Localisation Task in Sewer Networks

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Abstract

Paper deals with the inverse / localisation task in sewer networks. An inverse problem is defined as the process of determining the causal factors from a set of observations. Applying this principle to the water management sector, it is often a matter of determining the location of the source of pollution based on monitored data on the concentration of pollution over time. From a mathematical point of view, to decrease the uncertainty of the inverse task solution, it is necessary to know the location of the source or the concentrations time course of the source (intensity function). In practice, we usually do not know any of these quantities, however, in the case of sewer networks we can accept some assumptions, which allow us to solve this inverse problem. Paper analyses specific conditions applied in the environment of sewer networks and describes proposed method for solving the source localisation task in the sewer network environment. The solution is based on numerical modelling of the pollution spreading in sewer system, accepting some process simplifications as well as assuming some source parameters. Typically, the solution of inverse task requires large and time consuming numerical simulations. This can be disadvantageous after recording the pollution event - a long calculation time reduces the efficiency and operability for the following pollution source reconnaissance. Therefore, our proposed method performs the necessary simulations in advance and the pollution source localisation after recording the pollution event is very fast, using a simple search and comparison in the simulation results database. The proposed method was tested on real sewer system and there were achieving promising results.

Keywords: localisation task, sewer networks, water quality, pollution

Introduction

Water quality is essential for the health and well-being of both humans and the environment. Water that is contaminated can lead to a wide range of health problems. Poor water quality can also lead to chronic health problems and to the loss of species, reduced biodiversity and ecosystem collapse. Quality of water is essential for crop irrigation and livestock production. Industries that directly and strongly rely on water, such as fishing, recreation, and tourism, can suffer greatly from poor water quality. In summary, water quality is critical to human health, environmental health, agricultural production, and economic prosperity.[1]–[3]

Sewer networks can affect surface water quality in several ways. When wastewater is discharged into surface waters without proper treatment, it can contain a variety of pollutants that can harm aquatic ecosystems and public health or even can be toxic to aquatic life and accumulate in the food chain.

In order to protect the quality of surface water, it is necessary to properly manage and treat wastewater from sewage networks. However, in the case of dangerous substances, it is of primary importance to prevent them from entering the sewage network itself. Regular monitoring and surveillance of sewer networks and surface waters can help identify and control sources of pollution, and also ensure that water quality standards are being met.

This paper aims to help with the identification of the unknown pollution sources in sewer systems. An innovative pollution source localization method is presented, which can help the sewer system operators to localize the unknown pollution sources based on the monitored pollution concentration in sewer network. In general, such task is called the Inverse task. The term "inverse task" generally refers to a type of problem where the goal is to determine the input or cause of a given output or effect. In other words, given some observed outcome or behaviour, the inverse task is to figure out what inputs or factors led to that outcome.

For example, in physics, the inverse task of determining the initial conditions of a system that produced a certain outcome is often of interest. In water engineering, inverse tasks are frequently encountered in fields such as water quality accidents, where the goal is to reconstruct an unknown pollution source based on its observed outputs. Reconstruction of the unknown pollution source means the source localization and determination of the time-concentration curve of the pollution substance inflow.

Inverse tasks can be challenging because they often involve solving an ill-posed problem, where there may be multiple possible solutions or the problem may not have a unique solution. Various mathematical and computational techniques can be used to address inverse tasks, including optimization methods, statistical inference, and machine learning algorithms.

The presented method is based on the specific ability of the pollution spreading in flowing water – hydrodynamic dispersion. Hydrodynamic dispersion is a process that affects the movement and transport of substances in water. It is caused by a combination of physical and chemical factors, including molecular diffusion, convection, and mechanical dispersion [4].

In sewer networks, hydrodynamic dispersion can also play an important role in the transport of pollutants and other substances. The extent of hydrodynamic dispersion in sewer networks depends on a variety of factors, including the flow rate, pipe diameter, roughness of the pipe walls, and the presence of obstructions or bends in the pipe. The presence of sediments, fats, oils, and grease in the sewer pipes can also affect the extent of hydrodynamic dispersion.

Understanding the extent of hydrodynamic dispersion in sewer networks is important for predicting the transport of pollutants and other substances and by this way localise the source of dangerous or toxic contamination of water. Proper management of sewer networks, including regular cleaning and maintenance, can help reduce the formation of any abnormality occurrence in dispersion process and reduce uncertainty range of the inverse task solution.

Theoretical Background

The developed method is based on hydrodynamic approach – on the idea of mass spreading and transport in flowing water and an inverse task solution suitable for use in real time and conditions.

For inverse task solution related to the pollution transport in the flowing surface water, various methods are presented in the literature [5]–[11]. A review of literature sources shows, that the research is very often focused mainly on developing mathematical methods evaluating these procedures with using hypothetical examples (verification), e.g. [12]–[20]; only very limited number of methods were tested in real conditions. The main problems are the computing time of the transport models, inverse task solution methods high uncertainty and the problems connected with collection of data. Besides, presented methods solve inverse problem very often in a simple stream branch. Complex hydrodynamic conditions of sewer network together with the ill - posedness of the source identification create a problem, which is hardly to solve.

No specific methods for the inverse task in sewer network have been published so far except the paper of Sonnenwald [21]. This tracer study was carried out in the combined sewer networks of four UK cities and method for estimating the dispersion coefficient in sewer networks using the recorded data was developed. A modelling approach was used to investigate source localization in the network.

Few similar studies for inverse task solutions in a river system were also published, [8], [9], [22], [23] but the substantial difference is the complexity of the network (number of network nodes, branches).

The identifiability of dangerous substance source in the case of sewer network requires to know some information about the source characteristics. We assume a situation, which can occur in practice: the source position as well as its concentration time course (intensity function) are unknown. The downstream monitored pollution concentration (concentration time course) in such case is not sufficient for solving the task, because there are unknown both the source position and the intensity function of the source. The solution of such inverse task cannot be unique (ill – posed task). This theoretically makes an exact solution of the inverse problem defined in this way impossible. To decrease the uncertainty of the task definition, it is necessary to assume the source of the pollution behaviour. In our case we assume to know the source intensity function shape, e.g. the instantaneous pollution flush, or it can be some other types of the intensity function. The pollution concentration of the source can be then derived from the total monitored pollution mass.

Inverse task requires typically large number of numerical simulations. Because of this, it is necessary to use simplifications (assumptions) to reduce the computation time [23].

In our study we adopted following main simplifications: first of all, we assume that the transported substance is conservative one and it will not react in the sewer environment. For the practical test and calibration, we assume that background concentration of the monitored substance is negligible. Because of that we used in the sewer network experiments the tracer Rhodamine WT, which is relatively unique in the sewer environment.

As mentioned in previous paragraph, we assumed, that the source intensity function shape is known – in fact, we used the instantaneous tracer release.

Other assumptions related to the network structure: a simple tree structure from the hydraulic point of view and no singularities in the network (e.g. tanks, pump stations). The last group of assumptions is related to the sewer hydraulics: the sewer branches can be regarded as the prismatic beds, the hydrodynamic process can be represented as the one-dimensional process, flow in the network reach is steady and uniform one, and there is ideal mixing in sewer confluence manholes.

Methods

The substantial part of the method for identification of the unknown pollution sources in sewer systems is the numeric hydraulic model for providing data about the flow rates and other hydraulic parameters in all branches of the sewer network. The flow rates were determined based on the number of connected inhabitants and the specific wastewater production.

The calculated flow rates allows us to determine remaining hydraulic parameters, e.g. flow velocity, flow depth, width, flow area as well other parameters for all branch in the sewer system by using the hydraulic tables for partially filled circular pipes [24] and assuming the uniform and steady flow. These parameters were also used to calculate the dispersion coefficient using the equation by [25] or its modifications [25]–[27], or using the equations published in [28].

For the modelling of pollution transport in this study, we used a simple 1D hydrodynamic dispersion model in the form of the Advection Dispersion Equation (ADE, Equation 1) [27]:

$$\frac{\partial(Ac)}{\partial t}+\frac{\partial(Qc)}{\partial x}-\frac{\partial}{\partial x}\left(AD_x\frac{\partial c}{\partial x}\right)=-AKc \tag{1}$$

where: c is a concentration (g. m^{-3}); D_x is the longitudinal dispersion coefficient (m^2.s^{-1}), A is the cross-sectional flow area (m^2), Q is a flow rate (m^3.s^{-1}), K represents a rate of growth or decay of contaminant (s^{-1}), x is a distance (m) and t is time (s).

Modelling of pollution transport in a simple branch was based on application of 1-D ADE (Equation 1), but for the designed method application, we used analytical solutions of the ADE. These analytical solutions of the ADE are represented mainly by [27], [29] which is based on the Gauss normal distribution. As it was found in our previous research [30], the dispersion process is very often disturbed by so called dead zones (transient storage and consequent slow release of the substance caused by irregularities in flow profile). Because of that the designed method also uses analytical solutions with asymmetric distributions – Gumbel and Generalised Extreme Values (GEV) distributions [31] in aim to take into account the influence of the dead zones [32].

Results

The designed method for identification of the unknown pollution sources in sewer systems / inverse task solution was calibrated using results of experiments on real sewer network in the city part Bratislava - Petržalka (Slovak republic). For the tests we used part of the sewer network with 247 manholes. The sewer structure of this test area has two main sewer branches with the signature B and BXV. The monitoring point was located approximately 200 meters downstream of the confluence of these two branches, (see the Figure 1).

Pollution source point

Monitoring point

Fig. 1. Hydraulic scheme of the sewer network

The tests were made in dry weather conditions, i.e. in the period without any precipitation to get closer to the conditions of steady and uniform flow. The flow velocities in sewer network were relatively low because the flat terrain of area. More details, particular results and conclusions of these tracer experiments are summarized in [30].

The localization tool was coded in the SW developing tool Visual Basic. Localisation tool results are presented in graphical form on the Figure 2.

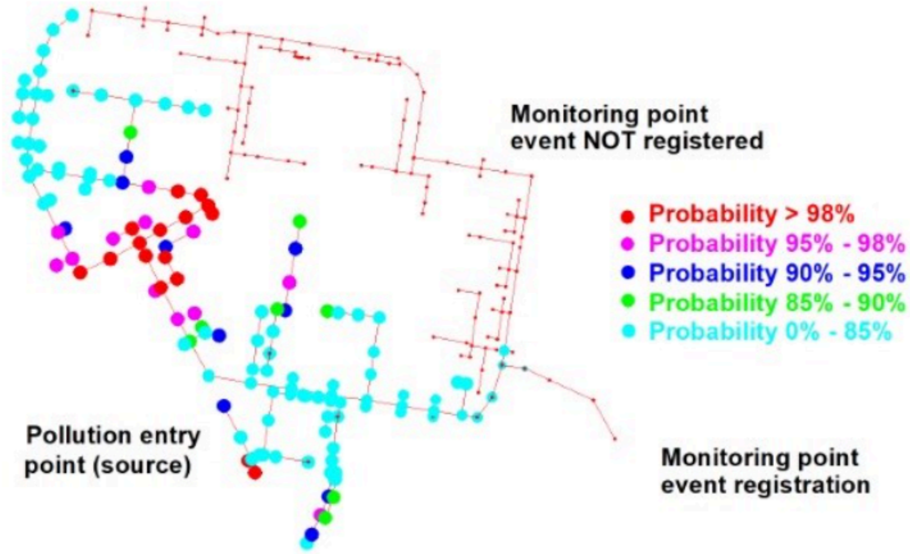

Fig. 2. Results of the localisation procedure

The probability of the source occurrence bigger than 98% was identified in a group of manholes, marked on the Figure 2 with red colour. Such (or higher) occurrence probability was identified as well as in 15 other manholes from total 139 possible pollution entry points on this sewer main branch. As it can be seen on the Figure 2, the selected manholes (red points) are located in a relatively small particular area of the overall experimental urban catchment. In fact, this limits the occurrence of possible substance sources to several houses.

On the main branch B and BXVII we activated the built-in model feature for elimination of a part of the sewer system from further analyse – if the monitored substance was not monitored/registered in the monitoring point, the whole upstream part of the sewer network will be excluded.

Discussion

In our tests, the localisation procedure selected 15 manholes (out of total 139 manholes, i.e. 10.8%) as the possible sources of pollution, which we consider as very good result.

On the other hand, the localisation procedure selected as possible source points also manholes, which are far from the real pollution entry point (see the bottom side of the Figure 2). This demonstrates the ambiguity of the inverse task solution – also these possible pollution sources can cause similar, almost identical response of the system (pollution time course) as the real event. In practice, this uncertainty has to be solved by the placement of the monitoring devices to the several monitoring points, which can confirm or disprove the occurrence of the pollution source on the particular sewer system branches, located upstream of the monitoring points.

We found the possibility of the use of asymmetrical Advection Dispersion Equation (ADE. Equation 1) [31] as very advantageous, because of the presence of sediments in sewer network. Sediments in sewer network form transient storage zones [33], and thus deforms the pollution time course concentration curve (steep rise and slow decline in concentrations over time). Description of influence of these zones can be found also in [34]–[36]. The use of the ADE analytical solutions, based on the Gaussian distribution was found as very inaccurate (see Figure 3). This could be a significant drawback, because the precision of the proposed pollution source localisation method is essentially dependent on the precision and accuracy of the dispersion model used. The best results were achieved using the approximation method (analytical solution) based on the GEV (Generalised Extreme Value) distribution [31] (Figure 3).

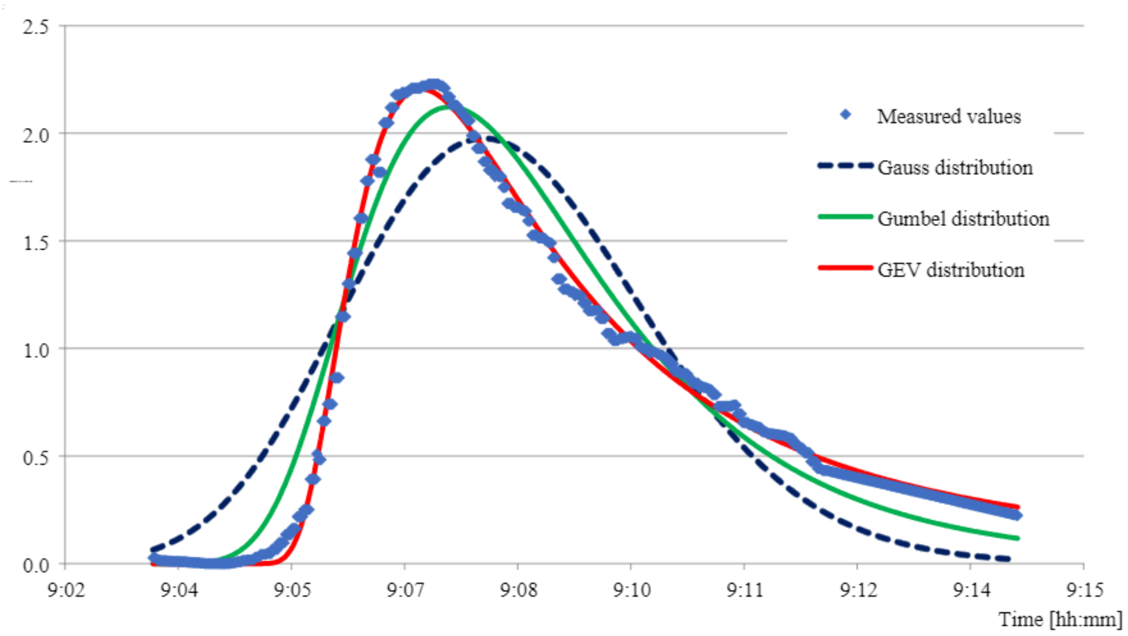

Fig. 3. Example of the experiment record and its approximations

The adaptation of the localisation procedure on various flow conditions (states) in sewer system was not performed due to the time and financial limits of our research. In that case it would be necessary to perform tracer experiments also in the night time (minimal flow rates), as well as during the peak hours (typically in early morning or evening hours).

As mentioned in the introduction part of this paper, for properly use of the proposed localisation method it is necessary to know the shape of the inflow (source) concentration time course. In case of our test (tracer experiments) we had in fact the knowledge of this concentration time course shape – we applied the sudden pollution inlet into the sewer system. This decreases in fact the ambiguity of the inverse task (problem) definition, but on the other hand, it is questionable, whether such condition can be assumed in real cases.

Conclusions

Presented source localisation SW tool procedure confirms its capability in real conditions. The main disadvantage of the presented method is the necessity (in aim to reduce the ill – posedness of the defined task) to predict the shape of the source time course concentration. However, it is sufficient to estimate the shape of the intensity function (i.e. the timely variations of the concentration). Based on this fact, such approach will be usable rather for the pollution spills similar to the instantaneous pollution release in the sewer network (short leakage events). In case of events with longer pollution release, the use of the presented method for source localisation can be more problematic.

Generally, we regard the achieved results as successful. The tests show, that the localisation precision is highly dependent on the transport model precision. A precise model requires precise calibration; so, the proposed method needs the calibration focused on spatial coverage of the possible source points, as well as the calibration for various flow rates in the sewer network, which can be very cost and time demanding task. However, comprehensive calibration is typically required almost in all water quality modelling studies.

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