Assessment of Numerical Groundwater Models

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Abstract: The numerical hydrological models which interested in the simulation and prediction the hydrological behavior were built relied on physically-based equations. The groundwater flow model was considered one of these models. The groundwater flow and contaminants transport model were used to monitoring, controlling, managing groundwater resources and forecasting the effects of varying both the recharge and groundwater abstract ion. Moreover, it developed a preventive planning to maintain the quality of the groundwater, identify flow patterns, and predict the future aquifer hydrodynamics. The groundwater software codes were constructed based on numerical methods of advection-dominated transport and inverse problems. Major of these software codes was relied on the numerical solution based specially of finite difference method (FDM) and finite element method (FEM). In addition, some of various numerical methods were also applied such as Upstream weighting method and moving point method. The numerical models were based on groundwater governing equation that used Darcy's low in addition to water mass balance. The evaluation of these groundwater models was presented and demonstrated the merits and demerits of each one. The results referred that the MODFLOW software package was the most spread software that used to simulate the groundwater flow and contaminants transport.

Keywords: Groundwater models, contaminants, Numerical methods, FED, FEM.

1. Introduction

A comprehensive Knowledge about the hydrologic process and the influence of the point and non-point sources pollution on water quality was required for the management of the watersheds. The numerical model was used to simulate the water flow and contaminants transport and predict the changes in the environment and water resources. These models included assumptions pertaining to several issues such as spatial variability, dimensionality, and the interaction between the flow and transport processes.

There were two classes that would be accepted to solve the groundwater flow equation, which were Finite Difference methods (FDM) and Finite Element methods (FEM) methods. Each of them contained a variety of subclasses and implementation alternatives. The two classes needed to divide the area of interest to subdivisions by grid into smaller subareas (cells or elements) which associated with nodes (the points at the centers of peripheries of the subareas). FDM is easy to understanding and programming, keyed to a relatively simple and rectangular grid which also eases data entry tasks. FEM required more sophisticated mathematics, and its solution was more accurate. Moreover, the FEM has a great flexibility for the FE grid, which permitted a close spatial approximation of irregular boundaries of the aquifer. Therefore, the construction and identifying of the input data set is more complicated than for a regular FD grid. Therefore, most of the software that expressed the numerical model of groundwater flow based on one of the above classes.

In last decades, several numerical models were developed to simulate the groundwater flow and contaminants transport. Waterloo Hydrogeologic Inc. developed the Visual MODFLOW (Wang, at al. (2008), Ou et al. (2016), Kumar, et al. (2017), Mohammadzadeha, et al. (2017)). The US department of interior established FEFLOW, interactive groundwater (IGW) was presented by Michigan State University (Diersch, (1988), Kolditz, (1990), Nixdorf, et al., (2017)). The OpenGeoSys is a numerical simulations of thermo-hydro-mechanical-chemical (THMC) processes in porous and fractured media to give solutions of flow equations and it is based on finite element method (FEM) (Kolditz, et al. (2012), Rink, et al. (2013), Sachse et al. (2015), Schulz, et. al., (2017)). Mike-SHE was developed by Water and Environmental (DHI) (DHI, (1998), Liu, et al. (2007), Sandu and Virsta (2015)), HydroGeoSphere (HGS) Simulations was a product of Aquanty Inc. (Therrien et al., Schepper, et al. (2015), Kurtz, et al. (2017), Tang, et al. (2017), Ghasemizade, et al. (2017)). HYDRUS-2D was established by Jirka Šimůnek Department of Environmental Sciences University of California Riverside (Mekala and Nambi (2016, Iqbal, et al. (2016), Xu, et al. (2017), Turco, et al. (2017), Hua, et al. (2017)).

In this paper, some of the common used software models that were used to simulate the groundwater flow and contaminant transport were discussed to assess the advantages and disadvantage of each other and identify the process to use this software.

2. Numerical Models

The protection of water source against contamination, which was categorized to the protection of surface water sources (rivers, lakes and manmade reservoirs) and the groundwater protection, is very crucial. Therefore, groundwater modeling has become a very useful and established tool for studying problems of groundwater management, quality and also to predict the future behavior of an investigated aquifer system. Contaminant transport models also simulate the movement and chemical alteration of contaminants as they move through the subsurface.

2.1 MODFLOW Software

Visual MODFLOW is one of the important easy to use modeling environments that are used to simulate the three-dimensional groundwater flow and contaminant transport. It was based on finite difference method (FDM). It spread in America and Europe and had then an advantage that being tested well. The instructions that illustrate the usage of the software were clear and can only simulate the groundwater flow below the water table [Odling (1994)]. The MODFLOW software package includes MODFLOW, MODFLOWSURFACT, MODPATH, ZoneBudget, MT3Dxx/RT3D, MGO, and WinPEST with graphical user interface (GUI). Several input data were necessary to obtained the output results of the mudflow. In addition, the accurate results from MODFLOW were obtained by taking small grid cell to solve the finite difference problem. smaller cell size and time steps were required to get proper simulation to be able to display spatial and temporal changes in hydraulic head [Spitz, 1996]. The input data to the model included

1. Vertical and horizontal hydraulic conductivities,
2. A define contour map geological model on a grid,
3. Cell type arrays,
4. Storage coefficients to simulate transient state for each grid block in each layer,
5. The properties and location of the rivers, wells, drains, constant head areas.

The graphical user interface tools in addition to the menu of the software permits;

- Dimension the model and define the units,
- Assign the model properties and define the boundary conditions,
- Obtained the model results by running it with the inputs,
- Calibrate the model,
- Optimize both the well rates and location,
- Develop the output in 2D and 3D graphics.

The structure and fixed data format of MODFLOW was benefit to integrate it with Geographic Information systems (GIS) technology for the process of water resource management. GIS technology incorporated with

MODFLOW provided an easy handling visual interface and many countries relied on it for groundwater evaluation and management [Wang (2008), Karu, et. al., 2013]. Furthermore, MODFLW was utilized as calculation program due to its simple methods, its simple structure, and its ability to handle with separate package for resolving several special hydrogeologic problems [Tenbus and Fleck (1996)].

Visual MODFLOW is groundwater model that helped to analyze groundwater issues using FDM to solve the flow equations. Samantaray et.al. (2017), studied the suitability of the MODFLOW software under various hydro-geologic conditions. It revealed that the results of the software relied on both quality and quantity of the data that were collected from the field. Kumar, et. al. (2017) investigated the groundwater resources assessment through steady-state flow modelling in Bina River basin using MODFLOW. The MODFLOW code with GSM interface was used to numerically simulated the groundwater flow system of Bojnourd aquifer in Iran (Mohammadzadeha, et. al., 2017). Steady state condition calibration was performed for the period from Sep. 2009 to Sep. 2010 and after that, the model was calibrated from transient state for the period from Sep. 2007 to Sep. 2009. Different management scenarios were adopted to the model after obtaining the hydraulic properties of the aquifer and checking its validity. Ghouili, et. al., (2017), quantified the groundwater recharge of Takelsa multilayer aquifer. The groundwater flow model (MODFLOW) was calibrated during steady state condition to evaluate the groundwater resources. In addition, the hydraulic head distribution was simulated by integrating the recharge distribution with the MODFLOW. Increased the packages in MODFLOW with increase complexity results in better representing recharge and evapotranspiration processes [Doble, 2017]. Several methods were used to model recharge and evapotranspiration which vary from simple presentations groundwater flow models to complex fully coupled groundwater models or the model that coupled between the groundwater and surface water [Doble, 2017]. The MODFLOW model presents evapotranspiration as a simple, inflexible and depth dependent function with evapotranspiration (EVT) or segmented evapotranspiration (ETS) packages. Increasing number of modules in MODFLOW gave batter evapotranspiration and recharge process. The other model such as HydroGeoSphere, Mike-SHE, Hydrus, Waves, and PRAMS coupled with groundwater models gave detailed conceptualization but on the other hands they experienced from complexity and longer time consumed [Doble, 2017]. Enhancement of the computational efficiency and reduction of the noises for stream depletion analysis was provided using a new MODFLOW package (MODFLOW-SDA). With a new MODFLOW package, the results revealed that a reduction in the numerical noises was significant in addition, a twenty-fold speedup was achieved when applied a new package for a regional groundwater model in Nebraska. Moreover, a new package can be used as a component of optimization tool for groundwater management scenario analysis in case of involving large number of scenario runs [Ou, et. al., (2016)]. The MT3DMS which is a module in MODFLOW was used to simulate groundwater age distribution that was controlled by advection and dispersion in a steady state mode. In addition MT3DMS can be also used to simulate the heat transfer in case of small effects of buoyancy and viscosity change [Cao, et. al., (2016)].

RT3D is another module in MODFLOW which is three-dimensional solute reactive transport model that was used to solve the coupled partial differential equations that depict the transport of multiple and immobile contaminants or species in saturated groundwater systems. In addition, the groundwater management optimization was developed by coupling genetic algorithm with MODFLOW and with RT3D to improve the searching efficiency to get the optimal solution for groundwater management issues [Wu, et. al., (2015)]. A developed equivalent porous medium (EPM) flow model is developed using MODFLOW 2000 to synthesize hydrogeological data in addition to quantify the regional water budget for Madison and Minnelusa aquifers. The transient transport model MT3DMS was also used to simulate the spreading of a point source TCE contamination. The main goal of this work is to evaluate the suitability of EPM to be applicable for major contaminated sites in Karst area [Ghasemizadeh, et. al., (2015)]. In some works, water quality analysis simulation (WSAP) is incorporated with MODFLOW and the Modular 3-D Transport Model (MT3D) to evaluate the impact of a trans-basin water diversion project on the groundwater [JIA, et. al., (2015)]. Wang, et. al., (2014), investigated the effect of soil and water conservation measures on the levels and recharge of the groundwater which were observed in experiments on laboratory scale and using the MODFLOW to model these experiments. Zhang et. al., (2013), used MODFLOW to simulate the cones of depression in the shallow across the entire North China Plain (NCP) in the period from1996 to 2011.

2.2 Open-GeoSys (OGS)

In order to guarantee the isolation of the underground repository from contamination, a numerical prediction of the solute transport processes under coupled condition should be performers involving some important study such as thermal loading from high level waste, mechanical stability, and the chemistry of groundwater. In addition, the construction planning requires a multiple process coupled code to deal with the field data. With the great steps in computer technology, geoscientific problems can be analyzed. However, understanding the complicated coupled processes regarding to the available data from the field and use it in the numerical code is considered a major issue for scientists, which need interdisciplinary and interactive cooperation [Kolditz, 2012]. Therefore, numerical codes were accomplished by cooperating between the scientific departments in the university and the financing support organization.

The OpenGeoSys is one of the numerical simulations of thermohydro-mechanical-chemical (THMC) processes in porous and fractured media to give solutions of flow equations and it is based on finite element method (FEM). In addition, it used in the application fields of water resource management, hydro-geology, geothermal energy, waste deposition, and hydrology. A graphical user interface (GUI) is used to supply the numerical model with the geometrical structure model domain. In this model, sets of Geo and hydro objects were supplied the geographical information to the model.

OGS framework included multi-algorithms that were used to simulate hydrological, thermal, chemical, and mechanical processes. The simulation is performed along large number of Finite element related functionality with several numerical solvers. There are several issues were encountered in the OGS, the first one is the difficulty to present functionality to construct the model, and the second issue is non-supporting data visualization or modification. Finally, the simulation results can be verified using other software. In order to address the previous issues, OGS saved OGSdata explorer as GUI to help in visualizing and assessing input data and results in a 3D space. A 2D window can also view non-spatial information including time series data or borehole which was attached to 3D data sets. Data explorer in OGS can employ the basic data structures and file format using command line tool and can be interfaces with large number of files created by geo-scientific software products as Arc GIS, GMS, and Gocad or Petrel. The results can be exported to graphics format to be able to visualize the projects for introducing complex environmental data and simulation is easy to understand form [Kolditz, 2012].

The data explorer helps the user to see the interaction between the various data sets which must be consistence with each other to avoid the encountered problem. In addition, number of visualization options can be provided to support users for the evaluation process in order to be able to adjust the number of parameters of the data. Moreover, it offers various options to modify the input data to a certain degree, i.e. polylines can be connected in a user-defined sequence, geometric surface can be triangulated, and finally, data can be mapped or converted to other data sets using different algorithms. Also, it offers to modify the mesh elements, model materials, and subsets of existing domain can be evolved based on the new triangulated surfaces [Rink, 2013].

The Finite element meshes for the studied model can be developed from the geometric data and, also from the digital elevation models. The user can define the mesh density and degree of adaptive refinement towards the desired features. The results can be visualized with input and model data and the visualization helps for verifying the plausibility of simulation results. The user can compare between the observed and simulated parameters based on the correlations to input data sets. Fig. 1 illustrates the data visualization at various stages of constructing the model.

OGS didn't include a function or module to setup a 3D spatial structure with borehole data, therefore, the groundwater modeling system (GMS) with its modules introduced different interpolation methods to identify the stratigraphic scattered points according to borehole logs. The GMS 3D mesh exported into an ASCII file that was imported to OGS which converted to syntax of OGS mesh file [Sun, (2011)].

The calibration procedure of OGS can be accomplished using practical nonlinear least square inverse modeling software such as MODINV, MODFLOWP, parameter estimation system (PEST), and UCODE which can be integrated with other groundwater models [sun, (2011)]. Other software codes should integrate with the OGS code to adjust and prepare the input information that was required for hydrogeological study such as GMS and PEST and the embedded inverse method in PEST was adopted with OGS to improve the accuracy of the groundwater model through preparing control files, in addition to corresponding input and output files.

Wu, et. al., (2011), used OGS which was programmed in C++ to simulate the groundwater flow system and groundwater levels in Wadi Kafrein area in Jordon. Due to the proximity of the active plate boundary and the complexity of the geology, it is very difficult to apply the model to the steep and complex geological layers which was considered the challenge to use the numerical model. Encapsulating the mesh and physical data, the geometry, and the corresponding methods in different objects was considered the main concept of the OGS. The OGS code can be extended to use for complex applications using the object-oriented programming.

Schulz, et. al., (2017), calibrated non-steady state groundwater flow models for a large aquifer system using a new method which was applicable to a large-scale 3D numerical groundwater flow model using OGS. This work was very important because it tried to solve the calibration problems. These problems were, firstly, the hydraulic conductivity of the aquifer and the storage coefficient have to be calibrated simultaneously in case of transient state which leads to non-unique solutions for the agreement between the observed and simulated head. The previous problem was called as equifinality. Secondly, the ground head distribution as the initial condition and the ground recharge as flux rates for transient models were necessary required over the entire model period.

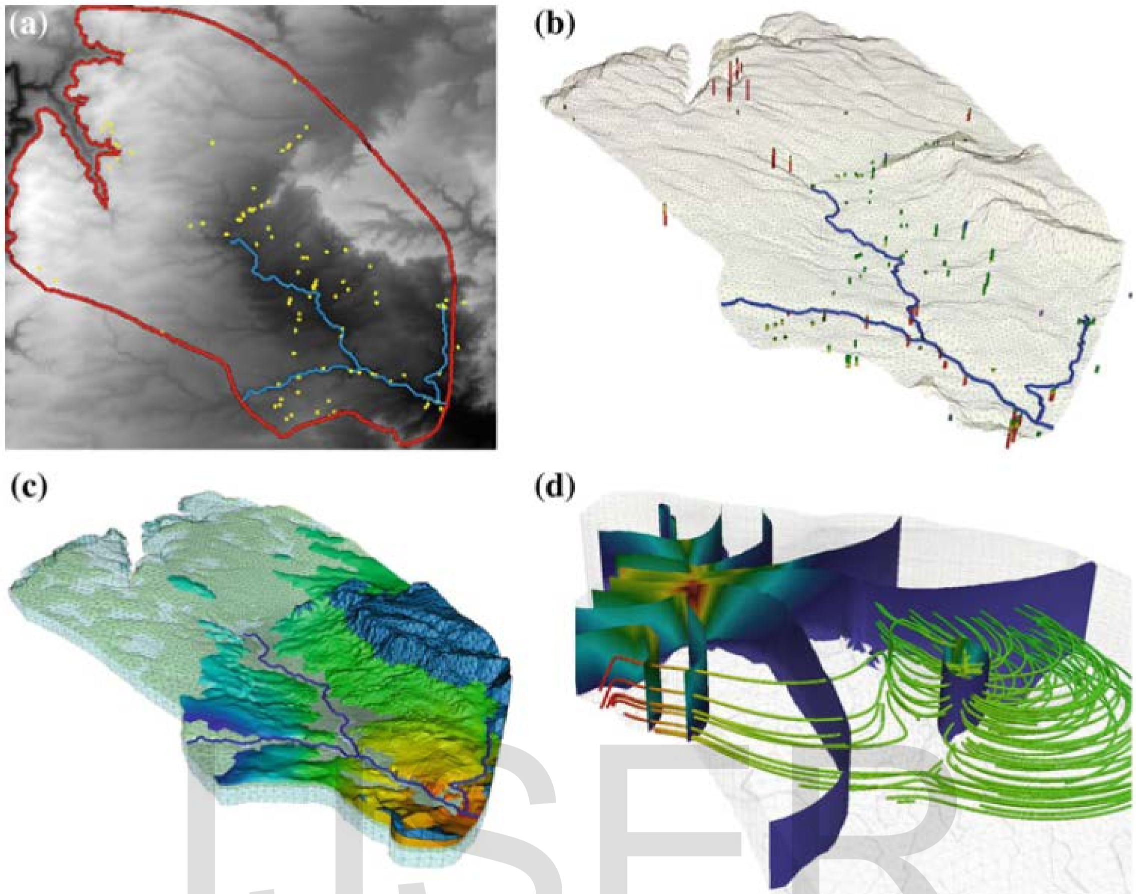

Fig. 1 Visualization of data sets at various stages of the constructing the model. a illustrate the data input process from geographic information systems (GIS). b GIS dta in 3D model. c Subsurface model with layers interpolated based on borehole data and explaining the data for each geological layer. d Representation of simulation results.

Peche, et. al., (2017) presented a new idea that focused on the coupling between the OGS and pipe ow simulator HUSTEM-EXTRAN using a bi-directional shared-memory based coupling and examined its validation of the coupling process. Nixdorf, et. al., (2017), estimated the depth of groundwater in Songhua River Basin using OGS. Sachse et. al., (2015) explained that in case of groundwater flow, the input files were constructed in a specific way to contain the necessary information that were required for the simulation. A new method was implemented to convert the corner point grids in static geological models to Finite Element (FE) meshes for dynamic models. In addition, the converting process permitted for consistency the transformation of spatially heterogenous material properties to avoid reparametrized the converted FE models. Moreover, the new approach provided the possibility to couple Eclipse simulator with OGS simulator to model induced geochemical impacts in the subsurface use (Wang, et. al., (2016). Selle, et. al., (2013), presented steady state groundwater model for Ammer catchment using OGS which allows to import data from geographic information system (GIS) or other software and to perform validation of input data, model setup, simulation and also the analysis of results in one framework. Beyer, et. al., (2016), developed and implemented numerical methods and required parameterizations to simulate the temperature effects on the groundwater aquifer using OGS.

2.3 FEFLOW

In the mid of eighties, the federal institute of geosiences (BGR) cooperated with the institute of Hydromechanics (University of Hannover) for developing a simulation for fractured rock. RockFlow was developed based on multi-dimensional finite element method to introduce the flow process in complicated geological structures. FEFLOW code was developed in the same time by Academy of science (Chemnitz) for density-dependent flow processes in porous media [Diersch, 1988, Kolditz, 1990]. The RockFlow and FEFLOW were implemented in FORTRAN code at that time. A finite element subsurface and transport system (FEFLOW) is a numerical groundwater model that can be used to simulate the groundwater and contaminant transport in 2D and 3D, transient and steady state and simulate flow, groundwater age, mass, and heat transport (FEFLOW® 7.1).

There is a great need for vast data, information and understanding of the aquifers so that an accurate, reliable and reliable groundwater model can be constructed. The first step of a groundwater model is the construction of a conceptual model which is often overlooked with its importance in producing an adequate model and is an opportunity for multiple interpretations and multiple discretizations. The conceptual model represents the mental representation of hydrogeology from the groundwater flow system. It considered the best way to represent how the aquifer works. Moreover, it represents a graphical representation of the complex natural aquifer system prior constructing the numerical model. Then, an increase in the effort to construct the conceptual model corresponds less effort for calibrating the numerical model. An error in the conceptual model leads to failure prediction results of the numerical model. The conceptual model can be sketched representing the following items;

- distribution of hydrogeologic layers,
- location of boundaries,
- 2D/3D representation of the domain,
- plan vs. cross-sections,
- tables of parameter input values,

In order to construct an efficient conceptual model the following requirements were prepared;

Groundwater flow directions, hydrologic boundaries (recharge, river, lakes, wetlands,...., etc), geologic formations, hydrologic parameters such as soil conductivity, storage, porosity,....), the well conditions (extraction or injection with the other valuable information about location, screen, depth, and rates), and finally the observations of groundwater head and groundwater quality.

The construction of groundwater model can be illustrated as the flowchart in Fig. 2. In Fig. 3, the numerical model of FEFLOW workflow is presented. The workflow of FEFLOW can be illustrated as follows;

- The first steps is preparing the input data such as importing shapes, wells, surfaces, XYZ points, cross-sections of the ground layer, and finally digitize new GIS layers.
- The second step is defining the super element mesh and 2D mesh.
- The third step is identifying slice elevations.
- The fourth step is assigning the property zones.
- The fifth step is defining the boundaries of the flow.
- Then, Run the simulation and analyze the results with checking the visualization results.

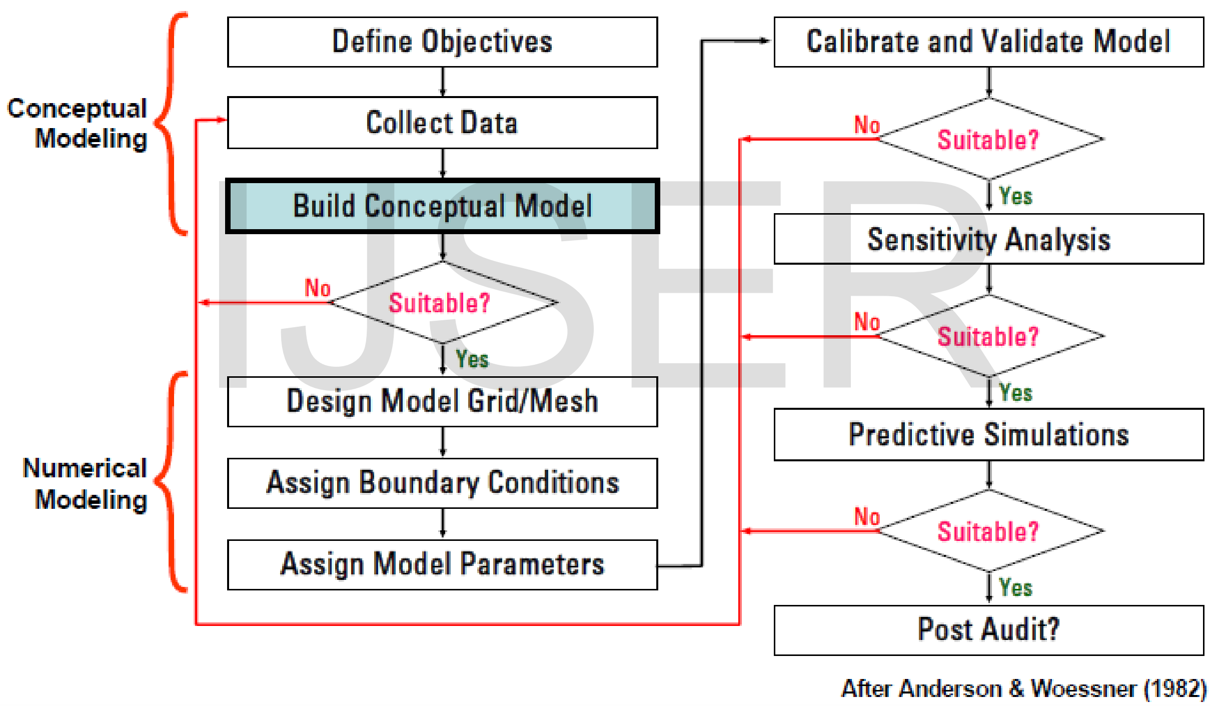

Fig. 2: groundwater model process (after Anderson & Woessner, 1982)

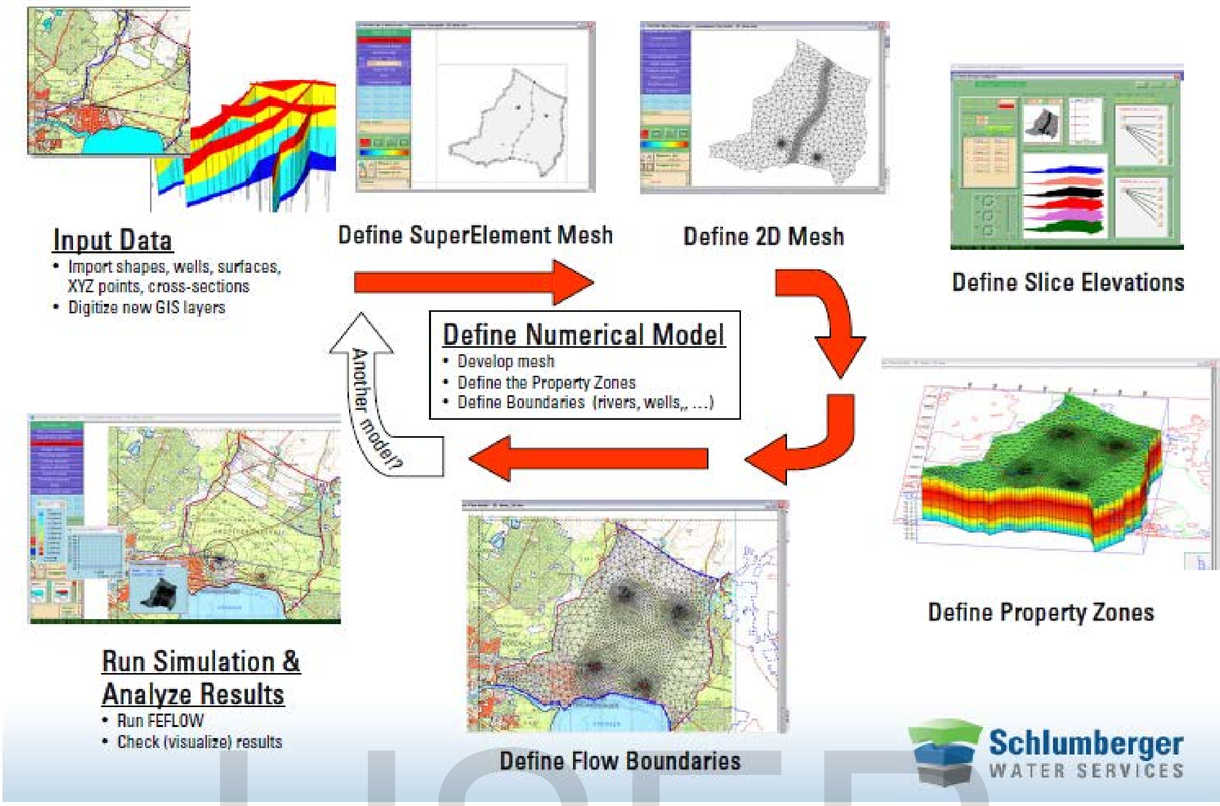

Fig. 3: The workflow of FEFLOW

Conceptual model is the base of the MODFLOW and FEFLOW code where, the designing of the grid or mesh for the studied model is the last step in modeling the problem. The advantages of using the conceptual model are as follows;

The boundary and model input of the conceptual model are independent on the numerical grid or mesh, it presents a freedom to design multiple conceptualizations of the studied site and the design is easy to modify after constructing, multiple grids or meshes with different sizes can be selected and choosing the appropriate one, convert the conceptual model with numerical grid to numerical model, the simulator can be changes based on the needs of the project, a new numerical model can be developed with a new grid if the old one is not appropriate, and finally, easily change the model after creating. Fig. 4 shows the workflow of FEFLOW and MODFLOW using the conceptual model and explain the requirement of each process and the visualization results.

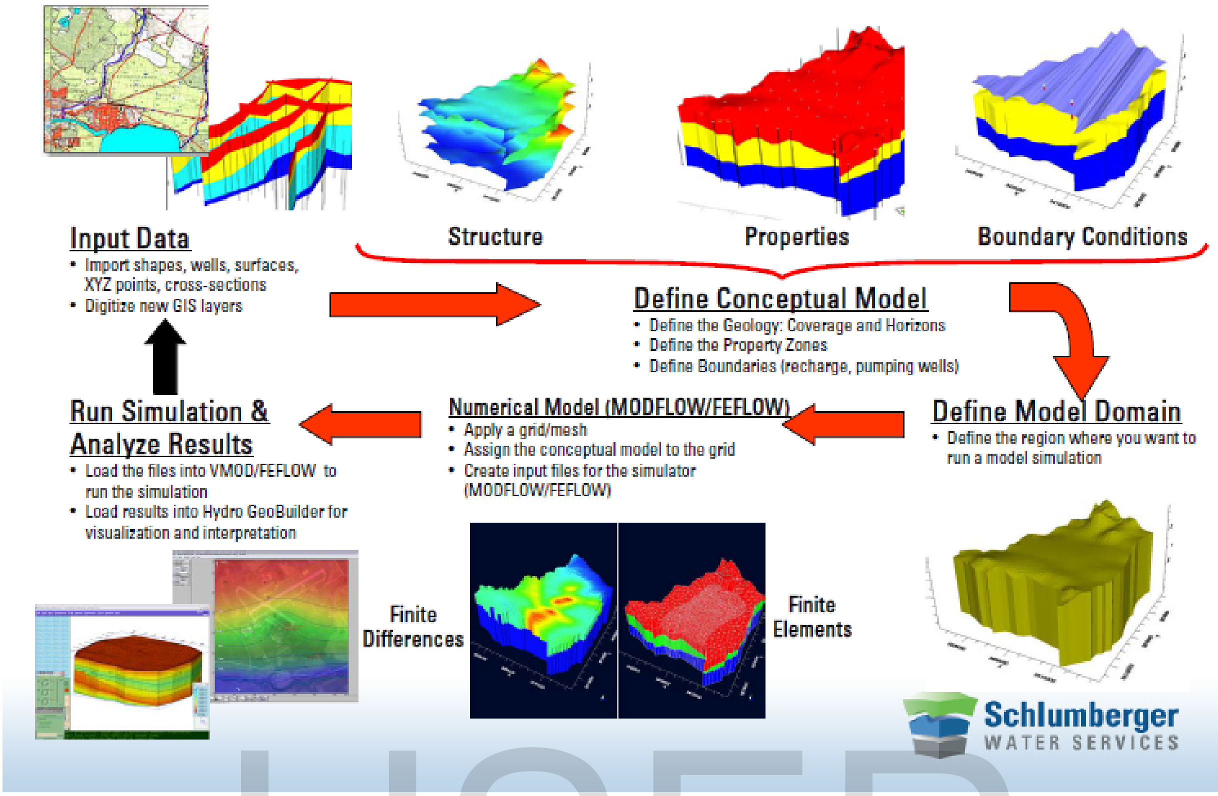

Fig. 4: FEFLOW and MODFLOW Codes based on the conceptual model.

Therefore, FEFLOW provides any easy tools to support the data before running process, the boundaries can be read from a map or from digitized on screen, the data was entered in files or in databases or entered manually. The FEFLOW support that data that should be seen at a certain stage. Every feature of FEFLOW was testing and benchmarking which were the important parts for any software codes. The results of FEFLOW can be illustrated through excellent planer, cross-sectional and 3D visualization featured. In the next section, some of literatures were utilized FEFLOW to investigate the contaminant transports to the groundwater.

Li et. al., (2017) established a comprehensive model to understand the impacts of water saving activities on regional hydrological processes. This model simulates the water balance in the Vadose zone, China, and the regional groundwater flow. It integrates the conceptual models in the Vadose zone with various landscape units, groundwater model flow (FEFLOW) under GIS (Li. Et. al., (2017)). Gerhard Rock, and Hans Kupfersberger (2017), presented a coupling between the SoilTemp and FEFLOW to simulate the effect of temperature emanated from different land use over 23 years period on the groundwater. Furthermore, the actual distance and temperature gradient between the ground level and heated basement were taken under consideration. FEFLOW was widely recognized comprehensive software package for subsurface flow that based on finite element which enhances the meshing capabilities with high flexibility degree in the modeling processes. In this software, rainfall and river losses were considered the input to the system and the model proposes an isotropic porous medium, heterogenous, and unconfined (Alvarez, et.al., (2016)). Alvarez et. al., (2016) mentioned also that FEFLOW was a more precise and sophisticated numerical groundwater model which depends on the precise of the input parameters. Zhang (2013), built a simple numerical model using FEFLOW to simulate the linearly decreasing discharge for transmissivity, and storage coefficients which were important hydrogeological parameters. Both of them were evaluated using linear decreasing discharge well curve. One of the most limits for FEFLOW was its complexity and time consumed.

2.4 Mike-SHE

MIKE SHE was originated in 1982 with the name of Système Hydrologique Européen (SHE) (DHI, 1998). Three organizations shared for developing MIKE SHE, the Danish Hydraulic Institute (DHI), the British Institute of Hydrology, and the French consulting company SOGREAH. Water resource managers are the main objective of MIKE SHE which was concerned with the rapidly changing that occurs in the landuse practices for agriculture and forestry. Due to the contamination of the surface and groundwater with fertilizers and pesticides that were associated in agriculture activities, in addition to contaminations from waste disposal sites, a new model was developed by DHI. The new MIKE SHE contained a water movement module in addition to the water quality modules. The upgrading of MIKE SHE was continued to develop an integrated surface and groundwater interaction model by merging MIKE SHE with Channel simulation component of MIKE 11(DHI, 1998) (the south Florida Water Management District (SFWMD) (Yan et. al., 1998, 1999). The MIKE SHE modeling system is used to simulate several water movement processes, including canopy and land surface interception after precipitation, evapotranspiration, overland and channel flow, saturated groundwater flow and finally, the major quality components. MIKE SHE grid network represented spatial distribution of the model parameters, inputs, and results with vertical layers of each grid.

MIKE SHE offers a truly integrated modeling of groundwater, surface water, recharge and evaporation to study water management, water movement, recharging and discharging groundwater process. In addition, it provides also the simulation of the pollutants transport that affects the quality of groundwater. The program is also characterized by the smooth integration of its tools in all processes related to the cycle of hydrology. It also includes a range of numerical methods to perform different hydrological process. It considered a conceptual, and model independent user interface with full water balance accounting in each hydrological processes. It is easy to combine between the hydrological processes and the numerical methods based on the available data.

Efficient uses of available multi-core resources can be accomplished due to the numerical engines in MIKE SHE are parallelized.

MIKE SHE contains 3D finite difference groundwater flow which enhances the ability to investigate the interaction between the surface and groundwater. A linear reservoir groundwater method is available for basin-wide water balance and management. Moreover, it includes a fully distributed rainfall-runoff modeling. It also includes fully dynamic random walk particle tracking to simulate the pollutant transport for source water protection and groundwater age analysis.

The MIKE SHE software includes threes packages such as MIKE SHE Studio for rainfall-runoff modeling and basin wide water balance and water management, MIKE SHE Enterprise for surface and groundwater modeling, including water quality, the third package is the MIKEHYDRO River-MIKE SHE Enterprise to ensure a dynamic, unlimited and fully integrated modeling to investigate the interaction between the surface and groundwater.

Mike-SHE was a numerical groundwater model flow that was derived from SHE model (Abbott et.al., 1986a, b). It integrates the whole land phase containing surface and subsurface water. Moreover, the spatial and temporal distribution of water resources can also be simulated. It was also considered complex model and comprehensive spatial and temporal data to drive it were required. In addition, it required also specification of many scale-dependent parameters (shu, et. al., 2012). The partial differential equations that describe the processes of overland, channel, saturated and unsaturated subsurface flows were solved using a finite difference approach (Qin, et.al., 2013). Usmanov, et. al., (2016), studied the hydrological balance of the Chirchik river basin in Uzbekistan using fully MIKE SHE model. The work of Usmanov aimed to study the hydrological processes in the basin territory. Moreover, the knowledge of surface and groundwater interaction and spatial variability of hydrological parameters was investigated. The input data parameters for MIKE SHE was independent in each grid, in addition, the spatial heterogenous of study basin can be illustrated detailly (Lie, et. al. 2016). Sandu and Varista, (2015), developed A MIKE-SHE model that helped the management decisions and the assessment of hydrological mitigation measures. The MIKE-SHE was efficient and widely used in many watershed studies, when the whole water cycle components couldn't be represented. The program flexibility came from the integration of different hydrological processes at different timescales. It covered all hydrological system on a catchment scale. Several processes constitute the hydrologic simulation such as evapotranspiration, overland and channel flow, unsaturated and saturated flow, channel/surface aquifer exchanges. The original MIKE-SHE module for channel flow didn't support hydraulic structure, which referred an issue for river flow simulation. Liu, et. al., (2007), explained that the MIKE-SHE was used to depict the hydrological cycle physical processes. In MIKE SHE model, overland flow is simulated by the solution of the diffusive wave approximation in two horizontal direction and the vertical flow in the unsaturated zones can be modelled using one-dimensional Richards equation. In the saturated zones the flow was modelled by three-dimensional Boussineqs equation. MIKE 11 is considered a river modeling system that built based on the dynamic wave formulation of Saint Venant equations. Coupling between MIKE-SKE and MIKE 11 used the bi-direction interaction between the watershed hydrological processes and the river hydrodynamics.

2.5 Hydrus

HYDRUS is a software package includes computational finite element models and was used to simulate water, heat, and solute movement in 2D and 3D variably saturated media. The model includes a parameter optimization algorithm for inverse estimation of a variety of soil hydraulic and/or solute transport parameters. It contains a computational computer program in addition to an interactive graphical user interface. This software is originated with the collaborative among U.S. Salinity Laboratory, the international groundwater Modeling center (IGWMC), the University of California Riverside, and PC-Progress, Inc. the program is updated completely with graphical interface in 2D and 3D. In 2011, Version 2 was released which was considered the great upgrading to HYDRUS. The last version of HYDRUS includes 2D-Lite, 2D-Standard, 3D-Lite, and 3D-Standard, with a new additional Level 3D-Professional.

3D professional was contained an option to identify various domain properties, and initial and boundary conditions. This option can be performed using geometric objects rather than FE-Mesh. Two solute transport modules were added (UNSATCHEM and Wetland) to evaluate both the major ions transport and simulating processes in natural or constructed wetlands. In 2012, Version 2.02 was released with three additional add-on Module (DualPerm, C-Ride, and HP2) that were used to simulate two dimensional variably-saturated water movement and solute transport in dual-permeability porous media, two dimensional colloid-facilitated solute transport, and couples Hydrus with the PHREEQC geochemical code [Parkhurst and Appelo, 1999] respectively.

Hydrus 2D was based on Galerkin finite element method and was coupled with implicit-splitting time methods to simulate the movement of the water. Despite, it was used for simulate the soil infiltration, but its applicability referred to good results to further types of porous media.

Figure 5 shows the new feature included in the last version of HYDRUS, Fig. 5A illustrates the general 3D geometries, discontinuous layers, Fig. 5B defines the properties on Geometrical objects, Fig. 5C explains how the FE-Mesh was generated, Fig. 5D shows the results in ISO-surfaces, Fig. 5E illustrates the intersections of the surfaces, and Finally, Fig. 5F explains how can the calculation performed in fast manner.

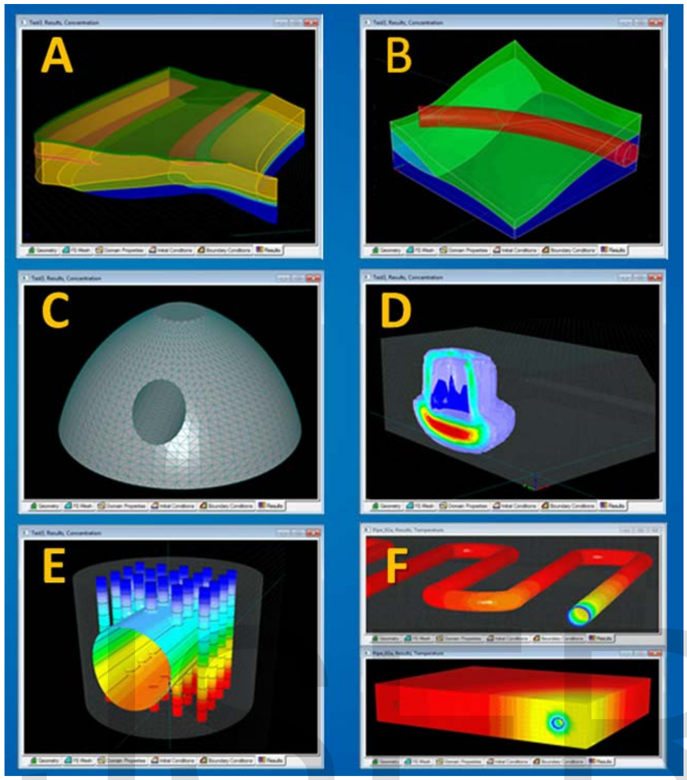

Fig. 5: The Features associated with HYDRUS software

Xu, et. al., (2017), recommended the utilization of Hydrus 2D model to simulate the movement of the water in a heterogenous soil. The performance evaluation of Hydrus 2D model can be done by observing the dynamic movement in differential loess soil under the constant water head and under conditions of different soil properties. They illustrated that the Hydrus 2D model was theoretically perfect in case of dual porosity and dual permeability model. Turco, et. al., (2017), proposed techniques/procedures to interpret the flow of the water through the construction system using the HYDRUS model. The assessment of the Hydrus 2D were accomplished by the analysis of the results of the experimental and mathematical procedures. The assessment was also done to interpret the hydraulic behavior of a lab-scale permeable pavement system. Moreover, the concrete blocks layer Ks, and a, n and Ks of the bedding layer were optimized with the HYDRUS-2D model from water fluxes and soil water contents measured during irrigation events. Mekala, et. al., (2016), used the Hydrus 2D to predict the water flow and transport of Nitrogen species in unsaturated subsurface system with varying irrigation and moisture conditions. Mekala carried out an experimental model to understand and predict the transport of Nitrogen compounds and avoid the uncertainty occurred in the field data due to the variation of climate and environment. In addition, the experimental model helped to simulate water fluxes in an unsaturated and unconfined aquifer system under certain conditions. Iqbal. et. al., (2016) presented a field experiments to investigate the transport of Nitrogen under furrow irrigation for maize fields in Pakistan. They also model the nitrogen transport using Hydrus 2D and estimate N losses from compost amended soils. They referred that the Hydrus 2D was useful to predict inorganic N losses in manure amended soil that irrigated with furrow irrigation. Hu, et. al., (2017), used Hydrus 2D/3D model to analyze four irrigation development scenarios in Aksu River Basin, china to study the effect of agriculture water saving on the dynamic of irrigation return flow in the basin.

2.6 HydroGeoSphere (HGS)

The hydrologic processes data and impacts of the point and nonpoint sources contamination on the groundwater quality were the requirement for the efficient management of the watersheds. Therefore, the requirement of the simulation model to present predictive capability in support of water resource assessment and environmental projects was very important. The simulation models tries to simplify the complexity of the hydrologic and transport processes and incorporate restrictive assumptions pertaining to spatial variability, dimensionality and interaction of various components of flow and transport processes.

Groundwater Simulations Group and Hydrogeologic, Inc. developed a fully integrated surface and subsurface flow and transport code to address the limitations of the current models. The subsurface module is based on FRAC3DVS developed as a collaborative between University of waterloo and Universitate Laval. In Addition, the surface flow module is based on MODHMS (surface Water Flow Package) and was developed as an enhancement of MODFLOW developed by U.S. Geological Survey. Therefore, a new software code was developed under the name of HydroGeo-Sphere, provides a rigorous simulation capability that combines fully-integrated hydrologic/water quality/subsurface flow and transport capabilities with a well-tested set of user interface tools.

HydroGeoSphere used the control volume finite element approach and provided a precision simulation capability that combined between the fully integrated hydrologic/water quality/subsurface flow and transport capabilities with a well-tested set of user interface tools. When the water flow was simulated in a fully-integrated mode in HydroGeoSphere, rainfall inputs was a part of overland, evaporation, infiltration, stream flow, recharge and discharge into surface water as streams and lakes and this was considered the unique feature of the HydroGeoSpher. Moreover, HydroGeoSphere allowed dissolved solutes exchanged between the surface and subsurface flow domain where solute concentrations were solved at each time in both regimes [hydrogeosphere manual (2010)].

Kurtz, et. al., (2017) combined the HydroGepSpher with ensemble Kalman filter-based data assimilation system to run in a cloud computing environment. Tang, et. al., (2017), explored the heterogeneity patterns using HydroGeoSphere. Data assimilation was utilized to investigate the ability of different riverbed hydraulic conductivity (K) patterns to reproduce the hydraulic heads, river aquifer exchange fluxes, and riverbed K. Schepper, et. al., (2015), mentioned that some of simulations were helped to identify the way to model tile-drained area using HydroGeoSpher code, which simulated water flow in tile-Drains in one dimensional. They provided also in this work an insight on design the large-scale models of complex tile-drainage system that in tradition method took more time. Ghasemizade, et. al., (2017), performed a temporal global sensitivity analysis and a temporal identifiability analysis of model parameters using the variance-based model of Sobol and dynamic identifiability method respectively. They used the HydroGeoSphere to simulate the water content, daily evaporation, and seepage at the lysimeter scale.

2.7 Software Features

Table 1 describes the comparison between the aforementioned software package that were used to simulate the groundwater flow and contaminants transport. This Table illustrates that if the code solves the resulting systems of equations itself or it uses another solver like graphical user interface (GUI). In addition, the table explains the method of solving the flow equation such as Finite Difference Method (FDM), Finite Element Method (FEM), or the Finite Volume (FV). The last column in the table explains some features of each program.

3. Statistical Analysis

Random samples were collected for the published articles that were addressed the usage of the numerical groundwater model to examine the spread program. The search was accomplished in the science direct website (Science Direct - Elsevier) which contains more journals that were focused in water quality, groundwater flow, and contaminant transport. Table 2 indicated that the Visual MODFLOW was the widely spread software that was used to simulate the groundwater flow and contaminant transport. The second grade was the FEFLOW which uses the finite element method to solve the flow equations. Some of groundwater software was not known and a few users used it for simulating the groundwater flow. Therefore, several software were removed from the comparison process.

Figure 6 illustrated the cumulative distribution function (CDF) that was calculated based on the mean and standard deviation of the number of publication of each numerical groundwater flow and contaminant transport model. The publication information was collected via science direct website to examine the spread of several numerical groundwater models. The mean and the standard deviation were estimated based on the number of publication of each software which indicated its importance and simplicity. The figure illustrated that a significant spread of MODFLOW model rather than the other model. Fig. 7 demonstrates the probability density function of different software that simulates the groundwater flow and contaminant transport. The figure explained that the widely use of the MODFLOW from the researchers all over the world.

Table 1. Software features

Code	Solver-GUI-Tool	FD-FE-FV	Short description
FEFLOW	Solver, GUI	FE	3D flow, Solute and heat transport
MODFLOW	Solver	FV	3D flow
MODFLOW GUI	GUI	FV	for MODFLOW and MOC3D, works under ARGUS ONE only
Visual MODFLOW	GUI	FV	for MODFLOW, MT3D, RT3D and PEST
MIKE-SHE	GUI	FD	3D, finite difference groundwater flow, which discharges groundwater drainage directly to surface water (Enterprise version only). A linear reservoir groundwater method is also available for basin-wide water balance and management as well as fully distributed rainfall-runoff modelling.
OGS	GUI	FE	OGS is implemented in C++, it is object-oriented with a focus on the numerical solution of coupled multi-field problems
HYDRUS	GUI	FE	a software package for simulating water, heat, and solute movement in two- and three-dimensional variably saturated media
HydroGeoSpher	GUI	FE	three-dimensional control-volume finite element simulator, HGS also dynamically integrates key components of the hydrologic cycle

Tables 3 and 4 explained the number of publication of each numerical groundwater model according to the article type and publication title respectively. Most of research articles that focused on the utilization of numerical groundwater model were published in Journal of Hydrology which is considered one of the high reputable journals. The impact factor of this journal is 3.483 in Thomson Reuters Score.

Table 2. Number of publications of the numerical groundwater model in the period from 2012 to 2017

Model	2012	2013	2014	2015	2016	2017
MODFLOW	121	114	107	172	133	145
MIKE-SHE	23	28	30	25	37	32
FEFLOW	28	32	38	64	62	50
GMS	3	2	3	4	0	6
IGW	0	1	0	1	0	0
HGS	20	19	33	40	30	20
PTC	1	0	0	1	0	0
PMWIN	0	0	0	0	2	0
OGS	6	25	12	24	17	28

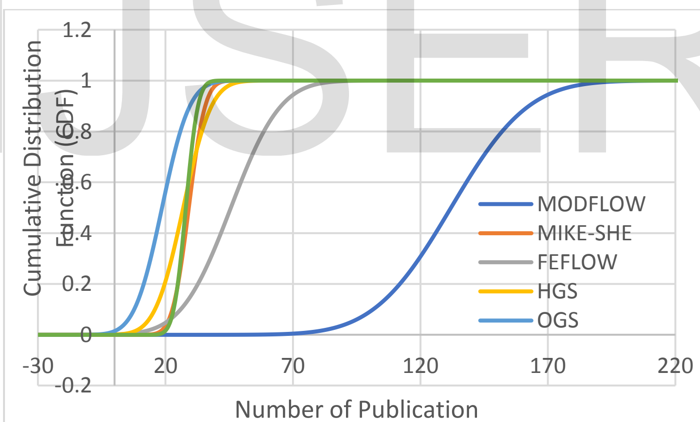

Fig. 6. The cumulative distribution Function (CDF) for the different groundwater flow and contaminant transport model

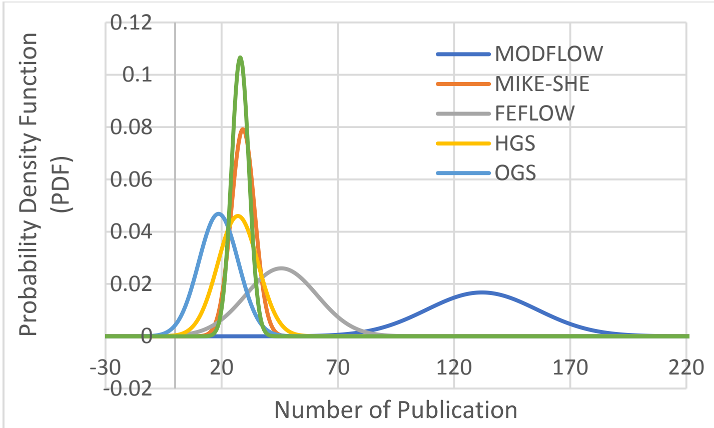

Fig. 7. The Probability Density Function (PDF) for the different groundwater flow and contaminant transport model

Table 3. Number of publications of the numerical groundwater model according to article type

Model	Review paper	Research article	Book chapters	Abstracts
MODFLOW	42	1514	64	83
MIKE-SHE	9	305	7	0
FEFLOW	17	360	22	7
GMS	0	39	1	0
IGW	0	2	0	0
HGS	11	194	1	1
PTC	0	6	0	0
PMWIN	0	7	0	0
OGS	3	119	3	0
Hydrus-2D	8	279	8	0

Table 4. Number of publications of the numerical groundwater model according to publication title

Model	Journal of Hydrology	journal of Contaminant Hydrology	Advances in Water Resources	Environmental modeling and software

MODFLOW	498	151	143	93
MIKE-SHE	71	0	12	20
FEFLOW	81	16	20	16
GMS	7	4	0	0
IGW	1	0	0	0
HGS	82	21	33	23
PTC	2	0	0	0
PMWIN	1	0	1	0
OGS	6	5	12	5

6. Conclusions

The tables and figures in section 3 illustrate that the MODFLOW software package was the most spread software that used to simulate the groundwater flow and contaminants transport. Therefore, the software package was convenient to utilize in our study.

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