A STUDY OF THE OPTIMISATION OF THE FORT CUMBERLAND STORM TANK USING COMPUTATIONAL FLUID DYNAMICS

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Abstract

During periods of heavy rainfall, Eastney WPS diverts flow to the Fort Cumberland Storm Tanks which has a capacity of 40,000 m^3. Currently, flow passing to the Storm Tanks passes through 6mm 2D band screens to remove solids. The screens have been subject to excessive solids loading caused by the first flush effect within Portsmouth's relatively flat sewer.

The Storm Tank is divided in to four blind tanks connected by high level overflow weirs. Each tank is sub divided into a number of lanes by dwarf walls which were intended to channel the fluid from Vac-Flush chambers. The Vac Flush equipment has never been commissioned.

The tanks and equipment at Fort Cumberland are to be re-configured so that all flow passes through all of the tanks before it is able to pass through the band screens. All tank compartments are to be connected by creating low level openings in the inter tank walls. The aim is to pre-settle the storm sewage before it is presented to the screens, so reducing the peak solids loading that the screens need to handle.

Two alternative methods of clearing settled solids from the tank floor at the end of a fill / empty cycle were considered:

1. Hydro-ejectors, which pump flow around the tank as the tank is emptied &
2. Re-commissioned Vac Flush chambers, which would release stored volumes of water into the empty tanks from chambers at their upstream ends causing deluge flushing of the tank floor.

This paper describes a programme of work in which the proposed modifications at Fort Cumberland were analysed and optimised using Computational Fluid Dynamics. The main areas of work were:

1. Estimation of the solids distribution through the storm tank for different positions of the openings in the dividing walls in order to optimise the tank configuration.
2. Assessment of the effectiveness of hydro-ejectors at suspending settled solids.
3. Assessment of the effectiveness of the vac-flush systems at clearing settled solids from the tank floor at the end of a filling and emptying cycle.

Keywords

Computational Fluid Dynamics, Numerical Modelling, Storm Tank, Hydro-ejectors, Vac-Flush System

Introduction

Portsmouth is built on a flat island and as it has grown in size, the sewage problem has become more difficult to deal with (cnplus, 2009). It is Britain's only island city, lying mostly on Portsea Island.

Portsmouth is also one of the most densely populated places in Europe, with the only place in the British Isles that is more crowded being Central London (cnplus, 2009). Like any crowded urban community, its population imposes a heavy burden on the city's network of drains and sewers. All sewers in Portsmouth lead to Eastney Wastewater Pumping Station (WPS), which is located in the south-east corner of the city. Not only does Eastney WPS deal with all of Portsmouth's sewage, it also plays a critical role in the flood protection system for the city. Eastney WPS is therefore a key site for the entire city (cnplus, 2009).

Due to the low number of natural water courses on the flat Portsea Island, most of the excess rainwater drains to the sewage system.

Flow from Eastney WPS is pumped to Budds Farm Wastewater Treatment Works (WwTW) for treatment. Treated effluent is returned to Eastney WPS and pumped through the Eastney Long Sea Outfall (LSO) to discharge into the Solent.

When the flow arriving at Eastney WPS increases due to rainfall and exceeds the capacity of the transfer pipeline to Budds Farm WwTW, storm flows are screened and pumped (with the treated effluent) through the Eastney LSO. During more severe storm events, the total flow can exceed the capacity of the Eastney LSO and at these times, the excess flow is pumped to Fort Cumberland where it is screened and held in 40,000 m^3 storm tanks. When the flow arriving at Eastney WPS falls below the transfer capacity to Budds Farm WWTW, the Fort Cumberland storm tank contents are drained back to Eastney WPS and transferred to Budds Farm WwTW for treatment (and ultimately returned and discharged via the Eastney LSO).

Large areas of Portsmouth are below sea level, which combined with the other issues explained, makes it very vulnerable to flooding, as was experienced in 2000, 2006 and June 2007 (BBC, 2007), (cnplus, 2009).

Within 20 minutes of a storm event, there can be up to forty times the normal dry weather flow entering Eastney WPS. This can therefore fill the storm tanks in a short time scale (cnplus, 2009).

The flat nature of the Eastney catchment causes grit and other sewer debris to accumulate within the sewerage system. The arrival of a rainfall event causes a 'first flush' of this material to arrive at Eastney WPS with the storm water flows. Whilst the pumps at Eastney WPS are able to handle such solids loads it has been found that the 6mm 2D band screens at Fort Cumberland have, during such first flushes, become overloaded.

For these reasons, in 2007, Southern Water announced a £20m, multiphase, plan to provide the city with better protection against flooding. The plan included the following elements:

- Construction of an underground pumping station on the site of Eastney WPS, to provide an additional 9000 L/sec of standby storm pump capacity (Roberts & Potter, 2010). The construction began in June 2008 and the completed works became operational three months ahead of schedule in March 2010. The project was managed, designed and delivered by 4Delivery, a consortium comprising United Utilities, Costain and MWH (Roberts & Potter, 2010).

- Surface water separation work at various locations throughout Portsmouth. Construction work is on-going, having commenced in 2012 and will be completed in 2014.
- Modifications to the layout and the operational philosophy for the storm tanks and equipment at Fort Cumberland. A number of options have been considered. The option adopted is to introduce the flow from Eastney WPS into the tank upstream of the screens, thereby ensuring pre-settlement before screening.

This paper describes a programme of work in which the proposed modifications at Fort Cumberland were analysed and optimised using Computational Fluid Dynamics. The main areas of work were:

1. Estimation of the solids distribution through the storm tank for different positions of the openings in the dividing walls in order to optimise the tank configuration.
2. Assessment of the effectiveness of hydro-ejectors at suspending settled solids.
3. Assessment of the effectiveness of the vac-flush systems at clearing settled solids from the tank floor at the end of a filling and emptying cycle.

Methodology

Computational Fluid Dynamics calculations have been undertaken using the general purpose Computational Fluid Dynamics code Ansys CFX v13 and v14.

Storm Tank

The Fort Cumberland Storm Tank is subdivided in to four tanks as shown in Figure 1. It was proposed that the storm flow would be received by Tank G.

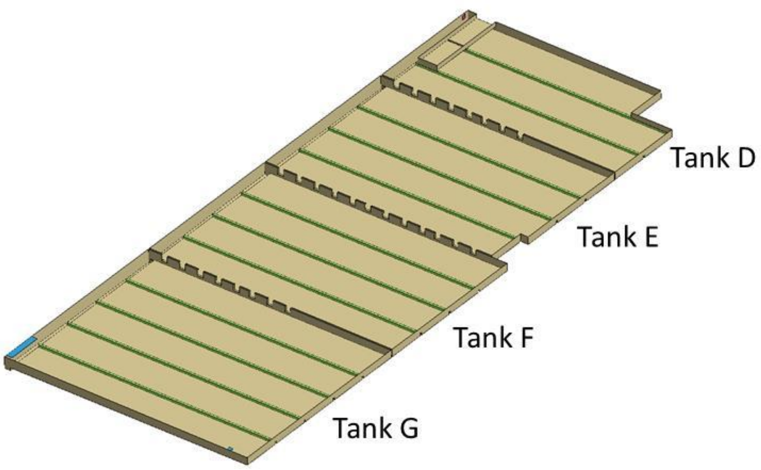

Figure 1: Fort Cumberland storm tank arrangement

The floor of the tank has a slope of approximately 0.3° to the horizontal. Dwarf walls are used to create lanes for channelling the flow from the vac flush chambers. Each dwarf wall has a constant height of 0.6 m above the tank floor. Vac flush chambers are located at the upstream end of each lane and at the downstream end there is a channel which collects the fluid and solids after vac flushing.

To investigate the effect of locating new openings in the walls at different elevations with respect to the influence on the distribution of solids within the tank, the following calculations were undertaken:

- Calculation 1 with Low Level Openings where the opening threshold was 0.6 m from the tank floor.
- Calculation 2 with Medium Level Openings where the opening threshold was located at +3m.
- Calculation 3 with High Level Openings where the opening threshold was located at +4m. In this calculation dip plates were incorporated on the upstream face of the dividing walls, as shown in Figure 2, to investigate the effectiveness of these plates at preventing floatable material from passing through the tanks.

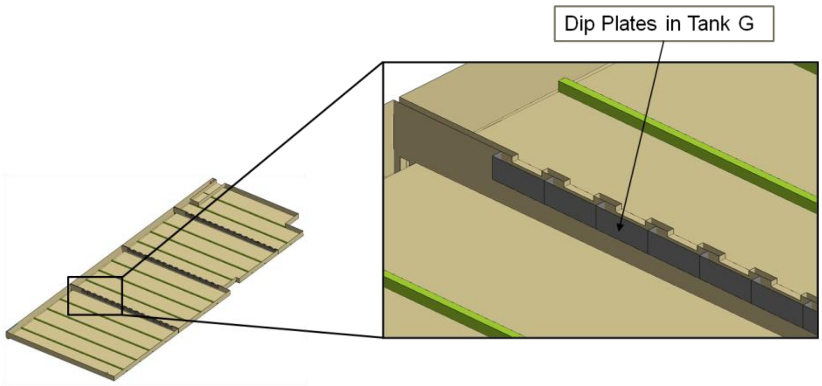

Figure 2.: Geometry of dip plates introduced in Calculation 3 with High Level Openings

The illustration of boundary conditions used is presented in Figure 3.

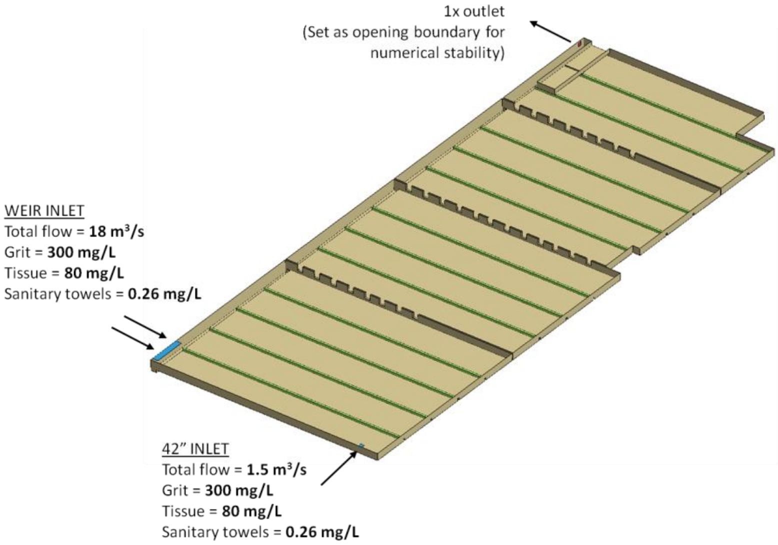

Figure 3: Boundary conditions prescribed.

Ideally the calculation to determine the distribution of solids would be solved using a free surface model that tracks the surface of the water as the tanks fill, and which therefore calculates the flow rate between the tanks based on the geometry of the openings and the head of fluid above the threshold of each opening. However, due to the computational expense of such a calculation which was estimated to take several months to complete, this wasn't a viable option. Hence, all calculations for solving the solids distribution through the storm tank were solved with the position of the free surface at a fixed location.

All calculations undertaken to determine the optimum tank configuration were solved as transient simulations. The duration of the calculations is such that a total fluid volume of 20,000 m^3 is passed in to the storm tank which was considered to be conservative. In order to approximate the effect of the tanks filling, mass sinks were applied over the entire fluid volume within each tank to remove water so that the flow in to the tanks was; Tank G: 16/16 x Q_{max}; Tank F: 11/16 x Q_{max}; Tank E: 7/16 x Q_{max}; Tank D: 3/16 x Q_{max}; where Q_{max} is the volumetric flow rate of water, being approximately 19.5 m^3/s.

The initial condition for transient calculations was that the tank contains water only. Therefore, a limitation of this approach is the initial solids concentration passed between tanks is lower than what would be present in reality due to mixing of the solids with the clean water in the tank. However, the method does provide a means of comparing different configurations of the openings in the dividing walls.

To represent the solids, the transport of ten particle size groups were solved with 5 size classes representing grit particles, 4 representing tissue and 1 representing floatable material. For solving the distribution of the solids the algebraic slip model was used, which solves a force balance on the particles to determine the particle slip velocity and tracks the mass fraction of solids within the computational domain.

Hydro-ejectors

The hydro-ejectors operate by discharging fluid from the ejector therefore generating a jet. Ideally the momentum of the jet will be sufficient to homogenise the solids that are distributed throughout the floor of the storm tank. If however, there aren't a sufficient number of hydro-ejectors operating or the ejectors aren't placed appropriately, there will remain regions with settled solids at the floor of the tank.

As tank G has the longest lanes, these were represented in a model comprising a single lane formed by the dwarf walls. The geometry of the lane was symmetrical, and therefore the flow and solids distribution in half a lane was calculated.

A schematic of a hydro-ejector and the principle of operation are presented in Figure 4. A pump is used to deliver flow (Q1) to a nozzle which is then discharged in to an ejector tube. The flow through the ejector entrains additional flow (Q2) from the tank so that the total flow through the end of the ejector (Q3) is greater than the pumped flow (Q1). In this work the nozzle is considered to be supplied with 120 L/s (Q1) and the flow through the ejector tube (Q1 + Q2) is 213 L/s.

Figure 5 shows the lane and location of the hydro-ejectors which were positioned along the centreline of the lane with one located adjacent to the channel and the other midway along the lane. The hydro-ejectors are simplified to the extent of the ejector tube only, as shown in Figure 6.

It was conservatively assumed that at the start of the calculation all the solids had settled and that a bed of solids was present where the volume fraction of solids was 0.6. This corresponds to the packing limit for monosized spheres. It was assumed that the solids within the bed were completely mixed and that the bed of solids was distributed uniformly and therefore at constant height above the floor of the tank. The mass of solids within Tank G was set to 80% of the assumed solids in a storm flow of 20,000 m^3. In order to represent the apparent viscosity of the water-solids mixture, a non-Newtonian model was implemented which was a function of the volume fraction of the solids (Brouwers, 2010).

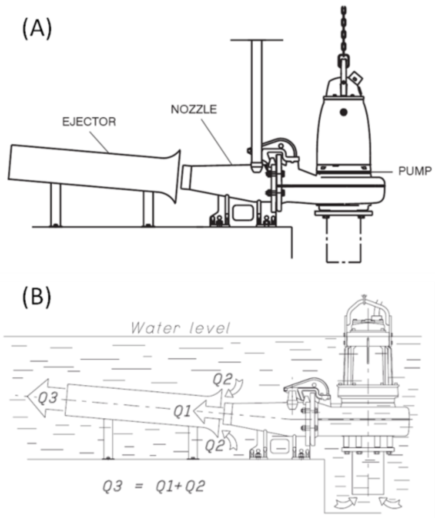

Figure 4: (A) Geometry of a hydro-ejector, and (B) a schematic of the operation of a hydro-ejector. (Figure provided by 4D).

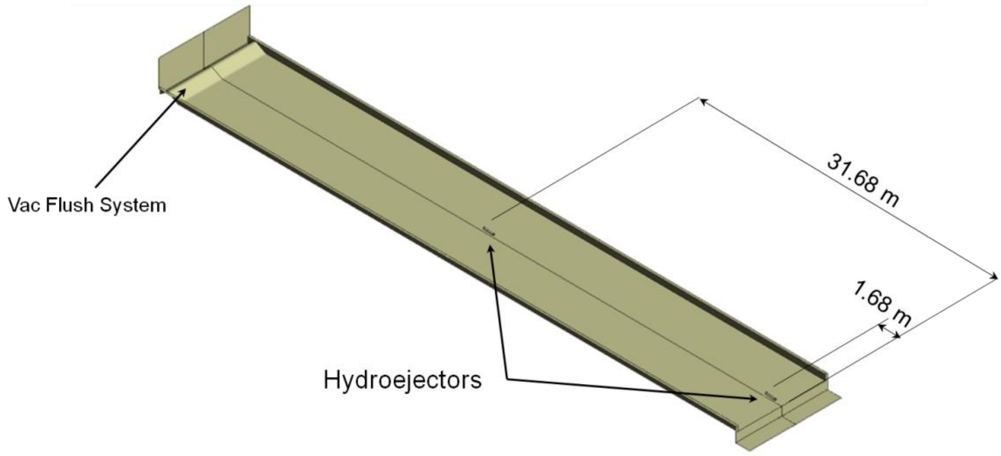

Figure 5: The geometry of a single lane representative of Tank G, with location of the hydro-ejectors.

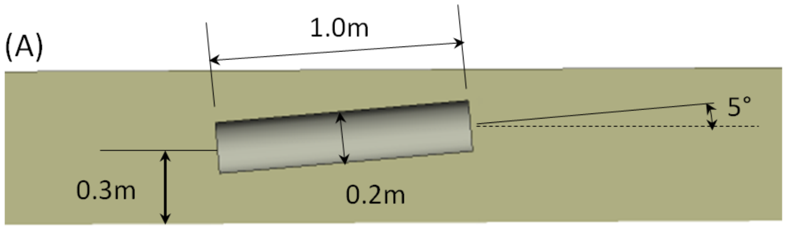

Figure 6: (A) The geometrical representation of the hydro-ejectors in the numerical model, with dimensions, and (B) flow direction through the boundaries of the hydro-ejector.

The solids represented in this calculation were the same as that used for calculating the distribution of solids in the Storm Tank with the exception that as the purpose of the calculation was to determine the effectiveness of the hydro-ejectors at homogenising a settled bed, flotable material was not represented.

Vac-Flush System

It is proposed that the vac-flush chamber will be fitted with a vac pump so that under conditions where the storm tank doesn't completely fill, the vac flush chamber will store the maximum quantity of water for optimum flushing of the tank floor.

A single lane was represented in the model and the length of the lane is representative of Tank G. Tank G was chosen as this tank contains the longest lanes and therefore the fluid will have a higher frictional head loss between the chamber and the end of the lane, which was considered to be conservative.

A small section of the adjacent lane was included at the upstream end to resolve any fluid that may overtop the dwarf walls. A section of lane at the downstream end was also included to resolve and quantify the amount of fluid that may splash back in to the adjacent lanes. Figure 7 shows the resolution of the geometry in the CFD model. The symmetry of the geometry allowed half the region shown to be resolved in the calculation.

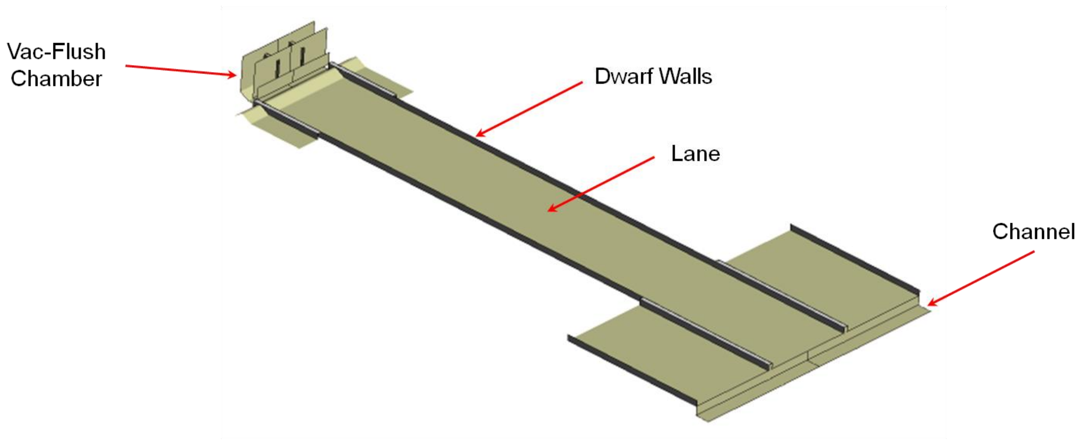

Figure 7: The geometry of the vac-flush system used in the CFD model.

The release of fluid from the flushing chamber was calculated using a 'free surface' model also known as a Volume of Fluid (VOF) model. This tracks the position of the interface between the fluid and air.

As Ansys CFX does not have any models for entrainment of solids, the potential for solids being entrained in to the flow of water was instead inferred from the Shields number and Rouse number.

The Shields number may be used to determine whether the bed shear stress exceeds the critical shear stress for incipient motion of a particle. Hence, the Shields number provides a means of estimating whether the shear stress at the floor of the tank is likely to mobilise particulates. An estimate of the critical shear stress has been made for the same particle characteristics as investigated by Adamsson, *et al.* (2003) and is 0.075 Pa. This is of the same order as determined by Adamsson, *et al*. (2003) which provides confidence in the use of the Shields number.

The Rouse number may be used to estimate the way in which the particle will be transported e.g. a bed load, suspended load or mixed load. From Reference 10, the mode of particle transport is:

- 1/(Rouse Number) > 3.33, a suspended load can be expected.
- 1/(Rouse Number) < 0.33, a bed load can be expected.
- Between 0.33 and 3.33, a mixed load can be expected.

The free surface CFD model is used to determine the flow of water down the lane and hence the shear stress at the floor of the tank. The calculated shear stress is then used to compare against the critical shear stress calculated from the Shields number, in order to infer if there will be incipient motion of particulates. If incipient motion is expected, the calculated shear stress is used to determine the Rouse number and hence infer the mode of particle transport.

The limitation of these calculations is that the accumulation of solids in the fluid is not taken in to consideration.

Solids Characteristics

The grit characteristics have been taken from an EPA report (Fan, Jan 2004). The total solids concentration of grit at the inlet is assumed to be 300 mg/L (Fan, Jan 2004). It is assumed that the solids density is close to that of sand and hence, a specific gravity of 2.65 has been used in this work (Calomino, *et al.*, 2007). The five size classes of grit used in this work are provided in

Table **1**. The settling data from Digman (2012) for tissue paper was used to generate 4 size groups.

In the absence of data relating to the mass of the tissue samples, a total solids concentration of 80 mg/L was distributed between the size groups based on the number of tissue samples in each settling group. A concentration of 80 mg/L is based on data provided by 4D and is a GROSSIM output.

Table 1: Settling velocity and concentration of five size classes of grit used in the CFD calculations

Size	Settling velocity	% mass of grit particles	Concentration
µm	cm/s	%	mg/L
2000	30.00	1	3.0
1500	20.77	2	6.1
542	7.70	9	27.5
132	1.04	35	104.1
33	0.07	53	159.2

The settling data provided in Digman (2012) was used to determine an average rise velocity of sanitary towels i.e. floatable material.

Results

Solids Distribution within the Storm Tank

In calculations 1, 2 and 3, the openings in the dividing walls are set to three different levels which are simplistically referred to as 'low', 'medium' and 'high', respectively.

Table 2 compares the distribution of the total mass of solids, which demonstrates that for the Low and Medium Level Openings, there isn't a significant difference in the distribution of solids. With High Level Openings however, Tank G contains approximately 10% more solids and Tank E approximately 10% less i.e. High Level Openings tend to hold back the solids resulting in more solids in the first two tanks.

Table 2: **Distribution of solids in each tank as a percentage of the total mass of solids.**

	% of total mass of solids		
	Calculation 1 Low Level Openings	**Calculation 2** Mid Level Openings	**Calculation 3** High Level Openings
Tank D	1 %	3 %	<1 %
Tank E	20 %	19 %	9 %
Tank F	26 %	26 %	30 %
Tank G	53 %	52 %	61 %

Table 3 compares the distribution of floatable material. For the case with High Level Openings, dip plates were included in the model, and these cause 98% of the floatables to be trapped within the first two tanks, i.e. Tank G and Tank F, and only 2% of floatables reach the third tank. Comparable results were obtained for Low and Mid Level Openings where more than 20% of the floatables are in the last tank (Tank D).

Table 3: **Distribution of floatables in each tank as a percentage of the total mass of floatables.**

	% of total mass of floatables		
	Calculation 1 Low Level Openings	**Calculation 2** Mid Level Openings	**Calculation 3** High Level Openings
Tank D	21 %	26 %	<<1 %
Tank E	38 %	23 %	2 %
Tank F	20 %	32 %	76 %
Tank G	21 %	19 %	22 %

Hence, for the purpose of preventing solids from reaching the screens, High Level Openings with dip plates are the most effective.

Hydro-ejectors

The mode of particle transport was estimated from the Rouse number using the floor shear stress calculated in the CFD model and is presented in Table 4. This suggests that 33 and 132 micron grit particles will be transported in suspension and as a mixed load respectively, and the three size classes of tissue with the lowest settling velocity transported as a mixed load. All other particulates are expected to be transported as a bed load i.e. with minimal resuspension.

Table 4: Estimated mode of particle transport based on the Rouse number (Udo & Mano, 2011).

Particle Group	Transport Mode
Grits	
33 microns	Suspension
132 microns	Mixed Load
542 microns	Bed Load
1500 microns	Bed Load
2000 microns	Bed Load
Tissues	
#1	Mixed Load
#2	Mixed Load
#3	Mixed Load
#4	Bed Load

Figure 8 presents the mass of suspended solids in each size group as a percentage of the mass of the respective size group within the lane. The mass of suspended solids is defined as the mass of solids above the top of the hydro-ejector tubes. It can be observed that there is no noticeable resuspension of any grit particles at 542 microns or larger, and this represents 10% of the total mass of solids which remains below the top of the ejector tubes. From the Rouse number analysis presented above, this result is as expected. Over the 3 min 40s duration, no more than approximately 30% of any particle size group is resuspended, with the exception of 33 micron grit particles.

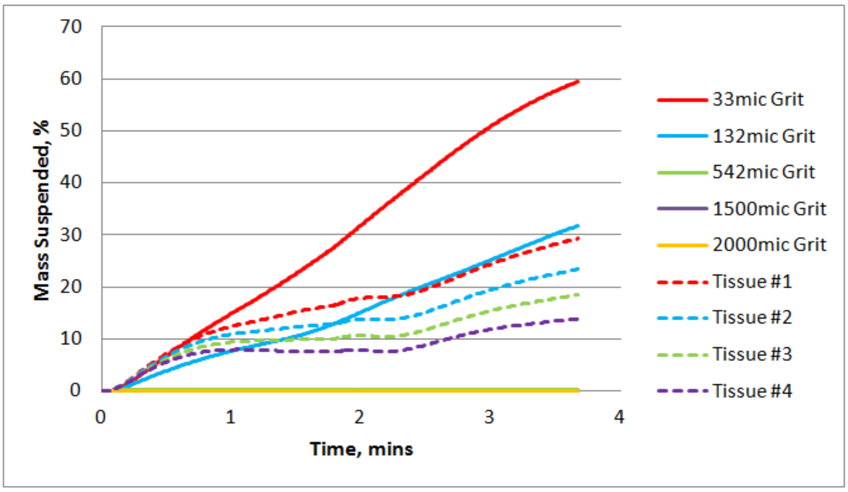

Figure 8: The mass of suspended solids in each size group as a percentage of the mass of the respective size group within the lane

A view of the solids distribution at 1 min 12 s is presented in Figure 9. This shows that a solids load is transported along the floor of the lane directly towards the vac-flush chamber. Some of this solids load could potentially be deposited close to or within the chamber, therefore increasing the solids load to be flushed by the vac-flush system. This result suggests that it may therefore be beneficial to relocate the hydro-ejector adjacent to the channel to the vac flush chamber and reverse the flow direction of both hydro-ejectors so that solids are transported towards the channel.

Figure 10 shows that although approximately 40% of the solids are resuspended at 3 mins 40, the solids remain stratified within the tank. This approximately reflects the mixed load condition estimated from the floor shear stress.

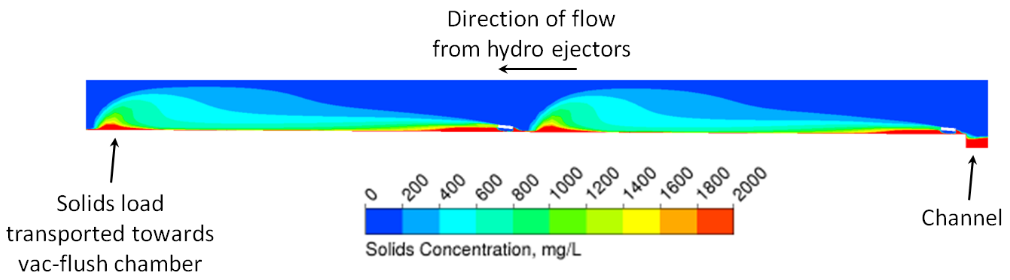

Figure 9: Solids distribution at 1 min 12 seconds plotted on a surface along the lane.

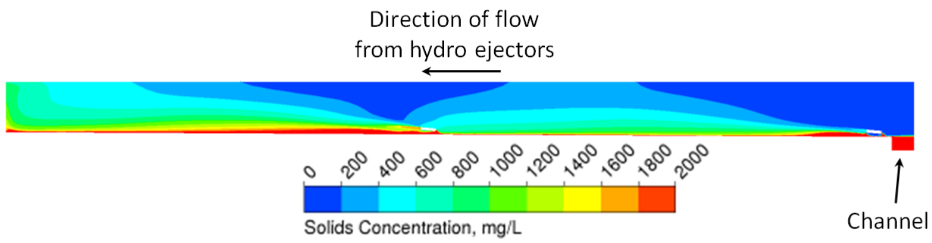

Figure 10: Solids distribution at 3 min 40 seconds plotted on a surface along the lane.

Solids Concentrations after Drain Down & Vac Flushing

To quantify the benefit provided by the hydro-ejectors, the solids concentration after vac flushing has been estimated assuming the vac-flush system is 100% efficient and that the solids remain completely mixed during drain down. It was also assumed that the percentage of solids entrained at the end of the CFD calculation at 3 minutes 40 seconds is representative of the quantity of solids resuspended for all tanks.

Table 5 presents the solids concentration in the fluid after vac-flushing for the tanks with high level openings. On average, it is estimated that there is a ~44% reduction in the solids concentration when mixers are used and that the hydro-ejectors are beneficial in reducing the solids load to be dealt with by the vac flush system and the pumps used to transfer the waste from the tank.

Table 5: Solids concentration in the tanks after vac-flushing.

	Solids Concentration, mg/L		
	Without Mixers	With Mixers	Reduction, %
High Level Openings			
Tank D	141	60	57
Tank E	3,653	1,783	51

Tank F	12,000	6,719	44
Tank G	19,790	13,098	34

Vac-Flush

The distribution of water at the chamber and the end of the lane at 3.5 and 14 s respectively is presented in **Error! Reference source not found.**. A small quantity of fluid (approximately 1%) overtops the dwarf walls upon release of the fluid. There is no significant quantity of fluid that splashes back from the channel in to the adjacent lanes.

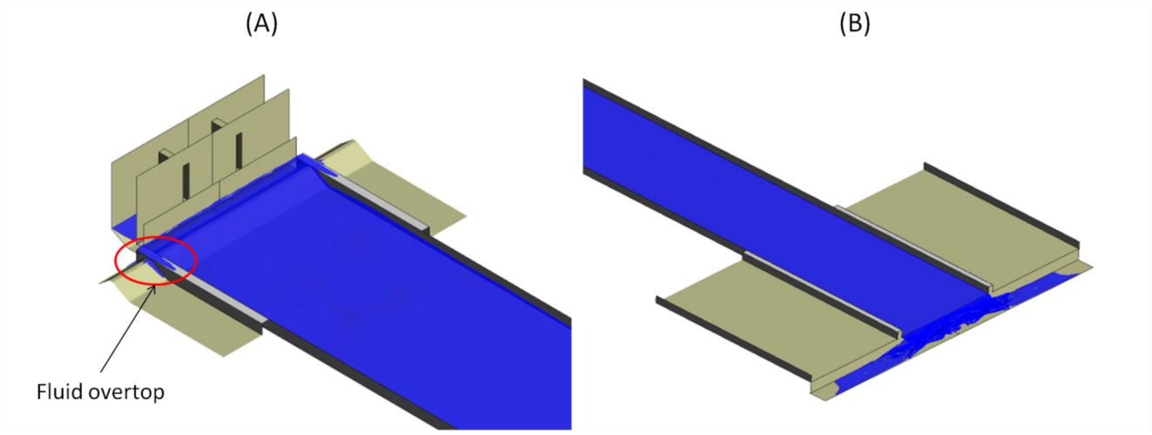

Figure 11: (A) Fluid flow near the vac-flush chamber 3.5 s after release, and (B) fluid flow at the end of channel 14 s after release.

For a 2000 micron grit particle, the critical shear stress for incipient motion is 1.3 Pa. For self-cleansing of sewers, a minimum shear stress of 2 Pa is suggested and for accumulated mature sediment, most deposits should be eroded at a shear stress exceeding 6 to 7 Pa (EPA, Dec 1998).

Figure 12 shows the bed shear stress relative to the critical shear stress for incipient motion of a 2000 micron particle at selected times from the release. This demonstrates that the bed shear stress is generally above 10 Pa and therefore above the critical shear stress for incipient motion of a 2000 micron particle and also for eroding 'mature sediment'.

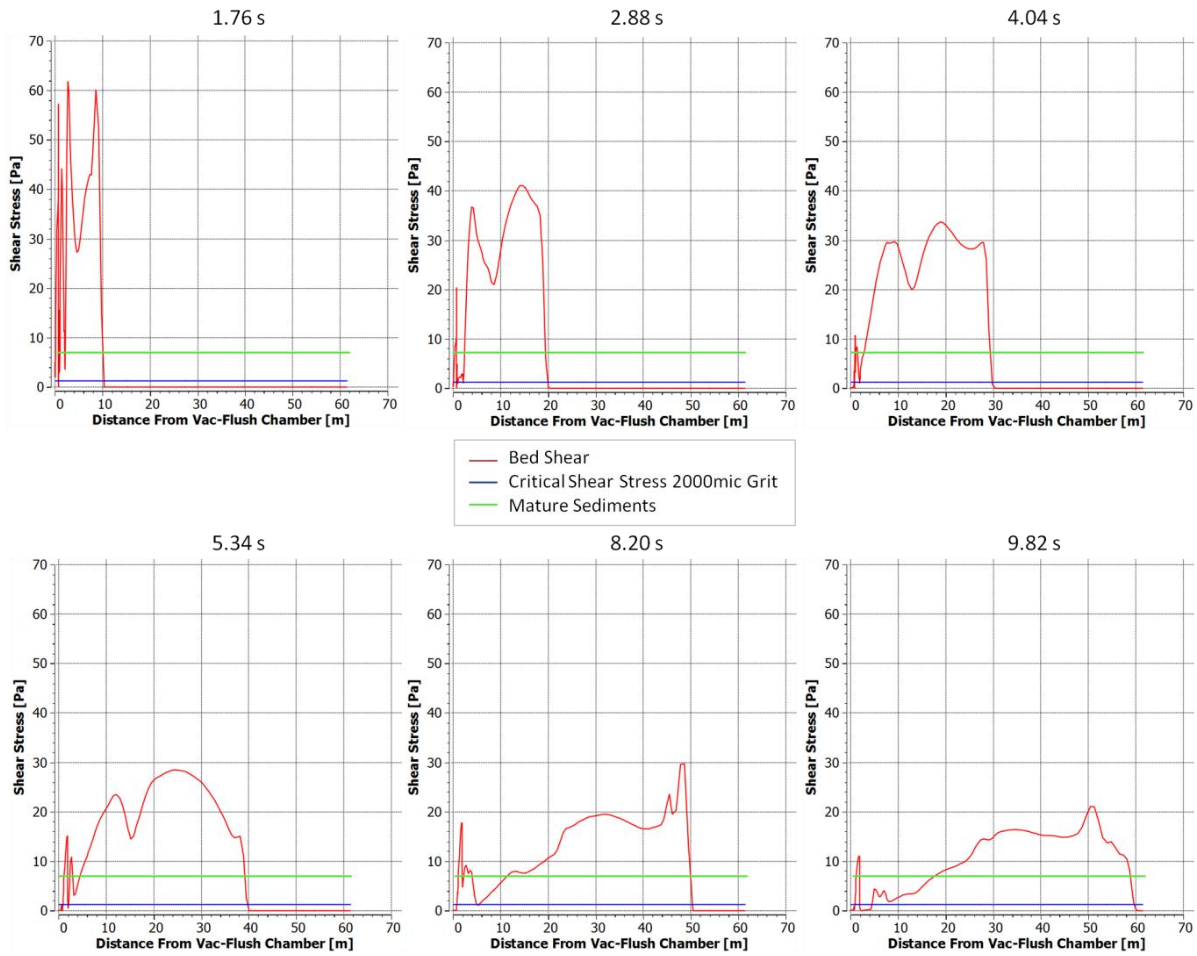

Figure 12: Bed shear stress as a function of distance from the vac-flush chamber at selected times from the release.

Plots of 1/(Rouse Number) for a range of particles as a function of distance from the vac-flush chamber at selected times from the release are provided in Figure 13. This shows that 132 micron grit particles can be expected to be transported as a 'suspended' load whilst 542 micron grit particles can be expected to be transported as a mixed load. Grits greater than 1500 microns can be expected to be transported as a bed load.

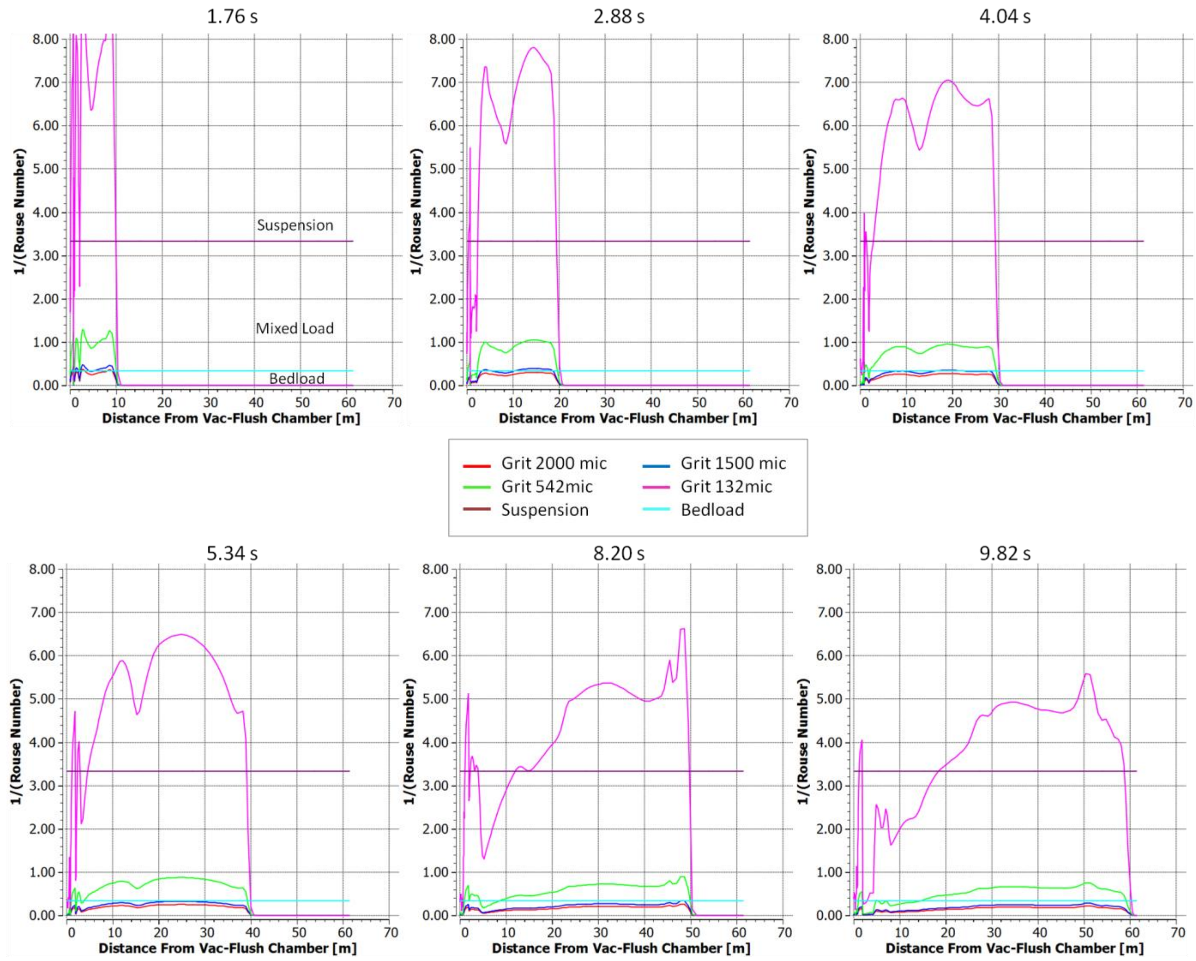

Figure 13: **Plots of 1/(Rouse Number) for a range of particles as a function of distance from the vac-flush chamber at selected times from the release.**

Conclusions

From transient calculations considering a solids load within a storm flow of 20,000 m^3, it was found that the distribution of solids within the tank was similar for 'low' and 'medium' level openings in the dividing walls. The 'high' level openings retained 90% of the solids in Tanks G and F compared to 80% with low and medium level openings and were therefore optimum.

It was also found that with dip plates located on the upstream side of the openings almost 100% of floatable material was retained within the first two tanks, compared to 40 to 50% without dip plates on the lower level openings.

With the hydro-ejectors discharging flow towards the vac-flush chambers, it was found that there was a significant quantity of solids transported towards the vac-flush chamber which could potentially be deposited close to or within the chamber, therefore increasing the solids load to be flushed by the vac-flush system. This result suggested that there may be benefit in locating a hydro-ejector adjacent to the vac flush chamber and one at the centre of the lane and discharging flow towards the channel so that solids are not transported towards the vac flush chamber.

Based on the results from the hydro-ejector calculations and the distribution of solids after a storm flow of 20,000 m^3, it was estimated that on average for all tanks, the hydro-ejectors may suspend enough particulates so that the solids concentration after vac flushing is reduced by approximately 45% compared to if the hydro-ejectors were not used.

From the calculation of the vac flushing process, the bed shear stress is generally above 10 Pa and therefore above the critical shear stress for incipient motion of a 2000 micron particle and also for eroding 'mature sediment'. The results therefore suggest that the use of a vac-flush system may be viable for flushing the floor of the tank.

The use of CFD was found to quickly establish the viability of the concept of using the storm tank for settlement of the storm solids. As the study was conceptual, the results of the CFD analysis were supported by results from scale models.

Acknowledgements

The authors wish to acknowledge 4D and Southern Water for allowing publication of this paper.

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