

Ex-post hydrogeological evaluation of a landfill using hydrochemical analyses and system identification techniques

A.Pistocchi, F.Ciancabilla, G.Gottardi

(Dipartimento di Ingegneria Chimica, Mineraria e delle Tecnologie Ambientali, Università di Bologna)

S.Simani

(Dipartimento di Ingegneria, Università di Ferrara)

Abstract

The paper illustrates the results of the dynamic identification of some series of water quality data from the monitoring of the landfill of Ginestreto at Sogliano al Rubicone, in North-Central Italy. The data concern different measurement points around the landfill, where water quality samples were collected in order to check about potential percolate leaking from the landfill and water pollution, during 1991-1999. Since no rainfall measurement was available, there was no point in making a hydrologic balance model of the landfill. A black-box identification has been therefore attempted, using an autoregressive MISO model. In particular, it has been supposed that response times of the landfill and surrounding groundwater bodies to rainfall were long enough and monthly cumulative rainfall data retrieved from stations in the area were used. The paper describes the identification method used and discusses the results obtained.

Introduction

A relevant problem in landfill management is the monitoring of environmental impacts due to leachate emissions. Very often, monitoring is conducted by taking water quality samples at the landfill drainage outlet, and in the main water bodies which might be in contact with it, in order to assess any trend in water quality degradation. Sometimes, however, the detection of episodes of contamination is made difficult due to the many potential paths pollutants may follow in the surroundings of the landfill. In addition, it is sometimes difficult to define a synthetic indicator to describe leachate pollution, especially in cases when groundwater chemical composition is complex. On the other side, it is important for the management of landfills to identify a synthetic indicator of the output due to waste wash off by rainfall, and a method to predict this evolution on the basis of relevant causal factors. While principal components analysis allows to define synthetic indicators on the basis of a reasonably short complete monitoring period, system identification techniques, describing the landfill as a black box, cope with predictive modeling of a very complex system, without using physically based methods which require detailed investigations on the processes taking place in the media involved.

The case study

The Ginestreto landfill was constructed in a small and almost uninhabited clayey valley in North-Central Italy. The area is impervious and shows a climate with arid features. A comprehensive monitoring system has been designed and implemented to monitor the landfill situation and to keep water pollution under control. Water quality was analysed through time in the following points around the landfill:

- surface water drained from the landfill (supposedly not in contact with pollutants)
- groundwater downstream with respect to the landfill
- surface water in a creek flowing at the landfill's foot
- 'sottotelo' water, which is a mix of water inflowing from boundary rock formations, and infiltrating from rainfall
- leachate coming from the landfill where a percolate recycling has been performed for a few years.

All monitoring data acquired over the period from 1991 to 1999 were inspected using correlation analysis, principal components analysis, hydrochemical balances and qualitative-conceptual interpretation of the flow and potential pollution processes. The results of the analysis are presented in Cacciaguerra *et al.*, 2000.

The analysis of monitoring data has been performed at first on a qualitative basis, taking in account the geological setting of the landfill. Most of the area is covered by clayey formations which show a high content in SO_4^{--} minerals, while some sandstone formation outcrops occur in the clayey matrix. There is no significant aquifer in the area, except some small water reservoir in the sandstones. All monitoring series were practically stationary, except for episodes of surface water pollution due perhaps to agricultural practices such as fertilization, and a phenomenon of diffusive propagation of a high sulfate concentration front which has been observed from the 'sottotelo' monitoring, and is reflected in the monitoring wells downstream. Figure 1 shows the described process. It has been supposed that the front be generated by the excavation works prior to the construction of the landfill. These works might have modified the circulation of water, and put in contact with the highly permeable waste mass the clays containing sulfate-rich formational groundwater, provoking the wetted front to be displaced.

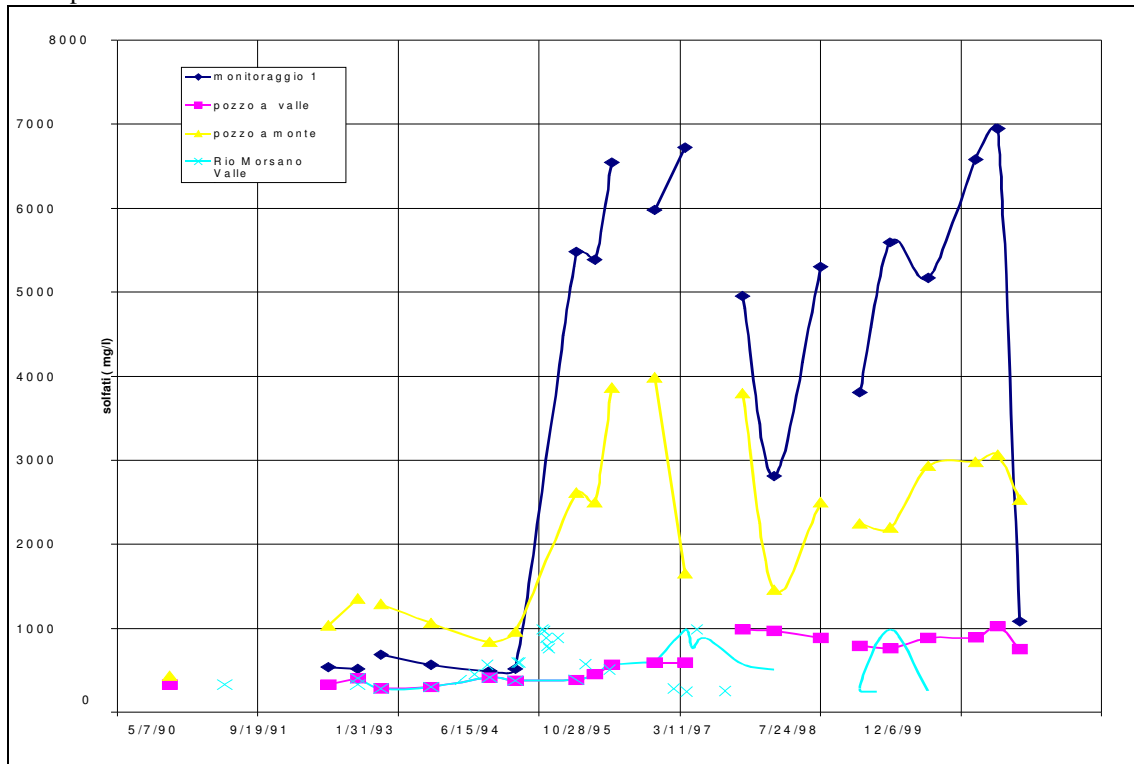


Figure 1 – Sulfate diffusion and advection from the 'sottotelo' water

The series concerning leachate evolution has shown the typical behaviour for urban waste disposals, with decay trends with different velocities in all chemicals (figure 2). All data series were submitted to principal components analysis (PCA) with the goal of extracting a small number of relevant indicators from the whole range of registered parameters. Details are given in Cacciaguerra *et al.*, 2000.

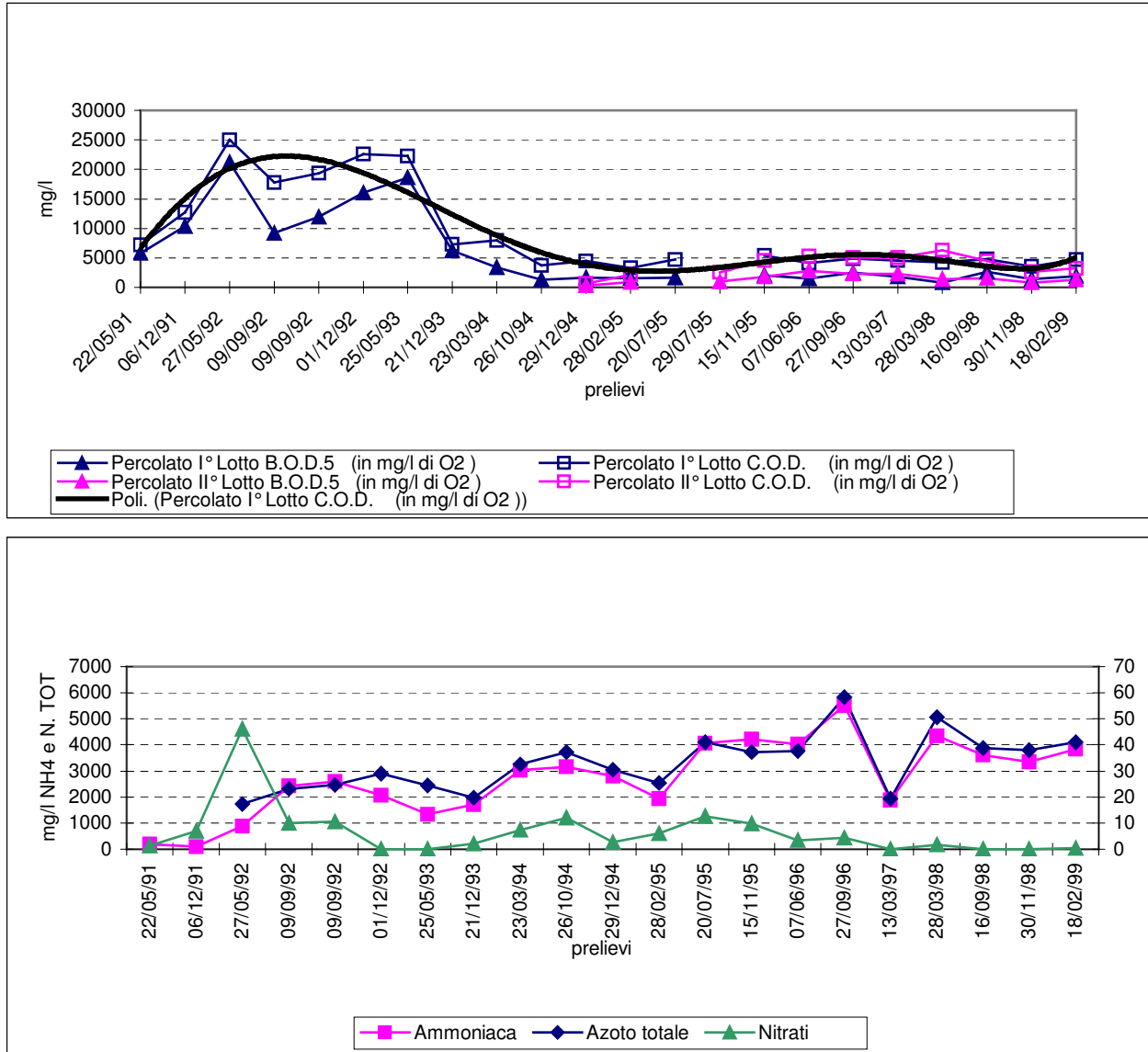


Figure 2 – Leachate quality trends observed in the landfill

After this analysis, it has been recognised that percolate is well represented by the first two principal components (computed out of 14 variables including BOD, COD, Cl^- , SO_4^{--} , NH_4^+ , NO_3^{--} , Ntot, Ptot, Zn, Cu, Cr, Mn, Ni, and Fe) named pc14 and

pc13 respectively, explaining about 52% of total variance. Pc14 is linked with quick degradation and shows an appreciable correlation with BOD and COD. Pc13 seems to represent slower degradation processes, and is more clearly correlated with nitrogen compounds.

The same type of analysis has highlighted that, in the ‘sottotelo’ water, the ‘step function’ like behaviour in SO_4^{--} concentration, which is well reflected in principal component named pc13. Superimposed to this step function, some oscillatory components have been detected, and conceptually interpreted as linked to NH_4^+ releases in surface water, possibly due to manure spreading in the surrounding fields. As pointed out in Cacciaguerra *et al.* (2000), the interpretation is much more difficult for the other components of the total variance.

Methodology

In what is sometimes called black box modeling, a physical system is studied by analysing its response $Y(t)$ to a relevant input $U(t)$, without bothering about the knowledge of laws ruling the system itself (figure 3).

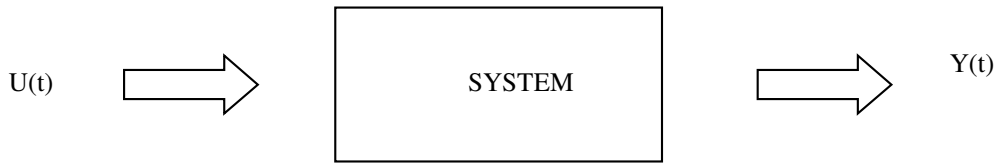


Figure 3- diagram of a black box modeling scheme

Identification techniques (Ljung, 1999, Soderstrom and Stoica, 1984) are a well-established methodology in many engineering sciences.

In many cases, including the one presented here, $U(t)$ and $Y(t)$ can be supposed to obey the following equation (defining the ARX-type processes – e.g. Bittanti, 1996):

$$Y(t) = VMY + \sum_{i=1}^{mo} \alpha(i) * (Y(i + t - mo - 1) - VMY) + \sum_{i=1}^{mo+1} \beta(i) * (U(i + t - mo - 1) - VMU) \quad (1)$$

which means that model output depends on current and past input and output up to a number of elapsed time steps which depends on the model order (mo).

Thus identifying the model requires both to evaluate the model order, and to determine the regression parameters of equation 1. Many techniques exist to evaluate how the model order can be estimated, as reported in Gottardi *et al.*, 2000. As far as the parameter estimation is concerned, usually least squares regression is used.

In the present study, system identification has been applied to simulate the temporal evolution of leachate quality and chemical features of water from the drainage under the landfill body, as a consequence of rainfall input to the landfill body. The results of the analysis are presented in the following.

Procedures, results and discussion

The analysis has been performed using monthly rainfall as the input to the systems inspected for identification. The output used for calibration and validation of the model was in each case the appropriate linear compound of the variables measured at each sampling point, representing the principal component in question. In particular, the principal components pc13 and pc14 have been considered for the percolate (ppc13 and ppc14), and the principal component pc13 for the ‘sottotelo’ water (spc13). The meaning of these principal components has been discussed above.

Due to irregular data sampling period, linear interpolation between existing data has been used to assign a value of ppc13, ppc14 and spc13 to each simulation month, while monthly rainfall has been computed by considering the average of the available measurements from three rain gauge stations in a radius of some kilometres around the landfill.

Due to the lack of on-site rainfall measurements (strongly influenced by local meteorological and topographic parameters) and because of the accuracy and the frequency of the water and percolate composition measurements, the input data quality for the identification process is very poor.

The principal components ppc13, ppc14 and spc13 have been considered each as a stand alone dynamic process, and thus three systems have been oriented for identification. Monthly rainfall represents the model input whilst the values of the principal component of concern, the outputs. It is worthy to point out that numerical values of the principal components are senseless *per se*, each being a linear compound of the variable values. The main aspect is the trend over time.

The analysis, whose results are shown in Figures 4, 5, and 6, has brought to choose the model orders as shown in Table 1. The indexes used to evaluate the model order are the Predicted Per Cent Reconstruction Error (PPCRE: Guidorzi, 1974, Guidorzi, *et al.*, 1992) and the FPE, AIC and MDL (Soderstrom and Stoica, 1987). The reader is referred to Gottardi *et al.*, 2000, for further details.

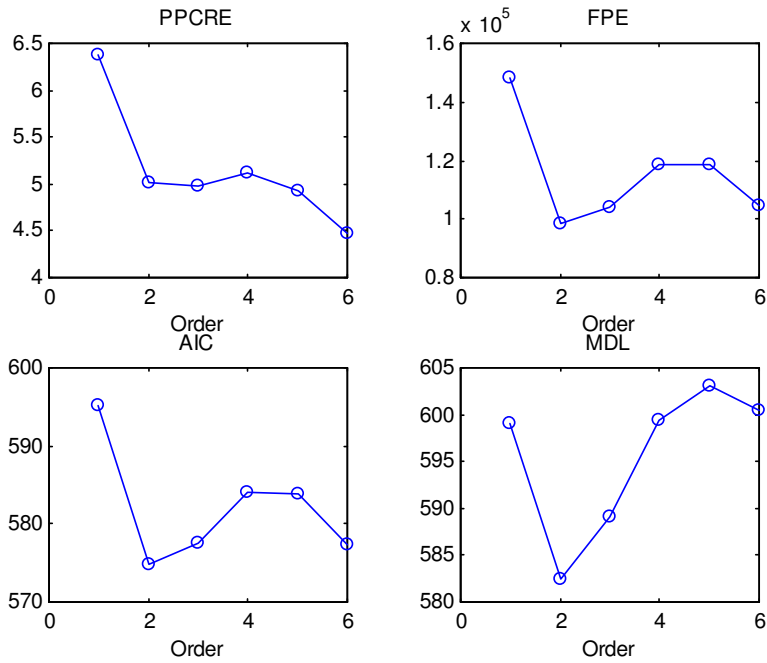


Figure 4: Model orders for ppc13 output.

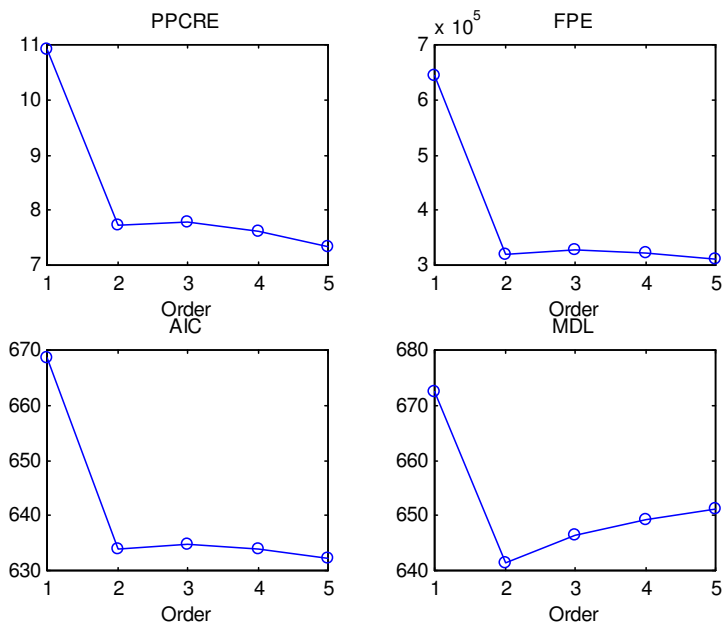


Figure 5: Model orders for ppc14 output.

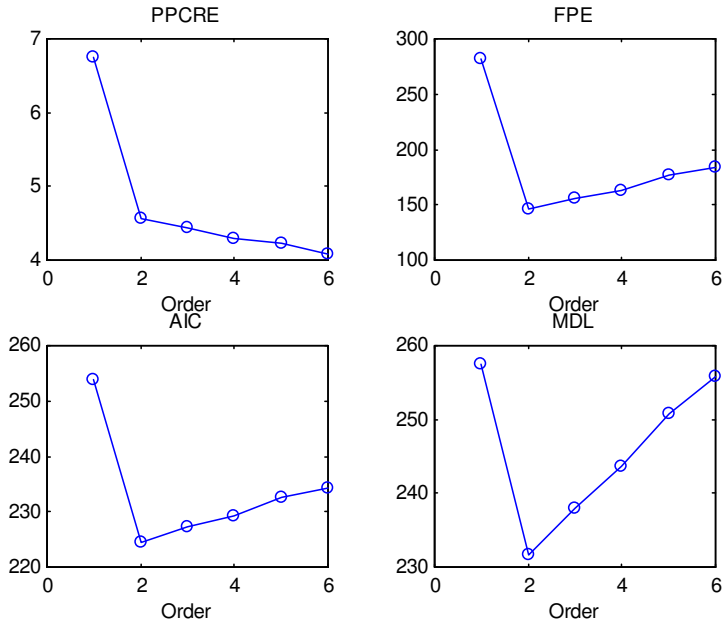


Figure 6: Model orders for spc13 output.

Figures 7 to 12 show the results of complete simulation using monthly rainfall as input series and the principal components as output series. In particular, it can be shown that spc13 is very poorly reproduced by the identified model, while in the case of ppc13 the result is appreciably fairer. It must be noticed that in this case a lag between input and output has been used, equal to 3 months, which improves the correspondence between measured and simulated output with respect to the case of no lag. When ppc14 is considered, the identified model reproduces an almost perfect theoretical exponential decay, showing that the dynamical process can be, from a mathematical point of view, easily linked to the washout of the biodegradable pollutants due to rainfall.

Table 1 – Model orders

Process	Order
Ppc13	3
Ppc14	2
Spc13	2

An attempt to improve the unsatisfactory results has been done by using the cumulative rainfall as the input series to the system represented by spc13 instead of the monthly amount. As shown in Figure 8, a better correspondence has been found with observed data, although some outphasing of the series comes out in the initial steps of the process.

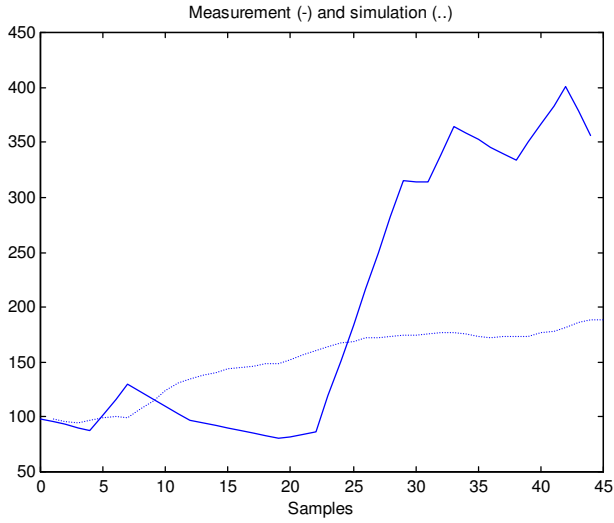


Figure 7- simulation results: spc13 as output using monthly rainfall as input (model order 2, no I/O lag)

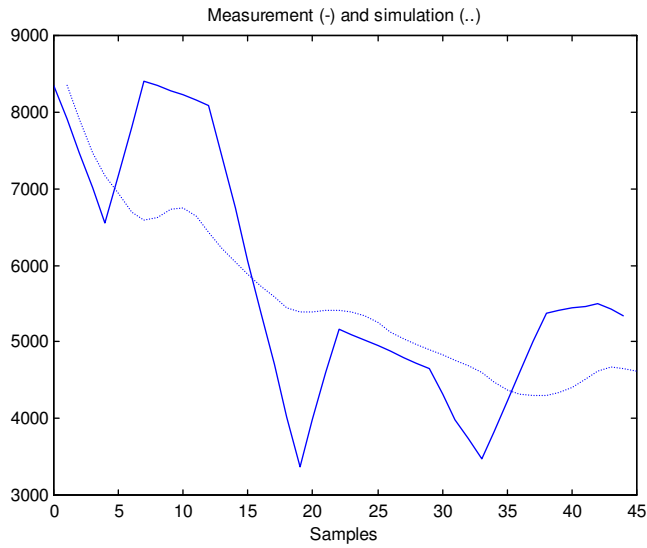


Figure 8- simulation results: ppc13 as output using monthly rainfall as input (model order 3, I/O lag= three months)

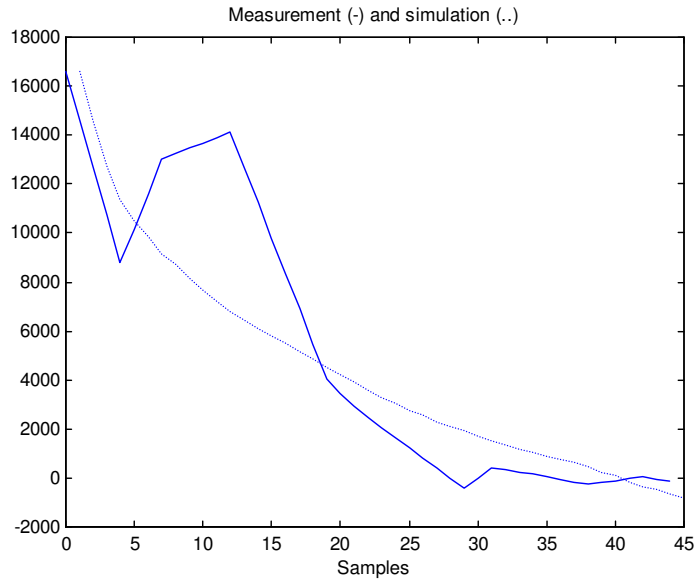


Figure 9- simulation results: ppc14 as output using monthly rainfall as input (model order 3, no I/O lag)

This allows to suppose that the phenomenon of SO_4^{--} , abruptly changing from a relatively low base level to a significantly higher one as described above, is linked to the advancement of a water front coming from reservoir rocks with high SO_4^{--} content, as the clays making the ground to the landfill, a process which is actually time-dependent irrespective of monthly rainfall.

Another identification tentative for ppc13 has been performed using both monthly rainfall and ppc14 as input. The rationale of this attempt is that degradation of BOD and COD, and degradation of nitrogen compounds are kinetically linked. Anyhow, as one can see in Figure 9, no significant improvement in simulation comes out, and perhaps the oversmoothing of the simulated series is even a negative effect.

The same result can be obtained for the model which links the ppc14 output to both the monthly rainfall and ppc13 inputs, as depicted in Figure 10.

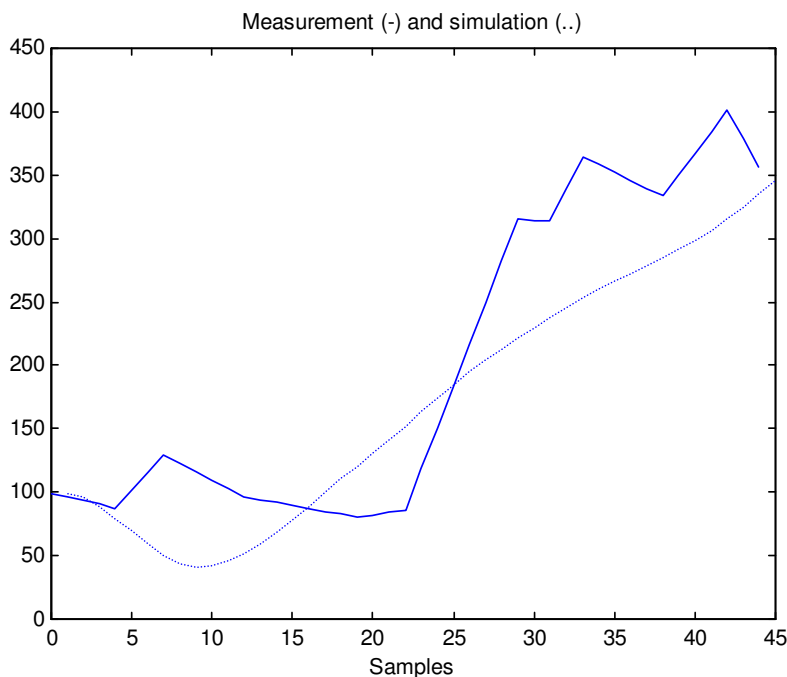


Figure 10- simulation results: spc13 as output using cumulative rainfall as input (model order 2, no I/O lag)

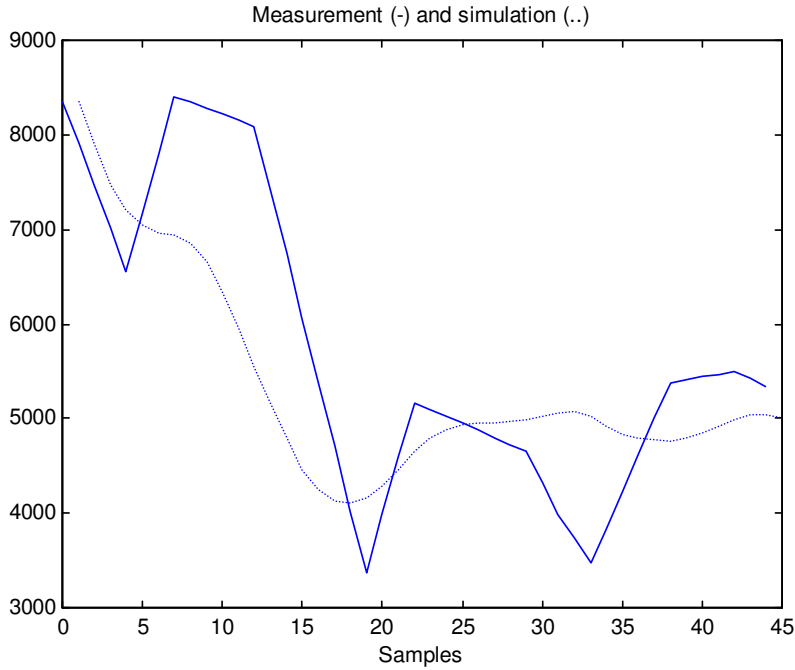


Figure 11- simulation results: ppc13 as output using both monthly rainfall and ppc14 as inputs (model order 3, no I/O lag)

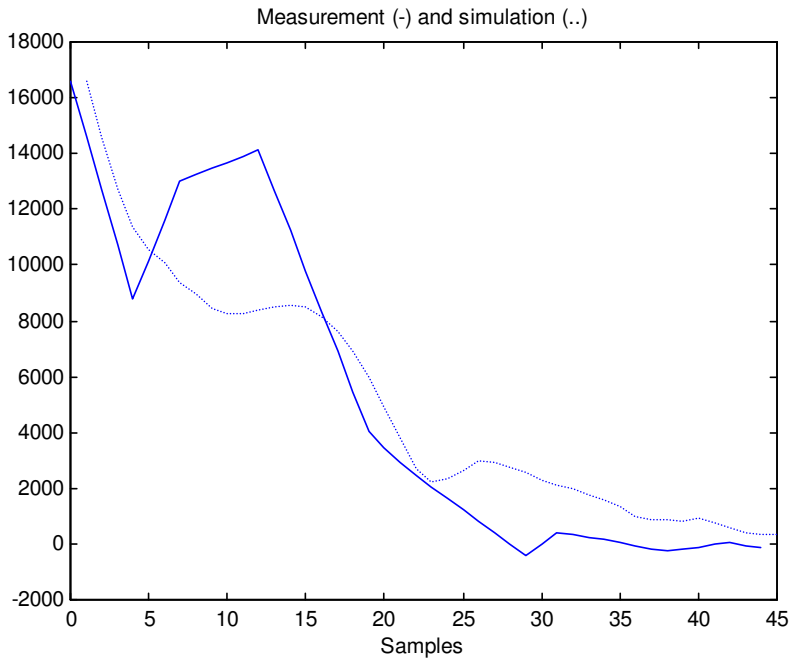


Figure 12- simulation results: ppc14 as output using both monthly rainfall and ppc13 as input (model order 3, no I/O lag)

Conclusions, and future lines of research

The hereby proposed approach presents some relevant advantages over more traditional modeling techniques in landfill management. First of all, the modeling process does not require any physical knowledge of the landfill components, and thus it can be applied to each situation. Second, the input is very simple and modelling comes out very simply from an automated calibration process, provided that variables of interest be fairly summarised by a few synthetic parameters.

The well known disadvantages of any black box model are that it cannot be used for any prediction of variables different from the ones for which it has been calibrated. In addition, as in the present case, there is no explicit indication about the relevance of different physical parameters on the system and, consequently, it is impossible to understand which input data play an important role for the prediction accuracy.

Finally, it can be argued that the use of this type of models can bring to a real time control of a landfill, and its effects in terms of potential pollution to soil and water, provided that a small number of representative variables have been identified, and regularly spaced measures are available about these variables, and rainfall. In such conditions, one should note that calibration of the models must be more accurate e.g. for the 'sottotelo' water, and allow for the detection of undesired effects from the landfill on water quality. In addition, the degradation of pollutants in percolate can be predicted, supporting a control on the decay and exhaustion time of the landfill, which are essential evaluation parameters for its *post-mortem* management.

It can be affirmed that identified models provide an interesting alternative to hydrologic evaluation models (e.g. Schroeder, 1994) in the control, early warning and management of landfills.

Different identification techniques can be used, but the simplest method was chosen because of the quality of the available data.

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