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Groundwater flow and contaminant transport models – a short review

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ABSTRACT

Over the last century, the impact of wide varieties of human activities on groundwater has grown intensely in many ways. As a consequence, groundwater quality and quantity are getting deteriorated with each passing year. Groundwater has become an essential commodity and is the most threatened resource nowadays due to its overexploitation by rapidly growing urbanization and industrialization. Many researchers, all around the globe, are taking initiatives to protect this important resource. A thorough study on some of the important contributions (theoretical and experimental) for the 50 years (i.e., 1950–2000) that laid the foundation for 21st-century researchers in the field of groundwater flow and contaminant transport modeling are discussed in this review. Based on the study, issues that remain unclear or unaddressed are listed out to simplify the future research guidelines and/or changes to advance technology for a better understanding and more wide-ranging analysis of the subject matter.

Keywords: Aquifer parameters; Groundwater contamination; Groundwater flow theory; Transport parameters; Transport theory

1. Introduction

Groundwater development dates back to ancient times and is considered an essential source of water for humans and environmental uses due to its good quality, occurrence, and its relatively low cost of development [1]. With the advance of the 21st-century, there has been a remarkable rise in demand for potable water due to the rising population, expansion of irrigation systems, and industrialization. Globally, regions with a sustainable balance of groundwater are declining every day because of the lack of permanent surface water supplies. The main processes resulting in this decline are quantity (overdrafts and groundwater depletion) and quality (man-made impacts: salinization, an increase of agrochemicals or groundwater pollution, etc.) [2]. Groundwater once contaminated, remains for quite a long time, or even decades, in unhealthy conditions. Thus, groundwater-related problems are an immense problem that has drawn the attention of social activists and scientists worldwide [3,4].

The study of groundwater flow and the transport of contaminants has become a primary concern of researchers all around the world. In the last few decades, the exponential growth of groundwater modeling was seen due to the availability of powerful computers, user-friendly modeling software, and Geographic Information System (GIS). Large scale steady- and transient-state groundwater models have been built to analyze flow systems with a focus on generic and site-specific contamination. Thus, Darcy's law, first derived empirically in 1856, forms the basis for most efforts to describe groundwater flow and the study of contaminant transport involves several mechanisms (i.e., advection, dispersion, adsorption and ion exchange, decay, chemical reaction, and biological process). The conceptual definition and reviews of these processes have been presented by many researchers over the year [5–13], and are avoided

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here for brevity [5–13]. Predictions of contaminant movement can be made accurately and quantitatively only when we understand these processes. Thus, a proper understanding of groundwater flow and contaminant transport mechanisms are essential for; (a) prediction and prevention of groundwater contamination, (b) understand various hydrogeochemical processes occurring in the aquifer, (c) landfills site management, and (d) renovation of wastewater using soil. Numerous amount of work has been carried in the past and the results are so vast and scattered that it is necessary to make an inventory of such investigations. Despite this, many aspects of understanding and handling groundwater as a resource remain complicated, and, in many situations, sufficient knowledge remains elusive. Hence, an effort has been made to review articles roughly between the periods from 1950–2000 to compress the volume of this paper. Articles printed after 2000 were considered too highly focused to be incorporated and is beyond the scope of this paper. The suitability of various groundwater contamination models is discussed and reviewed in three different sections below.

2. Theory behind groundwater flow and contaminant transport phenomena

Groundwater contamination studies usually include; understanding of biological, chemical, and physical processes controlling the fate and transport of contaminants in the saturated and vadose zone and their mathematical representation to predict the contaminant movement, field and laboratory measurement of different aquifer parameters, development of sustainable models to remove or prevent contamination to the point necessary to efficiently protect the environment.

Except for Darcy's pioneering work (1856), most early experiments involving soil columns were conducted using lysimeters. A concise review of the theory, focusing on physical relevance within the context of groundwater flow analysis for contaminant transport studies has been presented in this literature [14–16]. Slichter [17] was the first scientist who reported the earliest discovery of dispersion phenomena through a soil column experiment using an electrolyte as a tracer. He demonstrated that it was practicable to measure the rate of flow of groundwater by using simple apparatus by conducting preliminary tests. Kohnke et al. [18] compiled an extensive bibliography and history of experimental work involving lysimeters. Early work is concerned mainly with the amount and quantity of percolate moving through the soil [19,20]. The early 20th-century saw the advent of soil columns studies on the chemical and solute movement in the pore water and the publication of dynamics of porous media flow and permeability studies in the 1940s [21–24]. Slichter's work was carried forward by Lapidus and Amundson [25]. They worked on experimental studies of the dispersion-equation solution for linear adsorption and concluded that the solutions obtained in their study converge to the solutions obtained from the equations when the nonlinear adsorption was considered, but dispersion was neglected. Reiniger and Bolt [26] presented a systematic review of applications for ion-exchange processes in soils. Mariño [27–29] proposed mathematical solutions for problems with dispersion and adsorption of porous medium flow solutions with varying contaminant input concentrations. Bear [30] also presented a methodology to measure dispersion. He conducted the one-dimensional experiment with a field of flow alternating in direction using a sand column. The sand column used for experimentation was initially diluted using a salt solution. De Josselin de Jong [31] in his study presented a test device which estimates longitudinal dispersion in granular deposits and showed that the longitudinal dispersion coefficient depends on the distance, which has been covered by the particle traveling at the mean velocity. Saffman [32] presented a theory of dispersion of porous media. He concluded that longitudinal dispersion towards the average flow can be written in terms of the effective dispersion depending on the average speed, the pore length, and the pore-radius that were demonstrated to be linked to permeability, molecular diffusivity and the time from the first instant. Scheidegger [33] presented the general form of the dispersion using Bear's hypothesis which states that only that part of each velocity component is of significance which is either parallel or normal to the direction of the mean flow. Via the classical dispersion equation of their laboratory experiments, these scientists noted variations between experimental findings and theoretical modeling findings. Scheidegger [34] attempted the presumption of computational errors due to finite distance boundary conditions, which proved unsatisfactory. Goodknight and Fatt [35], and Coats and Smith [36] attempted to explain these observed theoretical and experimental differences with the presence of dead-end pores. Deans [37] demonstrated a qualitative analysis of the three parameters mathematical model to accurately predict longitudinal dispersion for one-dimensional flow in porous media over a wide range of Reynold's number. The general equations of the hydrodynamic dispersion of fluid in cartesian co-ordinates were presented by Bachmat and Bear [38] using a homogenous, isotropic, saturated, and steady-state porous medium. The tensorial form of equation was later derived using non-uniform flow for any coordinate system. Shamir and Harleman [39,40] presented the analytical and numerical solution of dispersion calculation in layered aquifers. Hoopes and Harleman [41] presented an analytical solution of dispersion in radial flow through a recharge well. Ogata [42] demonstrated the theory of dispersion in granular media based on the applicability of a heuristic expression similar to Fick's law. Thus, equations approximating dispersion in a two-fluid system (salt-fresh water) were also presented. Bredehoeft and Pinder [43] demonstrated the use of mass transport equation and equation of motion in a saturated isothermal groundwater system having no chemical reaction involved. Knight and Philip [44] obtained solution to the one-dimensional, nonlinear diffusion equations subject to instantaneous moisture injection over a finite-length domain by assuming a constant diffusivity value. Chang and Slattery [45] presented a new description for dispersion in their study by introducing a simplified one-dimensional model that is different than those used by previous workers [30,31,33]. They showed that their model contained two empirical parameters for dispersion calculation. In the case of the previously used model, there are three empirical parameters, two can be estimated using one-dimensional experiments while the third, transverse distribution, can be calculated using experiments with a two-dimensional concentration profile. Most of the experimental studies described above were carried out in unconsolidated porous media. The unconsolidated porous medium slowed down the dispersion process [46]. There have been very few studies in the case of consolidated porous media [47,48]. Klotz and Moser [49] demonstrated how dispersion increases with a decrease in porosity by conducting a series of tests. In the case of highly consolidated porous media, very limited experimentation has been carried out to our knowledge. Simpson [50] used a rather loosely consolidated medium, and consolidation, in this case, has little effect on dispersion phenomena. Readers should refer to Bear [51,52] for complete system development of the theory of groundwater flow and contaminant transport mechanisms. His work has been carried forward and presented by various other researchers [53–60].

3. Modeling groundwater flow and contaminant transport

The basic step of groundwater modeling is to develop a conceptual model. A conceptual model is designed to build a conceptual picture of the site geology and hydrology to build a basic understanding of the natural and anthropogenic processes occurring at the site, to see how fast the contaminant may travel, and to aid remediation processes design and forecast prediction. Numerical modeling is one of the world's leading methods for answering various questions raised by groundwater management. Several numbers of numerical models are available as a result of different concepts to investigate groundwater flow and contaminant transport mechanisms [61]. Although the following is only a literature review, it cannot include a thorough and systematic overview of this very complex subject; however, it can serve as a guide for a person to various references in the field of modeling of groundwater flow and contaminant transport.

Pinder and Gray [62] surveyed finite element methods (FEM) simulations in surface and subsurface hydrology. Konikow [63] in its survey did a review related to deterministic modeling of groundwater flow and transport processes and showed how isotopic analysis can be merged with quantitative groundwater model analysis. Bachmat et al. [64] surveyed 138 and 39 flow and mass transport models, respectively, related to the use of numerical techniques in groundwater management in 14 countries. Gillham and Cherry [7] reviewed the processes affecting contaminant transport in porous media. They stated, extensive research has been done over recent decades on the transport of contaminants in groundwater flow systems, this area of research is still in its early stages. There are still many laboratory and field experiments to be carried out to provide a basis for the development of mathematical principles from the knowledge of the transportation processes already occurring on the field scale. Some other studies that made use of numerical modeling techniques in various fields are presented ahead. Reddell and Sunada [65] solved the convection-dispersion equation using an implicit numerical technique (method of characteristics) with a tensor transformation and used the results to resolve the flow equation. The results showed that hydrodynamic dispersion in a homogeneous and isotropic media is a valid and reproducible phenomenon. Kimbler et al. [66] presented a study on freshwater storage in saline water by using finite difference methods (FDM) models. Marino [67] resulted in a convection-dispersion equation analytical solution using time-variable limits to non-interact, adsorb, and decay chemical types. Gupta and Singh [68] presented a study considering semi-infinite and homogenous soil profile and resulted in an analytical solution to the convection-dispersion equation for solute movement under exponential decrease. Heinrich and Chung-Chi [69] presented the solution for simple one-dimensional convection-dispersion equations using the FEM technique with second and third-order time and space accuracy, respectively. The theoretical framework to analyze and model physical solute transport in groundwater was provided by Reilly et al. [70]. Andersen et al. [71] used three numerical models (i.e., well field, regional, and cross-sectional model) and demonstrated the numerical modeling of saltwater intrusion in Florida. Hassanizadeh and Leijnse [72] presented brine transport modeling in porous media using the Newton-Rapson method. They resolved a set of two partial differential nonlinear coupled equations derived from the modified formulation of laws of Darcy and Fick. Finally, several numerical schemes involving sequential solving or iterative solution of nonlinear equations have been discussed. Weber and Miller [73] devised a mathematical model by conducted laboratory experiments with aquifer materials to remove hydrophobic pollutants using a dual resistance diffusion model. Naymik [74] and Abriola [10] reviewed most papers concerning the mathematical modeling of the subsurface mechanism for the transport of solutes in a systematic manner.

In the late 1950s, researchers such as Day and Luthin [75] began modeling of saturated-unsaturated groundwater flow in the field of agricultural engineering. One of the first scientists to develop transitional numerical models combining saturated and unsaturated zones was Rubin [76]. He presented a transient numerical model in which the flow-equation for two-dimensional, rectangular, unsaturated soil slabs were solved numerically using implicit FDM. Several other two-dimensional applications followed his paper to different unique problems [77]. He studied the composite soil moisture groundwater system and presented a transient moisture movement model. In response to a collapsed water table, the model simulates dual-dimensional flux and demonstrates the relation between the saturated and unsaturated parts of the subsurface layer. All these studies were for small regions with different boundary configurations. Only Jeppson [78] considered a wide-scale basin saturated-unsaturated flow system, but he restricted himself to a steady-state treatment. Verma and Brutsaert [79] presented an alternating explicit-implicit FDM to analyze a two-dimensional unconfined aquifer of a rectangular cross-section to determine the fall of the water table, the water content and the rate of outflow into an adjoining water body which fully penetrates the aquifer. Richard's equation was used to study the capillary or unsaturated flow above the water table. Freeze [80] established a transient, saturated, unsaturated three-dimensional flow model that regarded the whole of the sub-surface regime as a unit by solving the saturated-unsaturated flow equation within the unconfined and confined aquifers. Cooley [81] also developed an FDM for unsteady flow in saturated-unsaturated porous media. Several analytical, quasi-analytical and numerical solutions have been developed for the classical Richards unsaturated water flow equation and the Fickian convection-dispersion equation for solvent transport. Inventories and reviews on these approaches have been given by Kincaid et al. [82], Kincaid and Morrey [83], van der Heijde et al. [84], and Nielsen et al. [85]. More robust one- and multi-dimensional numerical solutions of unsaturated water flow equations for several different applications have been included in this literature [86–92]. The work of Huyakorn et al. [93], and Voss [94] demonstrated progress in one- and multi-dimensional number models of combined unsaturated water flow and solute transport, while Morel-Seytoux and Billica [95,96] discussed improving two-phase air/ or water models. Initial attempts to model one-dimensional non-interacting soil columns in the case of unsaturated flow in spatially variable soils (with uniform depth and soil properties) have been presented in this literature [97–101]. Mantoglou and Gelhar [102] found that the properties of different types of soil were not even over depth and that the lateral flow was important as well. Van Genuchten and Jury [103] in their survey reported advancement made in unsaturated flow and transport modeling. In his analysis, Clement et al. [104] found that the models developed by Freeze [80] and Cooley [81] were not robust because the saturated-unsaturated flow equation used in these models has numerical instability and convergence problems. Celia et al. [105] and Kirkland [106] stated that a highly nonlinear constituent relationship between the pressure head and moisture content in the Richards pressure-based numerical solution has a weak mass balance in the unsaturated area. For more work related to saturated-unsaturated groundwater flow models, readers should refer to this literature [10,51,52], and are avoided here for brevity.

In agricultural and industrial settings, the pollution of groundwater from various anthropogenic organic compounds has been a major concern [107–110]. Several organic pollutants in the subsurface ecosystem are permanent and are biodegradable under aerobic and/or anaerobic conditions [111,112]. Wilson et al. [113] were the first to research the biochemical fate of organic and inorganic components in groundwater. Srinivasan and Mercer [114] demonstrated the use of a one-dimensional FDM in porous media for biodegradation and sorption simulation. Sorek [115] solved the two-dimensional advection-dispersion equation using the Eulerian–Lagrangian scheme and deformed concentration and its partial differential operator into advection and dispersion terms. To solve the problems of advection, it was formally separated from the dispersion using the forward particle tracking technique. The hypothetical experiments were conducted by Widdowson et al. [116] and a non-linear equation model was developed to simulate organic carbon biodegradation by facultative porous bacteria using oxygen or nitrate-based respiration. Before the Widdowson study, all the previous studies conducted on aerobic microbial degradation used oxygen-based respiration only [117]. Several reviews have been published that discussed the physical, chemical, and biological conditions needed to promote the biodegradation of contaminants. The effect of physical interactions between site and contaminant such as mass transport [118] and sorption [119] was also given consideration. The need for optimal microbial growth was also extensively evaluated under different circumstances [120], and degradation pathways for petroleum hydrocarbons were identified in detail [121]. Suarez and Rifai [122] discussed how biodegradation is important to fuel and chlorinated solvent plumes and submitted an in-depth review of biodegradation rates from field and laboratory studies. This literature [122,123] includes relevant chemical and biodegradation characteristics of selected organic volatile compounds (VOCs), including oxygenated fuel additives. Aerobic biodegradation of vinyl chloride by naturally occurring microorganisms in groundwater was discussed by Davis and Carpenter [124]. Previous aerobic biodegradation studies of vinyl chloride have shown degradation using the addition of exogenous nutrient products such as methane [125,126]. Reviews of available field methods for bioremediation and biotreatment screening of contaminated sites have concluded that consideration of scale-dependent phenomena, such as mass transport and interfacial transfer mechanisms, is a prerequisite for success in the field [127–129]. The key work needed to promote progress in bioremediation was identified by Rittmann et al. [130], by means of quantifying the scale of microbial kinetics, sorption kinetics, biologically induced obstructer and colloidal transport. Sturman et al. [131] augmented much of the current research by providing a structure for evaluating the relevance of observation scale to a specific outcome or inference, thereby providing an integrated approach to the scale-up process.

Many investigators also studied the factors which contributed to the leaching of pesticides [132–135]. The mobility of pesticides has been identified for many years as an important element in assessing groundwater contamination potential [136–138] and resulted in the use of factors such as soil-water partition coefficient [139], the coefficient of octanol-water partition [140], and the distribution of pesticides or the coefficient of organic partitioning [141,142]. The soil's ability to degrade pesticide products depends largely on the physical and biological properties of soil, with two key factors being sorption and microbial degradation [143,144]. Efforts have been made by many researchers globally, to develop a simpler deterministic approach model that is useful for pesticide management. These models used the simplified representation of basic transport processes but resulted in a computer-efficient model that can be used without a significant amount of input data [145–148]. Other such models developed/or usable for pesticide fate assessment are Behavior Assessment Model (BAM) [149], Leaching Estimation and Chemistry Model (LEACHM) [150,151], Pesticide Root Zone Model (PRZM) [152], Seasonal Soil compartment model (SESOIL) [153].

The stochastic modeling approach also received considerable attention from researchers during that time. Gelhar [154] demonstrated stochastic analysis of phreatic aquifer subject to variable time and stream stage fluctuations. The model was found based on the dupuit approximation when a single parameter was properly modified to the behaviour of a distributed linear model. Freeze [155] presented a one-dimensional, stable, stochastic analysis of groundwater flow between two specified heads and the transient consolidation of clay in non-uniform, homogenous media. The main output achieved was the hydraulic head's mean and standard deviation. Dagan [156,157] demonstrated steady-state stochastic modeling of groundwater flow to analyze the effect of the conditional probability of the input variables upon the dependent variables. The hydraulic conductivity, transmissivity head, specific discharge, and solute concentration have been regarded as random variables subjected to uncertainty. The conclusion was that the application of the modeling techniques to field problems was already feasible. Two studies using stochastic methods have investigated the impact of spatial variation on unsaturated flow. Andersson and Shapiro [158] used perturbation and Monte Carlo approaches to study the one-dimensional steady-state flow. A three-dimensional stochastic approach and a linearized disturbances system were used by Yeh et al. [159–162] to examine the effects of spatial variation on steady, unsaturated flow. The results provided new insights into the anisotropy of a large, steady, unsaturated flow. Duffy and Gelhar [163] demonstrated stationary stochastic processes in the analysis of temporal variations of environmental tracers in groundwater using spectral analysis and linear filter theory. The model was used for three transport models, namely, (a) a lumped parameter model, (b) convection (advective) transport in a curvilinear flow field, and (c) convection-dispersive transport in a uniform flow field. Mantoglou and Gelhar [164] used a three-dimensional stochastic approach to develop a general methodology for deriving large-scale models of transient unsaturated flow in spatially varying soil structures and providing analytically tractable relationships to depend on the different soil properties and flow characteristics of the effective large-scale parameters. Thus, the stochastic modeling approach despite its expansion and considerable attention from researchers worldwide hasn't yet become a regular tool in hydrological modeling.

One of the most remarkable advances in the scientific community that has drawn the attention of researchers worldwide is Artificial Intelligence (AI) upsurge. Since machine learning dominated mainstream research in the 1990s, AI technology has grown rapidly and many AI methodologies are being developed and improved. AI technologies mainly refer to the artificial neural network (ANN), the support vector machine (SVM), the genetic algorithm (GA), the fuzzy logic (FL), etc. Haykin and Lippmann [165] have identified ANN as a massively simultaneous distributed data processing system with certain features similar to human brain neural biological networks. For multiple pumping purposes, Rogers and Dowla [166] used an ANN to simulate a regulatory index with multiple plumes at a polluted site. Rogers et al. [167] used three ANNs to calculate a regulatory index, remedial index, and expense index for simultaneous pumping at a Superfund site. Many other authors used ANN and discussed its history, architecture, and functioning [168–173]. Holland [174] introduced GA as a search-based heuristic optimization method modeled on the natural biological evolutionary process. Goldberg [175] talked about the GA mechanism and strength in the resolution of non-linear optimization problems and GA was applied quite robustly by Montana and Davis [176] for ANN training. Numerous application and transport simulations of the artificial neural network and genetic algorithms have been presented in the study of Morshed and Kaluarachchi [177]. AI technology can thus be useful in solving many different inverse environmental modeling and operational research issues.

The main problem associated with modeling groundwater flow and contaminant transport was the ambiguity linked with the values of aquifer parameters to be used for model calibration and simulation. One such parameter is hydraulic conductivity since its distribution is of utmost importance as it relates to fundamental mechanics of flow when combined with hydraulic gradient and porosity. In most cases, laboratory tests are used to determine these values which cannot determine the fate and movement of the contaminants in the field as there exists no definite correlation with the measured field values. Also, contaminant transport is a natural phenomenon that involves various physical, chemical, and biological activities and is difficult to incorporate all in one model. Therefore, the validity of the assumptions made during contaminant transport modeling is of paramount importance to reduce the complexities.

3.1. Existing groundwater flow and contaminant transport models limitations

Numerous researchers tried their best to figure out ways to tackle most of the problems associated with groundwater flow and contaminant transport taking into account most of the processes responsible for it. Still, some areas of concern have been left untouched. Some of them are listed below (these are only based on the time span taken for this study):

- Groundwater hydrologists are aware that results from the laboratory are conditioned by the scale of samples or process development; it is clear that obtained data constitute an indication of transport parameters under real conditions in the field.
- The general media should have been subject to the principle of dispersion. For homogeneous media, the results are valid, but numerical values in the domain have changed.
- Very few models were available to address on-site bioremediation.
- Most of the existing analytical and numerical models were Peclet number limited. The solution will oscillate when the absolute value of the Peclet number is taken high.

4. Studies on model parameters

In numerical modeling (Table 1), the accuracy of the prediction depends upon the consistency of calculated model parameters. The accuracy and effectiveness of a model depend on numerical and boundary approximations used for the spatial gradient and time derivative evaluation. Various inverse methods and algorithms have been developed by researchers for parameter identification. Inverse problems may become ill-posed if the number of model parameters is large [178].

Table 1
Numerical modeling scheme [11]

Conceptualization		Model development		Calibration	
Analysis of data	• Flow system • Volumes of water balance • Reactance of system • Area of uncertainty	Model selection	1D, 2D or 3D finite difference, finite element, and immission frequency	Matching flow history	Steady state Transient state Adjustment of variables
			Distribution model		
		Boundary condition	Type 1, 2, 3 or other initial conditions		
		Discretization of time and space			
		Transfer of data to model	Surfaces Input/output	Sensitivity analysis	Test each variable for dominance in flow or contaminant control

Chavent [179,180] investigated the problem of unique parameter identification using the steepest method of descent and conjugate gradient method in a distributed system. He stated, "The uniqueness problem in parameter identification is closely related to identifiability". Similar work was done by Chen et al. [181], McLaughlin [182], and Wilson et al. [183]. They all demonstrated the use of the Kalman filtering (KF) technique (first introduced by Kalman [184]) in parameter identification and concluded that the KF technique is a sequential data assimilation approach, which can be used to enumerate and decrease the uncertainty of groundwater flow and solute transport models by estimating joint probability distribution. Travis [185] did a review of various mathematical models used in the identification of adsorption between the soil solution and soil matrix. An Extended Kalman Filter (EKF) method was proposed by Eppsten and Dougherty [186] to simultaneously estimate transmissivity values and zonation patterns. When applied to the heterogeneous transmitting measurements, it showed three changes to traditional algorithms. First, more efficient approximations have been replaced for the costly EKF covariance updates. Secondly, a partial cluster algorithm has been used to evaluate and refinish the zoning structure of the distributed Parameter field. Third, a new method has been introduced for combining initial and second random fields with heterogeneous statistics. Though, Ensemble Kalman filtering (EnKF), proposed by Evensen [187] was seen to be the most promising solution concerning strong nonlinear physical systems and major problems. His algorithm was slightly modified by Burgers et al. [188] which was referred to as stochastic EnKF. Hoeksema and Kitanidis [189] demonstrated the inverse problem in two-dimensional groundwater modeling using Geostatistical Approach (i.e., maximum likelihood method (MLM) and kriging) to estimate transmissivity from head measurements. Similar work has been demonstrated by Kitanidis and Vornvoris [190]. For the estimation of aquifer parameters, Carrera and Neuman [191–193] proposed an MLM algorithm using synthetic and field data in steady- and transient-state conditions. Chin [194] presented an algorithm for the estimation of the dispersion coefficient using the Taylor hypothesis. Wagner and Gorelick [195] reported a statistical methodology in one-dimensional advective-dispersive systems for estimating transport parameters using the simulation results of FDM contaminant transport combined with nonlinear weighted least squares multiple-regression procedure. Jobson [196] established an algorithm for estimation of hydrodynamic dispersion and first-order rate coefficients using lagrangian based numerical routing scheme. Moltyaner and Champ [197] used the least square fitting and time moment method to simulate the transport of reactive solute using small-scale laboratory columns. The two methods used provided a good equivalent estimate of the dispersion and the flow rate. Taylor et al. [198] did a comparison of different field and laboratory test methods used for determining contaminants flow parameters. Yeh [199], and Yeh and Wang [200] did a review on most of the parameter identifications procedures in groundwater hydrology. Rowe et al. [201] talked about laboratory methods to determine diffusion and distribution coefficients using undisturbed clay soil. Goldberg [175] demonstrated the use of a Genetic algorithm (GA) in parameter identification and groundwater remediation. GA encodes the decision variables by forming codes for parameters using finite-length strings of alphabets of certain numbers. Schubert et al. [202] discussed different alternative methods suitable for stochastic dynamic prediction. Thus, a prior structure parameter is usually assumed in the aforementioned studies of the groundwater model parameter identification, with parameter values only identified within the structure. Sun [203,204] was the first one to propose a general formulation of inverse problems that incorporated parameter structure identification. His work was attempted later on by many researchers. They tried to provide details on the geological structure obtained through well logs and seismic measurements in the inverse problem solution [205,206]. The simulated annealing and tabu search techniques have been presented by Zheng and Wang [207] in the parameter identification. Tabu search was seen to perform extremely well. Sun et al. [208] later suggested a step by step regression approach for the identification of structural model and solved the problem of remedial design using hydraulic conductivity as a random area with a certain pattern. Fogel [209] presented most of the articles related to evolutionary global search algorithms (EGSA) based on machine learning. Some of the EGSAs include "ant colony" [210–212], "particle swarm" [213,214], and "honey bee" [215]. EGSAs are effective but like any other system, they have drawbacks and problems. The main issue is whether the solution found is a local, global maximum or minimum [216]. The following works are available to readers interested in learning more about EGSAs [217–222].

4.1. Identification of unresolved problems

The problem of groundwater flow and contaminant transport is an interdisciplinary one and is quite scattered. Based on the research conducted during the period of this paper (1990–2000), several sources and contaminants have been highlighted as potential priorities. Some of the areas that remained unresolved or untouched are listed below:

- Most of the models described in this study were based on laboratory simulations that can't predict the fate and movement of contaminants in the field reliably. The data sets provided here may provide groundwater practitioners with a preliminary guide to estimate values at different scales and to guide and verify scaling behavior theories.
- No reliable correlation was listed between field and laboratory values of various parameters (i.e., between hydrodynamic dispersivity and hydraulic conductivity) used as input to contaminant transport models.
- The stochastic modeling approaches despite its expansion during the period of study hasn't become a regular tool in hydrological modeling. More work can be carried out in this field.
- Most of the existing analytical and numerical models were Peclet number limited.
- Of the numerous microbiological issues not solved, it is proposed that special attention should be given to the following:
  - Monitoring of contamination control in the food chain, together with human disease surveillance, epidemiological investigations, and isolated events continue to be valuable sources of knowledge for evaluating the effectiveness of the existing food safety management processes and detecting potential hazards.
  - The extent of preserving and increasing the population of the degrading organisms.
  - Even if 90% of the contaminant is removed, say, it may not be possible to achieve a 99% removal, as there may be threshold values below which degradation rates are slow or even low.

5. Conclusion

A groundwater model provides a quantitative basis for field knowledge synthesis and hydrogeological cycle conceptualization. Groundwater models aim to recreate the past and predict the future. They will tell you when, and where, decades of chemical spills have occurred, the supply of groundwater to a city is due, or how best to clean up groundwater contamination at a site in years. Computer-based groundwater modeling became an important part of groundwater research. Sophisticated groundwater models for a desktop computer are easier accessed by the majority of the researcher society. The time needed to develop groundwater models is significantly limited throughout the years. Therefore, enormous development has occurred in the past few decades in the field of groundwater modeling.

An effort has been made through this study to build an inventory of experimental, analytical, and numerical modeling covering a large array of problems for the period 1950–2000 showing how a problem was solved, making it easier for a person to make use of them. Experimental, computational, and numerical modeling aimed at a wide variety of problems has seen tremendous growth over the last few decades. The progress made in the scientific understanding of various processes influencing the transport and persistence of pollutants in the subsurface environment shows the difficulty of the subsurface transport processes. Proper treatment of this complexity requires a growing specialization in groundwater studies. In reality, no person can hope to understand all of the phenomena in depth. For future developments in groundwater contamination problems, the need for interdisciplinary cooperation among investigators is essential. A further overall observation that investigators from different areas realize that controlled field tests are required to verify, develop, and calibrate modeling approaches for the future is necessary. Thus, the future looks bright because the research of such natural systems is an ongoing activity and continuous improvements are made as more understanding and information becomes available.

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