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A chemical sensor array based system for protecting wastewater treatment plants

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Abstract

A chemical sensor array (consisting of eight conducting polymer (CP) sensors) was used to continuously monitor for sudden changes in the quality of wastewater over a 12-month period. The headspace gas generated from a sparged liquid sample within a temperature controlled flow-cell was directly transferred to the sensor chamber for analysis. Results from the field study at a wastewater treatment plant (using a fully automated system) provided high resolution profiles and showed the detection of accidental and simulated pollution events. A model was developed for the detection and identification of sudden changes in the sensor responses, and was successfully tested using large datasets acquired over several months. This simple data mining approach showed a great sensitivity and flexibility, independent of long-term drift effects, diurnal variations and changes in temperature and humidity levels. The findings demonstrate that a chemical sensor array can be operated under harsh environmental conditions and act as an upset early warning device for the detection and identification of wastewater treatment process failure.

Keywords: Conducting polymer; On-line monitoring; Wastewater; Early warning; Pollution

1. Introduction

Wastewater treatment plant operators have long been faced with the lack of suitable sensors and measurement systems for on-line monitoring of wastewater quality. Wastewater that arrives at a municipal sewage works is highly variable in nature and the influent to be treated can be of different origins, such as domestic and industrial sewage and surface run-off. Intermittent or accidental discharge of chemical pollutants and toxic substances into the sewers can have a damaging effect on the bioprocesses involved in treating wastewater. Consequently, polluted waters have the potential to pass through a treatment works untreated and reach the receiving waters where they can have a harmful effect on the environment and threaten drinking water abstraction points down the river.

Traditionally, wastewater treatment plant operators monitor the quality of the effluent at the outlet of the treatment works using global parameters, such as biological oxygen demand (BOD), chemical oxygen demand (COD), total organic carbon (TOC) and total suspended solids (TSS) [1–3]. In addition to providing vital information on the quality of the effluent and treatment efficiency, these procedures demonstrate that a wastewater treatment plant meets statutory discharge requirements [4]. These procedures are mainly based on sample collection and retrospective laboratory analysis, which are resource consuming and do not facilitate early warning of process failure. Additionally, they cannot provide a high resolution picture of the nature and variations in wastewater quality and expose companies to the risk of undetected incidents. Despite the increasing range and diversity of techniques available, on-line measurement systems have generally remained limited by environmental factors, short lifetimes and fouling problems, mainly because of the harsh environment in which they have to be located. Increasingly, stringent regulations under the new EU. Water Framework Directive and the growing public concerns regarding the protection of the aquatic environment has created the need for new monitoring systems to be developed in order to identify sudden changes in the wastewater quality before its discharge from the treatment works.

The application of sensor arrays for the study of wastewater [5–7] has demonstrated that this technology can be used for monitoring wastewater organic content. However, these studies have mainly been based on the laboratory analysis of discrete samples after collection and not on

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the real-time monitoring of a continuous stream. Bourgeois and Stuetz [8] have reported on the development and use of a temperature controlled flow-cell for the generation of a headspace gas for on-line sensor array analysis of liquid samples. These results showed the reproducibility of the sensor response and demonstrated that such systems can be used for real-time monitoring in the field. Further advances and the development of sampling methodologies for continuous monitoring of water and wastewater samples were described by Bourgeois et al. [9].

In this study, a fully automated measurement system was successfully implemented for real-time monitoring at the inlet of a small wastewater treatment plant (Cranfield University Sewage Works). Results obtained from a 12 month monitoring study are presented that show the effect of unknown acute pollution events on the sensor response. A simple data mining approach for the rapid on-line detection and identification of anomalies is proposed.

2. Experimental

An on-line measurement system was developed and constructed to continuously monitor the wastewater for 12 months at the Cranfield University Sewage Works. The system consisted of a sampling vessel (on-line flow-cell), a sensor array module and PC for data analysis (Fig. 1). The principles of the monitoring system were previously described by Bourgeois and Stuetz [8]. The study was carried out inside the department's pilot hall located on-site. Wastewater from the primary settlement tank is re-circulated through a ring main inside the pilot hall from which 200 ml/min was continuously pumped through the flow-cell between acquisitions. During acquisition the sample was sparged with zero grade nitrogen to generate the headspace gas for sensor array analysis. The gas sample generated from the flow-cell was analysed using a commercial sensor array (ProSat, Marconi Applied Technologies, UK). The instrument consists of an array of eight conducting polymer (CP) sensors of broad selectivity in a temperature controlled sensor chamber (35 °C) and has a built in PC for controls and data acquisition and network connection for data transfer. Analysis of the headspace gas was carried out every 5 min according to the following protocol: 40 s

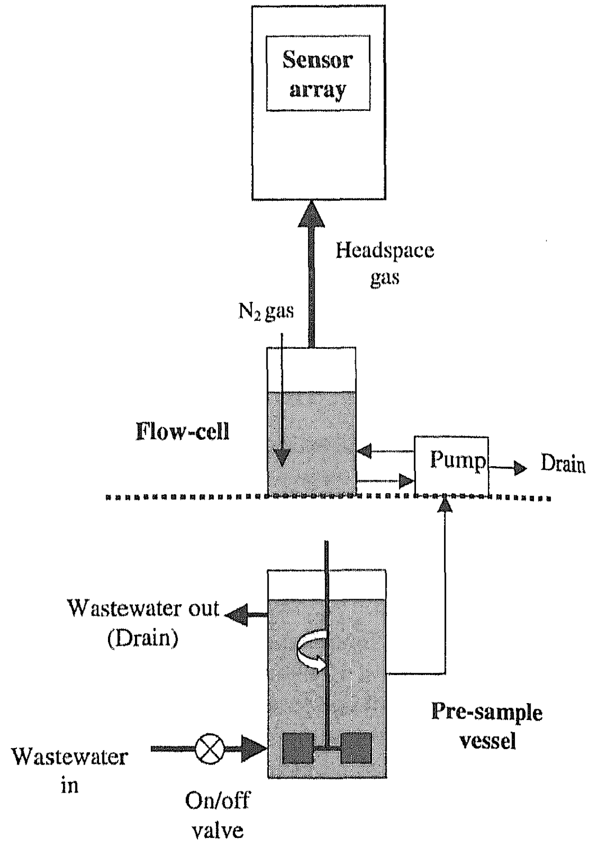

Fig. 1. Schematic of on-line monitoring system (Cranfield University Pilot Hall), showing pre-sample vessel, flow-cell and sensor array module.

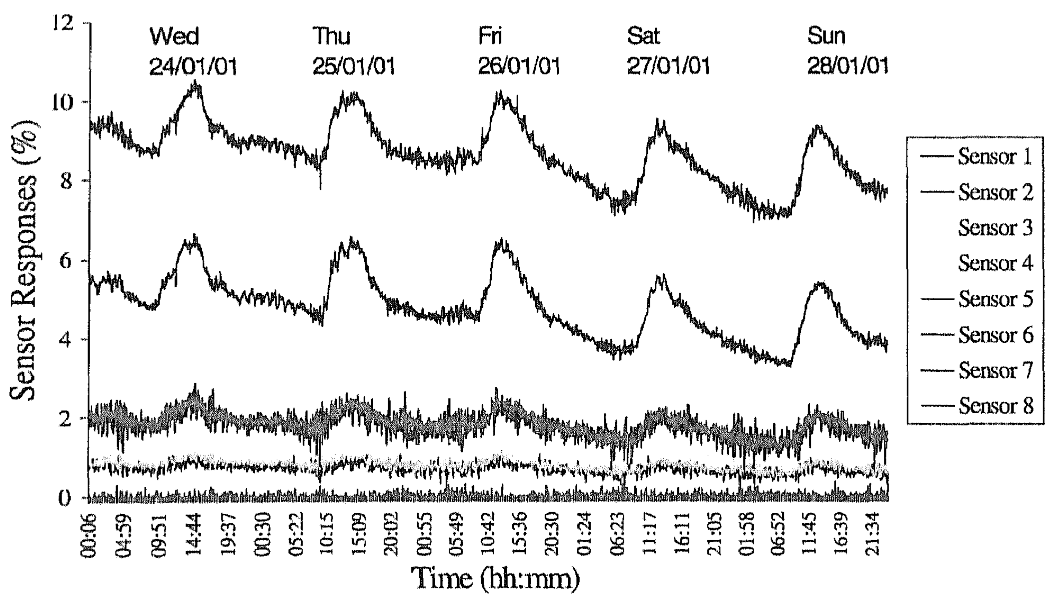

Fig. 2. Typical sensor responses observed over a 5-day period, showing diurnal variations in the headspace of a wastewater influent.

pre-purge of sampling line (to avoid cross contamination and dilution of the headspace sample with dead volume of gas in the circuitry); 1 min acquisition and 3 min 20 s de-purge (sensor clean-up with zero grade nitrogen). Changes in sensor resistance ($\Delta R/R$) at the end of the acquisition phase (1 min) were used to characterise the sample headspace.

3. Results and discussion

The 12 month continuous wastewater monitoring study resulted in the generation of over 105,000 acquisition points. In addition to the sensor responses (60 points per acquisition per sensor), the data files contain measurements of gas flow rate, wastewater temperature, sensor module temperature and humidity and temperature of the gas phase. Fig. 2 shows a typical example of a sensor response profile for the eight CP sensors observed over a 5 day sampling period. The data shows the variations in the wastewater composition at the sewage works being reflect in the different magnitudes for each sensor. These same changes are observed at the same time each day and correspond to the diurnal pattern of activity within the university's wastewater collection network. In Fig. 3 the same data is presented over a 24 h scale and demonstrates the increase in the sensor responses, starting at 9.00 and normally peaking between 13.00 and 14.00, with lower values overnight. This observation shows the repeatability and predictability of the response pattern at any time of the day and illustrates how an offending sample outside the accepted normal dynamic range could be easily

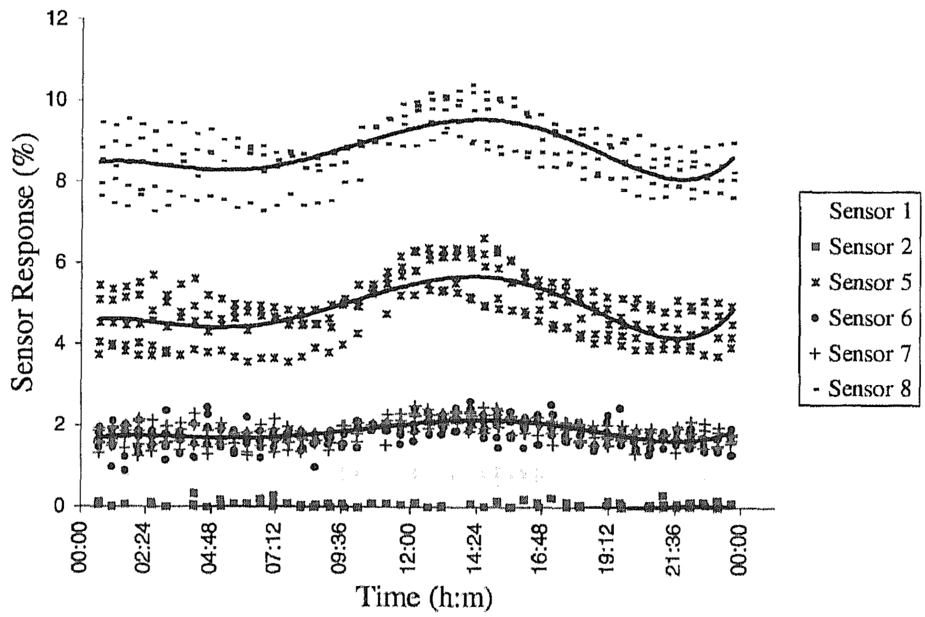

Fig. 3. Plot of sensor responses on a 24 h scale showing the repeatability of the diurnal pattern of wastewater headspace over a 5-day period.

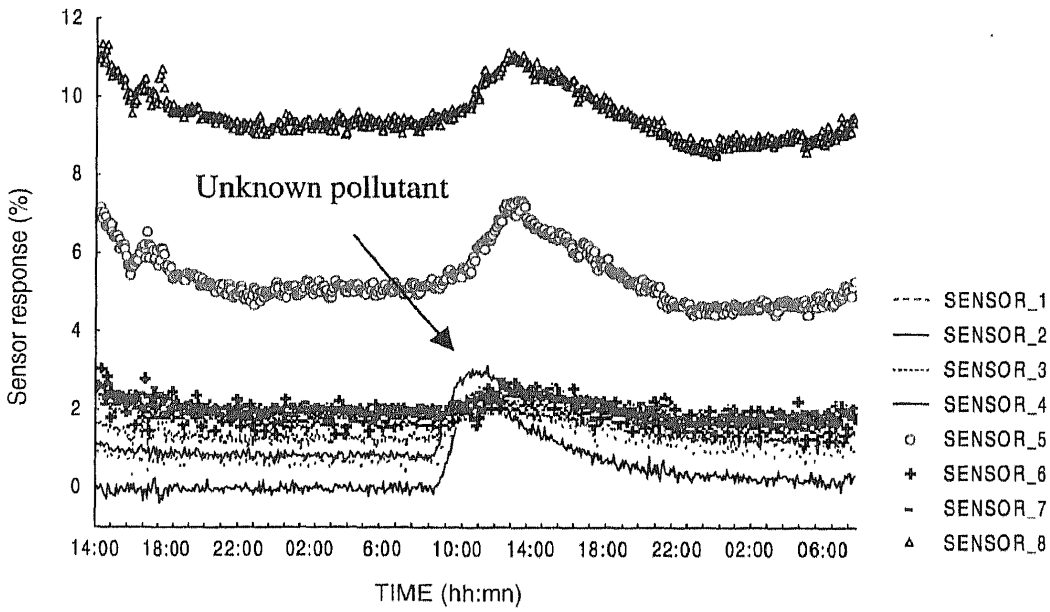

Fig. 4. Plot of sensor responses showing the detection of an unknown discharge in the wastewater influent.

detected and identified as a potential pollution event or abnormality.

Fig. 4 illustrates such a pollution episode and shows the effect of an unknown pollutant on the individual sensor responses. The rapid increase in the profiles of four of the eight sensors (sensors 1–4) corresponded with reports of a strong petroleum smell in the wastewater at the sewage works. Sensors 5–8 did not show significant changes in their response as a result of this incident but followed the diurnal patterns described in Figs. 2 and 3. This behaviour demonstrates the interest of using a sensor array of broad selectivity for this type of application. In Fig. 5, a principal component analysis of the data presented in Fig. 4 clearly shows the evolution in time of the intermittent discharge This suggests that the unknown pollutant was present in the wastewater treatment plant for approximately 24 h and demonstrates the sensitivity of the system. After reaching a peak within 2–4 h, the polluted wastewater then gradually diluted and eventually reverted to its original quality at approximately 18.00 the following day.

In an attempt to simulate similar pollution episodes, different concentrations of diesel were injected into the pre-sample vessel on 17 and 18 April (0.2% (v/v) and 0.4% (v/v), respectively). Fig. 6 shows the sensor responses

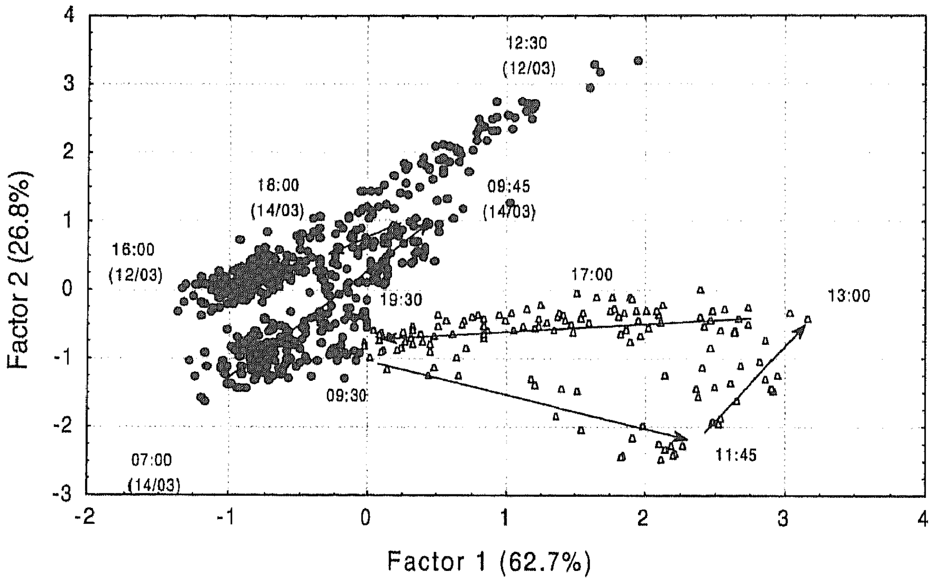

Fig. 5. Plot of principal components showing the separation of an unknown discharge (Δ) at the wastewater treatment plant, and a gradual return to the original wastewater quality.

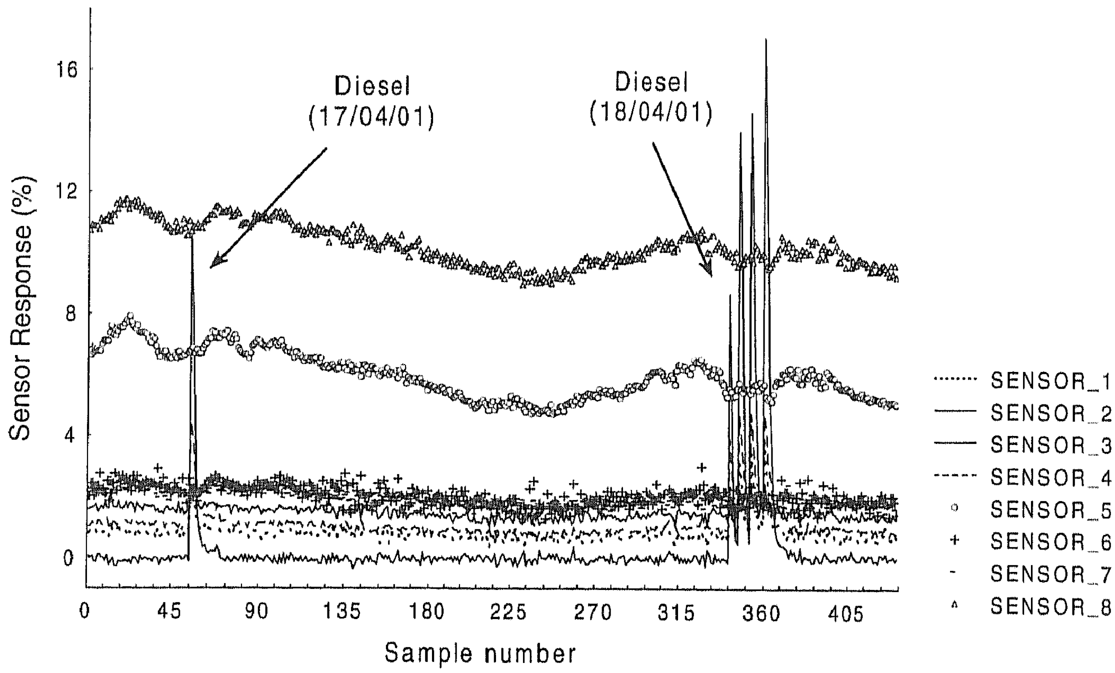

Fig. 6. Plot of sensor responses showing the detection of diesel spikes (0.2% (v/v) and 0.4% (v/v)) in the wastewater on two consecutive days (17 April 2001 and 18 April 2001, respectively).

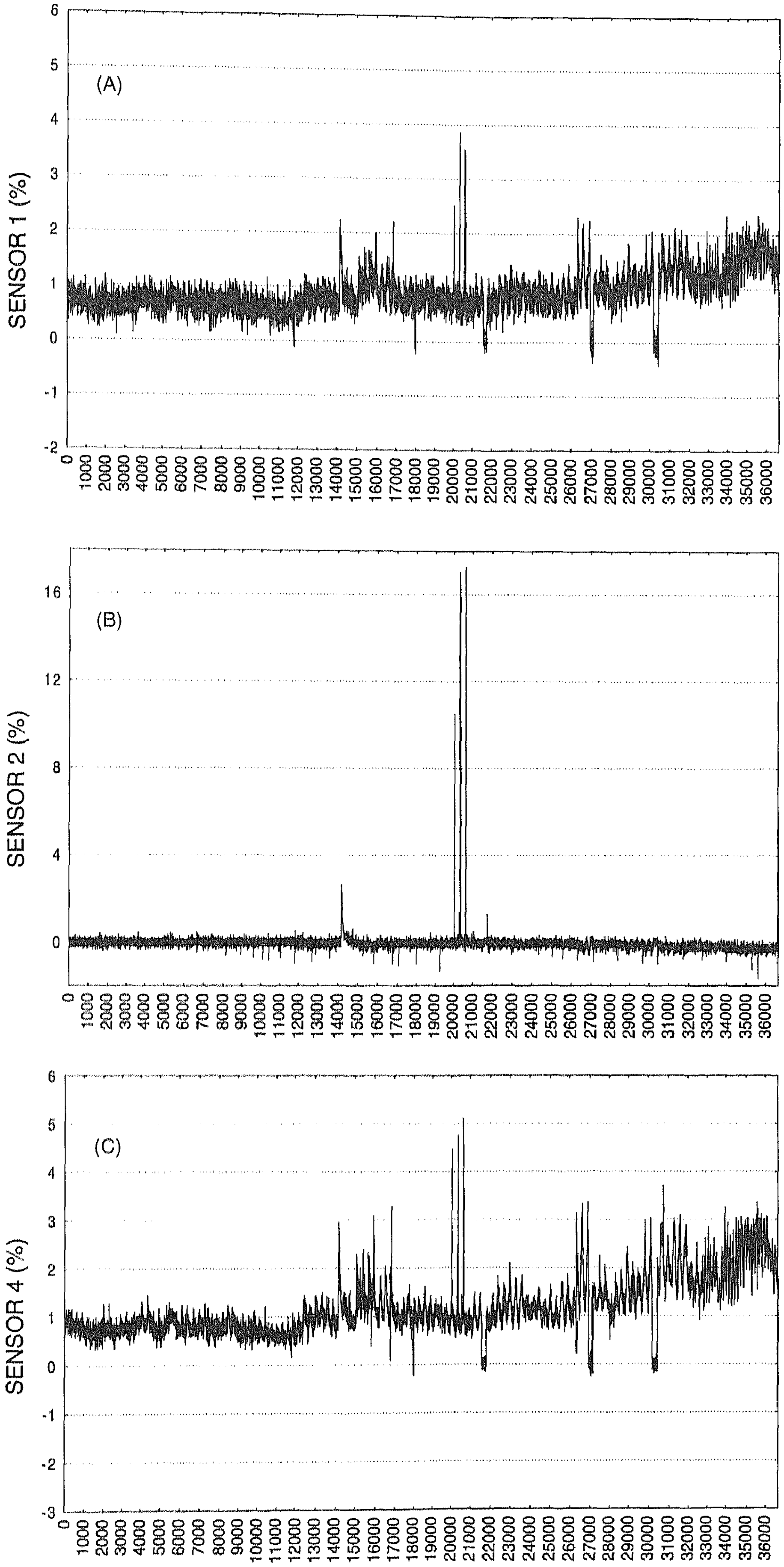

Fig. 7. Examples of observed sensors responses over a 6-month period: sensor 1 (A), sensor 2 (B) and sensor 4 (C).

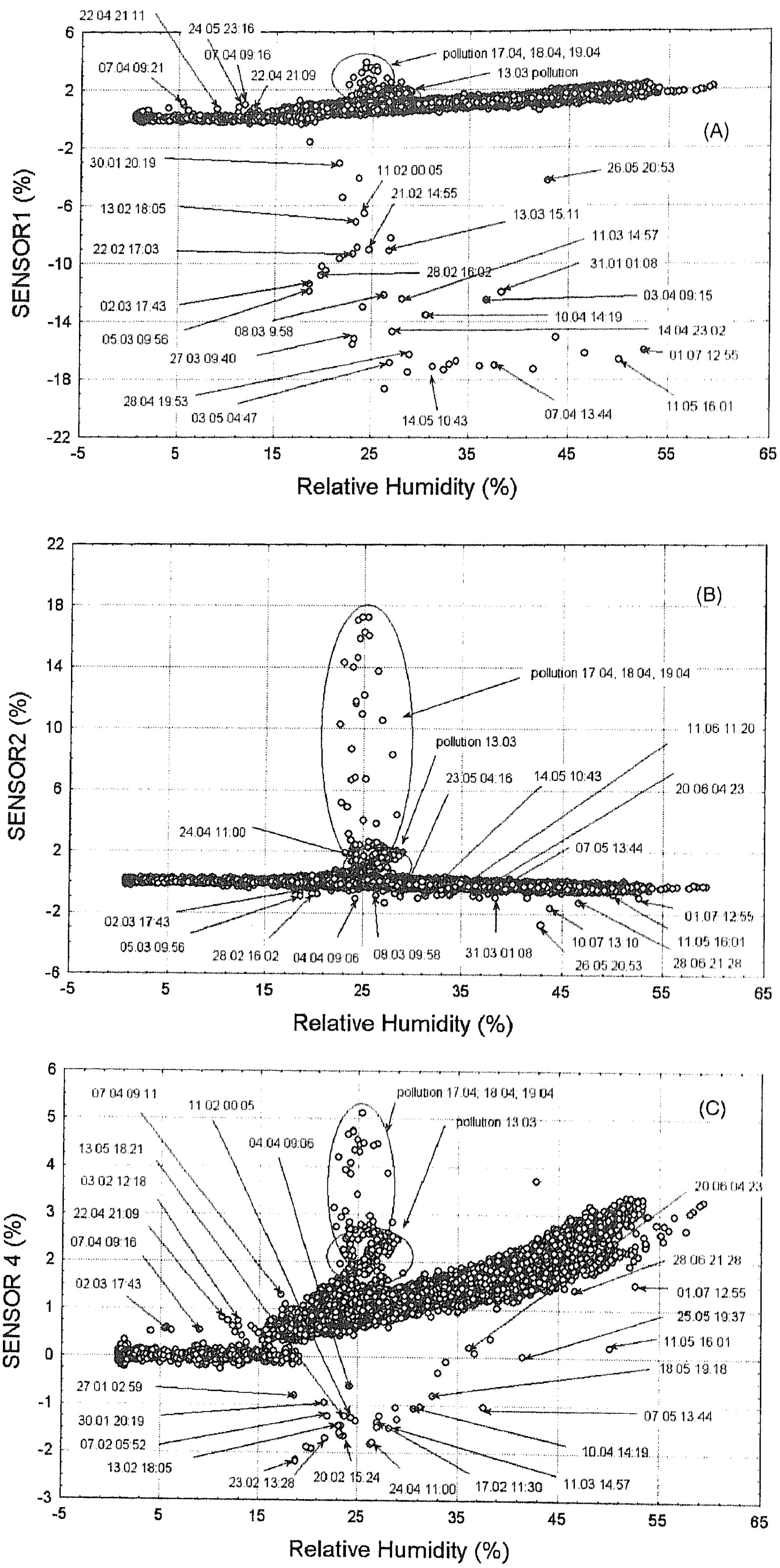

Fig. 8. Plot of sensor sensors responses (sensors 1, 2 and 4) vs. relative humidity (A, B and C, respectively) showing unusual patterns. The marked points represent incidents identified by the plant operators.

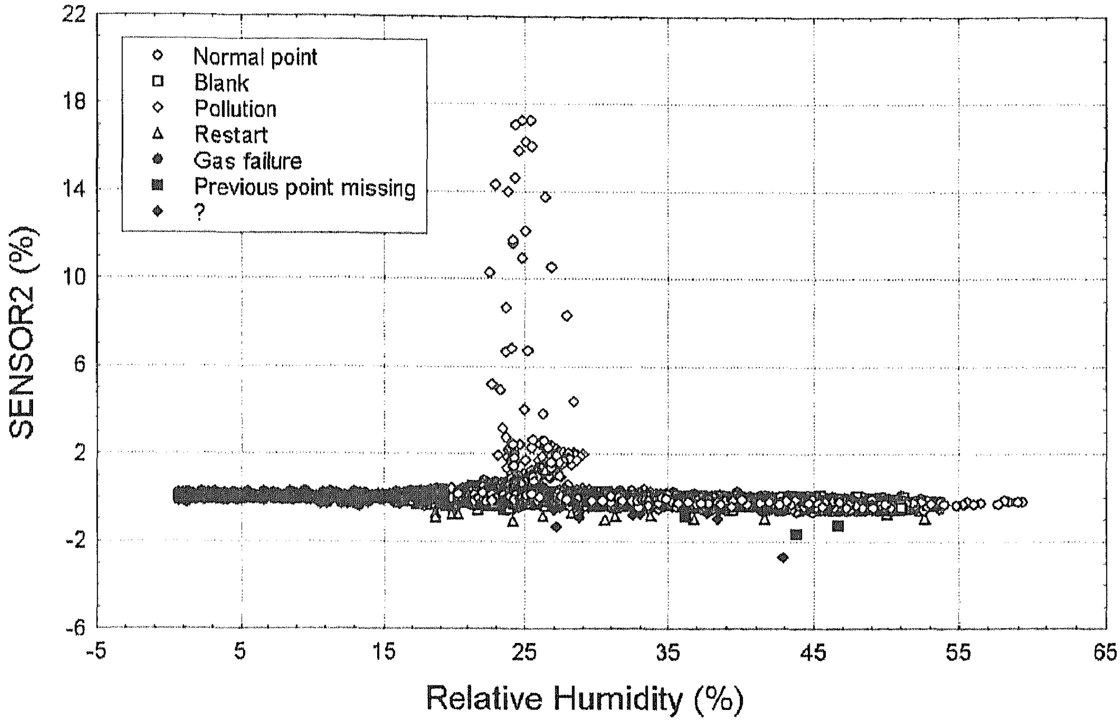

Fig. 9. Example of simulated detection and identification of a range of incidents by the data mining algorithm using 6-months of continuous data.

for these additions. As in Fig. 4 a very similar sensor response pattern to that of the unknown pollutant can be observed for sensors 1–4 showing some sensitivity. Given the small quantities of diesel added to the wastewater, a much more rapid return to normal could be observed within 15–20 min (3–4 acquisition cycles) for all sensors. The observed differences in the magnitude of the sensor response (on 18 April) shows the result of the different mixing time used in the pre-sample vessel prior to sampling and sensor array analysis and reflects the concentration effect of diesel in wastewater with time.

Over a 12-month sampling period, it is highly likely the quality of wastewater will vary due to changing environmental conditions (such as rainfall) and intermittent industrial discharges. Fig. 7 shows the relative responses of three sensors over 6 months of continuous monitoring. While a great number of anomalies can be observed in these sensor responses, such episodes may not always be detectable by simple visual examination of individual response profiles. Since manual screening of such large datasets would not be practical and extremely consuming, the development a rapid screening method for the real-time detection of pollution incidents and operating anomalies is needed.

A simple approach to the detection of upset events within the gradual environmental changes in influent composition is proposed. In Fig. 8, a study of the sensor response (using data from Fig. 7) versus relative humidity provides a simple but effective way to detect unusual patterns. These plots show that a large number of incidents can be detected over long periods of time independently of drift and diurnal variations. The marked points match incidents that were logged and identified by the plant operators. A model was built to simulate on-line detection using data acquired over a 6-month period. The method is based on the comparison of the sensor's relative response to a moving average. The difference is then weighed against the standard deviation for that sensor (multiplied by a pre-defined coefficient) for each new data point. The sensitivity and selectivity of the model can be adapted by changing the size of the moving window (from a few minutes to a few days) and by selecting individual sensors as well as adjusting their respective threshold coefficient. Fig. 9 shows an example of such an analysis where the model successfully detected a whole range of pollution episodes and operating anomalies (diesel, gas failure, pump failure). The marked symbols show the points as identified by an integrated recognition algorithm that is called every time an outlier is detected. Currently, appropriate pattern recognition techniques are being investigated in order to be incorporated in an alarm generating software.

4. Conclusions

A conducting polymer based sensor array system coupled with a headspace generating flow-cell was used for on-line monitoring of a domestic wastewater influent over a 12-month period. High-resolution sensor profiles showed the effect of diurnal cycles of activity within the wastewater and corresponding changes in the influent quality to unknown pollutant as well as artificial spiking with diesel. A model was successfully developed for the rapid detection and identification of pollution events as well as operating anomalies. The working principle is based on a moving window that can be used for the detection of sudden changes in the sensor responses and is not affected by long term drift, diurnal variations or normal changes in temperature and relative humidity. The results have demonstrated how a chemical sensor array based system coupled with a simple data mining algorithm can be used for real-time process monitoring and upset early warning at a wastewater treatment plant. Current work is focussing on the development of a non-invasive monitoring system that can be operated above a wastewater stream at the inlet of a sewage works. Such a system would provide early warning of process failure in order to either bypass a pollutant to storm tanks alter the treatment process.

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