Continue

Computer models of groundwater flow systemsGroundwater models are computer models of groundwater flow systems, and are used by hydrologists and hydrogeologists. Groundwater models are used to simulate and predict aquifer conditions.Typical aquifer cross-sectionAn unambiguous definition of "groundwater model" is difficult to give, but there are many common characteristics.A groundwater model may be a scale model or an electric model of a groundwater situation or aquifer. Groundwater models are used to represent the natural groundwater flow in the environment. Some groundwater models include (chemical) quality aspects of the groundwater. Such groundwater models try to predict the fate and movement of the chemical in natural, urban or hypothetical scenario.Groundwater models may be used to predict the effects of hydrological changes (like groundwater pumping or irrigation developments) on the behavior of the aquifer and are often named groundwater simulation models. Groundwater models are used in various water management plans for urban areas.As the computations in mathematical groundwater models are based on groundwater flow equations, which are differential equations that can often be solved only by approximate methods using a numerical analysis, these models are also called mathematical, numerical, or computational groundwater models.[1]The mathematical or the numerical models are usually based on the real physics the groundwater flow follows. These mathematical equations are solved using numerical codes such as MODFLOW, ParFlow, HydroGeoSphere, OpenGeoSys etc.Various types of numerical solutions like the finite difference method and the finite element method are discussed in the article on "Hydrogeology".For the calculations one needs inputs like: hydrological inputs,operational inputs,external conditions: initial and boundary conditions,(hydraulic) parameters.The model may have chemical components like water salinity, soil salinity and other quality indicators of water and soil, for which inputs may also be needed.Hydrological factors at the soil surface determining the rechargeThe primary coupling between groundwater and hydrological inputs is the unsaturated zone or vadose zone. The soil acts to partition hydrological inputs such as rainfall or snowmelt into surface runoff, soil moisture, evapotranspiration and groundwater recharge. Flows through the unsaturated zone that couple surface water to soil moisture and groundwater can be upward or downward, depending upon the gradient of hydraulic head in the soil, can be modeled using the numerical solution of Richards' equation[2] partial differential equation, or the ordinary differential equation Finite Water-Content method [3] as validated for modeling groundwater and vadose zone interactions.[4]The operational inputs concern human interferences with the water management like irrigation, drainage, pumping from wells, watertable control, and the operation of retention or infiltration basins, which are often of an hydrological nature. These inputs may also vary in time and space.Many groundwater models are made for the purpose of assessing the effects hydraulic engineering measures.Boundary conditionsBoundary conditions can be related to levels of the water table, artesian pressures, and hydraulic head along the boundaries of the model on the one hand (the head conditions), or to groundwater inflows and outflows along the boundaries of the model on the other hand (the flow conditions). This may also include quality aspects of the water like salinity.The initial conditions refer to initial values of elements that may increase or decrease in the course of the time inside the model domain and they cover largely the same phenomena as the boundary conditions do.The initial and boundary conditions may vary from place to place. The boundary conditions may be kept either constant or be made variable in time.Example of parameters of an irrigation cum groundwater modelThe parameters usually concern the geometry of and distances in the domain to be modelled and those physical properties of the aquifer that are more or less constant with time but that may be variable in space.Important parameters are the topography, thicknesses of soil / rock layers and their horizontal/vertical hydraulic conductivity (permeability for water), aquifer transmissivity and resistance, aquifer porosity and storage coefficient, as well as the capillarity of the unsaturated zone. For more details see the article on hydrogeology.Some parameters may be influenced by changes in the groundwater situation, like the thickness of a soil layer that may reduce when the water table drops and/the hydraulic pressure is reduced. This phenomenon is called subsidence. The thickness, in this case, is variable in time and not a parameter proper.The applicability of a groundwater model to a real situation depends on the accuracy of the input data and the parameters. Determination of these requires considerable study, like collection of hydrological data (rainfall, evapotranspiration, irrigation, drainage) and determination of the parameters mentioned before including pumping tests. As many parameters are quite variable in space, expert judgment is needed to arrive at representative values.The models can also be used for the if-then analysis: if the value of a parameter is A, then what is the result, and if the value of the parameter is B instead, what is the influence? This analysis may be sufficient to obtain a rough impression of the groundwater behavior, but it can also serve to do a sensitivity analysis to answer the question: which factors have a great influence and which have less influence. With such information one may direct the efforts of investigation more to the influential factors.When sufficient data have been assembled, it is possible to determine some of missing information by calibration. This implies that one assumes a range of values for the unknown or doubtful value of a certain parameter and one runs the model repeatedly while comparing results with known corresponding data. For example, if salinity figures of the groundwater are available and the value of hydraulic conductivity is uncertain, one assumes a range of conductivities and the selects that value of conductivity as "true" that yields salinity results close to the observed values, meaning that the groundwater flow as governed by the hydraulic conductivity is in agreement with the salinity conditions. This procedure is similar to the measurement of the flow in a river or canal by letting very saline water of a known salt concentration drip into the channel and measuring the resulting salt concentration downstream.Groundwater models can be one-dimensional, two-dimensional, three-dimensional and semi-three-dimensional. Two and three-dimensional models can take into account the anisotropy of the aquifer with respect to the hydraulic conductivity, i.e. this property may vary in different directions.Two-dimensional model of subsurface drainage in a vertical planeThree-dimensional grid, ModflowOne-dimensional models can be used for the vertical flow in a system of parallel horizontal layers.Two-dimensional models apply to a vertical plane while it is assumed that the groundwater conditions repeat themselves in other parallel vertical planes (Fig. 4). Spacing equations of subsurface drains and the groundwater energy balance applied to drainage equations[5] are examples of two-dimensional groundwater models.Three-dimensional models like Modflow[6] require discretization of the entire flow domain. To that end the flow region must be subdivided into smaller elements (or cells), in both horizontal and vertical sense. Within each cell the parameters are maintained constant, but they may vary between the cells (Fig. 5). Using numerical solutions of groundwater flow equations, the flow of groundwater may be found as horizontal, vertical and, more often, as intermediate.Map of a radial semi 3-dimensional model consisting of vertical concentrical cylinders through which the flow passes radially to the wellIn semi 3-dimensional models the horizontal flow is described by 2-dimensional flow equations (i. e. in horizontal x and y direction). Vertical flows (in z-direction) are described (a) with a 1-dimensional flow equation, or (b) derived from a water balance of horizontal flows converting the excess of horizontally incoming over the horizontally outgoing groundwater into vertical flow under the assumption that water is incompressible.There are two classes of semi 3-dimensional models:Continuous models or radial models consisting of 2 dimensional submodels in vertical radial planes intersecting each other in one single axis. The flow pattern is repeated in each vertical plane fanning out from the central axis.Discretized models or prismatic models consisting of submodels formed by vertical blocks or prisms for the horizontal flow combined with one or more methods of superposition of the vertical flow.An example of a non-discretized radial model is the description of groundwater flow moving radially towards a deep well in a network of wells from which water is abstracted.[7] The radial flow passes through a vertical, cylindrical, cross-section representing the hydraulic equipotential of which the surface diminishes in the direction of the axis of intersection of the radial planes where the well is located.Map of a two-dimensional grid over an alluvial fan for a prismatic semi 3-dimensional model, SahysModPrismatically discretized models like SahysMod[8] have a grid over the land surface only. The 2-dimensional grid network consists of triangles, squares, rectangles or polygons. Hence, the flow domain is subdivided into vertical blocks or prisms. The prisms can be discretized into horizontal layers with different characteristics that may also vary between the prisms. The groundwater flow between neighboring prisms is calculated using 2-dimensional horizontal groundwater flow equations. Vertical flows are found by applying one-dimensional flow equations in a vertical sense, or they can be derived from the water balance: excess of horizontal inflow over horizontal outflow (or vice versa) is translated into vertical flow, as demonstrated in the article Hydrology (agriculture).In semi 3-dimensional models, intermediate flow between horizontal and vertical is not modelled like in truly 3-dimensional models. Yet, like the truly 3-dimensional models, such models do permit the introduction of horizontal and vertical subsurface drainage systems.Semiconfined aquifers with a slowly permeable layer overlying the aquifer (the aquitard) can be included in the model by simulating vertical flow through it under influence of an overpressure in the aquifer proper relative to the level of the watertable inside or above the aquitard.Analytic Element MethodFEFLOWPORFLOWSVFluxFEHMHydroGeoSphereIntegrated Water Flow ModelMicroFEMMODFLOWGMSVisual MODFLOWProcessing ModflowOpenGeoSysSahysMod, Spatial agro-hydro-salinity-aquifer model, online: [8]US Geological Survey Water Resources Ground Water SoftwareMARTHE from the French Geological Survey (BRGM)ZOOMQ3DFree groundwater modelling course for startersAquiferGroundwaterGroundwater flow equationGroundwater energy balanceHydraulic conductivityHydrogeologySalinity modelWatertable controlGroundwater drainage by wells^ Rushton, K.R., 2003, Groundwater Hydrology: Conceptual and Computational Models. John Wiley and Sons Ltd. ISBN0-470-85004-3^ Richards, L. A. (1931), Capillary conduction of liquids through porous mediums, J. Appl. Phys., 1(5), 318333.^ Ogden, F. L., W. Lai, R. C. Steinke, J. Zhu, C. A. Talbot, and J. L. Wilson (2015), A new general 1-D vadose zone solution method, Water Resour. Res., 51, doi:10.1002/2015WR017126.^ Ogden, F. L., W. Lai, R. C. Steinke, and J. Zhu (2015), Validation of finite water-content vadose zone dynamics method using column experiments with a moving water table and applied surface flux, Water Resour. Res., 51, doi:10.1002/2014WR016454.^ The energy balance of groundwater flow applied to subsurface drainage in anisotropic soils by pipes or ditches with entrance resistance, International Institute for Land Reclamation and Improvement (ILRI), Wageningen, The Netherlands. Download from: [1], or directly as PDF: [2] Archived 2009-02-19 at the Wayback MachinePaper based on: R.J. Oosterbaan, J. Boonstra and K.V.G.K. Rao, 1996, The energy balance of groundwater flow. Published in V.P.Singh and B.Kumar (eds.), Subsurface-Water Hydrology, p. 153-160, Vol.2 of Proceedings of the International Conference on Hydrology and Water Resources, New Delhi, India, 1993. Kluwer Academic Publishers, Dordrecht, The Netherlands. ISBN978-0-7923-3651-8. Download as PDF: [3] . The corresponding EnDrain model can be downloaded from: [4]^ Online guide to MODFLOW-2000 and MODFLOW-2005^ Subsurface drainage by (tube)wells: well spacing equations for fully and partially penetrating wells in uniform or layered aquifers with or without anisotropy and entrance resistance. Paper explaining the basics of the WellDrain model, International Institute for Land Reclamation and Improvement (ILRI), Wageningen, The Netherlands. Updated version of: R.J.Oosterbaan, Tube well spacing formulas for subsurface drainage. Published in: Smith, K.V.H. and D.W. Rycroft (eds.) Hydraulic Design in Water Resources Engineering: Land Drainage. Proceedings of the 2nd International Conference, Southampton University, p. 7584. SpringerVerlag, Berlin, 1986. Download as PDF: [5] . Download the WellDrain model from: [6]^ ILRI, 1995. SahysMod: Spatial Agro-Hydro-Salinity Model. Description of Principles, User Manual, and Case Studies. International Institute for Land Reclamation and Improvement (ILRI), Wageningen, Netherlands. On line: [7]Retrieved from " A, Sefelnasr A, Ismail E (2019) Numerical modeling technique for groundwater management in Samalut city, Minia Governorate Egypt. Arab J Geosci 12:124Article Google Scholar Abdelrady A, Sharma S, Sefelnasr A, El-Rawy M, Kennedy M (2020) Analysis of the performance of bank filtration for water supply in arid climates: case study in Egypt. Water 12:1816Article Google Scholar Abdelshafy M, Saber M, Abdelhaleem A, Abdelrazek SM, Seleem EM (2019) Hydrogeochemical processes and evaluation of groundwater aquifer at Sohag City, Egypt. Sci Afr 6:e00196 Google Scholar Aghlmand R, Abbasi A (2019) Application of MODFLOW with boundary conditions analyses based on limited available observations: a case study of Birjand plain in East Iran. Water 11:1904Article Google Scholar Ahmed AA (2009) Using lithologic modeling techniques for aquifer characterization and groundwater flow modeling of the Sohag area Egypt. Hydrogeol J 17:11891201Article ADS CAS Google Scholar Al-Maktoumi A, El-Rawy M, Zekri S (2016) Management options for a multipurpose coastal aquifer in Oman. Arab J Geosci 9:114Article Google Scholar Al-Maktoumi A, Zekri S, El-Rawy M, Abdalla O, Al-Wardy M, Al-Rawas G, Charabi Y (2018) Assessment of the impact of climate change on coastal aquifers in Oman. Arab J Geosci 11:114Article CAS Google Scholar Al-Maktoumi A, Zekri S, El-Rawy M, Abdalla O, Al-Abri R, Triki C, Bazargan-Lari MR (2020) Aquifer storage and recovery, and managed aquifer recharge of reclaimed water for management of coastal aquifers. Desalin Water Treat 176:6777Article Google Scholar Anderson MP, Woessner WW (1992a) The role of the postaudit in model validation. Adv Water Resour 15(3):167173Article ADS Google Scholar Anderson MP, Woessner WW (1992b) Applied groundwater modeling: simulation of flow and advective transport. Academic Press, San Diego, Elsevier, p 381p Google Scholar Anderson MP, Woessner WW, Hunt RJ (2015a) Applied groundwater modeling: simulation of flow and advective transport, 2nd ed. Academic Press, Elsevier, New York. ISBN 9780120581030 Google Scholar Anderson MP, Woessner WW, Hunt RJ (2015b) Model calibration: assessing performance, chap 9. In: Anderson MP, Woessner WW, Hunt RJ (eds) Applied groundwater modeling, 2nd edn. Academic Press, San Diego, pp 375441Chapter Google Scholar Anon (2000a) SSG Software. The Scientific Software Group, Washington (2000b) Visual MODFLOW V.2.8.2 Users manual for professional applications in three-dimensional groundwater flow and contaminant transport modeling. Waterloo Hydrogeologic Inc, Ontario Google Scholar El Arabi N (2012) Environmental management of groundwater in Egypt via artificial recharge extending the practice to soil aquifer treatment (SAT). Int J Environ Sustain 1 Google Scholar Arnold JG, Srinivasan R, Muttiah RS, Williams JR (1998) Largearea hydrologic modeling and assessment: Part I. Model development. J Am Water Resour Assoc 34(1):7389 Google Scholar Arnold JG, Fohrer N (2005) SWAT2000: current capabilities and research opportunities in applied watershed modeling. Hydrol Process 19(3):563572Article ADS Google Scholar Attard G, Rossier Y, Winiarski T, Eisenlohr L (2016) Deterministic modeling of the impact of underground structures on urban groundwater temperature. Sci Total Environ 572:986994Article ADS CAS PubMed Google Scholar Awad A, Eldeeb H, El-Rawy M (2020) Assessment of surface and groundwater interaction using field measurements: a case study of Dairut City, Assuit Egypt. J Eng Sci Technol 15:406425 Google Scholar Awad A, Luo W, Zou J (2021) DRAINMOD simulation of paddy field drainage strategies and adaptation to future climate change in lower reaches of the Yangtze river basin. Irrig Drainage Google Scholar Aziz K, Settari A (1979) Petroleum reservoir simulation. Applied Science Publishers, London, pp 135139 Google Scholar Baalousha H, Kngeter J (2006) Stochastic modelling and risk analysis of groundwater pollution using FORM coupled with automatic differentiation. Adv Water Resour 29(12):18151832Article ADS Google Scholar Baalousha H (2007) Application of automatic differentiation in groundwater sensitivity analysis. In: Oxley L, Kulasiri D (eds) MODSIM 2007 international congress on modelling and simulation. Modelling and Simulation Society of Australia and New Zealand, pp 27282733, Dec 2007. ISBN: 978-0-9758400-4-7 Google Scholar Baalousha H (2008) Fundamentals of groundwater modelling. In: Konig LF, Weiss JL (eds) Groundwater: modelling, management and contamination. Nova Science Publishers, Inc.: New York, pp. 149166; ISBN 9781604568325 Google Scholar Bear J (1979) Hydraulics of Groundwater. McGraw-Hill, New York, p 567p Google Scholar Bear JJ, Cheng HDA (2010) Numerical models and computer codes. In: Modeling groundwater flow and contaminant transport. Theory and applications of transport in porous media, vol 23. Springer, Dordrecht. J, Verruijt A (1987) Modeling groundwater flow and pollution. Springer, Berlin, p 432 Google Scholar Bishop JM, Glenn CR, Amato DW, Dulai H (2017) Effect of land use and groundwater flow path on submarine groundwater discharge nutrient flux. J Hydrol Reg Stud 11:194218Article Google Scholar Bossavit A (1998) Computational electromagnetism. Academic Press, BostonMATH Google Scholar Bossavit A (2005) Disctretization of electromagnetic problems: the generalized finite difference approach. In: Ciarlet PG (ed) Handbook of numerical analysis, vol XIII. Elsevier, North Holland, Amsterdam Google Scholar Campos E (2009) A groundwater flow model for water related damages on historic monumentscase study West Luxor Egypt. Vatten 65:247254 Google Scholar Cao W, Bowden WB, Davie T, Fenemor A (2006) Multi-variable and multi-site calibration and validation of SWAT in a large mountainous catchment with high spatial variability. Hydrol Process 20:10571073Article ADS Google Scholar Chavent G, Jaffr J (1986) Mathematical models and finite elements for reservoir simulation. Elsevier, North-Holland, AmsterdamMATH Google Scholar Cooley RL, Naff RL (1990) Regression modeling of ground-water flow. U.S. Geological Survey Techniques of Water-Resources Investigations, 03eB4, p 232. RL (1977) A method of estimating parameters and assessing reliability for models of steady state groundwater flow, 1. Theory and numerical properties. Water Resour Res 13(2):318e324. RL (1979) A method of estimating parameters and assessing reliability for models of steady state groundwater flow, 2. Application of statistical analysis. Water Resour Res 15(3):603e617. JH, Tartakovsky DM (eds) (2016) The handbook of groundwater engineering. CRC Press Google Scholar Davis PA, Olague NE, Goodrich MT (1992) Application of a validation strategy to Darcys experiment. Adv Water Resour 15(3):175180Article ADS Google Scholar Dawoud MA, Ismail SS (2013) Saturated and unsaturated River Nile/groundwater aquifer interaction systems in the Nile Valley Egyt. Arab J Geosci 6:21192130Article Google Scholar De Smedt F, Zijl W (2018) Two-and three-dimentional flow of groundwater. CRC Press, Boca Raton, p 61 Google Scholar De Smedt F, Zijl W, El-Rawy M (2018) Double constraint method for pumping test analysis. J Hydrol Eng 23(7):06018003Article Google Scholar Delleur JW (ed) (2006) The handbook of groundwater engineering. CRC press Google Scholar Diersch HJG (2005) WASY software FEFLOW, finite element subsurface flow and transport simulation system, users manual. Berlin, Germany Google Scholar Doherty J, Brebber L, Whyte P (1994) PESTModel-independent parameter estimation. Users manual. Watermark Computing. Australia Google Scholar Doherty J (1990) MODINV e suite of software for MODFLOW preprocessing, postprocessing, and parameter optimization. Users Manual: Australian Centre for Tropical Freshwater Research (various pagings) Google Scholar Doherty J (2014a) PEST, Model-independent parameter estimationd user manual (fifth ed., with slight additions). Watermark Numerical Computing, Brisbane, Australia Google Scholar Doherty J (2014b) Addendum to the PEST manual. Watermark Numerical Computing, Brisbane, Australia Google Scholar Driscoll FG (1986) Groundwater and wells. 2nd Edition, St. Paul, Minnesota, Johnson Division Google Scholar Du X, Lu X, Hou J, Ye X (2018) Improving the reliability of numerical groundwater modeling in a data-sparse region. Water 10(3):289Article Google Scholar El-Rawy M (2013) Calibration of hydraulic conductivities in groundwater flow models using the double constraint method and the Kalman filter. Doctoral dissertation, Ph.D. thesis Vrije Universiteit Brussel, Brussels, Belgium Google Scholar El-Fakharany Z, Fekry A (2014) Assessment of New Esna barrage impacts on groundwater and proposed measures. Water Sci 28:6573Article Google Scholar El-Rawy M, De Smedt F (2020) Estimation and mapping of the transmissivity of the Nubian sandstone aquifer in the kharga oasis, Egyt. Water 12(2):604Article Google Scholar El-Rawy M, Zijl W, Batelaan O, Mohammed GA (2010) Application of the double constraint method combined with MODFLOW. In: Proceedings of the Valencia IAHR international groundwater symposium. Valencia, Spain, 2224 Sept 2010 Google Scholar El-Rawy M, Mohammed GA, Zijl W, Batelaan O, De Smedt F (2011) Inverse modeling combined with Kalman filtering applied to a groundwater catchment, In: Proceedings of the MODFLOW and more conference, Golden, USA 68 June (2011) Google Scholar El-Rawy MA, Batelaan O, Zijl W (2015a) Simple hydraulic conductivity estimation by the Kalman filtered double constraint method. Groundwater 53(3):401413. CAS Google Scholar El-Rawy MA, Batelaan O, Zijl W (2015b) A simple method to apply measured flux and head data for the estimation of regional hydraulic conductivities. In: First EAGE/TNO workshop. European Association of Geoscientists & Engineers, p cp-450 Google Scholar El-Rawy M, De Smedt F, Batelaan O, Schneidewind U, Huysmans M, Zijl W (2016) Hydrodynamics of porous formations: simple indices for calibration and identification of spatio-temporal scales. Mar Petrol Geol 78:690700. Google Scholar El-Rawy M, De Smedt F, Zijl W (2018) Zone-integrated double-constraint methodology for calibration of hydraulic conductivities in grid cell clusters of groundwater flow models. Trans Porous Media 122(3):633645Article MathSciNet Google Scholar El-Rawy M, Al-Maktoumi A, Zekri S, Abdalla O, Al-Abri R (2019a) Hydrological and economic feasibility of mitigating a stressed coastal aquifer using managed aquifer recharge: a case study of Jamma aquifer Oman. J Arid Land 11(1):148159Article Google Scholar El-Rawy M, Batelaan O, Buis K, Anibas C, Mohammed G, Zijl W, Salem A (2020a) Analytical and numerical groundwater flow solutions for the FEMME-modeling environment. Hydrology 7(2):27Article Google Scholar El-Rawy M, Abdalla F, El Alfy M (2020b) Water resources in Egypt. In: The geology of Egypt. Springer, Cham, pp 687711 Google Scholar El-Rawy M, Moghazy HE, Eltarabily MG (2021a) Impacts of decreasing Nile flow on the Nile Valley aquifer in El-Minia governorate Egypt. Alexandria Eng J 60:21792192Article Google Scholar El-Rawy M, Makhloof AA, Hashem MD, Eltarabily MG (2021b) Groundwater management of quaternary aquifer of the nile valley under different recharge and discharge scenarios: a case study assiut governorate Egypt. Ain Shams Eng Univ 12(3):25632574Article Google Scholar El-Rawy M, Abdalla F. Negm AM (2021c) Groundwater characterization and quality assessment in Nubian sandstone aquifer, Kharga Oasis, Egypt. In: Negm AM, Elkhouly A (eds) Groundwater in Egyptian deserts, Springer International Publishing (accepted for publication) Google Scholar Elsheikh AE, Barseem MS, Sherbeni WA (2020) Susceptibility of shallow groundwater aquifers to water logging, case study Al Marashda area, West Nile Valley, Qena, Egypt, bulletin of the faculty of engineering. Mansoura Univ 40:128 Google Scholar Eltarabily MG, Negm AM, Yoshimura C, Saavedra OC (2017) Modeling the impact of nitrate fertilizers on groundwater quality in the southern part of the Nile Delta Egypt. Water Sci Technol Water Supply 17:561570Article CAS Google Scholar Eltarabily MG, Negm AM, Yoshimura C, Takemura J (2018) Groundwater modeling in agricultural watershed under different recharge and discharge scenarios fort quaternary aquifer eastern Nile Delta Egypt. Environ Model Assess 23:289308Article Google Scholar Enemark T, Peeters L, Mallants D, Flinchum B, Batelaan OA (2020) Systematic approach to hydrogeological conceptual model testing, combining remote sensing and geophysical data. Water Resour Res 56(8):e2020WR027578 Google Scholar Esfahani SG, Valocchi AJ, Werth CJ (2021) Using MODFLOW and RT3D to simulate diffusion and reaction without discretizing low permeability zones. J Contam Hydrol 103777 Google Scholar Fetter CW (2001) Applied hydrogeology. Prentice Hall. 4th edn Google Scholar Fleckenstein JH, Krause S, Hannah DM, Boano F (2010) Groundwater-surface water interactions: new methods and models to improve understanding of processes and dynamics. Adv Water Resour 33:12911295Article ADS CAS Google Scholar Fouad M, Hussein EE (2018) Assessment of numerical groundwater models. Int J Sci Eng Res 9(6):951974 Google Scholar Franke OL, Reilly TE, Bennett GD (1987) Definition of boundary and initial conditions in the analysis of saturated ground-water flow systemsAn introduction: techniques of water-resources investigations of the United States Geological Survey, Book 3, Chapter B5, p 15 Google Scholar Gleeson T, Wada Y, Bierkens MFP, van Beek LPH (2012) Water balance of global aquifers revealed by groundwater footprint. Nature 488(197200):2012. CAS Google Scholar Gupta HV, Sorooshian S, Yapo PO (1998) Toward improved calibration of hydrologic models: multiple and noncommensurable measures of information. Water Resour Res 34(4):751763Article ADS Google Scholar Harbaugh A, McDonald M (1996) User's documentation for MODFLOW-96, an update to the U.S. Geological Survey modular finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 96-485, p 56 Google Scholar Harbaugh AW (2005) MODFLOW-2005, the U.S. Geological survey modular ground-water modelthe Ground-water flow process. U.S. Geological Survey Techniques and Methods 6-A16 Google Scholar Harbaugh AW, Banta ER, Hill MC, McDonald, MG (2000) MODFLOW2000, the U.S. geological survey modular ground-water modelUser guide to modularization concepts and the ground-water flow process, U.S. Geological Survey Open-File Report 00-92, p 121 Google Scholar Hassan A (2003) A validation process for the groundwater flow and transport model of the faultless nuclear test at central Nevada test area(No. DOE/NV/1360927; DRI Pub. No. 45197). Desert Research Institute, University and Community College System of Nevada (US) Google Scholar Hassan AE (2004) Validation of numerical ground water models used to guide decision making. Groundwater 42(2):277290Article CAS Google Scholar Henriksen HJ, Troldborg L, Nyegaard P, Sonnenborg TO, Refsgaard JC, Madsen B (2003) Methodology for construction, calibration and validation of a national hydrological model for Denmark. J Hydrol 280(14):5271Article Google Scholar Hill MC (1992) A computer program (MODFLOWP) for estimating parameters of a transient, three dimensional, ground-water flow model using nonlinear regression. U.S. Geological Survey Open-File Report 91-484, p 358. MC, Tideman CR (2007) Effective groundwater model calibration: with analysis of data, sensitivities, predictions, and uncertainty. Wiley-Interscience, p 455. ISBN 978-0-471-77636-9 Google Scholar Hill MC, Banta ER, Harbaugh AW, Anderman ER (2000) MODFLOW2000, the U.S. geological survey modular ground-water modelUser guide to the observation, sensitivity, and parameter-estimation processes and three post-processing programs, U.S. Geological Survey Open-File Report 00-184, p 210 Google Scholar Hlting B, Coldewey WG (2019) Numerical groundwater models. In: Hydrogeology. Springer Textbooks in earth sciences, geography and environment. Springer, Berlin. SC (1996) Aleatory and epistemic uncertainty in probability elicitation with an example from hazardous waste management. Reliab Eng Syst Saf 54:217223. 96)00077-4Article Google Scholar Huyakorn PS, Pinder GF (1983) Computational methods in subsurface flow. Academic Press, p 473 Google Scholar Igboekwe MU, Achi NJ (2011) Finite difference method of modelling groundwater flow. J Water Resour Prot 3:192198. Google Scholar Igboekwe MU, Gurunadha Rao VVS, Ok-wueze EE (2008) Groundwater flow modelling of Kwa Ibo river watershed Southeastern Nigeria. Hydrol Proc-Esses 22(10):15231531. ADS Google Scholar Ismail E, El-Rawy M (2018) Assessment of groundwater quality in West Sohag, Eypt. Desalin Water Treat 123:101108Article CAS Google Scholar Kaasschieter EF (1990) Preconditioned conjugate gradients and mixed-hybrid finite elements for the solution of potential flow problems. Ph.D. thesis, Delft University of Technology, Delft, Netherlands Google Scholar Kaasschieter EF, Huijben SJM (1992) Mixed-hybrid finite elements and streamline computation for the potential flow problem. Numer Methods Partial Differ Equ 8:221266Article MathSciNet MATH Google Scholar Katpatal Y, Thakare P, Maunika S (2021) Groundwater modeling in a semi-confined aquifer using GIS and MODFLOW, in water management and water governance, Springer, Berlin, pp 179187 Google Scholar Kenda K, erin M, Bogataj M, Senoetnik M, Klemen K, Pergar P, Laspidou C, Mladeni D (2018) Groundwater modeling with machine learning techniques: ljubljana polje aquifer, in Multidisciplinary Digital Publishing Institute Proceedings, p 697 Google Scholar Khadim FK, Dokou Z, Lazin R, Moges S, Bagtzoglou AC, Anagnostou E (2020) Groundwater modeling in data scarce aquifers: the case of Gilgel-Abay, upper blue nile Ethiopia. J Hydrol 590:125214Article Google Scholar Kisi O, Azad A, Kashi H, Saeedian A, Hashemi SAA, Ghorbani S (2019) Modeling groundwater quality parameters using hybrid neuro-fuzzy methods. Water Resour Manage 33:847861 Google Scholar Kori SM, Lashari BK, Memon NA (2008) Calibration and validation of groundwater flow model under scavenger wells operation. Mehran Univ Res J Eng Technol 27(2):213228 Google Scholar Kumar CP (2004) Groundwater flow models. Technical Note, National Institute of Hydrology, Roorkee, (Uttaranchal), India Google Scholar Kumar C (2019) An overview of commonly used groundwater modelling software. Int J Adv Res Sci Eng Technol 6:78547865 Google Scholar Kunstmanna H, Kastensb M (2006) Direct propagation of probability density functions in hydrological equations. J Hydrol 325(14):8295Article Google Scholar Lin HCJ, Richards DR, Yeh GT, Cheng JR, Cheng HP (1997) FEMWATER: a three-dimensional finite element computer model for simulating density-dependent flow and transport in variably saturated media; CHL-97-12; DTIC Document: Vicksburg, MS, USA Google Scholar Liou T, Der Yeh H (1997) Conditional expectation for evaluation of risk groundwater flow and solute transport: one-dimensional analysis. J Hydrol 199(34):378402Article CAS Google Scholar McDonald MG, Harbaugh AW (1988) A modular three dimensional finite difference groundwater flow model. Techniques of Water Resources Investigations, Chapter A1, US Geol. Surv, p 586 Google Scholar Meredith E, Blais N (2019) Quantifying irrigation recharge sources using groundwater modeling. Agric Water Manag 214:916Article Google Scholar Nagels K, Schneidewind U, El-Rawy M, Batelaan O, De Becker P (2015) Hydrology and ecology: how Natura 2000 and Military use can match. Ecol Quest 21:7985 Google Scholar Negm AM (Ed) (2018) Groundwater in the Nile Delta (73). Springer International Publishing. AM, Elkhouly A (2021) Groundwater in Egyptian Deserts, Springer International Publishing (accepted for publication) Google Scholar Nriagu JO (2019) Encyclopedia of environmental health. Elsevier Google Scholar Peaceman DW (1978) Interpretation of well-block pressures in numerical reservoir simulation. SPE J 18(3):183194 Google Scholar Pham HV, Tsai FT (2017) Groundwater modeling. Chapter 48. In: Singh VP (ed) Handbook of applied hydrology. McGraw-Hill, New York, pp 481488 Google Scholar Pinder G, Gray W (1970) Finite element simulation in surface and subsurface hydrology. Academic Press Inc. p 295 Google Scholar Pinder GF, Gray WG (1977) Finite element simulation in surface and subsurface hydrology. Academic Press, New York, p 295 Google Scholar Poeter EP, Hill MC (1997) Inverse models: a necessary next step in ground-water modeling. Ground Water 35(2):250260Article CAS Google Scholar Poeter EP, Hill MC (1998) Documentation of UCODE, a computer code for universal inverse modeling, U.S. Geological Survey, Water-Resources Investigations Report 98-4080 Google Scholar Poeter EP, Hill MC, Banta ER, Mehl S, Christensen S (2005) UCODE_2005 and six other computer codes for universal sensitivity analysis, calibration, and uncertainty evaluation. U.S. Geological Survey Techniques and Methods, 6 A11, p 47. p 283. DW (1990) Documentation of computer programs to compute and display path lines using results from the US Geol. Surv. Modular three dimensional finite diffeence groundwater flow model. US Geol. Surv. Open-File Report 89, pp 381388 Google Scholar Polomi D, Baji D (2015) Application of groundwater modeling for designing a dewatering system: case study of the Buva Open Cast Mine, Bosnia and Herzegovina. Geol Croat 68:123137Article Google Scholar Rahnama M, Sohrabipour N, Barani G (2020) Investigation of groundwater level variations in Shahdad aquifer. Iran J Irrig Drainage 14:16501663 Google Scholar Reilly T, Harbaugh A (2004) Guidelines for evaluating ground-water flow. Scientific Investigations Report 20045038. U.S. Department of Interior, U.S. Geological Survey Google Scholar Remson I, Hornberger GM, Molz FJ (1971) Numerical methods in subsurface hydrology. Wiley-Interscience, New York, p 389 Google Scholar Roscoe Moss Company (1990) Handbook of ground water development. Wiley, New YorkBook Google Scholar Salem A, Dezs J, Lczy D, El-Rawy M, Slowik M (2018) Modeling surface water-groundwater interaction in an oxbow of the Drava floodplain. EPiC Ser Eng 3:18321840Article Google Scholar Salem A, Dezs J, Lczy D, El-Rawy M, Loczy D (2020) Hydrological modeling to assess the efficiency of groundwater replenishment through natural reservoirs in the Hungarian Drava River floodplain. Water 12:250Article Google Scholar Sashikkumar M, Selvam S, Kalyanasundaram VL, Johnny JC (2017) GIS based groundwater modeling study to assess the effect of artificial recharge: a case study from Kodaganar river basin, Dindigul district, Tamil Nadu. J Geol Soc India 89:5764Article Google Scholar Sathe SS, Mahanta C (2019) Groundwater flow and arsenic contamination transport modeling for a multi aquifer terrain: assessment and mitigation strategies. J Environ Manage 231:166181Article CAS PubMed Google Scholar Sefelnasr AM, Omran AA-K, Abdel-Hak HA, El Tahawy WS (2019) GIS-based numerical modeling for the groundwater assessment: a case study in the Quaternary aquifer, Assiut Governorate, Egyt. Arab J Geosci 12:113Article Google Scholar Senge RS, Bsner DK, Haasenritterb J, Hirsch O, Donner-Banzhoff N, Hllermeier E (2014) Reliable classification: learning classifiers that distinguish aleatoric and epistemic uncertainty. Inf Sci 255:1629. MathSciNet MATH Google Scholar Shamrukh M, Corapcioglu MY, Hassona FA (2001) Modeling the effect of chemical fertilizers on ground water quality in the Nile Valley Aquifer Egypt. Groundwater 39:5967Article CAS Google Scholar Simunek J, Wendroth O, van Genuchten MT (1999) Estimating unsaturated soil hydraulic properties from laboratory tension disc infiltrometer experiments. Water Resour Res 35(10):29652979 Google Scholar Singhal BBS, Gupta RP (2010) Groundwater modeling. In: Applied hydrogeology of fractured rocks. Springer, Dordrecht. G, Arevalo C (2017) Numerical methods for differential equations. Numerical analysis. Lund University (20082009) [retrieved on Aug. 3, 2017]. Retrieved from Google Scholar Srivastav AL (2020) Chemical fertilizers and pesticides: role in groundwater contamination, in agrochemicals detection, treatment and remediation. Elsevier, pp 143159 Google Scholar Strack ODL (1989) Groundwater mechanics. Prentice Hall Inc., Englewood Cliffs, New Jersey Google Scholar Suring LH (2020) Freshwater: oasis of lifeAn overview Google Scholar El Tahlawi M, Farrag A, Ahmed S (2008) Groundwater of Egypt: an environmental overview. Environ Geol 55:639652Article ADS Google Scholar Theis CV (1941) The effect of a well on the flow of a nearby stream. Am Geophys Union Trans 22(3):734738Article Google Scholar Tian Y, Zheng Y, Wu B, Wu X, Liu J, Zheng C (2015) Modeling surface water-groundwater interaction in arid and semi-arid regions with intensive agriculture. Environ Model Softw 63:170184Article Google Scholar Torak LJ (1993) A MODular Finite-Element model (MODFE) for areal and axisymmetric ground-water-flow problems, part 1--model description and user's manual: U.S. Geological Survey Techniques of Water-Resources Investigations, book 6, chap. A3 Google Scholar Toth J (1962) A theory of groundwater motion in small drainage basins in central Alberta. J Geophys Res 67(11):43754387Article ADS Google Scholar Trykozko A (2001) Numerical homogenization of the absolute permeability using the conformal-nodal and mixed-hybrid finite element method. Transp Porous Med 44:3362Article Google Scholar Trykozko A, Zijl W, Bossavit A (2001) Nodal and mixed finite elements for the numerical homogenization of 3D permeability. Comput Geosci 5:6164Article MATH Google Scholar Walton W (1989) Analytical ground water modeling. Lewis Publishers, Chelsea, Michigan Google Scholar Wang S, Shao J, Song X, Zhang Y, Hu Z, Zhou X (2008) Application of MODFLOW and geographic information system to groundwater flow simulation in North China Plain. China Environ Geol 55:14491462Article ADS Google Scholar Wasy GmbH (2005) FEFLOW: finite element subsurface flow and transport simulation system. Reference Manual. Wasy GmbH, Berlin Google Scholar Weiser A, Wheeler MF (1988) On convergence of block-centered finite differences for elliptic problems. SIAM J Numer Anal 25:351375Article MathSciNet MATH Google Scholar Wingle WL, Poeter EP, McKenna SA (1999) U