Leaky sewers: assessing the hydrology and impact of exfiltration in urban swers

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INTRODUCTION

The UK *Sewer Rehabilitation Manual (SRM)* (WRc, 2000) defines exfiltration in sewers as "*the escape of flow from the system into surrounding ground through weak points*" such as structural defects which include cracks, fractures, joint displacements, unsealed connections and deformational gaps. The causes of such structural defects can be primarily attributed to poor construction and materials (especially in brick sewer construction from the 1925–1950 period), heavy traffic loadings as well as operational and service damage (Anderson *et al*., 1995: Davies *et al*., 2001). One estimate suggests that up to 40% of UK sewers have structural defects and about one in twelve (of the 302 000 km of public sewers) have serious defects, with some £8 billion needed to alleviate the most immediate problems (Hayward, 2002). Whilst there has been considerable attention given to sewer infiltration, surprisingly little work has been undertaken to identify and quantify potential sewer losses or to their modelling. This is despite the fact that groundwater studies have identified elevated concentrations of ammonia, boron, chloride, nitrate, phosphate and bacteria in localised 'pools' beneath a number of urban areas such as Nottingham, Liverpool, Birmingham and Luton (Hughes *et al*, 1999; Ellis and Revitt, 2002) and assertions that sewer exfiltration is likely to play a more important part in such contamination than has been previously assumed (Reynolds and Barrett, 2003). However, whilst geochemical, microbiological and nitrogen isotope studies yield useful groundwater markers for sewage, they are not absolute indicators due to die-off of microbiological organisms and the mixing and fractionation processes affecting isotopes as well as some (e.g chloride, nitrate, etc.) being of multi-origin and also being found in unpolluted waters.

Various incidents of sewer leakage have been documented (Lerner *et al*., 1994; Ellis and Revitt, 2002) but they remain rare with only some 70 officially documented cases in the UK over the past 60 years or so (Blackwood *et al*., 2001). Thus the overall impact of urban sewer exfiltration on groundwater quality would not appear to be that severe, despite the fairly widespread acknowledgement within the UK water industry that sewer exfiltration could be a common occurrence even though most water companies are unable to measure leakage from their sewer systems with CCTV procedures being unsuccessful in detecting the majority of loss points. However, such a conclusion would seem to be at odds with the high quantified rates of sewer infiltration, which should imply that at low groundwater levels there might be expected to be substantial losses. This implication is supported by the widespread occurrence of structural sewer defects with, for example, some 5000 sewer pipe collapses per annum being recorded in UK urban areas (OFWAT, 2000). The water industry has requested OFWAT in the current AMP5 review to allow them to spend £8.5 billion on their infrastructure in order to redress a historic neglect of sewers. Past investment has been driven largely by EU directives which have focused principally on sewage treatment and CSOs, not on the sewer pipes which convey the sewage to treatment and discharge. This paper explores the likely pathways and rates of exfiltration into the surrounding environment and identifies potential mechanisms which may serve to limit the receiving waterbody impact of wastewater losses from sewerage systems.

EXFILTRATION PATHWAYS AND RATES

Leakage sources and pathways

Figure 1 is a conceptual representation of the hydrological pathways whereby exfiltrating sewage effluent might reach both surface and groundwaters. Direct contamination of the groundwater zone (5) by downward percolation (via fissure and matrix flow) through the unsaturated zone is only likely to occur during prolonged dry periods when the water table falls below the invert level of the sewer pipe. The sub-lateral seepages (2 and 4) through the unsaturated zone contribute to the contamination of surface water drainage that is exacerbated by the cross-connections (3) which all too frequently occur between the foul and surface water sewer systems. The latter discharge directly and untreated to receiving watercourses and

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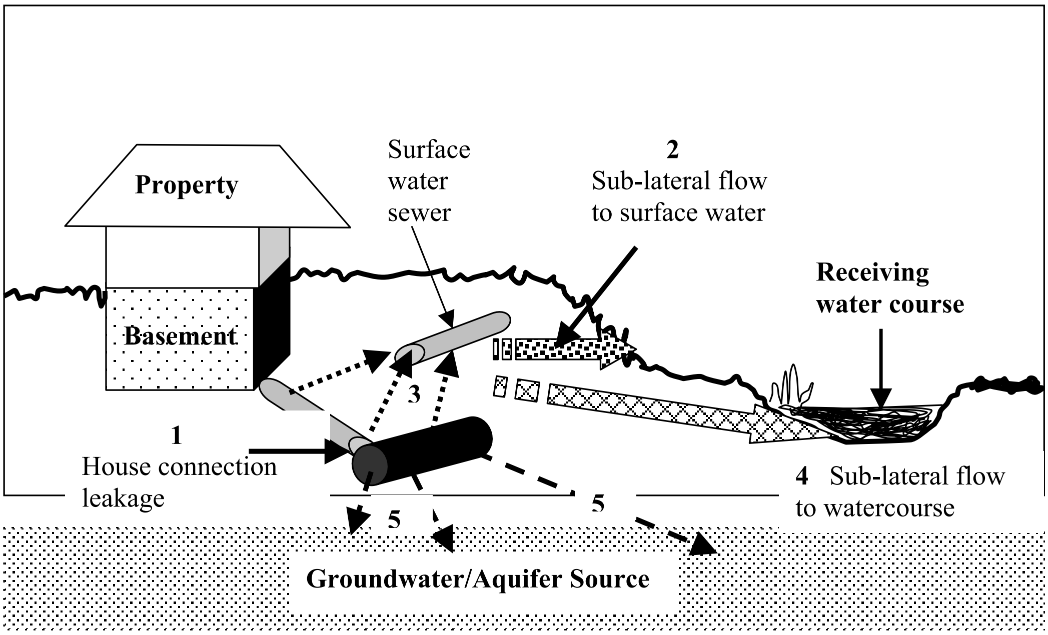

Fig. 1 Hydrological pathways of sewer exfiltration

present major sources of urban runoff pollution (Ellis, 1991).

A principal source and pathway of sewer exfiltration may well be related to leakage from house connections (1) especially at the junction point with the main sewer line and because such connections are generally above the groundwater level for much of the time.

Field evidence

Studies undertaken within the context of an EU 5th Framework project (APUSS) have noted, for a small 0.25 ha housing development in the Troja district of Prague, an average exfiltration loss of 0.23 l s^{-1}; expressed in terms of unit pipe length this is equivalent to 3.5×10^{-3} l s^{-1} per metre and represents some 75% of the connecting pipe hydraulic capacity (Kohout *et al*., 2003). Such high exfiltration rates may not be typical of the large majority of house connections in the UK, but anecdotal evidence in the UK water industry would suggest that such sources can provide substantial leakages to the surrounding soil and groundwater environment, particularly via defects at the junction between the house connection pipe and the main sewer (Figure 1). There is some discussion within the water industry at the present time of the possibility of designating the length of house connection beyond the immediate property boundary to the main sewer as a '*public lateral drain*'. This length would become the responsibility of the water company and have a terminal manhole. However, such re-designation would add some further 6% of pipes (an extra 18 000 km or so) to the current public sewer network and would also require appropriate legislation. When house connection leakage is combined with loss from the main sewer lines, such combined sources— especially during high flow periods — can lead to out-of-sewer flooding. For sewers located within Groundwater Protection Zone 1 areas, this could lead to contamination by List I and II substances and potentially prejudice water supply boreholes. Reported internal sewer flooding incidents in the UK public sewer system increased from 5000 to 5300 in 2001–2002 (at an annual cost of about £177M) with Severn Trent Water, for example, experiencing 600 sewer ruptures or rising main bursts. 16.4% (5175) of all pollution incidents in 2002 within England and Wales were caused by sewerage compared with 14.1% in the previous year, despite a total expenditure during the year of £1.7 billion on sewerage maintenance (0.2% of total asset value per annum with a gross replacement cost of £104 billion).

UK water authorities have recognised that sewerage exfiltration can be a factor in basement flooding as illustrated in Figure 2 which is based on the OFWAT *Flooding from Sewers* DG5 sewer replacement indicator. Typically, 55– 60% of sewage flooding of properties is attributable to 'other causes' of which only some 2–3% might be attributed to exfiltration.

However, some UK water authorities such as Yorkshire Water suffer inordinately from such 'other cause' property flooding (Figure 3), of which a substantial proportion are associated with pre-1936 housing and can be related to leakage via structural defects as determined by dye tracer studies and sewer surcharging tests. Environment Agency (2000) guidance

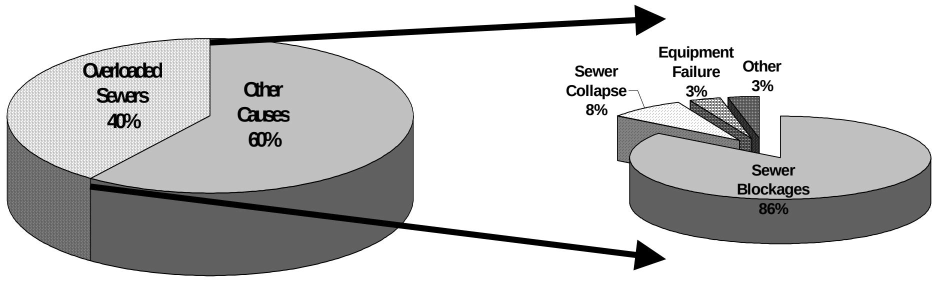

Fig. 2 Causes of basement flooding

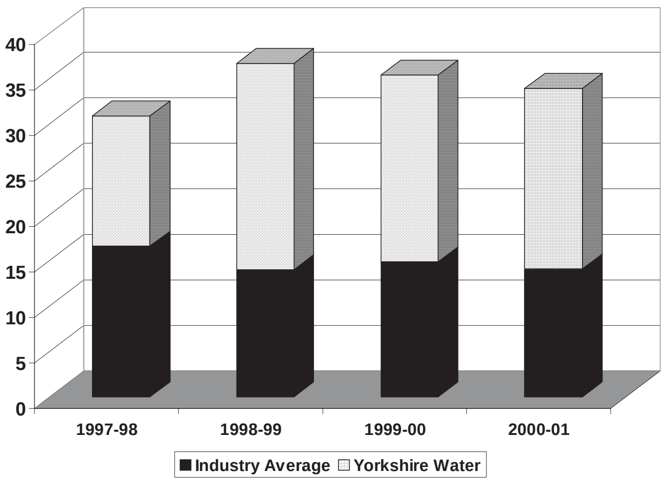

Fig. 3 Properties flooded (per 100,000) by "other causes"

suggests that there should be a minimum travel distance of 50 m within the Inner Groundwater Protection Zone 1 between a contamination point (such as an exfiltrating sewer) and the receptor waterbody, although the CIRIA 1995 report notes that the majority of recorded groundwater pollution incidents were within a distance of 100 m from sewer to the affected receptor (Anderson *et al*., 1996). Clearly, sewers of brick and clay construction with rigid joints dating from the 1925–1950 period (SRM internal condition grade 5, 4 or 3), located in vulnerable groundwater zones, subject to high traffic loads and within 100 m of a receptor body present the highest pollution risk.

A survey of 180 km of sewers in the Southern Water area showed that 56% of the joints were faulty (TRRL, 1989) and the CIRIA 1995 report estimated sewer exfiltration at 3% of total average annual flow within the Thames Water region, which would be equivalent to about 300,000 m^3 day^{-1} (109.5M m^3 $year^{-1}$). Based on the water balance determinations and a 10 mm per annum recharge rate provided by Yang *et al* (1999) for the Nottingham aquifer, estimates based on equivalent rainfall volume suggest that about 1% to 2% of average sewer flow is lost through exfiltration.

German studies (Ullmann, 1994) have noted exfiltration rates of 0.0013–0.009 l s^{-1} for half-filled pipes, increasing to 0.04 l s^{-1} at full bore flows in main trunk sewer lines and being equivalent to some 1.2×10^{-5} l s^{-1} per linear metre of sewer (Hoffman and Lerner, 1992) This would yield overall leakage rates of between 5–20% for gravity sewers above the water table. The lower 5% loss figure is quoted as an average by Gruenfeld (2000) for various US studies, with noted field exfiltration rates varying between 1.39×10^{-3} to 3.9×10^{-3} l s^{-1} per linear metre sewer length. Much higher leakage rates for German sewers have been reported by Decker and Risse (1993). Their studies of a 300 mm diameter Aachen sewer showed exfiltration rates ranging between 0 to 0.056 l s^{-1} under full bore flow and increasing to 0.083 l s^{-1} for surcharged conditions. The highest exfiltration rates occurred via longitudinal cracks in the pipe invert and arch springer line. They noted a general linear trend of exfiltration rate with flow head. Utilising a field tracer technique developed within the EU 5th Framework APUSS project (Rieckermann and Gujer, 2002), exfiltration rates of between 0–13% have been recorded in two east German cities although there are statistical uncertainties associated with the methodology, mainly due to background disturbance of the NaCl dosing procedure (Rutsch *et al*., 2003). Parallel APUSS tracer studies conducted in Rome within a 13-year old concrete sewer set in a normally dry coarse gravel backfill, demonstrated an exfiltration range varying between 0.24–2.96% for two test reaches (Giulianelli *et al*., 2003), although again considerable uncertainty was associated with the results.

However, such average percentage exfiltration rates for observed flow volumes as given above must be treated with some caution as in addition to variability in sewer age, diameter, depth, condition and surrounding soil permeability, exfiltration patterns from specific defects are unlikely to be constant over time. Actual exfiltration rates depend on the balance between the geometry and size of the defect with the properties of the enveloping soil and this balance will change considerably with flow pressure head and soil wetness conditions. Given constant soil moisture and constant pressure head, an extensive and stabilised exfiltration flowpath might be expected to develop which would be most likely to occur following the establishment of prolonged dry weather conditions. Interruptions to this balance due to intensive rainfall events and rapidly changing discharge or to operational failure (e.g. damage resulting from pressure testing, high pressure jetting, deformational collapse, etc.), can cause large increases in exfiltration until a new balanced state is reached.

It is clear that the exfiltration rates derived from these various field studies show considerable variation, but the body of available evidence reviewed above would suggest that average exfiltration rates of between 3–5% (and in the order of 10^{-3}–10^{-5} l s^{-1}) may potentially be expected in pre-1960 sewer pipes. Based on 100 defects per kilometre sewer run, this would yield overall annual average leakage rates ranging between 32–3150 m^3 km^{-1} $year^{-1}$. If such overall losses were occurring (at a 3–5% loss rate), persistent sewer exfiltration might also be expected to have demonstrated its existence by a more widespread and concentrated urban groundwater contamination than appears to be the case for most UK situations. This discrepancy might be due partly to a paucity of detailed urban groundwater studies or to problems associated with the scaling-up procedure and may also be explained by clogging of the sewer invert level by sediment deposition and biofilm growth which may block and seal the majority of structural defects. This potential sealing mechanism and the factors affecting the cohesion and sealing effectiveness have been the subject of a number of experimental test rig studies.

EXPERIMENTAL RIG STUDIES AND THEIR IMPLICATIONS

Exfiltration studies have been undertaken on experimental test rigs using both clear and live wastewater flows. German and Danish wastewater investigations have demonstrated typical exponential trends, with high initial exfiltration rates rapidly decreasing to low constant levels (3.47×10^{-6} l s^{-1}) within a few hours at most (Dohmann, 1999; Vollerstsen and Hvitved-Jacobsen, 2003). It is interesting to note that even at such reduced exfiltration rates, the overall extrapolated loss would still be in the order of 110 m^3 km^{-1} $year^{-1}$. These workers invoke a colmation process caused by solids deposition and biofilm growth which induce a ‘clogging zone’ at the crack/defect. Following cleaning of the pipe, Dohmann found that the exfiltration rate returned to its original high initial level, subsequently declining back to the ultimate equilibrium level observed prior to cleaning.

Ellis *et al*. (2003) have shown that the self-sealing capacity is further enhanced by the presence of a tight trench backfill and high groundwater levels. Figure 4 illustrates this for a short-time experimental clearwater run (of 20 minutes) for a 10 mm^2 hole (10 mm × 1 mm joint gap) during which equilibrium conditions were not achieved. The packed dry gravel run shows a considerable suppression on the free-draining exfiltration rate after the initial maximum loss rates have been achieved, illustrating the important role played by the trench backfill material in reducing exfiltration loss. Whilst there is a rapid initial exfiltration rate with increasing head when the hole is enveloped by a wet gravel jacket, as would occur under high groundwater conditions, the overall loss rates are an order of magnitude less than for either the dry gravel or free draining conditions. The hydrostatic pressure exerted in the fully saturated trench backfill, combined with the gravel blocking, clearly prevent major exfiltration from the pipe even at high flow and pressure heads in the sewer pipe. Experimental runs under free-draining conditions using road surface sediments, sand/peat mixes and artificial cohesive sediment showed ultimate equilibrium exfiltration rates at DWF levels ($Q_{10/15}$) as low as 5×10^{-4} l s^{-1} for a range of joint openings and pressure heads. Even following full bore flushing of the pipe, leakage rates fell back rapidly to nearly the same low level once the 10–15% DWF had been re-established, confirming the wastewater observations of Dohmann.

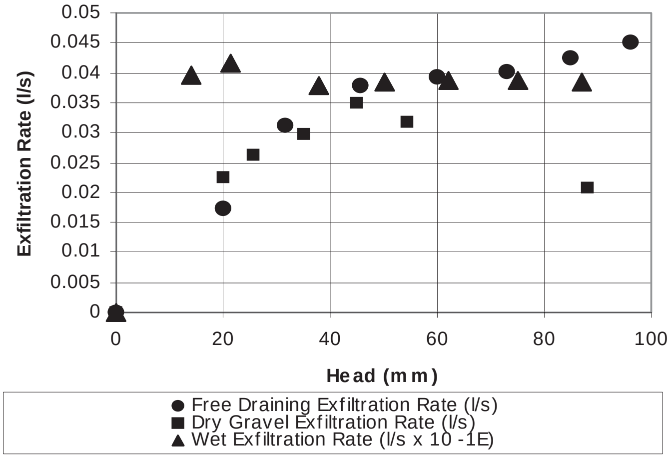

Fig. 4 Exfiltration rates for clearwater flows through a 10 mm² invert hole for free-draining, dry and wet gravel backfill conditions.

Experimental runs on pumped live wastewater flows at Dundee exhibit similar trends to those noted in the clearwater rig. Figure 5 shows test runs for varying 3 mm gap geometries (holes, half-horizontal and vertical joint openings) at near constant head under free-draining conditions; the high initial exfiltration rates and rapid decreases noted by other workers are clearly replicated with ultimate equilibrium rates for the half-horizontal gap opening being just under 0.002 l s^{-1} and for the 40 mm^2 hole being 0.001 l s^{-1}. The reduction in final equilibrium level from 0.23 l s^{-1} in the clearwater test runs to

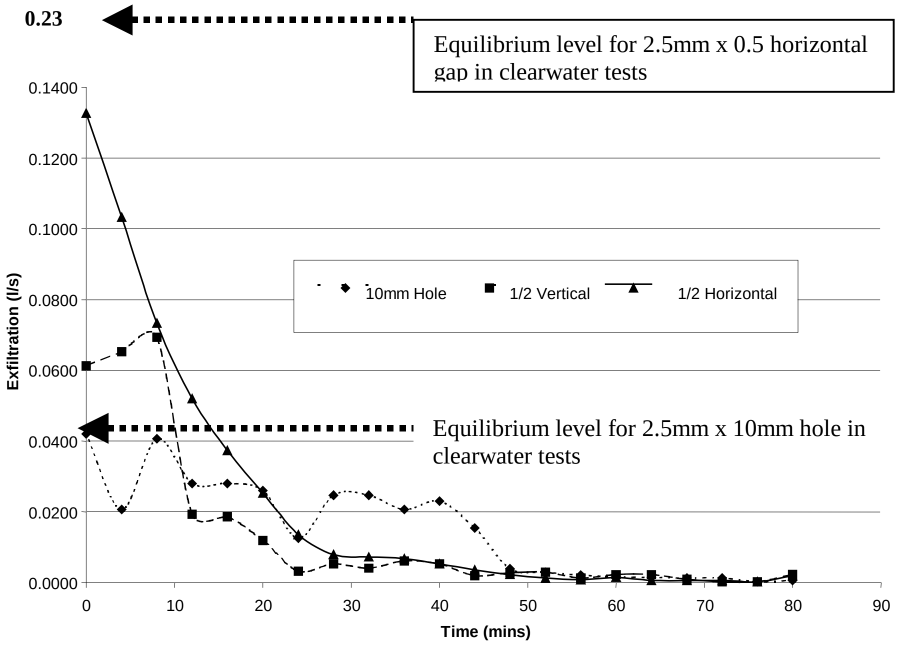

Fig. 5 Comparison of exfiltration rates for varying 3 mm gap geometries and constant head (42–44mm) in a live wastewater test rig.

0.002 l s^{-1} in the equivalent wastewater rig tests illustrates the effect of sediment on the loss rates. A similar but lower reduction in exfiltration rate from 0.045 l s^{-1} to 0.001 l s^{-1} was observed for the 10 mm long hole. Figure 6 shows the exfiltration rates for varying 10 mm gap geometries and illustrates the effects obtained when the pipe is wrapped in a compacted dry gravel backfill. A similar pattern of rapid reduction, particularly for the half-round gap configurations, was observed, tending towards a final equilibrium rate of between 0.001 and 0.006 l s^{-1}.

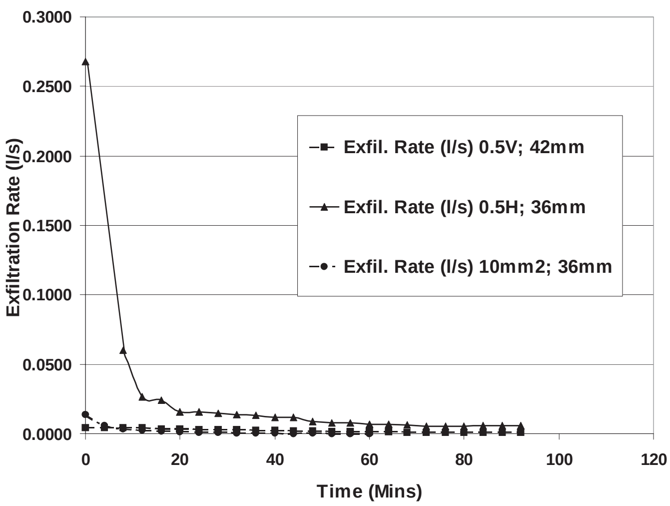

Fig. 6 A comparison of exfiltration rates for different 10 mm gap geometries for dry gravel trench backfill conditions in a live wastewater rig

However, even assuming that sewer joints occur at intervals of 2.5 m and that 10% of joints were defective in a kilometre sewer length, the live wastewater rig outcomes for 10 mm wide defects in pipes in dry gravel surrounds would still imply ultimate overall loss rates of between 1261–7568 m^3 km^{-1} $year^{-1}$. If this is scaled-up to the 25% Grade 5 and 4 sewers of the total 64 374 km network of Thames Water, this would yield losses due to exfiltration of between 20.3M and 122M m^3 $year^{-1}$. The higher exfiltration rate is roughly equivalent to the 1995 CIRIA reported value (i.e 3% exfiltration and 109.5M m^3 $year^{-1}$). Further field research within the Thames Water region using lithium and bromide tracer techniques, based on the QUEST methodology developed under the EU 5^{th} Framework APUSS programme (Rieckermann and Gujer, 2002), will be undertaken to establish the validity and accuracy of the experimental wastewater rig estimates.

Thus the live wastewater test runs confirm the additional confining effect of trench backfill on leakage loss and the scale-up for the poorer sewer grades derives realistic loss figures for the catchment level and gives some confidence in the general validity of the experimental rig approach. However, even given that such a simplified scale-up procedure might be inappropriate, the rig results still mean that that the effect of extensive in-pipe sediment and biofilm growth, combined with compacted trench backfill (and frequent high groundwater levels), collectively and substantially reduce the overall loss rates in the real sewer network. On the other hand, it is also evident that there is considerable potential for exfiltration loss at low dry weather flows in old sewers, particularly if intensive maintenance procedures clean out and expose the open joints and other structural defects. Exfiltration loss provides a direct measure of asset performance in terms of the adequacy of sewer pipe hydraulics and as such offers an enhanced serviceability indicator for sewerage operations.

In terms of environmental risk, both the probability and consequences of exfiltration loss are likely to be of an increasing nature such that the source, pathway and receptor impacts may become more evident and widespread. Whilst this paper has considered the potential scale of the problem based on experimental rig tests, it must be stressed that the field outcomes are very likely to be site-specific, with differing sewer networks reacting differently, depending upon the composition, age and deterioration status of the local system.

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