The effect of extended in-sewer storage on wastewater treatment plant performance

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Abstract A project funded by UKWIR is under way in the UK to develop a relatively simple methodology whereby the effects of the introduction of extended in-sewer storage at CSOs on downstream sewerage and treatment can be assessed. Recent legislation (UK and European) has compelled many sewer system operators to introduce systems which increase in-sewer retention times, and also retain more flow and load within sewer networks. The project has reviewed existing knowledge about the interaction between in-sewer flow and treatment plants, together with available models. The study is utilising a “benchmark” of 3 configurations of treatment plant and dynamic simulation using the WRc STOAT software, with minor modifications to ensure that effects on odour generation and nutrient removal processes are adequately modelled. As no existing sewer flow quality model can represent the range of conditions possible in sewer networks, a combined application of the Hydroworks model and a new model developed at Aalborg University is being used for this part of the study.

Keywords CSO storage; modelling; WWwTP interactions; septicity

Introduction
In the UK in-sewer storage (or equivalent) is increasingly being specified as a solution to Combined Sewer Overflow (CSO) problems. Some 4000 unsatisfactory CSOs must be improved within the next 5 year asset management period (Foundation for Water Research, 1998; Morris and Crabtree, 2000). This will entail considerable industry activity and little time to consider the detailed aspects of CSO operation through, for example, computer models. Required solutions comprise the addition of storage at unsatisfactory CSOs and also screens (or equivalent) to retain solids with dimensions of 6 mm (in 2 directions) or larger. Debate in the UK is still evaluating the relative solids retention performance of storage chambers and screens. Before the current round of water industry investment, the implementation of the Urban Wastewater Treatment Directive (UWWTD), via the UK Regulations (e.g. DETR and Welsh Office, 1997), has led to more reliance on the use of pumped sewage mains. Collectively these will potentially lead to problems:

1. In-sewer
• Increase in-sewer sedimentation (grit and organics), also in tanks and pump sumps
• Increase in abrasion of pump impellers and potential for clogging
• Potential risk of septicity occurring, resulting in corrosion, odour and possible VFA problems
2. At downstream treatment plants
- Increase in foul flush loads (grit and organics)
- Longer drain down times and operation of downstream treatment plants at full hydraulic load
- Disruption of treatment process efficiency for carbon, nitrogen and phosphorus removal
- Increase in screenings, grit and sludge masses

Because of these problems the UK Water Industry Research Ltd (UKWIR) has commissioned a review of the problem of prolonged in-sewer storage, and its potential effect on downstream treatment processes. The study aims to develop a method for wastewater utilities which will allow them to assess if the introduction of extended in-sewer storage at remediated CSOs may lead to downstream (treatment) problems, and comprises:
- A survey of the extent of the problem in existing UK wastewater systems, via questionnaire and subsequent workshop
- A review of problems identified worldwide
- Definition of key scenarios for more detailed study via modelling
- Development of a methodology to be used by wastewater utilities to avoid the problems

The study is also considering the effects of infiltration and the potential problems accompanying climate change. The design of storage in the UK is driven by the need to comply with the Fundamental Intermittent Discharge Standards specified in the UPM manual. Typically, the needs of the receiving water “drive” the selection of storage (e.g. Artina et al., 1999), although the UPM manual does point out the potential danger in terms of downstream treatment effects of this approach, and recommends integrated system modelling.

Review of problems
In general, higher peak combined sewage flows are now being retained in sewerage systems and passed downstream to WwTP, together with greater masses of suspended solids and floatables. Higher CSO weir settings and the use of screens or “screen equivalents” (Saul and Harwood, 1998) are responsible for a much greater retention of all types of solids within systems. The use of devices such as hydrodynamic separators can minimise the additional storage required, thus not introducing WwTP problems related to prolonged periods of dilute inflows. Most of the retained solids will pass to the WwTP, although a proportion will cause in-sewer problems due to settlement in slack pipes or quiescent flow areas. Subsequent storms may cause re-entrainment and high solids loads (of all types) to impact on inlet works, via “foul flushes”. Although there has been considerable research to assess the performance of storage tank structures, including the testing of full scale structures under controlled conditions (e.g. Balmforth et al., 1999; Stovin et al., 1996) the qualitative impact of tanks remains incompletely understood. The role of sediments is fundamental to understanding this impact, particularly the settlement process and the subsequent transport of deposited sediments to downstream treatment works, either by the use of flushing systems or by manual maintenance, when the flows to the works are reduced. As well as requiring a better understanding of tank treatment to protect water-courses, the impact due to the retention of gross solids by the inclusion of screens in tanks has also to be addressed. UKWIR (2000) recently reported on the hydraulic and total solids separation performance of 17 different proprietary screen arrangements suitable for use in tanks showed that most screens were effective at retaining solids with dimension 6 mm in two directions.

A recent study (Krebs et al., 1999), has illustrated that load flushes of dissolved pollutants (specifically ammonia) arrive at the WwTP in advance of the flow peak; effectively being displaced by the flood wave. This causes ammonia overload at the plant on the rising
flow part of the storm, because of the displacement of the soluble pollutants from the primary clarifier. In the USA, the treatment of more wet weather flows using high rate processes is advocated (Heaney et al., 1999), although there are concerns that this will reduce treatment efficiency. There is a greater concern with bacteria removal in the USA than in Europe, and nutrients have only relatively recently become a concern. Where storage basins are used, these prevent the hydraulic alleviation of a sewerage system by way of flooding or overflow operation, resulting in greater overall storm volumes being conveyed to the treatment plant, over longer time periods (Henze, 1987). The filling and emptying processes of storage tanks and the overflow processes are rarely analysed in the UK with respect to their influence on the treatment plant. By increasing the storage capacity, the stored storm water, which after the rainfall event is discharged to the wastewater treatment plant, reduces the treatment plant efficiency and increases the pollutant discharge compared with the normal dry weather load (Durchschlag and Schilling, 1988, 1990).

There are a number of potential effects on downstream WwTPs, described in Table 1. In extreme cases, prolonged sewer residence times may also lead to septicity where dissolved oxygen levels are low, or allow more in-sewer transformations with changes in COD and nitrogen, not anticipated in the original downstream treatment plant design, Table 2. A recent study of four treatment plant inlets (Blanksby et al., 2000), showed that the effect of screenings removal on the subsequent BOD in the flow was dependent on the type of screen and the way in which it was operated. At one location, the reduction in BOD load was 27%, whereas at another the reduction was about 6%. The return of washwater from the screenings handling plant compensated for this, and the average load to the secondary treatment process was only 1.5% less than the load at the inlet. However, the range of BOD load changes due to screening facilities varied between −9% and +7%. Hence where in-sewer storage retains more screenings in the flow, there will be attendant effects on the dissolved as well as particulate pollutants conveyed into the works. Screening plant may in itself affect the dissolved as well as particulate associated pollutants.

Questionnaires sent to each of the UK’s Wastewater Service providers reveal a mixture of perceived and actual problems arising from in-sewer detention and effects on downstream treatment, with a number of discharge consent failures. Some appear to experience few problems, while others claim that there are too many problems to detail for each individual works. Most existing wet weather flow problems appear to relate to the initial shock loads caused by flushes of solids at the inlet works, biomass displacement due to hydraulic overloading (loss of plant efficiency and failure of discharge consents), and the slowness of plant recovery after a storm due to dilute inflows. The latter is also significant for systems with high rates of infiltration. The problems of septicity are confined to the sewer systems (pump mains) and the outlets therefrom. In the treatment plant, little disruption to efficiency, or odour problems are reported as due to upstream sewers (Vincent, 2001). In the future, however, the increased solids being passed forward to treatment may place stress on the existing sludge management process, with sludge in settlement tanks held longer before desludging, increasing odour problems.

**Modelling**

Various approaches to modelling the interacting effects of sewer flows under prolonged residence times, and/or during wet weather have been used. These are summarised by Schutze (1998). It is apparent that there are no current sewer flow quality models which accurately represent in-sewer processes (Ashley et al., 1999a). The limitations vary from model to model, but the common deficiencies are: Inadequate modelling of sediment deposition, erosion and transformation processes, and linkage to transport; Poor represent-
tation of tank and chamber sewage quality behaviour; Crude representation of in-sewer transformations; Inability to model both aerobic and anaerobic processes. Some researchers have utilised specific commercial models to study particular processes, for example, (Krebs et al., 1999b) report on the successful application of MOUSETRAP to investigate ammonia impacts from a sewer to a WwTP. In the study reported here, the models selected have been to fulfil the following requirements:

- Detailed performance of WwTP processes likely to be affected by prolonged in-sewer residence times and long drain-down periods
- Sewage flow quality inputs to WwTP which adequately represent the in-sewer transport and transformation processes likely during wet weather and/or prolonged residence times, covering aerobic and anaerobic conditions
- An event based approach which can accurately represent the effects of storm sequences, but does not necessitate expensive (in computational time) continuous simulation
- Whilst recognising the importance of the individual receiving water’s assimilative capacity, to use models for the sewer and WwTP system only to provide generic information to assist system operators with determining if the introduction of in-system storage may cause problems for WwTP performance.

Methodology

As it is the WwTP performance that is being assessed, selection of generic systems being modelled is directed toward a “benchmark” of three WwTP configurations:

1. Primary sedimentation, trickling filter, effluent ammonia consent 5 mg/l, recirculation, loading rate 0.07 kg BOD/m²/d
2. Primary, activated sludge, 8 day SRT, 10% anoxic volume, 4 stages, 8 h retention time
3. Primary, biological phosphorus removal, 3-stage Bardenpho, 8 day SRT, 8 h retention time. Anaerobic zone 12% of the total volume, anoxic zone 15%. Target effluent 2 mg/l P.

\( \text{H}_2\text{S} \) and VFA emissions are of interest because of their odour effects. \( \text{H}_2\text{S} \) is treated as independent of any process effect. VFAs have a process effect and volatilisation has been modelled by per cent loss estimates between interconnecting units. A modified version of the STOAT model is being used for dynamic simulation (Foundation for Water Research, 1998). The ASM2 model has been used, modified to better support a preference for VFAs over other forms of degradable COD. (Bailey and Ollis, 1987; Dudley et al., 2001). Two baseline scenarios have been used. The first is the effluent quality before the introduction of additional sewer storage, and the second the effluent quality with additional sewer storage but no control action. These have been used to assess the performance of various control strategies, the assumption being that the target of the control options is to restore effluent quality back to something comparable to the original effluent quality.

Selection of rainfall inputs has been based on the method proposed by (Jack et al., 1999; Jack and Ashley, 2001), known as the “Total Emission Analysis Period” (TEAP). A critical sequence of wet and dry weather is selected based on historical annual data. The future rainfall, accounting for climate change has also been addressed. An existing sewer flow model (Hydroworks) has been used for a system for which storage is being introduced. However, the WwTP scenarios above have been synthetically generated for the catchment using STOAT. Despite the known limitations, the sewer flow and quality model has utilised the Hydroworks to represent the hydraulics and storage systems. The quality aspects have been modified to include new knowledge about quality and solids changes and retention at the enhanced CSOs. The study also considered the relative effects of utilising equivalent structures, such as hydrodynamic separators rather than straightforward storage chambers and/or screens.
<table>
<thead>
<tr>
<th>Origin phase</th>
<th>Time</th>
<th>Effects on wastewater composition</th>
<th>Effects on WwTP*</th>
<th>Final effluent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Dissolved Substances</td>
<td>Particulates</td>
<td></td>
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<tr>
<td>DWF patterns</td>
<td></td>
<td>Diurnal and weekly variations.</td>
<td>Foul flushes of solids can occur at peak DWF times, resulting from deposition during low flows</td>
<td>Normal DWF patterns are allowed for in peak design flows. Smallest catchments have largest peaking ratio. Inlet works are usually designed to adequately handle DWF flushes of solids. Infiltration has most effect on WwTPs designed for foul only flows. Where high infiltration can cause hydraulic overloading and/or lack of sufficient substrate for efficient operation.</td>
</tr>
<tr>
<td>Rising stage</td>
<td></td>
<td>Potential displacement from sewer system</td>
<td>As for DWF initially, flushes of solids occur later than for dissolved substances, but for near bed solids.</td>
<td>Shorter residence times of units. Displacement of dissolved pollutants from primary clarifier, causing shock load to reactor and FST. Solids flush impact on inlet works later than the above. PST sludge dilute.</td>
</tr>
<tr>
<td>Combined flow</td>
<td></td>
<td>Potential displacement from sewer system</td>
<td>As for DWF initially, flushes of solids occur later than for dissolved substances, but for near bed solids.</td>
<td>Shorter residence times of units. Displacement of dissolved pollutants from primary clarifier, causing shock load to reactor and FST. Solids flush impact on inlet works later than the above. PST sludge dilute.</td>
</tr>
<tr>
<td>Peak combined flow</td>
<td>Dilution to lower concentrations than DWF</td>
<td>Wholesale surface wash-in and in-sewer sediment erosion at peak.</td>
<td>Shortest residence time. Particles less biodegradable, nutrient concentrations reduced (depending upon duration, may be later in storm). Sludge displacement from reactor to FST. Increasing TKN/Alkalinity ratio lowers buffer capacity.</td>
<td>High suspended solids and BOD</td>
</tr>
<tr>
<td>Recession in storm flow</td>
<td>Weak sewage possible</td>
<td>Start to deposit in sewerage</td>
<td>Low nutrient levels. Biodegradability poor. Sludge balance disturbed.</td>
<td></td>
</tr>
<tr>
<td>Draining down of storage</td>
<td>Draining down of storage</td>
<td>Higher concentrations possible than during normal DWF, although may be weaker sewage</td>
<td>Load may still be higher than normal DWF</td>
<td>Critical stage for disruption of nitrogen removal processes.</td>
</tr>
<tr>
<td>Subsequent dry weather period</td>
<td>May take several days to re-establish normal DWF quality</td>
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<td>Increased sludge and nitrifying bacteria removal. Higher strength supernatant.</td>
<td>High BOD and ammonia</td>
</tr>
</tbody>
</table>

FST – Final Settlement Tank, PST – Primary Settlement Tank, * Strong industrial effluent inputs are not considered here.
Table 2  Effect of septic conditions on performance

<table>
<thead>
<tr>
<th>Wastewater characteristics</th>
<th>Organic matter concentration</th>
<th>Organic matter quality</th>
<th>Sewer and storage tank characteristics</th>
<th>Biofilm area to bulk water volume</th>
<th>Effect on in-sewer transformations</th>
<th>General effects</th>
<th>Effect on WwTP Nitrogen and biological phosphorus removal</th>
<th>Mechanical treatment (sedimentation)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Aerobic conditions</strong></td>
<td>Diluted. The wastewater may be dilute due to infiltrations of groundwater or mixing with stormwater. Furthermore extended transport time under aerobic conditions will result in diluted wastewater.</td>
<td>Slowly degradable. Old wastewater or resuspended sewer sediments</td>
<td>High reaeration. Steep sewer, high flow velocity, little relative water depth, high turbulence and large water surface to bulk water ratio will give a high reaeration.</td>
<td>Biofilm area. When water levels rise during storms, the newly wetted surface will not have developed a biofilm. Hence, no oxygen uptake will take place on this surface. Furthermore, as hydrogen sulphide production takes place in the biofilm only (due to the low growth rates of the bacteria involved), the newly wetted surface will not contribute to the hydrogen sulphide production.</td>
<td>Degradation of readily biodegradable organics (including VFAs) takes place under aerobic (and anoxic) conditions, particulates (bacteria) are produced. Removal (oxidation) of hydrogen sulphide takes place.</td>
<td>&quot;Normal&quot; treatment prevails</td>
<td>Adverse effects. Readily biodegradable organics are not present or only present in insufficient concentrations. As they are needed for both nitrogen and phosphorus removal, readily biodegradable organics must be added to the treatment plant to secure the operation of the processes.</td>
<td>Beneficial effects. Readily biodegradable organics have been removed and transformed into particulates (biomass) that can be removed mechanically. The effect is a better treatment efficiency for organic matter resulting in decreased receiving water oxygen depletion.</td>
</tr>
<tr>
<td><strong>Anaerobic (septic) conditions</strong></td>
<td>Concentrated. Wastewater without stormwater and stormwater containing large quantities of resuspended sediments will have a high concentration of organics.</td>
<td>Readily degradable. Fresh wastewater or fermented wastewater, i.e. wastewater after prolonged storage under septic conditions.</td>
<td>Low reaeration. Quiescent water in storage tanks, small sewer slope, low flow velocity, high relative water depth, and small water surface to bulk water ratio will give a low reaeration.</td>
<td>Conservation and production of readily biodegradable organics (including VFAs) takes place under septic conditions. Production of hydrogen sulphide and other odorous compounds take place.</td>
<td>Adverse effects. Hydrogen sulphide and other odorous compounds, which have been produced in the sewer, are released at places with high water turbulence (aerated silt traps, pumping installations, screens, etceteras). The effect is corrosion and odour problems.</td>
<td>Beneficial effects. The produced readily biodegradable organics are needed for both nitrogen and phosphorus removal. For biological phosphorus removal, the produced VFA’s are essential.</td>
<td>Adverse effects. The produced readily biodegradable organics will not be removed by mechanical treatment. They will hence cause increased oxygen depletion in the receiving waters.</td>
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</tr>
</tbody>
</table>
The Hydroworks model has been used in conjunction with the Aalborg University WATS model to deal with in-sewer processes. WATS has been modified to account for wet weather flows and the effects of sediment erosion (Tanaka and Hvitved-Jacobsen, 1998; Vollertsen and Hvitved-Jacobsen, 1998; Ashley et al., 1999b). The formation of odorous compounds was not explicitly represented, but hydrogen sulphide was used as an indicator of odours (Hvitved-Jacobsen et al., 1999; Gostelow and Parsons, 2000). Gudjonsson et al. (subm) showed that dissolved oxygen concentrations in a gravity sewer could be simulated when sufficient data on the wastewater composition could be obtained. They showed that the model concept could simulate and predict low DO concentrations, allowing the simulation of alternating aerobic/anaerobic conditions. Tanaka et al. (1998) obtained good results for an air-injected pressure sewer. Tanaka et al. (1998) and Tanaka and Hvitved-Jacobsen (1998, 1999) also showed that the formation of VFA’s (fermentation), hydrolysis and hydrogen sulphide formation under anaerobic conditions could be simulated using the WATS model approach.

Conclusions
Increasing use of storage as a means of controlling unsatisfactory CSO discharges, together with more large (aesthetic polluting) organic solids retention in sewer systems, will inevitably lead to more problems downstream. These will occur in the chambers themselves and in the sewers. At WwTPs the problems are generally well known, due to higher hydraulic loads, ammonia flushes, high solids loads and disruption of nutrient removal processes. Prolonged in-sewer storage (or storage in WwTP storm tanks), either of wet weather flows, subsequently released to cause late flushes (off-line), or lengthy periods of high hydraulic loading with low substrate for many days after a storm can cause higher WwTP effluent loads to occur and/or poor biomass performance. The increasing use of pumped systems has also increased the risk that septic conditions can occur in systems, with resultant odour, corrosion and health hazard problems, as well as potential effects on downstream treatment processes.

Unfortunately, where sewer and treatment systems are operated separately, communication and understanding of the consequential interactive effects may be poor, resulting in transferability of problems from CSOs downstream. This project defined a relatively simple way in which all of the operators of the parts of a wastewater system can determine if the introduction of solutions to their CSO problems entailing extending in-sewer storage are likely to lead to other problems. The best solution to these problems is likely to entail a combined approach which addresses the sources of flows and loads entering sewer systems, and also addresses alternative ways in which peak flows can be handled at WwTP by intermittently operated physico-chemical processes.

Acknowledgements
The authors are grateful to UKWIR Ltd, particularly Gordon Wheale, for permission to publish this paper.

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