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On the Importance of MODFLOW Software in Urban Planning of Cities

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1 ABSTRACT

The quality of groundwater in the country of iraq has been on the decline in recent years following the enhanced use of groundwater as a major source of water, especially in the kurdistan region. thus, groundwater flow and the movement of contaminants in aquifers is an important aspect that should be studied to determine the quality of groundwater, forecast on the future effects of pollutants, and to estimate the duration it takes the contaminants to reach certain points. in the last twenty years, there is a lot of literature on groundwater modeling in iraq.the purpose of the proposed study is to assess, analyze, and summarize the conclusions of published researches about the modeling of groundwater flow and contamination transportation in different cities of iraq and the kurdistan region using different numerical programs, especially, modflow. the current review relies on already published works that examined the hydrogeological situations of their study regions. the majority of researches have gathered information on levels of groundwater, hydraulic conductivity, and effective porosity to model groundwater movement, drawdown and contaminant transportation.

Most of the studies reviewed indicated that the predicted simulated hydraulic heads (predicted with the help of the modflow) were in good agreement with the measured field values, and it shows that numerical model approaches are reliable. modflow has since been a valuable and useful instrument of comprehending the behavior of aquifers and processes of pollutant migration. additionally, groundwater modeling, basing on the modflow, can be very useful in the context of urban planning, representing the trend of assessing sustainable groundwater extraction, sensitive recharge areas, wellfield locations, and the environmental effects of urban growth and development of infrastructure.

Keywords: Urban planning, MODFLOW, MT3DMS, MODPATH, Modelling

2 INTRODUCTION

Groundwater is a significant source of water, particularly in dry and semiarid areas. Understanding aquifer performance under present conditions and anticipating the impact of recharge and increased discharge on that aquifer are required for groundwater resource management. The aquifer may be modelled using numerical flow modeling to estimate the influence of recharge, discharge, and various hydrologic and hydrogeologic impacts on the water table (Asghari, 2005). Groundwater models may be used to evaluate and estimate hydraulic parameters and to test alternative conceptual models. They may also be used to estimate how the aquifer will respond to changes in pumping, hydraulic characteristics, and climatic change, as well as pollutant transit in the aquifer (El Yaouti et al., 2008). For varied aquifer systems and formations, numerical modeling is an essential approach for managing groundwater resources and anticipating future reactions. MODFLOW (modular finite-difference groundwater flow model) is a computer software that simulates groundwater flow systems (McDonald and Harbaugh, 1988, Harbaugh and McDonald, 1996). Different types of models, such as analytical and numerical models, can be used to solve the equations that govern groundwater flow. Field conditions that fluctuate over time or space, such as groundwater flow rate, groundwater direction, and other hydraulic variables, cannot be accounted for because of the simplifications inherent in analytical models. Many analytical models also need that the medium be homogenous and isotropic, which makes the employment of numerical models a highly plausible scenario (Wang and Anderson, 1995). The more complicated equations that explain groundwater flow can be solved using numerical models. Since the mid-1960s, when high-speed digital computers became widely available, this model has been frequently utilized for groundwater analysis (Mercer, 1981). Groundwater modeling is a valuable technique for determining how groundwater extraction will affect the elevation of the water table and the accessibility of groundwater. The method of discretization is commonly used to create a finite-element or finite-difference grid in a given region. The number of cells in a discretized grid is a compromise between obtaining precise numerical answers for groundwater flow and the cost and resources needed to build, calibrate, and run the model (Klaas et al., 2017). To simulate groundwater flow in a region, these models require a variety of variables, including topography, hydrogeological, hydrological, and climatic data (Rapantova et al., 2017). These data may be lacking in developing countries, making groundwater modeling experiments much more challenging (Hogeboom et al., 2015). The type of data used in groundwater models can have a considerable impact on the model's results, hence precise data should be given as model inputs wherever feasible. This study aims to review the preview research that was used to simulate groundwater flow and contamination transport in Iraq and the Kurdistan region and some other area and to show the ability of MODFLOW in Modelling and its advantage in urban planing .

3 BASIC CONCEPT OF GROUNDWATER FLOW MODEL

3.1 The structure of a model

MODFLOW Software that used to solve the flow partial differential equation which is base on Darcy law and conservation equation:

$$\frac{\partial}{\partial x}\left(Kx\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(Ky\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(Kz\frac{\partial h}{\partial z}\right)=S_s\frac{\partial h}{\partial t}-\mathrm{W}$$

S_s : is a specific storage of the porous material (L^{-1}),

t: is the time (T),

W: is the flux of volumetric per unit volume describing sources / sinks of water (T^{-1}),

h: is the Hydraulic head (L).

Kx, Ky, Kz are the hydraulic conductivity in x,y and z direction (L/T)

The equation that covers groundwater contaminants transport (Javandel, 1984), which is solved by MODFLOW software, is:

$$\frac{\partial \mathrm{C}}{\partial t}=\frac{\partial}{\partial \mathrm{x_i}}\left(\mathrm{D_{ij}}\frac{\partial \mathrm{C}}{\partial \mathrm{x_i}}\right)-\frac{\partial}{\partial \mathrm{x_i}}(\mathrm{v_i C})+\frac{\mathrm{q_x}}{\mathrm{n}}\mathrm{C_s}+\sum_{\mathrm{k-1}}^{\mathrm{N}}\mathrm{R_c}$$

Where:

C: is the contaminant concentration in groundwater,

t : is the time (t),

vi is the seepage velocity,

qx is the volumetric water flux per unit volume of the aquifer,

Cs is the source or sinks concentration,

Dij is the coefficient of hydrodynamic dispersion,

n is the porous medium porosity,

Rc is the term for a chemical reaction.

4 APPLICATION OF MODFLOW

4.1 Basic Data Requirements of MODFLOW Modeling

MODFLOW is one of the commonly used numerical ground water flow simulation models known as finite difference method. Successful model implementation requires correct input data for hydrogeology and hydrology. Some of the most important input parameters are (Yashooa et al., 2024):

- Hydraulic head data, which is normally measured from water levels in observation wells.
- Distribution of Hydraulic conductivity (K) in model layers.
- Effective porosity of each hydrostratigraphic layer.
- Thickness and stratigraphy configuration of the aquifer.

- Rates of recharge commonly obtained from rainfall infiltration.
- Boundary conditions such as constant head boundaries, rivers, drains and no-flow boundaries.

4.2 Ground Water Flow Modeling at a Local Scale in Iraq

Numerous studies of Iraq have been undertaken to apply the use of MODFLOW and similar software packages to model the ground-water flow under various hydrogeological conditions.

Early work by (Alsalim and Faozy, 2004) used the finite difference method to calculate the groundwater flow direction and water levels in the Bashiqa area, northern Iraq. Subsequently, Al-Taiee and Hasan (2006) simulated the ground water movement in the Mosul City with the help of the water resources software (MODFOW), showing the flow towards west and southwest with a value of transmissivity about 30 m^2/day. They suggested strategic placement of wells to prevent further groundwater decline in their study.

In Alton Copri Basin, Processing MODFLOW (V.7) integrated with GIS for spatial analysis was used for (Jawad et al. 2010). The model discrepancy was reported as 1.17% indicating the accurate numerical solution of groundwater flow equation and strong correlation between observed and simulated heads.

Similarly, (Al-Fatlawi,2011) simulated ground water levels in Umm Er Radhuma aquifer using Processing MODFLOW (V.7.0.2). The model discrepancy was 0.68% and attributed to the use of water budget option. Despite the increase in the number of wells drilled, despite the increase of discharge by about 50 m3/day per well, the recharge remained constant and the discharge increased, with good agreement between the observed and simulated head.

In Missan Province, (Al-Aboodi et al. 2013) simulated ground water flow in Quaternary deposits. Strong agreements were found in the results of calibration (RMSE = 0.246 m; MAE = 0.221 m). Hydraulic conductivity varied between 1-10 m/day and specific yield varied between 0.1-0.4 illustrating the sensitivity of model performance to hydraulic conductivity.

(Seeyan and Merkel 2015) used Visual MODFLOW in the case of Shaqlawa-Harrir Basin to investigate the hydrological changes under different pumping scenarios. Increasing pumping rates to 200% and 400% led to head declines of up to 18 m in Harrir Plain, and hence proved aquifer vulnerability to overexploitation.

In Khanaqin, (Ali and Oleiwi 2015) showed localized groundwater rise (0.87 m) caused by proximity to Al-Wind Lake, while other cells showed declines. Increased discharge for irrigation changed head distribution, but while predicted increases in the number of wells had limited impact on flow pattern overall.

(Kareem et al.,2016) have modeled the impact of groundwater extraction in Al-Najaf City. The correlation coefficient between observed and simulated heads was found to be 0.971. Water balance analysis showed significant interaction with the Euphrates river, putting the river-aquifer exchange to the foreground.

Climate change impacts were assessed by (Al-Dabbas et al., 2016) on Salah Al-Din Province which showed a decreasing water tables due to a reduction in recharge and an increase in abstraction. Rainfall was found as the major recharge source.

Regarding the flow of groundwater in the area of Baghdad, (Mustafa et al.,2017) modeled the flow of groundwater in the vicinity of the Tigris River. Raising river water levels caused an increase in hydraulic heads, while a proposed pumping well changed flow direction in steady state conditions.

At a larger scale, the regional groundwater dynamics have been evaluated with the assistance of MODFLOW.

(Al-Ansari et al., 2013) used the Euphrates-Tigris Basin to apply the model MODFLOW to the basin and calibrate it using 15 years of water levels data. The study highlighted the significance of regional recharge patterns for the control of long-term fluctuations of groundwater.

(Shaban et al., 2012) modeled the aquifer of Basrah in which the strong effect of spatial variability in hydraulic conductivity on the flow direction and sustainability of pumping strategies has been shown.

Urban groundwater systems also have been studied extensively, (Al-Jubouri and Salman, 2017) reported that drawdown is significant in Baghdad as a result of uncontrolled abstraction. (Hussein et al., 2020) combined irrigation regimes in Diyala Governorate and showed seasonal water table behaviors related to farming activities. (Ali and Mohammed, 2019) found increasing water tables at the urban fringe of Erbil as a result of leakage from the drainage system, indicating surface water/groundwater interaction.

A recent work is a significant contribution to the subject is the three dimensional ground water flow model proposed for Erbil Basin by (Mustafa and Mawlood,2024). Developingthree-dimensionalgrou. This study is one of the most comprehensive 3D groundwater model studies in northern Iraq. groundwater - Using the Groundwater Modeling System (GMS) with the MODFLOW-2000-solver, The calibration statistics showed that the model performance was excellent with Mean Error (ME) = -0.03 m, Mean Absolute Error (MAE) = 0.24 m, and RMSE = 0.36 m and an excellent coefficient of determination (R2 = 0.9998) between observed and simulated heads Developingthree-dimensionalgrouThis recent 3D modeling endeavor greatly advances the earlier two-dimensional and local studies in terms of the basin-wide simulation capability, the ability to integrate the hydrogeological complexity, and the ability for scenario-based groundwater management planning.

5 APPLICATION OF MT3DMS

For simulations of contaminant transport (in most cases coupled with MT3DMS or other similar transport codes), additional parameters are needed:

- Initial contaminant concentration, characterization of the source.
- Effective molecular diffusion coefficients.
- Longitudinal Dispersion Coefficients and Transverse Dispersion Coefficients
- Groundwater velocity and groundwater flow direction fields based on calibrated-flow models.

In their article, (Al-Saadi and Abdullah, 2016) used the model, which is the MT3DMS, to model the landfill leachate as a source of nitrate in Basra, southern Iraq. Their model findings revealed that in a decade, the nitrate plumes were capable of spreading 4 to 6 km with a massive potential hazard to the surrounding drinking water wells. The paper highlighted the necessity of using engineered landfill liners and monitoring systems to ensure that ground water resources in the city are not compromised.

On the same note, (Al-Suraifi, 2017) employed the use of Visual MODFLOW and a three-dimensional model of dispersion to evaluate the transport of contaminants at the Basrah landfill. The outcome was that much expansion of the plumes was expected with the continuity pumping and with the forecast that the horizontal transport rate was about 285 m/year. The experiment revealed the process of increasing the rate at which contaminants spread in urban aquifers through groundwater abstraction.

(Khayyun, 2018) in his study made use of Processing MODFLOW 5.3 to determine the rates of pumping needed to hydraulically segregate a contaminated zone of cobalt-60 (Co-60) in the Al-Tuwaitha district, Baghdad. The study offered useful information on design of containment systems in radioactive contamination cases by simulating fully penetrating pumping wells during the design that were placed next to the contamination source.

The article by (Kareem and Mustafa, 2018) examined the contamination of BTEX (benzene, toluene, ethylbenzene, and xylene) in the Tanjero landfill site in Sulaimani City using the VLEACH model. The simulation study examined the changes in concentration at a variety of depths over a period of 25 years, and determined the long-term effects on groundwater quality. Findings revealed that there was progressive vertical migration and a possible danger to deeper layer of aquifier.

(Kareem et al., 2020) used PHREEQC to simulate the process of groundwater contamination in the Shiwashok Oil Field (Kurdistan Region, Iraq) with a one-dimensional transport model. Their findings indicated a high level of contaminants penetrating water wells and they indicated that it took a very long time in reaching the steady state contamination or acceptable levels. The research study mentioned the significance of geochemical processes in poor organic matter degradation and cation exchange capacity (CEC) in regulating contaminant movements.

The Groundwater Modeling System (GMS) was used to model groundwater flow and solute transport along the two sides of the Tigris River floodplain (Khayyun and Sharif, 2021). The model included the use of water table and total dissolved solids (TDS) data of sixteen observation wells. They showed the spatial variability of the quality of groundwater and highlighted the importance of combined flow and transport modeling as the means of controlling river and aquifers interactions.

(Shukri et al. 2017) modeled the chlorinated solvent transport in an industrial area around Kirkuk with the help of MODFLOW and the MT3DMS. The model forecasted travel periods of contaminants of over eight years to be used in designing specific monitoring and remediation activities.

(Hassan and Yousif 2021) integrated MODFLOW and MT3DMS to assess the effects of landfill leakages in Erbil. With their simulations, they showed that without mitigation efforts, major contaminators will access residential wells in 3-7 years. The paper highlighted the susceptibility of urban aquifers to the unregulated waste disposal activities.

6 APPLICATIONS OF MODPATH GROUNDWATER FLOW PATH AND CAPTURE ZONE ANALYSIS

6.1 Wellhead Protection and Particle Tracking

(Pollock, 2016) created a particle-tracking post-processor called MODPATH that is used in MODFLOW to compute the flow paths and travel time of groundwater. It is nowadays a mandatory instrument of wellhead protection planning and capture zone demarcation.

On the same note, (Seeyan, 2020) used MODFLOW and MODPATH in the Qushtapa Basin (Erbil) to determine the time taken by particles to reach a location and to map the area of recharge. Forward and backward tracking identified the possible pathways of the contaminants migration and was useful in the planning of the protection of the ground water.

7 COMBINED MODFLOW-MT3DMS-MODPATH INVESTIGATIONS

(Fadlallah, 2020) A number of researches have combined the groundwater flow, solutes transport and particle tracking models to create holistic aquifer management models.

Although Lebanon boasts of relatively high water resources through rainfall, karstic geology, over exploitation and poor sanitation have resulted in ground water contamination. The present research examined the processes of groundwater moving and contaminant movement in karst aquifers based on experimental modeling and computational modeling (MODFLOW, MT3DMS, and MODPATH). Findings indicated that there was a good correspondence between experimental and simulated hydraulic heads, contaminated concentrations, and travel times. It was also established that a regression model can be used to predict the contaminant levels.

Field case study in Chadra village verified that the amount of nitrate exceeded acceptable levels and laboratory results could be replicated using numerical modeling. Taking the flow simulation and transport simulation into consideration, safe rates of abstraction and protection levels were suggested to shape the management of groundwater and enhance water safety in karst areas.

One of the most recent pervasive uses of combined groundwater modeling in Iraq was done by (Yashooa and Mawlood, 2023) in the Kaniqurjalal region of the Central Basin of the city of Erbil. This simulation was performed with MODFLOW to describe groundwater flow, MT3DMS to model solutes transport calculation (Total Dissolved Solids -TDS), and MODPATH to conduct the analysis of particle mobility with the Groundwater Modeling System (GMS v10.6).

The results of the calibration of hydraulic conductivity were 3.647×10^{-6} m/s, 2.8935×10^{-9} m/s, and 3.24074×10^{-6} m/s in the three layers respectively. Optimization of the model indicated good correlation between experimental and theoretical hydraulic heads of 0.9935 coefficient of determination (R^2) and RMSE of 1.49 m, which means the numerical model is very reliable.

The simulation in the case of 10, 20, 30, 40, and 50-year predictions was carried out using MT3DMS. Findings have revealed that TDS pollution (generated by landfill leachate) (initial concentration 27,660 mg/L) flowed downstream and upstream of the landfill. Fifty years later, the contamination spread about 1 km on each side and the average speed of the transport was 40.9 m/year. It was found that dispersion process had more effect on solute migration as compared to advection and diffusion processes.

The results of the MODPATH particle tracking also helped in better understanding of the direction and path that ground water flows in the basin between the eastern and western regions and highlighting the likely routes in which the contaminant can flow in the eastward direction to residential and commercial areas. The velocities of groundwater in the upper layer were 0.0728-0.00011 m/day and the velocities in the clay layer were much lower because the clay layer was less permeable.

(Yashooa et al., 2023) Ground water is a major source of water in the Kurdistan Region and Erbil City. The increase causes the deterioration of the quality and amount of ground water. The model to be used in the proposed study was to model groundwater flow in the central basin and simulate the movement of nitrate through Erbil dump site (10, 20, 30, 40 and 50) years using Groundwater Modeling System (GMS) version 10.6.2 using MODFLOW and MODPATH and MT3DMS. To determine the properties of a landfill leachate wastewater, a sample was taken. The landfills have leachate which are considered point source of pollution. The GMS is an efficient software with which to model groundwater flow and contaminants transfer. The findings indicate that there exists a high correlation between the estimated and actual values and the model has got a R 2 of 0.9917. The sources of nitrate pollution were both horizontal and vertical length in the range of approximately 1.5 km of downstream and upstream of the landfill. Nitrate enters the third layer after 50 years reaching a depth of more than 325 meters.

(Yashooa et al., 2025) Ground water is an important asset in the Erbil city, and due to high rates of urban growth, the quantity and quality of groundwater has been deteriorating. This paper involved the Groundwater Modeling System (GMS 10.6.2) to model groundwater flow and chloride movement of a dump site under both steady and dynamic conditions by using MODFLOW and Mt3DMS. Calibration of a model revealed good correspondence between observed and simulated heads (R 2 = 0.9917), with calibrated values of 1.4 m/d, 0.0025 m/d and 1.35 m/d being the three layers hydraulic conductivity, and the porosity being 0.23, 0.095 and 0.37 respectively.

The results of the simulations showed that at the current rates of pumping 25 percent more pumping would lead to the maximum drawdown of 9.24 m in a year, and 50 percent would lead to 14.2 m drawdown in ten years (since 2022). It was estimated that chloride contamination would extend the distance of about 1.6 km in the span of 50 years, with the average rate of 113.9 m/year. The paper establishes that GMS is a useful instrument of forecasting groundwater reactivity and migration of the contaminants, which underpin sustainable management of groundwater in Erbil.

This paper shows that flow, transport, and particle tracking models should be combined when analyzing the long-term risk of urban groundwater. As an urban planning, the results give quantitative results of:

- Setting up protection zones in landfills.
- Controlling the future residential and industrial developments around polluted plumes.
- Creating surveillance systems on expected migration directions.
- Favouring landfill management and remediation techniques.
- The use of the groundwater exposure maps in urban master planning.

The Kaniqurzhala case is one of the most elaborated cases of coupled MODFLOW-MT3DMS-MODPATH modeling in the Kurdistan Region and it shows the value of the numeric groundwater modeling in the context of the urban environmental management.

8 URBAN PLANNING AND URBAN POLICY GROUNDWATER MODELLING

In addition to a technical use, groundwater modeling software like MODFLOW, MT3DMS, and MODPATH have been noted to be used as decision-support systems in urban planning and sustainable water management.

According to (Foster et al., 2010), the inclusion of groundwater models in the urban water planning structures is necessary in order to control abstraction and land-use planning, as well as be used to determine the long-term sustainability.

(Lerner, 2002) has performed a review of the urban recharge processes and pointed to the important contribution of the impervious surfaces to the process of groundwater replenishment. It was suggested in the study that numerical models should be used to quantify variability in recharge when urbanization is taking place.

In developing countries, (Howard, 2007) explained how groundwater models can be used whereby the results of the models are essential in ranking groundwater infrastructure and groundwater and pollution control projects as well as groundwater protection programs.

Together, these studies indicate that the modeling systems based on MODFLOW give efficient tools to simulate the groundwater flow, movement of contaminants, and flow paths. The inclusion in the work of urban planning increases the evidence-based decision-making process, assists the groundwater protection policies, and favors the sustainable management of urban aquifers.

9 SIGNIFICANCE OF GROUND WATER MODELING STUDY IN URBAN PLANNING

The literature review reveals that numerical groundwater model using the MODFLOW, MT3Dms and MDPATH is a major scientific and strategic paradigm of sustainable urban planning particularly in semi-arid areas like Iraq. Urbanization has greatly put pressure on the groundwater systems in the fast growing cities such as Erbil, Basra, Baghdad and Sulaimani. The elevated groundwater extraction, growth of urban landfills, industrial effluents, discharge of sewer networks and agricultural-urban transition areas have all augmented the susceptibility of aquifers. In water-deficient areas where groundwater often forms the main or crisis source of drinking water, ensuring the integrity of the aquifers is directly related to health of the population, economic and climate stability.

The U.S. Geological Survey has created a powerful model of groundwater flow simulation in three dimensions under both steady-state and transient conditions called MODFLOW (McDonald and Harbaugh, 1988. The flow direction analysis, water budget, and hydraulic head distribution of the aquifer permit the planners to comprehend the behavior of the aquifers at different rates of recharge and pumping pressures through the use of the MODFLOW software. Such simulations are critical in semi-arid settings where recharge rates are low and evapotranspiration rates are high as to the assessment of the sustainability of aquifer and the avoidance of overexploitation.

In addition to flow simulations, a quantitative modeling of the contaminants transport processes by advection, dispersion, diffusion, and chemical reactions can be implemented with the help of the MT3DMS (Zheng and Wang, 1999). Transport simulations are also applicable in urban situations where landfill leachate, industrial effluents, hydrocarbons, nitrates and heavy metals are dangers of contamination. MT3DMS can forecast the future groundwater quality under various development conditions by predicting the movement of plumes, the patterns of dispersion, and the patterns of concentrations in the groundwater over long periods of time (10-50 years). The ability to predict over long periods is invaluable to intergenerational plans and strategies of climate adaptation.

The protection of groundwater is also furthered by the analysis of particle-tracking where the MODPATH is applied to calculate capture zone, recharge region, and wellhead protection boundaries (Pollock, 1989; Pollock 2012) based on the standards of travel-time. Protection zones of the hazardous land use around the public supply wells are scientifically defensible (e.g. 2-year, 5-year, 10-year travel time areas) and can be regulated by the municipalities unlike the empirical buffer distances. This is especially true in Iraqi cities, where the regulations are being changed, and space planning needs technically-grounded boundaries that would reinforce environmental policies.

As an urban planning tool, modelling Integrated MODFLOW-MT3DMS-MODPATH has a number of strategic purposes:

(1) Master Planning and Zoning of Land-Use.

The outputs of models determine areas of vulnerable recharges and pathways of high risk to contaminant sources so that planners can limit residential development or sensitive infrastructure development in the areas prone to contamination. Hydraulic conductivity, recharge distribution, and dispersion characters are used to derive ground water vulnerability maps to facilitate the sustainable zoning of ground water resources.

(2) Wellhead Protection and Public Health Protection.

This gives the opportunity of capture zone delineation whereby targeted restrictions of landfills, fuel stations, industrial facilities and waste disposal sites can be made within specified travel-time zones. This minimises chances of contamination to municipal drinking water wells and improves international standards of water safety.

(3) Design and Optimization of Infrastructure.

The consequences of pumping rates, engineered landfill liners, upgrading of a wastewater network and artificial recharge systems are analyzed in modeling scenarios. Simulation can be used by authorities to optimize the pumping schemes to reduce the plume spreading and lower long-term costs of remediation.

(4) Environmental Impact Assessment (EIA).

Numerical models are used to give quantitative evidences that are necessary in licensing new industrial facilities, granting landfill sites, and issuing ground water abstraction permits. Regulatory agencies are increasingly demanding predictive evaluation of hydraulic head change, contaminant travelling time as well as long-term forecasts of concentrations as part of EIA processes.

(5) Urban and Climate Change Adaptation.

Semi-arid areas are especially susceptible to extended drought and a decrease in surface water. Ground water usually proves to be the major buffer source in periods of oppressive weather. The uncertain conditions of recharge and abstraction modeling under varying climate conditions improves the urban resilience planning process and provide the sustainable distribution of scarce water resources.

Taken together, the studies that were reviewed allow concluding that groundwater modeling tools are not just scholarly exercises, but viable decision-support systems. They change groundwater management into non-reactivity in responding to contamination, but risk prevention. These models offer spatial visualization of pollution hazards, temporal prediction of aquifer quality, and scenario-oriented assessment of policy options, which explains the reason why they can bridge the gap between the hydrogeological science and urban governance.

To sum up, the combination of MODFLOW, MT3DMS, and MODPATH creates a full-fledged modeling system that can be used to address the needs of evidence-based urban planning, environmental protection, and sustainable management of groundwater in semi-arid and fast-urbanizing areas.

10 CONCLUSION

The analyzed literature confirms the fact that numerical modeling of groundwater with the use of MODFLOW, MT3DMS, and MODPATH is a significant instrument to the sustainable urban planning in semi-arid areas like Iraq. These models have scientifically reliable information on land-use zoning, infrastructure design, and environmental protection by simulating the movement of contaminants, forecasting their movement, and defining their capture zones in wells. They allow planners in urban areas to predict potential risks in the future, protect drinking water resources and facilitate evidence-oriented policy making. The inclusion of groundwater modeling into the structure of municipal planning is thus very imperative in safeguarding human health, improving the resilience of the climate, and attainment of sustainable urban development in fast growing urban centers.

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