progress report. Particle sediment modelling: PSM software' (Wu,j. et.al., 2003)

Particle Sediment Modelling (PSM) is used to predict sediment mass distribution in drinking water distribution systems and to predict particle mass into customer's taps. PSM requires input of flow date based on hydraulic modelling as well as input of particle concentration loading at the inlet of the distribution system.
Calculation of particle mass build up in the distribution system is based on two mechanisms:

- *Settling of particles under gravity*
  A simple model is used to model gravitational settling. Particle dynamics are characterized by three statuses, depending on the flow velocity.
  1. $u>u_{rs}$, al sediments will resuspend. u_{rs} is the critical velocity beyond which particles are resuspended. u_{rs} increases with pipe diameter and is a function of particle diameter, density and packing of sediment.
  2. $u_d \leq u \leq u_{rs}$, particles are transported with no settling or resuspension.
  3. $u<u_d$, particles will settle with a downward velocity of u_s.

- *Deposition of particles onto the pipe wall due to particle/ wall surface interaction*
  Experiments showed that even at flow velocities of 0.3 m/s particles disappeared from the suspension, whilst it was observed that from a flow velocity of 0.15 to 0.25 m/s particles would resuspend from the bottom. It was assumed that this was caused by particles attaching to the pipe wall. This process is formulated with the following equations:

$$\frac{\partial C}{\partial t} = -\alpha(C - C_\infty) \qquad \textbf{\textit{equation 1}}$$

$$C_w = \beta \cdot C_\infty \qquad \textbf{\textit{equation 2}}$$

Where

C	concentration of particles in suspension	[mg/l]
C_w	mass of particles attached to the wall, per unit of water	[mg/l]
C_∞	final steady state concentration of particles in suspension	[mg/l]
α	decay coefficient	[-]
β	wall mass coefficient	[-]

Equation 2 shows the amount of particles attached to the wall calculated from the steady state concentration and the coefficient (β). Values of α and β are quantified using a test rig for different water types at different flow velocities. With α, β and C_∞ known, the value of C_w can be calculated. The steady state mass of particles on the pipe wall can be calculated with:

$$\frac{M_w}{L} = C_w \frac{1}{4}\pi d^2 = \beta C_\infty \frac{1}{4}\pi d^2$$ ***equation 3***

Where

M_w/L	particle mass per unit of pipe length	[mg/m]
d	pipe diameter	[m]

figure 2.2 Particle sediment test loop (PSTM)

The particle sediment test loop (PSTM) has been used to model the process of wall deposition. Studied were the effects of different pipe materials and sediment types and particle concentration. Results of the experiments were used to develop the particle sediment model.
Experimental data show an exponential decay of the particle concentration. The form of these exponential curves is of the form:

$$C = C_\infty + (C_0 - C_\infty)e^{(-\beta \cdot t)}$$ ***equation 4***

with:

C	concentration at time t	[mg/l]
C_∞	concentration after a large time	[mg/l]
β	decay constant	

This corresponds with the hypothesis of a decay of the particle concentration until equilibrium (C_∞) is reached between settling and resuspension of particles, as is described in paragraph 4.3.

3 Theory

3.1 Mass Balance

One of the objectives of the Q21 project is to develop a relation between the particle load originating from the treatment plant and the sediment build up in the network. To do this the different processes contributing to the mass balance are researched separately. Results of different research projects can be combined to form a complete model of the mass balance.

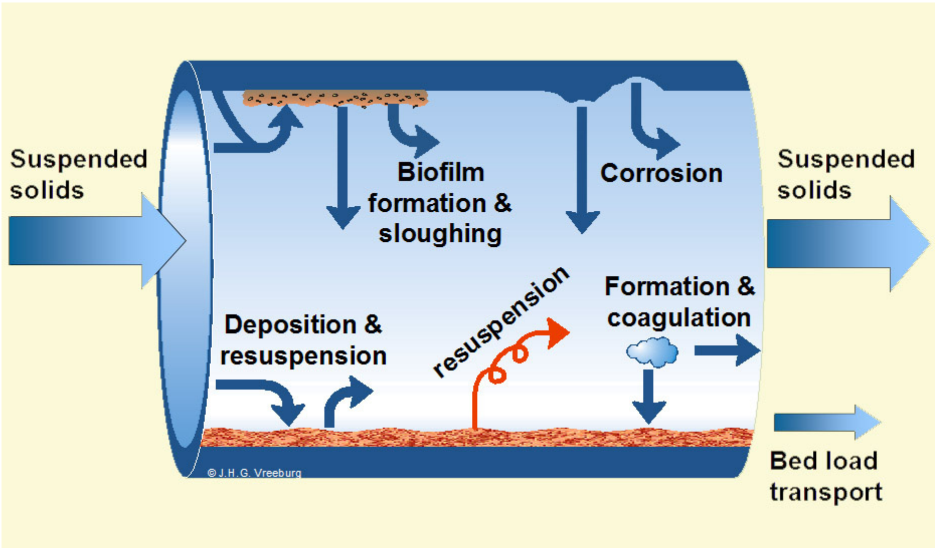

figure 3.1 Mass balance for a distribution system

Lots of research has been done to the development of biofilms[1] and the corrosion[2] of, for example, cast iron pipes, using a laboratory scale test rig. An article about corrosion in iron pipes, written by McNeill et.al. (2001) summarizes the results of numerous articles relevant to the drinking water industry. Other researchers try to reach a better understanding of the processes in a distribution system by conducting on site measurements, either in line[3] or by analysing grab samples.

Other processes which contribute to the mass balance are deposition and resuspension of particles. These particles can be introduced to the system at the treatment plant or can be formed in the distribution system. Although there is a numerous amount of articles available about the sedimentation of particles, most of these articles describe relative large particles in open water flows. Little information is available about the sedimentation of small particles (<20 μm) in a drinking water distribution system. Research to the behaviour of particles in distribution pipes has been done by Gauthier (1996, 1997), van der Meulen (M.Sc. thesis, 2004) and Kivit (M.Sc. thesis, 2004).

[1] Boe-Hansen et al. (2003); van der Kooij et al. (1995)
[2] Chung et al. (2004); Mesman and Slaats (2004)
[3] van der Meulen (2004); Kivit (2004)

A mass balance is based on the law of the conservation of mass. In general this means that whatever particles enter the system or are formed inside the system will either leave or stay inside the system. In formula form a mass balance can be written as:

$$\text{Delta mass} = \text{Mass}_{in} + \text{Mass}_{production} - \text{Mass}_{out} \qquad \textit{equation 5}$$

The following processes contribute to the mass balance for a drinking water distribution system:

- Deposition of suspended particles
- Resuspension of settled particles
- Development and sloughing of biofilm
- Corrosion of pipe materials
- Formation and coagulation of particles

While other studies are focussed on analysing differences in ingoing and outgoing particle concentration (Kivit (2004) and van der Meulen (2004)), the field of research of this project will be the generation of sediment layers caused by the processes of deposition and resuspension of particles in the water phase.

3.1.1 Deposition of particles

Assumed is that settling of particles takes place according to Stokes' Law, but is influenced by wall effects like electrostatic forces and turbophoresis. Turbophoresis is a process which is responsible for the transport of particles from regions of high turbulence to regions of low turbulence without being able to return. This would mean particles could be trapped in the laminar sub layer close to the pipe wall.

Stokes' Law:

$$v = \frac{2r^2(\rho_{sphere} - \rho_{fluid})g}{9\mu} \qquad \textit{equation 6}$$

Where

v	= settling velocity	[m/s]
r	= radius of a particle	[m]
ρ	= density	[kg/m^3]
g	= gravitational constant	[m/s^2]
μ	= fluid viscosity	[Ns/m^2]

With gravity as the main driving force of settling, particles will primarily deposit on the bottom. This means that deposition of (loose) particles will result in accumulation of sediment on the bottom half of a pipe.

Very small particles may, driven by turbulent forces, travel to the pipe wall and caught in the laminar sub-layer. Particles trapped in a laminar sub-layer will stay there as long as there are no changes in the flow velocity.
An electrostatic force between the pipe wall and the water may result in adsorption of small particles to the pipe wall.

3.1.2 Resuspension of particles

Resuspension of particles may occur when the hydraulic circumstances change. When the flow accelerates, the wall shear stress increases, and when the shear stress reaches a critical value particles will start to move and eventually resuspend.
A commonly used theory to calculate the critical shear stress is the Shields theory, which is used to calculate the critical shear stress (τ_{cr}). This is the shear stress at a flow velocity where settled particles start to move. This flow velocity is called the critical flow velocity (u_{*cr}).

$$u_{*cr} = \sqrt{\psi_{cr} \cdot g \cdot \Delta \cdot d} \qquad \textbf{\textit{equation 7}}$$

$$\tau_{cr} = \rho \cdot \left(u_{*cr}\right)^2 \qquad \textbf{\textit{equation 8}}$$

with:

τ_{cr}	critical shear stress	[N/m^2]
u_{*cr}	critical flow velocity	[m/s]
g	gravitational acceleration	[m/s^2]
d	particle diameter	[m]
Δ	relative density ($\rho_{particle}$-ρ_{water}/ρ_{water}) = 1.6	[-]
Ψ_{cr}	Shields parameter	[-]

The critical shear stress for a 100mm pvc pipe and particles with a diameter of 10μm follows from the following calculation, with:

D	Pipe diameter	0.1 m	[m]
d	Particle diameter	10 μm = 1*10^{-5}	[m]
k	Wall roughness	0.05 mm = 5*10^{-5}	[m]
D/k	Relative wall roughness	2000	[-]
ν	Viscosity	1.33*10^{-6}	[m^2/s]
U	Flow velocity	0.15	[m/s]

The friction coefficient f can be read from a figure as a function of the Reynolds number and the relative wall roughness. With Re = uD/ ν = 11278 and D/k = 2000 → f = 0.03.
f can be calculated to the factor c_f which is f/8 = 0.0038.
The shear stress (τ) can be calculated with the formula:

$$\tau = c_f \cdot \rho \cdot u^2 \qquad = 0.084 \qquad [\text{N/m}^2]$$

The corresponding shear stress velocity (u_*) and Reynolds number (Re_*) are:

$$u_* = \sqrt{c_f} \cdot u \qquad = 0.01 \qquad [\text{m/s}]$$

$$\mathrm{Re}_* = u_* \cdot d / \nu \qquad = 0.07$$

With Re_* known, the shields coefficient (Ψ_{cr}) can be read from the Shields diagram. As the value of Re_* is lower than 0.2 the extended Shields diagram by Mantz has been used.

Ψ_{cr} = 0.3

With equation 7 the critical shear stress velocity (u_{*cr}) cab be calculated:

u_{*cr} = 0.006 m/s

τ_{cr} follows from equation 8:

τ_{cr} = 0.04 N/m^2

From this calculation can be concluded that particles with a diameter of 10 μm will resuspend at flow velocities above 0.15 m/s.

However, the Shields theory is implicitly derived for sandy to gravely sediment and may not be applicable to fine sediments. A number of assumptions have been made that may be invalid with the fine sediments found in drinking water distribution systems:

- Electrostatic forces may become important
- Definition of a sediment 'bed' is more difficult
- Movement of particles is influenced by turbulence.

Because of this the Shields theory may not be applicable to the entrainment or resuspension of particles in a drinking water distribution system.

Another problem with the entrainment of particles is the composition of sediment. Sediment from a drinking water distribution system consists of a great variety of particles with different properties (like grain size, density) (Gauthier et.al.(1996), Gauthier et.al.(1998), Gauthier et.al.(2001)). Because of this variety it is difficult to predict the amount of particles that will resuspend at certain flow velocities.

An assumption that can be made is that the amount of particles that resuspend per unit of time is dependent on the total amount of sedimentary deposits in the pipe and is influenced by the flow velocity. This means the more particles are settled in the pipe the more particles will resuspend. Also an increase in the flow velocity shall increase the amount of resuspended particles.

3.1.3 Biofilm

On the pipe wall in drinking water pipes a biofilm is formed of organic material. A biofilm covers the entire pipe wall and therefore influences the roughness of the pipe. Also particles that settle may be attached to the biofilm. Biofilms are formed by bacteria which grow on nutrients in the drinking water. The growth rate of a biofilm depends mainly on the amount of nutrients in the water which can be determined by measuring the concentration of biological dissolved organic carbon (BDOC) and assimilable organic carbon (AOC). An estimation of the biological activity can be given by measuring the concentration of adenosinetrifosfate (ATP).
When changes occur in the hydraulic conditions, parts of the biofilm may detach from the pipe wall and possibly settle in the pipe.

Biofilms are considered to contribute considerably to the fouling of a drinking water distribution system by growth and detachment of the biofilm and by attaching loose sediment to the pipe wall.

3.1.4 Corrosion

Another common phenomenon that contributes to the particle load in a distribution system is corrosion. Corrosion is the release of wall material, caused by chemical reactions of the wall material. The main problems following from corrosion are the loss of pipe wall material and the contribution to the particle load of the water.
The amount of corrosion in a drinking water system is influenced by:

- Water quality parameters like pH-value, Saturation Index, buffer capacity.
- Charasteristics of the distribution system like retention time, flow velocity and the condition of the wall material.

To determine the corrosion potential of water a number of methods can be used:

- Langelier Saturation Index (LSI):
  One of the most common methods is the Langelier Saturation Index. This method gives an indication of the saturation of water with respect to Calcium Carbonate. A LSI number of 0 means the water is in a state of equilibrium and shall not dissolve $CaCO_3$ or lead to scaling of the pipe wall. A positive LSI number means scaling of $CaCO_3$ will occur, and a negative LSI number means the water will dissolve $CaCO_3$.
  Because the LSI can be influenced by water quality changes. Therefore a buffer of HCO_3^- particles is necessary. In the Netherlands the current norm is an LSI of approximately zero and a buffer capacity of at least 2.0 mmol/l HCO_3^-.
- Corrosion potential[4]:
  The risk of corrosion problems is implemented in the German guidelines for materials applied in drinking water (DIN 50930, part 2, 1980). According to these guidelines the risk of corrosion can be neglected when:

  $$\frac{[Cl^-] + 2[SO_4^{2-}]}{[HCO_3^-]} < 1$$ ***equation 9***

  In general an index higher than 1 is an indication of aggressive water which means there is a certain corrosion potential. Basis for this guideline is the work of Larson and Skold.

3.1.5 Post coagulation

Post-coagulation may be the result of chemical processes originating from the treatment plant which have not yet reached a chemical equilibrium. Another

[4] van den Hoven and van Eekeren (1988)

cause of post-coagulation is the mixing of different types of water in the distribution system, changing the characteristics of the water.

3.1.6 Sedimentary deposits

Al of the before mentioned processes play a role in the development of sediment layers. Some processes like settling of particles and corrosion result in an increase of accumulated particles, while other processes like resuspension and bed load transport lead to a decrease in the amount of sediment.

3.2 Hydraulics

3.2.1 Turbulence

Under normal circumstances the flow in a drinking water distribution system can be considered as turbulent. This means a Reynolds number larger than 4000. The used definition of the Reynolds number is:

$$Re = \frac{u \cdot D}{\upsilon} \qquad \textbf{\textit{equation 10}}$$

Where:

u	= flow velocity	[m/s]
D	= diameter	[m]
ν	= viscosity ($1.33 \cdot 10^{-6}$)	[m^2/s]

As can be seen in Table 3.1 a flow velocity of 0.06 m/s is necessary for pipes with an inner diameter of 100 mm to reach a Reynolds number larger than 4000.

Table 3.1 Hydraulic conditions for a pipe diameter of 100 mm

Diameter	u	Q	Reynolds
[mm]	**[m/s]**	**[l/h]**	**[-]**
100	0.04	1130.97	3007.52
100	0.05	1413.72	3759.40
100	0.06	1696.46	4511.28
100	0.07	1979.20	5263.16

Table 3.2 shows that when the pipe diameter decreases a higher flow velocity is necessary to realize turbulent flow.

Table 3.2 Diameter and required flow velocity to have Re>4000

Diameter	u	Q	Reynolds
[mm]	**[m/s]**	**[l/h]**	**[-]**
10	0.60	169.65	4511.28
50	0.12	848.23	4511.28
100	0.06	1696.46	4511.28
500	0.01	8482.30	4511.28

When the flow velocity becomes too low to have turbulent flow, the flow becomes laminar. The effect of laminar flow is that while settled particles may start to move due to a high enough shear stress, they are not able to resuspend as there is no turbulence, required to lift the particles from the bottom of the pipe.
As laminar flow conditions do not occur frequently in drinkwater distribution systems it may become a problem when designing and operating a test rig with a relative small pipe diameter (d<50mm).

It should be noted that the viscosity is influenced by the temperature. When the temperature increases the viscosity will be lower, resulting in a higher Reynolds number.

Table 3.3 Influence of temperature on viscosity and Reynolds number (d=100mm, v=0.06m/s)

Temperature	Viscosity	Reynolds
°C	ν	Re
10	$1.31 * 10^{-6}$	4592
20	$1.01 * 10^{-6}$	5965
30	$0.81 * 10^{-6}$	7452

Table 3.3 shows that an increase of the temperature from 10°C to 30°C results in an increase of the Reynolds number with 62%. This could be of influence on the experiments because during the experiments the temperature of the water reached values up to 28°C. This was caused by the temperature in the laboratory and by the recirculation pump.

3.2.2 Shear stress

This paragraph is based on the report 'Zelfreinigend vermogen – invloed van de dynamiek van afname patronen' by van den Boomen and van Mazijk (2002).

The general equation of motion for closed pipes with a gradient β is:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial t} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + g \cdot \sin\beta - \frac{\tau}{\rho \cdot R}$$ ***equation 11***

From this equation a formula can be derived to calculate the shear stress in a pipe (equation 12). (See also Appendix A)

$$\tau = -\rho \cdot R \cdot \left(\frac{\partial u}{\partial t} + g \cdot \frac{\partial \varphi}{\partial x} \right)$$ ***equation 12***

Where

τ	= shear stress	$[N/m^2]$
ρ	= density of the water sediment mixture	$[kg/m^3]$
R	= hydraulic radius	[m]
g	= gravitational constant	$[m/s^2]$
u	= average flow velocity	[m/s]
φ	= piezometric level	[m]
∂u/∂t	= acceleration term	$[m/s^2]$
∂φ/∂x	= velocity term	[m/m]

equation 12 shows that the shear stress depends on the pipe diameter, velocity term and the acceleration term. Because this study focuses on a stable flow, the acceleration term can be discarded (∂u/∂t = 0). equation 12 reduces to:

$$\tau = -\rho \cdot R \cdot g \cdot \frac{\partial \varphi}{\partial x}$$ ***equation 13***

For a turbulent, uniform and stable flow, the formula of Chézy can be used:

$$u = C\sqrt{R \cdot \left|\frac{\partial \varphi}{\partial x}\right|}$$ ***equation 14***

With
C = Chézy coefficient $[m^{½}/s]$

As the flow in a distribution system will almost always be turbulent, equation 13 and equation 14 can be combined to:

$$\tau = -\rho \cdot g \cdot \frac{u^2}{C^2}$$ ***equation 15***

For a pipe with a diameter of 100 mm and a flow velocity of 0.06 m/s this results in a shear stress of 0.015 N/m^2 (See Appendix B for an example of the calculation).

In Table 3.4 the shear stress and Reynolds number are shown for the flow velocities that were used during experiments. Shear stress and Reynolds number were calculated for a water temperature of 28 °C, which was a normal operating temperature during the experiments.

Table 3.4 Shear stress and Reynolds number for different flow velocities

Flow velocity	Shear stress	Reynolds number
[m/s]	[N/m^2]	[-]
0.06	0.015	7142
0.14	0.066	16667
0.25	0.184	29761

3.2.3 Distribution of concentration across pipe height

One of the assumptions that have been made is that the concentration is uniform across the entire pipe. A method to verify this assumption is to calculate the Rouse distribution which represents the distribution of the concentration along the height of the pipe.
According to Rouse, the concentration at a certain height in the pipe is given by:

$$C = const. \cdot \left[\frac{1-\zeta}{\zeta}\right]^Z$$ ***Equation 16***

With

C	concentration	[mg/l]
ζ	z/a	[-]
z	height	[m]
a	maximum height	[m]
Z	W/ Ku_*	[-]
W	settling velocity	[m/s]

K	von Karman = 0.4	[-]
u_*	friction velocity	[m/s]

The value of $Z = W/ Ku_*$ gives the relation between the settling velocity (W) in downward direction and the turbulent diffusion (Ku_*) in upward direction. For small particles with a diameter of approximately 10 μm the settling velocity is low. Consequently, the value of Z would also be low.
For instance:
d=10μm and ρ=2600kg/m^3 → W = 1.08*10^{-4} m/s
With u_*=0.01m/s and K=0.4 → Z = 0.027

Calculation of the distribution of the concentration with Equation 16 gives the distribution shown in figure 3.2.

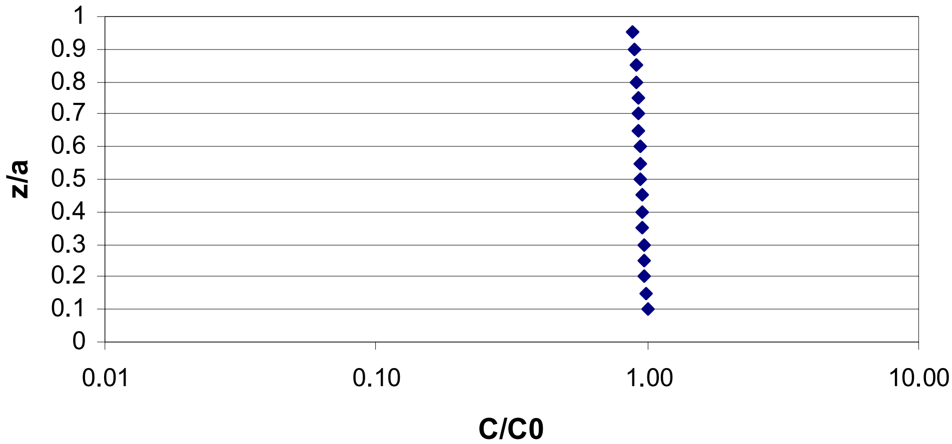

figure 3.2 Distribution of the concentration along the height of the pipe

This shows that the concentration can be considered uniform across the height of the pipe for particles with a diameter of 10 μm.

4 Experimental set up

4.1 Problem Statement

The particle load originating from the treatment plant is increasingly recognized as a major source for deposits in the distribution system. Because of the complexity of the total mass balance it is almost impossible to study the processes separately in a practical situation. By using an experimental setup this problem can be resolved as processes like biofilm formation and corrosion can be eliminated.

4.2 Objectives

The goal of this thesis project is to determine the feasibility of a test rig to study the effect of the sediment load of drinking water on the mass balance in a drinking water distribution system.
This goal will be reached in two steps:

- The design and build of the test rig
- Carrying out a number of experiments to study its feasibility

While the main goal of the experiments is to study the feasibility of the test rig, the results of the experiments will also be used to study the sedimentation process in a distribution pipe.

4.3 Hypothesis

It is hypothesized that settling of particles will occur according to Stokes' Law and, dependent on the flow characteristics, a certain amount of the settled particles will resuspend. As settling of particles takes place according to Stokes' Law the amount of settled particles per unit of time is dependent on the particle concentration. A higher concentration will result in a higher amount of settled particles.
Shields theory is probably not adequate to describe the resuspension process. A simple approach is followed in assuming that a fixed part of the deposits will resuspend depending on the wall shear stress.
In time these two processes will reach a state of equilibrium where the amount of particles that settle is equal to the amount of particles that resuspend.

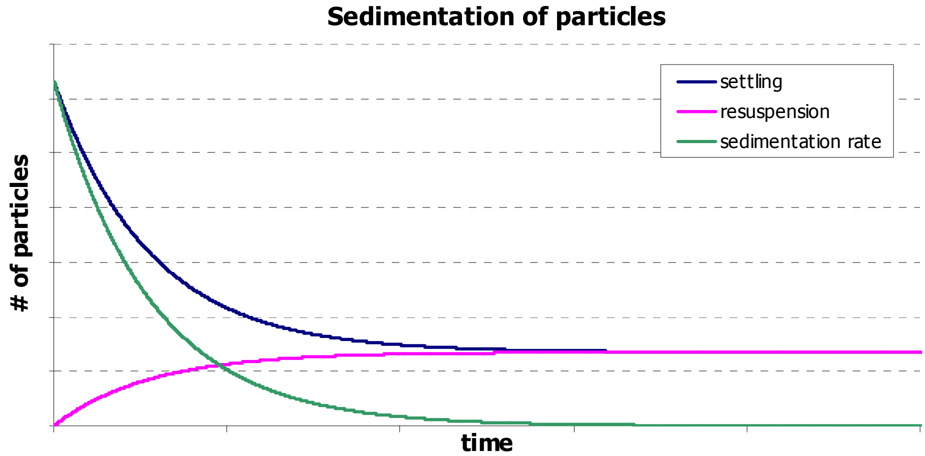

figure 4.1 Hypothetical sedimentation process

In figure 4.1 a graphical visualization is given of the processes which lead to equilibrium. The processes of settling and resuspension of particles are presented as the amount of particles that settle or resuspend per unit of time. The difference between settling and resuspension per unit of time is called the sedimentation rate which represents the amount of particles that accumulate on the pipe wall per unit of time. Development of a sediment layer will take place until equilibrium is reached. The process of layer development is visualized in figure 4.2.

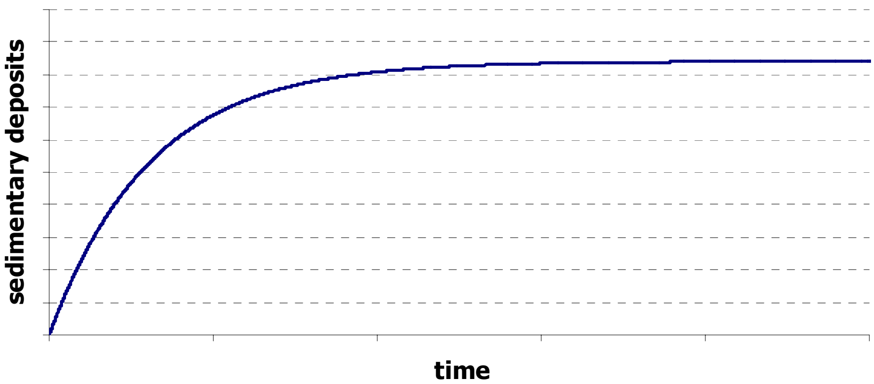

figure 4.2 Development of sedimentary deposits until equilibrium is reached

4.4 Expected results

- According to the hypothesis, equilibrium will develop, as the amount of particles that settle is equal to the amount of particles that resuspend per unit of time.
- Development of a layer of sediment only occurs as long as there is no equilibrium.
- Characteristics of settled particles are dependent on the average flow velocity and shear stress.
- There will be a relation between the hydraulic conditions and a developed equilibrium.

5 Design of the test rig

5.1 Introduction

As shown in figure 3.1, different processes contribute to the build up of sediment layers. To study the build up of a sediment layer as a result of particle load from the treatment plant under similar conditions as in a distribution system a test rig has been build. By using a test rig it is possible to monitor the build up during a longer period of time and to remove the sediment from the pipe for further analysis.

5.2 Initial lay out

5.2.1 Multiple pipe set up

The considered possibilities to measure the amount of sedimentary deposits in a pipe are:

- Taking out a pipe and determine the amount of stored sediment by filtration
- Monitor the ingoing and outgoing particle load and calculate the stored mass
- Measure the in situ build up of a sediment layer by shining light through the layer and measuring the transparency

As taking out a pipe and measuring the amount of stored sediment was the simplest way to realise in a test rig, this method was chosen.
The main problem of removing a (piece of) pipe is that it is impossible to continue the process of sediment build up after disturbing the sediment layer. To be able to determine the amount of sediment at different times, it is possible to use multiple parallel pipe sections fed by the same water source at the same time. As the hydraulic circumstances and the composition of the water is the same in every pipe section at every moment in time, the build up of a sediment layer should be the same in every pipe section. By removing the pipe sections at different times and analysing the sediment, the development of a sediment layer can be determined.

Another idea was to be able to use different kind of pipes to be able to do comparative experiments to determine the influence of processes like bed load transport. A basic unit of pipes would consist of three pipes:

- an unobstructed clean pipe, which will result in a normal build up of a sediment layer
- a pipe with an obstruction at the bottom, which should prevent particles from leaving the measuring section as bed load transport
- a pipe with a wall obstruction to prevent possible transport of particles along the wall surface of the pipe

An obstruction at the end of a pipe would prevent particles from leaving the pipe by near wall transport. An obstruction at the entrance of a pipe would prevent particles from entering the pipe by near wall transport.

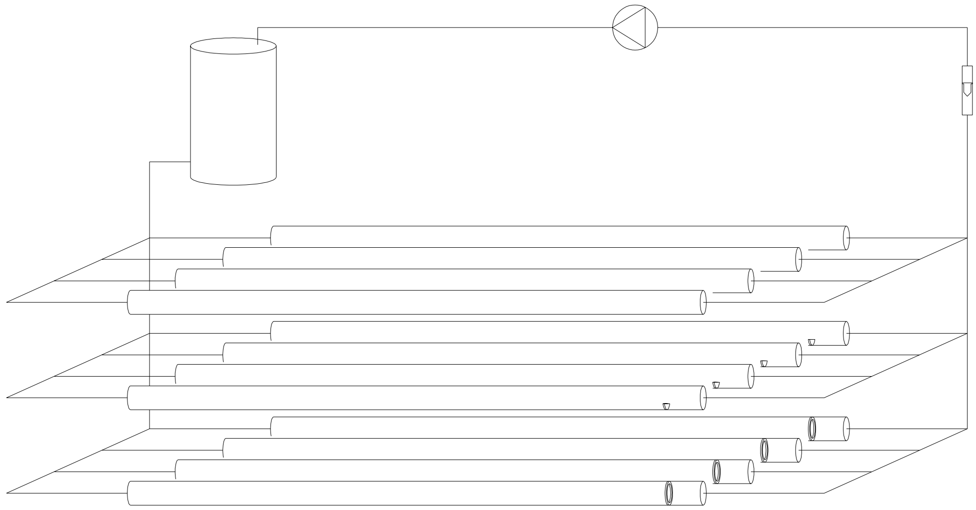

figure 5.1 Impression of a multiple pipe setup with different kind of wall obstructions

5.2.2 Scaling down

The problem with a multiple pipe set up was that by using more than one pipe the required volume flow would be rather high. Using 6 pipes with a diameter of 100 mm at a flow velocity of 0.1 m/s would mean a volume flow of 17 m^3 per hour.
To limit the volume flow, the pipe diameter would have to be scaled down. Using a diameter of 50 mm instead of 100 mm would mean a decrease in volume flow to 4.2 m^3 per hour. Using 25 mm would result in a volume flow of 1.1 m^3 per hour.
The problem with scaling down is that by decreasing the diameter the Reynolds number will drop. To be certain of turbulent flow the flow velocity would have to be raised. However, by raising the flow velocity the wall shear stress would become higher, which would eventually result in remobilisation of sediment.

To eliminate possible problems with shear stress and/or laminar flow, the decision was made to do a feasibility study with one pipe in realistic circumstances.

5.3 Single pipe setup

To explore the possibilities of a test rig a first design was made consisting of a single pipe. To approach a real life situation as much as possible the single pipe setup was made with a main pipe with an inner diameter of 100 mm. Although the multiple pipe test rig would be preferably operated in a flow through setup fed with normal drinking water, this single pipe setup will be a circulation system, to minimize the use of water. To operate the test rig under controlled circumstances, 'artificial' water will be used. This water will be normal drinking water with added particles. These particles may be kaolinite, sediment from a distribution system or iron flocks formed by dosing iron chloride.

The test rig consists of the following parts:

- The main pipe with an inner diameter of 100mm
- Additional piping
- A reservoir of 250 litres
- A pump
- Flow regulation by a diaphragm valve in combination with a rotameter (flow meter l/h)

The test rig is capable of flow velocities up to 0.25 m/s which are normal conditions for a distribution system. Higher flow velocities may be possible by adaptation of the test rig. The flow is driven by a constant head tank to be sure of a constant pressure.

figure 5.2 Single pipe test rig

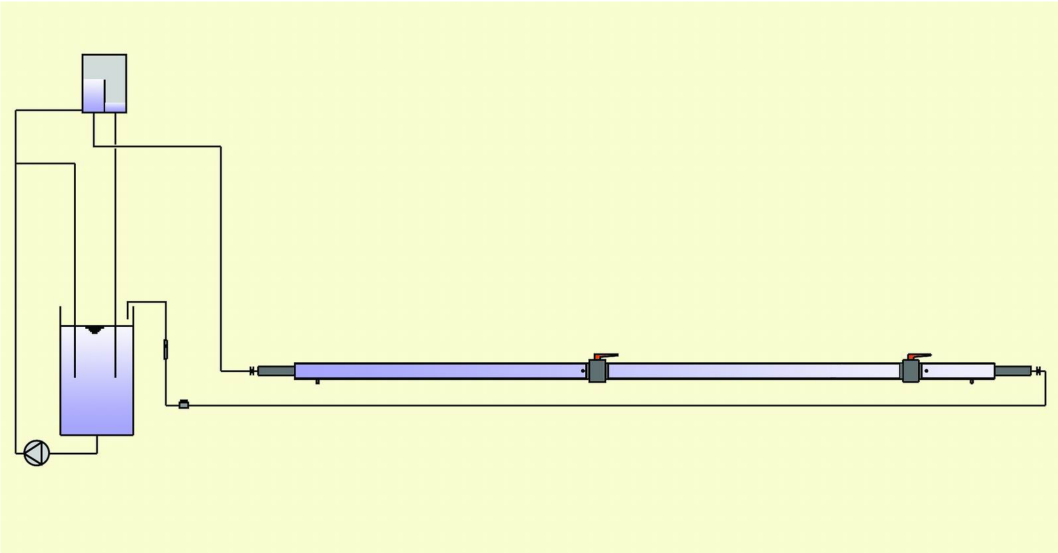

figure 5.3 Schematic drawing of the test rig

To reduce the costs of the test rig, some parts like the flow regulation and acrylic pipes were reused parts of an old test rig. These parts only needed some small adjustments. The pump was provided by the Section of Fluid Mechanics of the department of Hydraulic and Geotechnical Engineering.

5.3.1 Main pipe

To approximate a normal distribution pipe as much as possible the main pipe section has an inner diameter of 100 mm. The main pipe consists of three parts, all of them with an inner diameter of 100 mm. The first part has an inlet structure and a length of approximately 2 metres, to allow the flow to stabilise after the bend and the sudden increase in diameter from approximately 55 to 100 mm. The second part is a 'measuring section' which can be used to determine the amount of sediment. The third part is an outlet structure and is used to attach a turbidity meter to the pipe. The measuring section can be removed by closing two valves, and removing the section including the valves. Subsequently the sediment can be removed from the section. The first section and the measuring section are transparent giving the opportunity to visually observe the processes in the pipe.

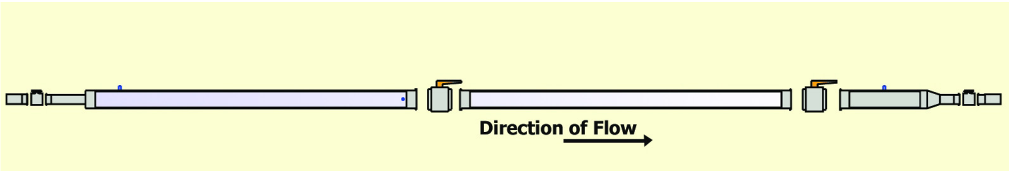

figure 5.4 Main pipe section

5.3.2 Additional piping

The rest of the piping consists of PVC pipes with an outer diameter of 50 or 63 mm (internal diameter depends on wall thickness) to allow flow velocities three to five times higher than in the main pipe. At these flow velocities the shear stress should be high enough to prevent particles from settling.

5.3.3 Reservoir

To be able to have a larger amount of sediment in the system without having to raise the particle concentration too much, a reservoir is used. Including the reservoir the total volume of the test rig is about 330 litres.
The reservoir is mixed by the recirculating water in the system. This prevents particles from settling in the reservoir.

figure 5.5 Reservoir of the test rig

5.3.4 Flow regulation

To regulate the flow a membrane valve is used in combination with two flow meters. Either one of the flow meters can be used depending on the desired flow velocity. The first one has a range of 0–2500 l/h, and the second has a greater capacity and will be used for flows up to 7000 l/h (the maximum capacity of the test rig in this setup).
At 7000 l/h the flow velocity in the measuring section is approximately 0.25 m/s.

figure 5.6 Flow regulation

6 Materials and methods

6.1 Introduction

The experiments carried out during this thesis project concentrate on two phenomena. The first one is the influence of the flow velocity and resulting shear stress on the development of a sediment layer and the second one is the influence of the composition of sediment (specific weight and size) on the build up of layers. Different particles have been used at different flow velocities to determine the relationship between flow velocity, particle source and the development of sediment layers. Particles that have been used are iron chloride, kaolinite, and sediment from a distribution system (from water flushing). Table 6.1 shows the different experiments.

Table 6.1 Particles used at different flow velocities

Flow velocity	$FeCL_3$	Kaolinite	Sediment from water flushing
0.06 m/s			
0.09 m/s			
0.14 m/s			

6.2 Sediment source

6.2.1 Iron chloride

Iron chloride is a chemical that is used as a coagulant. When added to water flocks are formed, which have a relative low density of approximately 1200 kg/m^3. These flocks have a relative low settling velocity and are assumed to be relatively easy to resuspend.
The main advantage of using iron chloride is that it is easy to dose and the effects of settling of iron flocks are easy to observe because of the colour of the flocks.
Because the pH value of the water is lowered when dosing iron chloride, a correction of the pH value is necessary. During the experiments the pH value is corrected to approximately 8.0 by dosing sodium hydroxide.

6.2.2 Kaolinite

Kaolinite is a common clay mineral, which for example is used in the ceramics industry. Kaolinite is inert and does not affect other chemical properties of the water (no pH correction is necessary).
Kaolinite is, in particle size and weight, similar to the particles found in sediment from drinking water distribution systems. figure 6.1 shows a comparison of the particle size distribution of kaolinite and of a drinking water sample.

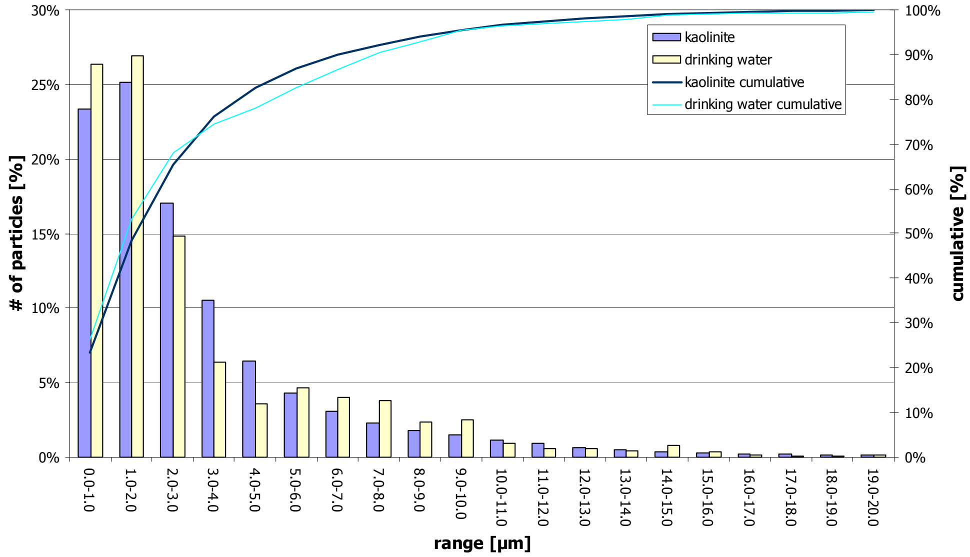

figure 6.1 Particle size distribution of kaolinite and a drinking water sample (particle count)

As can be seen from figure 6.1, 75% of the particles have a diameter smaller than 4 µm. However, when looking at the volume of the particles, the contribution of these particles to the total volume of particles is less than 10%. This is shown in figure 6.2.

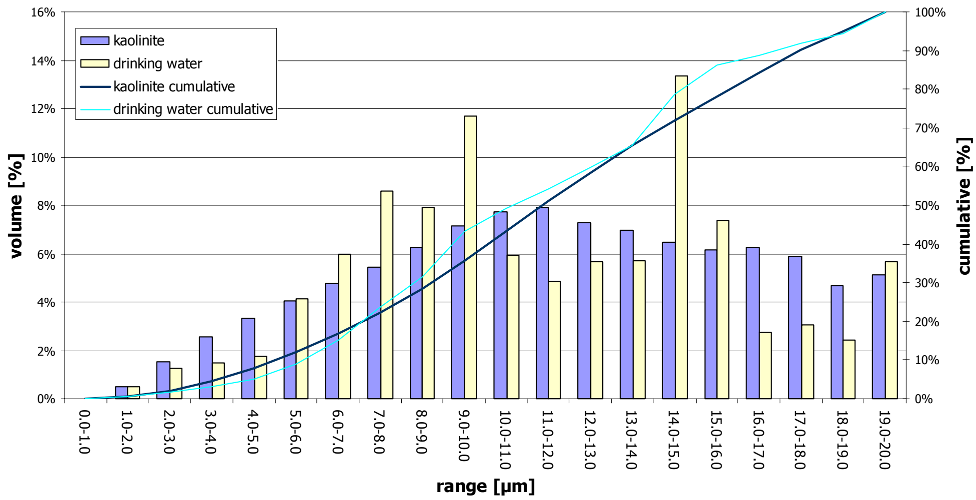

figure 6.2 Particle size distribution of kaolinite and a drinking water sample (volume)

6.2.3 Sediment

To examine if the results from experiments with iron chloride and kaolinite are comparable to a 'real life' situation, an experiment has been done with sediment collected from the drinking water distribution system of the city of Leusden (Utrecht). This sediment has been collected while conducting flushing actions in the distribution system. The high concentration part was taken shortly after opening a fire hydrant.

Although the sediment may consist for the largest part of inorganic material comparable to kaolinite, another part of the sediment consists of organic material and other particles. Because the composition of sediment may vary considerably between different sediment samples, experiments with these samples may be difficult to reproduce. The choice was made to use particles like kaolinite or iron flocks for most of the experiments, while experiments with sediment samples could be used for comparison of the results.

6.3 Measuring equipment

6.3.1 Turbidity

During the experiments the turbidity has been measured. It is assumed that the turbidity is representative for the particle load. This is supported by measurements done by van der Meulen (2004). This means that when the turbidity decreases with 10 percent, the particle concentration would also decrease with 10 percent.
Two different turbidity meters were used:

- Sigrist turbidity meter with a data logger
- Hach turbidity meter

Sigrist turbidity meter
A Sigrist turbidity meter was used to measure the turbidity in line with the test rig. Measurements were done with an interval of 5 minutes. The measuring range of the Sigrist is from 0 to 5 FTU.
Caused by the dosing of material at the beginning of the experiments, the turbidity may reach values of up to 18 FTU. Because of this, it was not possible to measure the turbidity during the first hours of an experiment, as long as the turbidity was above 5 FTU.

Hach turbidity meter
To be able to measure the turbidity in the range of 5 to 18 FTU a Hach turbidity meter was used. Samples were taken out of the reservoir, and analysed with this turbidity meter.
The Hach turbidity meter was also used as a control method to test the values given by the Sigrist turbidity meter. For example, a number of times the measuring cell of the Sigrist was fouled with organic material growing inside the measuring cell. By checking the Sigrist with the Hach, this problem was detected and could be solved by regular cleaning of the measuring cell.

It should be noted that the values given by the Sigrist and the Hach are not always the same. Both turbidity meters use a different measuring technique which could result in different values for the same sample. For example, when using kaolinite the measured value of the Hach would always be 30 to 40% higher than the measured value of the Sigrist turbidity meter.

6.3.2 Iron concentration

When conducting experiments with iron chloride as sediment source, it was also possible to measure the dissolved iron concentration in addition to the turbidity measurements. The corresponding measurements of turbidity and dissolved iron show a linear relationship, shown in figure 6.3. The measurements support the assumption of a linear relation between particle turbidity and particle load.

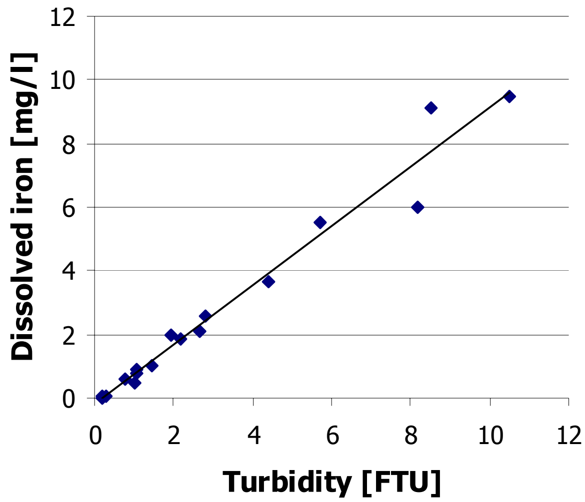

figure 6.3 Relationship between turbidity and dissolved iron concentration

6.4 Measuring strategies

6.4.1 Setup

As the test rig is operated in a recirculation setup, 330 litres of water will be used per experiment. To be certain that the water contains enough particles for the development of sediment layers, water with a high sediment load is used. Particles are added at the start of the experiment resulting in a high turbidity. As particles settle and sediment layers are formed, the turbidity will decrease. The turbidity is monitored and for experiments with iron chloride the dissolved iron concentration is measured from time to time.
The collected data is used to examine some phenomena that might influence the sedimentation process:

- The influence of the flow velocity on sedimentation
- The influence of the composition of sediment particles on sedimentation
- The influence of layer development on the sedimentation rate

The duration of most experiments will be less than one week. Because of this the process of biofilm development is considered to be of little influence on the development of sediment layers. As PVC and acrylic pipes are used for the test rig, corrosion can also be discarded as an element of the mass balance.

6.4.2 Experiments

A number of experiments have been done with different sediment types and at different flow velocities. All combinations of particles and flow velocities are

shown in Table 6.1. All experiments are done with normal drinking water with added particles to reach a high particle load. Particles are added at the beginning of each experiment. Iron chloride is dosed until a concentration of approximately 10 mg/l is reached, resulting in a turbidity of 10 to 12 FTU. Kaolinite is dosed until a turbidity of approximately 10 FTU is reached.
After dosing the particles the turbidity is checked with the Hach turbidity meter. As long as the turbidity is out of range of the Sigrist turbidity meter, the Hach turbidity meter is used to measure the turbidity. As the turbidity gets in range of the Sigrist, the Hach will be used to check the data of the Sigrist.
Each experiment is done until equilibrium is reached, with a maximum duration of 120 hours (5 days). The measuring data of experiments can be combined to study the influence of flow velocity or particle source on the sedimentation process.

6.4.3 Influence of flow velocity on sedimentation

To determine the influence of the flow velocity on the sedimentation of particles the following experiments are studied:

Table 6.2 Experiments to research the influence of the flow velocity on the sedimentation process

Flow velocity	particles
0.06 m/s	$FeCl_3$
0.09 m/s	$FeCl_3$
0.14 m/s	$FeCl_3$
0.06 m/s	Kaolinite
0.14 m/s	Kaolinite

Different experiments have been carried out with flow velocities of 0.06, 0.09 and 0.14 m/s and with iron chloride or kaolinite as sediment source.
It is expected that as the flow velocity increases the time until a state of equilibrium is reached will shorten. As is hypothesized a higher flow velocity should result in an increase of the amount of particles that resuspend while the amount of particles that settle per unit of time will stay roughly the same (according to Stokes' Law).

6.4.4 Influence of the composition of sediment on sedimentation

Sedimentation is also influenced by the composition of sediment. Particle size and weight are of influence on settling as well as resuspension of particles. While light organic material with a relative density of 1.2 has a relative low settling velocity and is easy to resuspend, heavier particles like sand or iron have a higher settling velocity and might be more difficult to resuspend. To study the differences between different particles the results of experiments with different particle sources are compared. In contrast to the first set of experiments the flow velocity was kept constant while three sorts of particles were used. These particles were iron flocks (by dosing iron chloride), kaolinite and sediment from a drinking water distribution system.

Table 6.3 Experiments to research the influence of the composition of sediment on the sedimentation process

Flow velocity	Particles
0.06 m/s	$FeCL_3$
0.06 m/s	Kaolinite
0.14 m/s	$FeCL_3$
0.14 m/s	Kaolinite
0.14 m/s	Sediment

6.4.5 Influence of layer development on sedimentation rate

When testing the test rig it appeared that sedimentation is influenced by the development of sediment layers on the pipe wall. There seemed to be a difference in the sedimentation rate for a clean pipe wall and a sediment covered pipe wall. As accumulation on the pipe wall increases, the sedimentation process after dosing new particles appears to be faster. When starting an experiment with a clean pipe wall the sedimentation rate seems to be lower.

To study this effect an experiment has been done with multiple doses of kaolinite. Starting with a clean pipe the system was not cleaned between doses. With each dose 10 grams of kaolinite was added to the system, resulting in further development of the sediment layer. The turbidity measurements were studied to determine a possible effect of the layer development on the sedimentation rate.

7 Sedimentation Resuspension Model (SRM)

7.1 Modeling sedimentation and resuspension

A model has been made to calculate the effect of settling and resuspension on the sedimentation process in pipes. The model is based on the hypothesis that particles settle and resuspend until a 'steady state' situation is reached. The main idea was that amount of sedimentary deposits in a pipe can be calculated from settling and resuspension of particles. The amount of sedimentary deposits would be the amount of settled particles minus the amount of resuspended particles.

The model calculates the mass of particles that settle when they pass the main pipe, in time steps equal to the residence time in the main pipe. To calculate the amount of settled particles during a time step, a 'Settlement Calculator' (spreadsheet made by Christian Kivit) is used. The settling velocity is calculated according to Stokes' Law, and using the systems geometry the residence time is calculated. From the settling velocity and the residence time the amount of settled particles per time step is calculated.

To take into account the influence of the reservoir, the particle concentration from the incoming flow is calculated from the particle concentration in the reservoir and the particle concentration of the outgoing flow of the previous step.

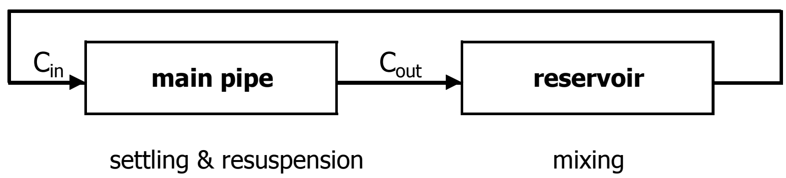

figure 7.1 Flow diagram of the model

In the model, resuspension is calculated with a resuspension factor which has to be given as input. The resuspension factor is the percentage of sedimentary deposits that resuspend per unit of time. Resuspension is calculated from the amount of sedimentary deposits present in the pipe.

The added value of this model is that for different kind of particles the sedimentation can be calculated according Stokes' Law and that the effect of resuspension can be seen for different values of the resuspension factor. From the calculated settling velocity and the resuspension factor a 'steady state' situation can be calculated as well as the sedimentation rate.

A more extensive description of the model is given in Appendix D.

7.2 Influence of the resuspension factor on sedimentation

In figure 7.2 the influence of different resuspension factors is illustrated. These are (from the top): 0.01%, 0.1% and 1%. It shows that with a resuspension factor of 1% equilibrium is reached in 6 hours, resulting in almost no development of sedimentary deposits.

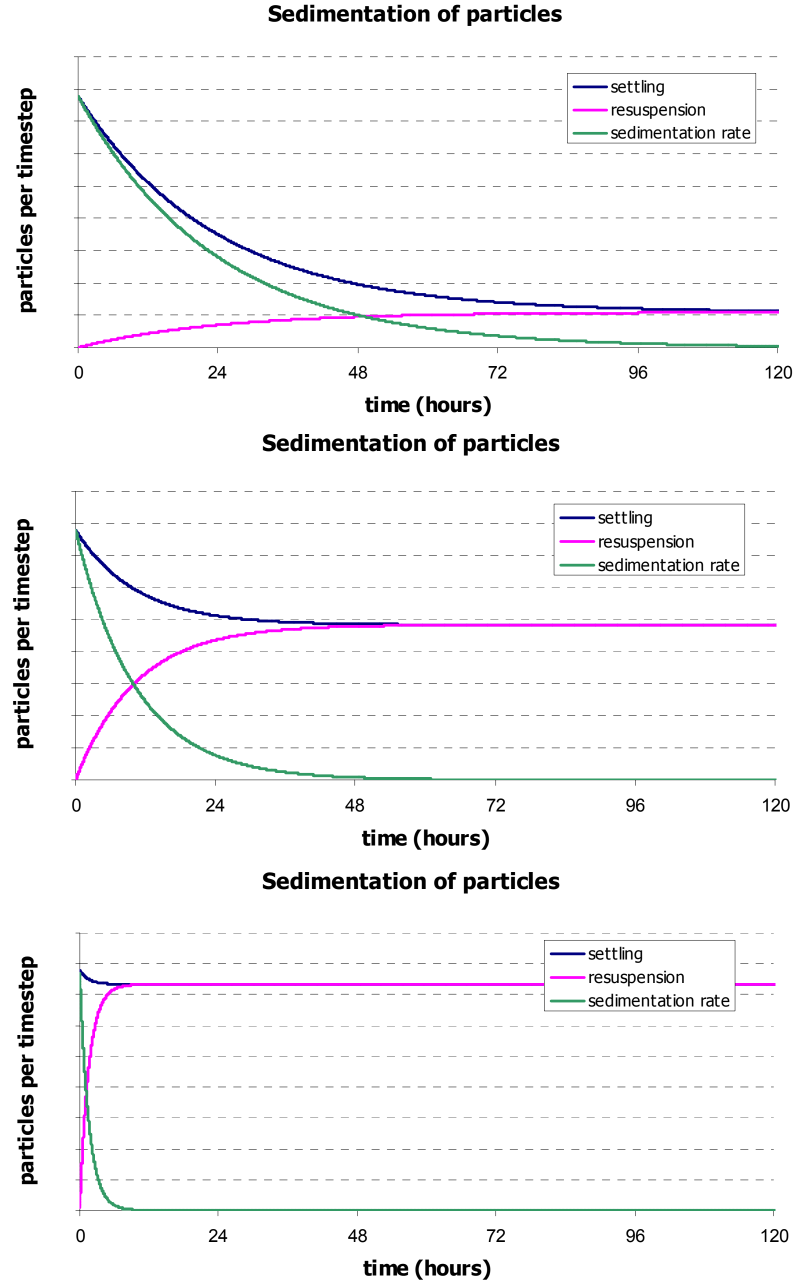

figure 7.2 Illustration of the influence of the resuspension factor on sedimentation

Parameters used are: T = 10°C; Particle size = 4 μm; Particle density = 2600 kg/m^3; Flow velocity = 0.06 m/s.
This results in a settling velocity of $1.07 \cdot 10^{-5}$ m/s and a Reynolds number of 4592

figure 7.3 shows the differences in the development of sedimentary deposits with different resuspension factors (0.01%, 0.1%, and 1%). All calculations are started with an amount of 10 grams of particles comparable to kaolinite (size, weight). With a resuspension factor of 0.01% approximately 85% of the particles will stay in the system as sedimentary deposits. At 0.1% this is about 40%, and at 1% this is less than 10%. This shows that the influence of the resuspension factor is considerable.

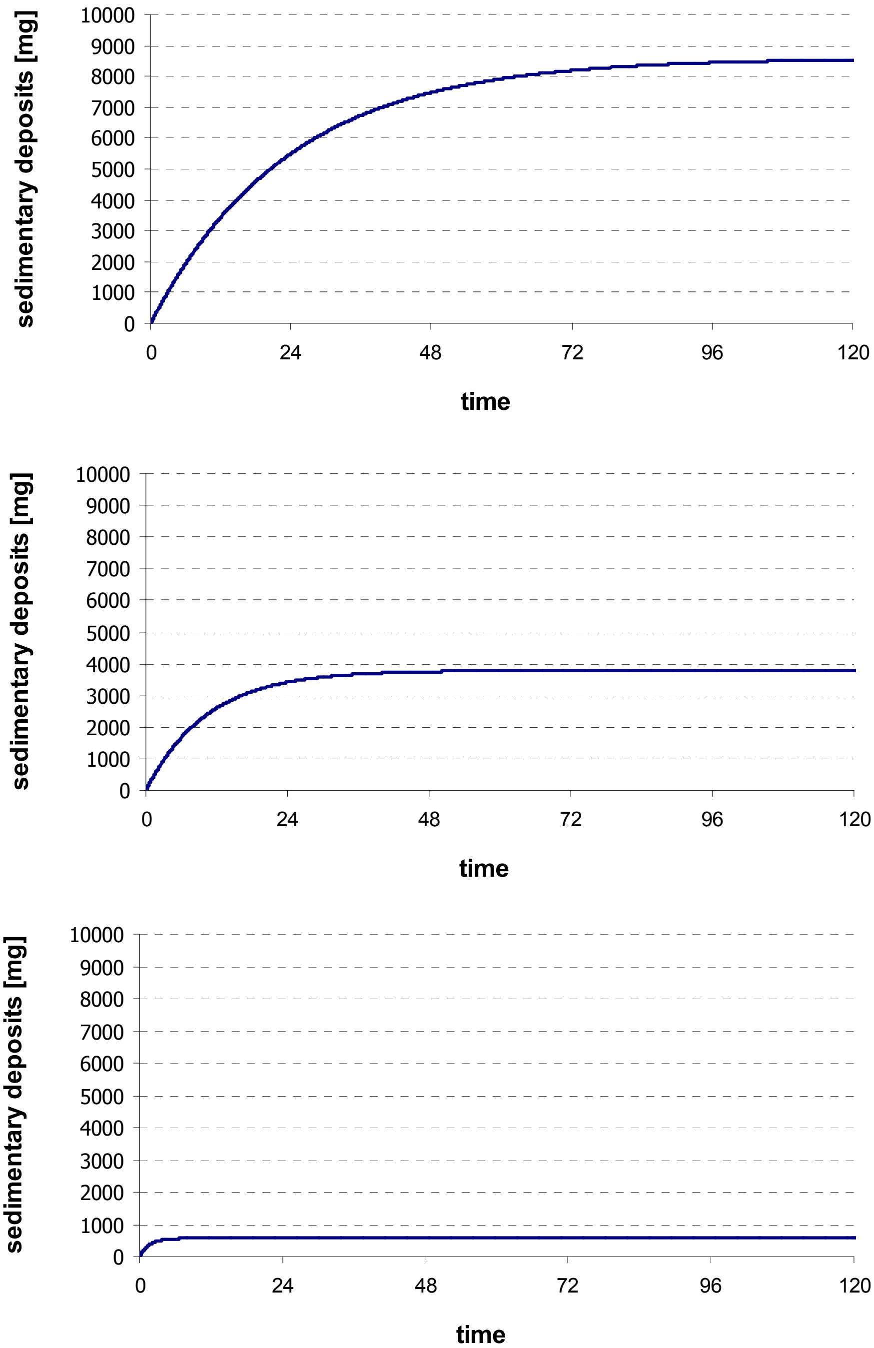

figure 7.3 Influence of resuspension factor on development of sedimentary deposits

7.3 Comparison of the model with experimental data

Comparing the model with experimental data will give an indication of the accuracy of the model and possibly the hypothesis. By adjusting the flow velocity, particle size and particle density the settling of particles can be calculated for different flow velocities and sediment sources. Resuspension of particles can be influenced by varying the resuspension factor.

The model can be fitted to the data by changing particle characteristics and the resuspension factor. Changing the particle characteristics influences the settling velocity of the particles. The primary effect of changing particle size and/or weight is that it influences the initial sedimentation rate. As at t=0 no sedimentary deposits are present there will be no resuspension. Therefore, the sedimentation rate at t=0 is directly related to the settling velocity of the particles. To fit the model to the steady state turbidity, the resuspension factor can be varied.

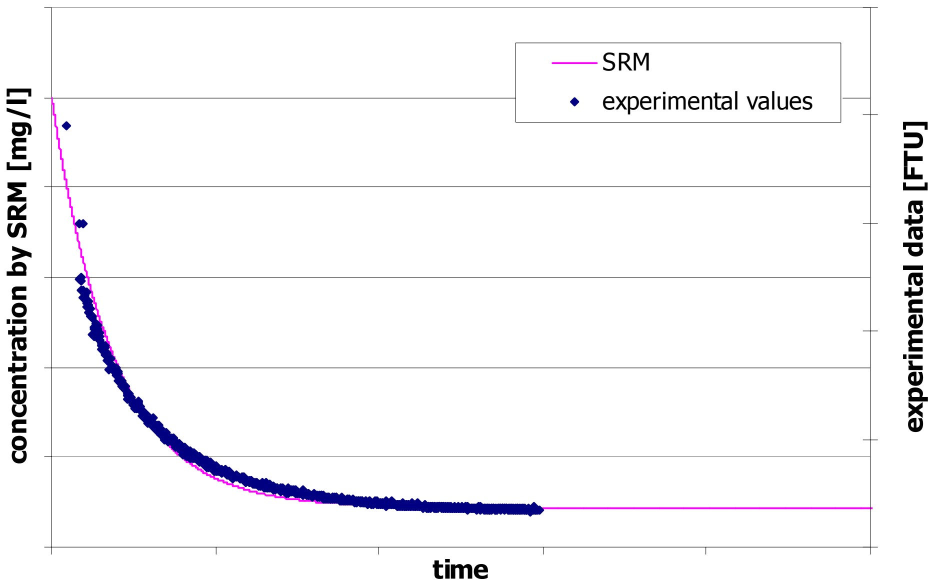

figure 7.4 Example of RSM fitted to experimental data

A comparison of the model with experimental data is made in paragraph 8.2.

8 Results

8.1 Visual observations

While carrying out the different experiments visual observations were made of the processes in the main pipe section and the rest of the system. Some of these observations gave insight in the development of sediment layers in the main pipe section and some other observations were linked to problems with the test rig.

8.1.1 Iron chloride

Characteristic of using iron chloride is that it affects the entire system. In time all the inner pipe walls (and especially the hoses) will get covered with a layer of iron flocks. This layer can be difficult to remove. Even after dosing acid to lower the pH, to dissolve the iron, the inner walls remain dirty. To clean the system it should be taken apart and cleaned manually.
It appeared that in the horizontal pipes as well as the vertical pipes and hoses, particles were attached to the wall. In the main pipe the influence of gravitational settling was visible, while in the vertical hoses wall effects may have resulted in attachment of iron flocks.
The development of sediment layers in the hoses may be the result of the formation of biofilm in these hoses. Research by van der Kooij (2002) shows that flexible hoses have the highest biofilm formation potential (BFP). The fact that the sediment in the hoses is difficult to remove might be explained by the attachment of these particles to a biofilm.

8.1.2 Layer development in the main pipe section

When conducting the first experiments with iron chloride at a flow velocity of 0.06 m/s, it was noticed that accumulation of particles was taking place mainly in the bottom half of the pipe. This means the main process of sedimentation is gravity induced.
When increasing the flow velocity to approximately 0.14 m/s layer development on the pipe wall also seems to occur in the top half of the pipe. However, the greatest amount of sediment appeared to be in the bottom half of the pipe. Fouling of the top half of the pipe could be caused by wall effects.

Pictures of the pipes after sedimentation at 0.06 m/s and 0.14 m/s are given in figure 8.1 and figure 8.2.


figure 8.1 Typical layer development with iron flocks (side view)
v = 0.06 m/s, T = 28°C, Re = 7142, τ = 0.015 N/m^2

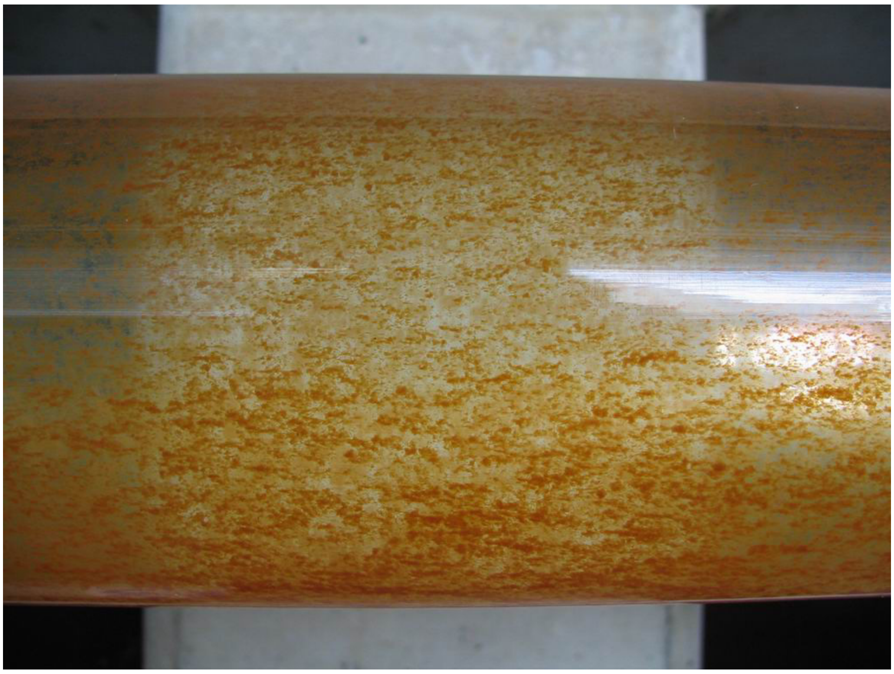
figure 8.2 Typical layer development with iron flocks (side view)
v = 0.14 m/s, T = 28°C, Re = 16667, τ = 0.066 N/m^2

When using kaolinite at flow velocities of 0.06 m/s and 0.14 m/s, layer development only occurred in the bottom half of the pipe. However, some differences in the sedimentation process were still visible. At a flow velocity of 0.06 m/s a large part of the sediment in the pipe seemed to form patches at the bottom of the pipe, as is shown in figure 8.3. This could imply that some kind of bed load transport took place. At a flow velocity of 0.14 m/s these patches were no longer visible. Sedimentation of particles took place along the entire bottom half of the pipe wall. In the top half of the pipe no particles were attached to the pipe wall. This is shown in figure 8.4.

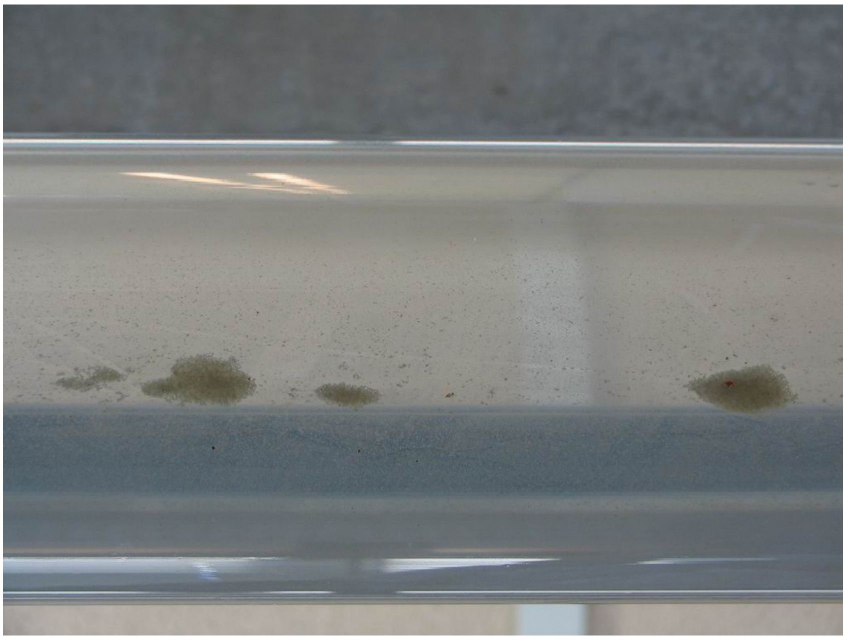

figure 8.3 Typical accumulation of kaolinite (picture taken from below)
v = 0.06 m/s, T = 28°C, Re = 7142, τ ***= 0.015 N/m²***

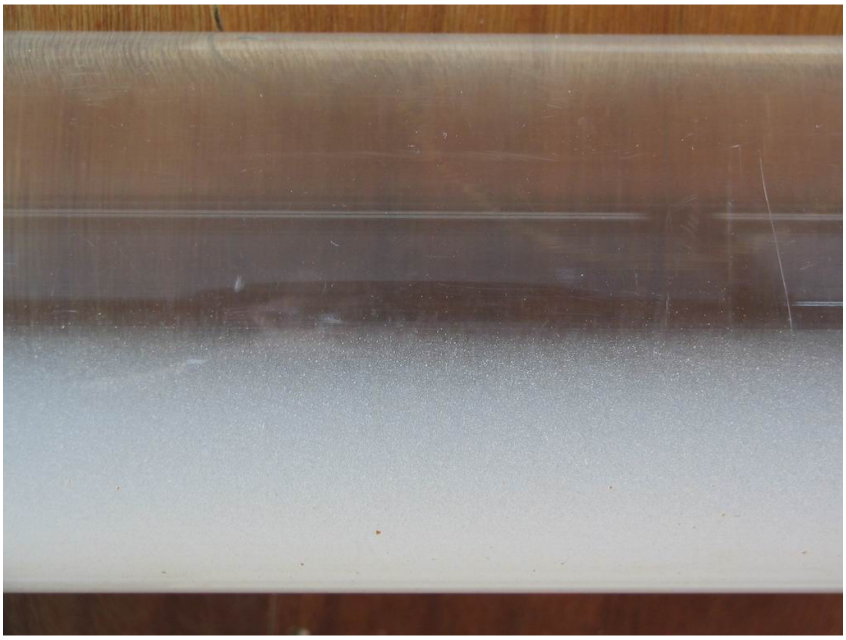

figure 8.4 Typical layer development with kaolinite (side view)
v = 0.14 m/s, T = 28°C, Re = 16667, τ ***= 0.066 N/m²***

8.1.3 Influence of air bubbles in the main pipe

Sometimes at the start of an experiment some fine air bubbles were visible on the top half of the pipe wall. These bubbles were caused by the filling of the system with water. When using iron chloride, small iron flocks attached to these bubbles, which resulted in fouling of the top half of the pipe.

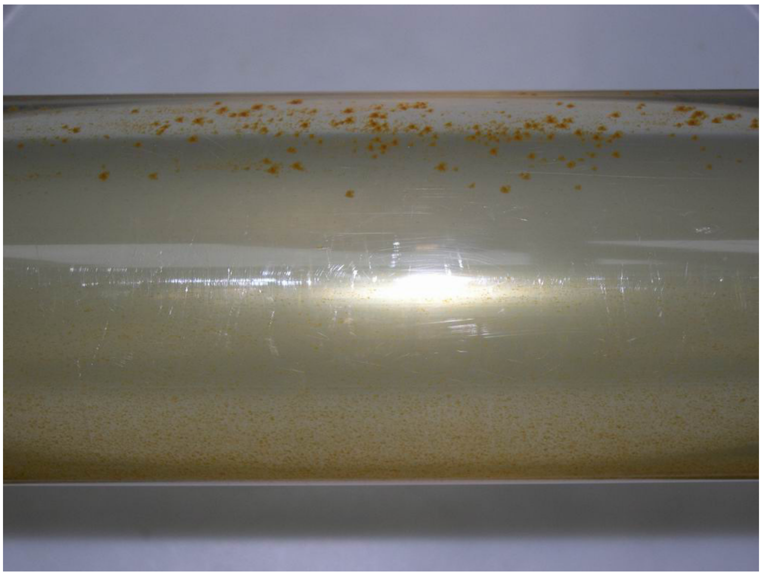

figure 8.5 Fouling of the top half of the pipe caused by air bubbles (side view)

8.1.4 Bed load transport

Bed load transport is the process of transportation of settled particles near the bottom of the pipe. Bed load transport of particles should be visible by moving particles near the bottom of the pipe.
During the experiments, movement of particles along the bottom was only visible when using iron chloride and at a low flow velocity of 0.06 m/s. Experiments with these characteristics show a relative large amount of bed load transport of iron flocks. These flocks accumulated in a drainage tap in the bottom of the pipe as shown in figure 8.6. Experiments with iron chloride at higher flow velocities did not show any visible bed load transport.

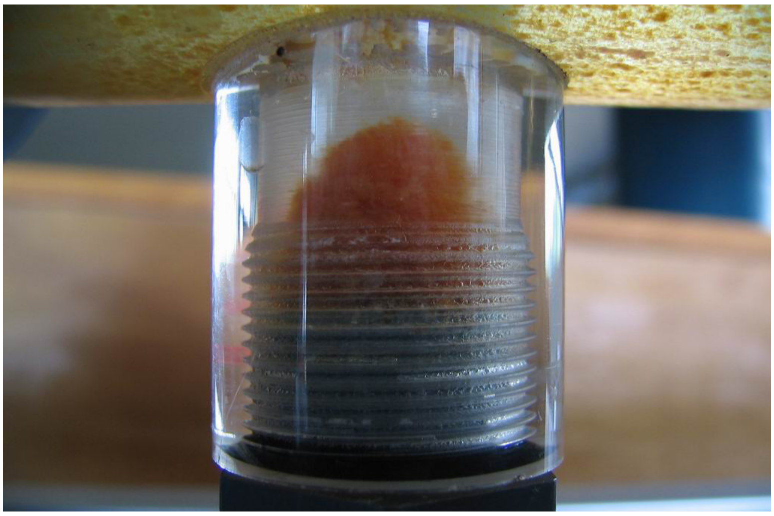

figure 8.6 Accumulation of sediment resulting from bed load transport

8.1.5 Cohesion of sedimentary deposits

During the first experiments it appeared that the cohesion of the deposits in the main pipe section was influenced by the flow velocity at which the sediment layer was formed. It showed that it was easier to resuspend the sediment at a flow velocity of 0.25 m/s when the deposits where formed at a flow velocity of 0.06 m/s than at a flow velocity of 0.14 m/s.

8.1.6 Entrance effect

During the experiments it showed that at the beginning of the pipe no sediment layer was formed. Because of effects caused by the sudden increase in diameter, particles are not able to settle. The first sediment in the pipe was found approximately 50 to 75 centimetres from the entrance.

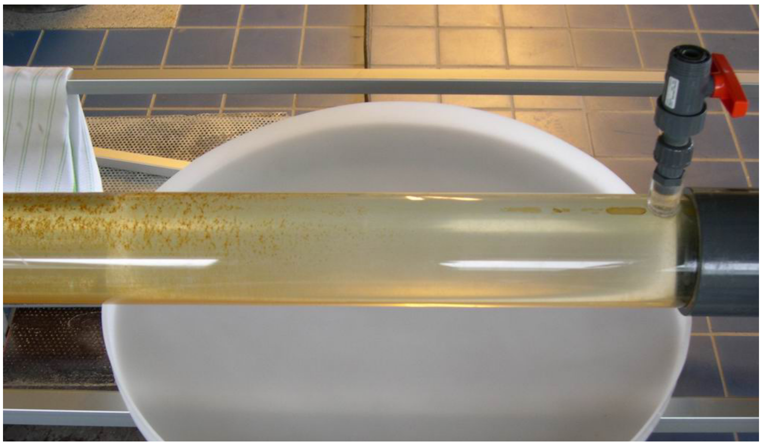

figure 8.7 Entrance effect

8.1.7 Air accumulation in hoses

When carrying out the first experiments a problem occurred with accumulation of air in one of the hoses. This problem was caused because the pressure loss through the flow regulation system was too high. The fact that the flow regulation was placed relatively high resulted in a negative pressure in the hose placed behind the flow regulation. Because of the high placement of the flow regulation system, air could accumulate in the hose behind this system. Because of the negative pressure it was impossible to remove the air by opening a valve. The problem was solved by lowering the flow regulation system. After lowering the flow regulation, problems with air accumulation no longer occurred. figure 8.8 shows the flow regulation setup after lowering.

figure 8.8 Setup after lowering the flow regulation

8.1.8 Electrostatic forces

To measure possible electrostatic forces between the water and the pipe wall surface, a small experiment has been done with Bram v/d Veer [Appendix C]. During this simple experiment no significant electrostatic forces were measured, but because of the course layout of the experiment, the existence could not be positively excluded.

figure 8.9 Bram v/d Veer looking for electrostatic effects

8.2 Influence of flow velocity on sedimentation

As described in chapter 6, experiments have been carried out to establish a relation between the flow velocity and the sedimentation process. The experiments can be divided in two groups:

- Experiments with iron chloride at flow velocities of 0.06, 0.09 and 0.14 m/s.
- Experiments with kaolinite at flow velocities of 0.06 and 0.14 m/s.

8.2.1 Iron chloride

figure 8.10 shows the results of the experiments with iron chloride.

- Remarkable is that at flow velocities of 0.09 and 0.14 m/s the initial sedimentation rate at the start of the experiments seems to be higher than at a flow velocity of 0.06 m/s.
- Another observation is that at 0.06 m/s the remaining turbidity is higher than the remaining turbidity at 0.09 m/s. Expected was that at a lower flow velocity the remaining turbidity would be lower.
- The sedimentation process at 0.14 m/s seems to lead to a higher 'steady state' turbidity than at 0.06 and 0.09 m/s.
- Remarkable about the experiment at 0.14 m/s is that in first instance a 'steady state' turbidity seems to be reached, but after reaching a value of approximately 2 FTU the turbidity seems to decrease linearly.

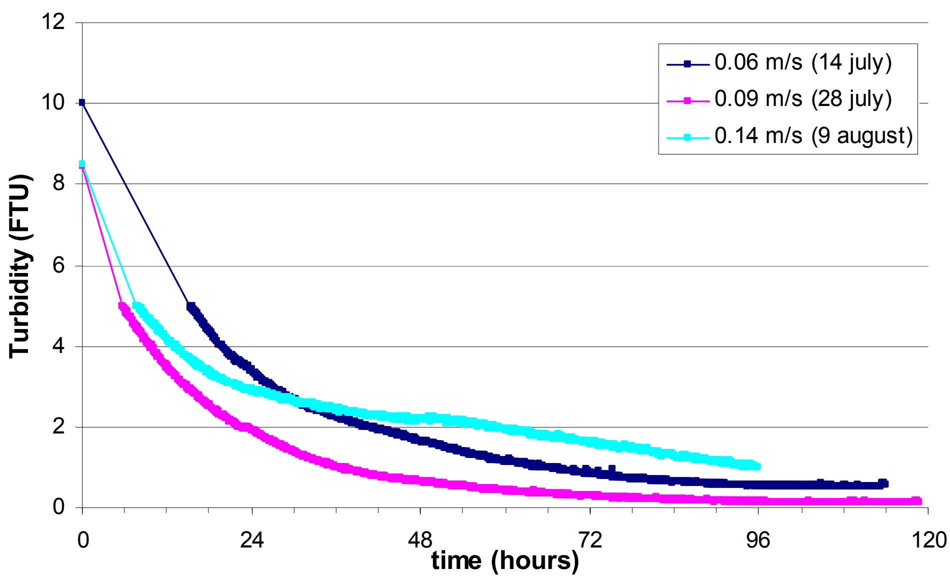

figure 8.10 Turbidity during experiments with iron chloride

Looking at the turbidity measurements of the different experiments with kaolinite it seems that the flow velocity is of influence on the sedimentation process. However, regarding the hypothesis, the data is not always as expected. For example, the 'steady state' turbidity is higher at 0.06 than at 0.09 m/s.

The question arises about the cause of the difference between these steady state turbidity values. A possible explanation is that, there may be another cause of a 'steady state' turbidity. For example, it may be possible that there is a part of the particles that does not settle at all.

8.2.2 Comparison of experimental data to SRM

A comparison has been made between data from the experiments with iron chloride and the sedimentation resuspension model. Sedimentation in the additional piping is discarded in the model. Because of this, the model is fitted first to the data of the experiment with the highest flow velocity, which would have the least amount of sedimentary deposits in the additional piping. At 0.14 m/s in the main pipe section, the flow velocity in the additional piping would be between 0.5 m/s and 0.8 m/s. It is assumed that sedimentation does not occur at these velocities. figure 8.11 shows the experimental data with the fitted model. The model fitted best with a particle size of 12.5 μm and a resuspension factor of 0.04%. The density of the flocks was assumed to be 1200 kg/m^3.

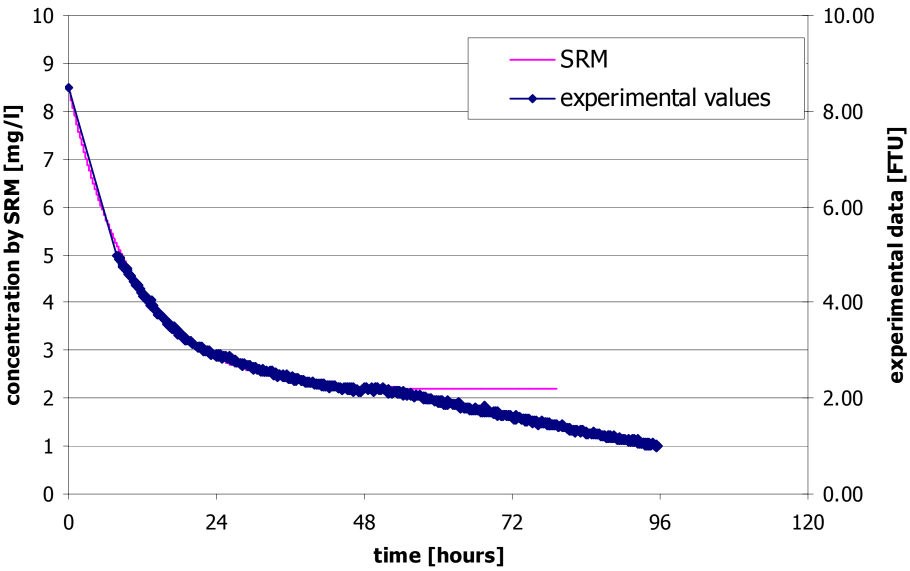

figure 8.11 FeCl3 and SRM
(v=0.14 m/s; resuspension factor=0.04%; particle size=12.5 μm)

It is assumed that the size of the iron flocks is defined by the mixing in the reservoir and the mixing energy of the pump. Therefore, the flock size would be the same at al flow velocities. Because of this the flock size for the experiments at 0.09 m/s and 0.06 m/s is chosen to be 12.5 μm as well. The model will be fitted to these experiments by varying the resuspension factor.

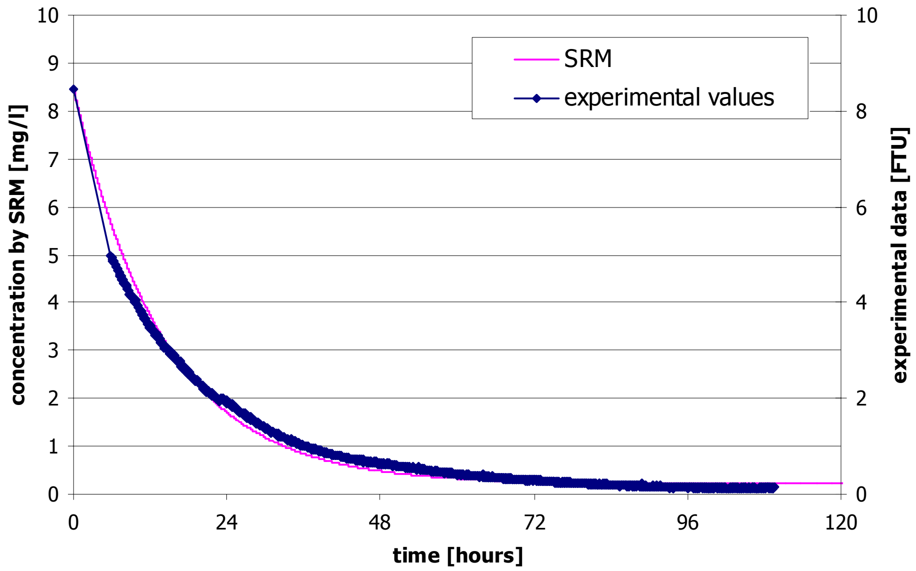

figure 8.12 FeCl3 and SRM
(v=0.09 m/s; resuspension factor=0.003%; particle size=12.5 µm)

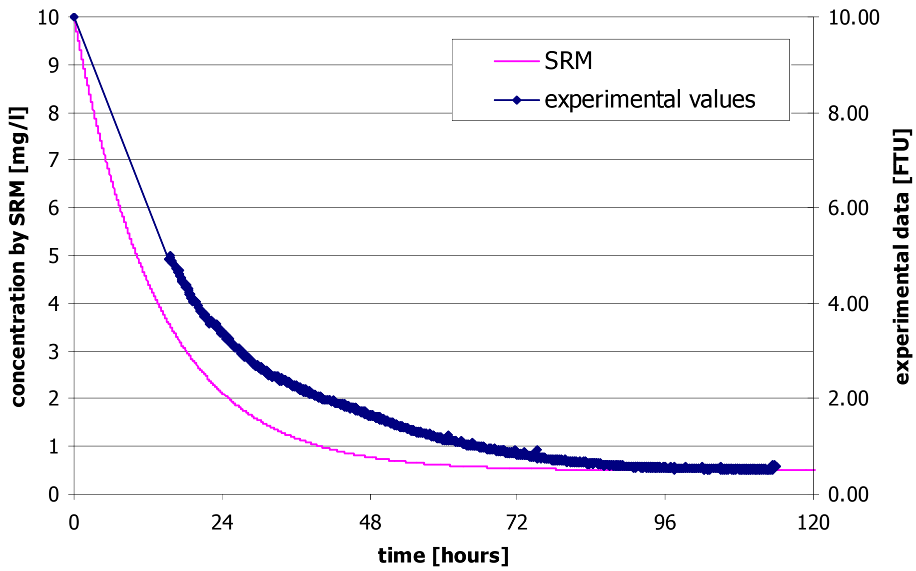

figure 8.13 FeCl3 and SRM
(v=0.06 m/s; resuspension factor=0.006%; particle size=12.5 µm)

figure 8.12 and figure 8.13 show the model fitted to the experimental data for the experiments at 0.06 m/s and 0.09 m/s. It seems that the initial sedimentation rate of the experiment seems slightly higher at 0.09 m/s. This would be the result of a higher settling velocity.
The experiment at 0.06 m/s (figure 8.13) shows a lower sedimentation rate at the start of the experiment, suggesting a lower settling velocity. This may be caused by a difference in the flock size or an influence of the flow velocity on the settling velocity. If the flow velocity influences the settling velocity this would mean Stokes is not applicable for the calculation of the settling velocity.

8.2.3 Kaolinite

When looking at figure 8.14 similar observations can be made for the experiments with kaolinite as for the experiments with iron chloride:

- As with iron chloride, the sedimentation rate at the start of the experiment is higher at a flow velocity of 0.14 m/s. This is in contrast with the expectation that the sedimentation rate would be higher at a lower flow velocity.
- The remaining turbidity seems to be higher at 0.14 m/s than at 0.06 m/s. This is as expected because, according to the hypothesis, the state of equilibrium between deposition and resuspension of particles should be higher at higher flow velocities.

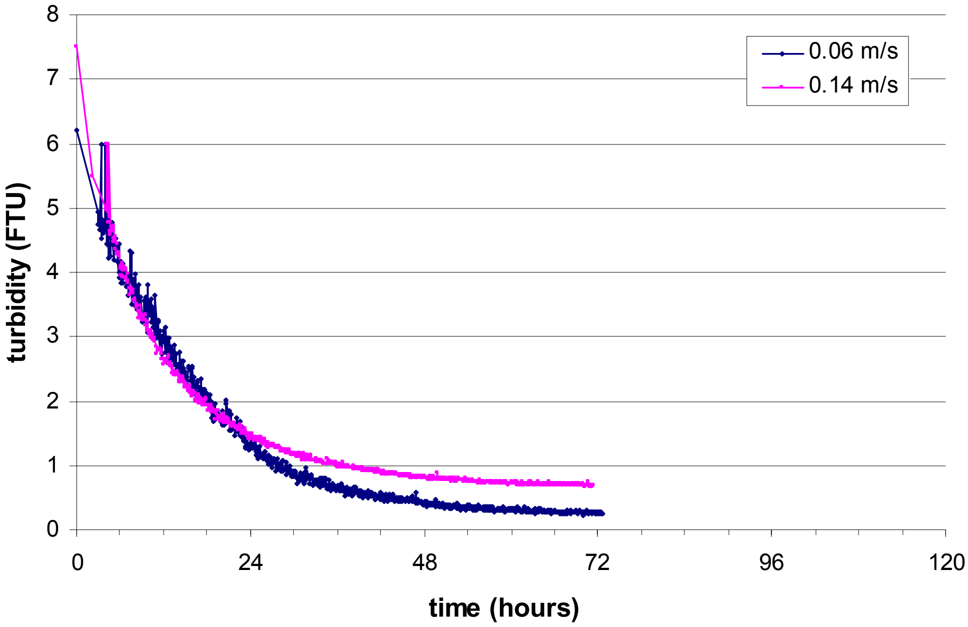

figure 8.14 Turbidity during experiments with kaolinite

The results of the experiments with kaolinite seem to correspond better with the hypothesis than the experiments with iron chloride, as the 'steady state' turbidity is higher at a higher flow velocity. As with iron chloride the initial sedimentation rate is higher at 0.14 m/s.

8.2.4 Comparison of experimental data with SRM

Similar to iron chloride, the model is also compared to the experimental data of the experiments with kaolinite. The model was first fitted to the experiment with the highest flow velocity. The particle size resulting from the fitting at 0.14 m/s was used for the fitting of the model to the experiment at 0.06 m/s. The results of the fitting of the model at 0.14 m/s and 0.06 m/s are shown in figure 8.15 and figure 8.16.

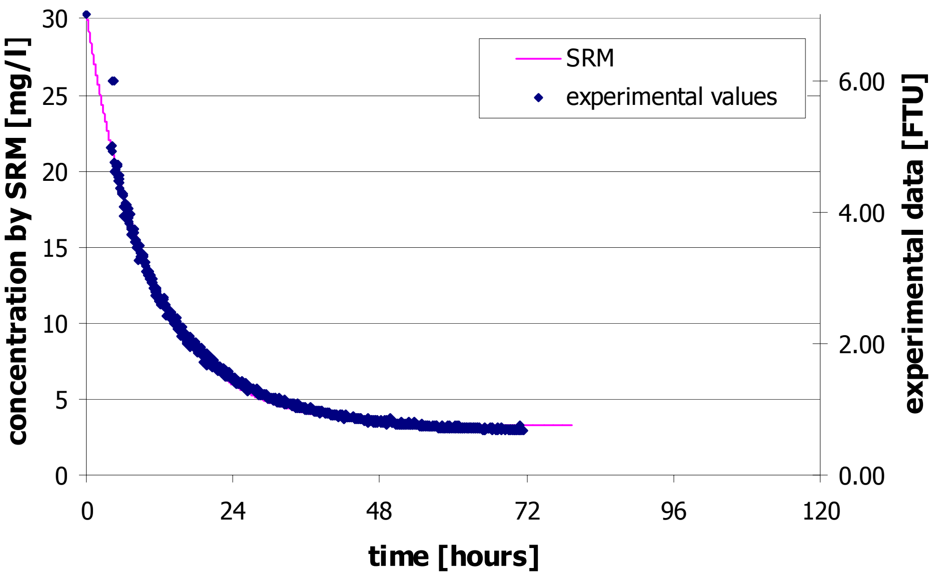

figure 8.15 Kaolinite and SRM
(v=0.14 m/s; resuspension=0.017%; particle size=4.9μm)

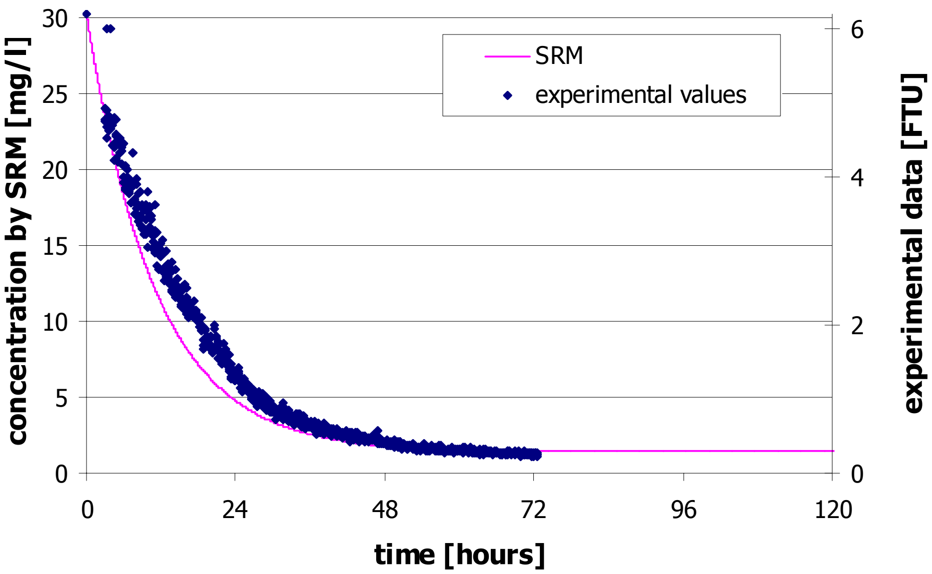

figure 8.16 Kaolinite and SRM
(v=0.06 m/s; resuspension=0.007%; particle size=4.9μm)

Unlike the results with the experiments with iron chloride, the fitting of the model to the experimental data of the experiments with kaolinite show better results. Although there are differences between the experiments at 0.06 m/s and 0.14 m/s, these differences are smaller than with iron flocks. The gradient of the model at t=0 does not differ that much from the experimental data. This means the settling velocity at 0.06 m/s is comparable to the settling velocity at 0.14 m/s. There seems to be no influence of the flow velocity on the settling velocity.

8.3 Influence of composition of sediment on sedimentation

Similar to differences in flow velocity, the composition of sediment could also be of influence on the sedimentation process. To determine this influence a number of experiments with different sorts of particles have been carried out under the same circumstances. These experiments can be divided in two groups:

- Experiments at 0.06 m/s:
  Two experiments have been done at this flow velocity. One with iron chloride and one with kaolinite.
- Experiments at 0.14 m/s:
  Three experiments have been done. The first two have been done with iron chloride and kaolinite. For the third experiment, sediment from the distribution system of Leusden has been used (6.2.3).

8.3.1 Flow velocity of 0.06 m/s

In figure 8.17 the results are shown of the experiments at 0.06 m/s.

- As can be seen the sedimentation rate of kaolinite is slightly higher than the sedimentation rate of iron chloride.
- Also the 'steady state' turbidity is slightly higher for iron chloride than for kaolinite. Equilibrium is reached first for kaolinite and later for iron chloride.

Both observations can be explained by the difference in density of the particles. As kaolinite is heavier than iron flocks, kaolinite particles are expected to have a higher settling velocity. The resuspension of particles with a higher density will be more difficult which explains the lower 'steady state' turbidity for kaolinite.

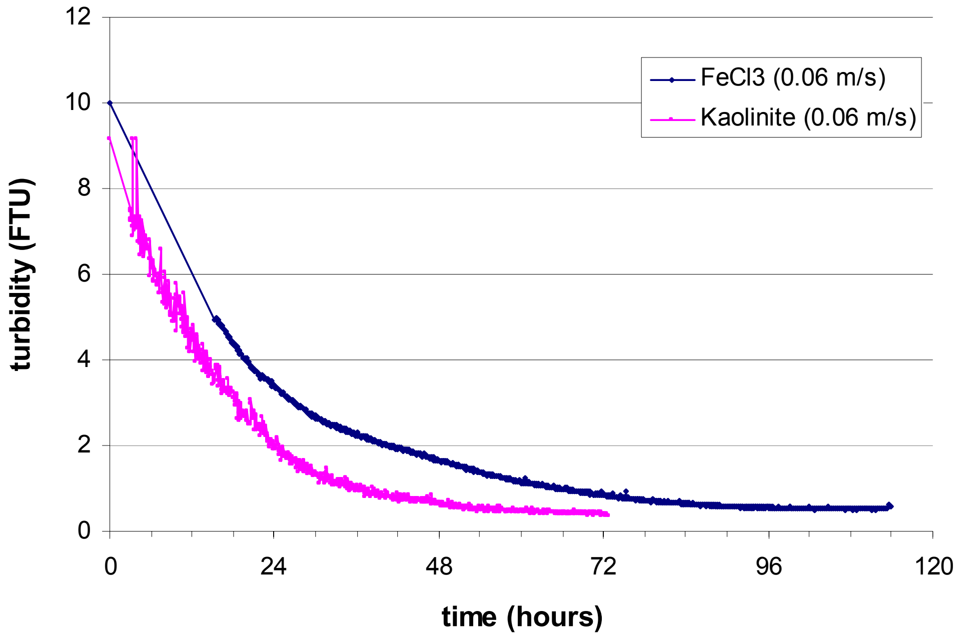

figure 8.17 Turbidity during experiments at 0.06 m/s

8.3.2 Flow velocity of 0.14 m/s

Shown by figure 8.18 is the turbidity during experiments at a flow velocity of 0.14 m/s. As can be seen the values of the experiment with sediment from Leusden are relative low. This is caused by the lower initial concentration of particles in the water.

- As with the experiments at 0.06 m/s, kaolinite has a higher sedimentation rate than iron chloride.

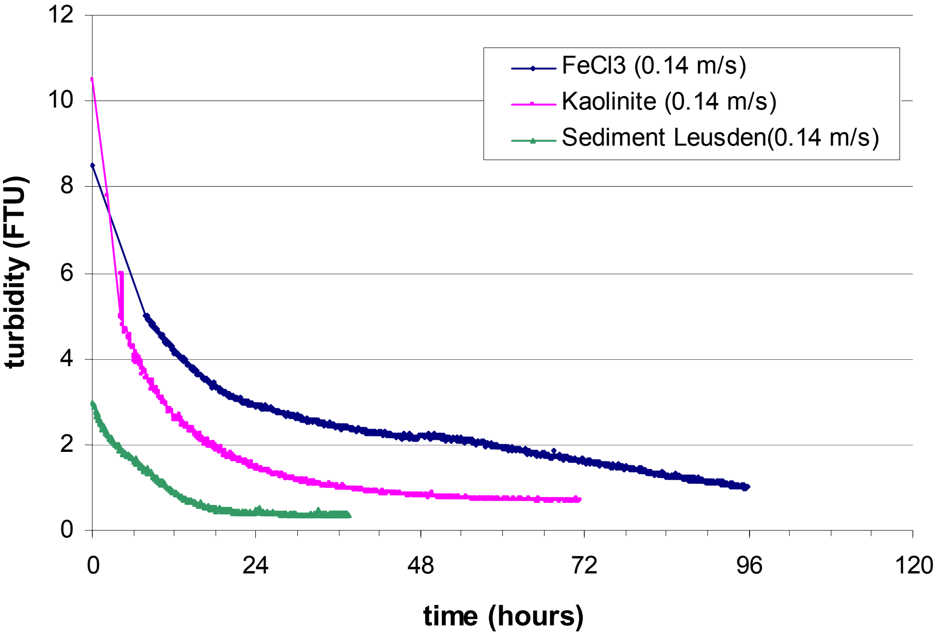

figure 8.18 Turbidity during experiments at 0.14 m/s

figure 8.19 shows the measurements of the turbidity lower than 3 FTU. By showing only these values a better comparison can be made between the different particles. The measurements show that iron chloride has the lowest sedimentation rate followed by kaolinite and the sediment sample.

The sediment sample from Leusden has the highest sedimentation rate. This can be explained by the fact that the sample is taken from a fire hydrant. It is assumed that by the sudden opening of the fire hydrant a lot of heavy particles near the fire hydrant were resuspended. This may heave resulted in a relative high concentration of relatively large and heavy particles in the sediment sample. Fact is that these particles do originate from the distribution system.

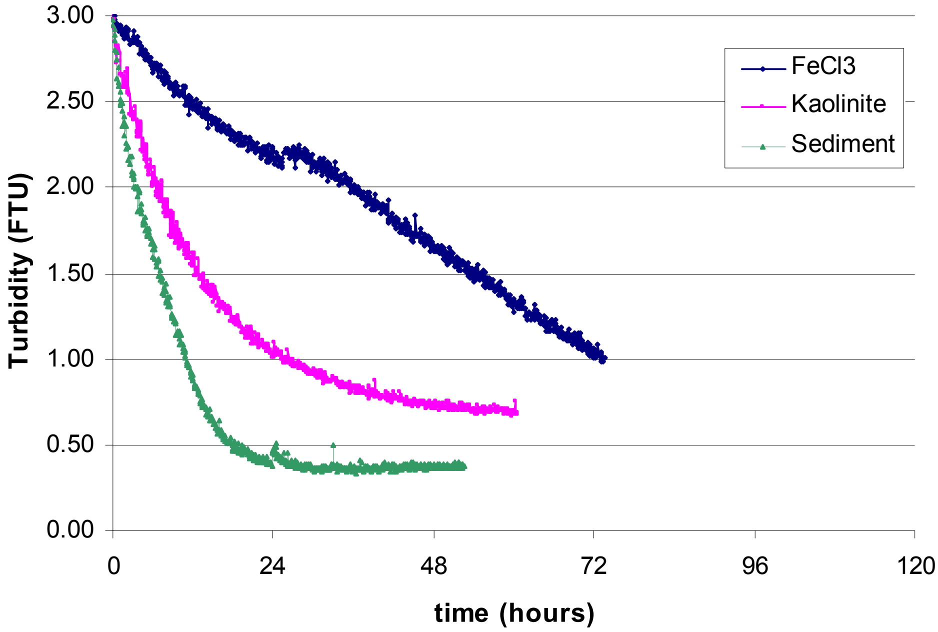

figure 8.19 Sedimentation at 0.14 m/s for turbidity lower than 3 FTU

Dividing the values of the turbidity by the corresponding maximum value at t=0, results in a non-dimensional concentration. figure 8.20 shows that by representing the data as a non-dimensional concentration, the graphs of kaolinite and the sediment sample show a number of similarities. First, the gradient of both graphs at the beginning of the experiment is nearly the same. And second, both graphs seem to reach equilibrium after approximately 90% of the particles have settled.

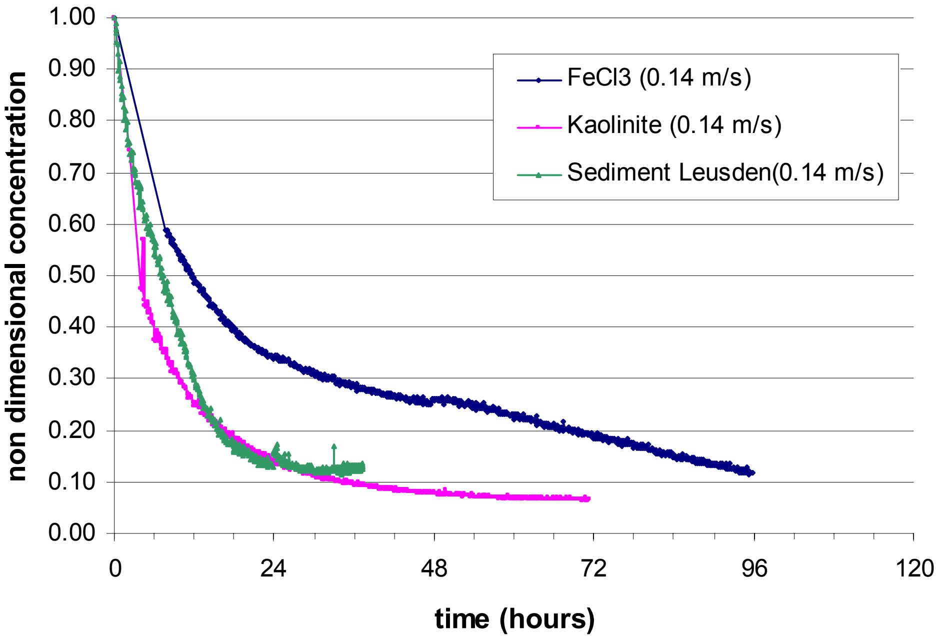

figure 8.20 Non-dimensional concentration during experiments at 0.14 m/s

8.4 Influence of initial sedimentary deposits on sedimentation

To study the effects of accumulated sediment on the sedimentation process an experiment has been done with recharging the sediment load after sedimentation of a previous dose.
This experiment consists of the following steps:

- Start of the experiment with a clean pipe. Flow velocity is 0.14 m/s.
- Dosing particles to the system (approximately 10 grams of kaolinite)
- After reaching a state of equilibrium new particles are dosed.
  The pipe wall is now fouled, thus any influence of accumulated sediment should be measured.
- The previous step is repeated for two more times.

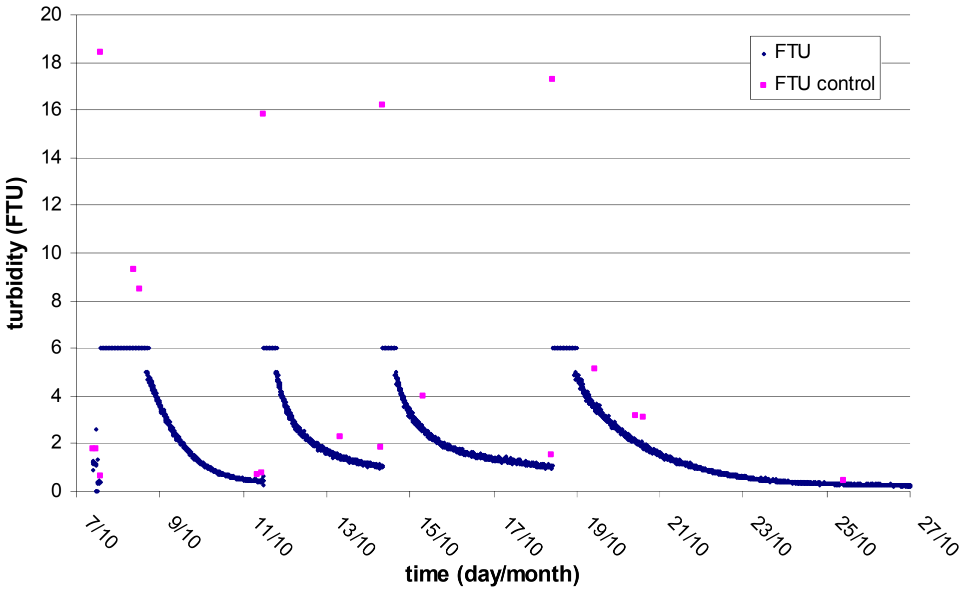

figure 8.21 Multiple doses of kaolinite

A visualization of the turbidity measurements during the experiment is given in figure 8.22.
The measurements of the turbidity show an increase of the sedimentation rate between the start of the experiment with a clean pipe (after the first dose) and the following doses. To make the difference more visible the graphs of the different doses are put in one figure, each dose starting at t=0.

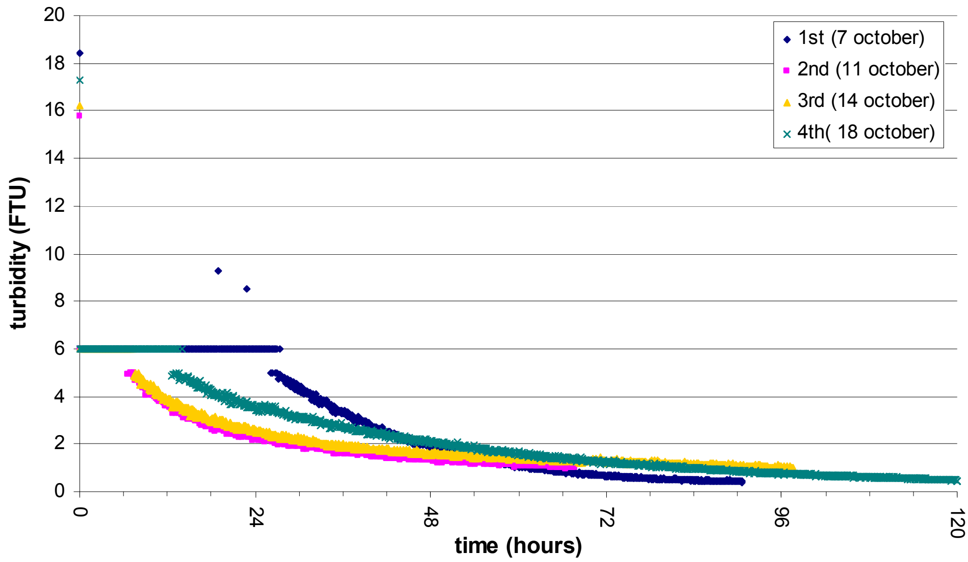

figure 8.22 Sedimentation for different successive doses of kaolinite

figure 8.22 shows the differences in sedimentation rate after each dose. When looking at the time it takes for each graph to reach a turbidity of 5 FTU, it shows that for the first dose (in a clean pipe) it takes more than 24 hours. The second and the third dose only take about 6 hours to reach 5 FTU. The fourth dose shows a lower sedimentation rate and reaches 5 FTU after 12 hours, which is still considerably faster than the sedimentation process after the first dose.

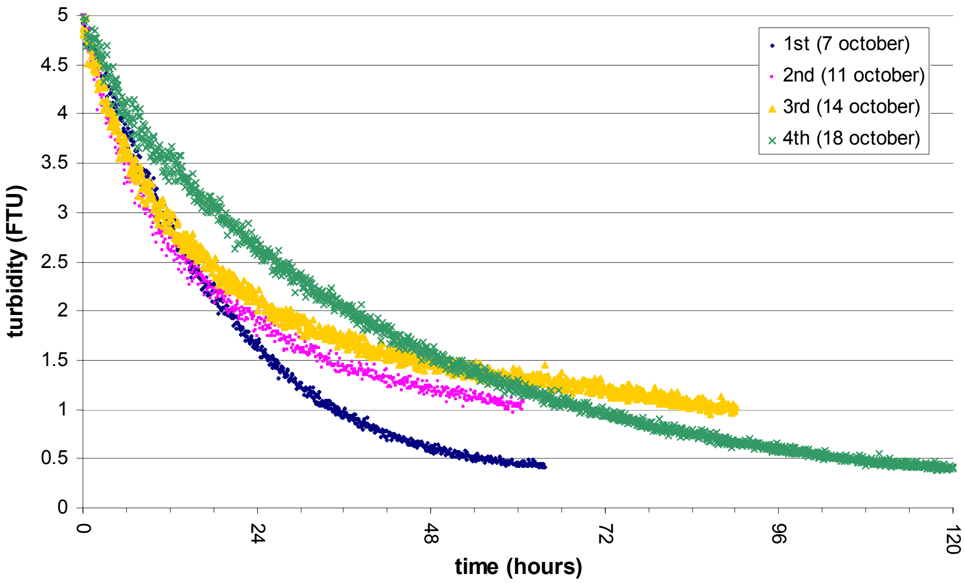

figure 8.23 Sedimentation for different successive doses of kaolinite [from 5 FTU]

However, when looking at the data for measurements of 5 FTU and lower, another picture is given. As is shown in figure 8.23, the gradient of the

graphs for the first three doses is practically the same at a turbidity of 5 FTU, but the gradient of the 4^{th} dose is lower.
Comparing the gradient of the graphs at 24 hours shows the sedimentation rate at this time decreases with each dose. The gradient of the first dose at 24 hours is higher than the gradient of the 2^{nd} dose. The gradient of the 3^{rd} dose is slightly lower than the gradient of the 2^{nd} dose. This can be the effect of an increased amount of resuspension, as more particles are added to the system.
An explanation for the differences in sedimentation rate between a clean pipe and a pipe with accumulated sediment might be that the roughness of the pipe wall surface changes as a sediment layer is formed. This may result in changes in the hydraulic conditions in the pipe.

An explanation for the unexpected results after the fourth dose can not yet be given. A possible explanation may be the influence of biofilm growth in the system, or the influence of sediment bed transformations.

8.4.1 Comparison with SRM

Simulation of the multiple doses with SRM shows an increase of the 'steady state' turbidity with every dose. For every dose the same particle size (4.9 µm) and the same resuspension factor (0.017%) was used. As can be seen in figure 8.24, the results from the model are different than the experimental data. The experimental data shows a decrease in the initial sedimentation rate with each dose. Also, the experimental data does not show the same increase in 'steady state' turbidity as the model.

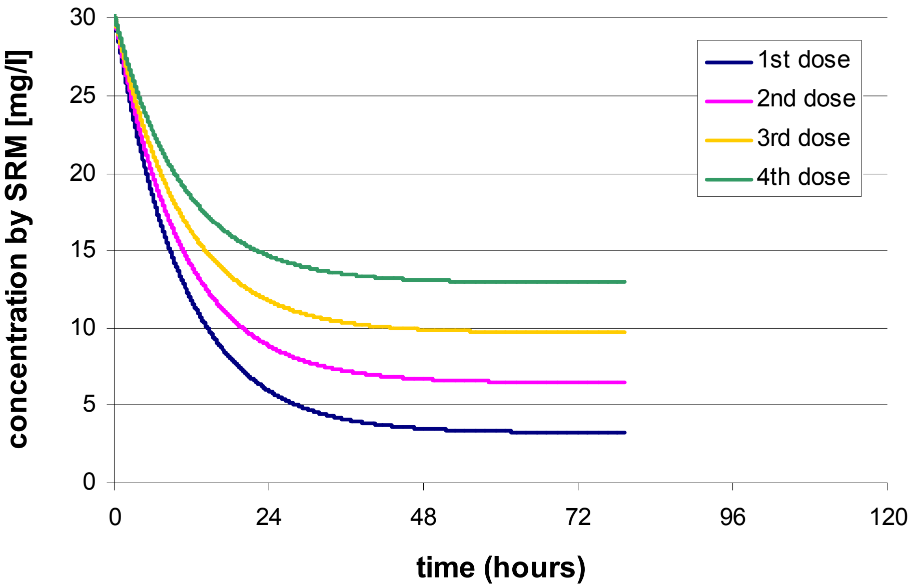

figure 8.24 Simulation of multiple doses with SRM

8.5 Sediment bed transformation

One of the processes that occurred during the last experiment with kaolinite was that a transformation of the sediment bed took place, as is shown in figure 8.25. At first the kaolinite settled along the entire bottom half, but as time passed by the sediment shifted to the bottom of the pipe. This transformation of the sediment bed might have contributed to the unexpected measurements during the experiment with multiple doses of kaolinite (paragraph 8.4).

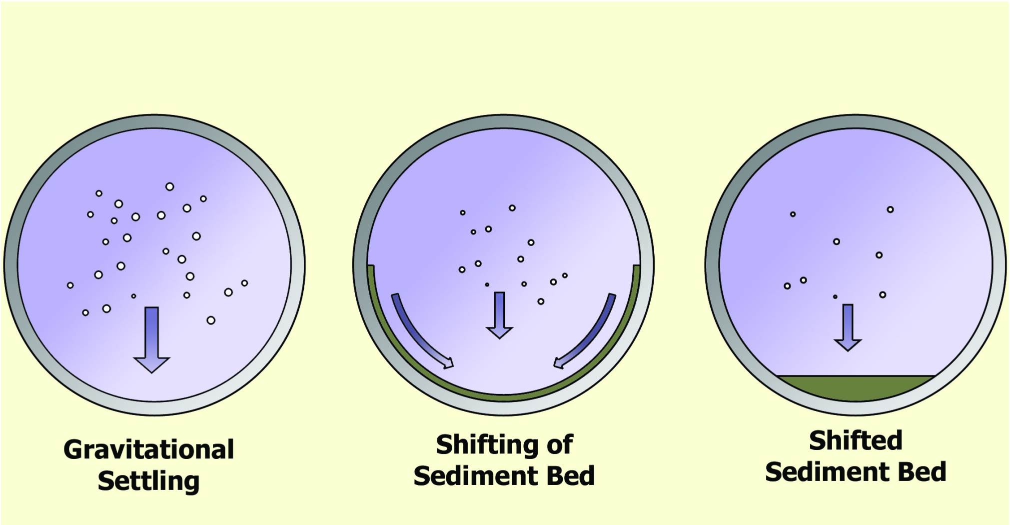

figure 8.25 Transformation of the sediment bed

An explanation could be that after reaching a certain thickness, the strength of the layer decreases, resulting in a remobilisation of the sediment. After remobilisation the kaolinite shifts to the bottom of the pipe.

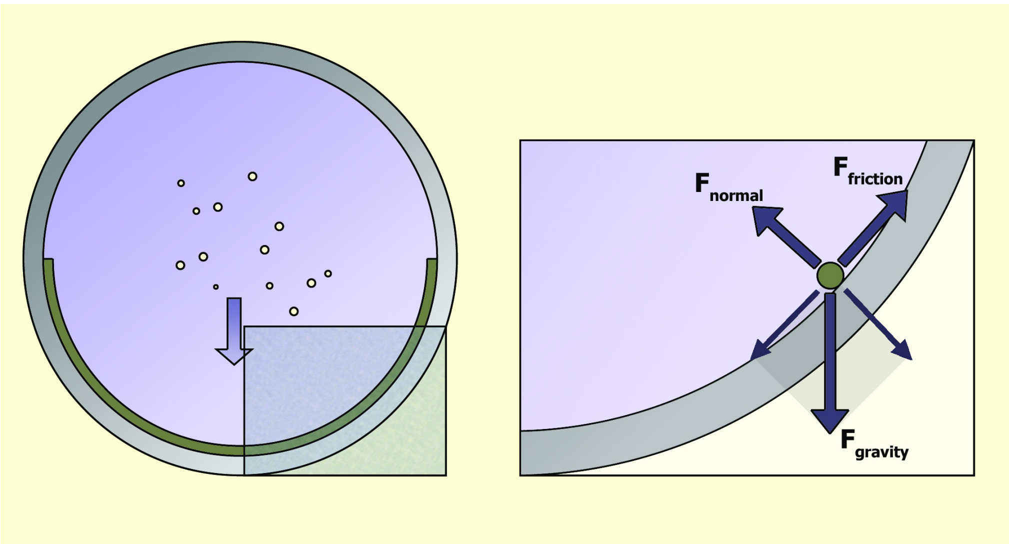

figure 8.26 Force analysis of a particle on the pipe wall

figure 8.26 shows the force analysis of a particle attached to the pipe wall. The particle represents the sediment layer on the wall surface. As the thickness of the layer increases the gravitational force ($F_{gravity}$) increases, resulting in a greater friction force ($F_{friction}$). When the value of $F_{friction}$ reaches a critical value the sediment layer will collapse and shift to the bottom of the pipe. This may happen when the friction between the sediment and the wall surface or the internal stress inside the sediment layer becomes too high.

8.6 Bed Load transport

To determine if bed load transport of sediment occurred, pictures were taken with an interval of 2 to 3 days. These pictures were taken at 2 locations in the main pipe section, as is shown in figure 8.27.

- Location 1 was chosen near the beginning of the main pipe section, where the first sediment is formed.
- Location 2 is just behind the first 100 mm valve.

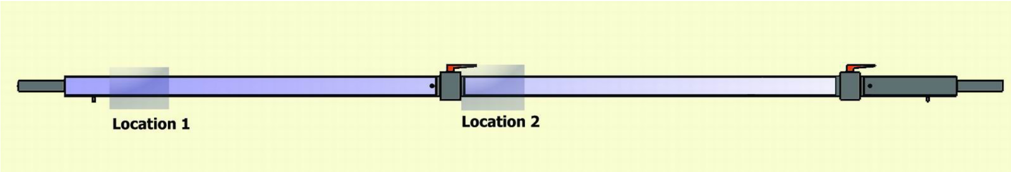

figure 8.27 Locations of the pictures taken for observation of bed load transport

The pictures were taken after the transformation of the sediment bed had occurred, as is described in paragraph 8.5. The flow velocity between photos was 0.14 m/s

As can be seen on the photographs in figure 8.28 and figure 8.29 no movement of sediment is visible. It seems that once the sediment has shifted to the bottom of the pipe it remains in the same location.

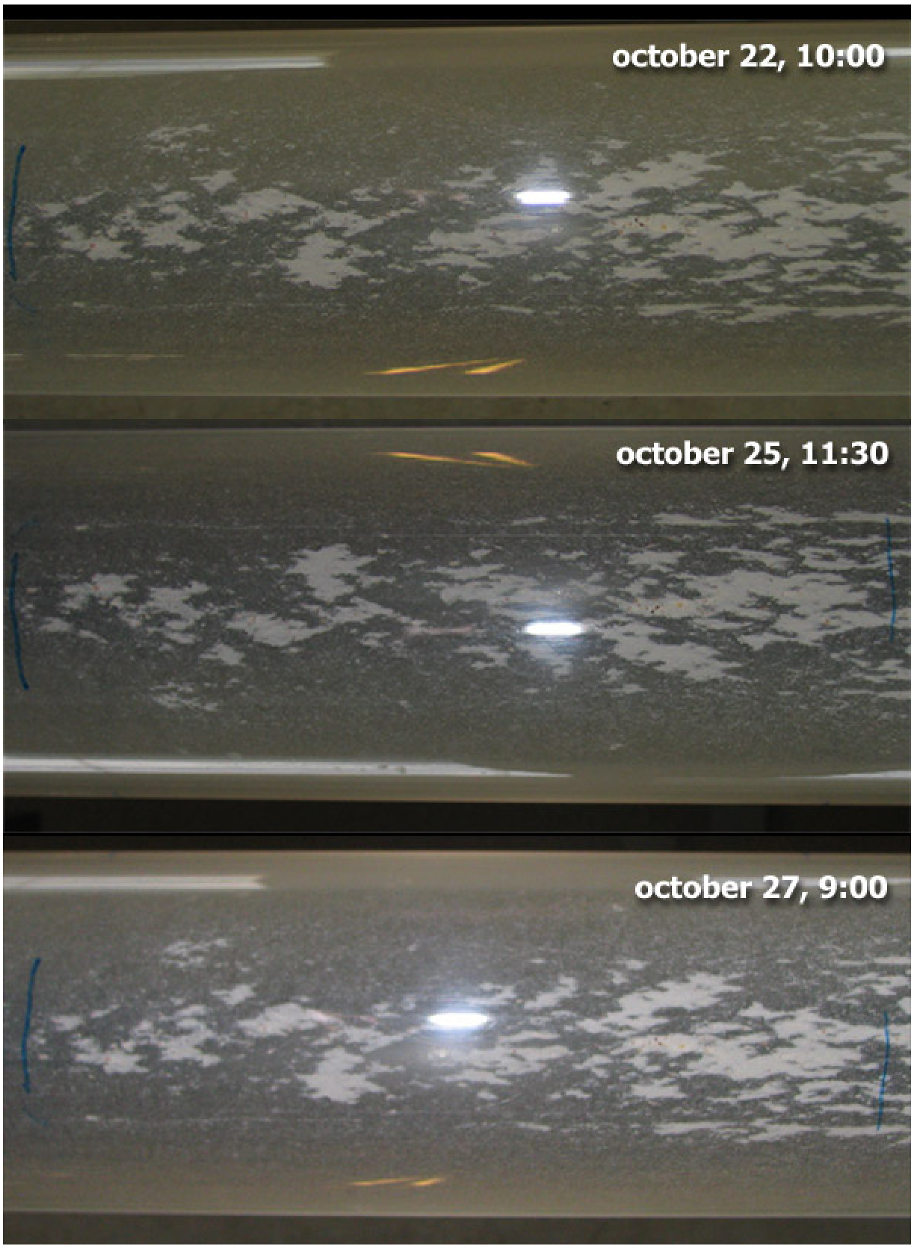

figure 8.28 Observation of bed load transport [location1]

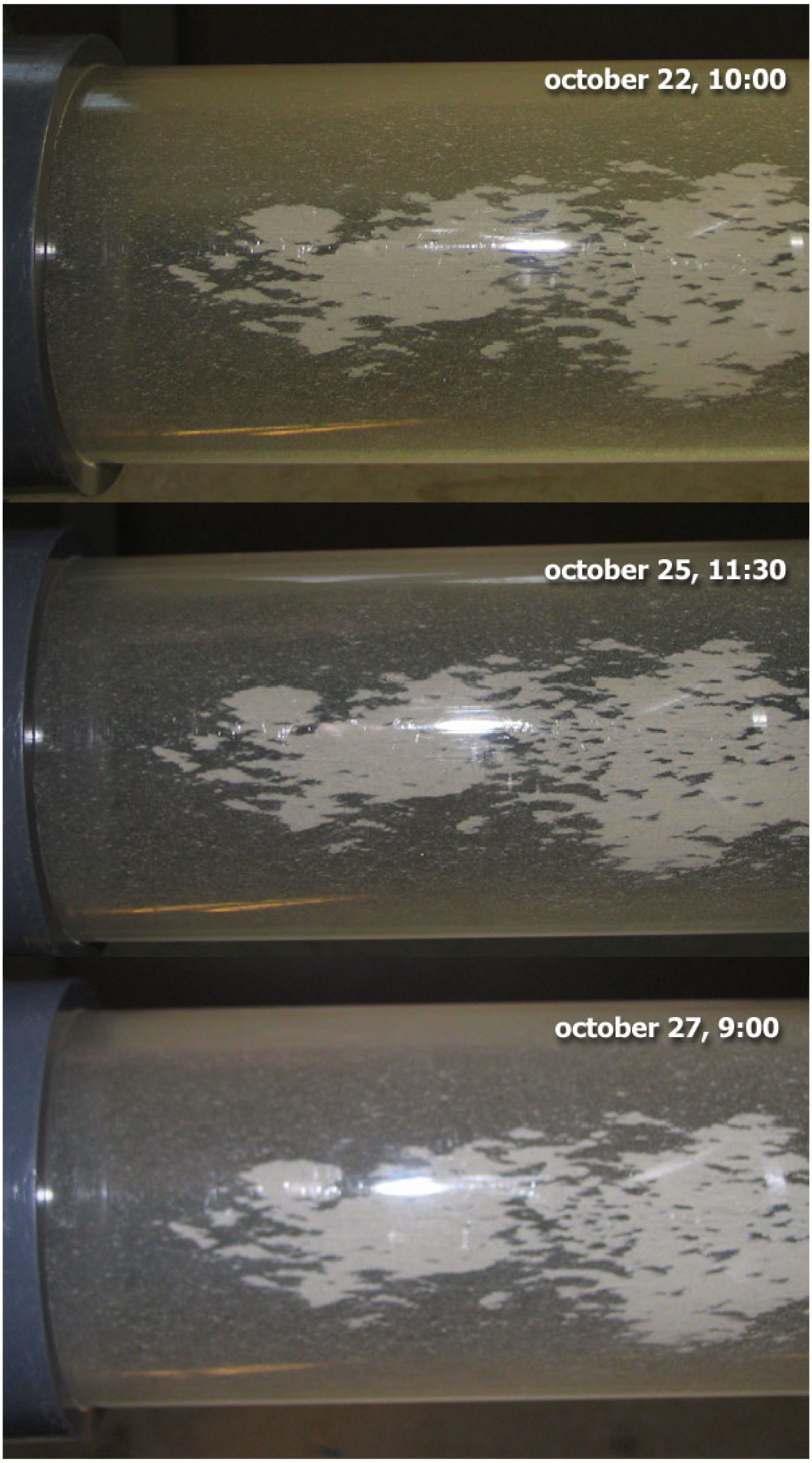

figure 8.29 Observation of bed load transport [location2]

8.7 Remobilisation of sediment

By increasing the flow velocity from 0.14 to 0.25 m/s, a part of the sediment bed was remobilised, as can be seen in figure 8.30. After increasing the flow velocity the turbidity increased gradually from 0.25 to approximately 4.7 FTU in a period of 3.5 hours. After reaching a maximum value the turbidity would decrease. This was not as expected as according to the Shields theory particles were expected to resuspend at flow velocities above 0.15 m/s. (see paragraph 3.1.2)
From this observation can be concluded that Shields theory is not fully applicable when looking at the sedimentation and resuspension process of fine particles in a drinking water system. There will probably be a number of other phenomena that prevent particles from resuspending. For example the cohesion or packing of the sediment bed may play a role.

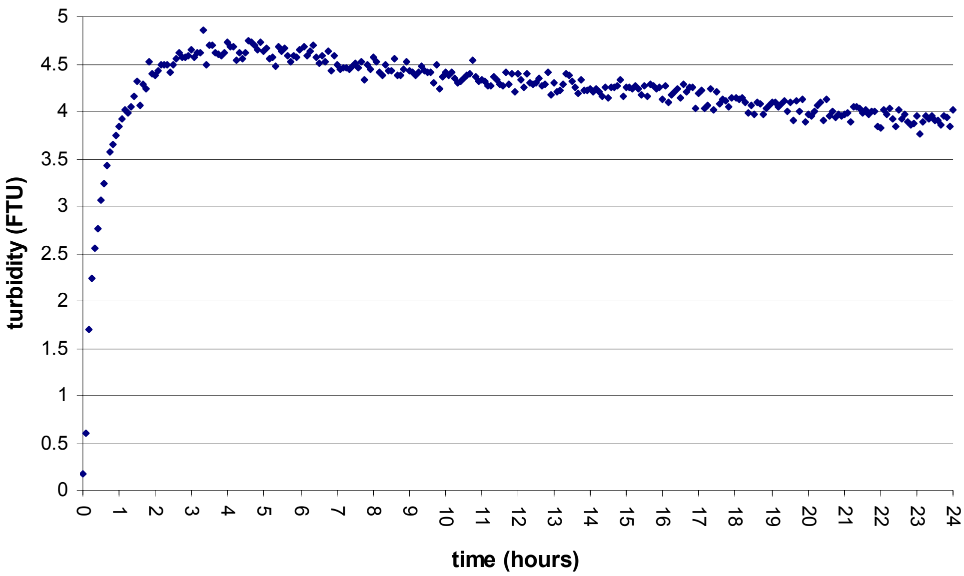

figure 8.30 Remobilisation of sediment after acceleration of flow velocity

figure 8.31 shows the changes in the sediment bed after increasing the flow velocity from 0.14 to 0.25 m/s in location1 (see figure 8.27). The photographs show the decreasing amount of sediment. It also shows that while the amount of sediment decreases, the sediment bed itself does not move. It seems that cohesive forces prevent the sediment from resuspending at once, resulting in a gradual decline of the sediment bed. This assumption is supported by the measurements of the turbidity which show that the maximum turbidity is reached after 3.5 hours, which is a relative long time.

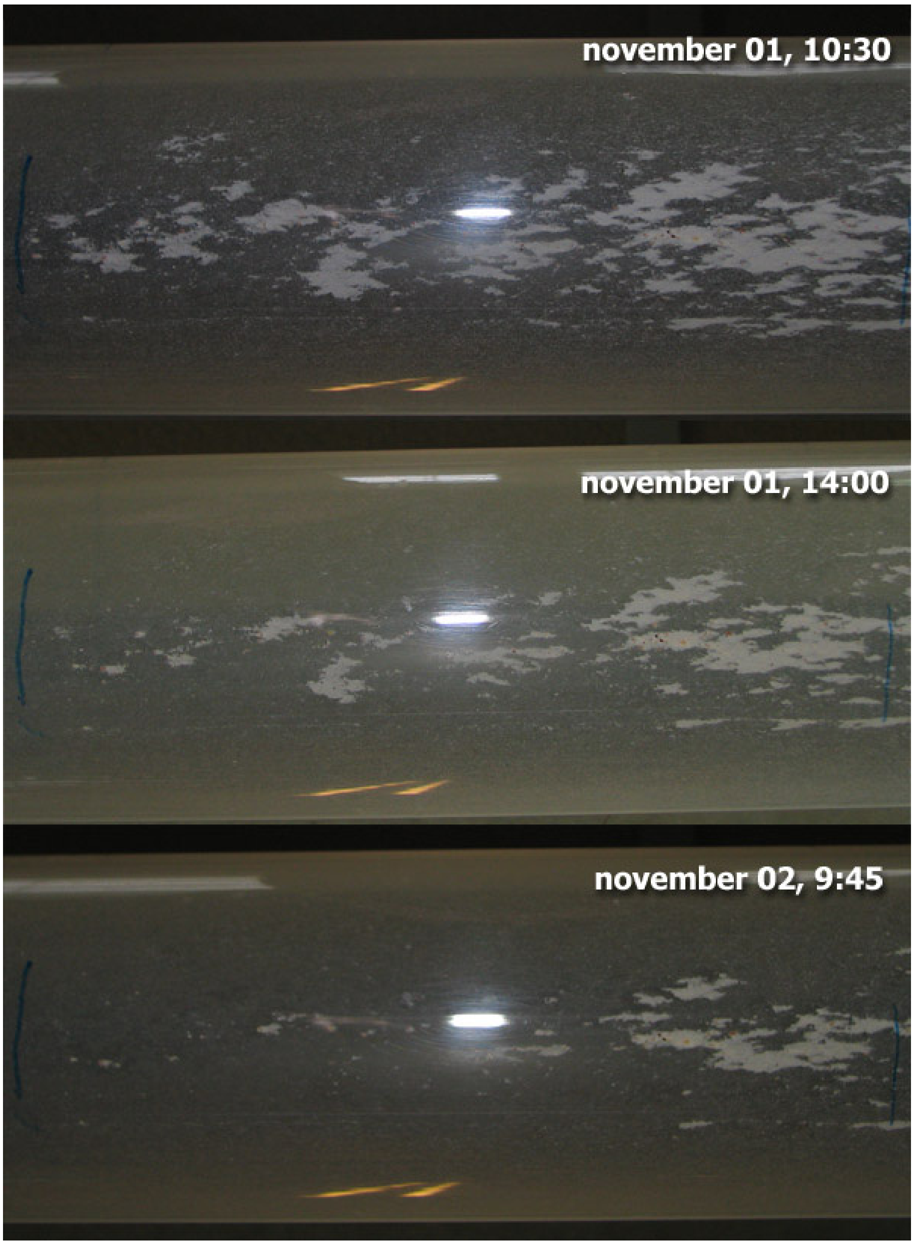

figure 8.31 Remobilisation of sediment [location1]

Although in location1 the sediment bed is influenced by the increase in flow velocity, it seems that in location2 no real big changes occurred. In figure 8.32 some photographs of location2 can be seen, taken at the same time as the pictures of location1. When looking at these photographs only minor changes in the sediment bed can be seen.

The question arises if the sediment that is resuspended at the beginning of the main pipe is sufficient to raise the turbidity to 4.7 FTU. As a dose of 10 grams of kaolinite results in an increase of roughly 16 FTU, an increase of 4.5 FTU would mean that approximately 5 grams of kaolinite has resuspended. It is not unthinkable that an increase of the flow velocity results in resuspension of particles that have settled elsewhere in the system, which would also result in an increase of the turbidity.

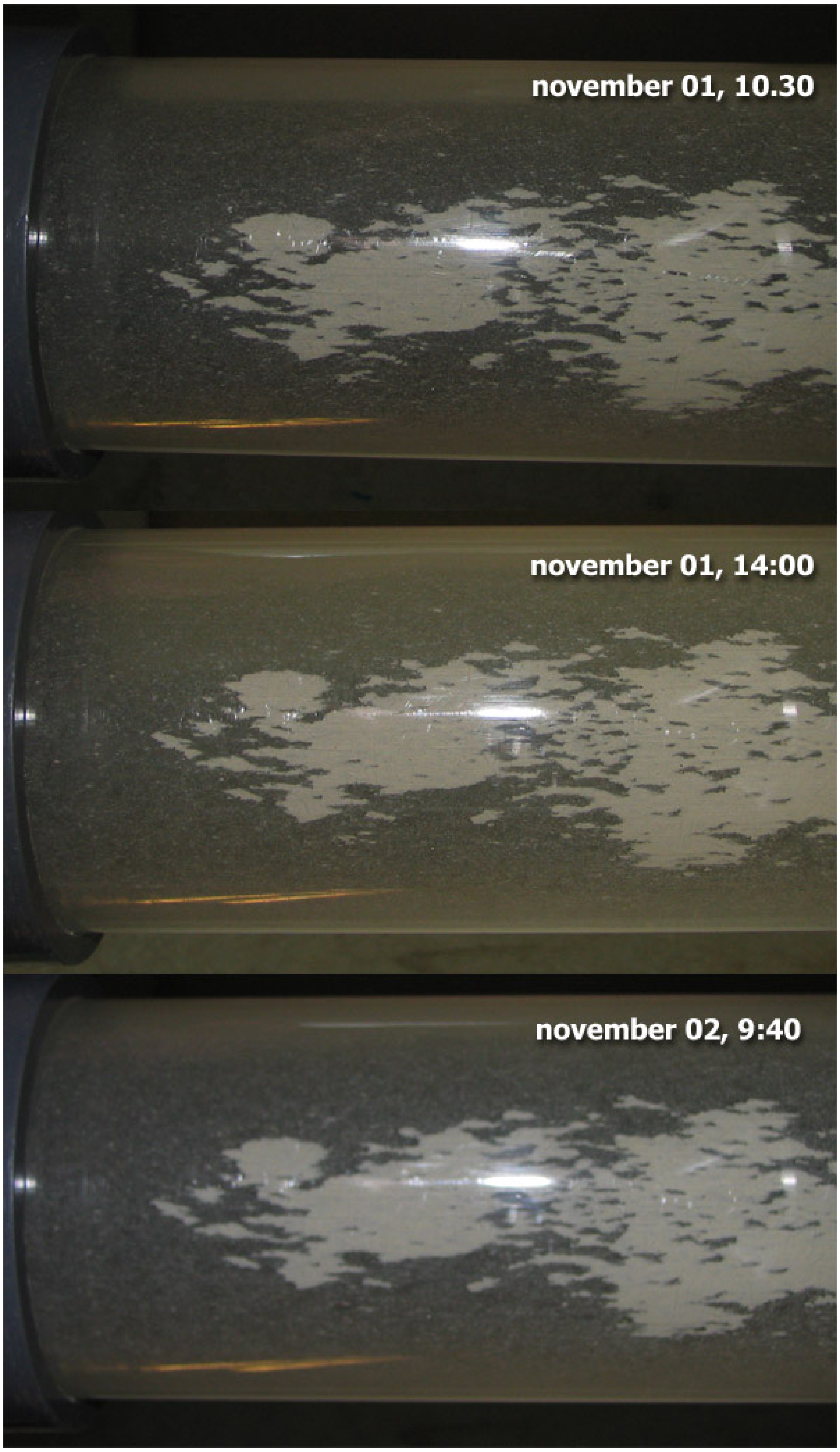

figure 8.32 Remobilisation of sediment [location2]

9 Conclusions

9.1 Feasibility of the test rig

- Working with this single pipe test rig gave a further insight in the process of layer development. Visual observations ass well as measuring the turbidity showed the influence of different flow velocities and the choice of sediment source on the sedimentation process.
- The results of the experiments show that using a test rig to simulate the process of layer development does work in a circulation setup. There is no reason to assume it would be otherwise in a flow-through setup.

9.2 Influence of flow velocity on sedimentation

- Bed load transport of iron flocks is visible at 0.06 m/s, not at 0.14 m/s.
- Experiments with iron flocks at a flow velocity of 0.06 m/s result in deposits in the bottom half of the pipe.
- Experiments with iron flocks at a flow velocity of 0.14 m/s result in deposits along the entire pipe circumference.
- Experiments with kaolinite at 0.06 and 0.14 m/s show development of sediment layers only in the bottom half of the pipe.
- The 'steady state' turbidity after reaching equilibrium does not always have a higher value at a higher flow velocity.
- The sediment bed is more cohesive when developed at higher flow velocity. Remobilisation of the sediment bed is harder when developed at higher flow velocity.
- Resuspension of kaolinite settled at 0.14 m/s after acceleration to 0.25 m/s mainly occurs near the entrance of the pipe

9.3 Influence of sediment source on sedimentation

- Iron flocks (with a low density) have a lower sedimentation rate than kaolinite particles (with a higher density).
- The sedimentation rate of the sediment sample from the distribution system of the city of Leusden is more similar to kaolinite than to iron flocks.

9.4 Influence of initial sedimentary deposits on sedimentation rate

- The presence of initial sedimentary deposits seems to influence the sedimentation rate.
- The build up of a sediment layer with kaolinite eventually leads to transformation of the sediment bed. In time the settled kaolinite particles will shift to the bottom of the pipe.

9.5 In general

- Visualising the process in transparent pipes is very illustrative.
- Local turbulence variations are of influence on development of sediment layers.
- All the experiments show the turbidity does not reach zero. This means there will always be particles in suspension. From the results of the experiments it is not clear if these particles are particles that do not settle or that they are resuspended particles.
- Still, a lot of phenomena are unclear, especially with regard to the resuspension of particles.
- When modelling the sedimentation process based on Stokes' Law and with a variable resuspension factor of settled particles, it shows that if particles would resuspend, the amount would be very small in comparison with settled particles.
- Experiments with a duration longer than one week may be influenced by biofilm formation.

9.6 Further design of the test rig

- When expanding the design to a multiple pipe setup, more thought has to be given to the downscaling of the pipe diameter. Problems are expected as either the influence of turbulence or the influence of shear stress has to be chosen as design parameter.

10 Recommendations

10.1 Additional experiments

- Conducting additional experiments using a particle counter would give more insight in changes of the particle size distribution during experiments and to verify Stokes' Law.
- To gain further insight in the process of resuspension a 'reversed' experiment can be done by loading the measuring section with a large amount of sediment (for example 100 grams of kaolinite) and filling the rest of the system with (preferably particle free) water. Subsequently, resuspension can be monitored at different flow velocities using a turbidity meter or a particle counter.
- It should be relatively easy to determine the amount of non settling particles in the water.
- During this research the influence of biofilm formation and corrosion was discarded. It is expected that when the duration of experiments is extended the influence of biofilm formation can no longer be discarded. When biofilm formation is undesired, disinfection of the system is required when experiments take longer than one week. Disinfection should be implemented by continuously dosing a small amount of disinfectant to prevent biofilm to develop.

10.2 Further development of the test rig

- Collecting the sediment from the measuring section is a method to determine layer thickness in the pipe. However, as the sediment layer is disturbed, this can be done only one time per experiment. To be able to measure at more than one time, multiple pipes have to be used. It is expected that when designing a multiple pipe test rig the pipe diameter has to be scaled down, which may give problems with hydraulics.
- It is recommended to look into other alternatives to measure layer development, like:
    - Determining layer thickness by measuring transparency of the sediment layer.
    - Using a single pipe with multiple removable pipe sections. Removing the pipe sections one at a time, starting from the downstream side, would give an image of layer development.
- When designing the multiple pipe test rig and scaling down the pipe diameter, it is preferred to use shear stress as design parameter instead of turbulence. Shear stress is chosen as it is of great importance for the remobilization of particles. Hence, the preference is given to a possible laminar flow with a normal shear stress instead of a turbulent flow with a shear stress higher than the critical shear stress.
- The influence of bed load transport could be further evaluated by applying an obstruction in the pipe.

10.3 Verification and development of models

- Results of experiments with the test rig may give useful information for the verification or development of sedimentation models.
    - Visual observations may give insight in the shape and size of sediment layers for different sediments and at different flow velocities.
    - Data of the sedimentation process acquired by turbidity meter or particle counter could be used to determine sedimentation rate for different sediments at different flow velocities.
- Further development of the 'Sedimentation Resuspension Model' may provide a tool which can be used when analysing experimental data.

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Appendix A Derivation equation of shear stress[5]

The general equation of motion for closed pipes with a gradient β is:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial t} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + g \cdot \sin\beta - \frac{\tau}{\rho \cdot R} \tag{A1}$$

The piezometric level φ is defined as:

$$\varphi = z + h = z + \frac{p}{\rho \cdot g} \tag{A2}$$

Differentiation of equation (A2) gives equations (A3) and (A4):

$$\frac{\partial \varphi}{\partial t} = \frac{1}{\rho \cdot g}\frac{\partial p}{\partial t} \tag{A3}$$

$$\frac{\partial \varphi}{\partial x} = \frac{1}{\rho \cdot g}\frac{\partial p}{\partial x} - \sin\beta \tag{A4}$$

Equation (A4) can be rewritten to (A5) by multiplying al terms with g:

$$g \cdot \frac{\partial \varphi}{\partial x} = \frac{1}{\rho}\frac{\partial p}{\partial x} - g \cdot \sin\beta \tag{A5}$$

Substituting equation (A5) into equation (A1) gives equation (A6)

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} = -g\frac{\partial \varphi}{\partial x} - \frac{\tau}{\rho \cdot R} \tag{A6}$$

For a prismatic pipe it applies that ∂u/∂x=0, so that equation (A6) can be rewritten as:

$$\frac{\partial u}{\partial t} = -g\frac{\partial \varphi}{\partial x} - \frac{\tau}{\rho \cdot R} \tag{A7}$$

The equation to calculate the shear stress (A8) follows from equation (A7):

$$\tau = -\rho \cdot R \cdot \left(\frac{\partial u}{\partial t} + g \cdot \frac{\partial \varphi}{\partial x}\right) \tag{A8}$$

[5] From van den Boomen and van Mazijk (2002)

Appendix B Calculation of the shear stress[6]

D = 0.1 k = $5*10^{-5}$ T = 28 U = 0.06 $\nu = 497*10^{-6}/(T + 42{,}5)^{1{,}5} = 8.40*10^{-7}$ R = ¼ D = 0.025 m	[m] [m] [°C] [m/s] [m²/s] [m]
Hydraulic smooth	$\delta = \dfrac{12 \cdot \nu \cdot 18 \log\left(\dfrac{48R}{\delta}\right)}{\sqrt{g} \cdot u}$ $\delta = 9.65 \cdot 10^{-4} \log\left(\dfrac{1.2}{\delta}\right)$ $\delta = 2.57 \cdot 10^{-3}$
Technical rough	$\delta = \dfrac{12 \cdot \nu \cdot 18 \log\left(\dfrac{12R}{k + 1/4\delta}\right)}{\sqrt{g} \cdot u}$ $\delta = 9.65 \cdot 10^{-4} \log\left(\dfrac{0.3}{0.05 \cdot 10^{-3} + 1/4\delta}\right)$ $\delta = 2.55 \cdot 10^{-3}$
Hydraulic rough	$\delta = \dfrac{12 \cdot \nu \cdot 18 \log\left(\dfrac{12R}{k}\right)}{\sqrt{g} \cdot u}$ $\delta = 9.65 \cdot 10^{-4} \log\left(\dfrac{0.3}{0.05 \cdot 10^{-3}}\right)$ $\delta = 3.65 \cdot 10^{-3}$
Determine hydraulic condition: hydraulic smooth (δ/k > 4) technical rough (1/6 < δ/k < 4) hydraulic rough (δ/k < 1/6)	$\delta / k = 2.57 \cdot 10^{-3} / 0.05 \cdot 10^{-3} = 51.4$ $\delta / k = 2.55 \cdot 10^{-3} / 0.05 \cdot 10^{-3} = 51$ $\delta / k = 3.65 \cdot 10^{-3} / 0.05 \cdot 10^{-3} = 73$
Conclusion: Condition is hydraulic smooth, with δ = $2.57*10^{-3}$ m	
With δ and the hydraulic condition known, the Chézy coefficient can be calculated: $C = 18 \log\left(\dfrac{48R}{\delta}\right) = 48.05$ m$^{1/2}$/s	
$\tau = \rho g \left(\dfrac{u}{C}\right)^2 = 1000 \cdot 9.81 \cdot \left(\dfrac{0.06}{48.05}\right)^2 = 0.015$ N/m²	

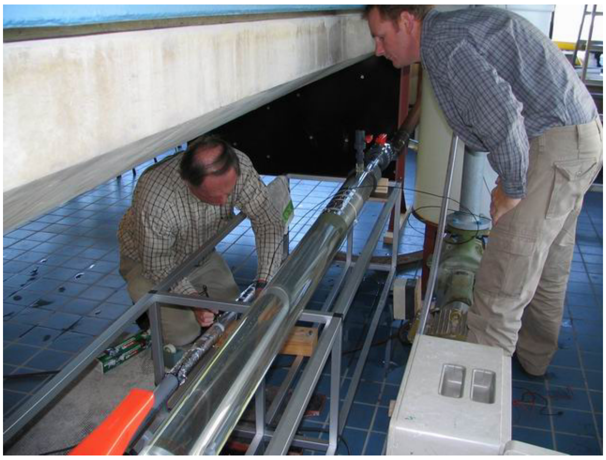
[6] From van den Boomen and van Mazijk (2002)

Appendix C Electrostatic forces

This appendix gives a description of a very simple experiment to determine if an electric potential exists between the pipe wall and the water flowing through the pipe. When such a potential exists, small particles might attach to the wall surface.

To be able to measure any electrostatic effects a part of the main pipe as well as a part of the additional piping was wrapped in aluminium foil. The electric potential between the pipe wall material and the water in the reservoir was measured. During this experiment the flow velocity in the main section was 0.25 m/s and the flow velocity in the part of additional pipe was at least 1 m/s.

The result of this experiment was that an electric potential could not be measured. Nonetheless, the existence of an electric potential can not be excluded, due to the course layout of this experiment.



Appendix D Sedimentation Resuspension Model

As described in chapter 7, a model has been made to calculate the effect of settling and resuspension on the sedimentation process in pipes, based on the hypothesis that particles settle and resuspend until a 'steady state' situation is reached. This model is called the Sedimentation Resuspension Model (SRM)

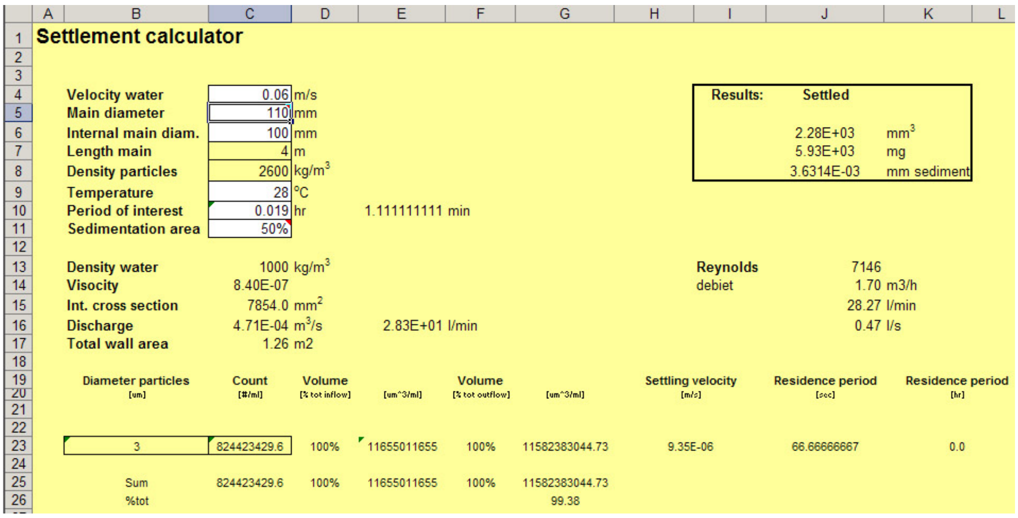
The model can be divided in two parts:

- *Settlement calculator*, which is used to calculate the settling velocity and amount of settled particles per time step.
- *Sedimentation Resuspension Model*, which is the actual model of the test rig.

Settlement calculator

The 'settlement calculator' is an excel worksheet made by C. Kivit and is used to calculate the amount of settled particles per time step. From the settling velocity and a given period of interest, the amount of settled particles is calculated as a percentage of the initial concentration for each time step. The main parameters needed as input are:

Pipe diameter	[mm]
Pipe length	[m]
Flow velocity	[m/s]
Density of water and particles	[kg/m^3]
Temperature	[°C]



Screenshot of the settlement calculator

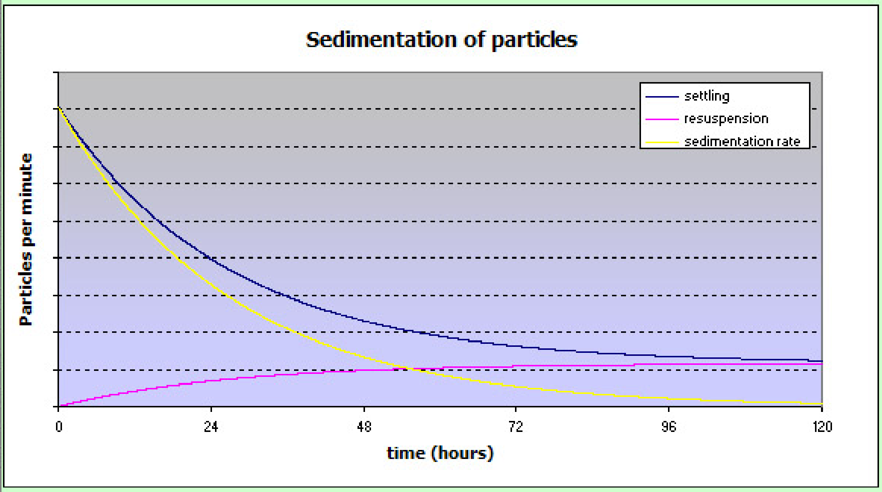
The calculated values of the settlement calculator are used in the sedimentation resuspension model to calculate the amount of settled particles per time step.

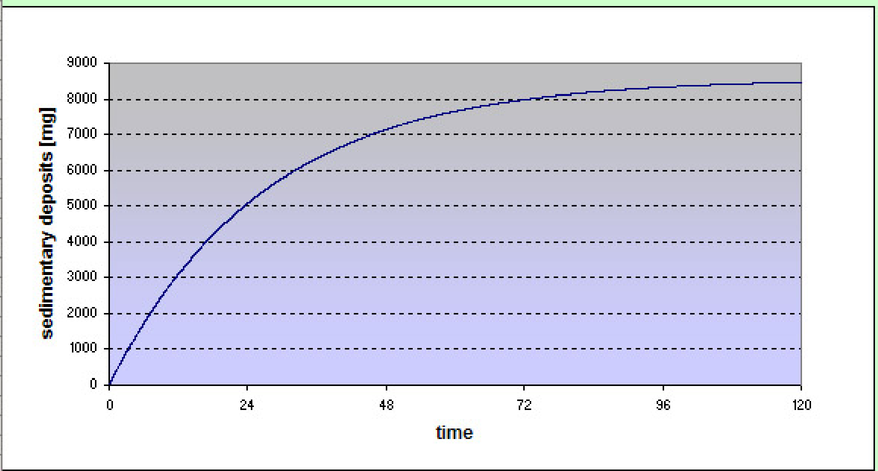
Sedimentation Resuspension Model

This is the actual model of the test rig. The input parameters are:

Particle diameter	[μm]
Particle density	[kg/m^3]
Total mass of particles	[mg]
Amount of suspended particles at t=0	[%]
Total volume of the system	[l]
Resuspension factor	[%]

	A	B	C
1			
2	particle diameter	3	um
3		0.000003	m
4	volume particle	1.41E-17	m3
5	density	2600	kg/m3
6	mass particle	3.67566E-14	kg
7		3.67566E-08	mg
8			
9	mass added particles	10000	mg
10	particles in system	2.7206E+11	#
11	volume	3.84615E-06	m3
12	particles in suspension at t=0	100	%
13	volume system	330	l
14	particle concentration at t=0	824423429.6	# / l
15	volume flow	28.27	l / min
16	particles per minute at t=0	23310023310	
17	sedimentation	0.62	%
18	resuspension	0.01	%





Screenshot of the Sedimentation Resuspension Model

The model calculates for each time step:

settling	[particles/time step]
resuspension	[particles/time step]
sedimentation rate	[particles/time step]
sedimentary deposits	[mg] & [# of particles]
cumulative amount of settled particles	[# of particles]
cumulative amount of resuspended particles	[# of particles]
particles entering the main pipe section	[# of particles]
particles leaving the main pipe section	[# of particles]
particles in suspension	[%]
layer development per meter pipe length	[mg/m]
particle concentration	[mg/l]

The parameter 'settling' represents the amount of particles that settle in the pipe during a time step. Settling is calculated as a percentage of the total amount of particles that flow through the pipe during a time step.

The parameter 'resuspension' represents the amount of particles that resuspend during a time step. Resuspension is calculated with the resuspension factor as a percentage of the amount of sedimentary deposits in the pipe at the start of a time step.

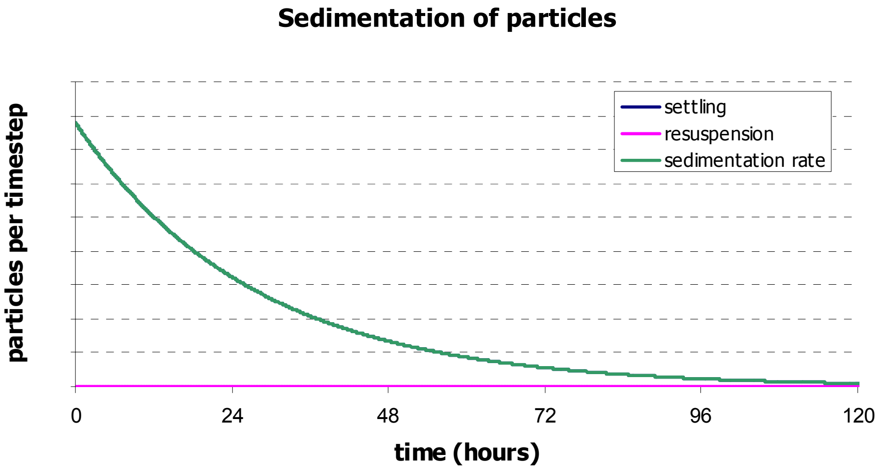
The parameter 'sedimentation rate' represents the amount of sedimentary deposits that are formed during a time step as a number of particles. The sedimentation rate is the difference between settling and resuspension. When the parameters settling and resuspension have the same value, equilibrium is reached and the sedimentation rate will become zero.

To take into account the influence of the reservoir, the particle concentration from the incoming flow is calculated from the particle concentration in the reservoir and the particle concentration of the outgoing flow from the previous time step.

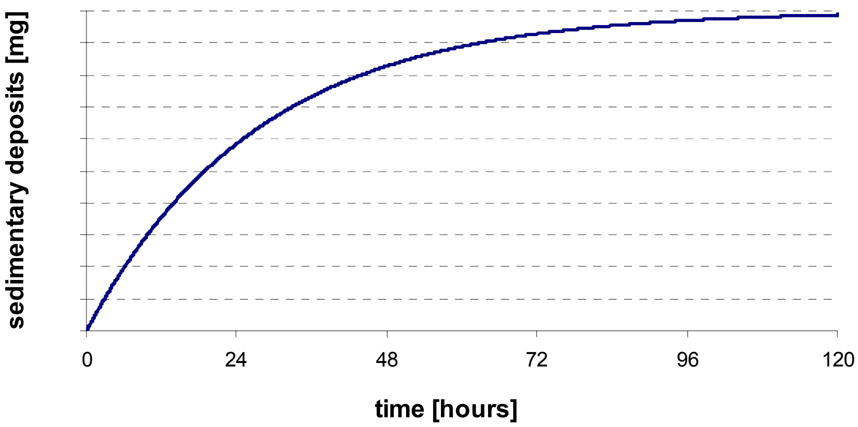
When the amount of sedimentary deposits is calculated, the amount of particles that are in suspension can also be calculated. Layer development per meter pipe length can be calculated from the amount of sedimentary deposits and the pipe geometry. Particle concentration is calculated from the amount of particles in suspension and the volume of the system.

Example 1 resuspension factor is 0%

When the resuspension factor is zero no particles will resuspend, resulting in settling of all particles. As resuspension does not occur, the sedimentation rate will be equal to settling.



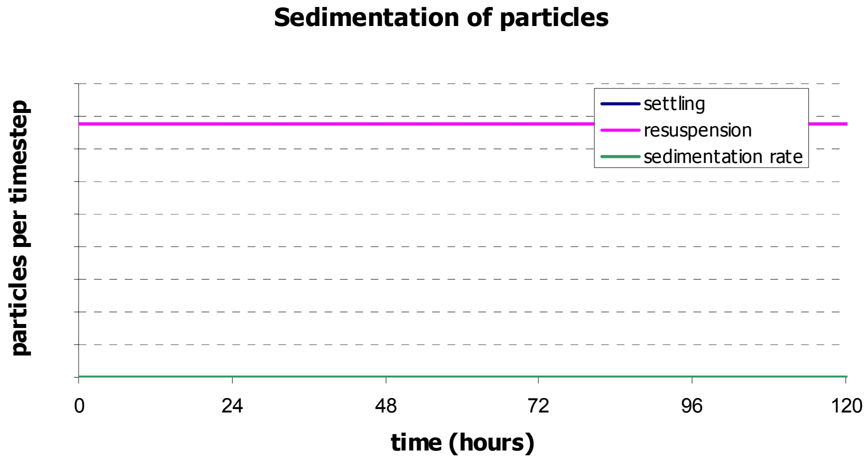
Sedimentation with a resuspension factor of 0



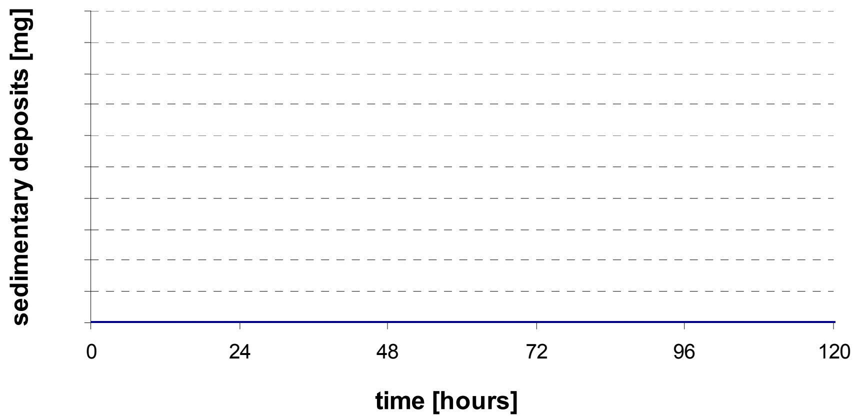
Development of sedimentary deposits

Example 2 Resuspension factor is 100%

When the resuspension factor is 100% all particles that settle will resuspend during the same time step. There will be no sedimentary deposits and the sedimentation rate will be zero.



Sedimentation process with a resuspension factor of 100%



No development of sedimentary deposits at a resuspension factor of 100%