The 2nd International Conf. on Water Resources & Arid Environment (2006)

Assessment of Sustainable Yield of Aquifers Using Groundwater Flow Modeling and Decision Support Systems: Western Aquifer Basin as a Case Study

[1]Muath Abu Sa'ada, [1]Amjad Aliewi, [2]P. E. O'Connell

[1]House of Water and Environment, HWE, [2] University of Newcastle upon Tyne

Abstract

The Western Aquifer Basin (WAB) is a shared aquifer between the Palestinians in the West Bank and the Israelis inside the border line where 75% of its recharge areas are located in the West Bank. The Palestinians abstract about 6.5% from the total aquifer abstraction (360 Mcm/yr). Studying the sustainable yield of WAB and the spatial distribution of the water availability within (WAB) is very important for its sustainability management so that the Palestinians can identify the most productive zones to help them develop their fair share of water utilization in the future negotiations over their water right, since there is an inequity issue over the utilization of WAB between Palestine and Israel.

This paper defines the means of sustainability in groundwater aquifers, develops analytical techniques for estimating the sustainable yield and then applies them to the WAB and then estimates the water availability (sustainable yields) in the Israeli side as well as in the three defined Palestinian zones (North, Middle and South). The final part of this study is to assess the impact of Israeli abstractions on the water availability in the West Bank part of WAB.

This study develops a flow model for the groundwater system of WAB and with the aid of DSS the sustainable yield of WAB can be estimated. In this paper three definitions of Sustainable yield were used; Perennial Sustainable Yield (PSY), Maximum Perennial Sustainable Yield (MPSY) and Stressed Sustainable Yield (SSY). The PSY and MPSY are functions of the annual recharge and the annual moving average of recharge respectively. The values of PSY and MPSY are ranging between 390-430 Mcm/yr. The SSY is more complex. It is a function of the stored water in the aquifer, the historical abstractions and the maximum accepted drawdown. This study also proves that most of the water is stored in the Israeli and the Palestinian middle zone while the southern Palestinian zone (Hebron and Bethlehem) has the smallest sustainable yield (less than 2 Mcm/yr).

Key words : Sustainable yield, groundwater model, management zone

Introduction

The safe sustainable yield is generally defined as that amount of water that can be extracted from an aquifer without affecting the aquifer in a detrimental manner. It is a widely known fact that the WAB holds the largest water reserve in Historical Palestine. A reliable sustainable safe yield value is therefore a vital factor for future water resources planning in Palestine. It is a generally accepted fact that the present per capita water consumption in the Palestinian populated areas is well below World Health Organization standards of 150 liters per day.

The demand for an increased consumption is taking place due to the increase in population and modernization. The increase in demand will be in all consumption areas, i.e. industrial, agricultural and domestic areas.

Presently Israel has the ultimate control of all water resources. However, in any future negotiations regarding water issues, the Palestinians will have to be ready to scrutinize conditional offers and to rebut arguments. The results of this study will arm the Palestinians with sound and invaluable tools that support the Palestinian demand for an equal share of the aquifer.

Western Aquifer Basin (WAB)

The Western Aquifer Basin (WAB) is one of the main water resources in the West Bank. It is a shared aquifer between the West Bank, Israel and Egypt, with a surface area of 11398 km2. WAB is the largest of all groundwater basins in Historical Palestine (West Bank, Gaza and Israel). Within the borders of Historical Palestine, the basin covers an area of 9158 km2. The rest of the basin is located in the northeastern Sinai in Egypt. The North-South direction of the WAB is more than 240km long and in the West-East direction it extends from the Mediterranean coast until the heights of the West Bank, Figure 1.

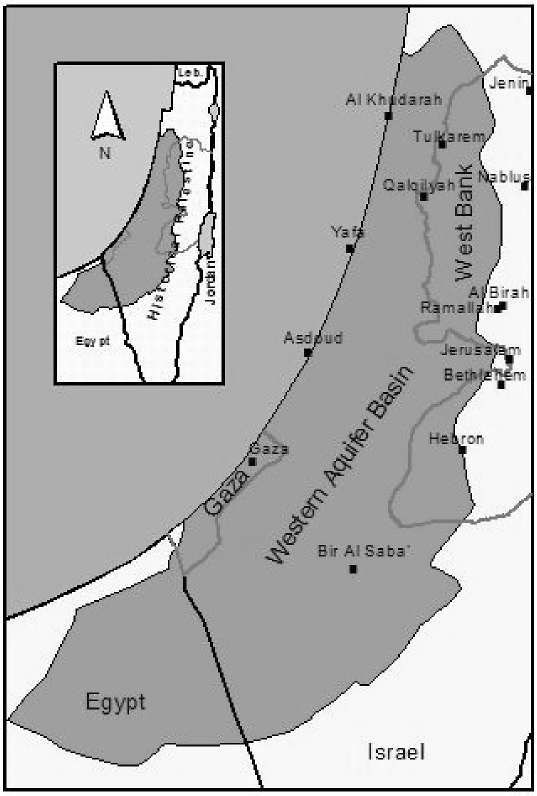

Figure 1: Location map for the Western Aquifer Basin

During SUSMAQ[1] project (1999-2004), steady state and transient flow models have been developed for the effective part of WAB, The modelled area to the south reaches only to a line between Bir al Saba' and the Afiq Channel near Gaza, Figure 2. It covers an area of 6035 km^2 with 1720 km^2 inside the West Bank. The studied area in this paper will cover the modelled part of the WAB, and especially the Palestinian areas.

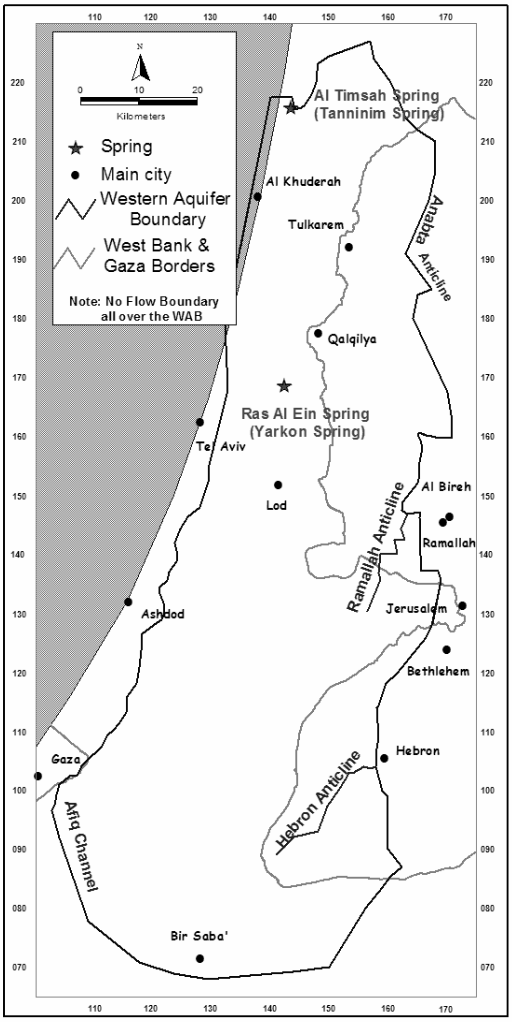

Figure 2: Boundary of the modelled area

1 Sustainable Management of the West Bank and Gaza Aquifers, funded by UK Government, Department for International Development "DIFD" and led by University of Newcastle upon Tyne & Palestinian Water,1999-2004

Steady state Models

Two groundwater flow models have been developed for the WAB system; the first model was developed to represent the basin before utilizing the aquifer, while the second model was developed to represent the basin during the period 1993 to 1998. These two models were used to estimate the sustainable yield of the WAB. The main achievements from these models were:

- Ideal water level distribution for aquifers (water level distribution before aquifer utilization).
- The geometry of the aquifer (top and bottom elevations for the aquifer layers was established.
- The calibrated hydraulic properties of WAB (horizontal and vertical conductivities) were determined.

Transient flow model

The transient flow model of WAB was developed to study the WAB response under environmental and hydro-political stresses (e.g. rainfall and abstraction). This model represents the WAB during the period 1986-1998. This model gives information about the storativity/specific yield distribution of WAB which will be used to estimate the volume of water stored in the aquifer, the change in water levels due to change in rainfall and abstraction in the modeled period. These information was used to develop rainfall-recharge regression equations which be used to estimate the recharge from any predicted rainfall scenario.

The Integration Management Tool (IMT) of WAB

The transient flow model was extended in time to cover the period 1986 – 2025, and the above models were integrated with WAB database to form "The Integrated Management Tool (IMT)", The IMT is defined as a multi-purpose software used to manage the WAB by integrating all available information resources (models and databases) in a simple way in order to be used by high-level decision makers. This IMT is used as follows:

- Evaluate the impact of abstraction scenarios on ground water levels (water availability).
- Evaluate the impact of any climatic change scenarios (rainfall scenario) on water levels**.**
- Produce more than 135 GIS maps, these maps represents the results of running the linked models.
- Estimate the sustainable yield of WAB under rainfall scenario.
- IMT can be linked with a multi-criteria analysis tool (MCAT) as an evaluation tool, so that the abstraction scenario can be imported from MCAT to run the IMT to evaluate the impact of this scenario, and then export the results to MCAT.
- Produce a summary report for the tested rainfall/abstraction scenarios (average abstraction, water levels).

The domain (WAB) is divided into four geographical zones (management zones): Northern, Middle and Southern zones located in the West Bank and the Israeli zone located outside the West Bank, Figure 3. Dividing WAB into these geographical zones will provide the Palestinian decision makers to analyze the spatial distribution of the water availability within WAB and also, provide them with the ability to test a large number of abstraction scenarios.

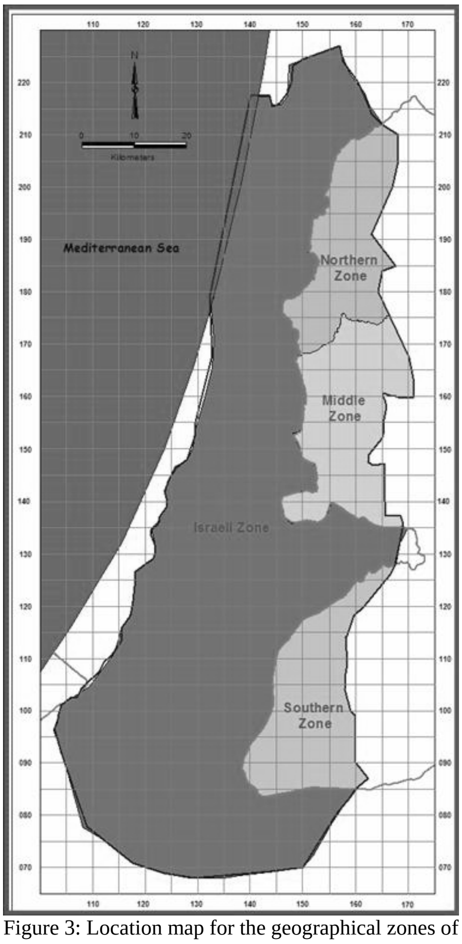

Figure 3: Location map for the geographical zones of WAB

The main purpose of IMT is to evaluate the impact of a rainfall and/or abstraction scenarios on water level distribution in the WAB (water availability), therefore, two indicators were introduced: "water level indicator" and "reliability indicator".

Water level indicator (EN01): This indicator will evaluate the impact of the abstraction scenario on water levels of the WAB. The best and the worst water levels for each management zone were defined, and then the evaluation of the tested abstraction scenario was based on the comparison of the resulted water level within each management zone with regard the best and worst values of water levels.

Reliability indicator (EN02): This indicator is a measure of the ability of the aquifer to discharge the needed amount of water within the management period without any failure years. A failure year is defined as the year that the water level in the management zone reaches a level below the worst water level for that zone.

Assessing the sustainable yield of WAB

In general, the sustainability yield of aquifer is defined as the amount of water that could be abstracted from the aquifer system which ensures that the benefits of use of a hydrological system will meet present objectives of society without compromising the ability of the system to meet future objectives. Estimating the sustainable yield of WAB in mathematical ways is not possible due to the complexity of the aquifer system. Therefore, the developed IMT provides an easy method for estimating the sustainable yield of the WAB under different climatic or hydro-political conditions. In this paper the sustainable yield of WAB was defined in four different ways:

Perennial Safe (Sustainable) Yield

Perennial safe yield is the amount of water that can be safely abstracted from the WAB without long term adverse conditions occurring. This means that the maximum abstraction from the WAB in any year must not exceed the recharge in the same year. This sustainable yield will maintain the water in the WAB at a constant level.

The recharge time series is one of the IMT outputs, so running IMT for rainfall scenario which is obtained from a rainfall model for the West Bank will lead to perennial sustainable yield, Table 1.

In order to validate the results of the perennial safe yield definition, the IMT is run with abstraction equal to estimated recharge in all years under the assumed rainfall condition; the result is shown in Figure 4 which shows no change in water levels during the management period.

Maximum Perennial Sustainable Yield

Maximum perennial sustainable yield is defined as the maximum yield available annually subject to all available recharge resources being utilized at optimum level by allowing specific drop in storage on the calculation that will be recovered during a 7-10 year cycle of recharge. It is the same as perennial sustainable yield but here the abstraction in any year may be larger than the recharge in that year under a condition that the difference between abstraction and recharge will be substituted within the hydrological cycle. Mathematically, Maximum Perennial Sustainable Yield can be expressed by the moving average (7 years) of the recharge time series which is estimated by IMT, Table 2.

Table 1: Rainfall and the estimated perennial sustainable yield

Year	Rainfall Depth (mm)	Recharge=Perennial Sustainable Yield (Mcm)	Year	Rainfall Depth (mm)	Recharge=Perennial Sustainable Yield (Mcm)
1998/99	971	867	2012/13	758	598
1999/00	502	333	2013/14	461	293
2000/01	653	479	2014/15	435	275
2001/02	516	346	2015/16	827	685
2002/03	503	334	2016/17	524	353
2003/04	827	685	2017/18	598	426
2004/05	520	350	2018/19	321	203
2005/06	556	385	2019/20	237	150
2006/07	652	478	2020/21	497	327
2007/08	404	255	2021/22	337	213
2008/09	636	462	2022/23	490	321
2009/10	576	405	2023/24	765	606
2010/11	581	409	2024/25	494	324
2011/12	538	367			
			Average Rainfall (1998-2025)=	562	mm/yr
			Average Recharge (1998-2025)=	405	Mcm/yr

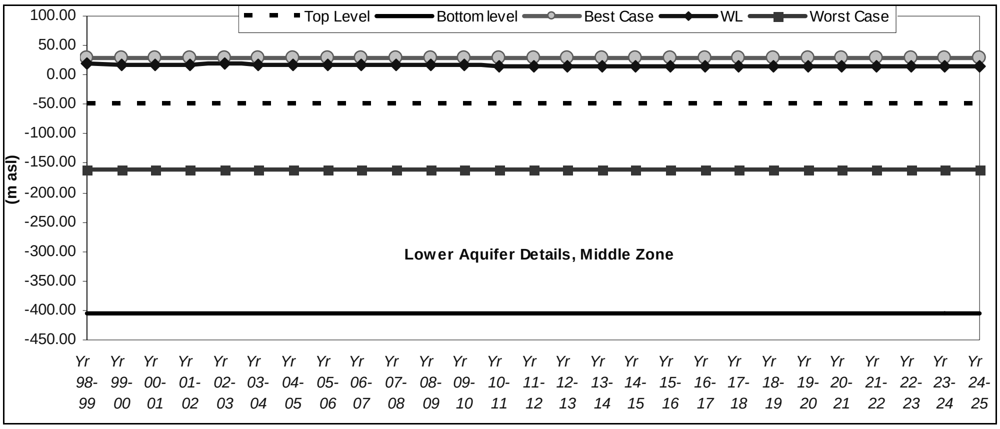

Figure 4: Validation of abstraction the perennial sustainable yield from WAB

Stressed Sustainable Yield

Stressed sustainable yield is the amount of water that can be extracted from the WAB larger than the perennial safe yield over a long planning period (25 years) on the condition that the over-pumped water can be recovered over a future period in which the basin can be managed wisely. This will give the evidence if high storage in the basin exists.

Table 2: Rainfall and maximum perennial sustainable yield of WAB

Year	Rainfall Depth (mm)	Maximum Perennial Sustainable Yield (Mcm)	Year	Rainfall Depth (mm)	Maximum Perennial Sustainable Yield (Mcm)
1998/99	971	419	2010/11	581	398
1999/00	502	423	2011/12	538	401
2000/01	653	480	2012/13	758	433
2001/02	516	485	2013/14	461	426
2002/03	503	416	2014/15	435	428
2003/04	827	437	2015/16	827	405
2004/05	520	405	2016/17	524	341
2005/06	556	421	2017/18	598	346
2006/07	652	431	2018/19	321	337
2007/08	404	392	2019/20	237	285
2008/09	636	395	2020/21	497	321
2009/10	576	425	2021/22	337	306
Average Rainfall (1998-2022)=				560	mm/yr
Average Recharge (1998-2022)=				398	Mcm/yr

Estimating the stressed sustainable yield is carried out iteratively using IMT. The first run of IMT is for current abstractions from the four management zones (the average abstraction over the period 1986-1998, Table 3). This run is conducted to ensure that the water levels over the management period (1998-2025) are in the accepted levels (30% of the saturation thickness). After that, an increase in the abstractions is made in steps (multiply the abstractions by the same percentage) until the water level indicator of any of the management zones reaches the unaccepted water level (worst water level), Figure 5.

Table 3: Current abstractions for the management zones

Management Zone	Average Abstraction (1986-1998) (Mcm/yr)
Northern Zone	19.9
Middle Zone	0.7
Southern Zone	0.4
Israeli Zone	317
Total	338

At the end, the following results were obtained:

- It has been shown that 760 Mcm/yr can be extracted from the basin until 2025 when the basin starts to reflect adverse conditions. This implies the great storage of WAB.
- The continuation of pumping at current levels until 2025 will lead to the worst limit for the southern zone (Current Abstraction = 0.4 Mcm/yr) while the central and northern zones will marginally be affected.
- Taking 760 Mcm from the WAB will reach the level of aquifer mining for the southern and northern zones of the WAB.
- After year 2025, the allowed abstraction should be less than or equal to annual recharge.

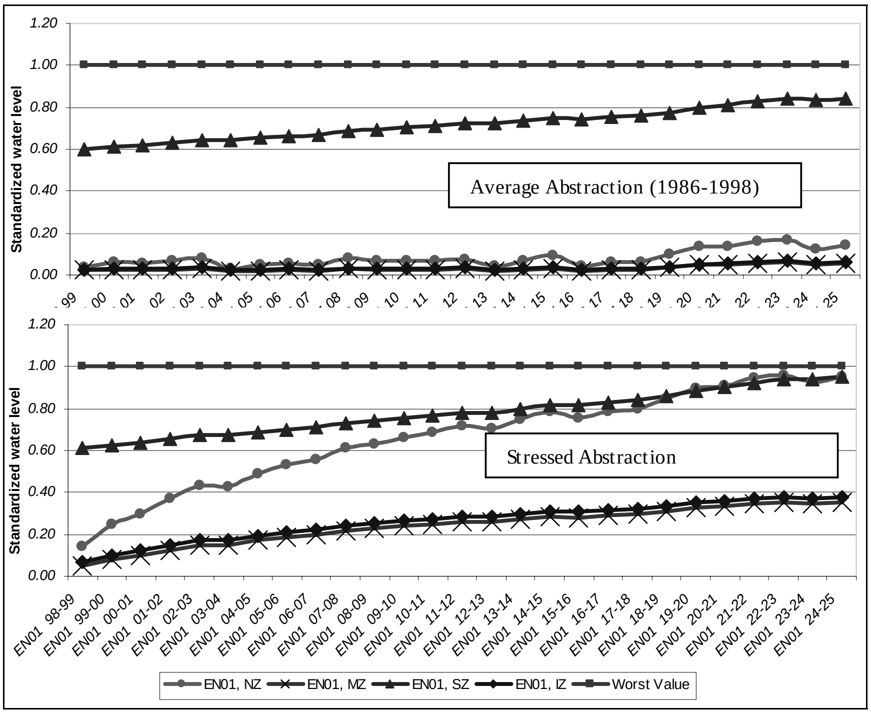

Figure 5: Comparison between water level indicator for current and Stressed abstractions

Estimating the maximum abstractions from Palestinian Management Zones in WAB

The aim here is to estimate the maximum possible abstraction in Palestinian management zones under different rainfall and Israeli abstraction scenarios. This estimation is based on:

- Rainfall scenario for the period (1998-2025), Table 1.
- Six Israeli abstraction scenarios (250, 317, 400, 500, 600 and 700 Mcm/yr)
- 30% of the saturation thickness as the maximum allowable drawdown in the aquifer.
- Using the current abstractions for the four management zones, Table 3, as a base for calculations.
- Calculations based on the definition of stressed sustainable yield.

For each proposed Israeli abstraction scenario, the abstraction in two Palestinian zones were fixed to the current abstraction values, while the abstraction in the third zone was increased gradually until the water level indicator reached the unaccepted water level. This value is considered as the maximum sustainable stressed yield that can be taken from that zone under the defined conditions. This will be repeated for the other two Palestinian management zones. The results for these calculations are shown in Table 4.

Table 4: Maximum Palestinian abstractions for different Israeli abstraction scenarios

Scenario	Abstarction (Mcm)					
	Israeli Zone	Northern Zone	Middle Zone	Southern Zone	Palestinian Zones (Total)	WAB (Total)
Sc01	250	465	0.7	0.4	466.1	716.1
		19.9	490	0.4	510.3	760.3
		19.9	0.7	1.9	22.5	272.5
Sc02	317	385	0.7	0.4	386.1	703.1
		19.9	420	0.4	440.3	757.3
		19.9	0.7	1.8	22.4	339.4
Sc03	400	315	0.7	0.4	316.1	716.1
		19.9	315	0.4	335.3	735.3
		19.9	0.7	1.5	22.1	422.1
Sc04	500	230	0.7	0.4	231.1	731.1
		19.9	235	0.4	255.3	755.3
		19.9	0.7	1.4	21.8	521.8
Sc05	600	140	0.7	0.4	141.1	741.1
		19.9	138	0.4	158.3	758.3
		19.9	0.7	1.2	22	622
Sc06	700	54	0.7	0.4	55.1	755.1
		19.9	38	0.4	58.3	758.3
		19.9	0.7	1	21.6	721.6

The results show that the value in a dashed box is the amount of abstraction that can be generated from a specific Palestinian Management Zone under the particular Israeli abstraction scenario without causing the WAB to reach adverse conditions.

Results and Conclusions

- The Southern Management Zone is very limited in its recharge and productivity. The maximum abstraction from this zone should not be increased above 1.9 Mcm/yr regardless of abstraction scenarios in other zones, Table 5.

Table 5: Maximum abstractions from Southern Zone for different Israeli abstraction scenarios

Scenario	Abstarction (Mcm)					
	Israeli Zone	Northern Zone	Middle Zone	Southern Zone	Palestinian Zones (Total)	WAB (Total)
Sc01	**250**	19.9	0.7	**1.9**	22.5	272.5
Sc02	**317**	19.9	0.7	**1.8**	22.4	339.4
Sc03	**400**	19.9	0.7	**1.5**	22.1	422.1
Sc04	**500**	19.9	0.7	**1.4**	22	522
Sc05	**600**	19.9	0.7	**1.2**	21.8	621.8
Sc06	**700**	19.9	0.7	**1**	21.6	721.6

- Water availability in the Middle Zone is much greater than the Northern Zone. This does not mean that the ability to extract water is easier; development costs should be prepared and a tradeoff between cost of development and drilling and quantity of extracted water should be made for the two zones, Table 6.

Table 6: Maximum abstractions comparison between Middle and Northern Zones for different Israeli abstraction scenarios

Scenario	Abstarction (Mcm)					
	Israeli Zone	**Northern Zone**	**Middle Zone**	**Southern Zone**	**Palestinian Zones (Total)**	**WAB (Total)**
Sc01	250	465	0.7	0.4	466.1	716.1
		19.9	490	0.4	510.3	760.3
Sc02	317	385	0.7	0.4	386.1	703.1
		19.9	420	0.4	440.3	757.3
Sc03	400	315	0.7	0.4	316.1	716.1
		19.9	315	0.4	335.3	735.3
Sc04	500	230	0.7	0.4	231.1	731.1
		19.9	235	0.4	255.3	755.3
Sc05	600	140	0.7	0.4	141.1	741.1
		19.9	138	0.4	158.3	758.3
Sc06	700	54	0.7	0.4	55.1	755.1
		19.9	38	0.4	58.3	758.3

- The negative impacts of abstracting water from the Israeli Zone or Palestinian Middle Zone are larger on the water levels dropping than the Northern Zone.
- It is shown that the Palestinians can abstract 420 Mcm/yr from the Middle Zone without causing significant harm to the Israeli wells, Figure 6.

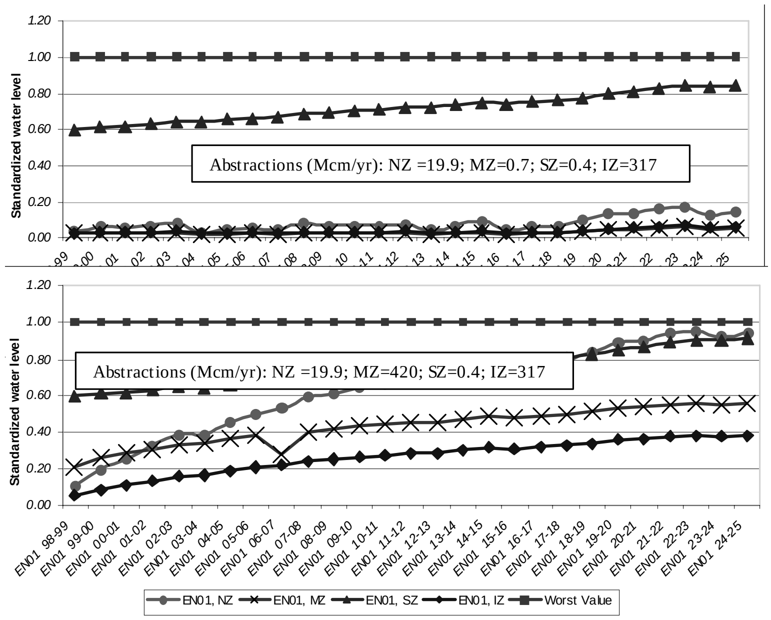

Figure 6: Impact of abstracting 420Mcm/yr from Middle zone of the Israeli zone

- Technically, the Palestinians can abstract an equal amount of water as the Israelis, Table 7.

Table 7: Maximum Palestinian abstraction for different Israeli abstraction scenarios

Scenario	Abstarction (Mcm)		
	Israeli Zone	Palestinian Zones (Total)	WAB (Total)
Sc01	60	670	730
Sc02	250	510.3	760.3
Sc03	317	440.3	757.3
Sc04	400	335.3	735.3
Sc05	500	255.3	755.3
Sc06	600	158.3	758.3
Sc07	700	58.3	758.3

References

Abu Sa’ada, M. 2004. Development of an Integrated Management Tool for the Western Aquifer Basin (WAB), Palestine. MSc Thesis, Sept. 2004. University of Newcastle upon Tyne, Department of Civil Engineering.

Abu Sa’ada, M.J., Aliewi, A.S, and Kawash, F. 2005. Toward Sustainable Management of the Palestinian Groundwater Aquifers, Western Aquifer Basin as a Case Study. Proceedings the International Conference Water: Values and Rights, 2-5 May 2005 Ramallah, Palestine.

Bachmat, Y. 1995. Hydrologic Model of the Western Mountain Groundwater Basin. Harvard Middle East Water Project, stage 1. Nov.1995.

Guttman, J. and Zukerman, C. 1995. Yarakon-Taninim-Beer Sheva Basin: Setup and calibration of the flow and salinity models. TAHAL 01/95/72. TAHAL Consulting Engineers, Ltd. In Hebrew, translated to English by SUSMAQ

Tahal .1996. Under-ground water Storage Study, The Hydrogeological Regime of the Turonian – Cenomanian Aquifer of Central Israel.

Zukerman .1999. Yarakon-Taninim-Bir Sheva’ Basin: Update of the flow model. Report number 6759-700.133, Tahal. In Hebrew, translated to English by SUSMAQ.

SUSMAQ .2000. Data Review on West Bank Aquifers, SUSMAQ-MOD#02 V2.0.

SUSMAQ .2001. Compiled Base Data for the Numerical Groundwater Flow Model of the Western Aquifer Basin, v1-v4, SUSMAQ-MOD #07 V0.3.

SUSMAQ .2002. Conceptual Flow Model of the Western Aquifer Basin, SUSMAQ-MOD#06 V0.3, 14/1/02

SUSMAQ .2003. Rainfall Variability and Change in the West Bank, SUSMAQ-RAIN #13 V0.1.

SUSMAQ .2003. Steady state flow model report of the Western Aquifer Basin, SUSMAQ-MOD#23 V0.1.

SUSMAQ .2003. Hydrological Service Yarkon - Taninim- Beer Sheva, SUSMAQ-MOD #26 V0.1.

SUSMAQ .2003. Environmental sustainability assessment for specific scenarios, SUSMAQ-SUS#51 V1.0.

SUSMAQ .2004. Rainfall phase B, SUSMAQ-RAIN#42 V1.0

SUSMAQ .2004. Transient Model of the WAB, SUSMAQ-MOD#49 V1.0.

تقدير قدرة السحب الآمن للأحواض المائية الجوفية باستخدام النماذج الرياضية وأدوات صنع القرار للأحواض المائية، الحوض المائي الغربي كحالة دراسية

معاذ جميل أبو ســـده

بيت المياه والبيئـــة – فلسطـــين

الحوض المائي الغربي هو حوض مشترك بين الفلسطينيين في الضفة الغربية والإسرائيليين خارجهـــا، 75% مـــن مناطق تغذية الحوض تقع داخل الضفة الغربية. يستخدم الفلسطينيون حوالي 6.5% من قيمة السحب الكلي للحـــوض البالغ حوالي 360 مليون متر مكعب سنوياً. أن دراسة قيمة السحب الآمن لهذا الحوض والتوزيع الجغرافي لكميات المياه المتوفرة سيمكن الفلسطينيين من تحديد الإمكان الواعدة لحفر آبار جديدة بالإضافة إلي انه سيدعم موقف الفلـــسطينيين في اي مفاوضات مستقبلية حول طبيعة استخدام هذا الحوض المشترك .

هذه الدراسة ستعرف النظريات والمعاني التي تدور حول السحب الآمن للأحواض المائية، ومن ثم تطوير أدوات لحساب قيمة هذا السحب من أجل تطبيقها لحساب السحب الأمن لمجمل الحوض الغربي بالإضافة إلي تقدير الـــسحب الأمن لكل من المنطقة الاسرائيلة من الحوض ولثلاث مناطق أخرى تقع ضمن الضفة الغربيـــة (المنطقـــة الـــشمالية، والوسطى والجنوبية من الحوض). الجزء الأخير من هذه الدراسة سيركز على دراسة تأثير السحب الإسرائيلي على توفر المياه في مناطق الضفة الغربية.

خلال هذه الدراسة تم تطوير نموذج رياضي للحوض الغربي بالإضافة إلي أداة إدارية لإدارة هذا الحوض ســـيتم استخدامهما لحساب قدرة هذا الحوض للعطاء. في هذه الورقة تم استخدام ثلاثة تعريفات للسحب الأمـــن، الـــسحب السنوي الامن والذي يعتمد على قيمة التغذية السنوية للحوض، السحب السنوي الأمن الأقصـــى والذي يعتمد علـــى معدل التغذية السنوية للحوض خلال الدورة المطرية (التي تقدر ب 7-10 سنوات)، واخيراً السحب الأمن المـــشروط الذي يعتمد على كمية المياه المخزنة في الحوض، السحب التاريخي وعلى اعلى قيمة مسموح بها لهبوط مستوى ســـطح الماء في الحوض. في هذة الورقة تم اثبات ان معظم المياه المتوفرة في هذا الحوض مخزنة في المنطقـــة الإســـرائيلية المنطقـــة الوسطى من الضفة الغربية (رام الله) بينما تفتقر المنطقة الجنوبية للمياة (بيت لحم و الخليل) حيث قدر السحب الامـــن لهذة المنطقة بما لا يزيد على 2 مليون متر معكب سنوياً.