GROUNDWATER MODELING OF ESHIDYA PHOSPHATE MINING AREA, SOUTHERN JORDAN

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ABSTRACT

The groundwater modeling is conducted to cover most of Jafr Groundwater Basin to represent the actual hydrogeological conditions of the Amman-Wadi Es Sir (B2/A7) aquifer system. For this purpose, a 3D model was constructed using Modflow to simulate the behaviour of the flow system under different stresses. The Geo-database in ArcGIS format was used to construct the model in order to estimate the missing hydraulic parameters, such as transmissivity and storativity. The model was also used to predict the possible future impacts of pumping by the on-going mining activities on the groundwater quantity and quality for instance, depletion and salinization. The model was calibrated for steady state condition by matching the measured and simulated initial head contour lines. Drawdown data for the period 1985–1995 were used to calibrate the transient model by matching simulated drawdown with the observed one. Moreover, the transient model was validated using drawdown data for the period 1995–2025. The water balance for the steady state condition of Jafr Basin indicated that the total annual direct recharge is 2.48 MCM/a. The calculated inflow from the western boundary is about 5.8 MCM/a, and the outflow across the eastern boundary value is 7.91 MCM/a. According to the model results the discrepancy value was about 8.1% which is an acceptable value. The model was run under unsteady state condition for 36 years (starting from 1989) with a total abstraction equal to 10 MCM, and the simulated drawdown in 1995 was 1.89 m, while the simulated drawdown in 2025 will be 8.6 m.

Keyword: Groundwater modeling, aquifer, recharge, water quality, flow system, Eshidya, Jordan.

1. INTRODUCTION

Jordan is one of the poorest countries of the world in terms of water resources where 94% of its area receives rainfall amount less than 200 mm/a. Groundwater contributes a significant portion to the water supply in Jordan (MWI, 2004 [1], 2006 [2], NMWP, 2003 [3]). Due to the increased demand on the groundwater, needs are emerging to improve the aquifer management with extreme understanding of recharge and discharge issues, planning rates of withdrawal, and balancing demands of multiple water users (Thompson et al., 1997 [4]). The increasing demands lead to the depletion of water resources and deterioration in the water quality (NWMP, 2003 [3]). The phosphate industry is a major contributor to the economy of Jordan. Large volumes of water are required by the mining industry from areas where water resources are limited. The pressure on water is liable to hamper the development of phosphate industry and results in competition with other water contingent economic sectors such as agriculture or tourism.

Generally, phosphate formations covers about 60% of the total area of Jordan mainly found in shallow potential phosphate deposits in central Jordan, while the deep potential phosphate deposits occur in the SE, E and NE of Jordan (NRA 2006 [5]). The Jordan Phosphate Mines Company (JPMC) is exploiting phosphate rock reserves from Al Hassa, Al Abiad and from Eshidiya mines. The mining activity goes back to the 50s of the last century (from Russeifa: Abandoned), where Eshidiya is the most recent and the largest mine of all (Abu-Hamatteh, 2007 [6], NRA 2006 [5]). Eshidiya mining area which is located within Jafr Basin, represents the largest surface water basin in Jordan. This basin is located to the east of the Western Highlands in the southern part of Jordan Plain (Figure 1).

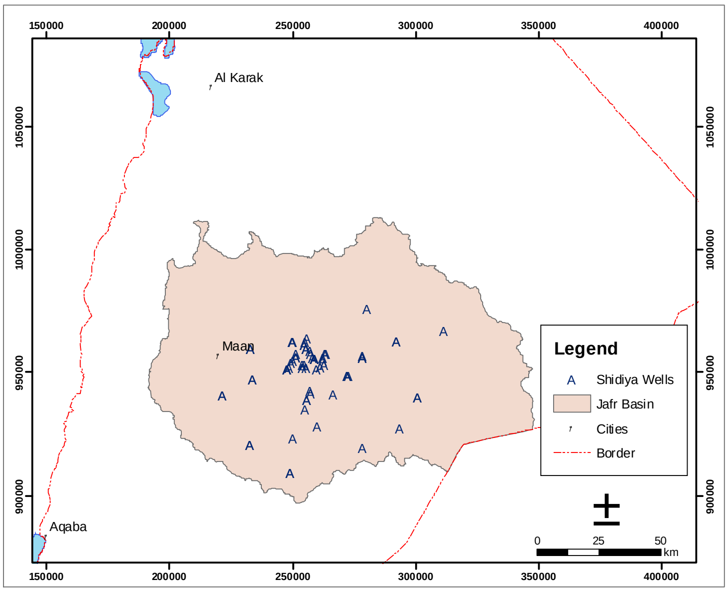


Fig. 1: Location map of the model area

The basin has an area of 13,000 km^2, mainly classified as arid desert with average annual rainfall less than 50 mm/a (MWI, 2004 [1]). The basin displays a classic centripetal drainage pattern with all wadis draining from the encircling highlands to the central part of Jafr Basin representing the largest conclave in Jordan. The catchment area lies at elevations between 850 m above sea level (a.s.l.) In Jafr plays and 1750 m a.s.l. In the Western Highlands. However, Eshidiya mine is located between 261 to 279 E and 915 to 935 N (Palestine Grid), corresponding to 36° 50´ to 36° 41´ longitudes and 29° 46´ to 29° 51´ latitude and the latitude at the Eshidiya mining area ranges from 950 m to 880 m a.s.l.

Two main aquifers occur in Eshidiya area, Intermediate Aquifer is known as Amman-Wadi Es Sir (B_2/A_7) which is being utilized for industrial purposes in the phosphate mines and the Deep Aquifer System (Kurnub and Disi aquifers) which are partially (limited) utilized. It is worth mentioning that no potential shallow aquifers occur within Eshidiya area. Since the Intermediate Aquifer is highly abstracted in the area, this encouraged the authors to conduct a 3D groundwater flow model using Modflow computer code to model the main aquifer, i.e., Amman-Wadi Es Sir (B_2/A_7) for predicting with reasonable accuracy, the response of Aquifer to different scenarios of future abstractions. The model was also used to determine the inflow and outflow of the aquifer, aquifer characteristics and prediction of drawdown due to abstraction.

2. HYDROGEOLOGY OF JAFR BASIN

A simplified geological map of the study area is presented in Figure (2a), whereas, the hydrogeological cross section of the study area is given in Figure (2b). Table (1) summarizes the geological and hydrogeological classification of rock units in Jordan (NWMP, 2003 [3]). The thickness of sedimentary succession varies between 2000-3000 m on the top of the Basement complex (Bender, 1974 [7], Humphreys, 1984 [8]). The detailed geological situation and structural elements of the area under study has been subjected to intensive geological and tectonics investigations within Jafr Basin (e.g., Bender, 1974 [7], Abed, 1994 [9], 1989 [10], Khalid, 1980 [11] Khalid and Abed, 1981 [12], 1982 [13]).

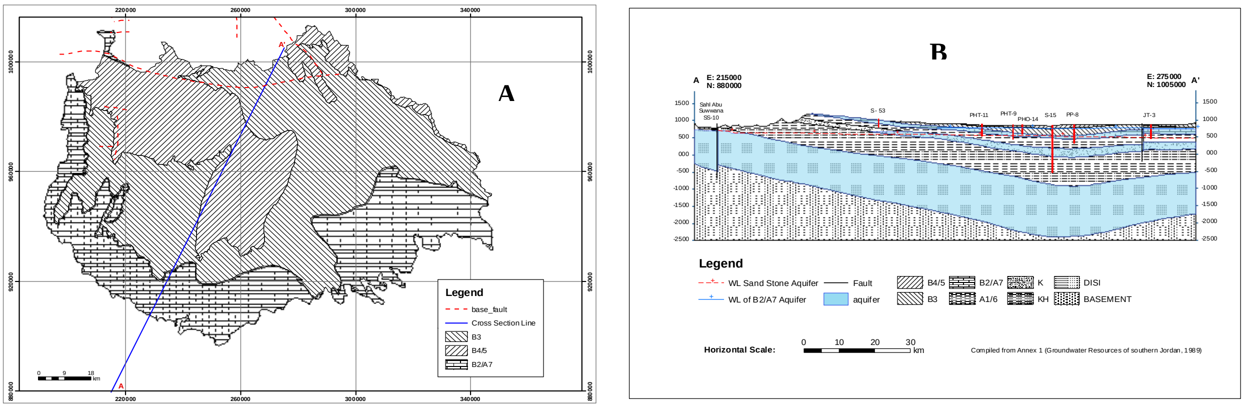


Fig. 2: (a) Simplified geological map of the study area and (b) Hydrogeological cross section of the study area

The Middle Aquifer System (B_2/A_7) the target of the current study represents the main aquifer system that feeds the area with water for domestic and industrial uses. It extends along the whole country and it is mainly of carbonate rocks with very good water quality. Moreover, it can be classified as renewable groundwater resource because it receives recharge from precipitation occurring at the Western Highlands where it is exposed at the surface.

In the southern part of Jafr Basin to the south of Eshidiya Phosphate Mines, the Amman-Wadi Es Sir (B_2/A_7) aquifers and the Lower Ajlun (A_{1-6}) aquitard are both thin and unsaturated. In the central part of the basin, the B_2/A_7 aquifer is confined by overlying thick impervious argillaceous unit of the Muwaqqar Formation (B_3), while the surrounding areas are unconfined (NRA, 2006 [5], MWI 2004 [1]). In the central part of the Jafr basin, the Umm Rijam (B_4) in localized areas is saturated under water table condition, while it is unsaturated in the surrounding areas.

The Eshidiya Phosphate Mine consumes a large amount of water for industrial and domestic purposes. The estimated safe yield for the aquifer system within the area is about 6 MCM/a, while the abstractions exceed 20 MCM/a. Consequently, a dramatic drop in the water level has occurred in the well field. Therefore, the Ministry of Water and Irrigation of Jordan (MWI) performs a ground and surface water monitoring system all over the country where, the groundwater level in the monitoring wells, quantity and abstraction amounts from the groundwater wells in addition to rainfall, runoff and potential evaporation are measured.

Table 1: Geological and hydrogeological classification of rock units in Jordan (NWMP, 2003 [3])

ERA	SYSTEM	EPOCH	GROUP	FORMATION	SYMBOL	LITHOLOGY	THICKNESS [m]	AQUIFER UNIT
CENOZOIC	QUATERNARY	Holocene	JORDAN VALLEY (JV)	Alluvium	Qal	clay, silt, sand, gravel		ALLUVIUM (AQUIFER)
		Pleistocene		Lisan	JV3	marl, clay, evaporites	> 300	
	TERTIARY – Neogene	Pliocene, Miocene		Samra	basalt, JV1-2	conglomerates	100 - 350	BASALT (AQUIFER)
		Oligocene		Neogene		sand, gravel		
	TERTIARY – Paleogene	Eocene	BELQA (B)	Wadi Shallala	B5	chalky and marly limestone with glauconite	0 - 550	B4/5 (AQUIFER)
		Paleocene		Umm Rijam	B4	limestone, ckalk, chert	0 - 310	
MESOZOIC	CRETACEOUS – Upper	Maastrichtian		Muwaqqar	B3	chalky marl, marl, limestone chert	80 - 320	B3 (AQUITARD)
		Campanian		Amman-Al Hisa	B2	limestone,chert, chalk, phosphorite	20 - 140	A7/B2 (AQUIFER)
		Santonian		W.Umm Ghudran	B1	dolomitic marly limestome, marl, chert, chalk	20 - 90	
		Coniacian	AJLUN (A)	Wadi as Sir	A7	dolomitic limestome, limestone, chert, marl	60 - 340	
		Turonian		Shueib	A5/6	marl, limestone	40 - 120	A5/6 (AQUITARD)
		Cenomanian		Hummar	A4	limestone, dolomite	30 - 100	A4 (AQUIFER)
				Fuheis	A3	marl, limestone	30 - 90	A3 (AQUITARD)
				Naur	A1/2	limestone, dolomite, marl	90 - 220	A1/2 (AQUIFER)
	CRETACEOUS – Lower	Albian, Aptian, Barremian	KURNUB (K)	Subeihi	K2	sandstone, shale	120 - 350	KURNUB (AQUIFER)
		Hauterivian, Valanginian, Berriasian		Aarda	K1	sandstone, shale		
	JURASSIC		ZARQA (Z)	Azab		siltstone,sandstone, limestone	0 - >600	ZARQA (AQUIFER)
	TRIASSIC			Ramtha		siltstone,sandstone, shale limestone, anhydrite, halite	0 - >1250	
PALEOZOIC	PERMIAN			Hudayb		siltstone,sandstone, limestone	0 - >300	
	SILURIAN		KHREIM (KH)	Alna		siltstone,sandstone, shale	0 - >1000	KHREIM (AQUITARD)
				Batra		mudstone,siltstone	0 - >1600	
				Trebeel		sandstone	0 - 130	
				Umm Tarifa		sandstone, siltstone, shale	0 - >1200	
				Sahl as Suwwan		mudstone, siltstone, sandstone	0 - 200	
	ORDOVICIAN		RAM (D)	Amud		sandstone	0 - >1500	RAM SANDSTONE DISI (AQUIFER)
				Ajram		sandstone	0 - ca: 500	
	CAMBRIAN			Burj		siltstone,dolomite, limestone sandstone	ca: 120	
				Salib		arkosic sandstone, conglomerate	0 - >750	
PRECAMBRIAN				Unassigned clastic unit		sandstone, argillaceous siltstone, claystone	0 - 1000	BASEMENT COMPLEX
				Saramuj		conglomerate, sandstone	up to 420	
				Aqaba Igneous				

3. GROUNDWATER FLOW MODEL

Due to the fact that the Lower Ajlun Group ($A_{1\text{-}6}$) aquitard is deep and not explored and the Umm Rijam Aquifer (B_4) is not of any significance within the study area, this model focuses on Amman-Wadi Es-Sir (B_2/A_7) Aquifer System as the main aquifer. A 3D model is constructed using the MODFLOW mathematical code (Harbaugh et al., 2000 [14]) and the Processing MODFLOW Pro (PMWIN) interface software (Scientific Software Group, 2000 [15]). Furthermore, the Geo-database in ArcGIS environment facilitates the model construction. Groundwater flow model was constructed to develop and calibrate the steady and unsteady state conditions of the B_2/A_7 Aquifer System, to calculate the water budget for the study area and to estimate the safe yield of the wells operating in the study area.

The continuity of the model is replaced by a set of discrete nodes in grid pattern covering the modeled area. A block centered grid technique was used, where the node point's fall in the center of the grid. The grid consists of 111 columns and 59 rows, giving a total number of 6549 nodes. A fine grid is used (Figure 4) where the cell width along the columns and rows is 1000 m. The groundwater flow model requires an accurate definition of the boundary conditions, which describe the physical boundary of the hydrogeological system. Three basic types of boundary conditions are known and represented in figure (3a), i.e., (1) the Dirichlet condition (constant head boundary), when water head value is known, (2) the Neuman condition (impervious boundary) there is no flow or constant flux of nonzero and (3) the Head-dependent flux for steady state condition with no change in head with time. A constant head boundary was assigned to give the amount of subsurface flow needed to maintain the water level.

The boundary conditions of B_2/A_7 Aquifer (Figure 3a) are defined in accordance with the groundwater flow pattern map (Figure 3b). The western boundary is essentially recharge area (as sub-surface flow) where the hydraulic head is known (1000 m a.s.l. line), and hence have been treated as a constant head boundary. Most of the outflow boundaries are occurring along the eastern part of the model area, these boundaries are assumed to be constant head and equal to the water table level (725 m a.s.l. line). The northern and southern model boundaries are considered as a no flow boundary. The input data for each cell in each layer required by the computer code PMWIN (Harbaugh et al., 2000 [14]) are dependent on the definition of the layer types, the B_2/A_7 Aquifer is under confined and unconfined conditions. Therefore, the data needed for this model are elevation of bottom and top of the aquifer, hydraulic conductivity of the aquifer, specific yield, storage coefficient (as specific storage) and initial head.

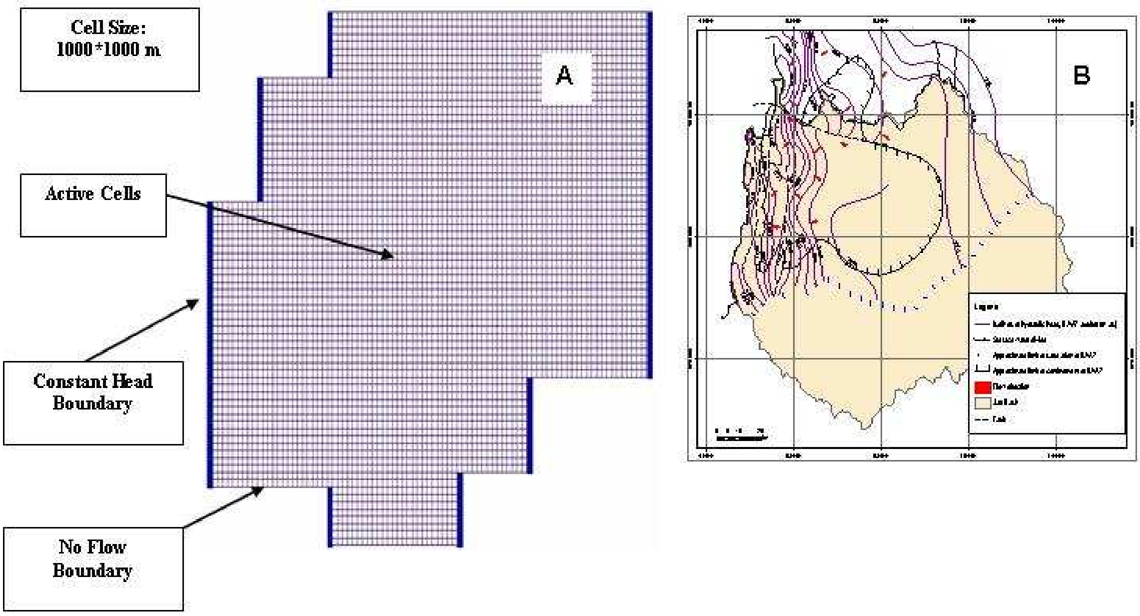


Fig. 3: (a) Model grid and boundary conditions (constant, active cells and no flow) of the study area and (b) Groundwater flow pattern of B_2/A_7 aquifer

3.1 Model Design

A preliminary pictorial representation is prepared for the main aquifer systems (Figure 4). This conceptual model includes all the available information about the aquifers, such as the model purposes, the water resources reassessment comprehensive study to provide a clear idea about which aquifers are to be modeled. However, the model is constructed to include two layers, B_3 as a confining aquiclude and B_2/A_7 as the main compsite in the area. Figure (5: a and b) represents the base of B_3 and base of B_2/A_7, respectively. These contour lines were manipulated and inserted into the model. In addition, the topography of the land surface is also inserted into the model at the top of both B3 and B_2/A_7 depending on their outcropping. Muwaqqar Formation (B_3) partially covers the B_2/A_7 with different thickness depending on the spatial geological distribution. Moreover, several faults are affecting the hydrogeological conditions of the B_2/A_7 Aquifer System.

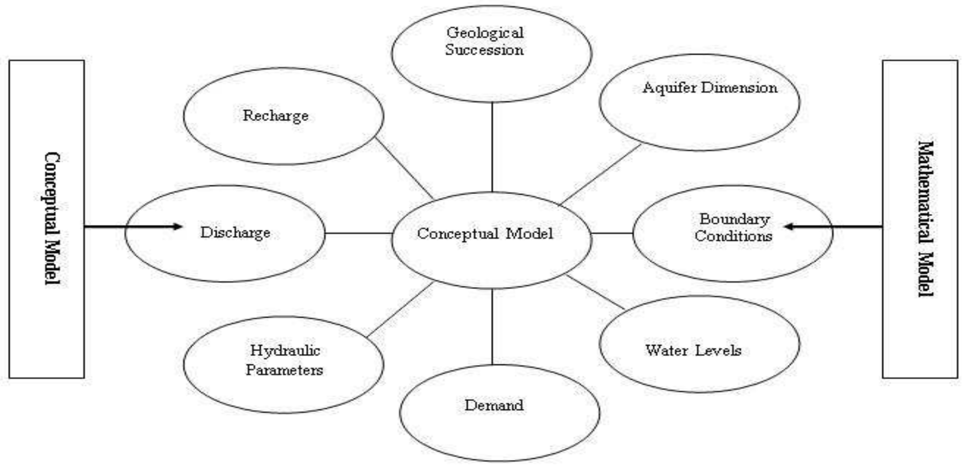
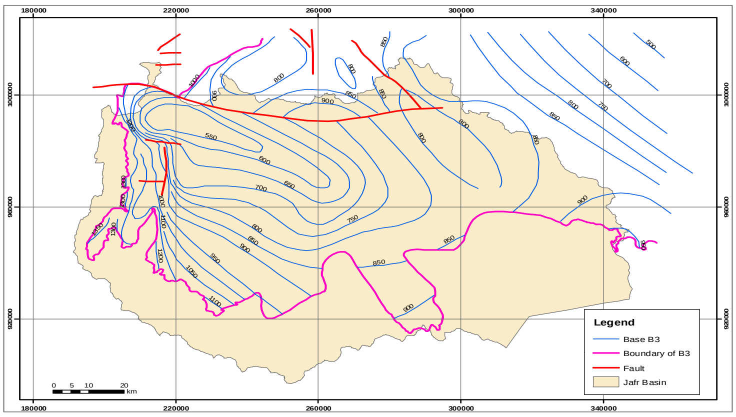


Fig. 4: Pictorial representation of the conceptual and mathematical model



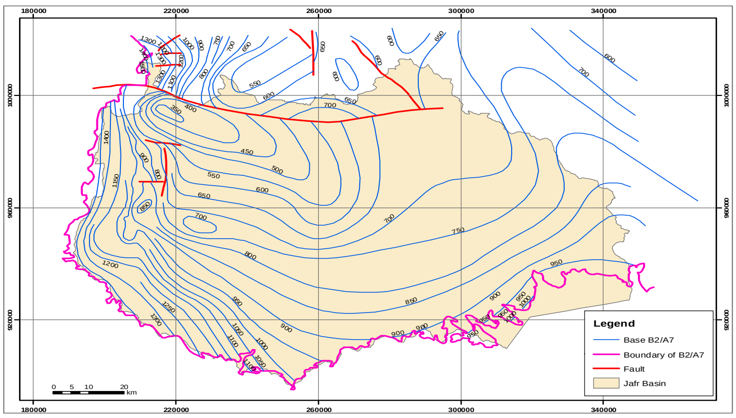


Fig. 5: Structure contour map of (a) base B_3 aquitard and (b) base B_2/A_7 Aquifer

3.2. Groundwater Flow Pattern

The regional groundwater flows in the B_2/A_7 aquifer are confined by the major faulting structural elements affecting the Jafr Basin as shown in Figure (3b). The hydraulic parameters of the B_2/A_7 Aquifer System have been calculated from the results of the pump tests were mostly of constant discharge rate and the water level is measured in the pumped well itself. Due to the variations in lithology of the rocks succession and structural elements affecting the area, the transmissivity and/or permeability of the aquifer are extremely variable. The transmissivities vary between less than 1 to more than 10000 m^2/d, depending on the size of fissuring and caving in the carbonate rocks. The lower transmissivity zones of less than 50 m^2/d are regionally mapped in the southern and western parts of Jafr Basin, where the aquifer thickness decreases to less than 50 m. The higher transmissivity zones of more than 100 to 200 m^2/d which locally include extremely high values of more than 1000 m^2/d are regionally mapped in the zones corresponding to the major groundwater flow paths.

3.3. Steady State Calibration

The calibration of the model is the only way to verify the mathematical model with the measured data. The calibration principle consists of simultaneously adjusting the permeability values of the aquifer and the subsurface recharge values through the assigned boundary conditions of each model. These parameters are the only parameters of importance under steady state conditions. To demonstrate the validity of the calibration of the steady state conditions of any model, a comparison between the measured data at certain groundwater observation points with the simulated ones is required. The calibration processes of the steady state conditions were successfully performed. Figure (6) shows the comparison between the calibrated head and the measured head whereas, Figure (7) shows the map of calibrated head to groundwater flow pattern head. The best fit was reached with hydraulic conductivities between 0.3 m/d and 10.0 m/d. The calculated inflow from the western boundary is about 5.8 MCM/a, and the outflow across the eastern boundary have the same value of 7.91 MCM/a, and the total recharge was 2.48 MCM/a. According to the model results the discrepancy value was about 8.1% which is a good acceptable value. Boundary conditions are assigned to the model using the water level contour map that is constructed for the water elevations before any development.

3.4. Unsteady State Calibration

The storage coefficient of the confined aquifer and the specific yield of the unconfined aquifer are the most important parameter in the unsteady state calibration, due to the sensitivity of the models to this parameter. The storage coefficient of B_2/A_7 Aquifer ranges from 0.00001 to 0.01 according to the previous studies (MWI, 2004 [1], 2006 [2]), where the specific yield is ranges from 0.01 to 0.15. The constant head boundaries of the steady state runs have been changed during the unsteady state to boundaries of constant flux and have been given to the model through injection nodes in the place of constant head boundaries to avoid any boundary condition effect which might introduce more water to the model area. The calculated heads of the steady state conditions after calibration were used as initial heads for the unsteady state conditions during the testing of different abstraction schemes. The model was run under unsteady state condition for 36 years (starting from 1989) with total abstraction from the wells equal to 10 MCM. Figure (8: a, b, c and d) show the simulated drawdown in 1995, 2000, 2005 and 2025 indicating maximum probable drawdown to be 1.89 m 9.95 m, 8.37 m and 8.6 m, respectively.

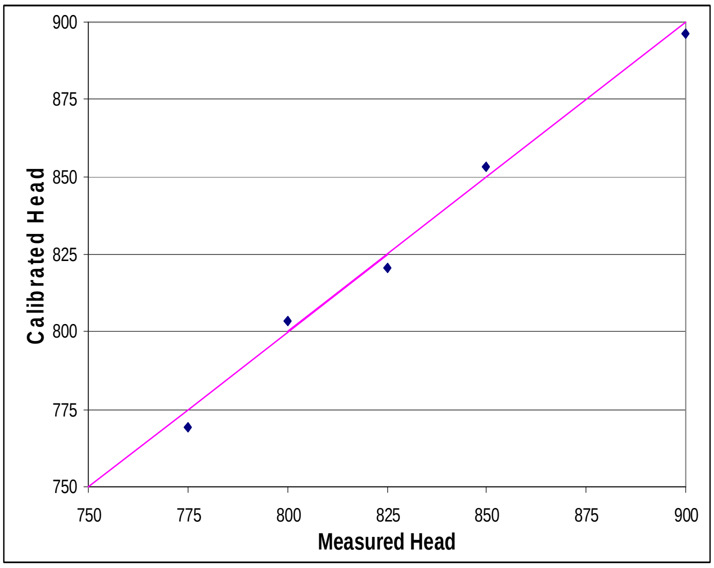


Fig. 6: Comparison between the measured and calculated head

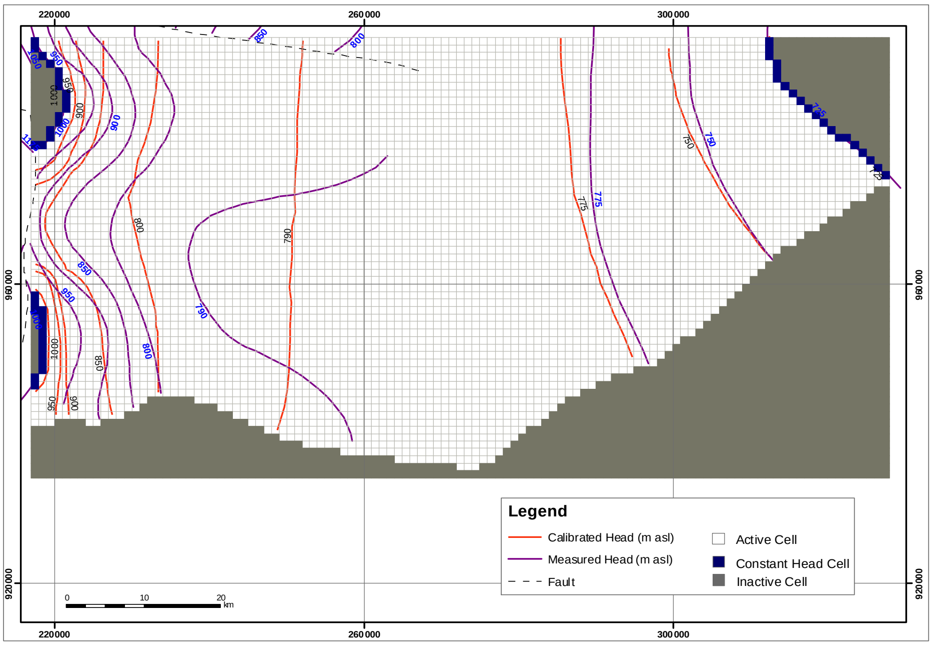


Fig. 7: Comparison between the measured and calculated head

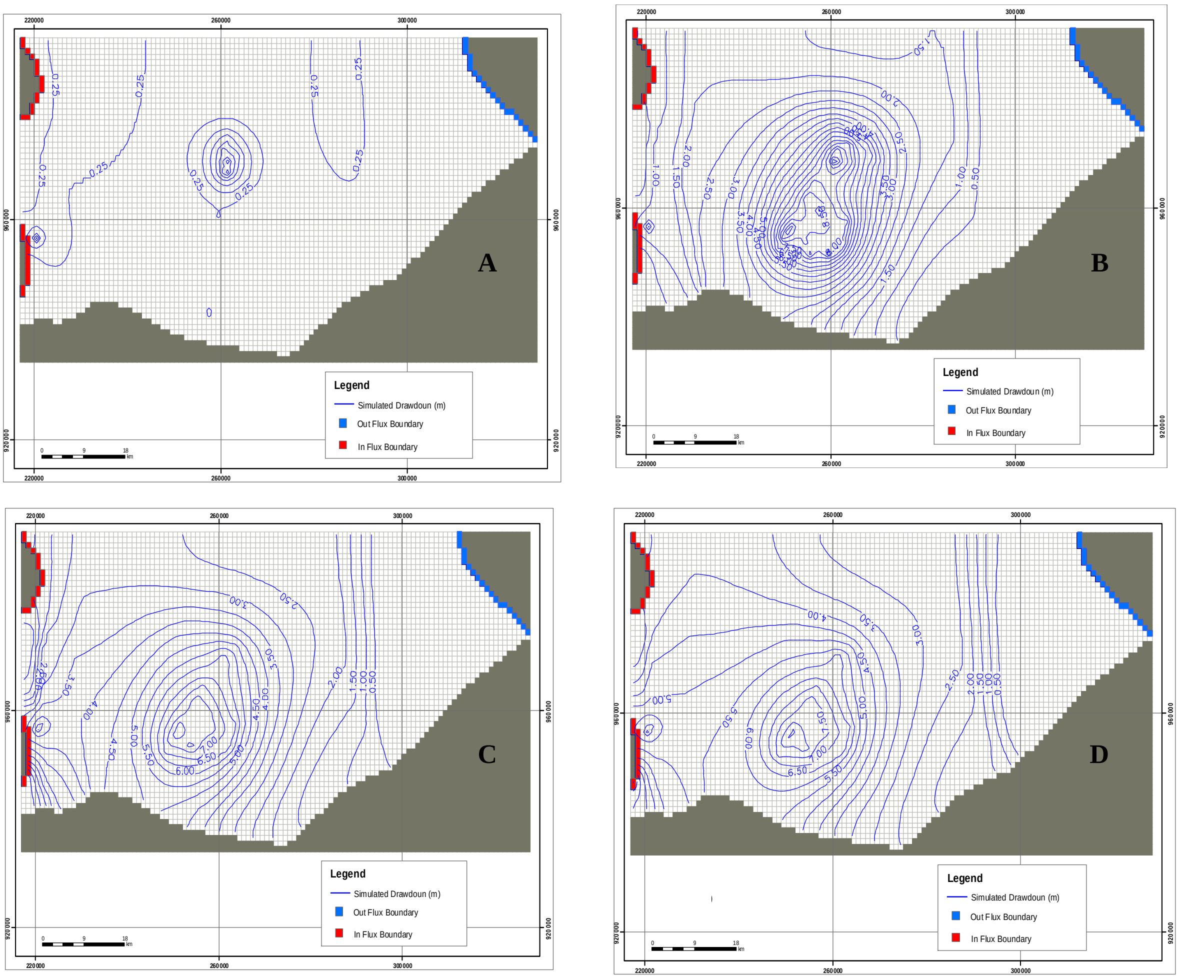


Fig. 8: Simulated drawdown after (a) 6 years of abstraction (1995), (b) 11 years of abstraction (2000), (c) 16 years of abstraction (2005) and (d) 20 years of abstraction (2025)

4. CONCLUSIONS

Processing Modflow version 5.0 (PM5) is used in this study to simulate the groundwater flow in the B_2/A_7 Aquifer System in Jafr Basin for both steady and transient conditions, in order to forecast the future changes that may occur under different stresses in the one hand and to investigate different scenarios of abstraction due to mining activities in Eshidiya area on the other hand. Model calibration for steady state condition shows very good agreement between observed and simulated initial water level contours. Transient state calibration also shows good agreement and verified by using drawdown data for 36 years from the period 1989 to 2025. The Results of the calibrated flow model (steady and transient states) indicate that the horizontal hydraulic conductivity of the B_2/A_7 Aquifer System in Jafr Basin ranges between 0.6 m/d and 26.6 m/d. The calibrated specific yield values range from 0.01 to 0.15. The water balance for the steady state condition of Jafr Basin indicated that the total annual direct recharge is 2.48 MCM/a. The calculated inflow from the western boundary is about 5.8 MCM/a, and the outflow across the eastern boundary have the same value 7.91 MCM/a. According to the model results, the discrepancy value was about 8.1% which is a good value. The total abstractions from the B_2/A_7 Aquifer were about 18.4 MCM/a. According to the current withdrawal rate (18.4 MCM/a), the maximum drawdown will reach about 9.95 m, 8.37 m and 8.6 m in the years 2000, 2005 and 2025, respectively in the wellfield of Eshidya Phosphate Mines. The abstraction rates simulation of the model of the B_2/A_7 Aquifer and resulting drawdowns are believed to simulate the correct magnitude order.

The groundwater system will not reach its equilibrium within the 50 years of abstraction. Yet, the rate of decline is expected to be almost negligible after 50 years, on account of wide extension of the cone of depression over large areas without any abstraction. The water will mostly come from the elastic storage within the Jafr Basin and will not deteriorate the conditions in neighboring basins. The simulated 20 MCM/a abstraction from the well fields may be accepted as a potential future yield from the B_2/A_7 Aquifer System within the Jafr Basins.

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