Interaction between Extended in-sewer storage and Wastewater Treatment Plant Performance – a protocol to avoid problems

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ABSTRACT

Recent legislation (UK and European) has compelled many sewer system operators to retain more flow and load within sewer networks. The systems used typically increase in-sewer retention times. A project funded by UKWIR has reviewed existing knowledge about the interaction between extended in-sewer storage and treatment plants, together with available models. The study utilised a questionnaire survey and dynamic simulation. As no existing sewer flow quality model could adequately represent the full range of conditions possible in sewer networks, a combined application of the Hydroworks model and a new model developed at Aalborg University (WATS) were used for the modelling. STOAT was used for the sewage treatment works. It is possible to reassure the water industry that the problems due to extended in-sewer storage are comparatively rare in properly designed and operated wastewater systems, and consequential failure to meet consents is unlikely. The plants most at risk are those operating very close to consent levels before the storage is introduced. A protocol has been developed to help system designers and operators avoid creating insurmountable problems at downstream treatment plants as a consequence of the introduction of extended in-sewer storage.

KEYWORDS

CSO storage, WwTW, interactions, modelling, septicity.

INTRODUCTION

In the UK, in-sewer storage (or equivalent) is increasingly being specified as a solution to Combined Sewer Overflow (CSO) problems. Required solutions frequently comprise the addition of storage at unsatisfactory CSOs and also screens (or equivalent) to retain solids. Together, these measures will retain more flow and loads of pollutants within the wastewater system, to be passed downstream to wastewater treatment plants (WwTW). Concerns about the consequential effects on WwTW performance prompted the UK water industry through UKWIR, to commission a study to analyse and evaluate the problems that long sewer residence times, caused by storage or otherwise, will have on (WwTW) consent compliance. The specific objectives of the study were (Ashley et al, 2001):

- To review literature on the effects, both theoretical and observed, of the impact of extended (in-sewer) storage on sewage treatment.
- To develop methodologies using proven tools that allow the potential problems that storage may have on treatment works to be assessed.
- To investigate suitable rainfall periods to carry out the analysis and to take into consideration the potential effects of climate change.

The study was led by the University of Bradford in partnership with WRc and included major contributions from the University of Aalborg, with specialist advice from the University of Sheffield. The study utilised a questionnaire survey of the UK water industry's experiences of the effects of extended in-sewer storage on WwTW performance, together with limited simulation of the performance of three synthetic WwTW (filter works; nitrifying activated sludge; 3-stage Bardenpho) where a variety of extended storage systems had been added to the upstream sewer network. It was concluded that evidence for consent failure problems due directly to extended in-sewer storage was limited. Despite this risks to consent compliance were identified from the modelling work and (largely) anecdotal evidence. A protocol was developed to assist designers and system operators with the identification of when there may be potential problems. Guidance is also provided for WwTW operational changes to alleviate any problems that do occur.

REVEW OF POTENTIAL PROBLEMS

Whilst there is a lot of information available for the wet weather operation of WwTW, little of this relates directly to the effects of upstream storage. The problems that may arise due to sewerage system operation on the performance of downstream WwTW are summarised in Table 1.

Foul flushes

In general, higher peak combined sewage flows are now being retained in sewerage systems and passed downstream to WwTW, together with greater masses of suspended solids and floatables. Higher CSO weir settings and the use of screens or 'screen equivalents' (Saul & Harwood, 1998) are responsible for a much greater retention of all types of solids within systems. Despite the increasing use of in-sewer storage tanks to address CSO problems, the problems that can arise from sediments deposited in storage chambers have been comparatively ignored (Stovin et al, 1996). Where tanks are designed to deposit solids, cleaning devices may be employed which flush the tank after the storm (e.g. Grande & Novaks, 1998; Pisano & Brombach, 1998). Similar devices are also used to keep the sewer clean (Chebbo et al, 1996). These devices will lead to an 'engineered' foul flush of solids and pollutants arriving at the WwTW after a storm.

Although alluded to by a number of authors, and reported anecdotally, little objective information is available about WwTW foul flush impact problems arising from increased extended in sewer storage, particularly at CSOs. In one reported field study, Bixio et al (2001), using actual measurements in Gent, report that storage in a pump station caused up to 90% of the solids to be deposited in the 835m^3 wet well during dry weather. This deposition also caused a loss of carbon source at the downstream plant, and a flush of solids and pollutants in wet weather as the solids were flushed out. This led to denitrification problems in dry weather and nitrification problems in wet weather, the latter also lasting for several days.

Prolonged peak hydraulic load

The problems caused by high hydraulic load are the most frequently reported. These occur during prolonged wet weather inflows to WwTW. Where there is significant extended storage upstream, flows to the plant may be maintained at peak for many hours, and even days (Harremoes et al, 1993). The nature of the flow arriving at the WwTW may correspond more with typical wet weather inputs for a prolonged period, although the nature of the solids and the relative biodegradability will vary during the wet period and the subsequent drain-down (Krebs et al, 1999). Hence sewage temperatures will usually be lower and biodegradability reduced, together with a lack of nutrients later in the combined flow period due to dilution.

Problem	Comments	Relationship to extended in-sewer storage
Problem A1* Flushes of solids during DWF peaks.	Problem would only arise where works is small and DWF peaking ratios are high. Could be a problem where additional catchments have been added.	Not an in-sewer storage problem unless long retention times. In-sewer storage may attenuate this problem.
Problem A2 Flushes of concentrated AmmN during DWF peaks	As above	As above
Problem A3 High hydraulic loading and or dilute inflows caused by infiltration during DWF	Infiltration endemic in UK systems. Dilutes sewage and increases hydraulic load.	Problem is mainly one of increasing hydraulic load at WwTW. Reactor may be adapted to weak sewage due to high infiltration. May be less resilient to higher concentrations during storms, with or without extended storage.
Problem A4 Wet weather Ammonia load flush	On rising stage of storms – dissolved pollutant peak precedes traditional foul flush.	Displacement from PST and possibly flows into storm tanks, followed by ammonia pulse into reactor. Provision of additional in-sewer storage likely to reduce this effect.
Problem A5 Solids and related pollutant flushes and peak loadings	High hydraulic loading, potentially high pollutants. In-sewer sediment erosion and re-erosion of deposits in tanks. More solids and flows retained with modified CSOs. Ultimately solids discharged from WwTW will be less biodegradable than where they are discharged from the CSO.	Impact on inlet works and preliminary stages notable. High hydraulic loads to reactor and FST. Provision of additional in-sewer storage likely to reduce concentrations and loads early on in event (although these may be increased overall by greater retention). Increased amount of solids conveyed likely to increase sludge volumes.
Problem A6 Prolonged peak hydraulic load overloading reactor and washing out biomass. Possible high/low strength.	High hydraulic load, but pollutants (and nutrients) possibly diluting. Although more intractable in-sewer sediments may still be eroding. Biodegradability poorer. Nitrogen removal affected by reduction in organic acids. Bio-P removal is affected by higher oxygen (anaerobic stage), redissolution of phosphates depends on the organic acids (lower in wet weather), and the process is affected by nitrates (higher in storms). Imbalance of P-release (recovers quickly with organic substrate) and P-uptake (slow to recover) can lead to increases in P in the final effluent at the end of a storm	Timing and nature of flow peak affected by in-sewer storage. Peak may be considerably prolonged (and have temporally variable biodegradable solids and nutrients). In-sewer storage will prolong period less degradable sewage enters WwTW and make this effect worse.
Problem A7 Draining down of storage with high/low strength.	Deposition of solids and associated pollutants in sewers and tanks. Initially strong, then weak sewage. May be problematic for nutrient removal.	As above, except hydraulic loading on WwTW reducing.
Problem A8 Re-establishment of DWF.	Establishment of 'normal' operation may take prolonged period.	Extended in-sewer storage may prolong this period.
Problem AN1 Low VFAs	High VFAs produced during septicity, otherwise bio-P removal requires chemical addition.	Increased retention times increase potential for VFA production and other readily biodegradable organics. Hence new storage may be beneficial if VFAs are generated.
Problem AN2 H_2S & VFA production	Toxicity, odours, corrosion effects and potential sludge bulking/foaming problems.	Extended in-sewer storage increases the risk that anaerobic conditions will occur. Requires moisture and contact with surfaces for corrosion.

*Key: A - Aerobic; AN – Anaerobic

Table 1 Overall specification of potential problems

The principal problems are related to the reduction in retention time in the primary clarifiers, with consequent loss of efficiency, and in the biological stages, for which the effects can be more significant for final effluents (Harremoes et al, 1989). A significant portion of the active biomass can be displaced from the reactor into the secondary clarifier during periods of hydraulic overloading and secondary clarifier efficiency drops drastically with the higher hydraulic loading (e.g. Henze et al, 1986; Lumley & Balmer, 1987; Durchschlag et al., 1992; Harremoes et al, 1996; Ekema et al, 1997). This problem is often attributed as a cause of observed failures of consent standards caused by disruption of nitrogen removal processes and loss of solids into the final effluent (Harremoes et al., 1993).

During a storm, initial flushing of ammonia from the sewer system (Krebs et al, 1999a) and the displacement from the primary tanks causes a rapid increase in nitrogen loading at the aerobic stage. This load may decrease during the storm by dilution, but can increase again when in-sewer storage and/or storm tanks are emptied. Where there is an increase in ammonia concentrations, there may be a faster growth of nitrifiers, however, this is offset by a fall in temperature. Where there is bio-P removal and/or denitrification, this also increases the nitrogen load as the tanks are flushed. Notwithstanding the growth in nitrifiers, the increased ammonia load typically passes straight through the aeration stage and into the final effluent. This is partly due to the displacement of nitrifiers from the aeration tank into the final clarifier and partly due to the hydraulic effects of high flow (Otterpohl et al, 1990; Longdong, 1994). Where denitrification processes are used, prolonged dilute loadings may limit availability of primary carbon sources, necessitating the production of secondary carbon sources by hydrolysis (Harremoes et al., 1993; 1996). During storm or prolonged drain-down of extended storage inflows, the readily biodegradable organic acids are diluted, thus nitrogen removal reduces commensurately (Durchschlag et al., 1991). In addition, denitrification will be reduced by the increased oxygen concentrations in the prolonged wet weather flow, the recirculation caused by the dilution of the sewage strength and the transport of sludge into the clarifier.

The difficulties of maintaining the bio-P removal process when the influent has been dilute for a period of 24 hours was examined in a combined pilot plant and model study by Kruhne et al (2000). Bio-P removal depends on an adequate degree of redissolution of phosphates in an upstream anaerobic tank. The IWA Activated Sludge Model (ASM) 2 was used and extended to include the anoxic growth of phosphate accumulating organisms (PAO) and the uptake of P under anoxic conditions, at the expense of internally stored PHA. The model and a pilot plant illustrated that the addition of a carbon source (sodium acetate) during the period of weak influent and increased hydraulic load was able to stabilise the bio-P removal process.

Draining down of storage with high/low strength & re-establishment of DWF operation

Following cessation of a storm the sewer system will drain down. The time taken to return to normal DWF will depend on the storage volume in the system. This may prolong the effects described above, resulting in sustained high hydraulic loading (e.g. Bauwens et al, 1996). In addition, the increasing bed shear stress as tanks drain down may cause a final flush of solids and pollutants. Pfister et al (1998) report the draining down of a large storage system following storm events, which causes subsequent ammonia overload of the downstream WwTW. However, these effects are unlikely to be significant provided the potential problems outlined in the previous section have been addressed. The use of devices such as hydrodynamic separators can potentially minimise any additional in-sewer storage required, together with the residence time (e.g. Alkhaddar et al, 2001) thus not introducing WwTW problems related to prolonged periods of dilute inflows as the device drains down. However, without the significant storage that tanks provide, the potential problems caused by flushes may not be alleviated.

Normal operation of a WwTW with established retention times and appropriate biomass concentrations and sludge thickenability may not be re-established for some time following a prolonged rainfall period (e.g. Durchschlag et al, 1991; Bertrand-Krajewski et al, 1995). It is possible that extended in-sewer storage may further delay the return to normal operation. Disruption of efficiency as described in the sections above may delay re-establishment of biomass, in extreme cases necessitating seeding from other WwTW; e.g. Temmink et al., (1996) and Kruhne et al., (2000) have examined dilution of influent, and the consequences for disruption of Bio-P processes.

Septicity and increased H_2S & VFA production

Sulphide production may start after only10 to 30 minutes in a pressure main where there is no opportunity for re-aeration, hence where a storage tank is full due to high flows, there is an opportunity for septicity to occur even for short retention times. Even at low temperatures, problems associated with sulphide formation may be clearly observed when the residence time exceeds 0.5-2.0 hours, (Hvitved-Jacobsen et al., 1995). Although sulphide is produced in biofilms and sewer sediments, aerobic conditions in the bulk water phase typically result in a corresponding oxidation of the sulphide produced, preventing occurrence of sulphide in the water phase. In countries with long pressure mains or high temperatures in wastewater in gravity sewers, significantly higher concentrations than 10 mgS/l (high) are reported, (e.g. Thistlethwayte, 1972; Pomeroy and Parkhurst, 1977).

Kollatsch and Schilling (1990) recommend that raw sewage is stored for no more than four hours, or anaerobic conditions will prevail, and hydrogen sulphide will be produced. In a study for Anglian Water, Bentzen et al, (1995) investigated the problems of hydrogen sulphide generation in a rising main leading to a coastal WwTW. The cause was attributed to the infiltration of seawater, and the average retention time of 5.4 hours in the main. Although VFAs are useful for bio-P removal (Hvitved-Jacobsen et al, 1995), problems arise from septic odour of these compounds (Hvitved-Jacobsen & Vollertsen, 2000) and from the toxicity and corrosion effects of hydrogen sulphide. Vincent (2001) suggests that where there is extended storage in the system, odour emission occurs during filling and emptying of storage systems. Odours may be generated where the sewage is accumulated, together with debris and sludge, although no details are provided. The release of odours occurs at the discharge point of a sewer, particularly where this is a rising main. Vincent (2001) identifies rising mains as the most common cause of odours at 26 WwTWs (12 instances), with gravity sewerage being responsible for only 2 (out of 55) reported odour problems.

REPORTED UK EXPERIENCE

Questionnaires were sent to identified individuals in each of the 14 utilities responsible for wastewater systems in the UK. Only 11 utilities ultimately responded. Hence the representativeness of the results is questionable. Of the 11 responders, 8 of the utilities claimed they had systems with extended in-sewer storage. This included in each case, tank sewers, storage chambers and storage at CSOs. Only one utility provided detailed information about the sizes and numbers of storage units, and whilst 3 utilities indicated problems in systems that had extended storage, the details of any interactions with downstream WwTW were unknown. Eighteen WwTWs were identified as ‘problem’ sites by the five utilities that provided further, more specific details, as shown in Figure 1. The data indicate that the most widespread problems (in terms of number of works) are the failure to meet discharge consents (11 works - although frequency and magnitude were not specified), high solids loadings during the start of storms and biomass disruption/loss (9 works each) due to high hydraulic loads often caused by in-sewer infiltration. These problems were generally associated with general wet weather performance rather than specifically extended in-sewer storage.

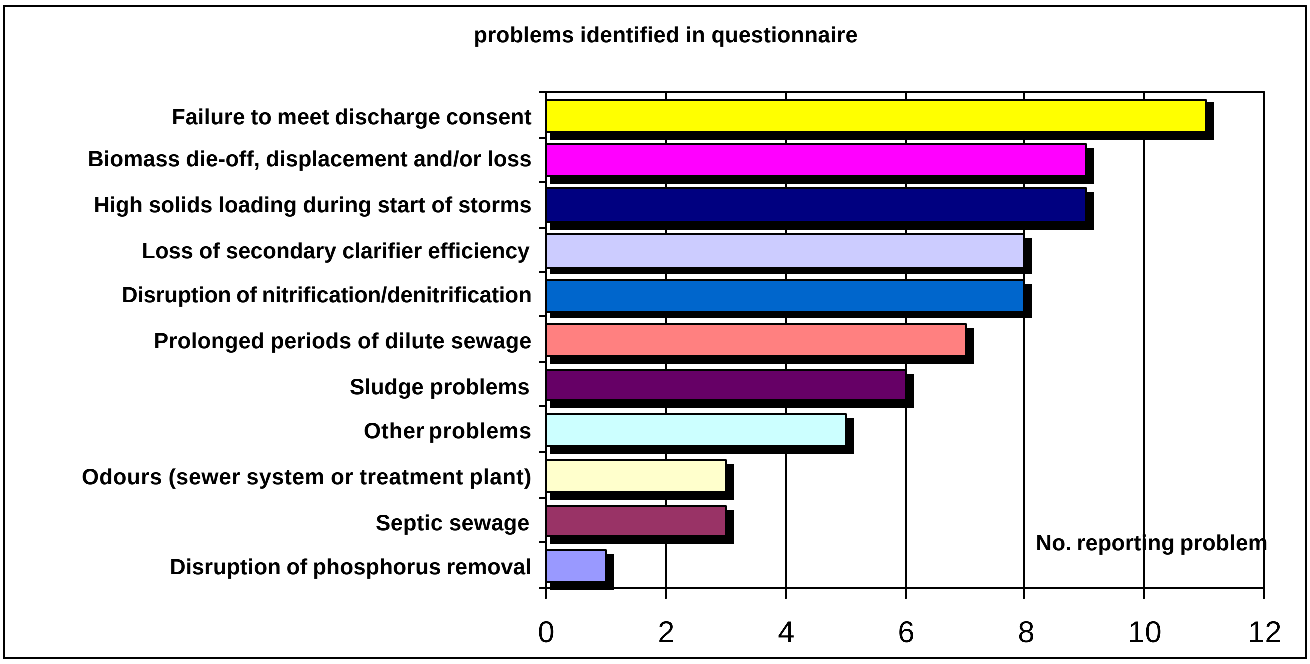

Figure 1: Questionnaire responses – problems identified for interactive effects from upstream sewerage and WwTW (5 utilities and 18 plants)

Seven utility returns indicated that there were problems encountered during wet weather and/or draining down of the sewer systems following wet weather. Of the 18 problem plants, only 3 were in systems where there was substantial upstream storage. Only one respondent reported in-sewer problems caused by prolonged retention times and one reported problems only at the WwTW. Of the three problem plants with upstream in-sewer storage, two had fixed film secondary treatment stages. One utility reports the greatest problems occur where the in-sewer storage is situated close to the WwTW. At one site (500,000PE) with large on-line storage chambers situated 'close' to the WwTW, high hydraulic loads lead to the contents of the primary settling tanks displacing onto the filters, and there are reportedly large changes in BOD loads at the plant. There is increased primary sludge production; some flush out of biomass from the filters, and loss of secondary clarifier efficiency due to these high loads. There is also some disruption of the nitrification/denitrification process.

Another works with major on-line storage upstream suffers from continual high flows, with WwTW storm tank emptying problems. At the third WwTW with major off-line storage tanks (2 x 60 000 m^3) and large in-line tank sewers, there is a severe odour problem. This is believed to be due partially to saline intrusion into the sewer, and to the use of a submerged biological contactor (SBC) at the WwTW.

The questionnaire has revealed that problems associated with extended in-sewer storage are either not widely experienced, or not reported for the systems currently existing. It is possible that there are as yet not enough in-sewer extended storage systems in operation to show the problems. Where problems are apparent, there is insufficient data available to generalise or make any meaningful analysis.

MODELLING

The design of storage in the UK is normally driven by the need to comply with the 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. Because of the high cost, fully detailed studies of the sewer-WwTW-receiving water system are comparatively rare, and in any case current knowledge and simulation models are inadequate to consider each of the potential problems outlined in Table 1 (Ashley et al, 1999; 1999a; Arthur et al, 1999; Rauch et al, 2001; Reichart et al, 2001).

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). The limitations of each model vary, but the common deficiencies are:

- Inadequate modelling of sediment deposition, erosion and transformation processes, and linkage to transport
- Poor representation of tank and chamber sewage quality behaviour
- Crude representation of in-sewer physical and biochemical transformations
- Inability to model both aerobic and anaerobic processes.

Specific commercial models may be used to study particular processes, for example, (Krebs et al, 1999) report on the successful application of MOUSETRAP to investigate ammonia impacts from a sewer to a WwTW. In the study reported here, the models selected have been to study the in-sewer processes associated with extended storage and the dynamic interaction with the WwTW.

As it was the WwTW performance that was being assessed the selection of generic systems being modelled was directed toward a ‘benchmark’ of three WwTW configurations:

1. Primary sedimentation, trickling filter, effluent ammonia consent 5 mg/l, recirculation, loading rate 0.07 kg BOD/m^3/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.

A modified version of the STOAT model was used for dynamic simulation (Foundation for Water Research, 1994; 1998). The ASM2 model has been used, modified to better support a preference for VFAs over other forms of degradable COD. (Bailey & Ollis, 1987; Dudley et al, 2001) as H_2S and VFA emissions were of interest because of their odour effects.

A real sewerage network (150,000 pop.) was used which had been included in a UPM study. New storage (UPM, inland) had previously been designed and constructed. The ‘no storage’ case was simulated using the original verified model. The peripheral sewers were simplified to speed up computation time and in-sewer processes were modelled only for the main sewers. Sewer flow quality has been modelled using a combination of HydroWorks (solids and nitrogen) and the Danish WATS model (carbon and oxygen transformations) (Gudjonsson et al, 2001). The quality aspects of the models have been modified to include new knowledge, with WATS 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., 1999a). The formation of odorous compounds was not explicitly represented, but hydrogen sulphide has been used as an indicator of odours.

There were three in-sewer storage options:

1. Normal, small storage – equivalent to a UPM ‘inland’ sewerage system CSO storage (as actually built) - storage in network 17,000 m^3 and storage in storm tanks 16,000 m^3.
2. Medium storage – equivalent to a UPM ‘coastal’ sewerage system - storage in network 44,000 m^3 and storage in storm tanks 45,000 m^3.

3. Large storage – larger than (2), based on an artificial simulation for storage of 89,000 m^3, by artificially increasing the diameters of the main intercepting sewers.

Selection of rainfall inputs has been based on the method proposed by (Jack et al, 1999: Jack & Ashley, 2001), known as the 'Reference Analysis Period' (RAP). A critical sequence of wet and dry weather is selected based on historical annual data.

Two baseline scenarios have been used for evaluating the WwTW operation. The first is the effluent quality before the introduction of additional in-sewer storage, and the second the effluent quality with the three additional sewer storage options. The performance of various WwTW control strategies has also been evaluated, with the assumption being that the target of the control options is to restore effluent quality back to something comparable with the original effluent quality.

The conclusions from the modelling were:

- The trickling filter systems are generally robust and largely insensitive to the effects of extended in-sewer storage.

This did not conform to one of the questionnaire returns, for which there were apparent problems in a filter, which was hydraulically overloaded. As there were no details available for the system (flows and loads) it was not possible to identify the precise reasons for these problems.

- Conventional activated sludge systems may be prone to significant increases in both TSS and ammonia concentrations and loads due to the introduction of either medium or large storage. However, biological phosphorus removal (where applied) was found to be improved for the scenarios with extended in-sewer storage. This improvement was a combination of dilution of phosphorus by the increased storage and the beneficial effects of VFAs when present in the sewage.
- The presence of VFAs may have a potential impact on effluent quality where there is large storage near the WwTW, and may also indicate the potential for odours, H_2S and associated problems. However, VFAs are rapidly oxidised within aerobic lengths of the sewer, so that unless the storage is close to the sewage works the VFA production in the storage tanks has little effect on the VFAs in the crude sewage at the sewage works.
- The effect of low temperatures may exacerbate the usual loss of nitrification capacity following a storm, as the extended in-sewer storage drains down.
- Controls can be effective at alleviating the problems caused by extended in-sewer storage. Although Return Activated Sludge (RAS) rate control was found to be effective at reducing ammonia discharge, step-feed was found to be the most appropriate control option to alleviate the effects of extended in-sewer storage, despite potentially increasing ammonia in the final effluent. For most scenarios the increase in effluent solids, in the absence of step-feed, was a greater threat to meeting effluent consents than the rise in ammonia levels.

PROTOCOL TO ASSESS THE LIKELIHOOD OF RISKS TO CONSENT COMPLIANCE

It was not found possible to develop generic and universal criteria for the avoidance of downstream treatment problems arising from the introduction of extended in-sewer storage. This was because of the wide variability in circumstances for specific catchments and plants. However, a 6 stage protocol has been developed to assist with the evaluation of potential problems and their avoidance as illustrated in Figure 2. It is important to follow sequentially the process given in Figure 2, which has been developed to allow the 'non-expert' to evaluate whether there may be a problem with initial WwTW operation and the potential effects on the WwTW due to introducing extended in-sewer storage. Initial assessment of the performance of the existing (before new extended in-sewer storage is introduced) may be made using the procedure given in Tables 2a and 2b. Tables 3a and 3b give information about the evaluation of potential problems once the extended in-sewer storage has been designed. Both Tables utilise simple process and hydraulic criteria that are presented in the final UKWIR report (there is insufficient space here to give these). They cover: A2 – Aeration Tanks; A3 - Final Settling Tank performance; A4 – an add-on to A3 for tank depth check; A5 – Oxygen supply to aerators; AN1 – Sulphide in gravity sewers; AN2 – Pressure mains; AN3 – Odours.

The protocol also includes advice on detailed modelling (and model validity) and advice for post-project monitoring.

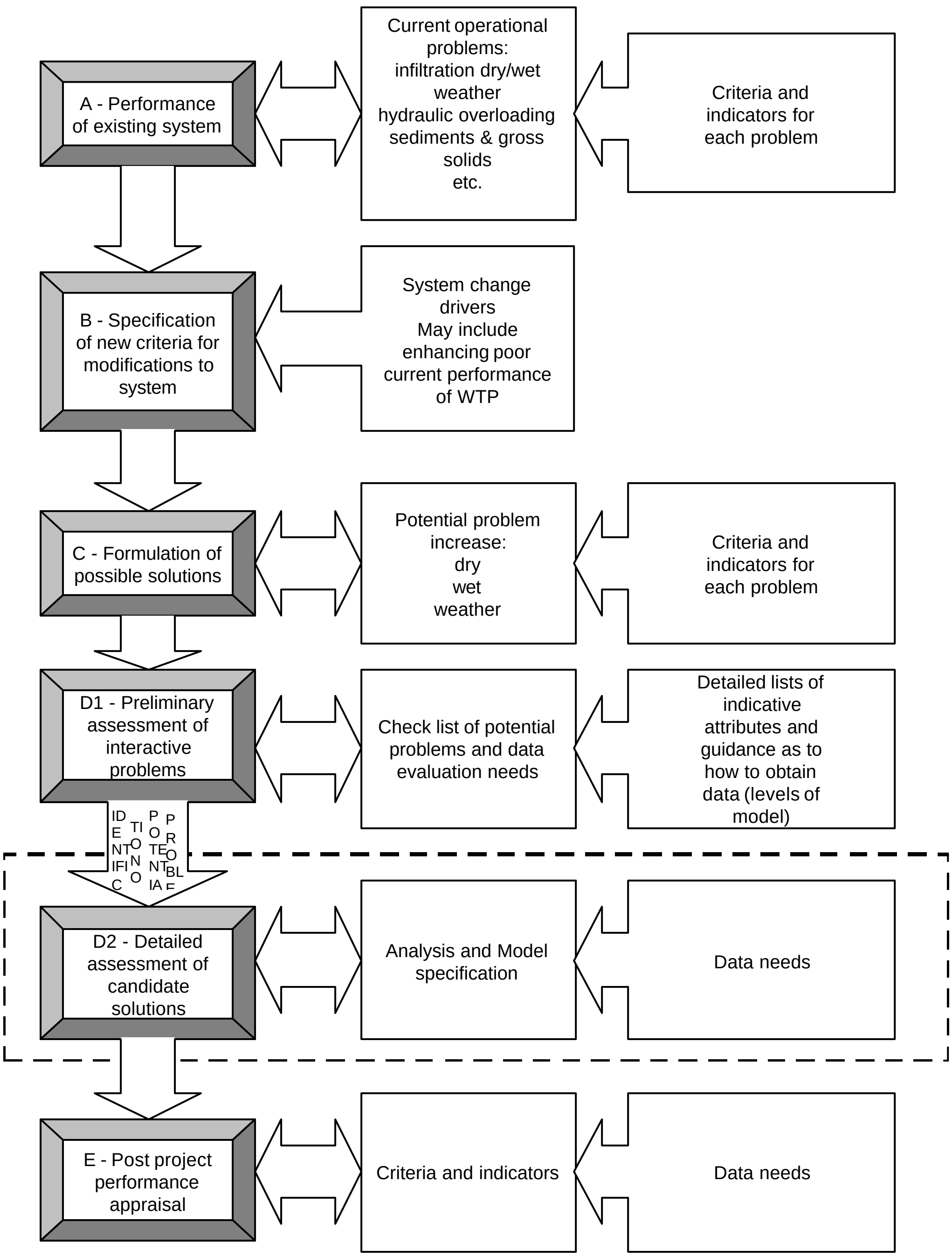

Figure 2 Protocol to assess potential risks to WwTW performance due to the introduction of extended in-sewer storage

Problem	Simple assessment	Equations and limits to assess potential problems	Problem remediation
A1 Solids flush in dry weather	Particular problems for screens and detritors. Check WwTW can handle increased solids loads. Where shear stress ranges in main sewer leading to WwTW are high at peak DWF, solids will be eroded. Where existing tanks in system see Table 3a/b.	Use duration for which shear stresses are exceeded as given by hydraulic model, where shear stresses in sewer leading to WwTW are > 0.5-1.0 N/m^2 then take: TSS = 2 x average DWF TSS, with high organic fraction and gross solids loads of 10 x average DWF concentrations. Default concentrations may be used.	Increase unit capacity at WwTW
A2 Ammonia flush in dry weather	Check WwTW bioprocesses can handle ammonia flush.	WwTW process assessment - Procedure A2*. Use inflow x daily peak ammonia concentration into works over the duration of the rising stage of DWF. Default concentrations can be used.	Increase unit capacity at WwTW. Alternatively it may be possible to increase sludge age.
A3 Infiltration causing high hydraulic loading and/or dilute flows during DWF.	Use only if infiltration suspected as being significant. Sewage likely to be dilute. Main problem will be hydraulic loading. Check also WwTW primary stages.	Procedure A3* Use flows >= 3 x ADWF during dry weather for 12 hours. Estimate concentrations using mass balances for normal strength sewage.	Reduce infiltration into sewer network. Adjust plant operation to ensure MLSS is appropriate for dilute sewage.
A4Ammonia load flush during wet weather onset	Check WwTW can handle peak load of ammonia arising from problem A2* followed by dilution, with higher flows (increasing load).	Procedure A2*. Use pollutograph as specified in A2 above, followed by average DWF ammonia concentration x flow hydrograph arising from a 1 year 50% summer storm of duration 3 hours.	Increase unit capacity.

* These procedures are given in the final report – there is insufficient space here.

Table 2a Investigations for problems apparent in existing systems prior to implementing increased in-sewer storage – problems not specifically related to extended in-sewer storage

Problem	Simple assessment	Equations and limits to assess potential problems	Problem remediation
A5.1 Solids flushes and peak loadings.	Check WwTW can handle peak load of suspended solids at the preliminary stage. Also effects on the reactor and final settling tank.	Procedure A3 plus Procedure A4. Assume a triangular solids pollutograph with a peak concentration of 2g/l for suspended solids corresponding with a one year design storm of duration equal to the time of concentration of the upstream catchment. Take gross solids loads of 10 x average DWF concentrations, arriving at the front of the hydrograph.	Increase unit capacity.
A5.2 Other associated pollutant flushes and peak loadings	Check retention time in aeration tank is adequate.	Procedure A5 . Check retention time in aeration tank is at least 2 hours using a retention time given by (tank volume)/(flow mean over the 2 hour peak period).	Increase unit capacity. Increase RAS flow. Consider step-feed.
A6 Prolonged peak hydraulic load	Potential overloading of reactor and washing out of biomass.	Procedure A3. Check retention time in aeration tank is at least 4 hours using a retention time given by (tank volume)/(flow mean over the 2 hour peak period).	Increase unit capacity. Increase RAS flow. Consider step-feed.
A7 Draining down of storage with high/low strength	Where the problems A4 – A6 are not significant, then this will not be a problem.	Only a problem where A6 significant.	
A8 re-establishment of DWF conditions	As above.	As above.	
AN2 H_2S and VFA production	Potentially causes odours, corrosion and other process problems such as sludge bulking. For gravity sewers there is not likely to be a problem unless the sewer is running full for most of the time. For rising mains, which discharge into a gravity sewer or direct to WwTW inlet problems may be common.	Procedure AN1, AN2. The effects of storage and mixing with gravity systems can only be considered for each case. Check sewerage retention time < 6 – 8 hours. For existing systems where odour measurements are feasible use Procedure AN3.	Avoid pipe-full flows for long in-sewer retention times. Reduce in-sewer retention times. Chemical addition (e.g. nitrates).

Table 2b Investigations for problems apparent in existing systems prior to implementing increased in-sewer storage – problems specifically related to extended in-sewer storage

Problem	Simple assessment	Equations and limits to assess potential problems	Problem remediation
A1 Solids flush in dry weather	May occur where in-line storage installed. Flushes of deposits from tanks might occur during peak DWF. Where tanks offline, then timing of pump return flow needs to be considered. Particular problems for screens and detritors. Check WwTW can handle increased solids loads. May occur where shear stress ranges in tanks and main sewer leading to WwTW are high at peak DWF, solids will be eroded and transported.	Use duration for which shear stresses are exceeded as given by hydraulic model, where shear stresses in tanks and sewer leading to WwTW are > 0.5-1.0 N/m^2 then take: TSS = 2.5 x average DWF TSS, with high organic fraction and gross solids loads of 10 x average DWF concentrations. For offline tanks and where tank sediment flushing is used, return and flush flows should avoid peaks in ambient DWF, but be at times to ensure solids are transported to WwTW and not deposited in the sewer (bed shear >> $1N/m^2$)..	Modify or fit DWF channel in tanks. Increase unit capacity at WwTW
A2 Ammonia flush in dry weather	Problem not likely to be increased by installation of extended in-sewer storage, other than associated with A1 above where near bed solids significant.	If problem A1 has been addressed this Problem A2 should not exist. Otherwise use WwTW process assessment - Procedure A2*. Use inflow x daily peak ammonia concentration into works over the duration of the rising stage of DWF.	Increase unit capacity at WwTW. Alternatively it may be possible to increase sludge age.
A3 Infiltration causing high hydraulic loading and/or dilute flows during DWF.	Where infiltration is significant it may utilise some of the extended storage capacity. However, problem will not be any worse than for pre-storage case.	See Table 2a. Problem A3.	Reduce infiltration into sewer network. Adjust plant operation to ensure MLSS is appropriate for dilute sewage.
A4 ammonia load flush during wet weather onset	Extended storage may attenuate flow peaks and hence reduce this problem. Check WwTW can handle peak load of ammonia arising from problem A2 followed by dilution, with higher flows (increasing load).	Procedure A2*. Use pollutograph as specified in A2 above, followed by average DWF ammonia concentration x flow hydrograph arising from a 1 year 50% summer storm of duration 3 hours.	Increase unit capacity.

* These procedures are given in the final report – there is insufficient space here.

Table 3a Investigations for potential problems arising from the introduction of extended in-sewer storage

Problem	Simple assessment	Equations and limits to assess potential problems	Problem remediation
A5.1 Solids flushes and peak loadings.	With extended storage deposited solids can be re-suspended at the start of subsequent storms. Storage tank detailing may also result in flushes at the end of events. Storage should attenuate peak flows. Check WwTW can handle peak load of suspended solids at the preliminary stage.	Procedure A3 plus Procedure A4*. Assume a triangular solids pollutograph with a peak concentration of 2.5g/l for solids corresponding with a one year design storm of duration equal to the time of concentration of the upstream catchment.	Increase unit capacity.
A5.2 Other pollutant flushes and peak loadings	Check retention time in aeration tank is adequate.	Procedure A5*. Check retention time in aeration tank is at least 2 hours using a retention time given by (tank volume)/(flow mean over the 2 hour peak period).	Increase unit capacity. Increase RAS flow. Consider step-feed.
A6 Prolonged peak hydraulic load	Extended storage may put the WwTW under peak flow conditions for a prolonged period. On-line storage is uncontrolled. Off line storage should be managed to avoid prolongation of peak hydraulic load if possible. Potential overloading of reactor and washing out of biomass.	Procedure A3*. Check retention time in aeration tank is at least 4 hours using a retention time given by (tank volume)/(flow mean over the 2 hour peak period).	Increase unit capacity. Increase RAS flow. Consider step-feed.
Problem A7 Draining down of storage with high/low strength	Where the problems A4 – A6 are not significant, then this will not be a problem.	Only a problem where A6 significant.	
Problem A8 re-establishment of DWF conditions	As above.	As above.	
Problem AN2 H_2S and VFA production	Extended storage may increase the opportunity for septic conditions to develop. Offline storage potentially the greatest problems. Avoid too long retention times in storage units. Potentially causes odours, corrosion and other process problems such as sludge bulking.	Procedure AN1*, AN2*. The effects of storage and mixing with gravity systems can only be considered for each case. Ensure retention times are less than 4 hours in online storage units. (3 hours where offline are pumped). Check sewerage system retention time < 6 – 8 hours.	Avoid pipe-full flows for long in-system retention times. Reduce in-sewer retention times. Chemical addition (e.g. nitrates).

* These procedures are given in the final report – there is insufficient space here.

Table 3b Investigations for potential problems arising from the introduction of extended in-sewer storage.

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, can lead to more problems downstream. These will occur in the chambers themselves and in the sewers. At WwTWs wet weather problems are well known, due to higher hydraulic loads, ammonia flushes, high solids loads and disruption of nutrient removal processes. However, the effects of extended in-sewer storage are less reported. Prolonged in-sewer storage (or storage in WwTW 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 potentially lead to higher WwTW effluent loads (particularly TSS and ammonia) 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. Nonetheless, where systems are designed and operated in accordance with current standards, the problems should not be insurmountable. The greatest risks occur for WwTW that are already operating regularly close to their consent standards. Even for these plants, judicious operation should prevent problems without significant additional investment.

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. The project has 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 is likely to lead to other problems.

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