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Modeling particle transport and discoloration risk in drinking water distribution networks

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Abstract. Discoloration of drinking water is a worldwide phenomenon caused by accumulation and subsequent remobilization of particulate matter in distribution systems (DWDSs). It contributes to a substantial fraction of customer complaints to water utilities.Accurate discoloration risk predictions could improve system operation by allowing for more effective programs on cleaning and prevention actions and field measurements, but are challenged by incomplete understanding on the origins and properties of particles and a complex and not fully understood interplay of processes in distribution networks. In this paper, we assess and describe relevant hydraulic processes that govern particle transport in turbulent pipe flow, including gravitational settling, bed-load transport, and particle entrainment into suspension. We assess which transport mechanisms are dominant for a range of bulk flow velocities, particle diameters, and particle mass densities, which includes common conditions for DWDS in The Netherlands, U.K., and Australia. Our analysis shows that the theoretically predicted particle settling velocity and threshold shear stresses for incipient particle motion are in the same range, but more variable than, previous estimates from lab experiments, field measurements, and modeling. The presented material will be used in the future development of a numerical modeling tool to determine and predict the spatial distribution of particulate material and discoloration risk in DWDSs. Our approach is aimed at understanding specific causalities and processes, which can complement data-driven approaches.

1 Introduction

Discoloration events in drinking water distribution networks occur worldwide as a result of accumulation of particulate material in pipes and subsequent remobilization due to hydraulic disturbances (e.g. Vreeburg (2007)). Strategies to reduce the risk of discoloration events include quality improvement of treated water (to reduce the particle load into the network), implementation of self-cleaning network layout (to prevent particle accumulation), and cleaning actions (to locally remove accumulated material from pipes before the amount becomes too high). Although these strategies are partly successful, the processes and mechanisms that cause discoloration events are complex and not yet fully understood, which hampers further risk reduction. For example, advanced treatment processes have enhanced the water quality that enters DWDSs, but cannot *fully* remove the load of particulate matter that enters DWDSs. The Resuspension Potential Method has

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improved the understanding in the local presence of particulate matter and the relationship to hydraulic events, but does not provide a comprehensive understanding of particulate matter transport (Vreeburg et al., 2005). Self-cleaning networks have been implemented and found effective in reducing discoloration risks in The Netherlands (Blokker et al., 2009) but have only been implemented in part of Dutch DWDSs installed after the mid 1990's.

Field measurements from an extensive and prolonged program of cleaning actions that covers ~450 km of pipes per year by Dutch water company PWN indicate that high turbidity events often occur in repeatable spatial and temporal patterns (Blokker and Schaap, 2011;Mounce et al., 2016). Factors that influence these patterns include the hydraulic vigor associated with the buildup and displacement of particles (Blokker and Schaap, 2007) and sediment load from the treatment plant and transport mains upstream from the DWDS (Blokker and Schaap, 2015). Although not all of the observed variability in particle accumulation can fully be explained, the repeatability suggests the possibility to describe the propagation and spatial distribution of particle cumulates in the DWDS with a model. Several models for discoloration in DWDSs exist, such as the Particle Sediment Model (PSM, Ryan et al. (2008)) and the Variable Condition Discoloration model (VCDM, Furnass et al. (2014)), which builds on the Prediction and Control of Discolouration in Distribution Systems (PODDS, e.g. Boxall et al. (2001b)). Although these models are partly successful in predicting patterns of local particle accumulation (e.g., (Vogelaar and Blokker, 2010;Furnass et al., 2014)), this success depends strongly on model calibration with local field measurements and laboratory data (for the Australian and British utilities, respectively). Available transport may be incomplete because of the absence of potentially important processes, such as bed-load transport. In addition, conditions and mechanisms may differ from DWDSs for which the model was not calibrated, such as different source quality due to other treatment processes or non-chlorinated Dutch systems that include self-cleaning network layouts.

The objective of the present paper is to develop a theoretical framework that describes the leading processes governing particle transport and causing discoloration events. The framework serves as a basis for developing a numerical modeling tool to determine and predict the spatial distribution of particulate material in (Dutch) drinking water distribution systems. System operation can benefit from successful predictions that allow for more effective programs on cleaning actions and field measurements, particularly in network areas where available data is limited or absent. Because field data indicate that multiple transport mechanisms (e.g. gravity and turbulence) and modes (e.g. bed-load transport and transport in suspension) can operate simultaneously or in succession, a model based on a description of processes rather than extrapolation of available measurements is more likely to result in reliable and generically applicable predictions. We assess which particle transport mechanism are dominant for a range of drinking water conditions and particle properties, in particular flow velocity, particle diameter, and particle size. This serves as a basis for later development of a numerical tool for the transport of particulate material. Our approach is aimed at understanding specific causalities and processes. This can complement data-driven approaches which give important understanding in key descriptive parameters for particular DWDSs (e.g., (Mounce et al., 2016), but do not investigate the causalities and processes explicitly.

2 Identifying relevant transport processes from current understanding of particle transport in DWDSs

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Several previous studies have demonstrated the importance of processes and mechanisms *within* DWDSs, in addition to processes at treatment plants and transport mains, to determine particle transport and discoloration risk. Laboratory experiments with smooth pipes have demonstrated that at low flow velocity only the lower half of pipes accumulate particles (iron flocs), while at a higher velocity, particles accumulate over the complete pipe circumference (Vreeburg, 2007;Ryan et al., 2008). Circumferential accumulation is likely associated with the process of turbophoresis; its contribution is mostly limited to large particles at high velocities in transport mains and not expected to play a major role in distribution mains (van Thienen et al., 2011). This study shows that turbophoresis is predicted to significantly contribute to radial sediment transport for flow velocities of >1 $m \cdot s^{-1}$ for ~50 µm particles and even higher flow velocities for smaller particles. Accumulation of particles on the pipe's lower half can plausibly be attributed to settling under the influence of gravitational acceleration.

DWDS pipelines with maximum daily velocities above 0.2 to 0.25 m/s are less prone to particle accumulation (Blokker et al., 2007;Blokker, 2010), plausibly because daily erosion of sediments prevents build-up to significant discoloration risk levels, and this has lead to the successful implementation of self-cleaning networks with pipeline diameters adjusted to attain this velocity in the Dutch drinking water sector (Vreeburg, 2007). The importance of hydraulic processes *within* the DWDS is further corroborated by evidence that the self-cleaning capacity can be regulated by valve manipulation and measurements suggest an influence of culverts, pipe junctions , and appurtances (Schaap and Blokker, 2013). In addition, independent studies suggest that sediment load and frequency of customer discoloration reports vary with the water temperature *within* the distribution pipes, as opposed to temperatures at the treatment plant (Blokker, 2015;Van Summeren et al., 2015). Furthermore, a cluster analysis of discoloration customer reports shows evidence that discoloration events are caused on the local level, suggesting that mechanisms in distribution pipelines rather than in transport mains critically control discoloration events (Van Rooij, 2016). Simultaneous lance measurements at various pipe depths suggest a downward positive concentration gradients during elevated turbidity events, suggesting the possibility of sediments mobilization through bed-load transport in distribution pipes (Schaap and Kivit, 2007).

With the above in mind, we decided to focus on a model for distribution pipelines that captures particle settling under the influence of gravity, particle resuspension by hydraulic forces, and sediment mobility by means of bed- load transport. We investigate how particle size, particle density and flow velocity and associated shear stresses affect these processes.

Other mechanisms related to turbulent motion-particle interaction are likely relevant but probably not dominant. Turbulent diffusion can perturb the trajectory of a suspended particle and, hence, its apparent settling velocity. Turbulent dispersion effects near the viscous sub-layer can also modulate particle concentration profiles. Turbulent fluctuations can influence incipient motions and resuspension but are only implicitly incorporated in our analysis.

Particulate accumulations is known to be related to biological activity (Gauthier et al., 1999). Organic matter in particulate accumulation may consist for 1-12% of bacterial biomass, making the deposits an important factor in biological safety of drinking water (Vreeburg, 2007). However, because interactions between particle transport and microbiological

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processes are complex and not yet fully understood, they are kept out of the scope of the current research. Cementation or armoring and compaction of sediment layers potentially strengthen sediments over time, but this aspect is out of the scope of this paper. Chemical processes such as flocculation may change the particles' size and density during transport. Consideration of this process requires detailed knowledge of particle properties and the local water chemistry and might be added in a later stage.

3 Model description for particle transport

3.1 General remarks

The particle transport model is outlined in the sections below and conceptually visualised in Figure 1. Parameter domains for stagnation, bed-load transport, and resuspension are separated by threshold values of a dimensionless shear stress (Shields number, θ). Key parameters used in this study are listed in Table 1.

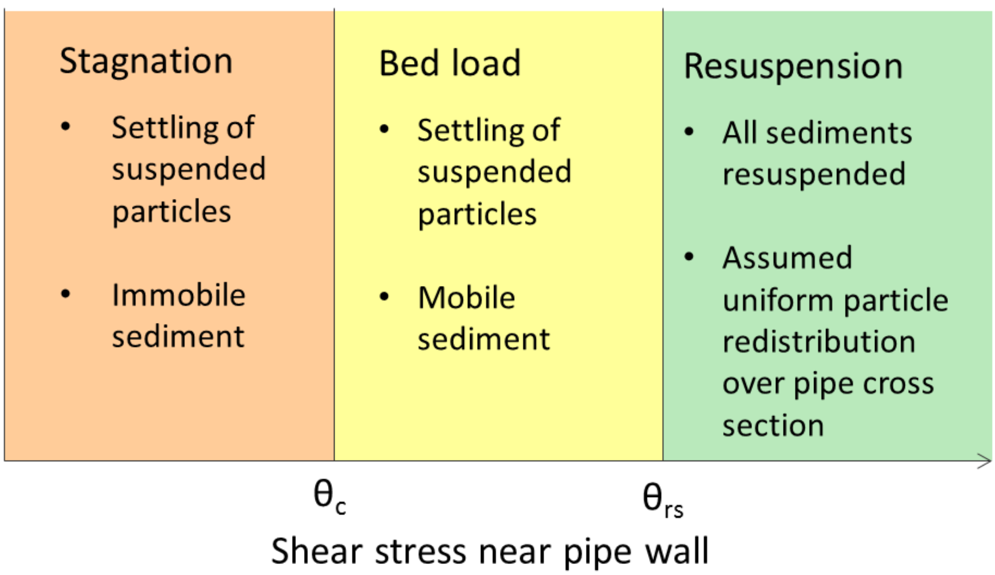

Figure 1. Conceptual representation of the particle transport model. Below a dimensionless critical shear stress (Shields number for incipient motion, θ_c, red area) particles in suspension settle to the bottom of the pipe under the influence of gravity and, once settled, remain immobile. Above the critical Shields number for particle entrainment (θ_{rs},, green area), we assume that all particles are resuspended instantly and redistributed uniformly over the cross section of the pipe. At intermediate shear stress conditions (yellow area), suspended particles settle and particles in the sediment phase move by means of bed-load transport.

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Table 1. Definitions of key parameters. Symbol dp is used for the particle diameter, $\boldsymbol{\rho_p}$ and $\boldsymbol{\rho_f}$ represent mass particle and fluid density, respectively, κ is the von Kármán constant, $\boldsymbol{\nu}$ is the (temperature-dependent) kinematic viscosity of water, g is the gravitational acceleration (taken 9,81 ms^2), C_d is the friction factor, and C_f is the Darcy-friction factor (taken 0.02 in this study).

Parameter description	**Formulation**	**Unit**
Particle Reynolds number	$Re_p = \frac{u_s d_p}{\nu}$	-
Boundary Reynolds number	$Re_* = \frac{u_* d_p}{\nu}$	-
Rouse number	$P = \frac{u_s}{\kappa u_*}$	-
Relative specific particle weight	$s = \frac{\rho_p - \rho_f}{\rho_f}$	-
Settling velocity (general form)	$u_s = \left[\frac{4gsd_p}{3C_d}\right]^{1/2}$	ms^{-1}
Settling velocity (for particle Reynolds numbers)	$u_s = \frac{gsd_p^2}{18\nu}$	ms^{-1}
Shields number	$\theta = \frac{\tau_b}{(\rho_p - \rho_f)gd_p}$	-
Critical Shields number for particle incipient motion	θ_c	-
Critical Shields number for particle entrainment	θ_{rs}	-
Shear velocity	$u_* = \bar{u}_f\sqrt{C_f}$	ms^{-1}
Shear stress near sediment bed	$\tau_b = \frac{\rho_f \bar{u}_f^2 C_f}{8}$	Pa

3.1 Gravitational settling of particulate material

We assume that at subcritical shear stress conditions (further described in Section 3.2) particles in the water phase sink under the influence of gravity with a settling velocity u_s and particles that reach the pipe wall remain immobile. The settling (or fall) velocity is formulated by Stokes' Law, first stated in 1851, which describes the balance between gravity, buoyancy and friction of a sinking particle. The settling velocity depends on particle properties and hydraulic conditions and is assumed to be independent of the larger-scale flow. The general form of the free (no interaction between individual particles) settling velocity for spherical, incompressible particles is:

$$u_s = \left[\frac{4gsd_p}{3C_d}\right]^{1/2}, \qquad 1$$

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with C_d the friction coefficient, g the gravitational acceleration, $s \equiv (\rho_p - \rho_f)/\rho_f$ the relative excess mass density, ρ_p and ρ_f the particle and fluid density, respectively, and d_p the particle diameter. In case of a small particle Reynolds number (<0.2), the fluid flow surrounding the particle is laminar, independent of the larger-scale fluid flow:

$$Re_p = \frac{u_s d_p}{\nu(T)} < 0.2, \quad (2)$$

with $\nu(T)$ the temperature-dependent kinematic viscosity. Under these conditions the friction coefficient is given by

$$C_D = \frac{24\alpha_{sh}}{Re_p}, \quad (3)$$

with α_{sh} the particle shape factor. We assumed spherically shaped particles, i.e., $\alpha_{sh} = 1$, because particle shape is difficult to determine. Substitution of the friction coefficient in Eq. (1) results in:

$$u_s = \frac{gsd_p^2}{18\nu(T)}. \quad (4)$$

The temperature-dependence of the viscosity is relevant, because a temperature increase from 5 to 25°C can lower the fluid viscosity and increase the settling velocity by ~70%, as pointed out by Kris and Hadi (2007). We use the free-fall velocity, because hindered settling, whereby the presence of surrounding particles decrease the settling velocity, can be ignored at typical particle concentrations in the ppm range.

Next, we asses expected settling velocities for DWDS conditions documented for The Netherlands, U.K., and Australia (

Table 2). Note that the particle diameter range for Australian utilities is comparatively wide, because we used the full range between minimum and maximum diameters documented for 20 locations and that the estimates include transport mains, as opposed to the estimates for the Netherlands and U.K. We represented settling velocities in a contour plot (Figure 2), which shows a strong positive dependence of the settling velocity to particle size and density: even within a limited density range of 1100-1300 kg·m^{-3}, the settling velocity for common Dutch DWDS condition varies over one order of magnitude. A default settling velocity of u_s=1.6·10^{-6} m·s^{-1} was determined from experiments of the Australian DWDS (Ryan et al., 2008), indicated by the blue line. Although the default value falls within the conditions of the three countries, a large variation of settling velocities may be anticipated, because of the strong sensitivity to particle properties.

It was pointed out by (Ryan et al., 2008) that the empirically derived settling velocity is higher than the Stokes velocity. Possibly, this is because they used a specific gravity derived from dried samples, whereas the (effective) density of suspended particle will be reduced due to the virtual mass effect, whereby a fluid boundary layer encloses a particle and acts as part of the particle in terms of inertia.

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Table 2. Overview of common particle diameter and density and bulk flow velocity conditions in DWDS for The Netherlands, the U.K., and Australia. (*):Following (van Thienen et al., 2011). For the Netherlands we assumed the same particle densities as those of the U.K.. Particle diameter for the Australian DWDS were derived from 6 locations ranging between 0.5 and 400 µm, while median values range between 8 and 27 µm (Ryan et al., 2008) . Particle densities for Australian utilities were derived from 20 locations (Ryan et al., 2008).

DWDS	**Particle diameter (µm)**	**Particle density (kg·m^{-3})**	**Bulk flow velocity (m·s^{-1})**
Dutch	3-12 (Vreeburg, 2007)*	1000-1300	0.05-0.2*
U.K.	5-30 (Boxall et al., 2001a)*	1000-1300 (Boxall 2001)*	0.05-0.2*
Australian	0.5-500; median: 8-27 (Ryan et al., 2008)	1180-2040 (Ryan et al., 2008)	0.05-0.2

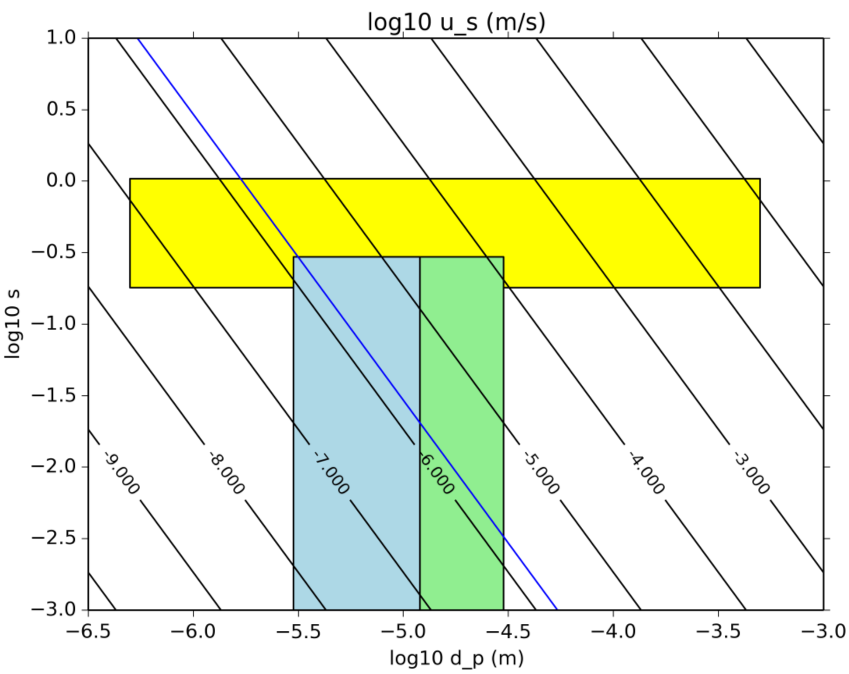

Figure 2. Contour plot of settling velocity u_s as a function of particle diameter d_p and excess density $\boldsymbol{s} = (\boldsymbol{\rho_p} - \boldsymbol{\rho_f})/\boldsymbol{\rho_f}$. The blue rectangle shows common conditions for Dutch DWDSs. The green rectangle shows additional common conditions for DWDSs in the U.K.. The yellow rectangle shows additional conditions found in the Australian DWDSs.

3.2 Critical wall shear stress for incipient motion and resuspension of particles

Initiation of particle motion is often determined using a non-dimensionalization of the shear stress, known as the Shields number θ, e.g., (Shields, 1936):

$$\theta = \frac{\tau_*}{(\rho_p - \rho_f) g d_p} = \frac{\bar{u}_f^2 C_f}{8 s g d_p}. \qquad (5)$$

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The Shields number gives the ratio of shear force exerted on the particle by the fluid and the particle's mass density. In principle, particle motion initiates when the shear stress near the sediment bed becomes larger than a critical value, $\theta > \theta_c$. In sediment transport literature the Shields diagram gives an empirical relationship for θ_c as a function of the boundary Reynolds number $Re_* = \frac{u_* d_p}{\nu}$ (Shields, 1936;Arolla and Desjardins, 2015). Although the Shields diagram is based on experiments with rectangular channels, it provides a starting point for cylindrically shaped pipes.

Figure 3 shows how larger fluid velocity and smaller particles promote the propensity to incipient particle motion (increasing θ). For increasing particle size, d_p ($1\cdot10^{-6}$ to $1\cdot10^{-5}$ *m)* and fluid flow velocity, $\bar{u}_f$ (0.01 to 0.1 m·s^{-1}) the boundary Reynolds number increases from $1.4\cdot10^{-3}$ to 14 and θ_c decreases from ~10 to ~0.05. The former value is a rough extrapolation from the Shields diagram and needs to be validated empirically. At an intermediate value of $\theta_c = 1$, the associated critical fluid velocity is $\bar{u}_{f,c}$=0.063 m·s^{-1}. By comparison, a default, fixed deposition velocity of 0.07 m·s^{-1} was derived from experiments on particle transport at conditions common to the Australian DWDSs (Ryan et al., 2008).

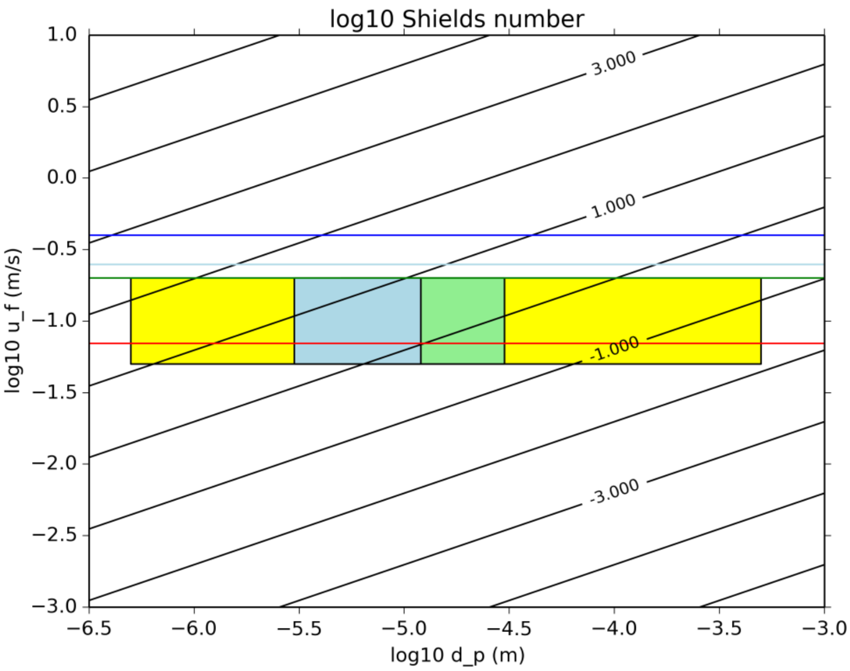

Figure 3. Contour plot of Shields number as a function of average fluid velocity $\bar{u}_f$ and excess density $\boldsymbol{s = (\rho_p - \rho_f)/\rho_f}$. The blue, green and yellow rectangles show common Dutch, U.K., and Australian drinking water conditions, respectively (see Table **2**). Blue, light-blue, green and red lines indicate a proposed (upper limit) of self-cleaning velocity of 0.4 m·s^{-1} (Vreeburg, 2007), a self-cleaning velocity of 0.25 m·s^{-1} (Blokker, 2010), default resuspension (0.2 m·s^{-1}) and deposition (0.07 m·s^{-1}) velocities for Australian DWDSs (Ryan et al., 2008). The threshold Shields number for incipient motion, $\boldsymbol{\theta_c}$, is estimated to vary between 0.05-10. Associated log$_{10}$-values are -1.3 and 1. The resuspension threshold is $\boldsymbol{\theta_{rs} \approx 10\theta_c}$ (see text) and thus varies between 0.5 and 100 (log$_{10}$-values of -0.3 and 2).

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Resuspension of particles occurs above a critical wall shear stress for entrainment by the passing fluid, θ_{rs}. The hydrodynamic forces and torque on a particle sitting on a bed with a destabilizing turbulent flow were developed in a model by Lee and Balachandar (2012). Entrainment occurs when the lift force on a particle exceeds the gravitational force and their model demonstrates that —similar to the threshold for incipient motion— the decrease in $\theta_{rs}$is nearly inversely proportional to Re_*, but values of θ_{rs} are approximately an order of magnitude larger than θ_c for Re_* <1. At Re_* =1, the resuspension threshold shear stress is $\theta_{rs} \approx 1$. By comparison, $\theta_c/\theta_{rs} \approx 0.1$ is similar to the ratio derived from default fluid velocity thresholds from experiments with drinking water from Australian utilities (u_c==0.07 m·s^{-1}, u_{rs}=0.20 m·s^{-1}, (Ryan et al., 2008)), i.e. $(u_c/u_{rs})^2 = 0.12$. The predictive power of a constant resuspension *velocity* threshold instead of a variable *shear stress* threshold , may be sufficient for narrow particle diameters and density ranges (such as those of the Netherlands and the U.K.), but are expected to become inexact for wider parameter ranges.

3.3 Bed-load transport, velocity and concentration profile

At moderate shear stresses, a fraction of particles on a bed can mobilize by means of sliding, rolling, and saltating, while maintaining contact with the immobile part of the sediment. The sediment bed is not resuspended but able to move relative to the fixed substrate at a fraction of the bulk flow velocity. This process is known as bed-load transport and plausibly occurs at wall shear stresses in between the threshold values for incipient motion, θ_c, and resuspension, θ_{rs} (Figure 1). We apply the commonly used expression for the (non-dimensional) bed-load transport rate, ϕ_B, known as the Meyer-Peter and Müller equation (Meyer-Peter and Müller, 1948):

$$\phi_B = 8(\theta - \theta_c)^{3/2}, \quad \textbf{6}$$

Experiments with turbulent water flows over a granular bed in rectangular channels by Florez and de Morales Franklin (2016) validated the Meyer-Peter and Müller close to the threshold region. They also demonstrated that far from the threshold region the experimental data better fits a $(\theta - \theta_c)^{5/2}$ function, but this was not taken into account in our model, because a comprehensive description is not available. Unsurprisingly, ϕ_B is a function of the Shields number, and only applies above the threshold shear stress for incipient motion, θ_c. The dimensional volumetric bed-load transport rate per unit width (in the cross-sectional direction of a rectangular channel) is

$$q_B = \phi_B \sqrt{sgd^3}. \quad \textbf{7}$$

The total volumetric bed-load mass transport rate is Eq. 7 multiplied by the effective channel width, for which we adopt the pipe radius (D/2):

$$Q_B = q_B D/2. \quad \textbf{8}$$

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The bed-load velocity u_B is readily derived:

$$u_B = \frac{Q_B}{A_B} = \frac{Q_B \rho_p}{m_B}, \quad \mathbf{9}$$

with A_B the surface of the bed in the cross-sectional direction and m_B the mass per unit length of pipe. Because transport is likely affected by boundary wall effects and the effective channel width may differ from *D/2*, transport rates should be verified for cylindrically shaped pipes.

Below the resuspension threshold, settled and suspended particles coexist. The associated vertical concentration profile and ratio of suspended to bed-load can be compared to predictions using the non-dimensional Rouse number, *P*. The Rouse number is the ratio between settling and upward velocity of suspended particles and used in fluid dynamics to define the transport mode and vertical concentration profile of suspended sediments (Rouse, 1937):

$$P = \frac{u_s}{\kappa u_*} \quad , \quad \mathbf{10}$$

with κ the von Kármán constant (κ ≈ 0.4). Experimentally derived *P*-values delimit the transport mode: stagnant sediment (*P*>7.5), bed- load transport (2.5<*P*<7.5), 50% suspended load (1.2<*P*<2.5), and 100% suspended load (*P*<1.2). We do not consider the condition for wash load (*P*<0.8), because it does not apply to closed pipes. The Rouse number also defines the concentration profile, derived from the diffusion equation (Rouse, 1937):

$$\frac{c(z)}{c(a)} = [(\frac{h-z}{x})(\frac{a}{h-a})]^P, \quad \mathbf{11}$$

with $c(z)$ the concentration at height z above the mean bed , $c(a)$ the reference concentration at a reference height z=*a*, *h* the water depth . The reference height *a* is generally taken as 0.05*h*. Eq. 11 implies steeper concentration values for larger *P*-values. This is relevant because lance measurements can probe the concentration at different depths and thus have the potential to verify concentration profiles. It should be verified, however, experimentally or theoretically to what extent concentration profiles in closed cylindrically shaped pipes follow Rouse's concentration profile derived for open channels .

4 Outlook and concluding remarks

The theoretical assessment presented in this paper serves as a basis for the development of a numerical tool aimed to improve understanding of particle transport and discoloration risk in DWDSs. This requires coupling of the particle transport model to a hydraulic distribution network model to quantify mass accumulation in the sediment and fluid phase. Ultimately, this can help to set up more efficient cleaning and measurement programs and assist operators and managers in pipe remediation strategies and the optimization of network designs used in the (re)construction of DWDSs.

Our analysis shows that for common DWDS conditions, a large range of settling velocities u_s, and shear stress thresholds for incipient motion, θ_c, and resuspension, θ_{rs}, can be expected, because of the strong sensitivity to the average

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bulk flow velocity $\bar{u}_f$, particle diameter, d_p, and density, ρ_p. The theoretical model predicts u_s, θ_c, and θ_{rs} values that are compatible with previously determined values of θ_c and θ_{rs} (or their velocity counterparts) and u_s that were derived from field measurements and modeling for Dutch DWDSs (Vreeburg, 2007;Blokker, 2010) or lab experiments with drinking water from Australian utilities (Ryan et al., 2008). However, a model that takes into account these dependencies is expected to result in a more comprehensive and generically applicable model to determine particle accumulation. Further work is required, however, to assess how the influence of turbulent diffusion, dispersion and transport characteristics based on the Rouse number can be used to improve the particle transport model. Although we primarily focus on hydraulic influences on particles, complex interactions with microbiological and/or chemical processes, as well as the influence of culverts, valves, junctions, etc, may hamper successful model predictions. A future comparison with field measurements and previously developed models is planned to evaluate the model results.

Laboratory and field experiments under controlled conditions are recommended to better understand the complex interplay between particle transport and particle properties, and hydraulic and pipe conditions. Validation of u_s, θ_c, θ_{rs}-values, bed-load transport rate, and vertical concentration profiles from experiments with pipes of circular cross-section is particularly important , because the theoretical relationship considered in this paper are largely derived from experiments using rectangular channels with different boundary wall effects than drinking water pipes.

Field measurements will be used in future model development. For example, because measured vertical concentration gradients suggest bed-load transport as a viable mechanism in DWDSs, we will investigate bed-load transport in real DWDSs. We will also examine if field measurements can provide independent estimates for settling velocity and threshold conditions for incipient motions and resuspension for model calibration purposes. Furthermore, extensive field measurements from cleaning actions of several Dutch water companies will be compared to temporal and spatial accumulation patterns from the future model.

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