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A numerical approach for the evaluation of sustainable yield of shared aquifer basins: a case study from the Mediterranean Countries

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ABSTRACT

The aim of this research is to illustrate that developing steady-state models for shared aquifer basins will provide an opportunity to better manage these shared aquifers by realizing the transboundary fluxes between sharing countries. This study addresses a case study in the Eastern Mediterranean Countries. The addressed case study is a source of high level of disputes between sharing countries with regards of water rights. Therefore, this study provides an important methodology to evaluate the sustainable yield of the shared aquifers in order to help develop optimum utilization plans especially for domestic and agricultural uses. An understanding of the regional scale hydrogeological processes and assessing their impact on the aquifer basins will lead to a significant improvement in the determination of the sustainable yield of the shared aquifer basins. A numerical model (GMS-MODFLOW) was developed for the shared aquifer addressed in this study which is the Western Aquifer Basin (WAB) in Eastern Mediterranean Countries. The model was calibrated using historic and recent data. The sustainable yield of the WAB has been considered as the calibrated long-term discharge of the main springs (Timasah and Ras Al-Ain) of the aquifer basin before its development. The results of the study show that the steady-state sustainable yield of WAB was 357.9 Mm^3/y, respectively.

Keywords: Steady-state flow model; Sharing countries; Utilization plans; Springs discharge

1. Introduction

The aim of current research is to assess the sustainable yield of shared aquifer basins within their hydrogeological boundaries using numerical modelling as the main approach. This current research mainly utilizes the results of a research project conducted by Newcastle University on the Western Aquifer Basin (WAB) in the Eastern Mediterranean Countries [1]. The numerical modelling approach was also used to estimate the sustainable yield of other shared aquifers in the Arabian Gulf Countries [2]. In the context of this paper, the term sustainable yield is referred to that percentage of the volume of aquifer annual recharge that can be extracted from the aquifer through means of pumping wells without causing severe drop in the water levels and without causing severe deterioration in its water quality [1]. The determination of the sustainable yield for shared aquifer basins can help develop realistic and reasonable future groundwater utilization plans in one sharing country without causing harm to other sharing countries. This is normally achieved if the hydrological regime of regional/shared aquifers is understood and is well conceptualization. Also, such studies improve and strengthen databases of all sharing countries with regards to deterioration in water quality and drawdowns in the water levels of shared aquifer basins. These studies normally illustrate to all sharing countries that technical cooperation and holistic management of shared aquifer

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basins is the best way to face challenges of droughts created by climate changes. Managing shared aquifer basins without holistic approach can lead to more difficult consequences. Examples of such shared aquifers are known worldwide and the Middle East [3–5]. In reality, most sharing countries face legal issues and conflicts related to the development of shared aquifer basins due to over exploitation of their part in the shared resource of water [4–7]. Hydrogeological assessments can predict the likely impacts of different groundwater exploitation scenarios, but they are unable to determine the best fit conditions [4–7]. The most important factor that affect the management of shared groundwater resources or aquifer basins is the recharge from rainfall. Basically, if the shared aquifers are not renewable on annual recharge basis, then the determination of the sustainable yield is of no importance. Pumping the shared aquifer basins by one or two sharing countries beyond their renewable capacity will create a lot of conflict and tension between the sharing countries [4]. It is not always the case that the shared aquifer basins yield freshwater as the case for the Eastern Mediterranean Countries, brackish water (with total dissolved solids of less than 10,000 mg/L) are also very important to the Arabian Gulf Countries where these sources are vital for agricultural use [8,9]. In these countries, brackish water can be used also for mixing purposes with desalinated water to convert the mixture to be suitable for domestic use [8,9]. It should be emphasized that the estimation of the sustainable yield of shared aquifer basins requires reasonable approximation to the cross-boundary fluxes. This requires information on the regional hydrogeology and recharge of the shared aquifer basins.

The study area of this research is the Western Aquifer Basin (WAB) in the Eastern Mediterranean region (Fig. 1). The study area of WAB is around 6,035 km^2 with 29% within the lands of West Bank and Gaza and 71% in Historical Palestine. The hydrogeological set-up of the two aquifer basins is provided in later sections of this paper.

Fig. 1 shows a number of shared groundwater aquifer basins in the Eastern Mediterranean countries. The current research, concentrates on the Western Aquifer Basin (WAB). The WAB basin has two aquifer units as shown in the geological cross-section of Fig. 2.

The two aquifer units as indicated clearly in Fig. 2 are the Upper Aquifer (UA) and the Lower Aquifer (LA). The UA has larger outcrop area than the LA, and confined conditions exist where the aquifers dip below the recent sediments. The karstified carbonate rocks of limestone and dolomites of the UA and LA persists within the West Bank and extends beneath the Mediterranean Sea. Numerous lineaments have been identified and some of these are likely to represent discontinuities that affect the hydraulic integrity of the dividing aquiclude. The groundwater divide is roughly north–south, groundwater flows east to the Jordan Valley, and west towards the Mediterranean Sea. The WAB has two prominent spring complexes (called Ras El-Ain and Timsah, Fig 3) in the discharge area for the karstic aquifer. The two complexes have similar water levels. The water quality of the springs is good. This implies that flow paths were long enough to prevent serious pollution from fertilizers.

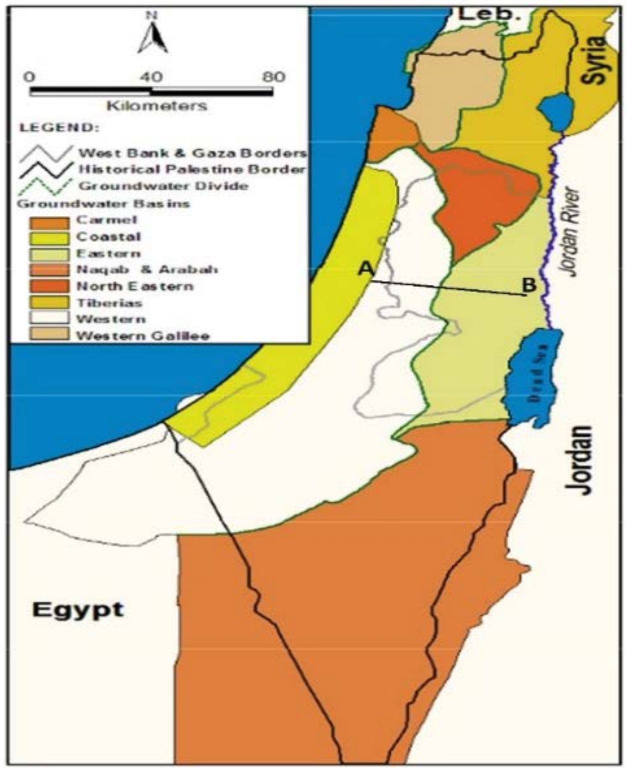


Fig. 1. Location map of the WAB study area WAB is in white color.

2. Methodology

2.1. Software and data

This research adopted a numerical approach (using the MODFLOW-GMS software) for WAB aquifer. This approach required detailed information and data on the geometry of the aquifers and their hydraulic properties. The geometry of aquifers was collected from many geological cross sections together with seismic data to determine the thickness of all encountered geological formations over the entire domain of the aquifer basin. The hydraulic properties of aquifers were collected from many pumping tests carried out at the pumping wells with observation or monitoring wells. Although this type of data exists but difficulties were encountered. In this sense, there is an uncertainty about the hydraulic properties of the aquifer but with a successful calibration process of these parameters the uncertainty has been reduced.

2.2. Conceptual and steady-state model of WAB

The aquifer system of WAB includes 3 layers: Upper Aquifer (UA), aquitard (Yatta) and Lower Aquifer (LA) as seen in the geological cross section (Fig. 2). The grid was constructed with a fine zone, in areas with high stresses, such as the regions located with wells and springs. Then the input data were assigned from the conceptual model to the cells of the grid. The size of the model cells is not the same for model area. The cell area varies between 0.25 km^2 around the main springs (Al Timsah and Ras El-Ein springs) to 4 km^2 far away from them which is the largest

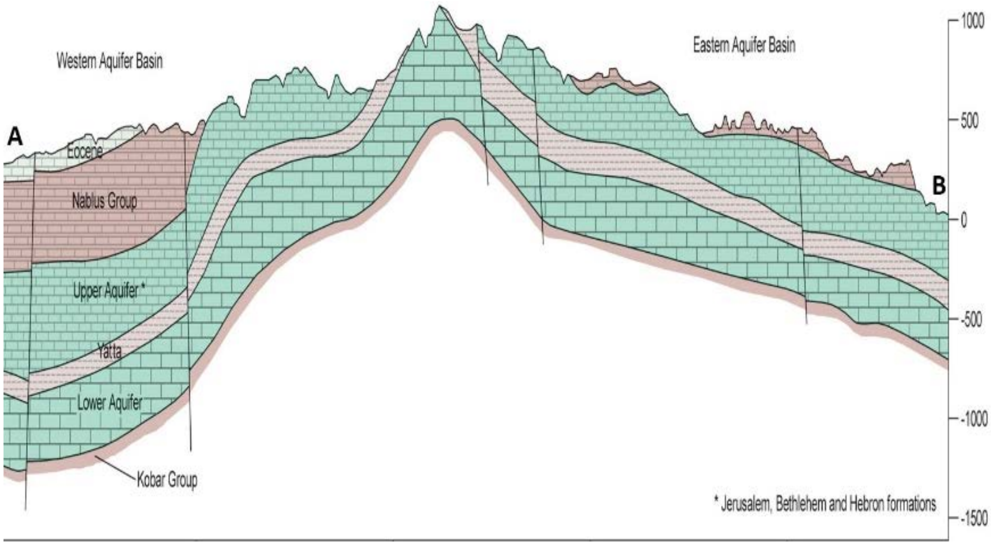


Fig. 2. Geological cross-section AB shown in Fig. 2 of the West Bank aquifer of Eastern Mediterranean Region.
Source: SUSMAQ, 2001, 2003 [10,11].

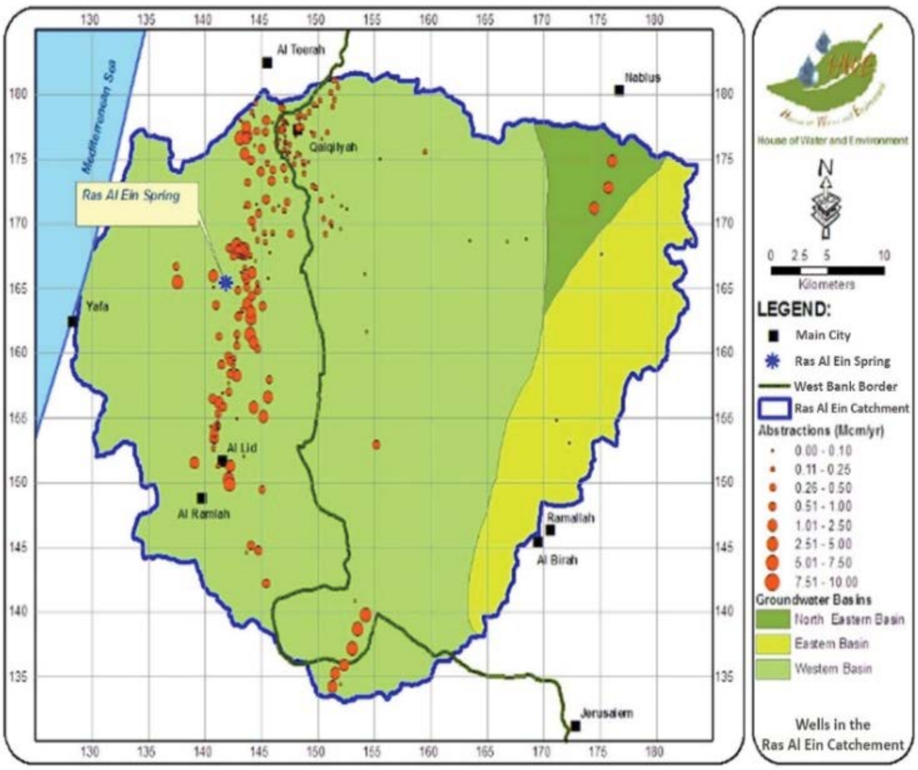


Fig. 3. Location of the main spring (Ras Al-Ain) in the WAB showing heavy pumping around it.

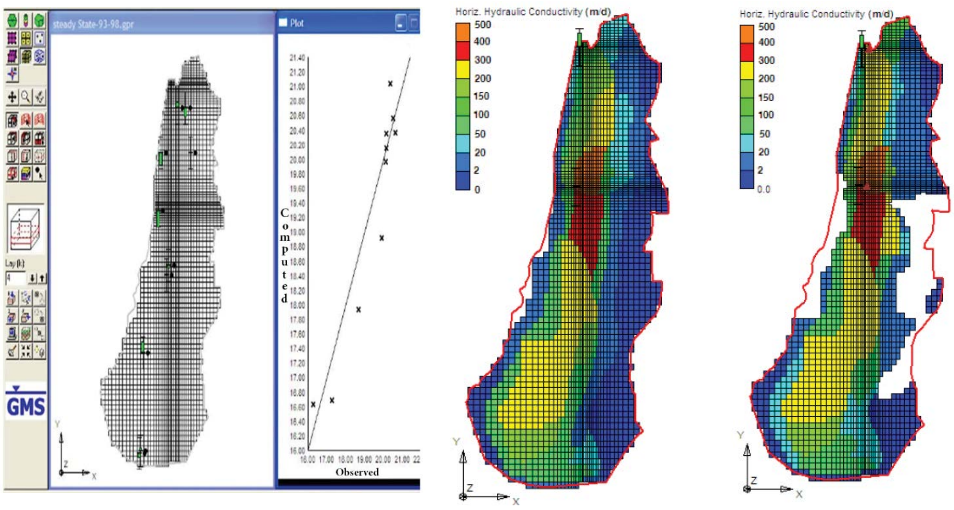
cell area used in this study. The WAB hydraulic boundaries were difficult to determine because the structural of the basin is complex with many faults and anticlines. No-flow boundaries were considered where erosion occurs and the aquifers were permanently above the water levels (and thus dry) or the regions with considerable changes in hydraulic properties that inhibit lateral flow. No-flow boundaries where assigned at groundwater divides near the high anticlines at the recharge zones (the eastern boundary of WAB). In addition, the litho-facies changes between the WAB and the Mediterranean constitute a no-flow boundary. Additionally, most of the southern boundary was considered as a no-flow boundary, since the permeability is very low (a barrier) compared to the rest of the aquifer area. Timsah and Ras El-Ein springs were considered a general head boundary. The recharge estimation of WAB is complex due to the complexity of its hydrogeology and structural geology [12]. However, the determination of the recharge volumes for the entire basin is very important to understand the sustainable yield of the basin. To enable recharge calculation on a physical basis considering aquifer outcrops, a distributed object-oriented recharge model was developed and tested by the British Geological Survey (BGS) [13]. An object-oriented approach was chosen to enable a range of recharge mechanisms to be incorporated easily into the model. Recharge is calculated at a node, which is held on a grid, which enables to consider a distributed recharge estimate. Four types of recharge node were used in this study: soil moisture balance method, wetting threshold, urban recharge process and irrigation losses.

In addition to these mechanisms, runoff routing to wadis and subsequent infiltration was also incorporated in the model. The values obtained from the BGS recharge model was used as an input data for the calibration process. After assigning initial recharge values from BGS recharge model [13] and hydraulic conductivity values (obtained from many pumping tests) [10–13] to the model cells, it was possible to adjust these values (calibration process) so that the computed results of water level and spring discharge match the observed ones. According to data availability in WAB, a set of target observation wells were chosen for calibration of the model. The calibrated results show (Fig. 4) clearly that the low permeability areas for both LA and UA are at the eastern recharge zone, the contact of the aquifer with the Mediterranean Sea and in the south region.

3. Discussion and results

The simulation results about the WAB model (Fig. 5) show that the movement of the groundwater flow moves towards the two major spring in the north (Timsah Spring) and in the middle (Ras Al-Ain Spring). Tables 1 and 2 represent the recharges from different components to WAB and spring discharges of WAB.

It is clear that the calibrated recharge of WAB is 357.9 Mm^3/y equals the measured spring complex discharges at 355.8 Mm^3/y with a relative error less than 1%. Thus, the steady-state modelling approach yields the sustainable yield of the WAB at 357.9 Mm^3/y. The Ras Al-Ain spring emerges from both the LA and the UA as they are connected hydraulically near the spring complex. The spring was subjected to heavy pumping (around 220 Mm^3/y) around it as seen in Fig. 5. Operating these wells has almost dried these springs in 1991 [15] and led to the change in groundwater flow direction towards the springs. Fig. 5 shows the direction of groundwater flow prior to the pumping by groundwater wells. When the winter season of the 1991/1992 brought rainfall with a huge amount of a few orders of the annual rainfall, the water levels of WAB raised to high levels of 50 y back causing Ras Al-Ain and



(a) (b) (c) (d)

Fig. 4. Location of observation wells (a), water level calibration (b), permeability calibration of LA (c) and UA (d) of WAB.

Table 1
Steady-state calibrated WAB recharge (Mm^3/y) from different components according to aquifer units [11]

Aquifer unit	From rainfall	From rainfall runoff	From wastewater runoff	From water supply leakage	From seawater intrusion	Subtotal
UA	244.92	16.99	1.55	5.47	3.6	272.53
Yatta	21.1	1.45	0.02	0.25		22.82
LA	55.4	3.75	0.29	0.71		60.15
Sub-total	321.42	22.19	1.86	6.43	3.6	**355.5**

Table 2
Steady-state calibrated spring discharges (Mm^3/y) from before utilization of WAB [11]

Spring complex	Observed discharge (Mm^3/y)	Modelled discharge (Mm^3/y)	Relative error
Al-Timsah	101.3	100.9	0.4%
Ras El-Ein	254.5	257	0.9%
Total	**355.8**	**357.9**	**0.6%**

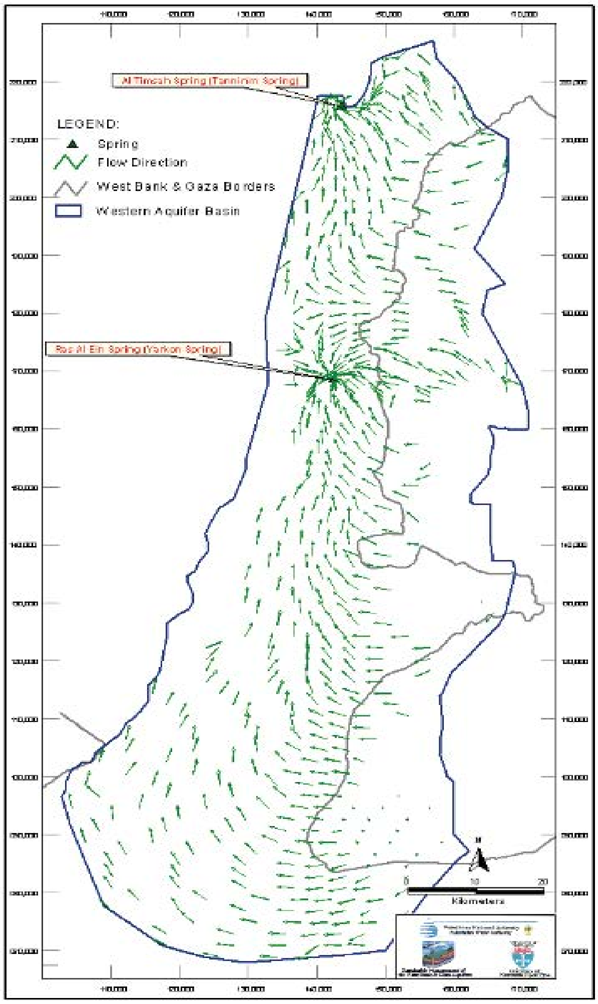


Fig. 5. Directions of groundwater flow of WAB before utilization (putting pumping wells into operation).

Timsah springs to discharge water again. The spring complex is located in a strong karstic system in both the UA and LA [15].

Although this study discussed the sustainable yield of WAB but in reality the shared aquifer basin is pumped beyond its sustainable yield capacity. This act creates a legal dispute of how these shared water resources should be managed with an agreement of all involved sharing countries. This type of agreement should be developed according to the international law of shared international aquifers.

4. Conclusion

The sustainable yield of shared regional aquifers was estimated in this study by utilizing the developed and calibrated steady-state numerical groundwater flow models. The MODFLOW-GMS software packages was used to estimate the sustainable yield for WAB. The sustainable yield of the calibrated steady-state numerical model for WAB was determined to be 357.9 Mm^3/y. The sustainable yield was estimated by developing a calibrated steady-state water budget of WAB. This paper calls for the international law to be applied in order to manage internationally shared aquifer basins.

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References

[1] SUSMAQ, Sustainable Management of the West Bank and Gaza Aquifers-Summary Report, Sustainable Management of the West Bank and Gaze Aquifers Project, Newcastle University and the Palestinian Water Authority, 2006.
[2] A. Aliewi, H. Bhandary, H. Al-Qallaf, C. Sabarathinam, J. Al-Kandari, Assessment of the groundwater yield and sustainability of the transboundary Dibdibba aquifer using numerical modelling approach, Groundwater Sustainable Dev., 15 (2021) 100678, doi: 10.1016/j.gsd.2021.100678.
[3] Y. Wada, L.P.H. van Beek, C.M. van Kempen, J.W.T.M. Reckman, S. Vasak, M.F.P. Bierkens, Global depletion of groundwater resources, Geophys. Res. Lett., 37 (2010) L20402, 1–5, doi: 10.1029/2010GL044571.
[4] A. Aliewi, Management and conflict aspects of waters between Palestine and Israel, J. Law Conflict Resolut., 1 (2009) 88–97.
[5] A. Aliewi, K. Assaf, Shared Management of Palestinian and Israeli Groundwater Resources: A Critical Analysis, Water Resources in the Middle East, Israel-Palestinian Water Issues – From Conflict to Cooperation, Vol. 2, Hexagon Series on Human and Environmental Security and Peace, H. Shuval, H. Dweik, Eds., Springer-Verlag, Berlin, Heidelberg, 2006, pp. 17–32.
[6] A. Al-Yaqubi, A. Aliewi, Z. Mimi, Bridging the domestic water demand gap in Gaza Strip-Palestine, Water Int., 32 (2007) 219–229.
[7] Z. Mimi, A.S. Aliewi, Management of shared aquifer systems using multi-criteria decision tool: a Palestinian-Israeli Mountain Aquifer as a case study, Arabian J. Eng. Sci., 30 (2006) 85–98.
[8] M. Al-Rashed, A.S. Aliewi, Water Resources Sustainability in Kuwait Against United Nations Sustainable Development

Goals, E. Azar, M. Raouf, Eds., Sustainability in the Gulf: Challenges and Opportunities, Routledge Explorations in Environmental Studies, 2018, pp. 37–56.

[9] UN ESCWA and BGR (United Nations Economic and Social Commission for Western Asia; Bundesanstalt für Geowissenschaften und Rohstoffe), Inventory of Shared Water Resources in Western Asia, Beirut, Lebanon, 2013. Available at: www.waterinventory.org

[10] SUSMAQ, Boundary Conditions of the Western Aquifer Basin, Report No. SUSMAQ-MOD#21V0.1, Sustainable Management of the West Bank and Gaze Aquifers Project, Newcastle University (UK) and Palestinian Water Authority, Contributors: A. Aliewi, C. Messerschmid, A. Kalbouneh, 2001.

[11] SUSMAQ, Steady State Flow Model of the Western Aquifer Basin, Report No. SUSMAQ-MOD#23V0.2, Sustainable Management of the West Bank and Gaze Aquifers Project, Newcastle University (UK) and Palestinian Water Authority, Contributor: A. Aliewi, G. Parkin, M. Abu Saada, C. Messerschmid, A. Kalbouneh, R. Yassin, 2003.

[12] SUSMAQ, Recharge Modelling for the West Bank aquifers, Report No. CR/05/087, Sustainable Management of the West Bank and Gaze Aquifers Project, Newcastle University (UK) and Palestinian Water Authority, Contributor: A. Hughes, M. Mansour, British Geological Survey, 2005.

[13] SUSMAQ, West Bank Aquifers – Conceptual Recharge Estimation, Report No. SUSMAQ-REC#04V0.1, Sustainable Management of the West Bank and Gaze Aquifers Project, Newcastle University (UK) and Palestinian Water Authority, Contributor: A. McKenzie, British Geological Survey, 2001.

[14] SUSMAQ, Compiled Base Data for the Numerical Flow Model of the Western Aquifer Basin, Report No. SUSMAQ-MOD#07V0.4, Sustainable Management of the West Bank and Gaze Aquifers Project, Newcastle University (UK) and Palestinian Water Authority, Contributor: A. Aliewi, G. Parkin, M. Abu Saada, C. Messerschmid, A. Kalbouneh, R. Yassin, 2002.

[15] HWE, Background Document for Ras Al-Ain Catchment, Improved Management of Water Resources in Palestine: A Key for the Future of Middle East Project, House of Water and Environment, Contributor: A. Aliewi, D. Abdelghafour, Y. Awayes, M. Abu Saada, 2005.