Original Article: Investigation of Network Models as a Numerical Method for Solving Groundwater Equations

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ABSTRACT

Network methods are one of the most widely used groundwater modeling tools that have become widespread and popular over the last two decades. In this research, with a new approach to network methods, these methods are introduced as a numerical model to simulate the movement of groundwater. With the development of this network model, a non-systematic model has been proposed to solve the flow in an arbitrary network. Although many of these problems occur on the surface of the earth, these pollutants enter groundwater after penetrating the earth. After joining the groundwater, these pollutants are transferred by moving groundwater and reach rivers, lakes and wells. On the other hand, the limited groundwater has made the groundwater increasingly important as a source of human drinking water. One of the first steps required to estimate the behavior of groundwater is to find a mathematical model that the application of these models in turn requires the collection of information. By using experimental systems, the cause of errors caused by human error or human ignorance can be greatly reduced and eliminated. For this reason, many studies have been done on issues such as maintenance of a wellhead, design of drinking water supply systems, estimation of movement and transfer of pollutants in the aquifer, etc., and mathematical models for these problems have been presented.

Introduction

Flow simulation within porous media has attracted the attention of many researchers over the past three decades (1).

Various applications of this simulation can be seen in branches such as water engineering, environmental engineering, petroleum engineering and groundwater hydrology (2). Groundwater pumped from underground structures is the main source of many water source systems. The amount of water output of a spring is considered as the output of the groundwater system can be greatly affected by the amount of pumping that is done from the same area. Water can be injected into wells drilled for storage, and groundwater levels can

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be raised using the same technique. These issues are among the issues that can have an impact on groundwater management.

In fact, in groundwater management system, quality and quantity issues cannot be considered as a separate issue. In many parts of the world, due to excessive groundwater abstraction, the quality of this water is constantly declining, which has caused the attention of consumers and producers to this issue. The deterioration of groundwater quality can be due to increased salinity of water or increased concentration of ions such as nitrate. As mentioned, the first step in estimating groundwater behavior is to obtain a mathematical model. According to the Darcy law and the establishment of mass conservation, it can be shown that the equation governing groundwater in stable conditions is the Laplace equation. Therefore, by obtaining the physical properties of the desired aquifer by using the experiment and understanding the boundary conditions governing that aquifer, a complete mathematical model governing the desired problem can be obtained. Unfortunately, since the physical properties of the problems in nature are not homogeneous and the boundaries of the studied problems are geometrically irregular, analytical solution of these problems is impossible. To solve this problem, researchers have been using numerical and laboratory methods for years. All numerical methods for solving the Laplace equation first break down the scope of the problem in the sense that they either divide it into multiple nodes or into multiple elements, and then, using mathematical methods, algebraic relations between they find different nodes or elements.

In other words, after parsing the scope of the problem, they turn the Laplace equation into a system of linear equations. One of the most widely used fields in the study of porous media is the Pore Network Model (PNM) method (3).

In this method, the cavities in the porous medium are simulated as a network of cavities that are connected to each other by connecting ducts. This method has become very popular over the past few decades and in recent years due to the development of computational systems as well as advances in the production of high-quality images of porous media has increased its acceptance and application by researchers. In this research, with a completely new approach and different from what has been presented so far about the PNM method, the equation of groundwater in saturated state is solved using the PNM method. In this research, instead of solving the flow equations in a porous medium, a network equation of pipes is solved. Since the relationship between the head of two points and the amount of current flowing between those two points in idle current is linear, the equation governing quiet current within a network of tubes can be written as a linear system of equations and unknowns. By solving this device, he obtained the approximate answer of the groundwater equations. The purpose of this study can be summarized as follows:

- How to construct a coefficient matrix using the PNM method for the first, second and third type boundary conditions?
- The effect of factors such as heterogeneity and heterogeneity of porous medium on the matrix obtained by PNM method.
- Solving groundwater equations using PNM method in different slopes with smooth or curved boundaries, in steady and non-steady state, despite the source of injection and harvesting and comparing the results obtained with finite difference methods and finite elements.

Analog models

Allegorical models are models that model the phenomenon under study with another phenomenon that is more understandable and easier. Since the law governing the groundwater equation is similar to the laws governing phenomena such as heat transfer, electricity, etc., the above-mentioned phenomena can be studied instead of studying the movement of groundwater. As mentioned, the physical properties of the system under study are one of the influential factors in presenting a mathematical model. Physical properties such as permeability, dispersivity, and electrical conductivity of a porous medium depend on the texture and structure of the solid part of the medium. One of the methods used to understand and show these dependencies is the study of a set of cavities called the cavity network (4).

Pore Network Models (PNMs)

Grid models are models in which the porous medium is a set of spheres and cubes that are connected by a network of tubes. In these networks, which are usually regular, the spheres and cubes represent the cavities and the network of pipes represents the ducts between these cavities.

The increasing acceptability of the network model can be attributed to a variety of phenomena such as wettability, multiphase flow dynamics, hysteresis, single-phase or multiphase mass transfer, and dispersion that can be studied with this model (5). Studies by Blunt et al. on lattice models have led them to the conclusion that the geometry of a complex cavity can be applied to the model in such a way that it can be used as a predictive model. After Fatt introduced the first two-dimensional model of a capillary network (6), network models were studied by other researchers. Koplic examined a network of communication channels and cavities, both of which were variable in size, and compared the results with the effective medium theory method, and concluded that the results obtained from the network method were effective. Medium theory differs by up to five percent (7).

In another study, he used a network model with circular cross-section ducts to study two-phase motion (8). Dias and Payatakes considered the communication channels between the cavities as a convergent divergent path that was sinusoidal. This path was assumed by considering the motion of the fluid between the spheres representing the grains of the porous medium (9). Using photo micrographic methods and pore size, Marios and Ioannis hypothesized the flow path to be compatible with the porosity of the porous medium.

They assumed the cavities to be a rectangular cube connected in six directions to a flow path with a rectangular cross section. The size of cavities and communication ducts was also obtained from the Weibull distribution function (10). Steele and Nieber concluded by increasing the number of networks from 9 × 9× 9 to 19 × 19 × 19 for a network model with an even distribution of holes that the answers would not change much. (11). Thauvin and Mohanty also examined non-Darcy flow in a network consisting of cylindrical ducts and spherical cavities and concluded that increasing the number of divisions in the results would not have a significant effect. To study the electrical resistance and capillary pressure, man and Jing considered different shapes for communication ducts and introduced the best cross section for predicting grain boundary laboratory results (12).

In recent years, two-dimensional microtomagraphy (such as CT and MRI to obtain a porous network has made it possible) (13); cavities and their connecting ducts by Acharya et al. spheres of different sizes and junctions were considered as incomplete cones.

They considered the equation of cavities as follows with radius of curvature r and power n (14). In this research, ninety-nine different networks were studied and each of these networks was analyzed for seven different values of n and line diagrams of both curvature and cavity were obtained. They concluded that the porosity permeability diagrams using the Carman-Kozeny equation and the lattice method are very well matched, and for more complex problems the lattice method with different values of n can be used.

Mazaheri *et al*. used a two-dimensional network of cavities of equal size but different diameters of throat to obtain the velocity distribution within the cavities, and finally obtained a good agreement between the results obtained by numerical and laboratory methods. To obtain the relationships between capillary pressure, saturation percentage, and permeability of biphasic motion, Joekar and colleagues studied two different models, the first consisting only of connecting ducts and the second consisting of ducts as well as cavities. They concluded that a model consisting of communication channels alone was not capable of modeling hysteresis. Based on the fact that the relationship between interfacial area and saturation percentage depends on hypotheses about how water is trapped, they performed the two trapping assumptions tight and loose trapping, and concluded that the loose trapping assumption for estimating the Pc-Sw curve -α is closer to reality (15).

In a study by Raoof and Hassanizadeh, they connected nodes in three-dimensional space to twenty-six other nodes by increasing node connectivity (16).

In a study by Nsir et al. to study the motion of DNAPL, a model with spherical cavities and cylindrical ducts was used. The values obtained for changing the inlet pressure in terms of time and time of arrival of the water front at a point in the network were very consistent with the experiments (17). Joekar et al. showed that in addition to the coefficient of shape, the cross-sectional shape will also have a significant effect on the inlet pressure and the radius of curvature. They also obtained very good results for the S-P and S-α relations by comparing the distributions for different cross-sections and different shape coefficients by comparing them with laboratory results (18). Jiang and his colleagues used the statistical data obtained from three-dimensional photographs of porous rock to construct PNMs.

Using this information, an appropriate number of nodes and ducts were generated and then the nodes were randomly distributed in the modeled domain. Due to the strongest dependence obtained from the statistical information, the nodes were connected to the relevant channels and the obtained network was used as an introduction of porous rock. Using this model, they predicted the properties of flow and porous medium with very high accuracy (19).

Nogues *et al*. used lattice models to study the precipitation and dissolution of carbonate in a porous medium (20). Mousavi and Bryant also investigated two-phase flow despite solidification and cementation factors. Using a lattice model instead of an environment consisting of dense spheres, they studied the stokes flow in that environment, and the results were in complete agreement with the results of the finite element method with very small elements (21). Kim and Lindquist also used this method to study and simulate chemical reactions in porous media.

Viscous fluid models

The motion of a viscous fluid between two plates that are very close to each other, assuming that the convective acceleration is equal to zero, using the Navier-Stokes equation will be as follows (22):

$$\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)=\rho\frac{\partial u}{\partial t}$$

Which can be written as standard $\frac{\partial u}{\partial t}=\alpha\nabla^2 u$

.

This equation is also the equation governing the movement of two-dimensional groundwater. Using this similarity, Hele-Shaw modeled the movement of groundwater around boundaries of various shapes using two almost contiguous planes (23). In the 60s and 70s, many researchers used the viscous fluid model to study scaling, seepage and drainage, the infiltration of saline water into fresh water, the effect of water injection and pumping in the groundwater aquifer, and so on. (24). Using the viscous fluid model (25). Yen and Hise also modeled the movement of water within a heterogeneous porous medium by varying the distance between two plates, and concluded that as long as the movement of groundwater follows Darcy's law and the Reynolds number between the two plates is in the Stokes range, the viscous fluid model is valid. In a study by Collins et al., the Hele-Shaw model was used to determine saline and freshwater flow in the Long Island area of New York City, and the researchers concluded that the response of saline water flow to hydrological changes in the region is slow. (26). Mizamura and Kaneda used the Hele – Shaw model to understand the effect of downstream boundary conditions on trapezoidal aquifers whose upstream end is vertical and downstream end is sloping, and obtained different values for the hydraulic gradient for different downstream slope angles. Other researchers have used the Hele-shaw model to investigate the phenomenon of two-layer static fingering instability or the absence of a permanent response to the movement of less viscous layers within more viscous layers.

Boundary element method

The numerical methods mentioned in the previous pages all required the decomposition of the whole domain, meaning that unknown values were obtained at points that belonged to the domain, while it is not always necessary to decompose the entire domain. There are other numerical methods called boundary methods that instead of obtaining unknown values over the whole range. These values are calculated only at the points belonging to the boundary. The advantage of these methods is that the system of equations is smaller and as a result, the volume of calculations is reduced and also the memory required by the computer is reduced. Another advantage of boundary methods is the networking of the desired domain. Because the networking points are all on the borders, the number of required points is less than the previous methods and as a result, it will be easier to produce a domain segmentation network.

However, the most important advantage of boundary methods should be sought in solving problems in which boundaries move, such as the movement of the free surface of water or the motion of the interface between two fluids. In domain parsing problems, when the boundary position changes with time, the distribution network must be adjusted over time, whereas in boundary methods this problem does not exist. The main problem of boundary methods is the inability to use these methods to solve all existing problems.

To solve problems with boundary methods, one must know the answer to the main problem, such as the general answer or the basic answer (Green function). In general, these solutions are only available for linear problems with constant coefficients, and this greatly limits the application of boundary methods. There are several boundary methods such as the fundamental solution method or the Trefftz method or the analytical element method (27). element (28) is one of them. To solve the Poisson equation using the left-hand boundary element method, the equation with the operator $\mathcal{L}$ is shown:

$$\mathrm{L}(u) = f(x)$$

Using Green's theorem, we can write:

$$\int_{\Omega} \{u\mathrm{L}^*(v) - v\mathrm{L}^*(u)\} dX = \int_{\Gamma} \{uB^*(v) - vB(u)\} dX$$

Where Ω is the total amplitude and ***Γ*** boundary L * of the additive operator and B and B * are equal to:

$$\mathrm{L}^*(v) = \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}$$

$$B(u) = \frac{\partial u}{\partial x}\hat{n}_x + \frac{\partial u}{\partial y}\hat{n}_y$$

$$B^*(v) = \frac{\partial v}{\partial x}\hat{n}_x + \frac{\partial v}{\partial y}\hat{n}_y$$

As mentioned, the main problem in solving equations using the boundary element method is to know the base answer or Green's function. The basic answer or green function for the operator $\mathcal{L}$ is obtained by solving the following equation:

$$\mathrm{L}\left(G\left(X - X'\right)\right) = \delta\left(X - X'\right)$$

And since the additive operator of the Laplace equation is the same as the operator itself:

$$\mathrm{L}^*\left(G\left(X - X'\right)\right) = \delta\left(X - X'\right)$$

By placing G instead of v in equation we will have:

$$\int_{\Omega} \left\{u\mathrm{L}^*\left(G\left(X - X'\right)\right) - G\left(X - X'\right) f(x)\right\} dx =$$

$$\int_{\Gamma} \left\{uB^*\left(G\left(X - X'\right)\right) - G\left(X - X'\right) B(u)\right\} dx \rightarrow$$

$$\int_{\Omega}\{u\delta(X-X')-G(X-X')f(x)\}dx=$$
$$\int_{\Gamma}\{uB^{*}(G(X-X'))-G(X-X')B(u)\}dx\rightarrow$$

$$\int_{\Omega}\{u\delta(X-X')\}dx=$$
$$\int_{\Gamma}\{uB^{*}(G(X-X'))-G(X-X')B(u)\}dx+\int_{\Omega}G(X-X')f(x)dx$$

Using the property of the Dirac delta function, $\int_{\Omega}u\delta(X-X')dX$ the value will be equal to:

$$\begin{cases} u(X') & X\in\Omega \\ 0 & X\notin\Omega \\ \frac{1}{2}u(X') & X\in\Gamma \end{cases}$$

To solve the Laplace equation, we will have:

$$\int_{\Omega}u\delta(X-X')dX=\int_{\Gamma}\{uB^{*}(G(X-X'))-G(X-X')B(u)\}dX$$

$$\alpha(X')u(X')=\int_{\Gamma}\left\{u(X)\frac{\partial G(X-X')}{\partial n_x}-G(X-X')\frac{\partial u(X)}{\partial n_x}\right\}dX$$

The method of approximation of the solution of the problem using a set of basic functions and unknown values is the same as the finite element method, with the difference that this approximation is done only for points on the boundary and as a result the number of equations obtained will be less. To do this, node i is placed equal to the nodes on the border each time, which means that the Dirac delta function is applied to the same node:

$$\frac{1}{2}u_i=\int_{\Gamma}\left\{\left(\sum_{j=1}^{n}u_j\Psi_j\right)\frac{\partial G(X,X_i)}{\partial n_x}-G(X,X_i)\frac{\partial\left(\sum_{j=1}^{n}u_j\Psi_j\right)}{\partial n_x}\right\}dX$$

After doing this, the following device will be obtained for each node belonging to the problem boundary:

$$[k]\{u\}-[G]\left\{\frac{\partial u}{\partial n_x}\right\}=0$$

where in:

$$K_{ij}=\int_{\Gamma}\left\{\Psi_j\frac{\partial G(X,X_i)}{\partial n_x}dX\right\}-\frac{\delta_{ij}}{2}$$

$$G_{ij}=\int_{\Gamma}\left\{G(X,X_i)\frac{\partial\Psi_j}{\partial n_x}\right\}dX$$

To solve the system of the above equations, it should be noted that for each node i of the two values {u} and $\left\{\frac{\partial u}{\partial n_x}\right\}$ only one is unknown and the other is known due to boundary conditions. Therefore, a device of n equation and n unknown will be obtained. Boundary element method due to no need to adjust the grid in problems where the boundaries are moving, such as obtaining a free water level in a porous medium motion of saline water with fresh water. Also, the motion of the fluid inside the heterogeneous porous medium has been used. Other applications of this method include groundwater simulation and saline water interference.

Differential quadrature method

In this method, like the finite difference method, derivatives are replaced by the difference of the values of the function, except that the partial derivatives of the function are expressed at a point in a certain direction, based on the linear weight of the values of the function in all or some neighborhoods of that point. This method arises from the idea of a quadratic integral.

If we want to use the above method to replace the derivative with a difference of the values of the function at different points:

$$\left.\frac{\partial u}{\partial x}\right|_{x_i} = \sum_{k-1}^{N} w_{i,k} f\left(x_k, y\right)$$

$$\left.\frac{\partial u}{\partial y}\right|_{y_j} = \sum_{k-1}^{M} w_{j,k} f\left(x, y_k\right)$$

The following formula can also be used for higher derivatives:

$$\left.\frac{\partial^n u}{\partial x^n}\right|_{x_i} = \sum_{k-1}^{N} w^{n}{}_{i,k} f\left(x_k, y\right)$$

$$\left.\frac{\partial^n u}{\partial y^n}\right|_{y_j} = \sum_{k-1}^{M} w^{n}{}_{j,k} f\left(x, y_k\right)$$

The weight function can be calculated based on various formulas proposed by researchers (Iserles, 2009). The advantage of the mentioned method is that since the derivative is calculated at a point based on a set of adjacent points, a larger network can be drawn to solve a problem with special accuracy by increasing the neighboring points in the derivative calculation.

Spectral methods

When we use methods such as finite difference, finite volume, and finite element methods to solve partial differential equations, the matrices obtained from these methods are sparse, meaning that most of the matrices in these matrices are zero. Therefore, to reverse these matrices, techniques can be used that greatly reduce the computational volume. The basic idea of spectral methods is that from the beginning, instead of producing a large matrix with most of its elements being zero, it produces a small matrix from the beginning with non-zero elements. The main advantage of this laboratory method over other laboratory methods is that it is easier to implement changes in aquifer characteristics in the laboratory model. For example, to simulate the change in hydraulic coefficient of an aquifer, it is only necessary to replace the relevant tubes in the experimental model with other tubes that simulate the changed characteristics of the aquifer.

This is while in physical methods the whole soil of the desired area should be removed and then replaced with suitable soil. In addition to the difficulty of execution, this also causes errors. One of these errors is when to replace the middle parts of the porous medium, the upper parts must first be removed and then dumped again on the replaced middle part. Due to re-casting, the properties of the top layer will definitely change. These tests, like all other tests, are not error-free. The following are some sources of errors:

1. The length of the pipes used in the construction of the network is not the same.
2. Inequality of plastic parts that connect plastic crossroads to pipes.
3. Error in sealing the laboratory device.
4. The presence of air bubbles inside the network and its ventilation, which can last up to several hours.
5. Impossibility of keeping the head fixed in both input and output power supplies.
6. Temperature changes during the test and as a result change the viscosity of the fluid.

Conclusion

The use of network models has grown significantly over the past decade. These models are widely used in the fields of petroleum engineering and the environment. The application of the network model in recent years is not limited to such things as two-phase current calculations or permeability calculations. The purpose of this study was to use the network model as a numerical method to solve the groundwater equation in saturated state, which means that the problem is divided into different nodes using the network model and instead of solving the equation. The partial differential governing the problem, the governing equation governing the network model was solved. The use of network models to simulate flow within a porous medium has grown significantly over the past decade, and many researchers have studied these networks using different pipes and cavities. However, none of these studies has been used to investigate the PNM method as a numerical tool for solving groundwater problems. The innovation of this research is in a new approach to PNM methods and introducing them as a numerical method and replacing them with conventional numerical methods such as finite difference and finite elements.

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