ZANCO Journal of Pure and Applied Sciences
The official scientific journal of Salahaddin University-Erbil
https://zancojournals.su.edu.krd/index.php/JPAS

ISSN (print):2218-0230, **ISSN (online):** 2412-3986, **DOI:** **http://dx.doi.org/10.21271/zjpas**

RESEARCH PAPER

Numerical Modelling of Groundwater Flow and Contamination Transport (TDS) in Kaniqurzala Area- Central Basin – Erbil City-Kurdistan - Iraq

[1]Noor Khalid Yousif Yashooa, [2]Dana Khider Mawlood

[1]Department of Water Resources, College of Engineering, Salahaddin University-Erbil, Kurdistan Region, Iraq
[2]Department of Civil, College of Engineering, Salahaddin University-Erbil, Kurdistan Region, Iraq

ABSTRACT:

Modeling groundwater is an effective method for predicting the hydrological characteristics of an aquifer and estimating the influence of pollution transport in groundwater. The objective of this study is to analyze groundwater flow and contaminant transport (TDS) over 50 years in the Kaniqurzhala region - Erbil City using GMS (Groundwater Modeling System) version 10.6. In April and May of 2022, the static water table for 27 wells was measured in a 60.80 km2 research area. A sample of landfill leachate, considered a point source of pollution in the research region, is collected. The dimensions of the model domain's 80 columns and 76 rows are (100m x 100m). The MODFLOW, MODPATH, and MT3DMS codes are utilized for modeling groundwater flow and pollution transfer. There was a strong connection between the measuring head and the estimated head, and the model's coefficient of determination was $R^2 = 0.9935$. After calibration, the hydraulic conductivity values for layers 1, 2, and 3 are (3.647222×10^{-6} m/s, 2.8935×10^{-9} m/s, and 3.24074×10^{-6} m/s, respectively). TDS concentrations travel upstream and downstream of landfills and pollute many wells in the research region.

KEY WORDS: Contamination, leachate, MODFLOW, TDS
DOI: http://dx.doi.org/10.21271/ZJPAS.35.3.2
ZJPAS (2023) , 35(3);17-29

1. INTRODUCTION:

Groundwater is an essential water source in many regions, particularly semiarid and arid regions. Due to urbanization, industry, and development, groundwater's quantity and quality have declined significantly in recent years (Gebrehiwot et al., 2011, Rajappa et al., 2011, Ghoraba et al., 2013, Lanjwani et al., 2019).

The impact of landfill leachate on groundwater and surface water has gained considerable attention in recent years. Without regulation, leachate may move from landfills, posing a grave hazard to water supplies (Al-Suraifi, 2017). Understanding the performance of the aquifer under present conditions and estimating the effect of increased discharge and recharge on the aquifer is necessary for groundwater management.

The aquifer may be simulated using a groundwater numerical modeling procedure in order to assess the influence of discharge, recharge, and other hydrological parameters of the aquifer, the hydrological effect on the water table, and the impact of pollution transit in groundwater (Asghari, 2005, Ali and Oleiwi, 2015). Modeling groundwater is vital for investigating groundwater flow and pollutant transfer by applying a finite-difference grid to the subject region via the discretization procedure (Klaas et al., 2017, Okuhata et al., 2022).

Modular finite-difference groundwater flow model (MODFLOW) is computer software that simulates groundwater flow systems(McDonald and Harbaugh, 1988, Harbaugh and McDonald, 1996). MT3DMS is a modular three-dimension multispecies solute transport model to simulate contamination transport, which studies the effect of dispersion, advection, molecular diffusion, and

* **Corresponding Author:**
Noor Khalid Yousif
E-mail: noorkhalid192@gmail.com

Article History:
Received: 21/09/2023
Accepted: 01/11/2023
Published: 20/06/2023

chemical reactions such as non-linear absorption and first-order radioactive decay or biodegradation. It is designed to model changes in contaminant concentrations in groundwater flow systems (Zheng et al., 2012). MODPATH is an article tracking code used to study the direction of groundwater and particle tracking. A groundwater modeling system (GMS) is software used to model groundwater flow and contamination transport(Panagopoulos, 2012)

Many types of research were done in this field and can be summarized as follows: (Duriez, 2005) modeled the groundwater contamination transport in the Wockatz site in Sweden using the MODFLOW code and the MT3DMS code. The result shows that the Wockatz site is contaminated. Pollutants are distributed in both water media and soil. (Ghoraba et al., 2013) Investigated groundwater quality in Egypt's middle Nile Delta by using MODFLOW and MT3DMS models to solve the problem of pollutants transport with time. The results suggest that groundwater quality has deteriorated, and ammonium concentrations have reached dangerous levels. (Al-Suraifi, 2017) three-dimensional simulation models were built and calibrated to describe groundwater flow and leachate pollutants transport from a dumpsite in Basra, Iraq, using Visual MODFLOW Version 4.2. The final simulation and prediction result reveals that the landfill is the primary source of contamination and pollutant transport in the aquifer with a rate of 285 m/year; according to the simulation result to 2031, the pollutant will reach a distance of 4 Km from the landfill with depth 60m. (Khayyun and Sharif, 2021)was studied groundwater quality on the left and right sides of the flood plain of Tigress River by modeling the groundwater flow and solute transport for 24 years using the Groundwater Modelling System (GMS). The study shows that industrial effluent had a more significant impact on the left bank of the Tigris River than on the right bank.

This paper aims to simulate groundwater flow and contamination transport in the Kaniqurzala dumpsite and predict the future effect of contamination using GMS software version 10.6.

2. MATERIALS AND THEORY

2.1. Mathematical Background

MODFLOW code is used to solve the groundwater flow partial differential equation, which is based on darcy law and conservation equation(Rushton, 2004):

$$\frac{\partial}{\partial x}\left(Kx\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(Ky\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(Kz\frac{\partial h}{\partial z}\right)= S_s\frac{\partial h}{\partial t}-W \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(1)$$

S_s: is specific storage of the porous material (L^{-1}), t: is the time (T), W: is the volumetric flux 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 et al., 1984)is:

$$\frac{\partial C}{\partial t}=\frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial C}{\partial x_i}\right)-\frac{\partial}{\partial x_i}(v_i C)+\frac{q_x}{n}C_s+\sum_{k-1}^{N}R_c \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

Where:-

C: is the contaminant concentration in groundwater, t: is the time (t), vi is the seepage velocity, q_x is the volumetric water flux per unit volume of the aquifer, C_s is the sources or sinks concentration, D_{ij} is the coefficient of hydrodynamic dispersion, n is the porous medium porosity, R_c is the term of a chemical reaction.

2.2 Study Area Description

The Kaniqurzhala neighborhood is located in Erbil's center basin. The research area is approximately 60.80 km^2 and is located between (43º51′12.67″-43º56′32.10″)E and(36º12′36.84″-36º8′32.98″)N. The Erbil landfill is located approximately 10 kilometers west of Erbil City in the Central Basin on a hill joined by two drainage valleys in the Erbil plain. It is situated at 36° 11' 40.60" N and 43° 53' 05.10" East, as seen in picture (1). Since 2001, the Erbil landfill has been functioning. The Erbil landfill site gets a distinct variety of home garbage, averaging between 1900 and 2000 tons of solid waste daily (Municipal ministry). As seen in fig.2, the geological formations of the research region include the Bai Hassan (Upper Bakhtiari) and Mukdadiya (Lower Bakhtiari) formations, as well as recent sediments and Quarternary. In the Pliocene Mukdadiya Formation, sandstone, gravely sandstone, and red mudstone are found in fining upward cycles(Jassim, 2006). The bulk of the study area is occupied by the Pliocene Bai Hassan Formation, which consists of molasses sediments that alternate between claystone and conglomerates and contain sandstone and siltstones (Hassan, 1998). The groundwater aquifer in the research region is an unconfined aquifer composed mainly of gravel, sand, silt, and clay, as seen in Fig.3the lithology description of the most bottomless well in the study area.

2.3 Data Collection

The fieldwork includes data collection on the research area and groundwater characteristics. Because there are no observation wells in this region, a sounder is utilized to estimate the static water table in 27 wells between (138m) and (6022) meters from the dump. The results of the chemical and physical analyses of water samples from the same wells and leachate samples from the landfill are provided in Tables 1 and 2.

2.4 Simulation Model Setup

A conceptual approach is used to build the model with a total area of 60.80 km^2 and a thickness of model 400m; the model domain is divided into 85 columns and 81 rows with dimensions (100 x 100) m, the active cell is 6080, and inactive cell is 1480. The aquifer is divided into three layers. The first layer is a silty sandy gravel formation with a top elevation of 434m and a bottom elevation134 m. The second layer is clay, with a top elevation of 134m and the lowest elevation of 109m. The third layer is silty sand with a top elevation of 109 and a bottom elevation of 34m. All the model boundaries are considered constant heads for steady-state conditions; these values vary between (258 – 345) m a.s.l. The initial head is the GMS software assumed as a default value, which equals top layer elevation. In order to simulate distributed groundwater recharge, the recharge package is used. The groundwater recharge is based on annual rainfall and study area(Al-Kubaisi et al., 2019). (Al-Kubaisi et al., 2019)calculated the groundwater recharge of the central basin from (1980-2016), and the result shows that the annual groundwater recharge was about 0.08782m/year. This study applies the constant groundwater recharge of 0.08782m/year, equal to 2.406027397 x10^{-4} m/d, to the study area's top layer. Well, packages with flux are added to the model. Also, TDS concentration was chosen to simulate this study. Constant concentration is added to the landfill location as a point source depending on the value of contaminates concentration in landfill leachate, the TDS concentration in landfill leachate is 27660mg/l. Three packages are selected to study contamination transport advection, dispersion, and sink/source mixing packages. The initial concentration of TDS is 814mg/l as the average value of TDS from the field measure, which varies between (2514- 539.4) mg/l. Three GMS codes are used MODFLOW to simulate groundwater flow, MODPATH to study the direction of groundwater flow, and MT3DMS to simulate contamination transport in the study area.

2.5 Aquifer Parameters

The hydraulic conductivity and porosity of the aquifer are determined based on the soil type of layer; the hydraulic conductivity can be present in fig. 4 (Heath, 1998). The initial porosity value is the average value, as shown in Table 3. The longitudinal dispersivity varies between (10^{-2}-10^{4}), which is assumed to be 250m in this study(Gelhar et al., 1992), and transverse dispersivity assumed to be (1/10) of longitudinal dispersivity; the effect of molecular diffusion is minimal can be taken approximately zero(Saatsaz et al., 2013, Khayyun, 2018).

3. RESULTS AND DISCUSSION

The most sensitive parameters in the numerical simulation were hydraulic conductivity, porosity, and recharge rate. The model was calibrated by using the trial and error method. The values of hydraulic conductivity and porosity were changed until they got good calibration results, while the recharge rate was assumed constant. The hydraulic conductivity was more affected in the model calibration than other parameters. Calibration was achieved when the estimated interval of error ±5% of the observed value, the best fitting curve between the calculated head and observed head can be presented in fig.5. The calibrated value of hydraulic conductivity, porosity, and recharge rate is presented in table 4. Groundwater flow contours for three layers were presented in fig. 6(a,b, and c), the groundwater flows from the right side of the model to the left side of the model (from high to low water head). Depending on the results of the observed and calculated head, some of the statistical parameters are calculated, such as root mean square error (RMSE) = 1.495166, mean error (ME) = 0.0371, mean absolute error (MAE) = 0.0371, coefficient of determination R^2=0.9935.

MODPTH code was used to study groundwater flow direction in the Kaniqurzalah area. Fig. 7 is illustrated how the particles move from the landfill site to the surrounding area. The value of groundwater velocity for the first layer varied between (0.0728-0.0001125643175) m/d, and the velocity in the second layer is small due to low permeability for clay, which varied between (0.0001690047357-7.02353918x10^{-6})m/d, and the velocity of groundwater in the third layer varied between(0.0498670525849-0.0004991621245)m/d.

MT3DMS code was run depending on MODFLOW available parameters for (April and May) 2022, and the TDS concentration was simulated 10, 20, 30, and 50 years from 2022, as shown in fig.9(a,b,c,d,e, and f). The result showed that the dispersion package highly affected transport TDS in groundwater more than other packages, such as advection and diffusion.

The variation of TDS concentration with different distances from landfills (upstream and downstream landfill) is presented in fig. 10(a,b) . The TDS concentration decreases with distance from the landfill site and increases with time. The highest TDS concentration was recorded in well11, 17, and well19 and in the Erbil store area. The pollution transport in this aquifer at a rate of 40.9m/year, and after 50 years, the TDS concentration reaches 1km upstream landfill site and 1 km downstream landfill site.

4. CONCLUSIONS

Groundwater modeling is a powerful tool to study the situation of the aquifer and then connect it to study the contamination transport in the aquifer. The primary aim of this paper is to evaluate the effect of leachate emitted from landfill and how the contamination is transported in groundwater. The results were shown that the value of hydraulic conductivity for the (first, second and third) layers were 3.647222 x10^{-6}m/s, 2.8935x10^{-9} m/s, and 3.24074x10^{-6} m/s, respectively. The model calibration showed a higher sensitivity to hydraulic conductivity than the porosity. It was essential to add wells flux to the model; significant and unique hydraulic conductivity calibration was possible if at least some flux was given explicitly. There was a good correlation between observed and calculated head R^2= 0.9935. TDS contamination transported from landfill leachate and contaminated a large area about 1km upstream landfill and 1 km downstream landfill. The dispersion package was more affected by contamination transport than the advection package.

Table1: Concentration of groundwater parameters in wells

NO.	Date	Location	pH	EC	TDS	Cl^-	Ca^{++}	Hardness	Alkalinity	Turbidity	NO_3^-	SO_4^{2-}	Mg^{++}	K^+	Na^+	PO_4^{3-}	Iron	Copper
Unit				µs/cm	mg/L	mg/L	mg/L	mg/L	mg/L	NTU	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Standard (WHO)				1000	500	250	75	300	200	5	50	200	30	10	200		0.3	2
1	10/4/2022	Sample 1 Well No.(1)	7.8	1360	765	75.55	70.4	268	90	1.72	35.44	260	22.38	5.3	83.1	0.01	0.06	0
2	10/4/2022	Sample 2 Well No.(6)	8	1436	818	75.52	68.89	270	108	9.33	22.98	210	23.78	7.2	73	0.001	0.05	0
3	10/4/2022	Sample 3 Well No.(5	7.9	1340	750	85.9	75.8	279	120	8.44	38.5	220	21.77	5.8	85.5	0	0.02	0.001
4	10/4/2022	Sample 4 well No.(3)	7.7	1190	667	75.82	75.2	282	116	7.5	47.1	228	22.87	4.5	75	0.05	0.011	0.002
5	10/4/2022	Sample5 Well No.(4)	8	1330	745	81.3	76.8	281	248	16.5	45.8	216	21.65	6.1	86	0.06	0.03	0
6	10/4/2022	Sample 6 Well No.(11)	7.9	1350	700	77.36	68.7	280	112	1.15	42	218	26.33	5.2	83	0.01	0.04	0
7	10/4/2022	Sample7 Well No.7	7.8	1310	734	75.51	78.4	283	114	8.17	39.87	267	21.16	5.1	78.4	0	0.01	0.004
8	10/4/2022	Sample 8 Well No.2	7.8	1434	804	78.89	73.6	280	94	7.32	41.5	272	23.35	6.1	85.6	0.002	0.09	0.005
9	18/4/2022	Sample 9	8.2	1440	864	101.31	84.8	348	88	2.44	26.58	280	42.03	10.1	119	0.06	0.06	0.001
10	18/4/2022	Sample 10	8.2	1315	789	99.41	62.4	276	80	1.19	32.78	300	29.19	5.1	113.6	0.04	0.04	0
11	18/4/2022	Sample11	8.1	1448	868.8	110.46	64	288	90	1.82	40.31	340	31.14	6.4	138.7	0.01	0.09	0.003
12	18/4/2022	Sample12	7.9	1453	871.8	121.5	57.6	240	84	1.03	22.15	344	23.35	6.7	174.9	0	0.002	0.001
13	18/4/2022	Sample 13	8.1	1231	738.6	77.32	59.2	305	156	1.43	70.88	284	38.19	5.7	107.7	0.001	0.001	0.002
14	18/4/2022	Sample 14	7.9	1006	603.6	58.91	75.2	360	202	1.05	48.41	112.9	41.84	3	69.3	0	0.008	0
15	18/4/2022	Sample 15	7.8	899	539.4	46.02	67.2	280	320	1.06	33.67	84	27.25	3.1	67.2	0.02	0.05	0.001
16	18/4/2022	Sample16	7.7	1284	770.4	154.6	80	384	186	1.47	33.66	112.3	44.76	4.8	118	0.09	0.009	0
17	18/4/2022	Sample 17	7.5	1112	667.2	99.41	51.2	260	80	1.4	21.26	280	32.11	6.3	104.2	0.07	0.07	0
18	19/5/2022	Sample 18 , Kani Qurzala Check point	8.2	1354	813	110	16	220	100	1	33.22	120.1	43.7	10.2	280.8	1.1	0.04	0
19	19/5/2022	Sample 19 gas factory	7.2	4190	2514	570	376	1268	406	25.2	58.6	374	79.8	9.1	366.3	3.1	2.8	0.5
20	19/5/2022	Sample20 Alaf(Kumrek)	7.6	1220	732	82.8	73.6	348	222	1.29	43.41	58.8	48.66	5.5	370.2	0.01	0.1	0
21	19/5/2022	Sample21 government gas factory	7.8	1016	609.6	66.3	51.2	256	200	42.7	51.2	46.9	31.14	6.9	439	0.05	0.008	0
22	19/5/2022	Sample 22 Sweri Village	7.6	968	580.8	57	65.6	304	238	1.1	22	47.9	34.06	5.8	469	0.03	0.001	0.002
23	19/5/2022	Sample23 (Alla oil station)	7.7	1156	693.6	71	78.4	420	146	1.23	36.4	28.6	54.5	7.4	623	0.04	0.008	0
24	19/5/2022	Sample 24 Erbil store 3	7.6	2180	1308	386	145.6	704	264	23.3	58.47	41.2	82.48	9	698	3.1	2.3	2.1
25	19/5/2022	Sample 25 Qaryataq village well2	7.9	1104	662.4	110.5	65.6	336	192	1.64	44	39.7	41.84	8.9	728.1	2.01	1.1	0.001
26	19/5/2022	Sample 26 Arab Kandi well 1	7.7	1210	726	62.6	73.6	456	370	1.74	70.8	23	66.18	8.8	728.9	1.5	0.07	0
27	19/5/2022	Sample 27 Turaq village well7	7.6	1080	648	60.8	78.4	352	244	0.93	23.1	36.3	37.95	8.5	792	1.4	0.01	0.001

Table2: Properties of Kaniqurzala landfill leachate

Physical and Chemical Parameters	**Results**	**Permissible level for wastewater**
Total Suspended Solids (TSS) mg/L	12000	40
Turbidity(NTU)	3300	5-25
pH	6.1	6.4-8.5
Temperature (C°)	18.9	12-25
Electrical Conductivity µs/cm	46100	3000
Dissolved Oxygen(DO)mg/L	2.01	More Than 5
Biochemical Oxygen Demand (BOD5)mg/L	14789	40
Chemical Oxygen Demand(COD)mg/L	21128	100
Oil and Grease mg/L	8.633	5
Chloride mg/L	6666	450
Calcium mg/L	3168	400
Total Dissolved Solid mg/L	27660	2500
Alkalinity mg/L	17820	250
Hardness mg/L	11880	500
Sodium mg/L	8733	230
Potassium mg/L	16632	20
Nitrate(NO3-) mg/L	5264	50
Sulphate (SO42-) mg/L	5999	400
Phosphate (PO43-) mg/L	1110	12
Magnesium(Mg2+) mg/L	963.5	150

Table 3: Porosity of soil layers.

Description	Porosity	Effective porosity	Reference
silty sandy gravel	0.18-0.28	-	(Dysli, 2000)
Clay	0.4-0.7	0.01-0.18	(Woessner and Poeter, 2020)
silty sand	0.25-0.49	-	(Dysli, 2000, Das and Das, 2008)

Table4: The parameters used in the model to get the best fitting curve in the calibration process

Description	Hydraulic conductivity m/d	porosity	Recharge Rate m/d
silty sandy gravel	0.29	0.23	$2.406027397 \times 10^{-4}$
clay	0.00025	0.095	-
silty sand	0.28	0.3	-

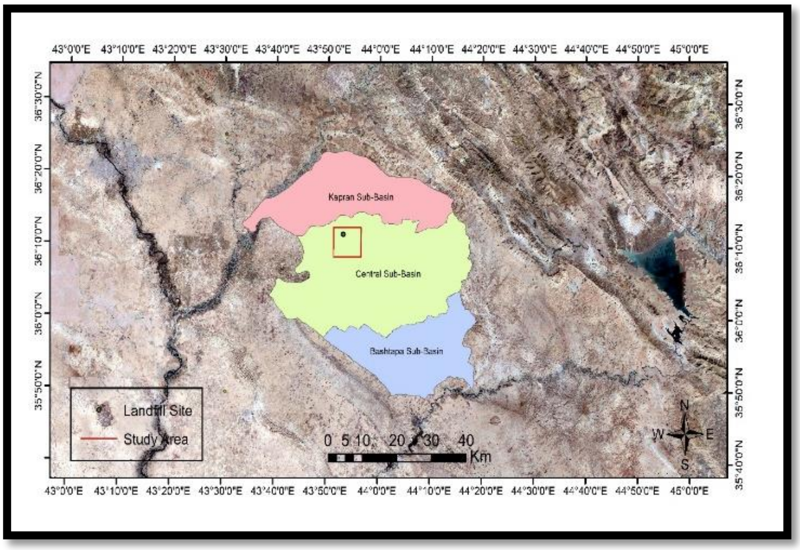


Fig.(1): The satellite image of Erbil city shows the study area's location, the Erbil landfill site, and three sub-basin.

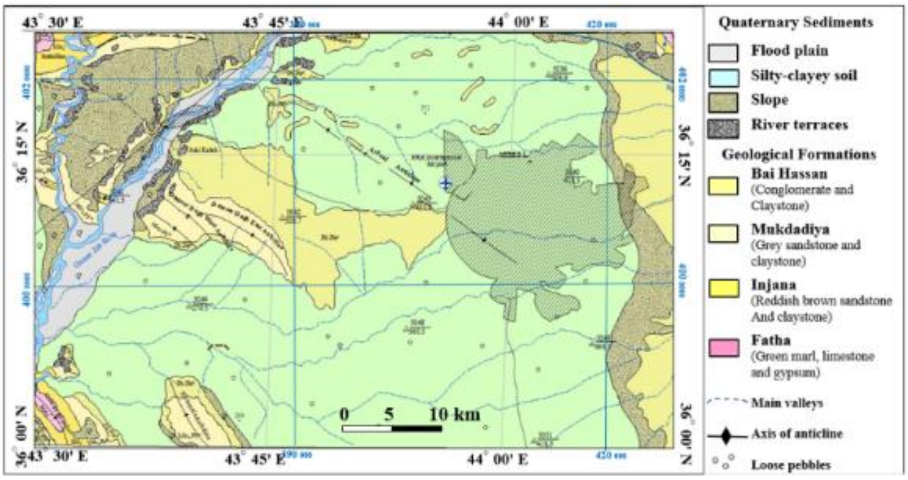


Fig.(2): Geological map of the Kaniqurzhala area and near surroundings (Sissakian and Fouad, 2014).

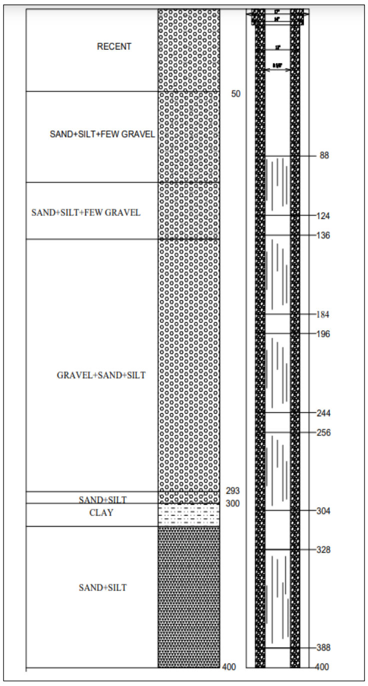


Fig.3: Lithology description (General Director of Groundwater)

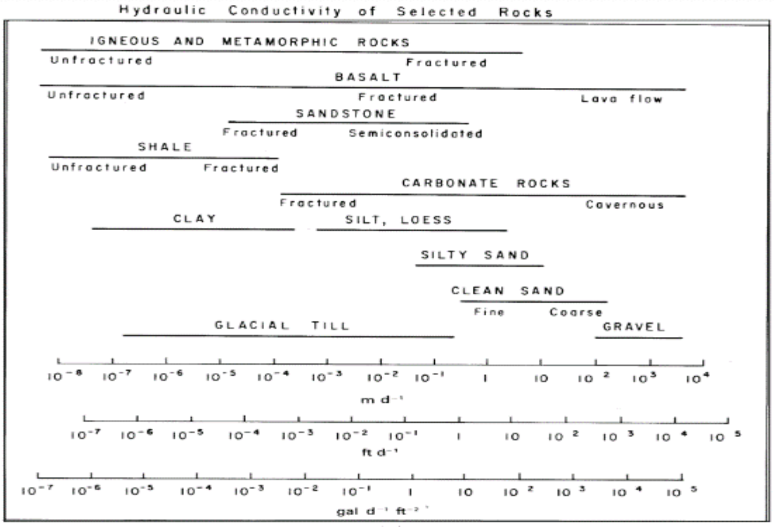


Fig. (4): Hydraulic conductivity of different soil types(Heath, 1998)

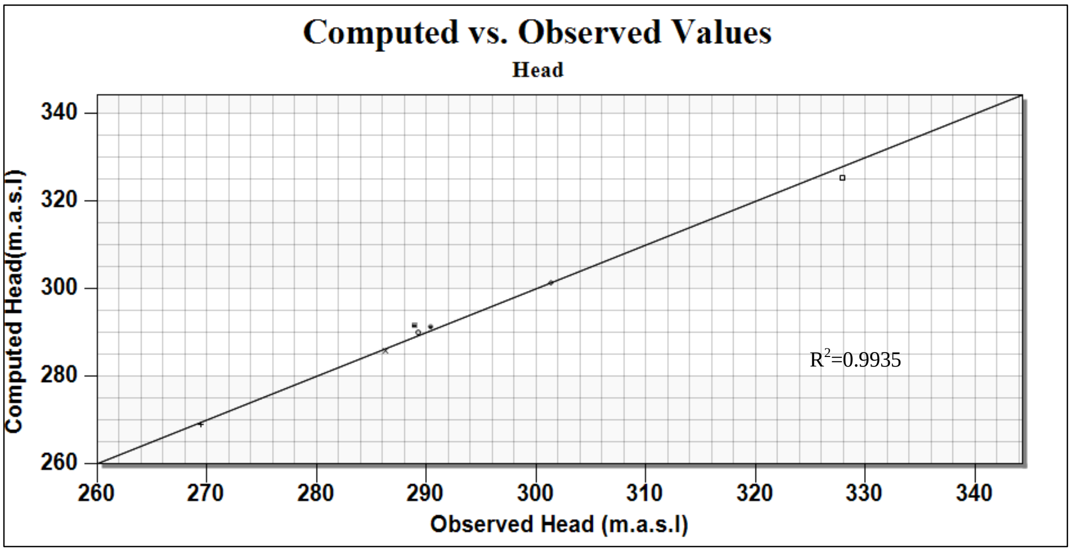


Fig. (5): Best fitting curve between observed head and calculated head

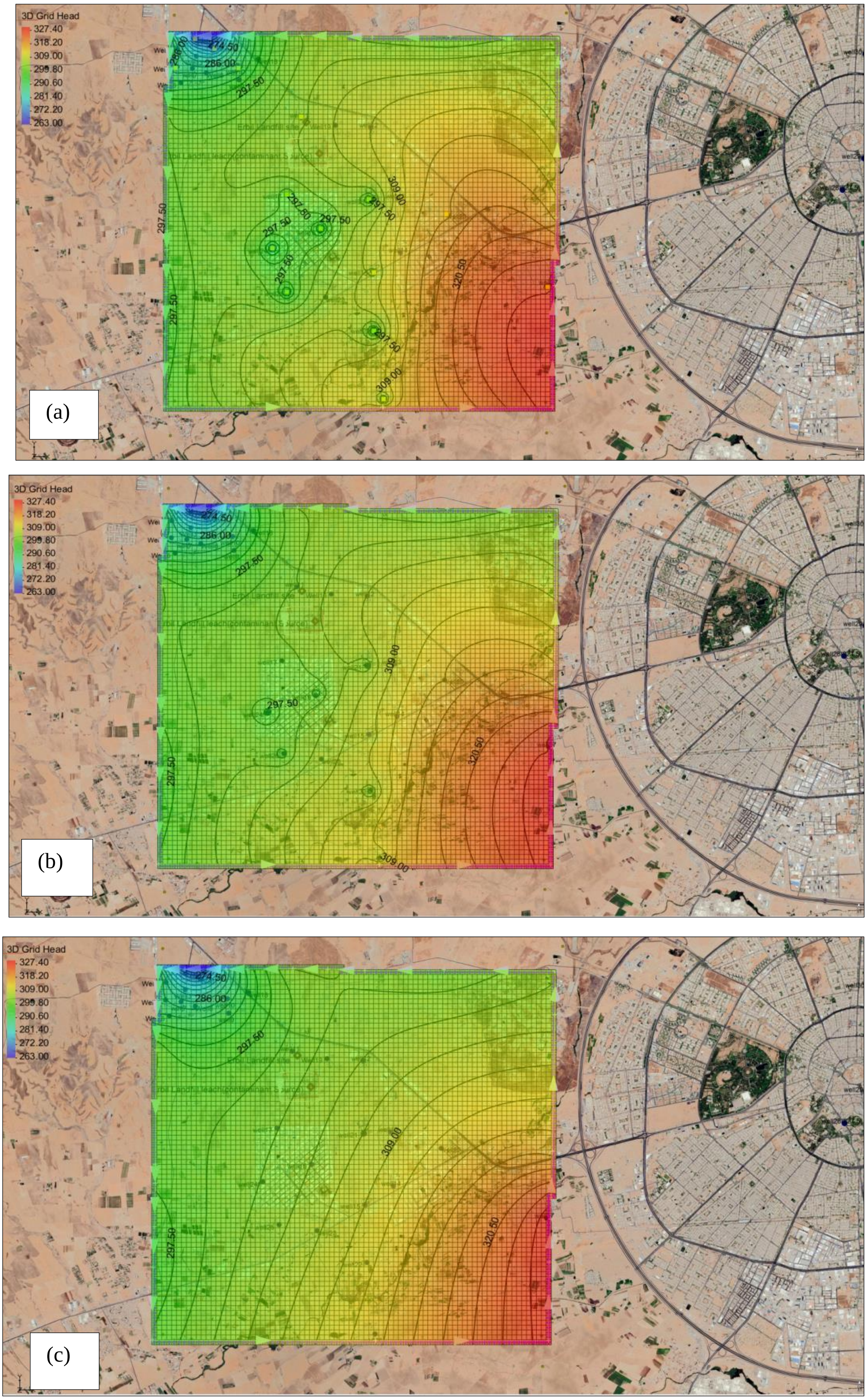


Fig.6: Groundwater flow contour at steady state condition a)layer1, b)layer 2, c) layer 3

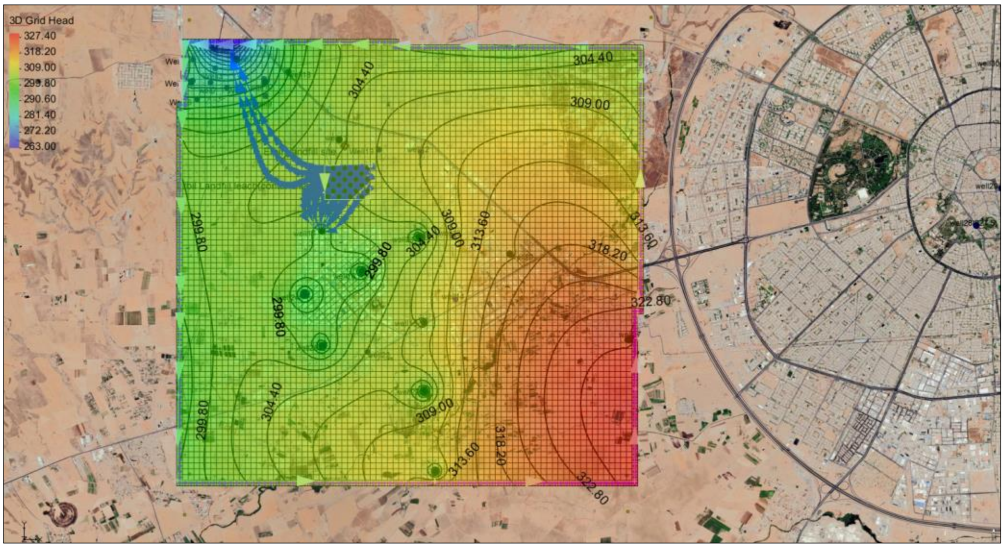


Fig. (7): Particles transported from the landfill site to the surrounding area

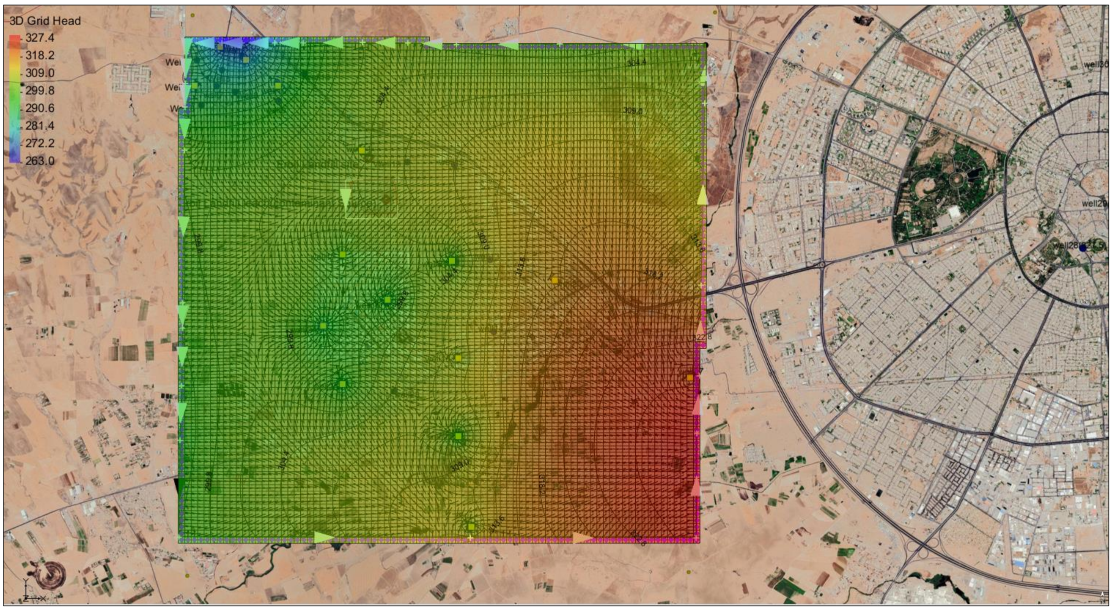
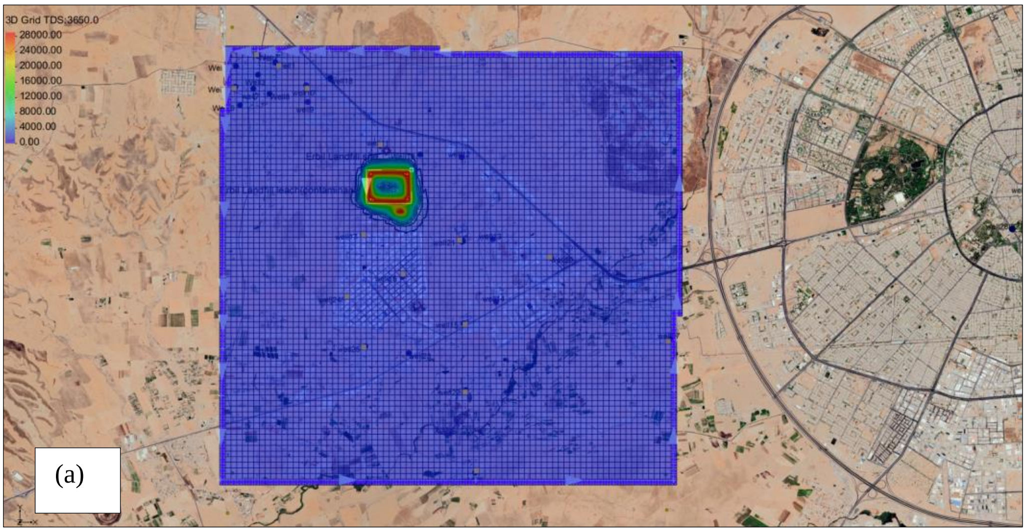
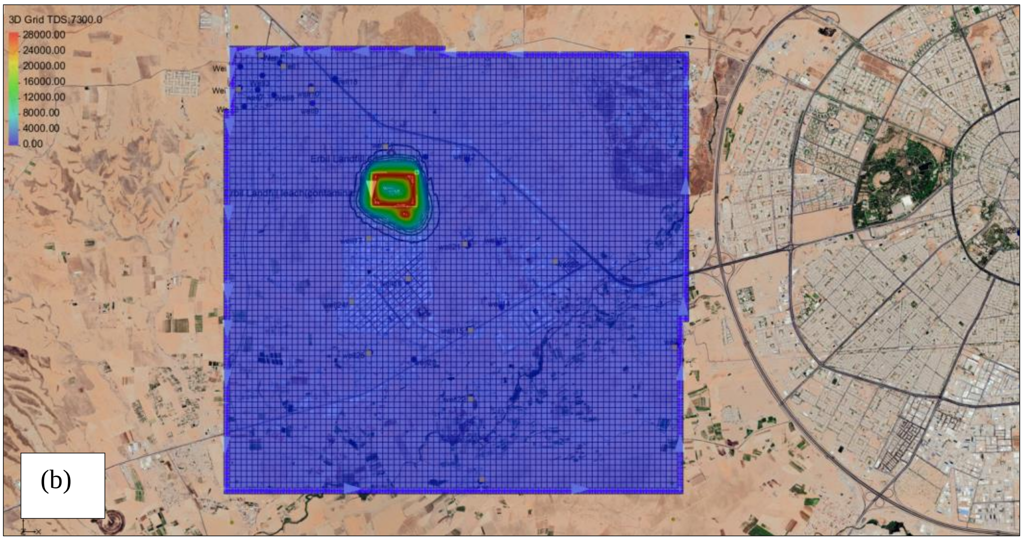
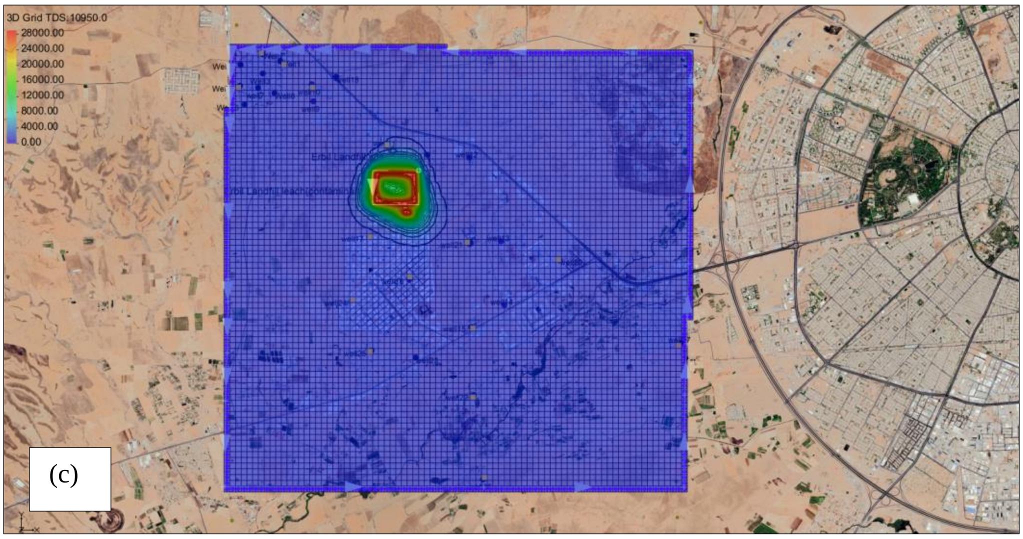
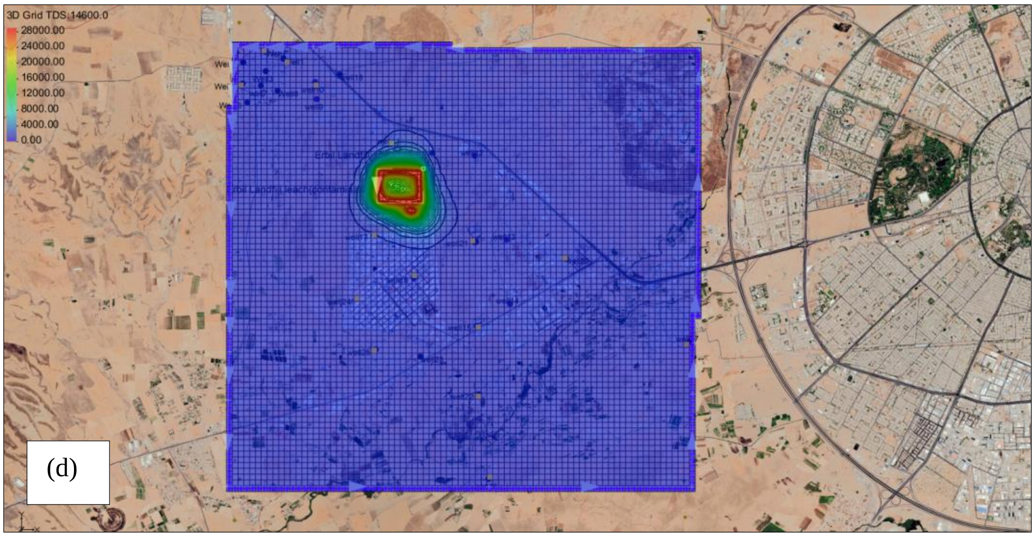


Fig. (8): Velocity vector for the first layer




3D Grid TDS:7300.0
28000.00
24000.00
20000.00
16000.00
12000.00
8000.00
4000.00
0.00
(b)


3D Grid TDS:10950.0
28000.00
24000.00
20000.00
16000.00
12000.00
8000.00
4000.00
0.00
(c)


3D Grid TDS:14600.0
28000.00
24000.00
20000.00
16000.00
12000.00
8000.00
4000.00
0.00
(d)

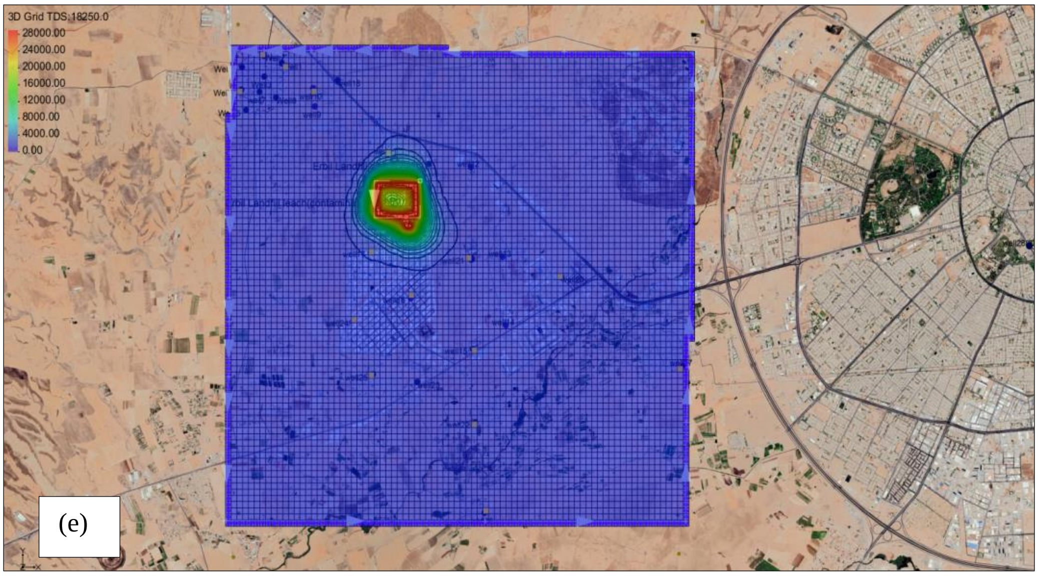


Fig. (9): TDS contamination transport after different periods a) 10 years, b) 20 years, c) 30 years, d) 40 years, e) 50 years.

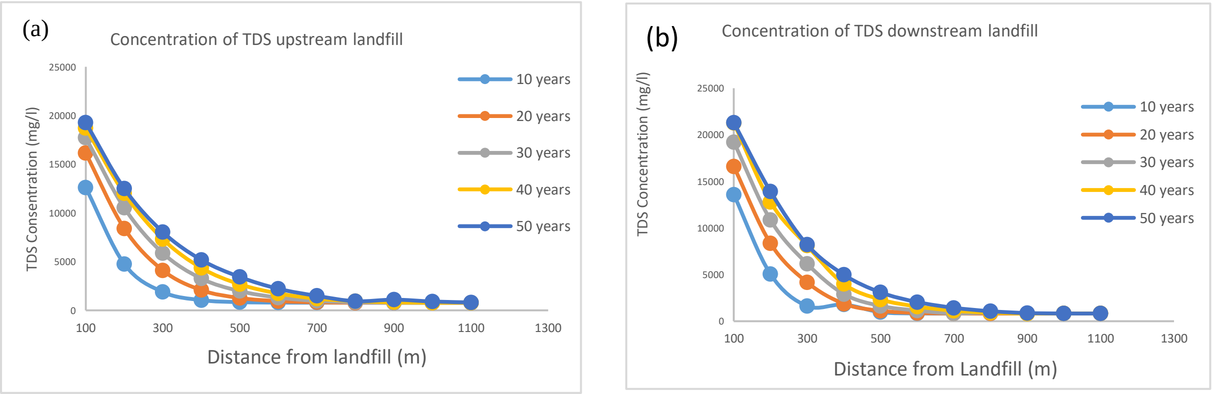


Fig. (10): variation of TDS concentration with distance from landfill a) upstream landfill, b) downstream landfill.

References

AL-KUBAISI, Q. Y., HUSSAIN, T. A., ISMAIL, M. M., ABD-ULKAREEM, F. A. J. E. & JOURNAL, T. 2019. Estimation of water balance for the central basin of Erbil plain (north of Iraq). 37**,** 22-28.

AL-SURAIFI, A. 2017. Simulation of Contaminants Transport and Groundwater Flow for Basrah Landfill Site. *Engineering and Technology Journal,* 35.

ALI, S. M. & OLEIWI, A. S. 2015. Modelling of groundwater flow of Khanaqin Area, Northeast Iraq. *Iraqi Bulletin of Geology and Mining,* 11**,** 83-94.

ASGHARI, S., SOORINEJAD, J. AND ZOLANVAR, AR, . 2005. Optmium performance prediction simulation-optimization method Barkhor aquifer. *Journal of Agricultural Sciences and Natural Resources,* 9**,** 13-24.

DAS, B. M. & DAS, B. 2008. *Advanced soil mechanics*, Taylor & Francis New York.

DURIEZ, S. 2005. *On the Use of Groundwater Contaminant Transport Modelling in Risk Assessments.*

DYSLI, M. J. S. U. V. 2000. Swiss Standard SN 670 010b, Characteristic Coefficients of soils. 86**,** 93-94.

GEBREHIWOT, A. B., TADESSE, N., JIGAR, E. J. I. J. O. F. & SCIENCES, A. 2011. Application of water quality index to assess suitablity of groundwater quality for drinking purposes in Hantebet watershed, Tigray, Northern Ethiopia. 1**,** 22-30.

GELHAR, L. W., WELTY, C. & REHFELDT, K. R. 1992. A critical review of data on field-scale dispersion in aquifers. *Water Resources Research,* 28**,** 1955-1974.

GHORABA, S. M., ZYEDAN, B. A. & RASHWAN, I. M. H. 2013. Solute transport modeling of the groundwater for quaternary aquifer quality management in Middle Delta, Egypt. *Alexandria Engineering Journal,* 52**,** 197-207.

HARBAUGH, A. W. & MCDONALD, M. G. 1996. Programmer's documentation for MODFLOW-96, an update to the US Geological Survey modular finite-difference ground-water flow model. US Geological Survey; Branch of Information Services [distributor].

HEATH, R. C. 1998. *Basic ground-water hydrology,* US Department of the Interior, US Geological Survey.

JASSIM, S. Z. A. G., J.C. 2006. *Geology of Iraq.* , Czech Republic, Dolin, Prague and Moravian Museum, Brno.

JAVANDEL, I., DOUGHTY, L. & TSANG, C. J. W. R. M. S. 1984. Groundwater Transport: Handbook of Mathematical Models, Volume 10 of.

KHAYYUN, T. S. 2018. Simulation of groundwater flow and migration of the radioactive Cobalt-60 from LAMA nuclear facility-Iraq. *Water,* 10**,** 176.

KHAYYUN, T. S. & SHARIF, M. T. Modelling of Groundwater Quality of Tigris River Reach-in Baghdad-Iraq Using Groundwater Modeling System Software. IOP Conference Series: Earth and Environmental Science, 2021. IOP Publishing, 012087.

KLAAS, D. K., IMTEAZ, M. A. & ARULRAJAH, A. J. H. R. 2017. Evaluating the impact of grid cell properties in spatial discretization of groundwater model for a tropical karst catchment in Rote Island, Indonesia. 48**,** 1757-1772.

LANJWANI, M. F., KHUHAWAR, M. Y. & KHUHAWAR, T. M. J. 2019. Groundwater quality assessment of Shahdadkot, Qubo Saeed Khan and Sijawal Junejo Talukas of District Qambar Shahdadkot, Sindh. *Applied Water Science,* 10**,** 26.

MCDONALD, M. G. & HARBAUGH, A. W. 1988. *A modular three-dimensional finite-difference ground-water flow model,* US Geological Survey.

OKUHATA, B. K., EL-KADI, A. I., DULAI, H., LEE, J., WADA, C. A., BREMER, L. L., BURNETT, K. M., DELEVAUX, J. M. S. & SHULER, C. K. 2022. A density-dependent multi-species model to assess groundwater flow and nutrient transport in the coastal Keauhou aquifer, Hawai‘i, USA. *Hydrogeology Journal,* 30**,** 231-250.

PANAGOPOULOS, G. J. E. E. S. 2012. Application of MODFLOW for simulating groundwater flow in the Trifilia karst aquifer, Greece. 67**,** 1877-1889.

RAJAPPA, B., MANJAPPA, S., PUTTAIAH, E. & NAGARAJAPPA, D. J. A. A. S. R. 2011. Physicochemical analysis of underground water of Harihara Taluk of Davanagere District, Karnataka, India. 2**,** 143-150.

RUSHTON, K. R. 2004. *Groundwater hydrology: conceptual and computational models,* John Wiley & Sons.

SAATSAZ, M., SULAIMAN, W. N. A., ESLAMIAN, S. & JAVADI, S. J. I. J. O. W. 2013. Development of a coupled flow and solute transport modelling for Astaneh-Kouchesfahan groundwater resources, North of Iran. 7**,** 80-103.

SISSAKIAN, V. K. & FOUAD, S. F. J. I. G. S. P., BAGHDAD, IRAQ 2014. Geological Map of Sulaimaniyah Quadrangle, scale 1: 250 000.

WOESSNER, W. W. & POETER, E. P. J. C., J., EILEEN, P., EDS 2020. Hydrogeologic properties of earth materials and principles of groundwater flow.

ZHENG, C., HILL, M. C., CAO, G. & MA, R. J. T. O. T. A. 2012. MT3DMS: Model use, calibration, and validation. 55**,** 1549-1559.