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GROUNDWATER MODELING OF WADI WALA DAM AREA AND THE HEEDAN WELLFIELD IN JORDAN

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Abstract

The potential of the groundwater resources in Wadi Wala Dam area was studied using the finite difference modeling method, the different parameters of the two dimensional governing equations of the groundwater flow in the area of interest were simulated. In general, the runoff was calculated and compared with the measured records in the catchment area of Wadi Wala, which is characterized by 176 mm average annual rainfall and a high calculated actual evaporation that reaches about 110 mm per year. Natural recharge of the (A_7/B_2) Aquifer System via the impoundment of the Wala Dam reservoir was observed to cause about 10 m raise in the water table of Heedan wellfield.

Keywords: Groundwater; Wadi Wala Dam; Reservoir; Aquifer System; Jordan.

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Introduction

The target area is located in east of the Jordan Rift adjacent to the eastern shores of the Dead Sea and about 10km east of the Wala Dam between the coordinates 218,000 – 245,000 East; and 98,000–118,000 North (Palestine Grid), where Wadi Wala and it's extent Wadi Heedan and their tributes drains west towards the Dead Sea [1]. The area indicated the presence of the three main Aquifer Systems recorded in Jordan, the Deep, the Intermediat and the Upper aquifer systems, the last one is under the scope of this study implementing the finite difference modeling. This aquifer system consists mainly of massive limestone interbedded with some chert noduls and thin lamina of ckalky limestones, while on other places marly limestones are observed [2]. The scattered groundwater wells in the eastern part of the modeled area and the Heedan wellfield used to extract water for domestic purposes were used to calibrate and verify the model. Thus, the interrelationship between the infiltrated water from the Wala Dam and the water resources of A_7/ B_2 Aquifer System of the Heedan wellfield were studied and a new appropriate wellfield to extract groundwater with minimum effects on the groundwater drawdown is recommended. Additionally, the runoff water calculations from the rainfall within the catchment area which covers the Eastern Highlands of Amman and Yadoudeh were carried out using the Curve Number method [3].

Geology and Climate

In general, no regional tectonics are found in the study area, but several minor and major faults crossing the wadi are present, the Wala Dam site is occupied by asymmetric anticline with northern flank has a dip of about 30^o northern direction, while the southern flank dips about 10^o southern direction (Figure 1). Its axis runs along the Wadi Wala for several hundred metres and passes under the right hand side of the Dam. The Heedan Quarry Flexure is located few hundred metres west of the quarries in Wadi Heedan. Due to a major fault crossing the Heedan in NNE-SSW direction, the strata are flexured roughly to the west with no major influence upon the groundwater flow [4,5]. This is possibly why there are no springs immediately westwards of this fault. The springs further west may be explained by recharging the aquifer beyond the extension of the fault (Figure 1).

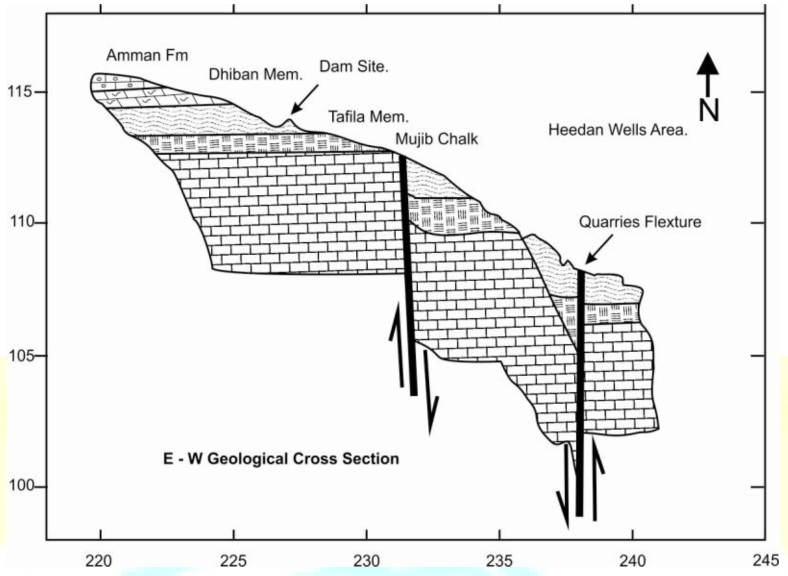

Figure (1): The geological structural features in Wadi Wala area.

Three aquifer systems are exist in the study area: The Deep Sandstone Aquifer System, Intermediate Aquifer System and the Upper Aquifer System. The last is the main productive aquifer in Wadi Wala catchment area,therefore, it is the objective of this study. The downwards movement of the groundwater is thus not drastically affected by the two chalk horizons of the Ghudran Formation. However, the base of this groundwater aquifer is the Shueib Formation which is well known throughout Jordan as an aquiclude.On the other hand, the recharge from the Wala Dam goes directly into the Tafila Member of the Ghudran Formation. This is because most of the water column within the dam reservoir is in contact with the Tafila Member. Reservoir water would seep through bedding planes and joints in the vertical sections on both sides of the reservoir. However, at the lake itelf bedding planes become second to wide open joints in accommodating the seepages from the reservoir [6, 7, 8].

The lithological characterristics of the different rock formations constitueting the Ajlun Balqa Group rock units are summerized in (Table 1).The Ajlun Group: formed dominently of bedded micritic limestone with chert nodules and thin bedded chert and dolomite with some dolomitic limestone and marly limestones [4]. From a hydrogeological view point, this group is an excellent aquifer throughout Jordan. area. Balqa Group: characterized by its abundant bedded chert and chert nodules alternated with limestone, chalk and micrite, phosphorite. Basalt Flows covers a small area with a little effect on the hydrogeology of the area. The Recent and Subrecent Deposits are of minor importance to the hydrogeology of the area, the recent deposits consist of limestone, chert, dolomite, phosphorite and basalt rock fragments, terraces and slope debris [4].

GEOLOGICAL TIME SCALE			LITHOSTRATIGRAPHIC AND HYDROGEOLOGIC UNITS			NATIONAL GEOLOGICAL MAPING PROJECT		
Era	Period	Epoch	Aquifer Type	Group	Formation	Symbol	Summarized Description	Thickness (m)
Cenozoic	Quaternary	Holocene (Recent)	Alluvium (aquifer)	Jordan valley	Alluvium	Q	Gravel, Sands, Talus	VARIABLE
		Pleistocene			Lisan		Gravels, Marl, Clay, Gypsum, Salts, Evaporites	> 300
	Neo-gene	Pliocene/ Miocene			Samra		Conglomerates, Fresh Water Limestone, Marine beds, Flinty Limestone, Shale, Sands.	100 - 350
	Paleogene	Oligocene	Basalt (Aquifer)		Neogene	BS		
		Eocene/ Paleocene	$B_{4/5}$ (Aquifer)	Belqa	W. Shallala	B_5	Chalk Limestone with Glauconite	0.0 - 555
					Umm Rijam	B_4	Limestone, Chalk, Chert	
			B_3 (Aquitard)		Muwaqqar	B_3	Chalky Marl, Marl, Limestone, Chert, Phosphates and Bitumen.	0.0 - 311
Mesozoic	Upper Cretaceous	Maastricht.						
			A_7/B_2 (Aquifer)		Hisa/Amman	B_2	Limestone, Chert, Chalk, Limestone interbedded with Phosphatic layers and Marl	
		Campanian			W. Umm Ghudran	B_1	Dolomitic Marly Limestone, Marl, Chert, Chalk	20 – 90
		Santonian						
		Coniacian						
				Ajlun	Khurij	A_7	Thin bedded Crystalline Limestone, Dolomitic Limestone, Chert, Marl.	25 - 125
		Turonian			W. Es Sir			
			$A_{1/6}$ (Aquitard)		Shuayb	$A_{5/6}$	Marl, Marly Limestone, Shale	40 - 120
		Cenomanian			Hummar	A_4	Limestone, Dolomite	30 – 100
					Fuheis	A_3	Marl, Limestone, Marly Limestone, Marl and Shale.	30 – 90
					Na'ur	$A_{1/2}$	Limestone, Dolomite, Marl.	90 - 220

Table (1): Lithological and hydrological unit in Wala area [10].

Hydrology

Wadi Wala catchment area covers about 1998 Km^2 lies east of the Dead See, the hills marking the edge of the Jordan Valley Escarpment lies at elevations of 700m to 900m above sea level, whilst in the west the Wadis have cut deep gorges through the escarpment to where they join some 2.5 km upstream of the Dead Sea [9]. There are several Wadis draining in the catchment area toward the Jordan Valley in the west. There are one evaporation station and six rainfall stations in the study area shown in Table (2).

Table (2): Rainfall stations in Wadi Wala catchment area for the period (1975-2013).

Rainfall Station Name	Coordinates		Altitude (m)	Type of Station	Mean Rainfall (mm)
	East	North			
Daba'a	250.500	111.600	750	Daily	119.4
Wadi Wala	223.000	107.500	350	Daily	226.3
Dhiban	224.000	100.800	745	Recorder	223.4
Madaba	225.500	125.000	785	Recorder	272.5
Um El Risas	237.500	101.000	750	Daily	144.0
Sahab	245.000	142.500	830	Daily	270.8

The study area has predominantly semi-arid climate, characterized by hot dry summers and cool to cold wet winters. Temperatures ranging from around 47° C in August to –5° C in January, while annual precipitation ranging from over 350 mm near the escarpment to less than 200 mm in the center of the catchment and to less than 150 mm in the extreme east (Table 3). The average annual evaporation from Class A pan amounts for the period under investigation (1975-2000) is found to be 7.3 mm/day. In general, the maximum evaporation values are observed in July with maximum monthly mean of 12.4 mm/day and minimum values are in January, with minimum monthly mean of about 2.4 mm/day in both stations [11, 12, 13]. The average annual evapotranspiration (ET) according to Penman for the period (1975-2003) was found to be 4.6 mm/day. It ranges from 1.02 to 4.6 mm/day in winter, while it ranges from 5.9 to 8.52 mm/day in summer (Table 3).

Table (3): Long term monthly averages of the climatological parameters for Wadi Wala station (1975-2000).

Climatic Parameters	**Months**											
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.
Maximum Temperature (°C)	25.8	19.0	13.2	11.5	13.6	16.3	21.0	26.1	29.1	29.5	29.7	28.8
Minimum Temperature (°C)	10.3	6.0	2.4	1.4	2.6	4.5	6.9	9.5	12.5	14.4	14.3	13.1
Mean Temperature (°C)	18.0	12.4	7.7	6.4	8.0	10.3	13.9	17.8	20.8	22.0	22.0	21.0
Wind Speed (m/sec)	2.2	2.4	2.6	2.5	2.6	2.6	2.4	2.3	2.7	3.0	3.0	2.5
Dominant Wind Direction	E	E	E	E	E	E	E	W	NW	W	W	W
Sunshine Duration (hrs/day)	9.0	7.7	6.0	6.3	6.4	7.2	8.4	10.3	11.7	11.9	11.4	10.2
Relative Humidity (%)	55	66	78	80	76	69	58	45	43	50	54	58
Average Monthly Rainfall (mm)	3.3	17.5	33.9	43.2	39.7	32.4	6.1	1.3	0.0	0.0	0.0	0.0
Class A Pan Evap. (mm/day)	7.5	4.4	2.6	2.4	3.6	4.7	6.8	9.7	12.2	12.4	11.7	10.0
Potential Evapotranspiration (mm/d)	4.6	3.0	1.3	1.0	1.8	2.3	4.0	5.9	8.4	8.5	7.9	6.6

The average annual measured runoff for Wadi Wala catchment area over the period (1975 – 2003) are presented in Table (4).

Table (4): Calculated average monthly and annual runoff (MCM) for Wadi Wala catchment area.

Water Year	**Oct (mm)**	**Nov (mm)**	**Dec (mm)**	**Jan (mm)**	**Feb (mm)**	**March (mm)**	**April (mm)**	**May (mm)**	**Annual Run off (mm)**	**Calculated Ann. Runoff**	**Measured Ann. Runoff**	**Base-flow MCM**	**Flood-flow MCM**
75 / 76	0	0	0	0	0.03	1.50	0	0	1.53	3.06	3.08	1.05	2.02
76 / 77	0	0	0	1.42	0.00	0.00	1.42	0	2.84	5.67	5.08	2.68	2.41
77 / 78	0	0	3.71	0.64	0	1.06	0	0	5.41	10.81	9.67	5.25	4.42
78 / 79	0	0	0	1.33	0	0.40	0	0	1.73	3.46	3.43	2.62	0.80
79 / 80	0	26.06	11.98	2.37	5.56	9.75	0	0	55.72	111.33	116.61	6.22	110.39

80 / 81	0	0	24.02	0.03	0	0	0	0	24.05	48.05	45.46	3.46	42.00
81 / 82	0	0	0	4.29	4.65	0	0	0	8.94	17.86	18.88	3.62	15.26
82 / 83	0	1.58	0	3.78	0.76	4.35	0	0	10.47	20.92	20.44	4.54	15.90
83 / 84	0	0.16	0	0.04	0	2.46	0	0	2.66	5.32	4.73	2.89	1.84
84 / 85	0.82	0	1.05	0	8.45	4.33	0	0	14.65	29.27	31.62	3.71	27.92
85 / 86	0	0	0.77	0.32	1.27	0	0	0	2.36	4.72	5.44	3.51	1.93
86 / 87	0	6.32	0	0.26	0	0.76	0	0	7.34	14.67	14.85	2.01	12.85
87 / 88	0	0	1.29	2.34	4.18	2.11	0	0	9.92	19.82	20.44	1.68	18.76
88 / 89	0	0	5.36	0.17	0.16	0.21	0	0	5.90	11.79	12.08	1.50	10.57
89 / 90	0	0	0	0.92	0.36	4.10	0	0	5.38	10.75	10.59	0.96	9.63
90 / 91	0	0	0	2.02	0	6.74	0	0	8.76	17.50	18.57	2.81	15.76
91 / 92	0	0	39.76	9.95	35.58	1.13	0	0	86.42	172.67	166.30	1.51	164.80
92 / 93	0	2.03	0	0.02	0.05	0	0	0	2.10	4.20	4.28	0.99	3.29
93 / 94	0	0	0.96	0.49	7.79	0	0	0	9.24	18.46	19.77	0.66	19.11
94 / 95	0	5.06	8.15	0	0.40	0	0	0	13.61	27.19	28.12	0.68	27.44
95 / 96	0	0	0	0.01	0.05	0.90	0	0	0.96	1.92	1.63	0.36	1.27
96 / 97	0	0	0	5.45	7.91	0.55	0	0	13.91	27.79	24.82	0	24.82
97/98	0	0	2.25	3.90	0	1.46	0	0	7.61	15.21	15.03	0	15.03
98/99	0	0	0	0.01	0.08	0	0	0	0.09	0.18	0.02	0	0.02
99/00	0	0	0	0.69	0	0.04	0	0	0.73	1.46	1.45	0	1.45
00/01	0	0	4.09	2.32	0		0	3.15	9.56	19.10	19.19	0	19.19
01/002	0	0	0	4.83	0	0	0	0	4.83	9.65	4.31	0	4.31
02/003	0	0	7.72	0.01	0.95	0.02	0	0	8.70	17.38	15.25	**0**	**0**
Average	**0.03**	**1.47**	**3.97**	**1.70**	**2.79**	**1.55**	**0.05**	**0.11**	**11.62**	**23.22**	**22.90**		

The perennial (Base) flow from springs may be seen in the main channel during the rainy season, where high amounts of rainfall may occur over the heights resulting intermittent flood runoff in winter months and in the other days of the year are marked in Figure (2). Daily rainfall records from (1975/1976-2002/2003) had been analyzed in terms of storms and frequency distributions. Curve Numbers were chosen in the range 65 to 75 for the individual wadi catchments, which gave long-term runoff coefficient ranging between 0.02% (1998/1999) and 21.69% (1991/1992) of rainfall over the 28 years period of analysis. Calculations were performed for each storm during the period 1975/1976 to 2002/2003. According to these calculations the heaviest floods occur between November and March and no significant floods occur in October and May [12, 13].

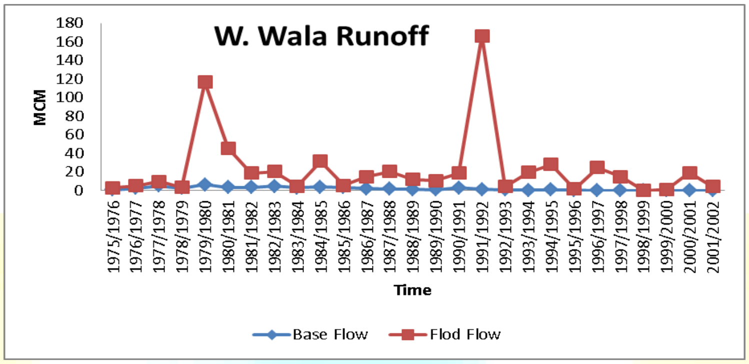

Figure (2): Runoff of W. Wala (1975 up to 2002).

There is no direct infiltration measurement in the study area. Accordingly, a "Water Budget" balance is estimated on daily basis, rainfall is usually concentrated between December and March. In this period evaporation is low, so that it can be concluded that recharge occurs mostly during this time. The rainfall and the runoff are the measured parameters, furthermore, the daily runoff were calculated to compare the results with the measured values to be used when there are missing data. The SCS-Curve Number method was applied for each storm during a specific year. The potential evapotranspiration was computed using Penman's Equation; then, the water budget was solved for all storms that occurred during the period of the water years (1975/1976-2002/2003) for Wadi Wala catchment area (Table 5). The infiltration rate ranges between 1.75 % in 1998/1999 water year and 14.2 % in 1979/1980 water year which correspond to 1.8 MCM and 93.3 MCM respectively. The long-term average amount of infiltration gives a value of about 21.5 MCM over the 28 years.

Table (5): Calculated water balance for Wadi Wala catchment area.

Water Year 1975-2003	Rainfall (MCM)	Runoff (MCM)	Loss * (MCM)	Infiltration (MCM)	Runoff Rate (%)	Infiltration Rate (%)	Loss Rate (%)
Average	356.9	22.9	312.5	21.5	5.2	5.5	89.4

* Loss Ed (Evaporation during the storm) and I_a (Initial Abstraction).

The groundwater modefied contour map of the Amman-Wadi Sir Aquifer System is constructed from the available wells data collected from the Ministry of Water and Irrigation (Figure 3). The Static water levels of the wells constructed in the early stages of the aquifer development were taken into consideration since the recently drilled wells gave lower values than it was in early eighties. Generally, the groundwater flows from the eastern direction towards western direction.

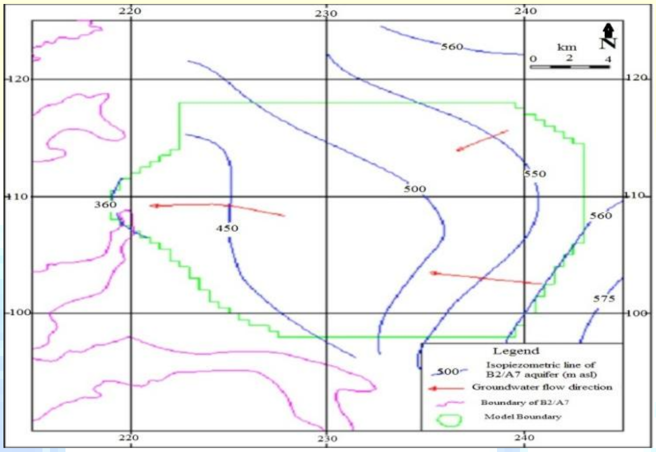

Figure (3): Groundwater contour map of Amman-Wadi Sir Aquifer System within the study area [14].

Groundwater Flow Modeling

The general shape of the catchment area is triangular, with the longer axis oriented in the model are pentrating both Wadi Sir and Amman aquifers systems without differentiation, the geological investigations showed that hydraulic interconnection between the two aquifers occurrs through the vertical fractures and joints of Umm Ghudran Formation. In addition, the interconection was proved by the recharging process from the Wala Dam when water level in Wadi Heedan wells (Wadi Sir Aquifer) was highly improved, due to these facts the model is carried out in two dimensions implementing the finite difference Modflow Computer Software Pro Version 6.0 to simulate the groundwater flow by solving the applied governing equations in tow dimensions. Thereafter, the study area was discretized into a representative regular grid divided into 200 rows and 250 columns makes 50000 square elements have (100 x 100) m sides and the total nodes were 49750 covers 500 km^2 (Figure 4).

The different parameters such as hydraulic conductivities and dispersivities obtained from the available pumping tests analysis are situated upon their representative nodes. Then constant head boundary conditions are used to define the eastern and western parts of the modeled area because water flows steadily either as input or output from these boundaries. The western constant head boundary is proved by the presence of discharging springs. This type of boundary condition is defined only at the period of Steady State Conditions. But, this boundary condition has been changed after operating the Heedan Wellfield, whereas this wellfield is considered to have marginal effect on the western constant head boundary. Due to this, specified discharging values at the cells of the western boundary were defined corresponding to the base flow amount of Wadi Wala at the boundary location. Inactive cells (no flow boundaries) were defined at the northern and southern parts of the modeled area. The internal cells were considered variable head cells (Figure 4).

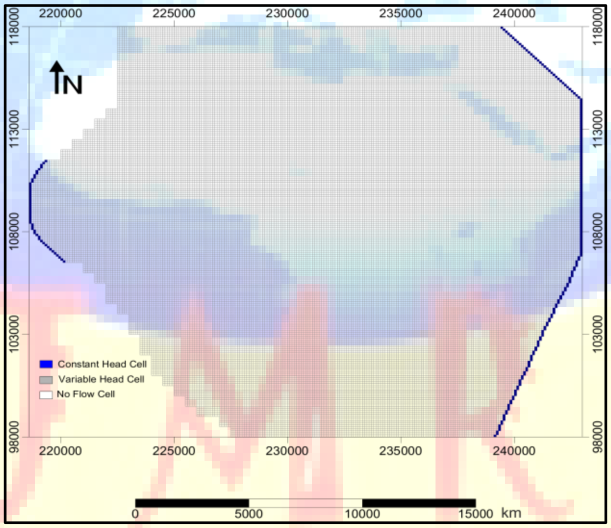

Figure (4): Model grid system and boundary conditions of the model area.

Initial conditions describe the state of the System at the start of the simulation using the historical measured data from the wells in the Heedan well field and the estimated values conducted by the regression analyses for absent readings or uncertain ones. Figure (5) represents the initial head distribution at the beginning of digging the wells in the study area. These initial heads were considered as initial condition for the steady state condition.

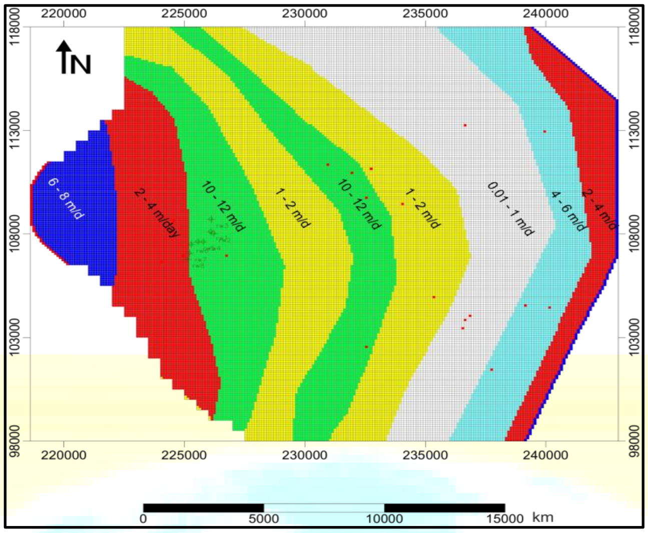

Figure (5): Calibrated hydraulic conductivity.

The results of the water head distributions in the different areas obtained from the simulation of the steady state (calculated values) are usually compared with the actual (observed) water head maps. Accepted results should be achieved when a good matching between the simulated head and the observed value (Figure 6). The simulated water head map is considered to be the initial condition of the transient state condition.

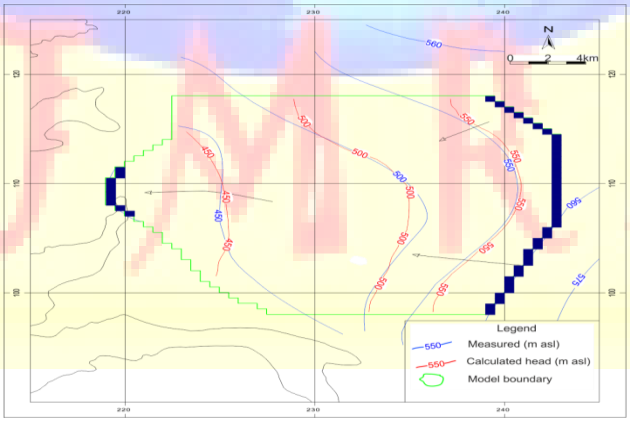

Figure (6): Comparison between measured and simulated hydraulic head.

The recharge was calculated using the water balance equation throughout the area, it was found to be (21.5) MCM, and discharge values are given in Table (6). It is clearly indicated that most of the abstracted water, 56% in 1995 to about 65% in 2001 was carried out though the governmental wells. According to the available data the authors assuming a constant density through the porous media as given in the following equations:

$$\partial/\partial x\,(K_x\,\partial h/\partial x) + \partial/\partial y\,(K_y\,\partial h/\partial y) - w = S_s\,\partial h/\partial t \qquad (1)$$

Where: Kx, Ky are values of hydraulic conductivity along the x and y coordinate axes (L/t); h: is the potentiometric head (L);w: is the volumetric flux per unit volume and represents sources and/or sinks of water per unit of time (t-1); Ss: is the specific storage of the porous material (L-1);and t is time (t). The first part of this problem was run to get a steady state solution, it takes the form as:

$$\partial/\partial x\,(K_x\,\partial h/\partial x) + \partial/\partial y\,(K_y\,\partial h/\partial y) = 0 \qquad (2)$$

The assured existing readings and measurements of the observation and production wells were implemented for the calibration and verification of the mode, thereafter the model can be run for prediction process and ready to conduct decision maker's scenarios.

Table (6): Groundwater abstraction from the study area [15].

Year	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
Heedan Wells	9252256	10782782	10241570	10114056	9254423	9533750	8840968
Wala Wells	1454032	1646901	1500756	1618440	1833391	1748294	1457942
Gov. Wells	10706288	12429683	11742326	11732496	11087814	11282044	10298910
Total Q m3/y	18980357	17914471	18703875	18417588	17371205	18389155	15928107
Private Q m3/y	8274069	5484788	6961549	6685092	6283391	7107111	5629197
Gov. Wells Abstraction %	**56.41**	**69.38**	**62.78**	**63.70**	**63.83**	**61.35**	**64.66**

Calibration of the steady state condition which can be considered as the static condition represents the un-deformed equilibrium conditions in the water budget of the aquifer system was enhanced for Hydraulic parameters conducted from pumping tests were the best fit between the observed and calculated water levels in the aquifer system by trial and error calibration (Figure 6). The horizontal hydraulic conductivity of the Amman-Wadi Sir Aquifer System in the study area ranges between 0.9 -10.9 m/d and with an effective porosity of 0.25. The specific yield values of the aquifer system are ranging between 0.03 and 0.09. Figure (6) represents the calibrated horizontal hydraulic conductivity calculated by the software for the Amman – Wadi Sir Aquifer

System. The groundwater balance for the steady state condition of the whole model domain for model area is summarized in Table (7). This table shows acceptable results since the discrepancy% is very low.

Table (7): Groundwater budget of the model domain during the steady state calibration.

Flow Term	IN m^3/d	IN MCM/a	OUT m^3/d	OUT MCM/a	IN-OUT m^3/d
Constant Head	3.5066E+04	12.81	4.3958E+04	16.06	-8.8923E+03
Recharge	8.8891E+03	3.24	0.0000E+00	0.00	8.8891E+03
Sum	4.3955E+04	16.05	4.3958E+04	16.06	-3.1523E+00
Discrepancy [%]	-0.01				

The gained results from the steady calibration were used in transient condition which describes the disequilibrium conditions of the aquifer system under drained or/and undrained conditions. Transient calibration was conducted to the years 1995 to 2001 where actual discharge measurements are available at the Ministry of Water and Irrigation. The steady state boundary conditions have been changed from the constant head boundary conditions at the eastern and western areas during the transient calibration to general head boundary in order to control the actual drawdowns in the wellfields near these two boundaries specially the western boundary whereas the baseflow has been dropped due to the abstraction from the Heedan wellfield. Additionally, the given values for the model cells at these two boundaries were reduced systematically by 20% for the years 1996, 1997; 30% for the year 1998; 40% for the year 1999; and 60% for the years 2000, 2001 and so forth. The reduction in the cells values of the Western General Head boundary correspond to the baseflow decrease as a function of time. The calibration was done by changing the specific yield and specific storage values for the aquifer system through several computer runs until reasonable matches were obtained between the observed and simulated drawdowns. The actual water level fluctuations recorded in the observation wells in the study area (Heedan Obs. Well No. 2) are shown in Figure (7). On the other hand, the water level drawdown recorded in Wala Observation Well No.14 during the period (1994 to 1999) was about 12m. Comparison between the observed and calculated water level fluctuations in the wellfield is acceptable and with a variance of about 0.4.

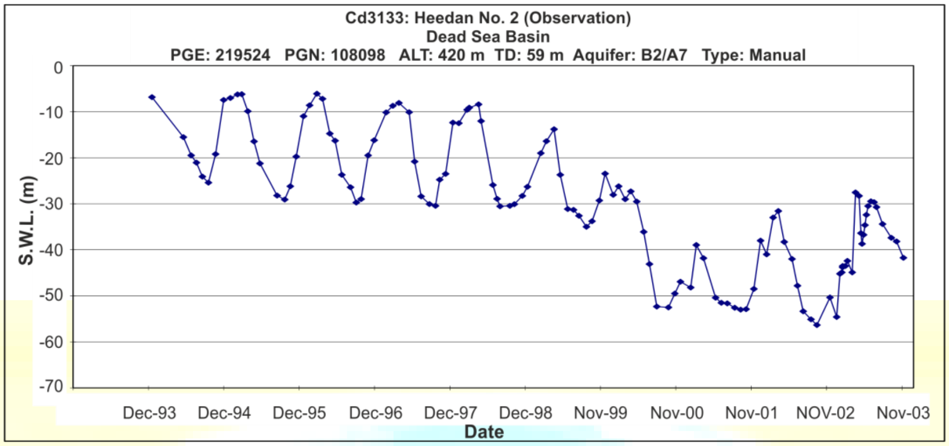

Figure (7): Water level fluctuations in Heedan Obs. Well No. 2.

The Wadi Wala dam constructed in 2002 was impounded by runoff water to achieve its main purpose of collecting flood water to be used it in artificial recharge, therefore eight wells were constructed downstream of the Wala Dam (RW1 to RW8) to supply the water into the aquifer system. The water levels in the RW1-RW8 were rising up while the dam water level was falling down (Figure 8).

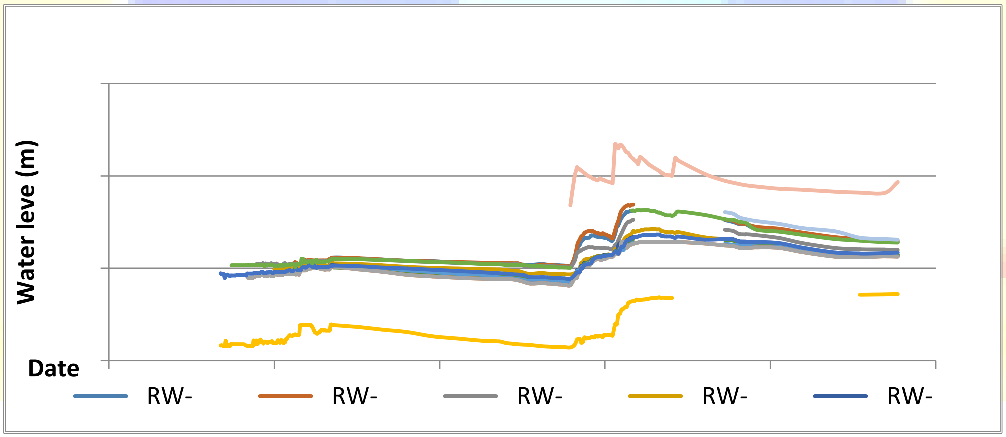

Figure (8): Wala dam water level fluctuations and the corresponding observation and recharge wells.

Model Prediction

Since the existence of the Wala Dam Reservoir as a natural recharge in the winter season of 2002 the model prediction can't be developed unless this new situation is taken into consideration.

Therefore the water levels raised up in the recharge wells (RW1-RW8) were calculated and compared with the observed values in these wells. Drawdown prediction for the years 2004 as indicated in model run of the year 2004 is represented in Figure (9). It is clearly noticed that the rise up of the groundwater levels of the recharge wells downstream the Wala Dam Reservoir as well as water level replenishments in the Heedan wellfield are due to the natural recharge process from the Wala Reservoir Dam. A visual comparison between water level drawdowns in the Heedan wellfield before and after the construction of Wala Dam is shown in Figure (9).

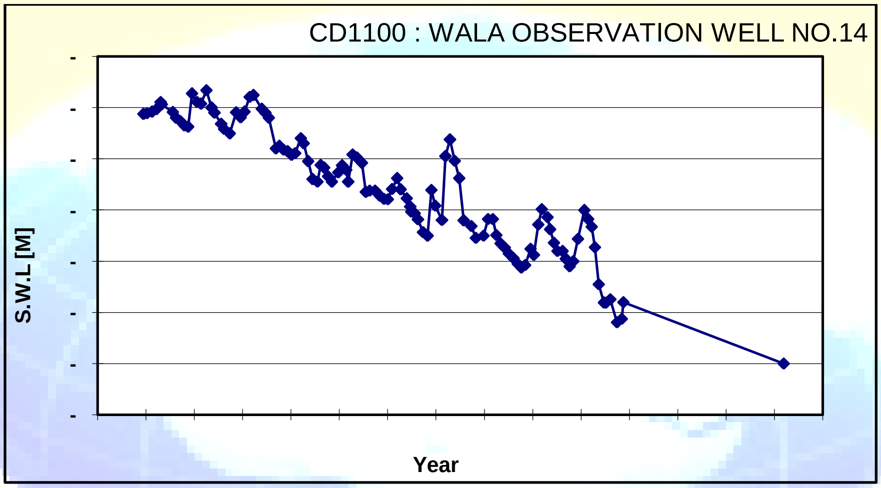

Figure (9): Drawdown in (2004).

In order to get benefit from the natural recharge and aquifer replenishment downstream the Wala Dam, special scenarios were developed. These are the model runs of Periods 13, 14, 15 and 16 of the transient state. In these scenarios, a new wellfield of 10 wells downstream the recharge wells (RW1-RW8) was located. In these scenarios, different amounts of groundwater abstractions of 2, 4, 6, 8 and 10 MCM/a, beside the same rate of the abstracted water amount of the year 2002 were used in the scenarios of the periods 13 to 16. The period length of each scenario is 20 years. This means that the model extends from the year 2006 to 2025. These scenarios were done in order to optimize the appropriate water volume that can be abstracted from the proposed wellfield. The simulated drawdown values in the proposed wellfield and in Heedan wellfield are shown in Table (8). According to the results it is found that the most suitable volume of abstracted water from the proposed wellfield is 6 MCM/a keeping the same abstraction quantity (10 MCM) from the Heedan wellfield as in the year 2002. This abstraction rate is selected since the drawdown rates in the Heedan wellfield as well as in the proposed wellfield are almost identical. This means that the future water table withdrawal will maintained in the two wellfields at a range between 14 and 18 m. At lower abstraction rates from the Proposed wellfield (less than 6MCM/a) will cause rise up in the water level in the Heedan wellfield and consequently after few years the baseflow partially will be recovered while at abstraction rates more than 6 MCM/a from the Proposed wellfield will cause abrupt water level withdrawal in the Heedan wellfield as well as in the Proposed wellfield.

Table (8): Drawdown values (m) in the Heedan and proposed wellfields taking into consideration different abstraction rates from the proposed wellfield (2, 4, 6, 8 and 10 MCM/a) and constant rate (10 MCM/a) from the Heedan wellfield.

YEAR	**Maximum Drawdown in Heedan Wellfield (m)**						**Maximum Drawdown in the Proposed Wellfield (m)**				
	0* MCM/a	2** MCM/a	4** MCM/a	6** MCM/a	8** MCM/a	10** MCM/a	2 MCM/a	4 MCM/a	6 MCM/a	8 MCM/a	10 MCM/a
2005	17.9										
2006	14.9	15.3	16.4	17.0	17.8	18.5	2.8	8.4	14.2	20.4	26.9
2007	11.9	13.6	15.4	17.2	19.0	20.7	2.5	9.5	17.0	25.1	34.0
2008	8.8	11.6	14.6	17.5	20.5	23.6	1.6	9.5	18.0	27.2	37.5
2009	5.7	9.7	13.7	17.8	22.1	26.6	0.6	9.1	18.3	28.4	39.7
2010	2.8	7.7	12.7	18.0	23.6	29.8	-0.4	8.6	18.4	29.2	41.5
2015	-10.4	-1.8	7.4	17.6	29.4	46.2	-5.5	5.6	17.7	31.4	47.5
2020	-20.8	-9.8	2.3	16.2	33.8	39.9	-10.1	2.8	17.0	33.1	51.0
2025	-29.1	-16.0	-1.9	14.9	38.2	40.0	-13.9	0.4	16.4	34.7	52.3

* The maximum drawdown in Heedan Wellfield with no abstraction from the proposed wellfield and with constant (10 MCM/a) abstraction rate from the Heedan Wellfield. ** The maximum drawdown in the Heedan wellfield at different abstraction rates from the Proposed wellfield (2, 4, 6, 8, 10 MCM/a) and with constant (10 MCM/a) abstraction rate from the Heedan Wellfield.

Conclusions and Recommendations

Based on the results of the groundwater flow model carried out for the Wala area, the followings can be concluded:

1. The steady and transient calibration of the flow model revealed that the horizontal hydraulic conductivities of the Amman-Wadi Sir Aquifer System are ranging between 0.9 and 10.9 m/day, while the specific yields of the Aquifer System are ranging between 0.02 and 0.09.

2. The water budget for the steady state conditions prepared for the whole domain area of the model was determined as follows:

3. The drawdown results of the different scenarios showed clearly that the recharged water from the Wala Dam is replenishing the exhausted aquifer since more than 25 m of the water level drawdown in the Heedan Wellfield are recovered. In addition, better water management will be achieved if a new wellfield is drilled in the area downstream the Wala Dam. By pumping additional 6 MCM/a the water level in Heedan Wellfield will be at least 20 m higher than the water level at the early period of 2002. In this case, no wells will stop pumping due to dramatic water level withdrawal.

4. Carry out regular sediments removal from the Wala Dam Reservoir to enhance the natural recharge process

5. Conducting a hydrochemical and water quality investigation of the aquifer system in the area.

6. Enhancing the existing monitoring system with new observation wells.

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