Józef CIUŁA[1]

[1] State University of Applied Sciences in Nowy Sącz, Institute of Technology, 33-300 Nowy Sącz, Zamenhoffa 1A street, e-mail: jciula@pwsz-ns.edu.pl

Examples of pollutant transport models in groundwater of a municipal waste landfill – case study

Abstract

Landfills must be constantly monitored in terms of their impact on soils, groundwater and surface water, as well as plants and air quality. Leachate with high content of inorganic and organic substances, heavy metals and toxic compounds pose particular hazard. Release of leachates from the landfill may occur as a result of insulation leakage, leading to the transfer of hazardous substances into the soil and the aquifer. This paper is an attempt to describe the structure of the mathematical model used for the analysis of groundwater flow and possible directions of contaminants migration in the aquifer of an active landfill as a result of leachate release. The models have been assessed, which indicated the necessity of validation and calibration in order to obtain credible results. The analysis of literature has shown that mathematical models are often used as a tool in scientific or industrial studies. Available software products used for modeling migration of contaminants in groundwater are a vital part in landfill management and forecasting its potential environmental impact.

Key words: landfill, leachates, environmental monitoring, mathematical models, migration of contaminants

Przykłady modeli transportu zanieczyszczeń w wodach podziemnych składowiska odpadów komunalnych – case study

Streszczenie

Składowisko odpadów jest obiektem wymagającym ciągłego monitoringu jego oddziaływania na gleby, wody podziemne i powierzchniowe, rośliny oraz powietrze. Szczególne zagrożenie stwarzają odcieki zawierające duży ładunek substancji nieorganicznych, organicznych oraz metali ciężkich i związków toksycznych. Uwolnienie odcieków z bryły składowiska może wynikać z nieszczelności jego izolacji, co skutkuje przedostaniem się do gleby i warstwy wodonośnej substancji niebezpiecznych. W artykule podjęto próbę opisu konstrukcji modelu matematycznego wykorzystywanego do wykonania analizy przepływu wód podziemnych i prawdopodobnych kierunków migracji zanieczyszczeń w warstwie wodonośnej czynnego składowiska odpadów w przypadku uwolnienia odcieków. Wykonano ocenę modeli wraz z koniecznością ich walidacji i kalibracji w celu uzyskania wiarygodnych wyników. Analiza literatury przedmiotu wykazała, że modele matematyczne są często wykorzystywane jako narzędzie w badaniach naukowych oraz branżowych. Dostępne programy komputerowe przeznaczone do modelowania migracji zanieczyszczeń w wodach podziemnych stanowią ważny element zarządzania składowiskiem i prognozy jego potencjalnego oddziaływania na środowisko.

Słowa kluczowe: składowisko odpadów, odcieki, monitoring środowiska, modele matematyczne, migracja zanieczyszczeń.

1. Introduction

Creating mathematical models of mass transfer is one of the ways of procuring credible projections for migration of anthropogenic contaminants in e.g. underground water reservoirs. In order for the transfer models to be credible they should be calibrated on the grounds of the data collected through observation, facility surveillance, measurements and simulations of migration of compounds from the existing contamination hotspots. One such facility which can potentially have a detrimental influence on the environment is a municipal waste landfill (Dąbrowski et al., 2010). A waste landfill is a special facility in the context of protecting environment and from the sanitary point of view because none of the currently utilized exploitation technologies guarantees complete protection of the environment against adverse influence of a landfill. Owing to these facts the demographic, topographic, geo-technical and climate conditions as well as spatial planning principles have to be taken into account in localizing and designing landfill infrastructure (Rosik-Dulewska, 2015). The primary threat presented by a landfill is the possibility of leachate generated by the landfill penetrating soil and transferring into aquifer. Leachates generated in the waste deposit are characterized by a very complex and diverse composition. Leachates include a number of inorganic and organic compounds and substances as well as heavy metals and toxic compounds. The studies performed for closed waste landfills indicate a higher concentration of polycyclic aromatic hydrocarbon and organic compounds in the underground waters in the area of a landfill. There is a relation between the content of ammoniacal nitrogen in surface waters and underground water located below a landfill and the increased concentration of NH_4-N correlated with the depth at which underground water appear. Such relations may suggest that leachates are permeating into waters (Przydatek, 2019). In the instance of improper operation of a landfill heavy metals and other chemical compounds present in leachates migrate into soil and underground water when the insulation is damaged and present an actual threat to human health and life. Such situations also can result in issues with exploitation of water intakes during technological water purification processes. This problem also concerns individuals using own water intakes for which water quality examinations are performed very rarely by owners (Rybicki, Wiewiórska, 2017). Municipal waste landfills are also a source of non-formal emission of landfill biogas (emission from the surface of the landfill) the main component of which is methane which is one of the primary greenhouse gases. The gas in the waste deposit is created as a result of the biological processes related to decomposition of organic fraction contained within mixed municipal waste. In such circumstances erecting a gas extraction installation responsible for reducing non-formal emissions from the area of landfill is a necessity (Ciuła et al., 2020). Taking into consideration constant changes in waste deposit composition introduction of environment monitoring regarding surface and underground waters, soils and emission to air is a crucial issue of exploitation of a landfill. The studies performed within the framework of monitoring frequently indicate presence of polychlorinated biphenyls in leachates. Although PCBs are effectively decomposed through in vitro photolysis they display significant persistence in environment. Purification of leachates removes only the PCB adsorbed onto particulates suspended in water. The dissolved fraction is not removed and along with purified sewage it is drained away into watercourses (Leah et al., 2001; Shaker, Yeung, 2010; Starek, 2001). In terms of landfill waste management it is recommended to create a numerical model for migration of anthropogenic contaminants in underground waters as well as creating a hydrodynamic models for the purpose of improving precision of waste decomposition process. It is a result of the need for learning migration mechanisms related to spatial and temporal changes during operation of a landfill as well as following closure of a landfill (Rouholahnejad, Sadrnejad, 2009). Schematization of hydro-geological conditions has been used in studies for over a hundred years. Currently it is one of the more important stages of constructing mathematical models for filtration and transfer of mass. It is also being applied in uniform studies of certain areas of underground water, in particular in assessment of the influence of environmental conditions – including influence of waste management on circulation and chemical composition of water for the purpose of limiting adverse influence on underground waters and soils (Berkhoff, 2007; Wysowska et al., 2020). Supporting scientific research through utilizing the available computer software, including GIS software, is currently becoming a standard for assessment of influence of waste management facilities on the natural environment as well as for the purpose of management and prediction (Gaska et al., 2018).

2. The goal and scope

The goal of this paper is presenting the structure of a mathematical model for describing the phenomenon of mass transfer (movement of particles other than water, e.g. chloride ions) in an groundwater stream in the area of a municipal waste landfill. The goal of the constructed model is determining the probable vectors for migration of anthropogenic contaminants and the rate of migration. The mathematical modeling has become a universal tool in realization of research tasks, including assessing influence of anthropogenic objects on the environment. In order to properly recognize the occurring phenomena and modeling methods the mathematical models are being constructed on the basis of the known distribution of underground water table (pressures). The identified parameters of an object, environmental and hydro-geological conditions as well as the results of surveillance of the objects influencing individual components of the environment will enable construction of a mathematical model in appropriate computer programs.

The scope of this paper covers:

- description of the mass transfer phenomenon;
- presentation of equations and boundary conditions determining structure of the mathematical model;
- the methods for assessing influence of uncertainty of data on the results of contaminants transfer modeling;
- The possibility of constructing models for migration and assessment of credibility of the produced results.

Constructing a model for migration of anthropogenic contaminants in underground waters on the basis of dedicated computer programs is essential for assessing possible influence of a waste landfill in the case of damage to insulation. Modeling is one of the elements of learning about the processes, enables defining the area under a possible threat of underground water contamination as well as an opportunity for taking preventative actions.

3. Models of migration of contaminants in an aquifer

The mathematical models are applied with the goal of describing the reality, predicting future events, assessment of their possible effects and explaining them. Apart from the research goals the modeling of migration of contaminants in underground waters is being performed with the primary goal of assessing the risk of water contamination and threat to human health (Xi et al., 2021).

Migration of contaminants in underground water is dependent on several factors:

- character of flow of groundwater;
- hydro-geologic properties of soil layers (wherein migration occurs);
- types of contamination.

The character of flow of underground waters is primarily dependent of the type of the aquifer and its hydro-geological properties. The accuracy of reproduction of the migration process is dependent on the accuracy of identification or estimation of hydro-geological properties of rocks (soils). The process of migration of contaminants can be analyzed on the basis of the hydrodynamic model of flow of underground waters. In order to assess range of filtration of underground water and migration of contaminants in the area of a landfill underground the water filtration equations and numerical methods of solving such equations, which serve as a basis for creating mathematical models, are being used (Kleczkowski, Różkowski, 2002).

The commercially available calculation models utilized in analysis of migration of underground waters are constructed on the grounds of appropriate algorithms and utilize various mathematical equations. The most commonly utilized models are: Gauss's model, Lagrange's model and Euler's model. However, a single model intended for general use does not exist and as a result the necessity for utilizing numerous calculating codes dedicated for calculating specific data arises. The majority of computer programs intended for calculating migration of contaminants in underground waters utilizes Lagrange's model. The most popular include: MODFLOW, MT3DMS and NAPL. MODFLOW software is based on two and three-dimensional water movement equation and is a mesh model operating on the basis of structural meshes (all elements are of the same shape). In its libraries it includes packages which enable, among other functions, defining the type of layers, determining permeability of layers over time and packages which account for supporting the aquifer by surface sources (Borysiewicz et al., 2019; Saghravani, Mustapha, 2011).

The MT3DMS (*Modular Three-Dimensional Multispecies Transport Model*) software is designed for simulating transfer of contaminants dissolved in underground water. It enables simulating transfer and dispersion of numerous chemical compounds in an aquifer as well as simulating chemical reactions between these compounds. The model generates a summary by taking into account concentration of all dissolved compounds, flow parameters as well as mass balance. The model also has certain limitations, e.g. it does not account for molecular diffusion, which means that the model should not be utilized in case of very small gradients of piezometric velocity. A computer program which can be used to model transfer and dispersal of oil in underground waters and soil is NAPL (*Non-Aqueous Phase Liquids*). The mathematical description of the model consist of two parts, the former of which consist of mass conservation equations and the latter of constitutive equations. These equations describe mutual relations between basic variables which are solved through mass conservation equations and secondary variables which are functions of the primary variables. The model interprets definitions of boundary conditions on the basis of the adopted type (Dirichleta, Neumanna) or direction of boundary conditions operations (Zdechlik et al., 2015; Borysiewicz et al., 2019).

3.1. Simulation methods and mass transfer algorithms

Differential equations describe mass transfer in the stream of underground waters by way of continuous variables such as concentration of the dissolved substance and soil hydraulic properties. In order to formulate a numerical equation these variables have to be transformed into a discrete form. A discrete form of an equation means that an approximate solution for the equation is determined solely in the discrete points in space (discretization mesh) and at discrete moments in time. The basic methods for approximate solving of equations for mass transfer in underground waters stream (along with appropriate initial conditions and boundary conditions) are:

- finite difference method;
- finite volume method;
- finite element method;

These methods are the most frequently utilized to describe mass transfer in underground water streams as well as flow of underground water (Michalak et al., 2011).

The finite difference method consist of approximating derivatives appearing in mass transfer equations through the use of difference quotient of the requested function's values in the nodes of the orthogonal discretization mesh. For the first and second derivative of a certain function *f* in relation to *x* the simplest discrete approximation takes the form of (1,2):

$$\frac{\partial f}{\partial x} = \frac{f_{i+1} - f_{i-1}}{2\Delta x} \tag{1}$$

$$\frac{\partial^2 f}{\partial x^2} = \frac{f_{i+1} - 2f_{i-1}}{2\Delta x} \tag{2}$$

where: f_i, f_{i-1}, f_{i+1} – the value of function in discrete points of the mesh.

Substituting derivatives with difference quotient leads to a system of algebraic equations for *N* indeterminate ($f_1, ... f_N$) where *N* is a number of discretization nodes. In case of the mass transfer a slightly different form of derivatives' approximating is being used which is called forward approximation (3):

$$\frac{\partial f}{\partial x} \frac{f_i - f_{i-1}}{2\Delta x} \tag{3}$$

If approximate solutions meet certain accuracy criteria the produced results may serve as basis for analysis regarding selection of appropriate methods for protecting aquifers or for remediation of aquifers in case of contamination (Anderson, Woessner, 1992).

The finite volume method is developed on the basis of mass conservation principle for the cuboid blocks into which the entire area through which contaminants flow is being divided (4):

$$\frac{\partial V}{\partial t} = Q_{i-} + Q_{i+} + Q_{j-} + Q_{j+} + Q \qquad (4)$$

where: V – mass of the substance in a block, $Q_{i-} + Q_{i+} + Q_{j-} + Q_{j+}$ – flow through walls of the block, Q – sources of mass.

The system of equations for required functions (concentration of a substance dissolved in water) is being created by indicating relations between flow through walls of blocks and these substances. The finite volume method accepts shapes other than cuboids which makes this method more flexible in terms of reconstructing the geometry of the area through which the mass of contaminants flows (Holzbecher, Sorek, 2005).

The finite element method displays a number of good qualities both in terms of possibility of approximation of the geometry of the mass transfer area as well as approximation of the indeterminate function. The shapes used the most frequently for the elements are: triangles – for 2D problems and triangle-based pyramids – for 3D problems (Anderson and Woessner, 1992).

One of the forms of the function approximating the value searched for in a given element *e* (a triangle) is a plane equation (5):

$$f^e(x,y) = a_0^e + a_1^e x + a_2^e y \qquad (5)$$

In finite elements method the indeterminate consist of the values of parameters for this function, i.e. for all elements comprising coverage for the entire mass transfer area. The algebraic equations the solutions to which consist of the sought parameters of the function, are formulated through the so called weak formulation describing a given instance of transfer of contaminants in underground waters (Wang, Anderson, 1982).

3.2. Mass transfer model

Creating mass transfer models is necessary for obtaining credible projections regarding migration of anthropogenic contaminants in underground water reservoirs. For the transfer models to be credible they have to be calibrated on the basis of experimental data (incl. monitoring of migration of compounds from the existing hotspots of contamination, experiments utilizing artificial markers or monitoring of behavior of environmental markers). The following phenomena occur during flow of contaminants in underground waters (Spitz, Moreno, 1996):

- advection – transfer of contaminants along with underground waters proceeding at an average rate of water flow;
- diffusion – a flow of stream of contaminants from the area of higher concentration to the area with lower concentration, irrespectively of the direction of flow of water;
- hydrodynamic dispersion – dispersion of the substance dissolved in water as a result of varying velocity of individual streams of water in different pore channels;
- sorption – accumulation of the particles of the substance dissolved in water on the surface of minerals or colloidal particles (adsorption) and release of previously adsorbed particles (desorption);
- radioactive decay and/or bio-deterioration – the processes which as a result of physico--chemical and biochemical reactions lead to decrease of concentration of a contaminant over time.

Processes of migration of contaminants in underground water can be considered by analyzing a one-dimension (1D) case describing changes in concentration of pollution within the filtration field. The one-dimension advection-sorption equation, supplemented with sorption and decay, can be demonstrated in the form of an equation (6) (Fetter, 1999):

$$\frac{\partial \mathrm{C}}{\partial t} = -v_x \frac{\partial \mathrm{C}}{\partial x} + D_L \frac{\partial^2 \mathrm{C}}{\partial x^2} - \frac{B_d\, \partial \mathrm{C}^*}{n_o \partial t} + \left(\frac{\partial C}{\partial t}\right)_{rxn} \qquad (6)$$

$$[advection][dispersion][sorption]\ [reactions]$$

where:

C – concentration of a component in water [mg·dm^{-3}],

t – time [s],

x – distance across the flow direction [m],

D_L – longitudinal hydrodynamic dispersion coefficient [m^2·s^{-1}], ($\mathrm{D_L} = \alpha_\mathrm{L} \mathrm{v_x} + \mathrm{D_M}$),

α_L – longitudinal dispersion constant [m],

v_x – average linear velocity of flow of water [m^3·s^{-1}],

D_M – molecular diffusion coefficient [m^2·s^{-1}],

Bd – volumetric density of granular soil structure [mg·dm^{-3}],

n_o – exposed porosity [-],

C^* – concentration of the sorbed substance in a solid state [mg·dm^{-3}],

rxn – the index indicating biological and chemical reaction of the substance (other than sorption)

The formula $\left(-v_x \frac{\partial \mathrm{C}}{\partial x}\right)$ on the left side of the equation refers to the advection flow, the second formula defines dispersion of a substance in water, the third formula determines sorption of the substance in its solid state (in the sorption complex) and the last formula indicates the possibility for change in concentration over time resulting from biological, chemical as well as radioactive decay. Similarly to flow equation establishing initial and boundary conditions is necessary for solving the mass transfer equation. The initial conditions correspond with concentration values of the substance migrating within the filtration field stated at the beginning of the simulation (for t = 0) whereas the boundary conditions define the reaction between the studied object and its surroundings (Dąbrowski et al., 2011; Zuber et al., 2007).

3.3. Influence of uncertainty on the results of contaminants' transfer modeling

Owing to the uncertainty accompanying the process of modeling the results are always burdened by errors. The basic reasons behind the modeling uncertainty are:

- assumptions and simplifications are a non-negotiable element of the modeling process;
- the data collected at the discreet points are usually interpreted in numerical models as variables and average parameters post volume;
- in the majority of cases we lack information regarding spatial variability of individual parameters;
- usually only approximations of boundary conditions and source members are known (Van Geer et al., 1991).

The diagram for the modeling process is presented in Figure 1. The underlined letters mark the basic elements of the modeling process defined as a process of converting an input signal into an output signal (an answer).

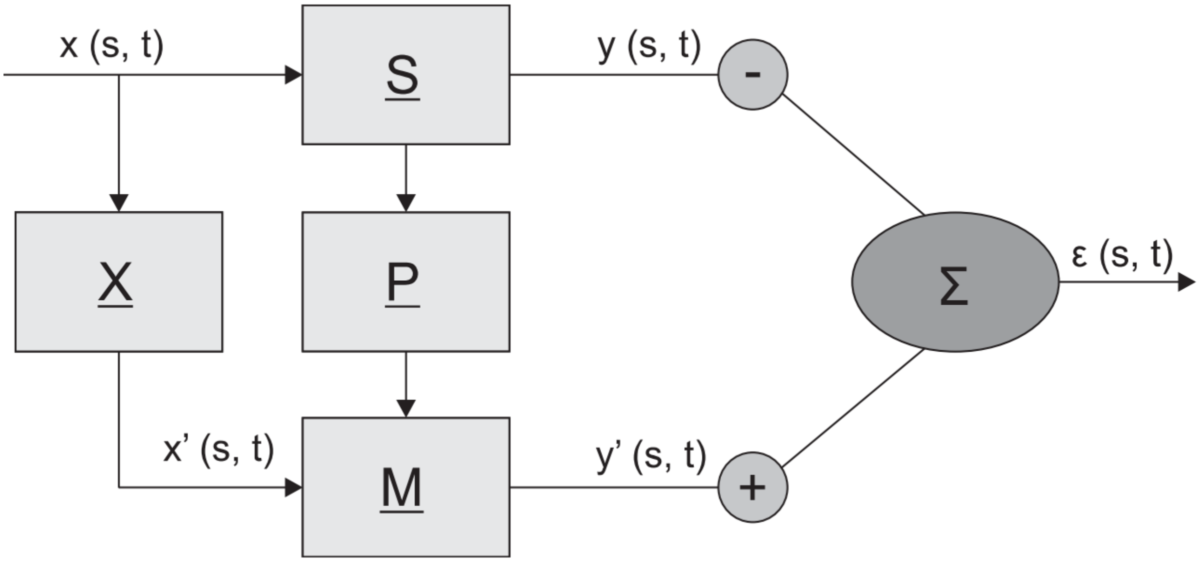

Figure 1. Diagram of contaminants' transfer modeling process

(source: Michalak et al., 2011)

Letter S marks the natural (actual) system which after receiving signal *x (s,t)* at the input (variable over time and space) generates a response *y (s,t)* which is also distributed over time and space. The natural system S is described by the model M which is a result of abstraction, i.e. it includes only these variables which are significant in the context of the purpose of the model. For the model to function it is required, among other necessary steps, to determine or estimate its parameters. The values of parameters are determined directly or indirectly on the basis of measuring (empirical) information from the original S system. In the majority of cases these values are determined in the form discrete in regards to space and time (Guymon, 1994).

The input signal for the model is signal *x (s, t)*. Both the input signal measurement as well as its quantification are sources of an error which propagates into model's output. Due to existence of errors in the modeling process the output signal *y'(s, t)* (model's response) never corresponds fully with the response given by the original system M. The difference *ε (s, t)* between responses *y* and *y'* is a modeling process error. The magnitude of this error is dependent on a number of factors and may originate from each of the M, P, X and S systems. Four types of errors related to: structure and limitations of the models, determining parameters of the model, type of coercion and determining initial state are indicated the most frequently. Defining these processes incorrectly directly influences accuracy and precision of the results of the mathematical model of mass transfer/migration and thus the produced results of model calculations are interpreted analogously to input parameters and variables, i.e. they include uncertainty (Guymon, 1994; Michalak et al., 2011).

In order to assess influence of data uncertainty on the results of modeling of contaminants' transfer in underground water stream two principal methods are applied, i.e. deterministic and statistic approach.

In the deterministic process modeling consists of determining input variables and their relation to output variables which are of interest due to the issue under study. The statistic approach, in turn, requires treating input variables as random variables and determining appropriate function of probability density.

3.4. Assessing the possibility of constructing migration models and credibility of the results

The model for transfer of contaminants is constructed on the basis of a calibrated model for hydrodynamic field. The flow model is calibrated through adjusting hydraulic soil properties and flow balance and thus it provides an inconclusive solution for calculating rate of flow of underground waters (Kania et al., Zuber et al., 2007).

Apart from the parameters considered within the flow model the basic parameters characterizing the process of transfer of contaminants in underground waters are:

- active (effective) porosity of water-bearing formations;
- longitudinal and transverse hydrodynamic dispersion constants;
- retardation factor which is a measure of sorption of contaminants;
- parameters characterizing decay (biodegradation).

Furthermore, producing credible results of calculations requires appropriate identification of hudrogeochemical field of the surveyed location along with the concentration values in boundary conditions. The most-time consuming operation during modeling of flow and migration of contaminants is the process of creating a model and calibrating it. As early as on the flow model's construction we must draw attention to the elements influencing proper functioning of the transfer model. Significant factors include size of calculation blocks for the model (Hill, Tiedeman, 2007).

To minimize the phenomenon of numerical dispersion during transfer simulation through classic finite difference method the size of a calculation block should be adjusted in consideration of the Peclet number (Spitz, Moreno, 1996; Van Geer et al., 1991) (7):

$$Pe = \frac{v_x \cdot \Delta_x}{D_L} = \frac{v_x \cdot \Delta_x}{\alpha_L \cdot v_x} = \frac{\Delta_x}{\alpha_L} \tag{7}$$

where:
Pe – Peclet number, [-]
v_x – factual rate of flow of underground waters in the direction of *x* axis [$m^3 \cdot s^{-1}$],
Δ_x – dimensions of an individual block in the direction of *x* axis, [m],
α_L – longitudinal hydrodynamic dispersion constant, [m],
D_L – longitudinal hydrodynamic dispersion coefficient, [$m^2 \cdot s^{-1}$].

The Peclet number expresses the ratio between advection transfer and dispersion transfer. The issues with numerical solution for advection-dispersion equation emerge particularly when the primary role is being played by advection transfer and thus size of the blocks for the model should meet the $Pe \leq 2$ ($\Delta_x \leq 2\alpha_L$) criterion in order to avoid numerical dispersion (Kinzelbach, 1986).

Apart from appropriate adjustment of size of the calculation blocks it is pivotal to determine the Δt time step for tracking migration of the element in order to ensure stability of calculations and avoid the numerical oscillation phenomenon. The conditions for stability of calculations are defined by Courant criterion (Kinzelbach, 1986; Spitz, Moreno, 1996) (8):

$$Co = \left| v_x \frac{\Delta_t}{\Delta_x} \right| \leq 1 \tag{8}$$

where:
Co – Courant's number, [-],
v_x – the actual rate of flow of underground waters in the direction of the *x* axis, [$m^3 \cdot s^{-1}$]
Δx – size of an individual block in the direction of the *x* axis, [m],
Δt – extent of the time step for a modeled migration of an element, [s],

The credibility of modeling of migration of contaminants is dependent on several basic factors:

- the software used for performing calculations should be proven;
- the conceptual models should properly take into consideration the processes which are to be modeled;
- the key issue is the limited availability of parameters for migration of contaminants (Małecki et al., 2006).

For contaminants transfer models to be credible they should be inspected and calibrated. Prior to calibration a mathematical model describing migration of contaminants should be inspected. Such inspection is usually performed through comparing results of numerical and analytical modeling (Bear, Cheng, 2010).

Calibration of a model (taring) is a process of reverse problem solving, i.e. the appropriate system parameters are being sought for by using trial and error method or automatically by using appropriate code on the basis of known input-output relations.

The experimental data necessary for calibration of transfer model are:

- observations regarding migration from the existing contamination hotspots;
- experiments utilizing artificial markers;
- monitoring behavior of environmental markers.

In turn, model validation is a process aimed at confirming that the model is a correct representation of a process or a system. Validation is particularly credible when the projections generated by the calibrated model are consistent with the new experimental data collected in conditions different than the conditions under which the model was calibrated (Zuber et al., 2007). During calibration of a model, when there is e.g. no strict relation between the height of water table and topography, the tools utilized during calibration consist of e.g. automatic visualization of the error of the value calculated and measured for a given point. If the model is deemed to be calibrated and validated (verified) it can be utilized to perform prognostic calculations as well as the simulations facilitating understanding of the process of migration of contaminants in underground water. The author of a model can always recalibrate it, e.g. when new input data appear (Michalczyk, 2018).

Credibility of the modeling results obtained through application of models for migration of contaminants in underground water is primarily dependent on input data. Associating these data with the Geographic Information System results in the visual calibration of the model in an appropriate scale, and, in combination with the GIS layer data, results of measurements and distribution of soil hydraulic properties, enables reducing errors and credible reproduction of errors in an appropriate scale (Guwrin, Serafin, 2008).

4. Discussion

The studies related to application of modeling of migration of contaminants for the purpose of assessing adverse influence of a waste landfill on underground waters are being realized on the grounds of specialized computer programs. To calculate water flow and transfer of mass in her paper Złotoszewska-Niedziałek (2007) utilized FEMWATER program which solves three-dimensional modified Richards' equations for transfer of mass by applying Lagrange-Euler's hybrid finite element method. The performed calculations confirmed that in the case of a landfill foundation constructed from permeable materials below which layers with weak permeability properties are located, the primary factor influencing the time in which contaminants reach underground waters is thickness of the layers with weak permeability. Increase in thickness of a layer with weak permeability by 0.30 m results in increasing the time required by contaminants to reach underground waters by 50 to 100%. The numerical model for flow of underground waters utilizing GMS/FEMWATER package, developed by Wiencław and Koda (2005), is a model for which the basis consist of a three-dimensional (3D) solution. The goal of the constructed model was to determine the influence of a vertical screen on the time in which leachates reach the level of underground waters table. The results of numerical modeling for the landfill indicated insulation properties of a vertical bentonite screen and projected that the leachates will infiltrate the groundwater level near the landfill after 40 years. In his studies on the influence of waste landfills on a water-soil environment Ukpaka (2016) constructed a mathematical model based on equations of continuity expressing the principle of conservation of water within a porouse medium. The results of work enabled formulating conclusions concerning rate and scope of dissemination of contaminants and constitute a significant material for management of the landfill.

The simulation calculations for a two-dimensional flat model for a point, momentary and constant source of contaminants were performed in the works of Chalfen (2012). The results of computer simulation of dissemination of chemical contaminants in underground waters are to a significant degree dependent on the values of longitudinal dispersion and transverse dispersion introduced into a mathematical model. Areas under the greatest threat of incorrect calculations during constant or momentary source of injection of contaminants are located on the threshold of contamination front. The kinetic approach to simulating processes of migration of contaminants in underground water near the landfill in Piemont has been utilized by Role et al. (2008). It is significant for utilizing the mathematical model for determining the boundaries of the contaminated area surrounding source of injection. Pliwińska and Kaleta (2016) utilized the MODFLOW software to simulate transfer of contaminants in the aquifer using the example of cadmium, the prevalence of which in the industry results in an increased risk of subjecting people to its carcinogenic influence. The object of modeling consisted of an area with surface of approx. 2 km^2. A three-dimensional model of the area has been developed on the basis the discretization mesh, maps were developed for dissemination of cadmium in the layers consisting of loose sands and tertiary silts. The results of modeling indicated that despite the fact that the initial concentration of cadmium was significantly reduced the risk of contaminating water courses still exists after lapse of the simulation period of 5 years. The three-dimensional kinetic model for projecting transfer of contaminants in underground water near waste landfill Kin REDOX has been used in studies of Kleczkowski and Różkowski (2002) who integrated their equations with ModFlow program. The utilized kinetic reaction equations have been used to simulate movement of leachates along with the aquifer. Such approach enabled estimation of changes over time and space in reaction to contamination and identification of active areas of contaminants' dissolution. The results of modeling, compared with a field survey, indicated the capability of the model for simulating direction and range of migration of highly concentrated contaminants. The studies of landfill management risks in case of contaminating underground water with landfill leachates performed by Bocanger et al. (2001) in Mar de Plata indicated that application of modeling enables optimization of anthropogenic influence of objects on various elements of natural environment in advance. The produced results indicated presence of contamination reaching further than 100 m from the place where waste is neutralized. Application of the models for transfer of contaminants in underground water is particularly desirable in case of industrial facilities which may adversely influence soil and water environment. The studies for the municipal waste landfill utilizing the one-dimensional model of transfer performed by Chawl and Singh (2014) indicated correctness of the adopted assumptions and confirmed directions for migration of contaminants and their concentration. In order to assess influence of a closed waste landfill on underground water environment Ujile and Owhor (2018) performed modeling utilizing the flat model for flow of underground waters. This model is utilized when hydro-geological schematization leads to emergence of the aquifers divided with continuous or non-continuous layers of low permeability. The resulting area of migration of contaminants was confirmed by laboratory tests of water quality within the environment which indicated presence of lead, cadmium and iron within the maximum distance from the source of contamination – the landfill.

Current models for transfer of contaminants in underground water located in vicinity of municipal waste landfills are constructed by utilizing commercially available computer software. The constructed migration model, calibrated and verified, reflects the actual process of migration of contaminants in underground waters with high accuracy. However, it must be considered that a model is always of authorial character. The responsibility for credibility of the model lies to the greatest extent with the author and the responsibility for results of modeling cannot be transferred to the computer software. Computer programs are solely tools used by the author of the model (Dąbrowski et al., 2010).

5. Conclusions

The studies concerning the phenomenon of mass transfer in an underground water stream in the area in the vicinity of a waste landfill performed through application of mathematical models are constructed on the basis of commonly available computer programs. The constructed models serve as tools for projecting transfer of leachate and assessment of influence of anthropogenic objects on environment. Furthermore, the goal of the model is determining probable directions for migration of anthropogenic contaminants and rate of emission. Authors of the utilized models confirm their effectiveness and draw particular attention to quality of input parameters derived from results of measurements. In order to be credible the contaminants' transfer models have to be calibrated and validated. Results of the model studies are most commonly utilized to assess risks in the field of waste landfill management in case of contamination of groundwaters resulting from leachates. Furthermore, using modeling also enables optimization of influence of anthropogenic objects on individual elements of natural environment in advance.

References

Anderson, M.P., Woessner, W.W. (1992). *Applied groundwater modeling: simulation flow and advective transport*. San Diego: Academic Press, Inc.

Bear, J., Cheng, A.H.-D. (2010). Modeling Groundwater Flow and Contaminant Transport. Series: *Theory and Applications of Transport in Porous Media, 23*.

Berkhoff, K. (2007). Groundwater vulnerability assessment to assist the measurement planning of the water framework directive – a practical approach with stakeholders. *Hydrology and Earth System Sciences Discussions, 4*, 1133-1151.

Bocanegra, E., Massone, H., Martínez, D., Civit, E., Farenga, M. (2001). Groundwater contamination: risk management and assessment for landfills in Mar del Plata, Argentina. *Environmental Geology, 40*(6), 732-741.

Borysiewicz, M., Kopka, P., Korycki, M., Kwiatkowski, T., Potempski, S., Prusiński, P., Wawrzyńczak--Szaban, A. (2019). Modele i programy obliczeniowe na potrzeby systemu wyznaczania ryzyka obszarowego. In: J. Połeć, B. Tępiński (eds.), *Metody i narzędzia wspomagające. Proces oceny ryzyka w zakładach przemysłowych*. Józefów: Wydawnictwo CNBIP-PIB.

Chalfen, M. (2012). An influence of measurement inaccuracy of dispersion coefficients on time-space pollutant distribution in groundwater. *Infrastructure and Ecology of Rural Areas, 3*, 167-179.

Chawla, A., Singh, S.K. (2014). Modeling of Contaminant Transport from Landfills. *International Journal of Engineering Science and Innovative Technology, 3*(5), 222-227.

Ciuła, J., Kozik, V., Generowicz, A., Gaska, K., Bak, A., Paździor, M., Barbusiński, K. (2020). Emission and Neutralization of Methane from a Municipal Landfill-Parametric Analysis. *Energies, 13*(23), 1-18.

Dąbrowski, S., Kapuściński, J., Nowicki, K., Przybyłek, J., Szczepański, A. (2011). *Metodyka modelowania matematycznego w badaniach i obliczeniach hydrogeologicznych – poradnik*. Warszawa: Ministerstwo Środowiska, WFOŚiGW.

Fetter, C.W. (1999). *Contaminant Hydrogeology*. New Jersey: Prentice-Hall, Inc. Upper Saddle River.

Gaska, K., Generowicz, A., Zimoch, I., Ciuła, J., Siedlarz, D. (2018). A GIS based graph oriented algorithmic model for poly-optimization of waste management system. *Architecture Civil Engineering Environment, 11*, 151-159.

Gurwin, J., Serafin, R. (2008). Budowa przestrzennych modeli koncepcyjnych GWZP w systemach GIS zintegrowanych z Modflow. *Biuletyn Państwowego Instytutu Geologicznego, 431*, 49-60.

Guymon, G.L. (1994). *Unsaturated zone hydrology*. New Jersey: Prentice Hall.

Hill, M.C., Tiedeman, C.R. (2007). *Effective Groundwater Model Calibration With Analysis of Data, Sensitivities, Predictions, and Uncertainty*. New Jersey: John Wiley and Sons Inc., Hoboken.

Holzbecher, E., Sorek, S. (2005). *Numerical models of groundwater flow and transport. Encyclopaedia of hydrological sciences*. Anderson, M.G., McDonnell, J.J., New York: John Wiley&Sons.

Kania, J., Witczak S., Duliński M., Kapusta M., Różański K., Jackowicz-Korczyński, M., Kinzelbach, W. (1986). *Groundwater Modeling: An Introduction with Sample Programs in BASIC*. Amsterdam: Elsevier Science Publishers B.V.

Kleczkowski, A., Różkowski, A. (eds.). (2002). *Słownik hydrogeologiczny*. Warszawa: Wydawnictwo TRIO.

Leah R., Johnson, M., Connor L., Fox, W., Levene, C. (2001). Dispersal of polychlorinated biphenyls from a closed landfill site. *Land Contamination & Reclamation, 9*(1), 1-8.

Małecki, J., Nawalany, M., Witczak, S., Gruszczyński, T. (2006). *Wyznaczanie parametrów migracji zanieczyszczeń w ośrodku porowatym dla potrzeb badań hydrogeologicznych i ochrony środowiska. Poradnik metodyczny*. Warszawa: Uniwersytet Warszawski, Wydział Geologii.

Michalak, J., Nawalany, M., Sadurski, A. (eds.). (2011). *Schematyzacja warunków hydrogeologicznych na potrzeby numerycznego modelowania przepływu w JCWPd*. Warszawa: Państwowy Instytut Geologiczny – Państwowy Instytut Badawczy.

Michalczyk, T., Bar-Michalczyk, D., Kania, J., Żurek, A.J. (2018). Niestacjonarny model migracji azotanów w wybranej zlewni na obszarze GZPW 326 w rejonie na północ od Częstochowy. *Biuletyn Państwowego Instytutu Geologicznego, 471*, 109-116.

Piwińska, D., Kaleta, J. (2016). Model rozprzestrzeniania kadmu w warstwie wodonośnej z wykorzystaniem programu Processing Modflow. *Czasopismo Inżynierii Lądowej, Środowiska i Architektury, 63*(3), 351-364.

Przydatek, G. (2019). Multi-indicator analysis of the influence of old municipal landfill sites on the aquatic environment: case study. *Environ Monitoring and Assessment, 191*, article number: 773.

Rolle, M., Clement, T.P., Seth, R., Di Molfetta, A. (2008). A kinetic approach for simulating redox-controlled fringe and core biodegradation processes in groundwater: model development and application to a landfill site in Piedmont, Italy. *Hydrological Processes, 22*, 4905-4921.

Rosik-Dulewska, C. (2015). *Podstawy gospodarki odpadami*. Warszawa: Wydawnictwo Naukowe PWN.

Rouholahnejad, E., Sadrnejad, S.A. (2009). *Numerical simulation of leachate transport into the groundwater at landfill sites*, 18th World IMACS / MODSIM Congress, Cairns, Australia.

Rybicki, S.M., Wiewiórska, I. (2017). Minimizing the concentration of aluminum in tap water after coagulation. *Przemysł Chemiczny, 96*(8), 1719-1722.

Saghravani, S.R, Mustapha, S. (2011). Prediction of contamination migration in an unconfined aquifer with visual MODFLOW: a case study. *World Applied Sciences Journal, 14*(7), 1102-1106.

Shaker, A., Yeung, W. (2010). *Trail road landfill site monitoring using multi-temporal landsat satellte data*. Toronto, Ontario: Department of civil engineering, Ryerson University.

Śliwka, I., Zuber, A. (2005). Kalibracja i walidacja modelu przepływu i migracji oraz korekty modelu koncepcyjnego GZWP-451 z wykorzystaniem znaczników. *Współczesne Problemy Hydrogeologii, 12*, 317-322.

Spitz, K., Moreno, J. (1996). *A practical guide to groundwater and solute transport modeling*. New York – Chichester – Brisbane – Toronto – Singapore: John Wiley & Sons, Inc.

Starek, A. (2001). Polichlorowane bifenyle – toksykologia – ryzyko zdrowotne. *Roczniki Państwowego Zakładu Higieny, 52*(4), 187-201.

Ujile A.A., Owhor, S.N. (2018). Developing mass transfer model for predicting concentration profiles of contaminants in groundwater resource. *Chemical and Process Engineering Research, 57*, 67-81.

Ukpaka, C.P. (2016). Empirical model approach for the evaluation of pH and conductivity on pollutant diffusion in soil environment. *Chemistry International, 2*(4), 267-278.

Van Geer, F.C., Stroet, B.M., Yangxiao, Z. (1991). Using Kalman filtering to improve and quantify the uncertainty of Numerical Groundwater Simulations. 1. The role of system noise and its calibration. *Water Resour Res Journal, 27*(8), 1987-1994.

Wang H.F., Anderson, M. (1982). *Introduction to groundwater modeling. Finite difference and finite element methods*. San Diego: Academic Press Inc.

Wiencław, E., Koda, E. (2005). Model przepływu wód podziemnych i transportu zanieczyszczeń dla składowiska z bentonitową przesłoną pionową. *Przegląd Geologiczny, 53*(9), 770-775.

Wysowska, E., Kicińska, A., Nikiel, G. (2020). Analysis of Natural Vulnerability of Groundwater Intakes to Migration of Surface Pollutants Based on a Selected Part of the Dunajec River Basin. *Polish Journal of Environmental Studies, 29*, 2925-2934.

Xi, B., Li, J., Wang, Y., Deng, Ch., Li, X., Ma, Y., Xiong, Y. (2021). Risk Assessment of Groundwater Contamination Sites. In: *Investigation and Assessment Technology for Typical Groundwater--contaminated Sites and Application Cases*. Singapore: Springer.

Zdechlik, R., Tomaszewska, B., Dendys, M., Pająk, L. (2015). A review of applications for numerical modeling of environmental processes in geothermal systems. *Przegląd Geologiczny, 63*, 1150-1154.

Złotoszewska-Niedziałek, H. (2007). Warunki migracji zanieczyszczeń w podłożu składowiska „Lipiny Stare”. *Architectura, 6*(3), 25-34.

Zuber, A., Różański, K., Ciężkowski W. (eds.). (2007). *Metody znacznikowe w badaniach hydrogeologicznych. Poradnik metodyczny*. Wrocław: Oficyna Wydawnicza Politechniki Wrocławskiej.