Performance Indicators for Complex Wastewater Pumping Stations and Pressure Mains

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***Abstract*— With increasing energy costs, concern on CO_2 emission and growing interest in asset management, the online evaluation of pressurized wastewater systems provides an opportunity for optimizing performance.**

This paper describes a method that uses performance indicators (PIs) derived from monitoring data and model simulation results using an online system. Malfunctioning, or underperformance can be detected in an early stage, which enables to take measures in terms of replacement or reparation based on the actual status of the system rather than rely on the effectiveness of regular, scheduled, inspection. The city of Almere's wastewater transport system is used as a case study and demonstrates the introduction, application and interpretation of these PIs as well as the obtainable reduction in energy consumption using on-line data on the systems behaviour.

Keywords—wastewater, performance indicator, pumping, online, monitoring, maintenance, energy

I. Introduction

In highly urbanized (delta) regions, pressurized wastewater mains are used to transport wastewater. These wastewater mains include many inverted siphons to cross channels, motorways, railways and other infrastructure. Gas pockets may accumulate in these inverted siphons causing significant capacity losses and extra power consumption, see Fig. 1.

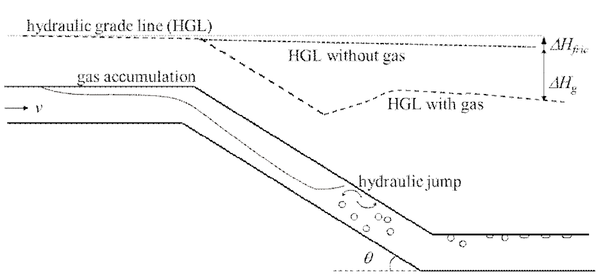

Figure 1. The effects of accumulating gas

In the Netherlands the extra electric power consumption is assessed to be at least 3 million EURO per year. Other consequences of the presence of gas pockets include increased maintenance costs, risk on corrosion of pipe materials, spills of untreated wastewater into open water courses and unnecessary investments.

Apart from pump failure [1] and inefficient operation, gas pockets in downward sloping sections are the main cause of increased energy consumption and reduced capacity of pressurized wastewater mains.

A better understanding of the dynamic behaviour of gas pockets in pressure mains and especially a new theory about the velocities related to stagnation and transport of these gas pockets, was established in the CAPWAT project [2], [3]. The abbreviation CAPWAT stands for CAPacitiy losses in WAstewater Transport. A comprehensive handbook of the results and the practical implications of the CAPWAT project is found in [4].

The aim of the water authorities is to guarantee wastewater transport while minimizing any operational and investment costs, such as energy consumption and excessive maintenance.

In the majority of cases one deals with a combined system, i.e. wastewater and storm water are collected and transported in one system. Based on the behaviour during dry weather conditions one wants to know whether the maximum discharge requirements can be obtained during storm weather conditions (typically the maximum discharge during storm events is 4 to 5 times larger than during dry weather). Key issues in achieving this are the ability to access the performance of the systems at any time, having quick access to the results of a performance analysis and the ability to control the system. This paper describes a method to quickly access the actual performance of complex pressurize wastewater systems using online monitoring and analysis. The drainage system of Almere is used as a case study.

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II. NEED FOR PERFORMANCE INDICATORS

Wastewater transport systems are becoming increasingly complex in the Netherlands. Extensive branched systems with numerous pumping stations are operated locally and real time performance analysis of the entire system is therefore crucial for efficient management. At present, the monitoring of measurement data is mostly limited to a few signals only and is mainly intended for pump operation or the reporting of failures. Analysis of the data is only done after an incident has occurred. Prior to this, inefficient operations may have gone unnoticed on a large scale, which can result in unnecessarily high maintenance and/or running costs.

III. DEFINITION OF PERFORMANCE INDICATOR

The performance indicator (PI) is the ratio between a reference value K_ref and the actual value K_act. The parameter K_act is based on the measured data gathered over time. For newly built systems, the parameter K_ref is determined in the engineering phase or at the commissioning of the system. In existing systems, a new baseline measurement (benchmark) can to be made under well-defined conditions.

A calibrated hydraulic model is indispensable for this reference determination. Normally a hydraulic model is only used in the engineering phase and is deemed to be useless when the system becomes operational. A calibrated hydraulic model can be of great value during the operation lifetime of the system.

The ratio is defined so that reduced performance leads to a PI < 100%.

For a decreasing K_act (e.g. capacity) in the case of reduced performance, PIs are defined as:

$$PI = \frac{K\_act}{K\_ref} \times 100\%$$

For an increasing K_act (e.g. energy consumption) in the case of reduced performance, PIs are defined as follows:

$$PI = \frac{K\_ref}{K\_act} \times 100\%$$

In existing situations the availability of monitoring data determines which PIs are used, for newly designed systems the monitoring network can be tailor made. In case of relatively small pumping stations, it may be sufficient to register the operating hours of the pumps in order to assess the performance of the system. For major pumping stations, it is necessary to monitor all relevant signals including discharge, suction and discharge pressure, pump speed, electrical power or current energy.

The primary function of the PI is to monitor the change in performance in time. For each system and each PI, individual limits can be defined to mark an unacceptable decrease in performance. The calculation of PIs can be incorporated into an existing monitoring system that is then also able to provide information if PI-limits are exceeded. TABLE I. shows the PIs applied in the city of Almere.

TABLE I. OVERVIEW OF PERFORMANCE INDICATORS

PI	Aim	Why
Capacity	Detects loss of capacity at an early stage	• monitors urban discharge requirements • reduces emissions on surface water
Pipeline System characteristic	Analysis of pipeline resistance based on flow rate and discharge pressure	• monitors extra losses due to air pockets or sedimentation • useful for state-dependent maintenance • improves energy efficiency
Specific energy	Energy consumption (kWh) to transport 1 m3 water	• quantifies the effect of changes, such as pump replacement, control changes
Pumping station	Analysis of pump performance and losses in the pumping station	• need for pump maintenance and de-clogging of check valves or pumps in the pumping station

IV. DESCRIPTION TYPICAL SYSTEM

A typical system of pressurized wastewater mains is shown in Fig. 2.

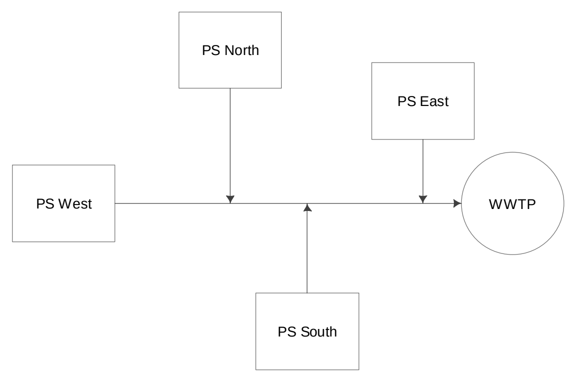

Figure 2. Typical waste water scheme

Several pumping stations are connected to a pressure main that discharges into the wastewater treatment plant or an intermediate pumping station that can be equipped with a booster pump or an open pump sump.

The design capacity of a pipeline depends on the pump's characteristics, the static head and the energy losses in the pipeline. The duty point of a pump is the intersection of the pump curve and the system energy loss characteristic, see Fig. 3. When other pumping stations are turned on, the pump's behaviour will be affected as the resistance in the system increases. This results in a reduced capacity for a fixed speed pump (Fig. 3) and in a increased speed for a variable speed pump (Fig. 4). In both cases, energy consumption increases significantly.

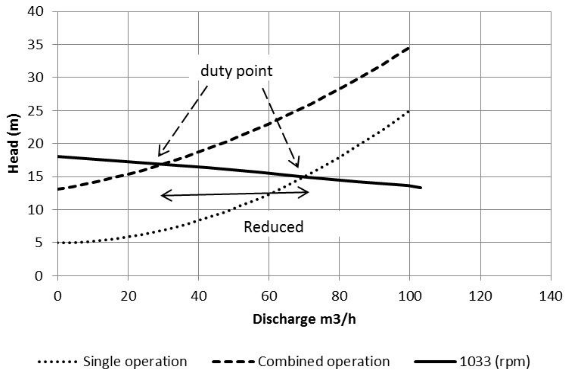

Figure 3. Different duty points for fixed speed pump in single operation and combined operation

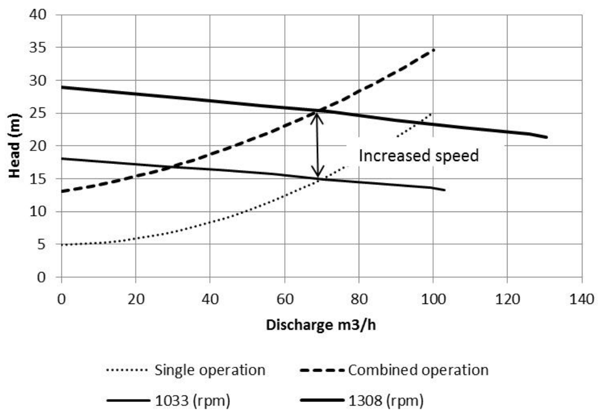

Figure 4. Different duty points points for variable speed pump in single operation and combined operation

By implementing an integrated control system, energy savings are therefore possible and each pump station is allowed to run in predefined fixed time-slots. For combined sewer systems, integrated control is only possible during dry weather conditions. This implies that the control system must have access to rainfall data so it can switch to local control during bad weather. When integrated control is applied, significant energy savings are noted at the pump stations furthest from the wastewater treatment plant.

V. IMPLEMENTATION

The online monitoring system is based on Delft-FEWS [5]. This provides an open shell system for managing forecasting processes and/or handling time series data and incorporates a wide range of general data handling utilities, while providing an open interface to any external (forecasting) model. The modular and highly configurable nature of Delft-FEWS allows it to be used effectively for data storage and retrieval tasks, simple forecasting systems and in highly complex systems utilizing a full range of modeling techniques. In Almere, PIs are calculated by comparing the real measured value and a reference value based on a hydraulic model. Fig. 5 shows the analogy between a real flood early warning system (fews) and the PI-information system.

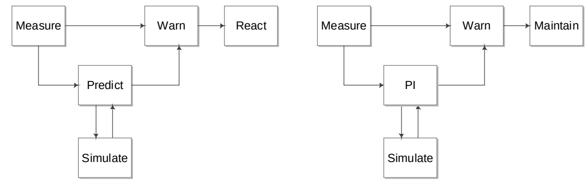

Figure 5. Analogy between FEWS and the PI-system

The pipeline software system WANDA is used for the hydraulic model calculations. It has been adopted by many Dutch water boards and municipalities to analyse steady and unsteady flow conditions in arbitrary pressurized pipeline systems. This integrated FEWS – WANDA tool is called TAMTAM: Toolbox wAstewater MoniToring for Asset Management. The flowchart for this process is shown in Fig. 6.

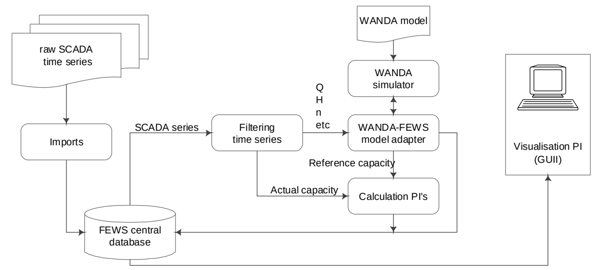

Figure 6. TAMTAM flowchart

Measurement data is collected in a database and subsequently validated. Performance Indicators can only be derived for stable (stationary) operating conditions. These are reached when an unsteady state (pressure wave) has subsided after a change in operating conditions, such as when a pump is switched off. The time required for the subsidence of the pressure wave depends on its travelling time. Stable operating conditions are identified by filtering algorithms.

Fig. 7 shows an example of the pressure at the discharge side of a pump, based on the results of a hydraulic model to illustrate the dynamic pressures due to start and stop. The marked areas can not be used for the PI determination.

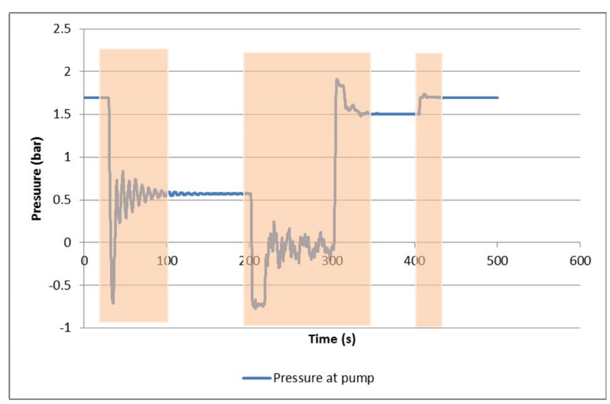

Figure 7. Unstable conditions due to pump start and stop

When a stable operating condition is identified, the WANDA model is started. Depending on the PI, one or more of the measured parameters are forwarded to the model and the reference value is calculated. For example, the 'system characteristic' PI can be calculated in one computation for each pipeline section. The measured discharges are given and the pressure heads at the beginning of all pipe sections are then known.

To calculate the 'capacity' PI, more than one computation is needed in a branched system. The actual speed and suction level of the specific pumping station are imposed on the model and the actual discharge is imposed on all remaining pumping stations. Due to the complexities in the data filtering and the large number of model calculations, the need for an automated performance system is obvious.

VI. The Case of Almere

The primary motivation for the municipality of Almere's participation in the TAMTAM project is to understand the real performance of its wastewater system. To date, no tool has been able to perform an integrated system analysis automatically and processing the signalling abnormalities has been undertaken manually. It is labour intensive, subjective and is consequently not be performed regularly. In addition, slowly changing values are hard to detect from previously monitored data. Applying the automated evaluation of PIs enhances the potential for optimum management. Almere city was a new development that started in 1976 and today has a population of almost 200,000. About 200 pumping stations have been installed in the mainly separated sewer system. The majority of these (185) have relatively small capacity (<70 m3/h) and have fixed speed pumps. The water level in the pump sump, energy consumption and pressure are all monitored. The other 15 pumping stations have a capacity varying between 70 m3/h and 250 m3/h and are equipped with variable speed pumps. Discharge and pump speed are recorded here as well and all the monitored signals are stored in a central database.

In the case study, 6 individual pipeline systems are implemented in TAMTAM, varying from a single system to branched systems of up to 6 pumping stations. In total, 15 pumping stations are analysed and all pumping systems are connected to pure wastewater pipelines. These 6 systems contain various signals, pump drive types and pipeline layout. The PIs received are capacity, pipeline system characteristics and pump characteristics. The measured discharge is required and it is necessary to obtain the discharge data for small pumping stations with no flow meter. Discharge is derived from the water level rise and fall in the pump sump. This method can be applied provided the water level is below the invert level of the incoming gravity sewer. The data logging frequency depends on the pump status: the frequency increases when a pump is in operation, this results in a non-equidistant time series. Interpolation is therefore applied to allow for the further processing of data (time series analysis). Data processing includes the following steps:

- generating a discharge time series for all pumping stations without a flow meter
- transforming all non-equidistant time series to equidistant time series
- filtering all time series for stable (i.e. stationary) operating conditions
- running each stable time step and for each required PI, the simulation model
- deriving the required PI based on the actual measurement value and the ideal simulation result
- presenting PIs on user interface

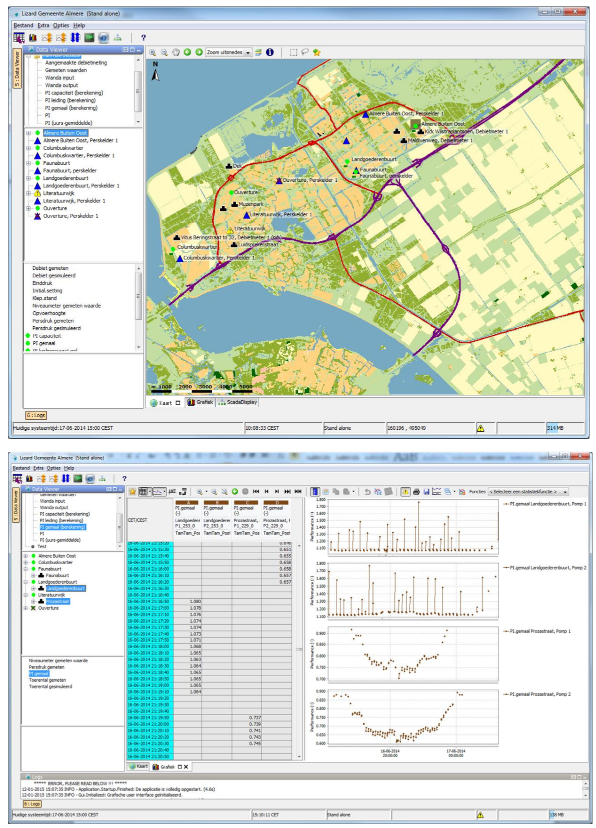

Figure 8. screen shots of TAMTAM User Interface

Two individual sub-systems are described hereafter to illustrate the overall system. The results from the sub-systems are discussed later.

The first system, the Landgoederenbuurt, has only one pumping station with two pumps that run alternately and a PVC ø 235 mm pipeline that is 1300 m long. Halfway down this pipeline, a five-meter-deep inverted syphon crosses a canal. Accumulated gas pockets in the downward sloping section are known to cause a significantly increased energy consumption and reduced capacity, see Fig. 1. The results of pressure relief are discussed in VII.C.

The second system, Almere Buiten-Oost, has 4 individual pumping stations, one (nr. 266) equipped with fixed speed pumps, the others equipped with variable speed pumps. The main dimensions are shown in Fig. 9. This sub-system can save energy by integrated control (see VII.D).

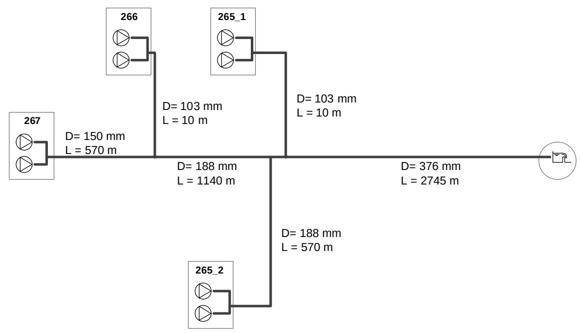

Figure 9. Schematisation of Almere Buiten-Oost system

VII. Results

Four different results are discussed below to demonstrate the effectiveness of the TAMTAM system: the definition of the reference situation; the interpretation of the 'pump capacity' PI; visualisation of the effects of maintenance action; and an assessment of the energy-saving potential of integrated control mechanisms.

A. *Defining the Reference Situation*

Defining the reference situation is crucial when interpreting the PIs. Two methods determine the reference situation: referring to the design situation or conducting measurements. If the design situation is applied as a reference situation, a design that is too conservative may influence the PIs. For example, the wall's roughness values, as they are used in the design phase, are too conservative in this study. They vary from 0,25 mm (PVC) to 0,50 mm (steel). Such values are commonly used average design values and include aspects like pipe aging, joints, bends and small gas pockets. However, the wall's real roughness must be lower as PIs above 100% are found (i.e. the systems outperforms its design).

B. *Pump Capacity*

The TAMTAM system provides reports to show the individual behavior of pumps e.g. to detect differences in capacity between identical pumps in one pumping station. Fig. 10 shows this effect.

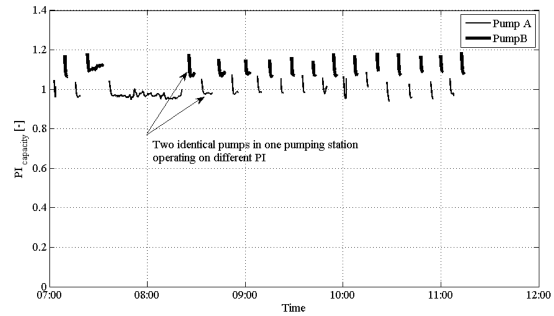

Figure 10. Different PIs for two identical pumps in one pumping station

Without a monitoring system, this different behaviour would be difficult to detect. Based on the 'capacity' PI, the maintenance schedule for pump inspection can be optimized. In this particular case, inspecting pump A is recommended.

C. *Effects of Maintenance Actions*

For the Landgoederenbuurt sub-system, the effect of maintenance was assessed. Fig. 11 shows the effect of the release of a local gas pocket when an air pocket was suspected upstream of an inverted syphon. The pump was switched off temporarily to store water in the sewer system. While the pump was switched off, air was expelled via a manually operated air release valve and the size of the air pocket was reduced. This resulted in increased pipeline performance. A permanent improvement has been achieved in the following operating cycle.

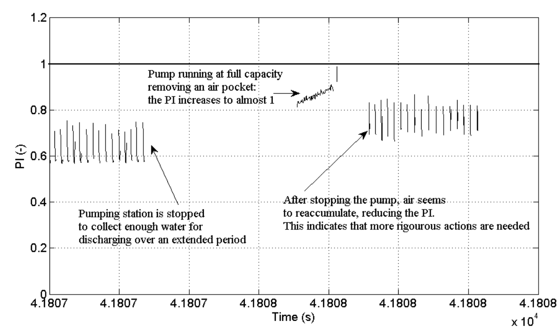

Figure 11. Release of air demonstrates the positive effect of PIs

D. *Energy Savings*

Since, in the case study presented, individual pumps are controlled locally and the wastewater level varies during the day, there are time windows when all the pumps are running and there is also a considerable amount of mutual idle time. Both situations preferably are to be avoided. Simultaneous running reduces energy efficiency, while long idle periods may result in sedimentation of solids in the pump sump potentially causing blockages. By minimizing the combined pump state, operational costs can be reduced. Such an optimum is obtained when only one pump is in operation. During peak hours, this is only possible if there is enough storage in the sewer system and no risk of spills. This optimisation can be achieved with integrated control and provide a rain fore- or now-cast for combined sewer systems as well. In dry weather conditions, the control system gives each pump station its own time slot. When a pre-set critical water level is reached, depending on the available storage in the sewer system, multiple operations of pumps is allowed. This type of control has not yet been implemented in Almere and this is why the potential energy savings are quantified using a numerical model. The Almere Buiten-Oost system includes 4 different pumping stations, one with fixed speed pumps and three with variable speed pumps. These ensure a daily supply of between 300 and 500 m3. Fig. 12 shows the typical pump status in the afternoon.

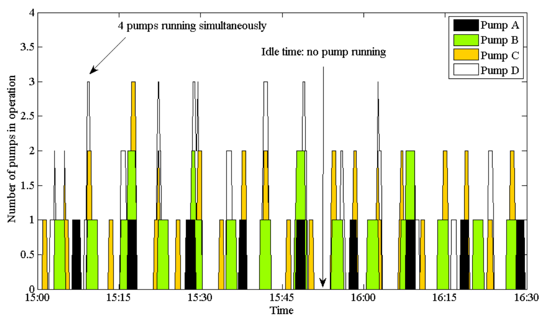

Figure 12. Pump operation in the afternoon

TABLE II. shows the results of normal (individual level control) operation and overall control, assuming that the available storage in the sewer is great enough to use only one pump.

TABLE II. COMPARISON OF ENERGY AND OPERATION TIME BETWEEN LOCAL CONTROL AND OVERALL CONTROL

	Individual level control		Overall control		Saving
	Hours in operation (hr)	***Energy (kWh)***	***Hours in operation (hr)***	***Energy (kWh)***	***(%)***
PS 266	4.0	24	3.2	22	10
PS 267	9.0	43	7.1	36	15
PS 265-1	5.4	22	7.1	17	24
PS 265-2	3.4	14	3.3	13	10
Total	21.7	104	20.8	88	15

Savings are strongly system dependent. In Almere, some pipelines have a relative small diameter, which results in high velocities and therefore in significant energy losses. An improved design combined with the implementation of integrated control could feasibly result in reduced energy losses of 25% or more.

VIII. Conclusions and Recommendations

A real-time performance assessment system called TAMTAM has been developed for Almere's sewer system which allows comparison of a reference situation with the current situation and the results are expressed in performance indicators (PIs). Performance assessment has been performed for four different situations: defining the reference situation; interpretation of the 'capacity' PI; the effect of maintenance; and an assessment of the energy-saving potential of integrated control.

It has been shown that a conservative design may induce PIs above 100%. It is therefore recommended to support the choice of the reference situation by measurements. It is best to conduct these measurements during commissioning when the system is put into operation. In addition, all models should be calibrated according to the measurement data. The 'capacity' PI has shown how maintenance actions for pumps can be planned and their effectiveness being quantified. Differences in performance between pumps in the same pump sump become visible and maintenance can be applied accordingly.

The effect of other types of maintenance can observed as well. In the Landgoederenbuurt sub-system, the removal of a gas pocket was monitored. It is clearly shown that the performance of the system increased notably after its removal.

The TAMTAM system is suitable for integrated control. Based on actual weather and pipe system conditions, time slots for individual pumps can be obtained. This is the optimum operation strategy and offers an energy saving potential of 25% in dry weather conditions. The examples presented show that the TAMTAM system and the application of performance indicators are suitable for assessing the performance of a pressurised sewer system. Future developments will focus on Real Time Control applications; the automated recognition of failure patterns and automated diagnosis of causes for decreasing PIs.

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