ACTA HYDROLOGICA
SLOVACA

Ročník 18, č. 1, 2017, 49 – 56

LOCALIZATION OF POLLUTION SOURCES – INVERSE TASK IN POLLUTION TRANSPORT

Marek Sokáč, Yvetta Velísková

Paper describes the current knowledge and possible methods to solve the inverse task of the pollution transport in watercourses. Inverse pollution transport task in watercourses arises in cases when place of the pollution entry into a watercourse is unknown (e.g. breakdown pollution leakage, ecological accident along a watercourse), but we know the pollution concentration time course in the monitoring profile. Solutions of such defined task are characterized by a high degree of uncertainty because the boundary conditions are not known: besides that, pollution source location is unknown, discharged amount of pollutant and the time course of the pollutant concentration in the efflux are unknown or unclear, as well. Problematic can be also to determine the hydraulic conditions in a watercourse as well as the dispersion parameters. Paper contains a definition of inverse task, brief description and categorisation of the methods used for solving inverse problems of pollution transport in watercourses, as well as the analysis of the problems and errors arising in solving of inverse tasks and proposed solution concept.

KEY WORDS: pollution source, localisation, inverse task, on-line monitoring, dispersion, watercourse

LOKALIZÁCIA ZDROJA ZNEČISTENIA – INVERZNÁ ÚLOHA TRANSPORTU ZNEČISTENIA. Príspevok opisuje súčasné poznatky a postupy riešenia inverznej úlohy transportu znečistenia vo vodných tokoch. Inverzná úloha transportu znečistenia vo vodných tokoch vzniká v prípadoch, keď nie je známe miesto vypúšťania znečistenia do vodného toku (napr. havarijný únik znečistenia, ekologická havária na toku), je však známy časový priebeh koncentrácie znečistenia v monitorovanom profile. Riešenia takto definovanej úlohy sú charakterizované veľkou mierou neurčitosti, pretože nie sú známe okrajové podmienky úlohy, t. j. okrem neznámeho umiestnenia zdroja znečistenia je to vypúšťané množstvo znečisťujúcej látky a časový priebeh vypúšťania. Problematické môže byť aj určenie hydraulických podmienok vo vodnom toku a parametre disperzie. Príspevok obsahuje definíciu inverznej úlohy, stručný opis a rozdelenie metód, používaných na riešenie inverzných úloh transportu znečistenia vo vodnom toku, ako aj analýzu problémov a chýb, vznikajúcich pri riešení inverznej úlohy a navrhovaný koncept riešenia.

KĽÚČOVÉ SLOVÁ: zdroj znečistenia, lokalizácia, inverzná úloha, on-line monitoring, disperzia, vodný rok

Introduction

At present time, the prevalent tasks in water quality modelling practice are those ones, in which initial and boundary conditions are known and the model is solving pollution concentration in downstream direction (Aral et al., 1996; Pérez Guerrero et al., 2010; van Genuchten et al., 2013a; van Genuchten, et al., 2013b). It is typically for the tasks of this type, that the quantity, the time course of discharge and concentration of emitted pollutant are known parameters, as well as the hydraulic conditions in the watercourse. The result of such modelling tasks is a time course of pollutant concentration in the watercourse locations. The overwhelming majority of existing simulation models is composed exactly for that purpose, i.e. such models can simulate the pollution spreading (concentration) only downstream from the pollutant source (De Smedt, et al., 2015; Fischer, et al., 1979; Thomann, 1973; van Genuchten, et al., 2013a). Together with that, these models strictly require all the initial and boundary conditions (discharges, location and concentration of the pollutant).
However, the opposite problems may occur in practice:pollution concentration time courses in specific

cross-section profile along a watercourse are known (e.g. based on the on-line monitoring), but pollution source location, as well as the pollution amount, are unknown. The objective of this task is to determine the location of pollution source (localization task) as well as the total pollution amount and time course of pollution efflux. This type of task can occur in case of accidental pollution, when the first cause of the pollution is not known, or even with intentional act that can be defined as an offense or crime (illegal business - production of various substances, illegal wastewater outlets, etc.).

Basic terms definition

On-line monitoring

The development of analytical and telecommunication technology leads to increase of monitoring options and needs. The water quantity monitoring today (discharges, water levels) is almost normal in watercourses and reservoirs or lakes, but also in other water structures, such as water supply and sewerage systems (discharge, water level in the drinking water reservoirs, inflow to the wastewater treatment plant...). With the improvement of telecommunications services and data transmissions comes also the possibility to monitor parameters in real time, i.e. introduction of systems for control and data acquisition (Supervisory Control and Data Acquisition – SCADA).

Monitoring of water quality is much more difficult and complicated in comparison with monitoring of water quantity. The basic problem lies usually in the fact that majority of chemical analysis cannot be carried out in real time, respectively on-site. Therefore, generally in on-line monitoring of water quality there are measured and recorded only easily measurable parameters such temperature, pH, turbidity, conductivity etc. These parameters may, of course, indirectly indicate the emergency situation, but it is necessary to make a sense that the specific pollutants do not have to affect monitored parameters in all cases. But new developments give rise to many automatic, respectively semi-automatic systems for monitoring of various water quality parameters. The problem could be only the fact that some of these systems work in a batch mode, i.e. values of monitored parameters are discontinuous, wherein the interval between each value depends on the time needed for processing and evaluation of a sample.

An interesting possibility with great potential is the development of so-called molecular imprinted polymers (MIP) (Wikipedia, 2016). These are polymers, which are designed to selectively extract the solid phase of specific substances. Their separation effect is based on the size and shape of the specific functional groups of the analyte substance molecules, which "fingerprint" corresponds with the size and shape of the cavities within the polymer. This principle is already known and used in passive samplers. The project GoldFish (SOVVA, 2014) used another feature of these polymers – change the amount of captured analyte involve a change of capacitance (capacitive reactance – apparent electrical resistance to alternating current). This variable can be relatively easily measured and calibration is possible to calculate the quantity of analyte concentration in water. The accuracy of such measurements has been declared in the project at $\mu g.m^{-3}$ up to $ng.l^{-1}$, however during the practical implementation the achieved accuracy is lower, about $mg.l^{-1}$. Molecularly imprinted polymer can be used only for one type of pollution, and mostly only to specific substances. They are therefore suitable only for a specific monitoring of pollution, such as micropollutants.

Definition of the inverse task of the pollution transport in watercourses

As it was mentioned above, most of the current models are focused on modelling of pollution spreading in downstream direction. Pollution source localization on the base of monitoring data is referred as an “inverse problem” (El Badia, et al., 1998). It is necessary to note, that such inverse task has not always an unequivocal solution, the result is usually a set of potential solutions. Inverse problem is far more understood as a mathematical problem, verified practical applications or commercial software dealing with the inverse problem are not currently known. A number of works about these issues can be found in the literature, e.g. (Andrle et al., 2012; El Badia et al., 2007; Andrle et al., 2011; Verdière et al., 2013). In general, the presented methods and solutions are rather complex and complicated, and many limitations and restrictions occur in their practical application. The inverse problem is usually ill-conditioned due to the limited observations and irreversibility of the dispersion phenomena (Xiaole, et al., 2017).

Based on such inverse task meaning, it can be assumed that the general and exact solution of this task is not possible: every solution, with using of any method, will generate only the approximate results or estimations, that should be represented with a particular - most probable - outcomes from number of potential solutions (simulations), the results of which are in best coincidence with monitored data.

Applied simplifications

The inverse task solutions are usually connected with many unknown characteristics, as well as some methods of their solution require a large number of numerical simulations. Therefore, simplifying assumptions are often used, results of which are simple numerical models (e.g. analytical solutions) that accelerate the numerical simulations and reduce the computing time required to solve the overall task.

For practical solution of an inverse problem the following assumptions are very often accepted:

1. Pollution is conservative
2. Pollution source is a simple one and is located at

a watercourse reach without any tributaries and lateral inflows
3. Prismatic river bed along watercourse reach.

Pollution conservatism means that examined pollution substance is not subject to any physical, chemical or biological (biochemical) processes that take place in a watercourse. It is obvious that absolutely conservative substance does not exist in practice, so it is more realistic to require that ongoing changes are not random and fast, but rather slow and gradual (slow changes mean that the concentration changes are reflected in the order of days or in a longer time period).
In case of not conservative pollutant (polluting substance is a subject of physical, chemical or biological processes), inverse problem could be solved by similar processes, but decomposition (concentration decrease) of the substance should be considered in the simulation (El Badia, et al., 2005).
Simple pollution source assumption means, that in the investigated watercourse reach is only one, spatially invariant source of pollution, which emits pollution directly into the watercourse (not into a tributary). Another assumption is linked with requirement concerning a watercourse reach without tributary. By this way the length of examined watercourse reach is given
For correct operation of so-called localization tool, it will be as a key task the determination of hydraulic parameters (discharges, cross-section profile area, flow velocity) in the watercourse. This task is even more complicated by the fact, that the hydraulic parameters vary depending on the hydrological situation (discharge) in a watercourse.

Approaches to inverse problems solution

Approach to solving inverse problems is very diverse and individual. Overall, known methods of inverse problem solutions can be divided into the following groups:
1. Methods for estimation of the time of pollution entry,
2. Simplified methods,
3. Inverse numerical simulations.

Similar classification can be found in (Mazaheri, et al., 2015), where existing approaches are classified as simulation-optimization approach, probabilistic, and mathematical approach.

1. The methods, focused to estimate the time of the pollution entry into a watercourse, are using the similarity or consistency of the ascending part of the concentration time course curve (monitored concentrations in the watercourse) with the curve modelled by simplified model (Šajer, 2014; Šajer, 2015). Based on the similarity these methods determine the contamination entry time, from which it is possible to locate the entry point in the next steps.
2. Simplified methods are aimed to the simulation of various / possible pollution incidents. They use simple calculation methods based on simplified analytical solutions and compare simulation results with measured (monitored) levels (Jandora et al., 2002; Ghane et al., 2016). The advantage of these methods is their simplicity, rapid implementation, the possibility of simple modifications of the basic control equation for specific conditions (e.g. the occurrence of dead zones, etc.). Their disadvantage is the necessity of a relatively large number of numerical simulation accomplishments, and by this way a long computation time. As an appropriate method for resolving this problem, the non-linear regression methods appear.
3. The inverse numerical simulation target more complex mathematical and numerical techniques (upstream flow). From a mathematical point of view they are more accurate, but also more complicated and more difficult to compiling computer programs (Verdière et al., 2013; El Badia et al., 2007). Their use is generally limited by used assumption reducing the uncertainty degree of the inverse problem, such as the immediate pollution entry, knowledge of the time function (functions) which describe the pollution entry, etc.

Problems concerning inverse problems solution

The problems affecting the accuracy or existence of the inverse tasks solution can be divided into the following areas:
1. Problems arising from the accuracy and representativeness of the concentration measurement in the watercourse
2. Problems arising from the diversity of theoretical assumptions and real conditions
3. Problem of large lengths

1. This type of problems can have different causes and origins. Measurement of pollution concentration can use various technology, and hence the accuracy of these measurements, as well as the time interval of individual values (time step). Practically all methods of inverse problems solution are based on the pollution concentration time courses in the watercourse, so that inaccuracies in their determination have a decisive influence on the solution accuracy. A long time interval between individual measured values can be also a problem because time variations of monitored pollution concentration could not be captured at all.
Another type of problem arises from the assumption, that the pollution in a watercourse is transversely and vertically homogenized, but in fact it may be not true. As we do not know the distance of the pollution source, it is possible that pollution in watercourse has not been homogenized yet. This may happen in the case of short distances of the monitoring cross-section profile from the contamination entry point, or in the case of water-

courses with large width and a relatively shallow depth (it requires relatively large distance for homogenization). Problematic may also be the location of the monitoring probe in such watercourses. The measured values should represent the mean cross-section pollution concentration values. Solution is to use multiple probes in monitored cross-section profile, but this would shift the general 1D inverse task to 2D.

2. Simplifying assumptions are very often used on inverse problems solution. They are mainly instantaneous pollution entry, which happens in fact very rarely. Pollution entry has rarely immediate and one-shot nature, it happens mostly in longer time (intervals) and pollution quantity (mass flow) may be significantly variable.

The problem may be also the entry of pollution into a watercourse itself. Theoretical assumption is that pollution enters in the centre of a watercourse, but in fact, typical case is that the pollution gets into the watercourse from its banks.

Problematic is also inverse problems solution in watercourses with occurrence of so-called dead zones (Shen et al., 2010; Bencala et al., 1983, Runkel, 1998). Dead zones can be, for example, morphological irregularities formed at watercourse bed, the areas with dense vegetation, non-overflowed watercourse side arms etc. Such zones distort the symmetry of the concentration time course curve in the watercourse and form a characteristic long "tail" of the pollution concentration time course curve. In principle, the dead zones disturb the assumption of symmetric dispersion (diffusion) of the substance in downstream and upstream directions.

Another case of problems which can occur in the examined watercourse reach are, for example, small lateral inflows (infiltration), variation of background concentration of the monitored substance or hydraulic parameter values, other pollution sources, etc. (Deng, et al., 2002).

3. Irregularities in the time course of pollution concentration, arising by irregularity of the pollution entry into the watercourse, fade-out with increasing distance (extension of the pollution entry time to a watercourse), until these irregularities completely disappear. The result of this is the "smooth" pollution concentration time course curve. Prolonged duration of the pollution entry into the watercourse may form substantially "flat" curve, similar to the steady state, e.g. the same shape of pollution concentration time course curve like in the case of continuous pollution inflow. In such cases, the inverse task solution is possible only by analysing of the ascending part of the curve (methods, focused to estimate the time of the pollution entry into the watercourse), other methods are not able to solve such inverse tasks. For this reason, authors of related studies often describe and demonstrate, solutions along a relatively short distance from the pollution source to the monitored cross-section profile (in order of hundreds of meters).

The proposed concept for pollution source localisation

The project VEGA Nr. 1/0805/16 focuses on the methods for practical solutions of inverse problems, i.e. localisation of pollution source. The following section describes proposed method, which will be further developed and improved.

Our goal is to develop as far as possible universal solution, i.e. the solution which takes into account the unknown parameters as much as possible. It means apart from the distance of the entry point also the possible variability of the time course pollution entry into a watercourse.

The general solution method is based on the computation of simulations for possible boundary conditions:

1. different distances between the pollution source and the monitoring cross-section profile,
2. for the various alternatives of pollution concentrations time courses.

After that, simulation results of each alternatives will be compared with monitoring data. Boundary conditions, simulation of which will match the monitored data the best, can be considered as probable solution.

In principle, it as a "brute force" method. The risk of such method is the computational time, which is necessary to carry out a huge number of numeric simulations. This time will be conditional to the length of simulated watercourse reach and time and length steps, which implies the total number of simulations needed.

We therefore consider as necessary (beside the inverse problem solution method development) to develop optimization methods for the proposed computational procedure to reduce the required number of simulations, which would speed up the overall inverse problem solution.

The definition of the parameters needed for the pollution transport simulation in a watercourse has to reflect the fact, that the basic hydraulic parameters, characterizing the flow in a watercourse, are variable in time, they depend on the current hydrological situation. Therefore, it is necessary or suitable to define or describe the discharge cross-section area, mean flow velocity, eventually the discharge as a function of depth of water in watercourse. This principle is commonly used in hydrological measurement cross-section profiles and hydrology service can provide such data, in general. Inverse task has to be solved with hydrological parameters which were monitored during examined event (accident).

Next problem is the spatial variation of hydraulic parameters. In solving inverse problems, we assume spatial discretization, it means the division of the investigated watercourse reach to several sections in which we can assume constant hydraulic conditions (flow velocity, depth, cross-sectional area...) – see Fig.1. Then, the resulting pollutogram will be the result of the partial transformation of the input pollutogram at particular sub-sections of the investigated watercourse reach.

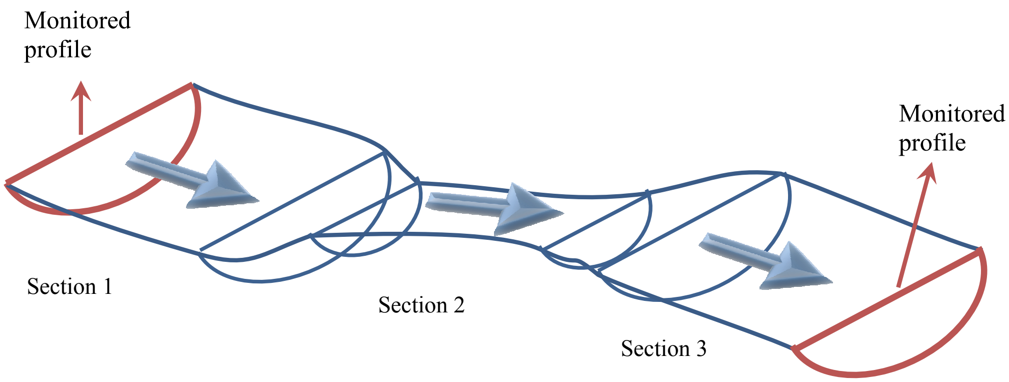

Fig. 1. Pollutogram transformation along the sub-sections of investigated river branch
Obr. 2. Transformácia polutogramu na čiastkových sekciách vyšetrovaného úseku toku.

Risk of the proposed inverse problem solution procedure is the sensitivity of the method to various influences, such as hydraulic watercourse parameters and the precision of numerical description of dispersion process in real watercourses , especially the presence of dead zones, singularities, etc. It comes from the fact that the solution of given inverse task is based on the search of the best similarity or correspondence of measured and simulated pollutograms. This clearly demonstrates the need for further research and improvement of modelling procedures focused on dispersion processes in conditions of real streams.

Conclusions

Systems for water quality on-line monitoring in rivers have great potential for the control, eventually management of water quality in rivers. They enable operational monitoring and control of discharges of specific substances. In case of water quality accidents (acute and extraordinary deterioration of water quality) such systems can provide the necessary information for operational measures, as well as to provide data for models to simulate a prediction of water quality in real time. Specific problems related to the on-line monitoring is the polluters identification. Task of this type can occur in the case of accidental pollution, where the polluter is unknown, as well as in the cases of operational or explorative water bodies monitoring. As noted above, general and accurate solutions of inverse problems have been still unknown and inaccessible, using any method always gives only the approximate solution or estimation, eventually the choice of a particular solution – the most probable case from a number of possible simulations, results of which fits the best with monitored data. In this paper we describe one possible approach how to solve the inverse problem, which we plan to explore more detailed in close future.

Acknowledgment

This work was supported by the Scientific Grant Agency VEGA – grant number VEGA 1/0805/16, title "Localisation of accidental point sources of pollution in water-courses based on-line monitoring data" and by the project ITMS 26240120004 "Centre of excellence for integrated flood protection of land" supported by the Research & Development Operational Programme funded by the ERDF.

Literature

Andrle, M. and El Badia, A. (2012): Identification of multiple moving pollution sources in surface waters or atmospheric media with boundary observations. *Inverse problems.* 2012, 28, p. 22.

Andrle, M., Belgacem, F Ben and Badia, A. El. (2011): Identification of moving pointwise sources in an advection–dispersion–reaction equation. *Inverse Problems.* 2011, 27, p. 21.

Aral, M. M. and Liao, B. (1996): Analytical solutions for two-dimensional transport equation with time-dependent dispersion coefficients. *J. Hydrol. Eng.* 1996, Vol. 1, 1, 20 – 32.

Bencala, K. E. and Walters, R. A. (1983): Simulation of solute transport in a mountain pooland- riffle stream: a transient storage model. *Water Resour Res.* 1983, Vol. 19, 3, 718 – 724.

De Smedt, F., Brevis, W. and Debels, P. (2005): Analytical solution for solute transport resulting from instantaneous injection in streams with transient storage. *J. Hydrol.* 2005, 315, 25 – 39.

Deng, Z. Q., et al. (2002): Longitudinal dispersion in single channel streams. *Journal of Hydraulic Engineering.* 2002, Vol. 10, 128, 901 – 916.

El Badia, A. and Duong, T Ha. (1998): Some remarks on the problem of source identification from boundary measurements. *Inverse Problems.*, 14, 883 – 891.

El Badia, A. and Hamdi, A. (2007): Inverse source problem in an advection-dispersion-reaction system: application to water pollution. 2007, Vol. 2007, 23, 2103 – 2120.

El Badia, A., Duong, T Ha. and Hamidi, A. (2005): Identification of a point source in a linear advection–dispersion–reaction equation: application to a pollution source problem. *Inverse Problems.* 21, 1 – 17.

Fischer, H. B., et al. (1979): *Mixing in Inland and Coastal Waters.* New York : Academic Press, 1979.

Ghane, A., Mazaheri, M. and Mohammad Vali Samani, J. (2016): Location and release time identification of pollution point source in river networks based on the Backward Probability Method. *Journal of Environmental Mangement.* 2016, 180, 164 – 171.

Jandora, J. and Daněček, J. (2002): Contribution to application of analytical methods solving advective-dispersion equation (in czech language, Příspěvek k použití analytických metod řešení transportně disperzní rovnice). *Jornal of Hydrology and Hydromechanic.* 2002, Vol. 50, 2, 139 – 156.

Mazaheri, M., Samani, J.M.V. and Samani, H.M.V. (2015): Mathematical Model for Pollution Source Identification in Rivers. *Environmental Forensics.* 2015, 16, 310 – 321.

Pérez Guerrero, J. S. and Skaggs, T. H. (2010): Analytical solution for one-dimensional advection-dispersion transport equation with distance-dependent coefficients. *Journal of Hydrology.* 2010, 390, 57 – 65.

Runkel, R. L. (1998): *One-dimensional transport with inflow and storage (OTIS): A solute transport model for streams and rivers.* Water-Resources Investigations Report 98–4018. Denver, Colorado : U.S. Geological Survey, 1998. p. 73.

Shen, Ch., et al. (2010): Estimating longitudinal dispersion in rivers using Acoustic Doppler Current Profilers. *Advances in Water Resources.* 2010, 33, 615 – 623.

SOVVA (2014): Slovakia in the Seventh Framework Programme (FP7) — Project Overview & Results. Project Goldfish, 114 – 115. [Online] 2014. http://www.sovva.sk/files/attachments/SOVVA_SLOVAK%20FP7%20SUCCESS%20STORIES_v00.pdf.

Šajer, J. (2014): Odhad času vnosu. 2014, Vol. VTEI 1/2014, 6, 12 – 15.

Šajer, J. (2015): Příklad využití výsledků stopovacích pokusů. 2015, Vol. VTEI 2/2015, 4, 1 – 7.

Thomann, R. V. (1973): Effect of longitudinal dispersion on dynamic water quality response of streams and rivers. *Water Resour. Res.* 1973, Vol. 2, 9, 355–366.

van Genuchten, M. T., et al. (2013a): Exact analytical solutions for contaminant transport in rivers. 1. The equilibrium advection-dispersion equation. *J. Hydrol. Hydromech.* 2013a, Vol. 61, 2, 146 – 160.

van Genuchten, M. T., et al. (2013b): Exact analytical solutions for contaminant transport in rivers. 2. Transient storage and decay chain solutions. *J. Hydrol. Hydromech.* 2013b, Vol. 61, 3, 250 – 259.

Verdière, N., Joly-Blanchard, G. and Denis-Vidal, L. (2013): Identifiability and identification of a pollution source in a river by using a semi-discretized model. *Applied Mathematics and Computation.* 2013, 221, 1 – 9.

Wikipedia (2016): Molecularly imprinted polymer. *Wikipedia.* [Online] 2016. https://en.wikipedia.org/wiki/Molecularly_imprinted_polymer.

Xiaole, Zhang and Meng, Huang. (2017): Ensemble-based release estimation for accidental river pollution with known source position. *Journal of Hazardous Materials.* March 2017, Vol. 333, 99 – 108.

LOKALIZÁCIA ZDROJA ZNEČISTENIA – INVERZNÁ ÚLOHA TRANSPORTU ZNEČISTENIA

Definícia inverznej úlohy transportu znečistenia v povrchovom toku

Ako bolo spomenuté vyššie, väčšina modelov v súčasnosti sa zameriava na modelovanie šírenia znečistenia v smere toku. Opačná úloha – lokalizácia zdroja znečistenia na základe známych meraní sa označuje ako tzv. inverzná úloha. Je potrebné uviesť, že ide o úlohu, ktorá nemá vždy jednoznačné riešenie, ale výsledkom je spravidla niekoľko pravdepodobných riešení. Táto úloha je zatiaľ skôr v štádiu riešenia matematického problému, verifikované praktické aplikácie alebo komerčný SW, ktorý by riešil problém inverznej úlohy, nie je v súčasnosti známy. V literatúre je možné nájsť viacero prác, zaoberajúcich sa touto problematikou, napr. (Andrle et al., 2012; El Badia et al., 2007; Andrle et al., 2011; Verdière et al., 2013), vo všeobecnosti je ale možné konštatovať, že prezentované metódy riešenia sú pomerne komplikované a pri ich praktickom využití narazíme na mnohé limity a obmedzenia.

Používané zjednodušujúce predpoklady

Pri riešení inverzných úloh sa spravidla vyskytuje veľký počet neznámych, resp. niektoré metódy riešenia vyžadujú veľký počet numerických simulácií. Preto sa často používajú zjednodušujúce predpoklady a z nich vyplývajúce jednoduché matematické modely (napr. analytické riešenia), ktoré urýchľujú realizáciu numerických simulácií a skracujú čas, potrebný na riešenie úlohy.

Pri praktickom riešení inverznej úlohy sa často uvažuje s nasledovnými predpokladmi :

1. znečistenie je konzervatívne
2. ide o jednoduchý zdroj znečistenia, ktorý sa nachádza na úseku rieky bez bočných prítokov a odberov,
3. koryto je prizmatické.

Predpoklad jednoduchého zdroja znečistenia znamená, že vo vyšetrovanom úseku rieky je iba jeden, priestorovo nemenný zdroj znečistenia, ktorý vypúšťa znečistenie priamo do rieky (teda nie do prítoku vyšetrovaného úseku. Pre správnu funkciu lokalizačného nástroja bude kľúčovou úlohou presné určenie hydraulických veličín toku, ktoré je ešte komplikované skutočnosťou, že tieto hydraulické veličiny sa menia v závislosti na hydrologickej situácii (prietoku) v rieke.

Rozdelenie prístupov k riešeniu inverzných úloh

Prístup k riešeniu inverzných úloh je veľmi rôznorodý a individuálny. Celkovo môžeme známe postupy riešenia inverznej úlohy rozdeliť do nasledovných skupín:

1. Metódy, zamerané na odhad času vnosu,
2. Zjednodušené metódy,
3. Inverzné numerické simulácie.

1. Metódy, zamerané na odhad času vnosu znečistenia do toku, napr. (Šajer, 2014; Šajer, 2015), využívajú podobnosť, resp. zhodu vzostupnej časti krivky časového priebehu nameraných koncentrácií vo vodnom toku so zjednodušenými modelmi. Na základe podobnosti je možné určiť čas vnosu znečistenia, z ktorého je potom možné lokalizovať aj miesto vnosu.

2. Zjednodušené metódy – tieto sa zameriavajú na simuláciu jednotlivých možných prípadov znečistenia pri použití zjednodušených analytických riešení a následné porovnanie výsledkov simulácie s nameranými (monitorovanými) hodnotami. Výhodou týchto metód je ich jednoduchosť, rýchla realizácia, možnosť jednoduchej modifikácie základnej riadiacej rovnice pre konkrétne podmienky (napr. výskyt mŕtvych zón a pod.). Ich nevýhodou je potrebná realizácia veľkého množstva numerických simulácií, resp. dlhý výpočtový čas.

3. Zložitejšie postupy sa zameriavajú na inverzné numerické simulácie (proti prúdu toku). Z matematického hľadiska sú presnejšie, ale zároveň aj komplikovanejšie a náročnejšie na zostavenia počítačových programov, (Verdière et al., 2013; El Badia et al., 2007). Ich použitie je však spravidla limitované použitým zjednodušujúcim predpokladom, ako napr. predpoklad okamžitého úniku znečistenia, znalosť časovej závislosti (funkcie), ktorá opisuje vnos znečistenia a pod.

Okruhy problémov pri riešení inverzných úloh

Problémy, vplývajúce na presnosť, prípadne existenciu riešenia inverznej úlohy, môžeme rozdeliť do týchto okruhov:

1. Problémy vyplývajúce z presnosti a reprezentatívnosti merania koncentrácií vo vodnom toku
2. Problémy, vyplývajúce z rozdielnosti teoretických predpokladov a reálnych podmienok na toku
3. Problém veľkých dĺžok.

1 Tento typ problémov môže mať rôzne príčiny a pôvod. Koncentrácie znečistenia môžu byť merané rôznou technológiou, z čoho potom vyplýva aj presnosť merania týchto ukazovateľov, ale aj časový interval jednotlivých hodnôt (časový krok). Prakticky všetky metódy riešenia inverznej úlohy vychádzajú z časového priebehu koncentrácií ukazovateľov znečistenia vo vodnom toku, takže nepresnosti v stanovení majú rozhodujúci vplyv na presnosť riešenia.
Iný typ problémov vyplýva zo toho, že predpokladáme dokonalé premiešanie v priečnom a j vertikálnom smere,, čo v skutočnosti nemusí byť pravda. Keďže vzdialenosť zdroja znečistenia nepoznáme, je možné, že ešte nedošlo k spomínanej homogenizácii znečistenia.

2. Pri riešení inverzných úloh sa veľmi často používajú zjednodušujúce predpoklady. Sú to najmä okamžitý, resp. jednorazový vnos znečistenia, čo je v realite málokedy splnené. Väčšinou ide o vnos znečistenia vo väčších časových úsekoch, pričom intenzita (hmotnostný tok) vnosu môže byť značné premenlivá.
Problémom je aj samotný vnos znečistenia do vodného toku: teoretický predpoklad je, že znečistenie sa dostane do stredu toku, ale v realite nastáva skôr prípad, že znečistenie sa dostáva do toku z jeho brehov.
Ďalším problémom patriacim do tejto skupiny je výskyt tzv. mŕtvych zón. Sú to oblasti tokov, zvyčajne s malou rýchlosťou prúdenia, v ktorých nastáva dočasné zachytenie transportovanej látky. Mŕtve zóny môžu byť napr. vytvorené morfologickými nepravidelnosťami koryta toku, oblasťami s hustou vegetáciou, bočnými neprietočnými ramenami toku a pod. Takéto oblasti deformujú symetriu krivky časového priebehu koncentrácie sledovanej látky v toku a vytvárajú charakteristický dlhý dobeh priebehu koncentrácie v čase, tzv. chvost. V princípe mŕtve zóny narúšajú predpoklad symetrickej disperzie (difúzie) látky v smere a proti smeru toku vody.
Ďalším okruhom problémov sú vplyvy, ktoré reálne prebiehajú na vyšetrovanom úseku toku, napr. malé bočné prítoky (napr. infiltrácia), kolísanie pozaďovej koncentrácie sledovanej látky, iné zdroje znečistenia a pod.

3. Nepravidelnosti v časovom priebehu koncentrácie znečistenia, ktoré vznikajú nepravidelnosťou vnosu znečistenia do toku, sa so zväčšujúcou vzdialenosťou zmenšujú, až napokon úplne zaniknú, takže výsledkom je nakoniec „hladká“ krivka časového priebehu koncentrácií. Pri dlhšom trvaní vnosu látky do toku (havarijného úniku) sa môže vytvoriť prakticky „plochá“ krivka, podobná ustálenému stavu, t.j. kontinuálnemu vypúšťaniu. V takýchto prípadoch je riešenie prakticky možné iba analýzou vzostupnej časti krivky (metódy zamerané na odhad času vnosu), ostatné metódy majú pri riešení takejto inverznej úlohy problémy. Preto sa v literatúre často stretávame s riešeniami, kde autori demonštrujú príklady riešenia inverznej úlohy na relatívne krátkych vzdialenostiach od miesta vnosu, rádovo v stovkách metrov.

Navrhovaný koncept riešenia pri lokalizácii zdrojov znečistenia

Projekt VEGA č. 1/0805/16 je zameraný na výskum možností praktického riešenia inverznej úlohy, t.j. lokalizácie zdroja znečistenia. V ďalšom texte je opísaný všeobecný návrh postupu lokalizácie zdrojov znečistenia, ktorý navrhujeme realizovať v rámci prác na tejto výskumnej úlohe.
Našou snahou je vyvinúť podľa možností čo najuniverzálnejšie riešenie, t.j. v riešení zohľadniť v maximálnej

možnej miere neznáme veličiny – okrem vzdialenosti miesta vnosu aj maximálne možnú variabilitu časového priebehu vnosu znečistenia do toku.
Riešenie úlohy preto navrhujeme na základe vykonania veľkého množstva simulácií pre rôzne okrajové podmienky úlohy (pre rôzne vzdialenosti zdroja od monitorovacieho profilu, pre rôzne alternatívy koncentrácie znečistenia a jeho časový priebeh). Výsledky simulácií každej z týchto alternatív budú porovnávané s monitorovanými údajmi. Najlepšiu zhodu s monitorovanými údajmi môžeme potom považovať za pravdepodobné riešenie našej úlohy.
V princípe ide o využitie metódy „brute force“, pričom limitom takto použitej metódy môže byť výpočtový čas potrebný na vykonanie značného počtu potrebných simulácií.
Preto považujeme za potrebné zároveň s vývojom tejto metódy riešenia inverznej úlohy posúdiť metódy optimalizácie navrhovaného výpočtového postupu, ktorý by v navrhovanom výpočtovom postupe zmenšil potrebný počet simulácií, čím by sa zrýchlilo celkové riešenie úlohy.
Pri definícii potrebných veličín pre výpočty a simulácie šírenia sa znečistenia v rieke je potrebné uvažovať so skutočnosťou, že základné hydraulické veličiny, charakterizujúce prúdenie vody v rieke, nie sú časovo konštantné, ale závisia od aktuálnej hydrologickej situácie v toku. Preto je potrebné veličiny ako prietočnú plochu, rýchlosť vody, prípadne prietok vyjadriť ako závislosť na hĺbke vody. Tento princíp je bežný v merných hydrologických profiloch, hydrologická služba zvyčajne má k dispozícii takto vyhodnotené merania v pevných merných monitorovacích profiloch.
Pri riešení inverznej úlohy predpokladáme priestorovú diskretizáciu – rozdelenie vyšetrovaného úseku toku na viacero sekcií, v ktorých môžeme predpokladať konštantné hydraulické podmienky (rýchlosť, hĺbka, prietočná plocha ...). Výsledný polutogram znečistenia potom bude výsledkom postupnej transformácie vstupného polutogramu na jednotlivých čiastkových sekciách vyšetrovaného úseku toku.
Rizikom navrhovaného postupu riešenia inverznej úlohy je citlivosť metódy na rôzne vplyvy, ako sú napr. hydraulické parametre toku, ako aj na presnosť matematického opisu procesu disperzie v reálnom povrchovom toku, najmä na prítomnosť mŕtvych zón, singularít a pod. Vyplýva to z faktu, že riešenie zadanej inverznej úlohy sa hľadá na základe podobnosti nameraných a modelovaných polutogramov, z čoho jednoznačne vyplýva potreba ďalšieho výskumu a zlepšenia modelovania reálnych procesov disperzie vo vyšetrovanom vodnom toku.

doc. Ing. Marek Sokáč, PhD.
Stavebná fakulta STU Bratislava
Radlinského 11
810 05 Bratislava
E-mail: marek.sokac@stuba.sk

Ing. Yvetta Velísková, PhD.
Ústav hydrológie SAV
Dúbravská cesta 9
941 01 Bratislava
E-mail: veliskova@uh.savba.sk