Field campaign on sediment transport behaviour in a pressure main from pumping station to wastewater treatment plant in Berlin

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ABSTRACT

As part of the project KURAS, the Berliner Wasserbetriebe realized a field campaign in 2015 in order to increase the process knowledge regarding the behaviour of transported sediment in the pressure main leading from the pumpstation to the wastewater treatment plant. The field campaign was conducted because of a lack of knowledge about the general condition of the pressure main due to its bad accessibility and the suspicion of deposits caused by hydraulic underload. The practical evidence of the sediment transport performance of this part of the sewer system, dependent on different load cases, should present a basis for further analysis, for example regarding flushing measures. A positive side-effect of the investigation was the description of the amount of pollutants caused by different weather conditions in combined sewer systems and the alterations of the sewage composition due to biogenic processes during transport. The concept included the parallel sampling of the inflow at the pumpstation and the outflow at the end of the pressure main during different weather conditions. By calculating the inflow to the pressure main, as well as its outflow at different flow conditions, it was possible to draw conclusions in regard to the transport behaviour of sediment and the bioprocesses within an 8.5 km section of the pressure main. The results show clearly that the effects of sedimentation and remobilization depend on the flow conditions. The balance of the total suspended solids (TSS) load during daily variations in dry weather shows that the remobilization effect during the run-off peak is not able to compensate for the period of sedimentation happening during the low flow at night. Based on the data for dry weather, an average of 238 kg of TSS deposits in the pressure main remains per day. The remobilization of sediment occurs only due to the abruptly increased delivery rates caused by precipitation events. These high pollution loads lead to a sudden strain at the wastewater treatment plant. It was found that the sediment transport behaviour is characterized by sedimentation up to a flow velocity of 0.35 m/s, while remobilization effects occur above 0.5 m/s. The assumption of bad sediment transport performance in the pressure main was confirmed. Therefore, the results can be used as a basis for further analysis, for example regarding periodical flushing as a means of cleaning the pressure main. The findings, especially regarding the methods and processes, are transferable and can be applied to other pressure mains in combined sewer systems. Besides the outlined evaluation of the sediment transport behaviour of the pressure main, the collected data were used in the project to calibrate a sewer system model, including a water quality model for the catchment area, and as a contribution towards an early physically based sediment transport modelling in InfoWorks CS.

Key words | combined sewer system, field campaign, pressure main, sediment transport

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INTRODUCTION

The drastic reduction of domestic wastewater while maintaining a steady pollution load and the reduction of sewer infiltration by groundwater cause a distinct decrease in the flow velocity, resulting in the wastewater staying in the pressure main and sewer network for an extended amount of time during dry weather conditions. In addition, the sewage composition has

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changed over the past years due to a higher percentage of textiles. This results in an increased sedimentation of pulp and solids, the formation of hydrogen sulphides and a shift in the ratio of carbon and nutrients of the sewage during low flow (Tränckner 2013). During storm events, on the other hand, the hydraulic load limit becomes apparent, leading to an increase in combined sewage overflow, flooding within the sewer system and impact loads at the wastewater treatment plant (overload).

The project 'Konzepte urbaner Regenwasserbewirtschaftung und Abwassersysteme' (KURAS) ('concepts of urban storm water management and sewage systems') was funded by the German Federal Ministry of Education and Research (BMBF). It analyses the characteristics of the wastewater discharge within the complete system (surface, sewer network, pump station, pressure main and wastewater treatment plant) during different loading conditions and develops primary solutions for prospective system operations. Special emphasis is given to the underload. In order to be able to deal with future operative challenges caused by underload, it is necessary to locate the problems, to quantify them and to understand their cause. The improvement of the system and process knowledge regarding sediment transport in the sewer and pressure main network under different hydraulic conditions is therefore essential, in order to increase the flexibility of the existing system.

The pressure mains are especially sensitive to a reduction of wastewater due to underload, since the reduction of flow within fully filled pipes with a constant cross-section leads directly to a reduction of the velocity of flow.

An unpredictable and sudden strain with high pollutants at the wastewater treatment plant, due to remobilization of deposits during storm events, challenges the operation of the mechanical sewage purification (screen, grit chamber) and substantiates the suspicion of sediment transport problems and deposits within the pressure mains.

Because of the bad accessibility of the subsystem, more practical evidence about deposits in pressure mains was needed as a basis for further investigations (Aldea *et al.* 2011). Therefore this field campaign is focused on the quantification of the sediment transport behaviour and the change in the sewage composition within the pressure main.

THEORETICAL BACKGROUND

Sediment transport

The sediment transport in sewers is a complex process. It depends on fluid properties (viscosity, carrying capacity, etc.), particle properties (shape, size, density, composition, cohesion, etc.) and transport relevant flow conditions (velocity of flow, shear stress, etc.) (Kirchheim 2005).

Sewage can be described as an inhomogeneous fluid, with its composition as well as its ingredients having a wide spectrum of variations (inorganic compounds such as sand, organic waste, textile pulp, etc.) (Koppe & Stozek 1993). Similarly, sediments are heterogeneous conglomerates with spatiotemporal variations. The reasons lie in the different sources of suspended solids, biochemical processes, ageing of sediments (solidification, consolidation, etc.) and also rearrangements (erosion, transport and sedimentation) as a function of varying flow conditions (Crabtree 1988).

The sedimentation process of deposits is generally caused by a flow condition with its velocity below the critical minimum and by oversaturation of the carrying capacity. Lows of discharge in the diurnal variation of dry periods, backflow effects and disadvantageous constructional design of sewers can reduce the velocity of flow and can lead to sedimentation (Kirchheim 2005). On the other hand, daily peaks of discharge and storm water run-off can result in discharge waves that lead to erosion and the transport of sediments. Due to long dry periods, daily peaks of discharge are usually not enough for a complete flushing of the sewerage system.

The critical flow condition describes the transition from sedimentation to erosion and transport. Relevant parameters are the critical velocity of flow and the critical shear stress. Shear stress is caused by inner (viscosity of the fluid) and outer friction (interface). An advantage of using shear stress to define critical flow conditions is that the influence of turbulent flow and roughness from the interface is directly included (Bouteligier *et al.* 2002). Still, due to the difference in composition of suspended solids and sediments, it is not possible to precisely specify critical values for sedimentation and erosion (Lange 2013). Worksheet DWA A110 recommends to avoid a shear stress below the limit of 1 N/m^2 in order to prevent sedimentation (DWA 2006).

Underload

The hydraulic underload of a sewer system leads to several negative effects, which have consequences on sewer operations. The low amount of wastewater leads mainly to a reduction in flow velocity below the hydraulic necessary minimum for the transport of suspended solids in the wastewater. This results in different subsequent problems, which are illustrated in Figure 1.

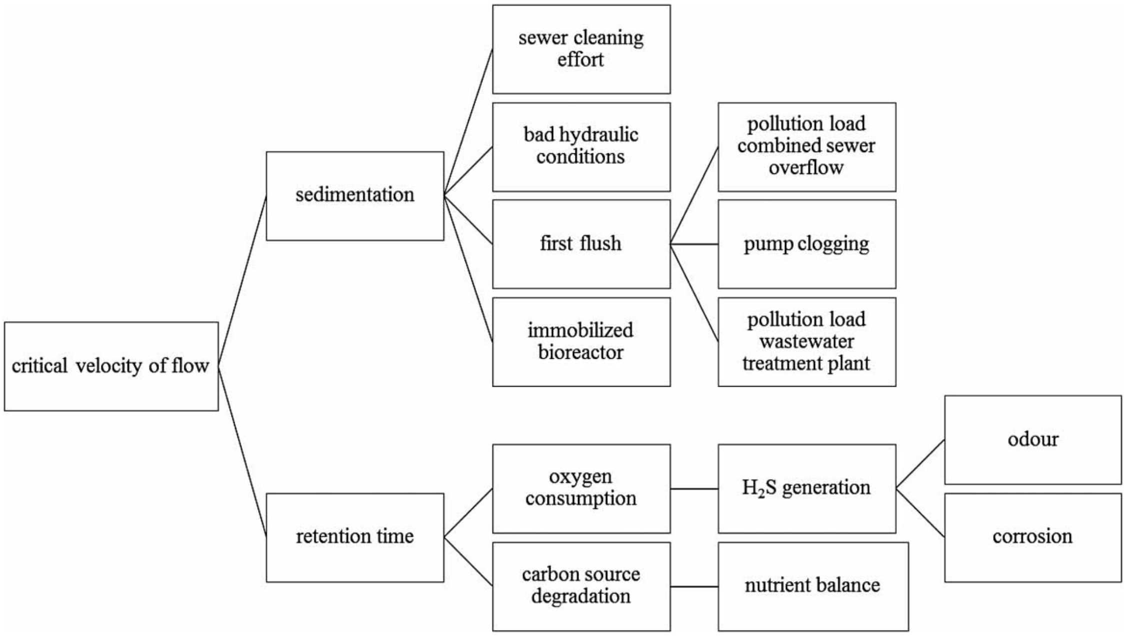

Figure 1 | Consequences of underload.

Problems due to underload conditions are visible in nearly all parts of the wastewater system. Sewers, pumping stations, pressure mains, screening plants and wastewater treatment plants are affected (Aldea *et al.* 2011; Lange 2013; Tränckner 2013). Usually, discharge routes that are filled out with wastewater, like culverts and pressure mains, are affected earlier by sediment transport problems than partly filled sewers. The main reason is that a reduced amount of sewage, and thereby a reduction of flow in a sewer with a constant cross-section area, has a direct impact on the flow velocity. Partly filled free-flow sewers are able to react more dynamically according to their profile.

Respectively, pressure mains represent an endangered element of the wastewater system, in which low velocity of flow and long retention times notably affect sedimentation and biological degradation.

FIELD CAMPAIGN

In 2015 the Berliner Wasserbetriebe performed a field campaign in the project KURAS to improve the knowledge about the sediment transport behaviour in the pressure main connecting the pumping station and the wastewater treatment plant.

Goal

One of the goals of the KURAS project was the calibration and validation of the physically based model of the pollution load in the sewage network with InfoWorks CS. Therefore, it was necessary to characterize the accumulation of pollutant in the combined sewer system during dry weather periods, as well as storm events.

The primary objective of the field campaign and the presented paper was to describe the sediment transport behaviour in order to get a better idea of the conditions in the pressure main and to quantify the load arriving at the wastewater treatment plant. This improvement of knowledge about sediment transport processes and biological degradation in pressure mains is necessary when thinking about measures to reduce underload problems in the wastewater system. Therefore, this project focused on the characterization of alterations in the sewage composition that are dependent on the retention time, as well as on the sedimentation or remobilization as results of varying hydraulic conditions.

A positive subordinate side-effect of the field campaign was that the collected data could also be used to validate a physically based model about sediment transport in InfoWorks CS. If sediment transport behaviour becomes quantifiable through physically based modelling in the future, optimization and adaptation of the sewer system would become much easier for prospective developments (Zug *et al.* 1998).

Model area

The model area examined in the KURAS project is an exemplary drainage system of municipal sewers. The catchment area of the sewerage is located in the central southwest of Berlin and is connected to the main pump station Wilmersdorf. It consists of one big combined sewer system connected with several separated sewer systems. This city area has a population of 263,000 and encompasses 31 km^2. The settlement structure shows a high variety in population density with little industry and is therefore representative of municipal wastewater. The wastewater reaches a volume of approximately 40,000 m^3 per day during dry weather conditions. The whole sewer network is generally very flat, which leads under dry weather conditions to increased problems with sediment transport and during overload to a backflow effect.

The pressure main from the main pump station Wilmersdorf to the wastewater treatment plant Ruhleben has a total length of 9.6 km and a varying diameter from DN700 to DN1400. The average diameter weighted after the length lies at DN1250.

Method

Due to the bad accessibility of the fully filled pressure main while in operation, the analysis of deposits and sediment transport via direct measurements was not possible (Aldea *et al.* 2011). Accordingly, a concept was developed that provides information about the accumulation or reduction of solids in a subsystem by comparing the in- and output, which permits a conclusion about sedimentation and remobilization of sediments within the inaccessible pressure main.

The samplings were taken parallel at the free-flow sewer in front of the pumping station and near the end of the pressure main through a vent cock. Sampling took place time proportional over a 24 hour period in a 10 minute interval via an automated sampler. The 10-minute samples were mixed up to 12 composite samples of 2 hours over the diurnal variation.

Afterwards the samples were analysed in the laboratory. The measured parameters are TSS (total suspended solids), COD (chemical oxygen demand), dissolved COD, BOD5 (biochemical oxygen demand), P_{total} (total phosphorus), N_{total} (total nitrogen) and NH_4 (ammonium). The parameter TSS, as a description of fine, undissolved particles, was used to approximate the concentration of solids in the sewerage.

The delivery rate of the pumping station was detected by magneto-inductive flow meters. These data were used to calculate flow conditions and to associate the sampling locations (or samples) for each time of the day via the retention time in the pressure main. The retention time was calculated piecewise for each part of the 8.5 km long pressure main depending on its diameter. Storm events were recorded by three rain recorders in the catchment area. The sampled events were defined as storm events if the rain intensity exceeded 1 mm precipitation per day. Additionally, the combined sewage samples were tested for their electric conductivity to point out the influence of storm water in the samples.

RESULTS

Samples were successfully taken on 17 days over a time period of 4 months. Nine days had dry weather conditions while on eight days precipitation events occurred.

Sewage composition and volume

Dry weather conditions

The evaluation of the data regarding the delivery rate of the pump station shows a typical diurnal variation in wastewater volume during dry weather with the daily high during the morning and a significant low during the night due to the consumption rate. The measured TSS concentration, averaged over 10 minute intervals, shows a similar trend, where the daily high and low coincide with that of the wastewater, as can be seen in Figure 2. This is due to the different proportion of sewer infiltration water and wastewater from domestic homes, as well as due to the different sewer hydraulics throughout the day (i.e. variations in the flow velocity) and the sediment transport performance that is affected by that. Further parameters depend strongly on the contained suspended solids. The higher the TSS concentration, the higher the oxygen consumption parameters as well as the nutrient content of phosphorus and nitrogen. During dry weather the measured COD/BOD_5-ratio is between 2.2 to 1 and 2.8 to 1. The ideal BOD_5:N: ratio for biological sewage treatment of 100:5:1 cannot be reached because an excess of nutrients leads to a ratio of 100:(14.0–34.1):(2.2–3.7) (Knerr 2012).

Storm

Figure 3 illustrates the TSS concentration in combined sewage at the pumping station for a storm event on 22 June 2015 compared to the average pollution during dry weather conditions. At 18:00, with the start of precipitation events, a higher pollution of the combined sewage with suspended solids occurs due to the increased surface discharge. During the next hours the combined wastewater gets diluted because of the added storm water.

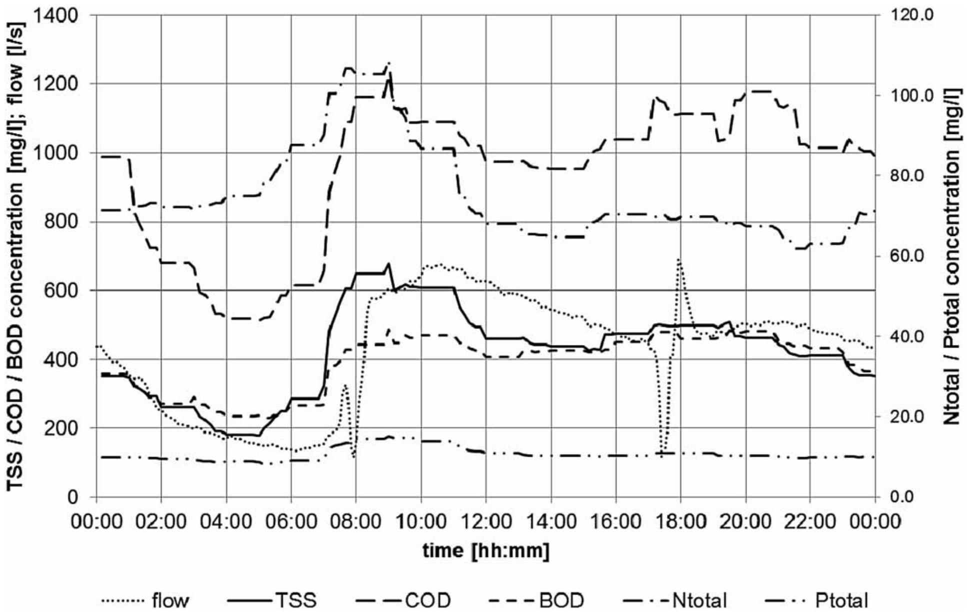

Figure 2 | Average concentration of pollutants during dry weather conditions at the pumping station.

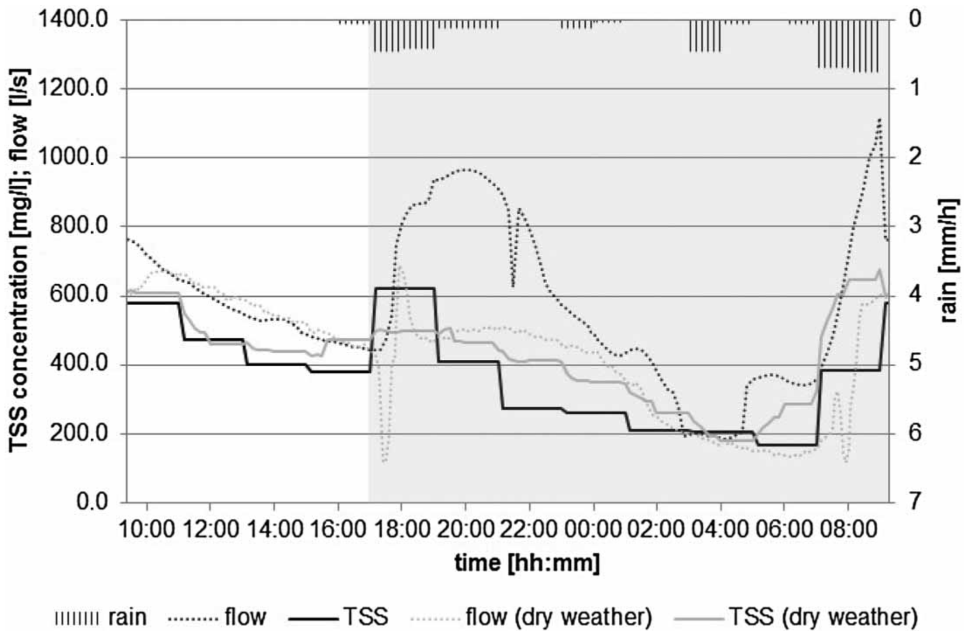

Figure 3 | TSS concentration at the pumping station during a storm event (22 June 2015).

Sewage transport

The balancing of the outflow and inflow of the pressure main shows clear differences in the concentration of TSS in the wastewater, dependent on the delivery rate.

Effects on sewage condition during the transport

In general, the parameters homogenize slightly during their way through the pressure pipes. The reasons for this effect are diffusion, retardation and acceleration of the wastewater due to changes in the diameter, as well as changes of the transporting capacity that are dependent on different particle concentrations over diurnal variation. Changes in ratio of COD, suspended COD and BOD_5 during dry periods are indicators for increased biochemical processes due to longer retention times and sediments in the pressure main.

Sediment transport

Depending on the flow, the TSS concentration at the outlet of the pressure main shows clear differences in comparison to the input. This difference between outflow and inflow of the pressure main indicates that solids accumulate in or are carried out of the subsystem and can be interpreted as sedimentation and remobilization effects of solids. Figure 4 shows the difference in TSS concentration during dry weather conditions, averaged over 10 minute intervals, while taking the retention time into account.

During the night, the TSS concentration of the outflow of the pressure main decreases in comparison to the concentration of the inflow, with the retention time taken into account. This is a consequence of sedimentation caused by a low flow velocity, leading to a negative difference in the TSS concentration. Daily peaks and sudden increases in flow rates are partly eroding existing sediment deposits and carrying them along the current. As a result the TSS concentration in the outflow increases after a higher flow velocity. Besides sedimentation during the night and remobilization at the run-off peak, a remobilization peak in the evening at 22:00 is recognizable. This can be explained by the daily flushing of the suction chamber at the pumping station, indicated by the change in flow rate at 18:00. This leads to higher TSS concentrations in the outlet, shifted by the retention time in the pressure main of 4 hours.

Figure 5 shows the average difference in TSS concentration in the pressure main depending on the flow velocity during dry weather conditions. The velocity of flow was calculated by the average diameter weighted by the length of the pressure main. Sediment transport behaviour is characterized by sedimentation with a flow velocity of up to 0.35 m/s. However, flow velocities above 0.5 m/s show remobilization effects. The transient zone between 0.35 and 0.5 m/s is not clearly explainable in the context of sediment transport. The daily flushing of the suction chamber at the pumping station and its effects on the concentration by the outlet of the pressure main, as well as on the hydraulic conditions of the pressure main, could play a role here.

Sedimentation during dry weather periods

The calculated difference in TSS loads is shown in Figure 6. The balance of the TSS loads during dry weather demonstrates that the remobilization effects of the daily peaks are not enough to compensate for the sedimentation occurring during the low discharge at night. For a dry day, an average of 238 kg of TSS sediments is calculated to remain in the pressure main.

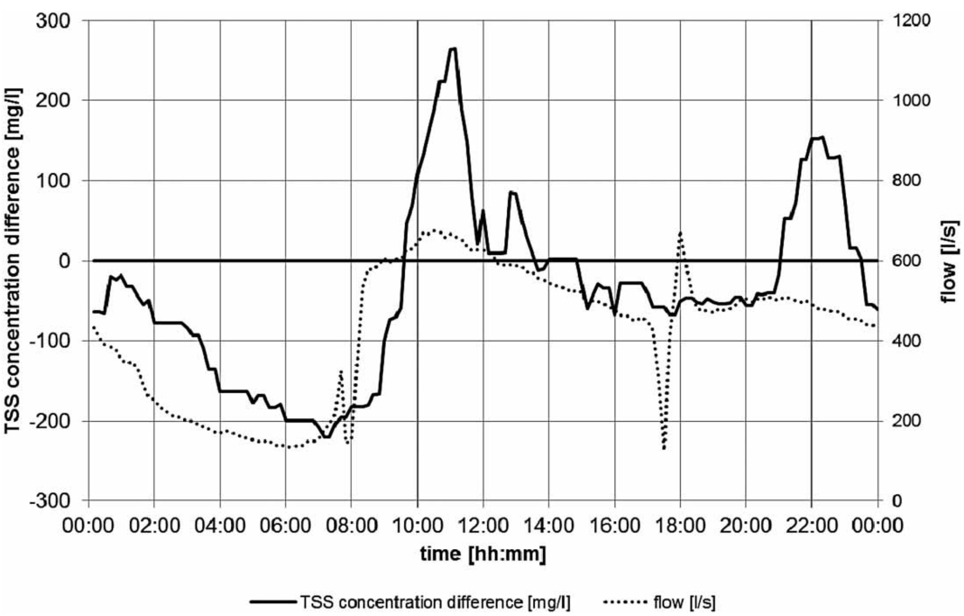

Figure 4 | Average difference in TSS concentrations between outflow and inflow of the pressure main during dry weather conditions.

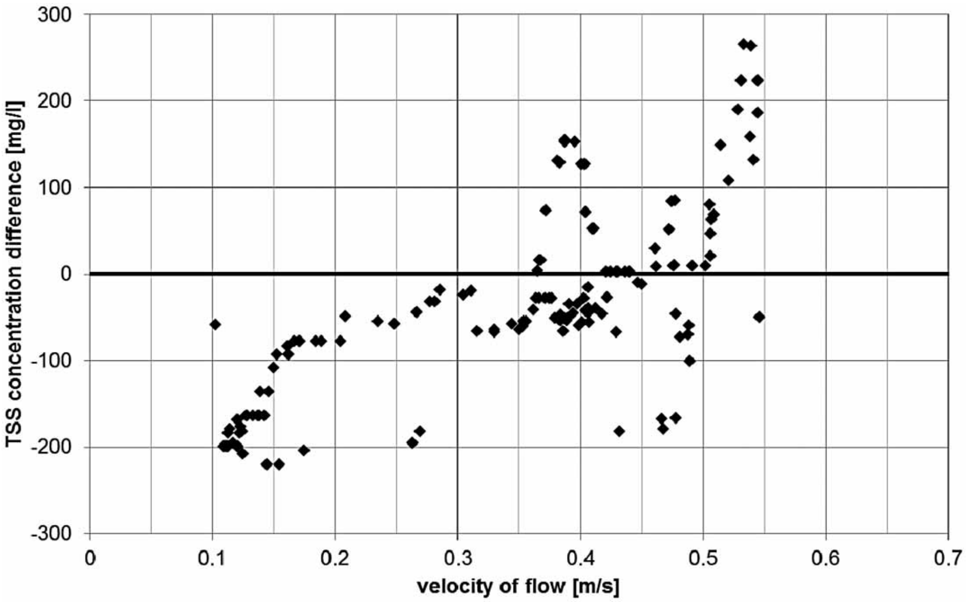

Figure 5 | Average difference in TSS concentrations between outflow and inflow of the pressure main depending on the flow velocity during dry weather conditions.

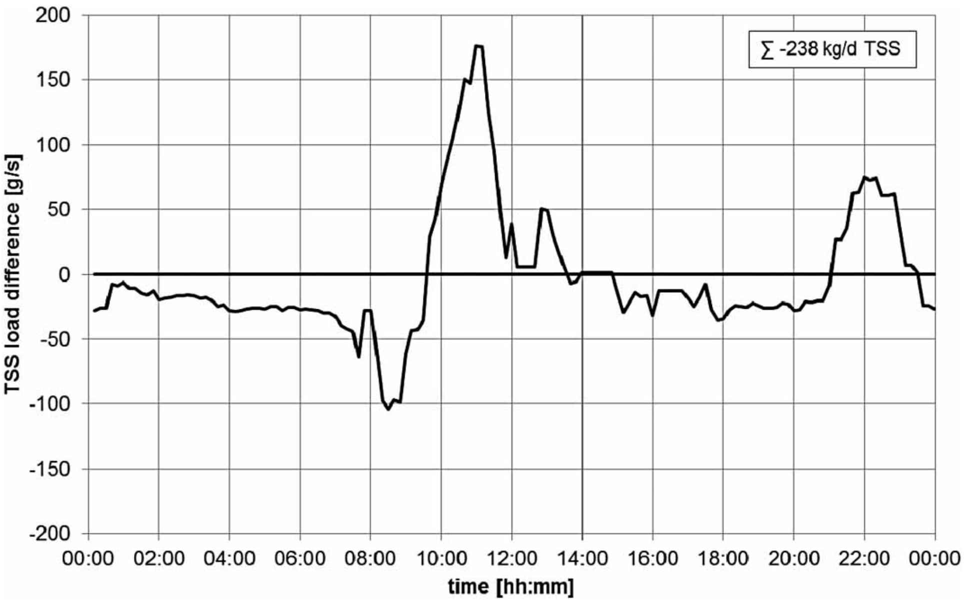

Figure 6 | Average difference in TSS loads between outflow and inflow of the pressure main during dry weather conditions.

Remobilization during storm events

Only increased flow rates as a result of storm events lead to intensive remobilization of sediments, flushing them out of the pressure main. However, because the high flow rates lead to a fast displacement of sewage and to the erosion of sediments, the wastewater treatment plant is stressed with a high pollution load in a short amount of time.

Figure 7 shows the TSS concentration for the in- and outlet of the pressure main during a storm event on 22 June 2015. The marked areas indicate that increased flow rates following storm events are leading to higher TSS concentrations in the outflow before storm water passes through the pressure main. This phenomenon can be explained by remobilization of sediments due to increasing flow rates (Dettmar 2005). So, high flow rates cause larger differences

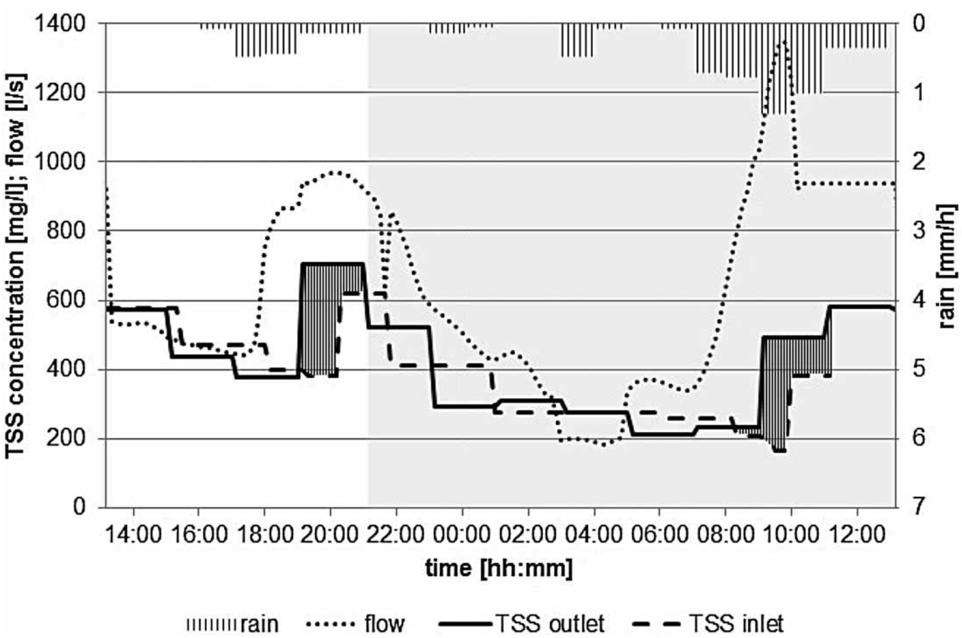

Figure 7 | TSS concentration of in- and outflow of the pressure main for a storm event (22 June 2015).

in TSS concentration between out- and inflow following a remobilization of particles out of the pressure main. The pollution peak as a result of the increased flow rate is very demanding for the wastewater treatment plant.

Sediment transport modelling

First pollutant load simulations show that sedimentation and erosion are qualitatively representable via computational physically based modelling with InfoWorks CS, though not yet quantitatively authoritative. But, without concrete data about particle size distribution and local deposits, the inhomogeneous properties of the solids are still a large challenge for the calibration of sediment transport models.

CONCLUSION

The field campaign has pointed out that sediment transport can be generally described by parallel sampling and balancing of the out- and inflow of sewer subsystems. Therefore the method is transferable to other sewer systems with bad accessibility.

The TSS concentration decreases during the transport through the 8.5 km long pressure main due to underload during dry weather flow conditions. Especially during the night, sedimentation caused by a low flow rate can be verified. Higher flow rates due to the run-off peak partly erode deposits but, all over the diurnal variation, sedimentation predominates. Therefore, the suspicion of sediment transport problems in the pressure main due to underload is confirmed.

Additional changes of the sewage composition, due to biogenic processes in the pressure main and depending on the retention time of the sewage, could be confirmed. Especially the degradation of biodegradable organic substances is important, because it leads to a shift in the ratio of carbon and nutrients and therefore to an overspill of nutrients at the biological sewage purification.

Remobilization of deposits takes place at higher flow rates following storm events. The increased flow rate, as well as the remobilization effects, causes a higher load at the outflow of the pressure main, which in turn puts a sudden strain on the mechanical sewage purification at the wastewater treatment plant.

The practical evidence about sediment transport behaviour in the considered operating sewer system (sedimentation for dry weather conditions and sudden remobilization effects due to higher flow rates) shows that it is necessary to continue investigations into this topic, and it acts as a basis for further analysis about automated regular flushing, in order to reduce or prevent the unpredictable, sudden strain on the wastewater treatment plant. The evaluation of hydraulic boundary conditions for sedimentation and erosion can serve as an indication for the design of prospective experiments.

The process knowledge about sediment transport behaviour, including hydraulic boundary conditions, is generally transferable to other combined sewer systems with similar conditions and underload problems.

While interpreting the results, the description of the solids in the sewage on the basis of the TSS concentration, has to be looked at critically, since it can only depict a small part of the ingredients of the wastewater composition. The sampling and evaluation of larger solids poses a practical problem during the realization of a field campaign about sediment transport behaviour in pressure mains. It can be assumed that larger solids require a higher velocity of flow in order to remobilize, making their transport behaviour even more critical. Thus, results on the basis of finer particles that already show negative effects of underload seem authoritative.

For future research and field campaigns, a solution should be found so that larger solids within the sewage can be also taken into account. A long-term evaluation of the screenings and accumulated sand at the wastewater treatment plant promises further potential.

The collected data on the amount of pollutants caused by different weather conditions can be seen as secondary results of the presented field campaign and can be used to calibrate a physically based model of the connected catchment area. Also, the results regarding the sediment transport processes could be compared to a physically based sediment transport model in InfoWorks CS. It is absolutely necessary to acquire further data about the particle size distribution and local deposits for the validation and calibration of sediment transport modelling approaches (Zug *et al.* 1998).

REFERENCES

Aldea, X., Massagué, A., Escaler, I. & Bertrand-Krajewski, J.-L. 2011 *PREPARED Deliverable 3.2.1: A Knowledge Base of Existing Methodologies for Sediments Monitoring in Sewer Networks*. CetAqua, Barcelona, Spain, PREPARED report 2011.006.

Bouteligier, R., Vaes, G. & Berlamont, J. 2002 *Deposition Erosion Criterion for Sediment Transport in Sewers based on Shear Stress Calculations*. Katholieke Universiteit Leuven, Leuven, Belgium.

Crabtree, R. W. 1988 *A Classification of Combined Sewer Sediment Types and Characteristics*. Report ER 324 E, WRc Engineering, Swindon, UK.

Dettmar, J. 2005 *Beitrag zur Verbesserung der Reinigung von Abwasserkanälen*. Dissertation, Fakultät für Bauingenieurwesen, Technische Hochschule Aachen (in German).

DWA 2006 ATV-DVWK Arbeitsblatt A 110. *Hydraulische Dimensionierung und Leistungsnachweis von Abwasserleitungen und -kanäle*. GFA Publishing, Hennef, Germany (in German).

Kirchheim, N. 2005 *Kanalablagerungen in der Mischkanalisation*. DWA, Hennef, Germany (in German).

Knerr, H. 2012 *Untersuchungen zur Zusammensetzung und zum Abbau von Schwarzwasser mittels des Belebungsverfahrens sowie zur Kinetik des heterotrophen und autotrophen Stoffwechsels*. Dissertation, Fachbereich Bauingenieurwesen, Technische Universität Kaiserslautern (in German).

Koppe, P. & Stozek, A. 1993 *Kommunales Abwasser – Seine Inhaltsstoffe nach Herkunft, Zusammensetzung und Reaktionen im Reinigungsprozess einschließlich Klärschlamm*, 3rd edn. Vulkan Verlag, Essen, Germany (in German).

Lange, R.-L. 2013 *Untersuchungen zum Ablagerungsverhalten in der Mischkanalisation als Grundlage der Optimierung von Reinigungsintervallen*. Dissertation, Fakultät für Bau- und Umweltingenieurwissenschaften, Ruhr-Universität Bochum (in German).

Tränckner, J. 2013 Auswirkungen des demographischen Wandels auf den Betrieb zentraler Abwassersysteme, Habilitation, Institut für Siedlungs-und Industriewasserwirtschaft, Technische Universität Dresden (in German).

Zug, M., Bellefleur, D., Phan, L. & Scrivener, O. 1998 Sediment transport model in sewer networks – a new utilisation of the Velikanov model. *Water Science and Technology* **37** (1), 187–196.

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