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IMPACT OF MINERAL PRECIPITATION ON THE DEAD SEA WATER LEVEL DESCENDS

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Abstract

The article deals with the effect of the impoundment of the proposed Red-Dead Sea Canal on water balance of the Dead Sea, as the water level of the Dead Sea basin will fluctuate accordingly. The capacity of the Red-Dead Sea Conveyance System (RDSCS) will play a criticl role on the water level of the Dead Sea. The water budget of the Dead Sea is performed with the available information during the last 55 years (1960's-2014). According to the available data, the accumulated drawdown of the Dead Sea surface level is about 39m. In this study, a comprehensive investigation on the available incoming water to the basin from the Jordan River and the wadis discharging directly to the basin as well as the contribution of the groundwater flowing to the basin from the adjacent aquifers. Beside all of these prevailing conditions, the changes in the water salinitly is considered in the water budget of the Dead Sea Basin as influenecing the water column elevation as a change of the bulk water volume loss due to evaporation and consequently the precipitation of the dissolved salts. Hence, the modification in derived water balance equation (**ʎs**) should be involved as a component for the deposited salts and other dissolved solids. It is found that this component **(ʎs)** is a controlling factor affecting

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the end result of the Dead Sea surface water level. The actual water level decline of the Dead Sea during this summer (30th May to 25th Oct. 2015) was measured to be 56.5cm which is in full agreement with the water budget derived equation. It is worth mentioning that the industrial abstraction plays an important factor in the water balance equation of the Dead Sea, as it contributes about 28% of the total annual water volume loss.

Keywords: water balance; salinity; water budget; Dead Sea; Jordan.

Introduction

Water will be an important theme in Jordan and bordering countries in near and far future. In general, Jordan is considered one of the ten poorest countries in water resources in the world (Ministry of Water and Irrigation-MWI, 2008). But, this situation does not reflect the exact reality as far as the long term average of the total country annual rainfall, which was calculated for 77 years found to be 8,590 * 10^6 m^3 (MWI, 2013). Consequently, the Ministry of Water and Irrigation should emphasise on implementing an effective integrated water resources management strategy to produce a complete surface and groundwater model.

Most of the highland areas drain the surface water runoff toward the west, to the Jordan Valley (JV). Due to this, many perennial and ephemeral streams are present in the Eastern and Western Highlands. Generally, the research on surface water in Jordan confronts three main difficulties, these are: the scarcity of presise data prior of 1970s, the unreleable records specially the manual readings and the absence of many records. Therefore, this study will emphasis mainly on the collected data since 1970s to present. In addition, any annual record for a period of less than 20 years were not considered in the study. The estimated 2015 annual water balance of the Dead Sea is around 940* 10^6 m^3 on the basis of bathymetric calculations. In addition, the strip element method was used to evaluate the surface water runoff. The analyses of data from 1960 up to 2015 showed an average declining of 0.709 m/yr in Dead Sea water level (see Table 3).

Many investigators worked on the water budget of the Dead Sea, Bentor 1961recorded that the total surface runoff flow into the Dead Sea is about 1600*10^6 m^3 /y. Recently other researches mentioned that the water inflows to the Dead Sea has been reduced from around 1500 * 10^6 m^3 /y to less than 150 * 10^6 m^3 /y (Salameh and El-Naser, 1999 and Al Weshah, 2000). The “Friends of the Earth Middle East” (2010) estimates the inflow water to the Dead Sea as low as 30 * 10^6 m^3 /y. Most of them did not consider actual situation of the water quality and the re-arrangement of the Dead Sea Basin. As well as, they did not consider the effect of the water level as influenced by the precipitated salts and other parameters which are discussed in this article.

Location

The Dead Sea is located within the Jordan Rift Valley (JRV) on 80Km away east of the Mediterranian, forming the lowest terrestrial point on the earth (Fig. 1). The JRV extends from Lake Tiberias in the north (water level lies at -210m) to the Red Sea at Aqaba. The Dead Sea is located at about 120Km South of Lake Tiberias and its water level lies at -429m. The Southern Ghors and Wadi Araba are located to the south of the Dead Sea form the southern part of the JRV. The JRV stretches from the Syrian border in the north to Aqaba in the south, with a width between 30 and 50km and altitudes over 1,194 m. a.s.l. near Ajlun and over 1,760m a.s.l. near Wadi Rum area as indicated on the available topographic sheets at the Royal Jordanian Geographic Center.

Climate

The JRV can be divided according to prevailing climatic conditions and drainage pattern into three main subareas:

1) The north Dead Sea area extends from the northern shoreline of the Dead Sea to the Lake Tiberias including both sides of western and eastern highlands, this area is characterized by a semiarid climate of a Mediterranean type with moderate warm and dry summers, but cold and wet winters with annual rainfall ranges between 200-600mm;

2) the Ghor area of the Dead Sea Basin and the surrounding highlands with annual rainfall between 100-300mm;

3) the southern Dead Sea desert comprises of Wadi Araba and Aqaba region, which has a warm Mediterranean climate with hot summers and warm winters with annual rainfall less than 50mm (Markus, et al 2006; Pidwirny, 2006). The summer extends from April to October while, winters last from November until March. The summary of the different climate parameters collected

from the available Meteorologic Data open files (Meteorological Department, 2014 and Water Authority of Jordan-WAJ, 2014) are presented in Table (1).

Table (1) Climate Parameters of JRV (Compiled by authors as found in WAJ open files)

Area	Mean rainfall (mm)	Mean temperature ºC		Mean relative humidity %		Mean wind speed knot		Mean global radiation Joule/cm^2	
		Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
North DS	329.3	23.3	8.1	48	71	37.3NW	46 SW	2322	1367
DS Basin	258.9	30.9	15	53	68	16.7NW	28.3SW	2384	1411
South DS	31.6	31.8	15.7	39	57	10 N	20 N	2534	1687

Seasonal fluctuation of the rainfall affects the JRV during the period from October until mid of May. Whereas, about 80% of the annual rainfall occurs during the period from December to March. Precipitation intensity is extremely variable and related to winter depressions affecting the area from the west and northwest, resulting in rapid decrease of precipitation amounts southwards (Fig. 4). The mean annual precipitation ranges from less than 50mm in the southern desert to more than 600mm over the Ajlun Mountains.

The annual average precipitation in the northern highlands ranges between 200 and 600mm, with a maximum in the Ajlun Mountains more than 600 mm, then decreases to 300-600mm in the Balqa Mountains, 200-350mm in the Moab Mountains, and 100-300mm in the Sharah Mountains in the south. In the Rift Valley Area, the annual average precipetation in the northern part reaches 300-400mm and droped to 100-200mm north of the Dead Sea, and 50-150mm in the Dead Sea area and northern Wadi Araba. The southern part of Wadi Araba and the Gulf and Aqaba regions get less than 50mm of rainfall (Fig.4).

Prevailing winds in the Jordan Rift Valley most of the year are light to moderate with a speed blow of 9.72 Knot, with mainly north-west direction. Hot dust winds from the east and south known as Khamaseen winds occur sometimes during winter and spring seasons. The mean sunshine in the Dead Sea area reaches 2384Joule/cm^2 in summer days, while it reduced to an average of 1411Joule/cm^2 in winter days (Meteorological Department Open files, 1922-2014).The average annual precipitation in the sub-catchment areas of Jordan Rift Valley is approximately 278mm. This value corresponds to a long term average amounts equal to 3620* 10^6 m^3 (Table 4) (Ministry of Water and Irrigation (MWI), 2013).

Dead Sea Surface Water Basins

The drainage pattern in the Dead Sea catchment area can be divided into three main categories according to the presented topographic barriers; The Northern catchment area mainly discharging towards the River of Jordan and the Dead Sea. The second group of basins drain the runoff through the wadis directly into the Dead Sea. The third is the Southern Catchment area draining partly into the Dead Sea and partly into the salt ponds of the southern division of the Dead Sea barrier at -390m elevation by the Lisan Peninsula (Fig. 1). The southern part ended at a distance of about 75 km from Aqaba at Wadi Namila. The Dead Sea water balance assumes the safe maximum water level as much as -395m. It is worth to mention that the runoff from the Egyptian part faced with a high elevation topography in Wadi Araba north, which prevent it to reach the Dead Sea.

The Jordan River receives its waters from three main sources outside Jordan; The Hasbani River in Lebanon supplies about 130 * 10^6 $m^{3/y}$. The Dan River with 250 * 10^6 m^3 /y and Banias River with 120 * 10^6 m^3 /y both flow into the Jordan River above the Huleh marshes (which have been drained by Israel since the early 1950s). The fourth large source is the Yarmouk River with an average flow of 360 * 10^6 m^3 /y. The Yarmouk flows into the Jordan River about 4 km south of Lake Tiberias and partially flows into King Abdulla Canal where about 130*$10^6$$m^3$ are deviated to be used as potable and irrigation purposes, Heinz H¨otzl 2009. The average annual surface water runoff of the Jordan River measured at King Hussein Bridge was 1,000 * 10^6 m^3 /y before reservoirs and diversion weirs were constructed. There had been a significant annual variation between 350 * 10^6 m^3 in a dry year to about 1,600 * 10^6 m^3 during a wet year. At present, Israel diverts 75% of the above mentioned tributaries before they reache the Jordan River.

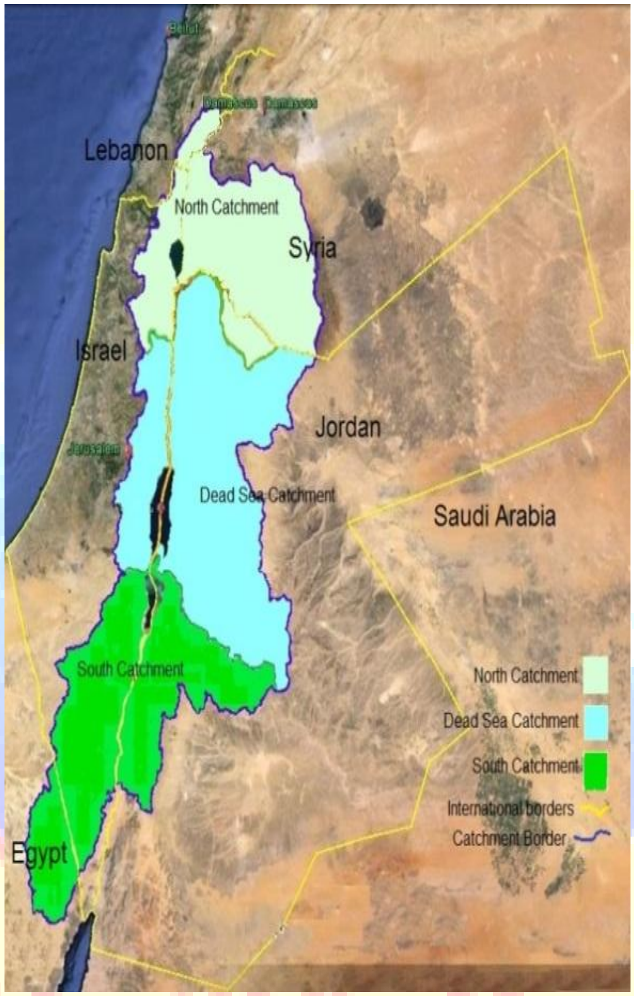

Fig. (1): Location map of the Dead Sea Subcatchment Areas on Google base map (by Authors).

Theoritical Calculations and Results Based on the Bathymetric Map

The calculated Dead Sea surface areas at different water depths are given in Table (2). These calculations are based on the bathymetric map of the Dead Sea (Hall, 2000) after digitization (Fig. 2).

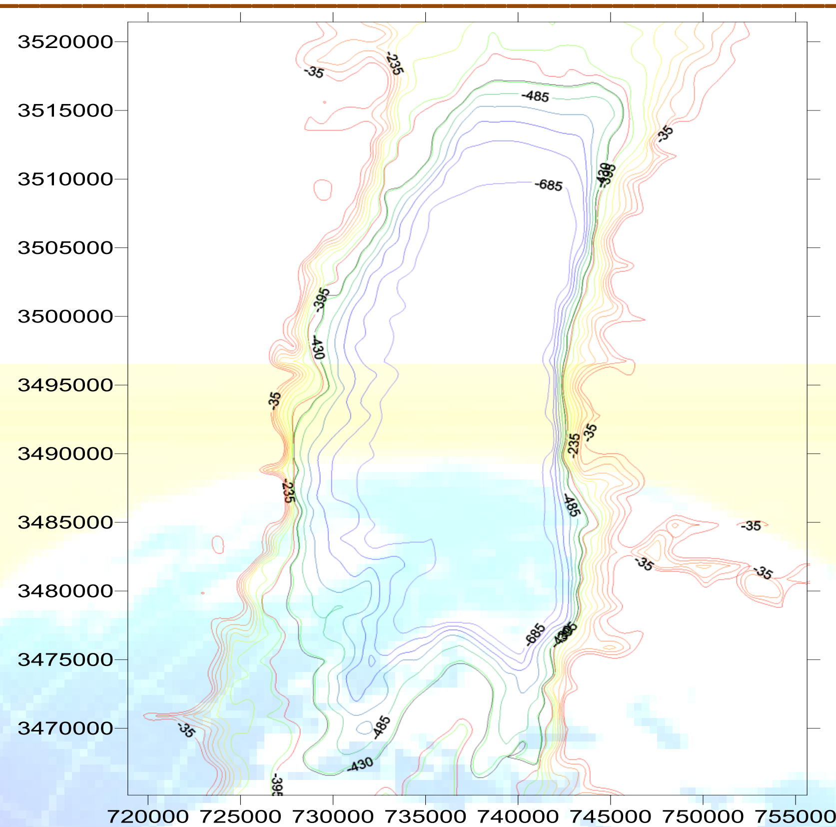

Fig. (2): Bathymetric map of the Dead Sea digitized after Hall 2000, (contour interval is 50 m).

Table (2): Dead Sea surface areas Calculated at different depths and the related (ʎs) values (Authors).

Surface water depth (m)*	Surface area km^2	Surface decline m	Surface area shrinkage km^2	Volume of water loss 10^6 m^3	Calculated decline time (Depth/ 0.709)	Calculated date	Cumulative water volume loss 10^6 m^3	Cumulative depth m	Cumulative surface area shrinkage km^2	Raise of water level due to volume of ɻ (0.342 /1.24)	Cumulative salt deposits m (ʎs)	** Real draw down m
-390	75	0.0	0.0	0.00	0.00	1960	0.00	0.00	0.00	0.00	0.00	0.00

	5	0	0								
-395	740	5.00	15.00	3737.50	7.05	1967	3737.50	5.00	15.00	1.39	1.39	3.61
-414	678.9	19.00	61.10	13479.55	26.80	1994	17217.05	24.00	76.10	5.48	6.87	17.13
-417	662	3.00	16.90	2011.35	4.23	1998	19228.40	27.00	93.00	0.84	7.71	19.29
-423	655	6.00	7.00	3951.00	8.46	2007	23179.40	33.00	100.00	1.66	9.37	23.63
-428	614.4	5.00	40.60	3173.50	7.05	2014	26352.90	38.00	140.60	1.42	10.80	27.20
-429	612.7	1.00	1.70	613.55	1.41	2015	26966.45	39.00	142.30	0.28	11.07	27.93
-430	610.9	1.00	1.80	611.80	1.41	2016	27578.25	40.00	144.10	0.28	11.35	28.65
-431	609.1	1.00	1.80	610.00	1.41	2018	28188.25	41.00	145.90	0.28	11.62	29.38
-432	607.3	1.00	1.80	608.20	1.41	2019	28796.45	42.00	147.70	0.28	11.90	30.10
-433	604.9	1.00	2.40	606.10	1.41	2021	29402.55	43.00	150.10	0.28	12.18	30.82
-434	603.4	1.00	1.50	604.15	1.41	2022	30006.70	44.00	151.60	0.28	12.45	31.55
-435	601.2	1.00	2.20	602.30	1.41	2023	30609.00	45.00	153.80	0.28	12.73	32.27
-440	565.7	5.00	35.50	2917.25	7.05	2031	33526.25	50.00	189.30	1.42	14.15	35.85
-460	536.6	20.00	29.10	11023.00	28.21	2059	44549.25	70.00	218.40	5.67	19.82	50.18
-480	51	20.	23.	1049	28.21	2087	5504	90.00	242.0	5.64	25.46	64.54

	3	00	60	6.00			5.25		0			
-490	500.3	10.00	12.70	5066.50	14.10	2101	60111.75	100.00	254.70	2.79	31.11	78.89
-500	489.6	10.00	10.70	4949.50	14.10	2115	65061.25	110.00	265.40	2.79	-500	489.6
-520	463.5	20.00	26.10	9531.00	28.21	2143	74602.25	130.00	291.50	5.67	36.78	93.22
-540	439.7	20.00	23.80	9032.00	28.21	2172	83634.25	150.00	315.30	5.67	42.45	107.55
-560	418.8	20.00	20.90	8585.00	28.21	2200	92219.25	170.00	336.20	5.65	48.10	121.90
-580	399.6	20.00	19.20	8184.00	28.21	2228	100403.25	190.00	355.40	5.65	53.75	136.25
-600	379.3	20.00	20.30	7789.00	28.21	2256	108192.25	210.00	375.70	5.66	59.41	150.59
-620	356.2	20.00	23.10	7355.00	28.21	2284	115547.25	230.00	398.80	5.70	65.11	164.89
-625	355.8	5.00	0.40	1780.00	7.05	2291	117327.25	235.00	399.20	1.38	66.49	168.51
-635	354.2	10.00	1.60	3550.00	14.10	2306	120877.25	245.00	400.80	2.76	69.25	175.75
-660	304.7	25.00	49.50	8236.25	35.26	2341	129113.50	270.00	450.30	7.46	76.71	193.29
-675	292.4	15.00	12.30	4478.25	21.16	2362	133591.75	285.00	462.60	4.22	80.93	204.07
-685	276.8	10.00	15.60	2846.00	14.10	2376	136437.75	295.00	478.20	2.84	83.77	211.23
-695	247.5	10.00	29.30	2621.50	14.10	2390	139059.25	305.00	507.50	2.92	86.69	218.31
-705	23	10.	13.	2407	14.10	2404	1414	315.0	521.0	2.84	89.53	225.4

	400	50	.50			66.75	0	0			7
-715	201.9	10.00	32.10	2179.50	14.10	2418	143646.25	325.00	553.10	2.98	92.50	232.50
-720	169.1	5.00	32.80	927.50	7.05	2425	144573.75	330.00	585.90	1.51	94.02	235.98
-725	161.4	5.00	7.70	826.25	7.05	2432	145400.00	335.00	593.60	1.41	95.43	239.57
-735	116.7	10.00	44.70	1390.50	14.10	2447	146790.50	345.00	638.30	3.29	98.71	246.29

* Negative values mean below sea level

** Real Drawdown corresponds to sea water level drawdown plus the precipitated salt column

Using the calculated depths of 55 years period between 1960 up to 2014 of the Dead Sea Basin, it is clear that the basin declined 39m from -390m to -429m, thus the average decline have approximately equal to 0.709 m/y. The measured record for the last 39 years during the period between 1976 and 2014 were taken from APC and presented in Table (3). The annual average decline of the Dead Sea surface water level was calculated to be equal 0.788m

Table (3) the Dead Sea water level measurements within the period 1976-2014.

Year	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Level Difference	10 Years Avg.
1976												-399.10		
1977	-399.11	-399.00	-399.03	-399.07	-399.08	-399.21	-399.32	-399.44	-399.57	-399.69	-399.79	-399.75	-0.65	
1978	-399.69	-399.62	-399.58	-399.56	-399.64	-399.74	-399.90	-400.03	-400.15	-400.22	-400.34	-400.31	-0.56	
1979	-400.29	-400.28	-400.27	-400.32	-400.42	-400.49	*******	-400.80	-400.80	-400.80	******	-400.56	-0.25	
1980	-400.28	-400.04	-400.55	-400.51	-400.56	-400.72	-400.89	-400.99	-400.17	-400.27	-400.32	-400.25	0.30	

1981	-400.09	-399.86	-399.61	-399.54	-399.57	-399.79	-399.91	-400.09	-400.29	-400.39	-400.50	-400.58	-0.33	
1982	-400.57	-400.53	-400.48	-400.43	-400.48	-400.68	-400.75	-400.91	-401.01	-401.15	-401.30	-401.44	-0.86	
1983	-401.44	-401.37	-401.07	******	-401.86	-401.26	-401.45	******	-401.71	-401.90	-401.97	-402.13	-0.68	
1984	-402.13	-402.23	-402.19	-402.22	-402.23	-402.31	-402.46	-402.62	******	-402.82	-402.92	-402.98	-0.86	
1985	-403.07	-403.08	-402.98	-402.92	-402.89	-403.03	-403.18	-403.30	-403.42	-403.57	-403.62	-403.67	-0.68	-0.508
1986	-403.65	-403.72	-403.73	-403.68	-403.74	-403.85	-404.02	-404.14	-404.23	-404.39	-404.39	-404.45	-0.79	
1987	-404.51	-404.49	-404.51	-404.52	-404.56	-404.68	-404.71	-404.87	-405.01	-405.01	-405.14	-405.19	-0.74	
1988	-405.20	-405.12	-405.95	-405.81	-405.84	-405.96	-405.14	-405.29	-405.48	-405.61	-405.68	-405.89	-0.70	
1989	-405.89	-405.93	-406.02	******	-406.05	-406.16	-406.28	-406.41	-406.52	******	-406.67	-406.69	-0.80	
1990	-406.70	-406.81	-406.85	-406.80	-406.87	-406.98	-407.15	-407.25	-407.35	-407.44	-407.53	-407.68	-0.99	
1991	-407.70	-407.70	-407.47	-407.51	-407.85	-407.89	-408.06	-408.26	******	-408.46	******	-408.49	-0.81	
1992	-408.39	-407.15	-406.68	-406.64	-406.58	-406.74	-406.82	-407.08	-407.26	-407.40	-407.44	-407.30	1.19	
1993	-407.10	-406.80	-406.75	-406.79	-406.81	-406.95	-407.20	-407.37	-407.58	-407.68	-407.80	-407.76	-0.46	
1994	-407.67	-407.61	-407.61	-407.66	-407.77	-407.91	-408.16	-408.26	-408.40	-408.48	-408.52	-408.46	-0.70	
1995	-408.42	-408.26	-408.26	-408.30	-408.37	-408.52	-408.70	-408.81	-408.95	-409.05	-409.18	-409.30	-0.84	-0.564
1996	-409.28	-409.26	-409.26	-409.32	-409.38	-409.52	-409.64	-409.78	-409.91	-410.03	-410.11	-410.10	-0.80	
1997	-410.03	-410.03	-410.08	-410.14	-410.20	-410.32	-410.48	-410.63	-410.76	-410.77	-410.84	-410.85	-0.75	
1998	-	-	-	-	-	-	-411.40	-	-	-	-	-	-1.06	

	410.92	410.98	410.99	411.12	411.19	411.28		411.53	411.65	411.65	411.76	411.91		
1999	-411.95	-411.95	-412.00	-412.06	-412.15	-412.26	-412.42	-412.55	-412.66	-412.73	-412.82	-412.98	-1.07	
2000	-413.06	-413.19	-413.20	-413.30	-413.49	-413.64	-413.77	-413.87	-413.96	-414.06	-414.14	-414.18	-1.20	
2001	-414.19	-414.25	-414.33	-414.47	-414.48	-414.60	-414.72	-414.86	-415.01	-415.13	-415.20	-415.24	-1.06	
2002	*****	-415.32	-415.38	-415.43	-415.52	-415.61	-415.76	-415.91	-416.04	-416.18	-416.29	-416.31	-1.07	
2003	-416.32	-416.19	-415.85	-415.82	-415.89	-416.01	-416.17	-416.36	-416.53	-416.68	-416.81	-416.89	-0.58	
2004	-416.87	-416.81	-416.79	-416.87	-416.95	-417.08	-417.20	-417.34	-417.41	-417.45	-417.46	-417.55	-0.66	
2005	-417.60	-417.63	-417.64	-417.71	-417.77	-417.92	-418.02	-418.15	-418.30	-418.41	-418.49	-418.57	-1.02	-0.927
2006	-418.65	-418.67	-418.55	418.64	-418.73	-418.88	-419.03	-419.22	-419.36	-419.48	-419.54	-419.74	-1.17	
2007	-419.77	-419.79	-419.84	-419.85	419.90	420.05	-420.19	-420.34	-420.44	-420.59	-420.65	-420.74	-1.01	
2008	-420.91	-421.00	-421.07	-421.12	-421.22	-421.36	-421.49	-421.70	-421.82	-421.88	-421.96	-422.12	-1.38	
2009	-422.27	-422.22	-422.27	-422.30	-422.36	-422.47	-422.69	-422.81	-422.94	-423.01	-423.15	-423.26	-1.14	
2010	-423.19	-423.02	-423.10	-423.18	-423.27	-423.36	-423.50	-423.70	-423.78	-423.88	-424.03	-424.13	-0.87	
2011	-424.24	-424.33	-424.36	-424.44	-424.54	-424.67	-424.79	-424.92	-425.05	-425.17	-425.30	-425.52	-1.39	
2012	-425.60	-425.71	-425.83	******	-425.99	-426.13	-426.28	-426.42	-426.56	-426.63	-426.75	-426.88	-1.36	
2013	-426.76	-426.76	-426.82	-426.91	-426.99	-427.10	-427.33	-427.47	-427.57	-427.68	-427.76	-427.83	-0.95	
2014	-427.91	-427.96	-427.97	-428.07	-428.04	-428.11	-428.40	-428.49	-428.59	-428.75	-428.80	-428.81	-0.98	
2015	-428.9	-428.8	-428.8	-428.96	-429.0	-429.1	-429.32	-429.45	-429.51	-429.60	******	-429.8	-0.99	-1.124

	0	8	9		2	2						0		
Averag e													-0.788	-0.781

On the other hand, it is clear that the drawdown of the Dead Sea water level is stepwise linear as indicated in Figure (3). The two humps present in the figure are actually related to wet years in 1980/1981 and 1991/1992.

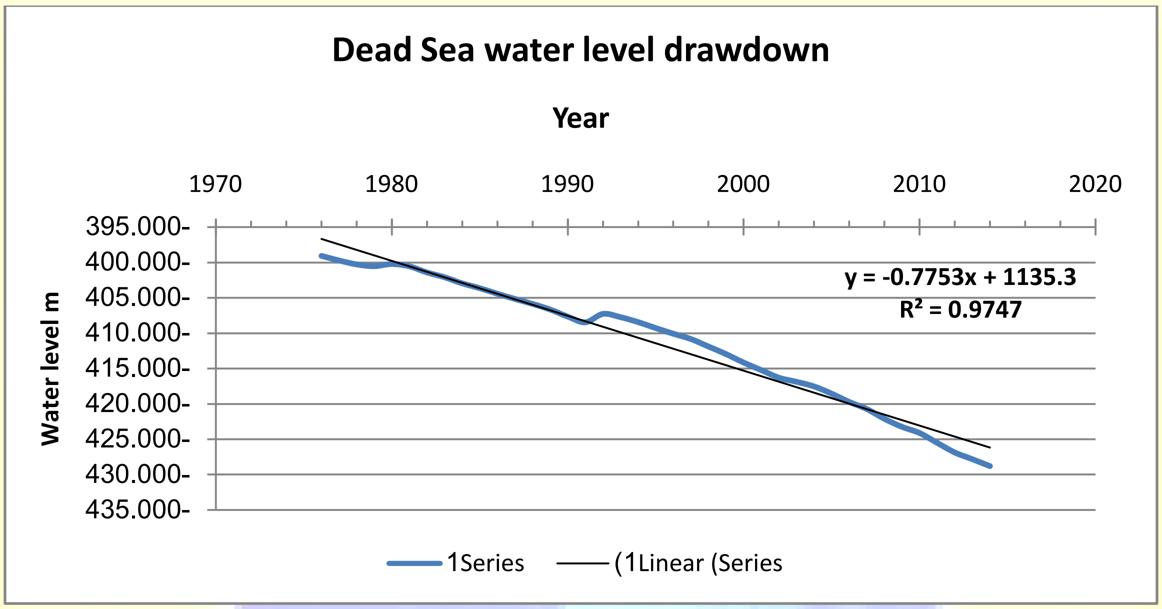

Fig. 3 Drawdown of the Dead Sea water level 1976-2014 as measure by APC.

In order to estimate the volume loss of the Dead Sea water, the authors derived the relation between the water depths of the Dead Sea in meters versus the corresponding Dead Sea surface area in km^2 (Fig. 4).

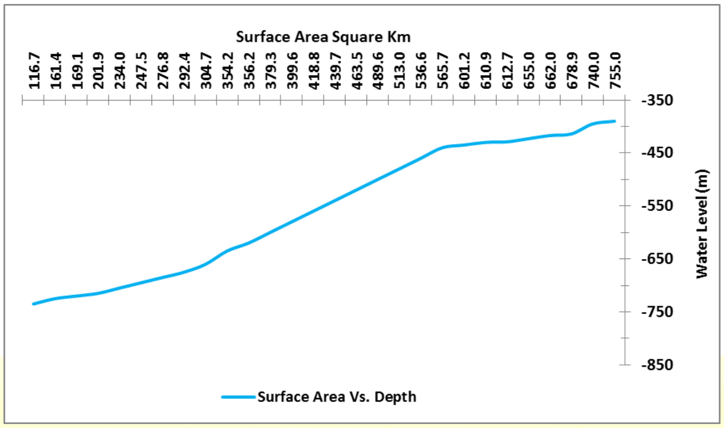

Fig. (4): The variation of surface water depth and surface water area of the Dead Sea.

Accordingly, the calculated average water volume of the Dead Sea using the calculated average surface area (437 Km^2) (based on the actual survey conducted by the digitized bathymetric map after Hall 2000), then multiplied by the today's total variation in depth ((-429)-(-735) = 0.306 Km) gives the total volume of the water which is equal to 133.722 km^3 (133.722*10^9 m^3). Then the average volume water loss per year is equal the total volume divided by the whole time needed for complete dryness of the Dead Sea water, that is: 146804.05/345 = 425.52*10^6 m^3/y. The calculated height of the salts after complete dryness of the present Dead Sea water is equal to 98.72m. Then, the actual dried Dead Sea floor will be at (-735+98.72 = -636.24 m). On the other hand, the lost water volume since 1960 up to 2015 is equal to (437 km^2)*(0.039 km) corresponding to 17.043km^3 = 17043* 10^6 m^3. The loss ratio of the Dead Sea within the last 39 years is equal to the lost volume divided by the total volume, which is equal to 11.61%.

The inflow water to the Dead Sea using the present direct rainfall volume 612.7 km^2 * 106 mm = 64.95 * 10^6 m^3 plus the related amounts of runoff within the Dead Sea basin catchment area, which has been calculated to be 145.84* 10^6 m^3 plus the assumed baseflow volume 232.77* 10^6 m^3 giving the value of 443.56 * 10^6 m^3.

To find the static compensation water level of the Dead Sea at which the water balance is in equilibrium, that is the direct water inflows equal to the direct evaporation without any external human activities to take place and consequently the obtained results are presented in last column of Table 2. Therefore, the Dead Sea surface area at the compensation water level equal the direct inflow 431.53 * 10^6 m^3 divided by the average annual decline 0.709m. Thus the calculated apparent depth is located approximately at –608.6 m then subtracting the deposited salt water thickness which is 61.69, thus the net depth will be equal to -546.91m, at which the surface area is calculated to be 432.5 km^2 and this will be reached in the year 2181 as in Table 2.

The water of the Dead Sea has a tremendous amount of dissolved solids (hypersaline) which reached up to 342 g/L. Some of evaporites were precipitated as the Dead Sea water becomes oversaturated through the evaporation process. Therefore, a considerable amounts of salts will be deposited on the bottom of the Dead Sea causing a rise in the water level of the Dead Sea. The following general formulated equations are used to calculate the salt deposit column corresponding to the surface water rise.

The dynamic state of deposition can be formulated as follows:

$$\frac{dSd}{dt} = \frac{d(\lambda s / \gamma s)}{dt} * \frac{d(Vw / Aw)}{dt} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

The static state of deposision can be formulated as follows;

$S_d = (\lambda_s / \gamma_s) * (V_w / A_w)$………………………….............. (2)

Where:

S_d is the precipitated salts,

λ_s is the amount of total dissolved solids,

γ_s is the density of the total dissolved solids,

V_w is the volume of water,

A_w is the surface area of the water.

For the Dead Sea case assuming no mixing with other waters, it is convienent to use λ_s=342 g/L and γ_s =1.24 g/L to calculate the precipitated salt column on the Dead Sea floor. The results for different bathymetric level are given in Table (2).

Direct Rainfall on the Dead Sea Basin and Its Catchment Areas

The rainfall contour map (Fig. 5) was created with Surfer Version 11 using the revised records mentioned in Table (4), (WAJ, 2014 open files). The mountainous highlands along the Jordan Valley-Dead Sea-Wadi Araba depression receive the majority of the total rainfall volume, which represents the main source of recharging the surface and groundwater basins (Table 5). Most of the rainfall occurs during the period between October and May. However, rarely rainfall occurs in June or September. The mean annual direct rainfall over the Dead Sea surface area is approximately 106 mm.

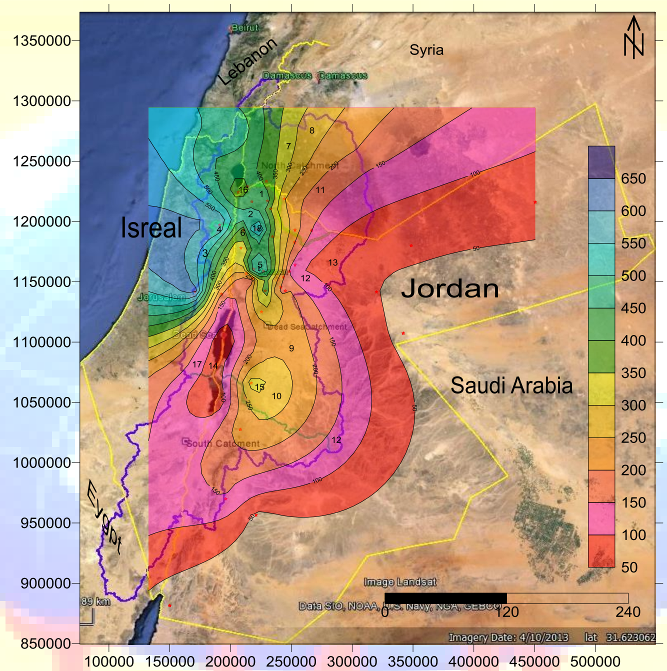

Fig. (5): Average Isohyetal Rainfall Map for the Last 55 Years.

The mean direct rainfall amounts received by the Dead Sea is a function of the water surface area at certain time, it is estimated for the year 2015 to be 612.7km^2*106mm=64.95* 10^6 m^3.

Table (4): Rainfall Gauge Stations located within and outside the Dead Sea Basin.

Station Name	Coordinates (PG)		Elevation (m)***	Average Rainfall mm/y
	Latitude N	Longitude E		
Ajlun RM	198.800	226.800	1150	594
Amman Airport	153.800	243.500	790	242

Aqaba	881.500	150.000	40	23
Baqoura	224.300	206.300	-205	356
Deir Alla	178.000	208.500	-224	267
Ghor Safi	45.500	194.800	-277	50**
Hummar	158.800	227.000	925	501
Ira	157.000	213.000	650	256
Jarash	187.500	234.500	585	343
Jiza	112.333	241.821	705	84
Karak	66.000	217.000	1000	324
Kh. Wahadna	192.800	210.800	590	364
Madaba	125.000	225.500	785	284
Na'ur	142.500	228.500	800	404
S. Shuna	146.000	210.500	-160	174
Salt	160.500	219.000	796	551
Shaubak	992.000	202.000	1300	312**
Tafila	27.500	208.000	1000	231
Umm Qis	229.000	214.000	360	397
W. Mousa	970.000	196.000	1100	148
W. Rayyan	199.500	207.000	-200	308**
Qatraneh	107.355	256.454	770	111**
Zarqa Refinery	163.800	253.000	610	145**
Palestinian Authority and Israel Rainfall Gauge Stations				
Jerusalem	114.1604	170.717	754	627**
Nablus	119.7067	191.044	550	619*
Jericho	113.9743	192.770	-258	190*
Kalia	112.6996	194.410	-360	94*
Ein Gedi	109.5384	188.115	-423	85*
Arad	107.3194	170.720	361	123*
Sedom	105.2921	188.187	-170	38*
Beer Sheva	107.3220	132.549	260	204*

*Internet Encyclopaedia

** Metrological Department measurements

*** Positive values mean above sea level while negative values mean below sea level

Using the geographic N-S arrangement of the rainfall stations in JRV, it is observed that the rainfall long-term average decreases in a general trend following the N-S geographic alignment, Fig. (6).

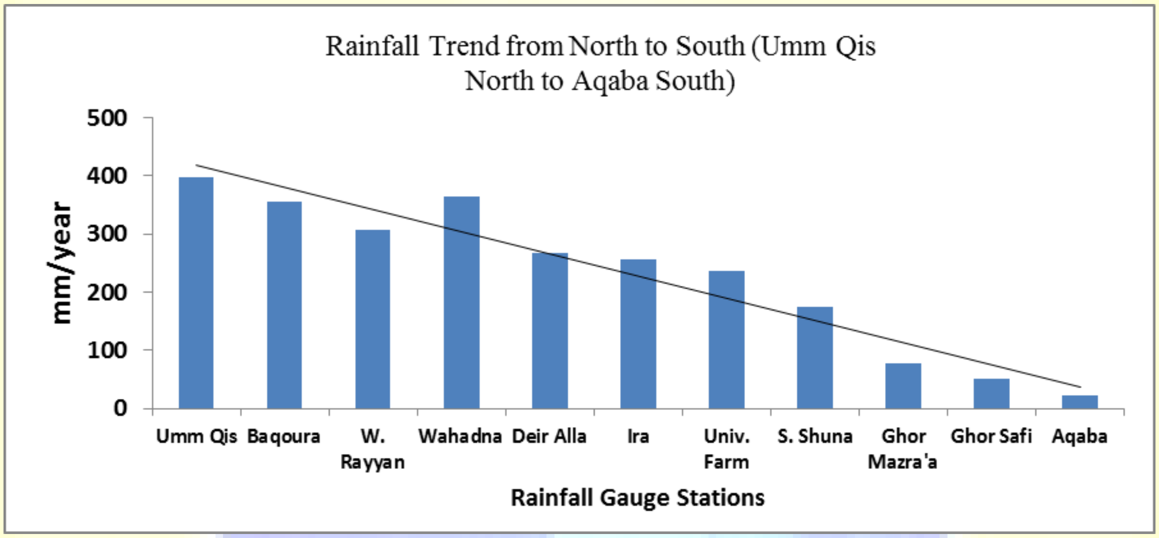

Fig. (6): Rainfall Trend from Northern Part to Southern Part of the Jordan Valley.

Using the Jordan Valley rainfall records for the Dead Sea derived in Table (5) during the period 1930 to 2014, it is found that the total catchment area of the Dead Sea in Jordan equal to 14803 Km^2, while the average annual rainfall is 278 mm and the total rainfall is equal to 3620 * 10^6 m^3 (WAJ 2014 open files).

Table (5): The annual calculated rainfall on the Dead Sea sub-basins (WAJ, 2014 Open files).

Area Name		Area	Mean Annual Rainfall	
Divisions	Subdivisions	km^2	mm	10^6 m^3
Jordan Valley (JV)	Northern JV	642	345	220
	Southern JV	463	220	100

Southern Ghors		1776	130	230
Northern Highlands	Ajlun - Kufranja	539	485	260
	Jarash	1645	415	680
	Amman	1695	295	500
	Zarqa	2919	210	610
Southern Highlands	Karak Tafila	4379	200	870
	Southern Mountains	745	200	150
Total		14803	278	3620

The subareas between successive contours of the isohyetal map of the Dead Sea basin are presented in Fig. (7). The calculations based on the strip element method use the area bounded by two consequent isohyetal contours and are considered as one element, the yellow colored area in diagram (1), while one element have irregular boundaries is accepted in this method as far as it is using the area as a strip element, the regular discretization of the area will cause intersection between the boundary of the elements with the isohyetal lines, therefore part of these elements will be out of consideration and on other positions part of the elements will be included (Fig.7)

The strip subarea rainfall and consequently the total volume of rainfall on the basin as shown in Table (6) is 4289.35 * 10^6 m^3, while using the average rainfall for the whole area to calculate the total rainfall volume shows a high estimated value: Total area * Average Rainfall = 17419 Km^2* 324 mm = 5643.756 * 10^6 m^3. This value exceeds the calculated value using the strip element method by 1354.41 * 10^6 m^3; leading to an increase in the annual runoff value by 46.05 * 10^6 m^3.

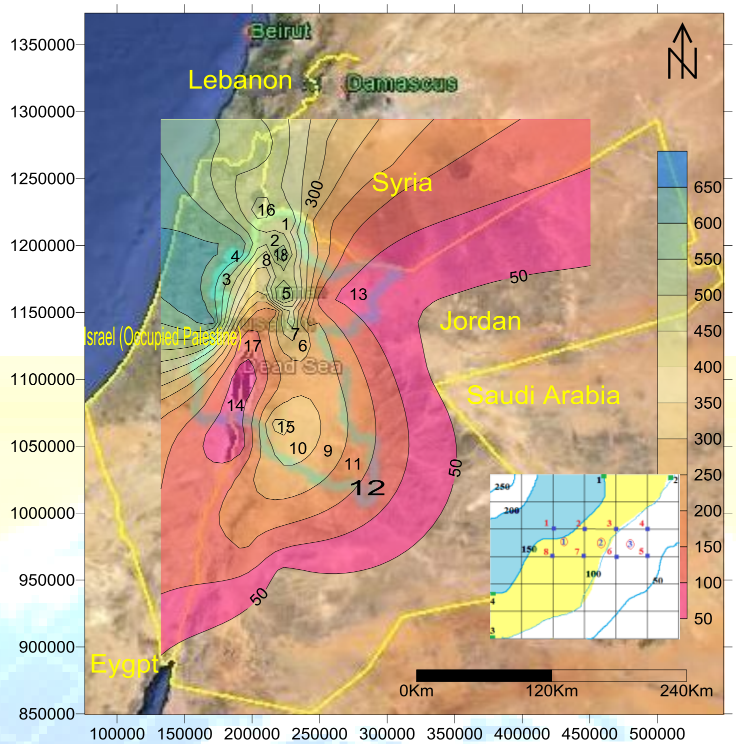

Fig. (7): Strip Element Rainfall Map. The comparison between the strip element and regular cells are also shown.

Table (6) Dead Sea Basin Strip areas, rainfall, runoff and evaporation.

Code	***Sub-Area**	**Average Annual Rainfall** mm	**Strip Rainfall volumes** 10^6 m^3	**Strip Runoff Volumes**10^6 m^3	**Strip Evaporation Volumes**10^6 m^3
1	1284	425	545.7	18.5538	509.6838
2	534	475	253.65	8.6241	236.9091
3	224	525	117.6	3.9984	109.8384
4	120	550	66	2.244	61.644
5	165	450	74.25	2.5245	69.3495
6	890	375	333.75	11.3475	311.7225

7	1221	325	396.825	13.49205	370.63455
8	1490	275	409.75	13.9315	382.7065
9	3985	225	896.625	30.48525	837.44775
10	1396	300	418.8	14.2392	391.1592
11	1650	175	288.75	9.8175	269.6925
12	1169	125	146.125	4.96825	136.48075
13	989	75	74.175	2.52195	69.27945
14	264	100	26.4	0.8976	24.6576
15	109	300	32.7	1.1118	30.5418
16	31	500	15.5	0.527	14.477
17	1246	125	155.75	5.2955	145.4705
18	74	500	37	1.258	34.558
Total	16841		4289.35	145.8379	4006.2529

*Subarea corresponds to the area between any two successive isohetal lines.

Dead Sea Stream Inflows

From the records of the Yarmouk River at Adasiya and the Jordan River at Degamya flood gauge stations (MWI 2014 open files), the successive ten years averages of these measurements are given in Table (7).

Table (7): The Dead Sea 10-Years Average Surface Water Inflows from the Jordan River (106 m3).

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
1928/29	38.5	50.5	88.8	160.1	554.5	390.7	273.3	200.8	115.5	71.3	50.7	45.3	2040.1
1930/39	70.5	91.7	100.9	128.0	204.1	133.5	97.7	87.5	73.9	73.4	74.9	70.0	1206.3
1940/49	91.5	84.2	96.9	131.7	159.8	154.3	122.8	97.8	85.1	84.6	83.7	80.4	1272.9

1950/59	68.5	82.1	111.5	131.8	138.7	137.6	92.4	63.6	49.3	48.5	51.6	53.3	1028.8
1960/69	38.4	51.2	113.4	180.7	186.6	156.1	77.5	43.7	27.2	24.8	24.0	24.5	948.0
1970/79	29.6	40.1	53.8	79.6	84.8	100.2	79.9	33.1	27.3	25.1	24.3	23.7	601.6
1980/89	33.4	54.5	80.7	84.9	128.4	136.6	62.3	36.7	30.5	29.5	27.6	25.5	730.5
1990/95	20.7	37.4	83.1	85.6	152.3	95.3	44.2	29.5	21.4	20.1	18.1	16.8	624.6

The values presented in Table (7) represent the total runoff coming through the northern catchment area of the Dead Sea. These records revealed a consecutive downward trends due to the increased deviation and abstractions in their upper catchments over time. The severe declination occurred since 1960s where the highest value recorded 2125 * 10^6 m^3 in 1968/1969. On contrary, the lowest record within the year reached 282 * 10^6 m^3 in 1990/1991.

The return flows to the Dead Sea in the JRV have been estimated to be about 15%. Other water withdrawals such as in the West Bank and Wadi Araba have been assumed to be taken mainly from groundwater and thus do not affect the surface water balance (WMI, 2013).

Surface water flow records for the wadis on the eastern and western side at the Dead Sea Basin and for the Wadi Araba are not precise enough to fix inflow amounts since the rainfall is very low (less than 50 mm/y) and consequently surface water flows are so limited. However, they contribute less than 10% of the total inflow into the Dead Sea; therefore, they induce a negligible error in the water balance equation. The dams on the side wadis capture most runoff waters and prevent this water to flow to the Dead Sea.

The base flows at surface runoff gauge stations do not reflect the whole resource of that catchment, because there is an upstream withdrawal for different uses, i.e. irrigation and downstream inflow to dam reservoir (Table 8). Furthermore, the groundwater table decline caused by excessive pumping exceeding the groundwater safe yield of the different basins because reducing the base flow.

Table (8): Base flow compiled readings by the authors from WMI open file 1970s up to 2014.

Basin	Wadi name	Dams name	Capacity 10^6 m^3	Storage 10^6 m^3	Mean base flow 10^6 m^3/y	WWTP 10^6 m^3/y	Flow in wadis without dam 10^6 m^3/y	Inflow to dam 10^6 m^3/y	Total base flow 10^6 m^3/y	Base flow 10^6 m^3/y *
	Jordan Valley				25.0				25.0	25
Jordan alley (North of the Dead Sea)	Yarmouk (AD)	AL Wehda	115	23.7					15.0	35
	Al Arab (AE)	AL Arab	16.8	2.4					1.5	0.0
	Attayyba				1.1				1.1	
	Ziglab (AF)	Ziglab	4	0.4	8.0			7.8	8.5	6.0
	Jurum (AG)				8.7				8.7	0.0
	Rayyan (AH)	Rayyan			3.2		4.7		4.7	1.5
	Kufrinja (AJ)	Kufrinja			8.9	0.4	12.0		12.0	5.0
	Rajib (AK)				6.0		6.5		6.5	3.5
	Zarqa (AL)	King Talal	75	40.5	66.5	49.0		17.5	36.5	15

	Shueib (AM)	Shueib	1.4	0.3	9.0	1.3		7.4	11.7	8.0
	Kafrein (AN)	Kafrein	8.5	1	13.9	0.2		12.9	14.7	8.0
	Hisban (AP)	Hisban			3.0		5.0		5.0	3.5
	Fari'a									
	Auja									
	Qilt									
Dead Sea Side Wadis	Hammad	Bin Hammad								
	Issal									
	Numeira									
	Wala	Wala	8.2	2.4						
	Mujib	Mujib	29.8	18.8						50.0
	Mujib/Ghor		16.8	6.8						
	Karak (CE)	Karak								6.0
	Hasa/Ghor (CF)	Tannor								20.0
South Dead Sea Side Wadis	Tlah				0.3				9.0	0.8
	Umruq				0.3				5.0	2.0
	Fifa (DB)				4.0	0.3	4.4		4.4	5.0
	Khuneizira (DC)				1.6		1.7		1.7	1.5
	Fedan (DE)	Fedan			1.6			3.3	3.3	1.5

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	Mousa (DG)									
	Dahal and Others (DD)						1.0		1.0	
	North Wadi Araba								11.6	

** Margane 2002.

The total stream flow which is not included in the calculations of the Dead Sea catchment area are those related to the Southern Dead Sea side wadis. The total inflows of these wadis is about 10.8* 10^6 m^3, this amount can be added to the lowest amount inflows equal to 282.5 * 10^6 m^3 coming by the Yarmouk Rive through the Jordan River.

Dead Sea Evaporation

According to the Aridity Index (AI) Classification (Table 9) adopted after the United Nation Environment Program (UNEP, 1992), the Dead Sea area is considered to be semiarid area; with an average rainfall of 324mm. This is in full agreement with the utilization of PET where,

$AI = \frac{P}{PET}$ gives AI= 0.204 which indicates semiarid zones (UNEP, 1992; Markus et al, 2006 and Pidwirny, 2006).

Table (9): Aridity index (AI) and climate classification, (UNEP, 1992; Markus et al., 2006 and Pidwirny, 2006).

Classification	P/PET	Rainfall (mm)
Hyper-arid	< 0.05	< 200
Arid	0.05 < P/PET < 0.20	< 200 (winter) or <400 (summer)
Semi-arid	0.20 < P/PET < 0.50	200 - 500 (winter) or 400 -

		600 (summer)
Dry sub-humid	0.50 < P/PET < 0.65	500 - 700 (winter) or 600 - 800 (summer)

The rate of evaporation from the Dead Sea surface as a function of its salinity and will increase with the conveyance of the Red Sea water, which will dilute the high saline Dead Sea water, since most of the Red Sea water will float at the surface due to density difference. However, evaporation is a function of the surface area, thus regarding the obtained data via bathymetric calculations in Table (2), the evaporation in the year 2015 is:

$\text{Evaporation}_{2015} = \text{Volume loss}_{2015} + \text{Inflow}_{2015} – \text{Industrial}_{2015}$

$\text{Evaporation}_{2015} = 613.55 + 726.02 – 256 = 1083.57 * 10^6 m^3$.

In other words;

$\text{Evaporation}_{2015} = 1083.57 * 10^6 m^3 /612.7km^2 = 1768.5$ mm/y.

Groundwater Inflows

Groundwater inflow from both sides directly or indirectly into the Dead Sea by some of the wadis in the area such as Wadi Qilt, Wadi Auja, Wadi Shueib and Wadi Kafrein, which receive the spring's flows along their path. The springs are of two types; the ephemeral springs are flows during the winter seasons and fluctuate as a response to rainfall intensity and dies out during dry seasons. The second type is the perennial springs characterized by stable discharge rate with small annual fluctuations such as Ein Fashkha and Qane-Samar on the west shores, which are discharges 80-95 * 10^6 m^3/y. That springs outlets from the regional sub-aquifers. The recharge area of these springs is located far away from their outlets indicates a large storage volume of water (Hoetzl 2009).

The springs on the eastern side of the Dead Sea occur along the rift's bounding faults discharge from the Upper Cretaceous aquifer system, the Lower Cretaceous sandstones and from the Triassic siltstones. Springs which flows out from the Triassic rocks are restricted to the Suweimeh area northeast of the Dead Sea. Over time, the discharge of these springs has been rather constant which indicates the large extent of the catchments and the large reserves of groundwater. The Lower Cretaceous sandstone aquifer springs and seepages are concentrated along the Kafrein, Shueib and Hisban wadis with less than 31.5 * 10^3 m^3/y discharges. The Upper Cretaceous limestone springs are generally karst springs with appreciable discharges, such as Wadi Es Sir, Naur, Hisban, Jadour, Hizzir, Fuheis and Mahis. The discharge of these springs ranges from a few m^3/hour (Hummar spring) to a few hundred m^3/hour (Fuheis spring). These springs immediately react to precipitation events, (Hoetzl 2009).

During the last 20 years, waste-water treatment plants of the main cities have discharged their effluents into the wadis thereby causing contamination of surface and groundwater bodies. The total amount of groundwater inflows to the Dead Sea were estimated from the records in Table (8) referred to the eastern Dead Sea side valleys and the discharge of Ein Fescha on the western side to equal about 197*10^6 m^3 /y (MWI, open files, TAHAL, 2011 and Margane, et al, 2002).

The authors recorded the appearance of about 47 new springs burst during this year 2015 at a level coincides with the previous position of the Dead Sea due to the water level drawdown. This indicates that the groundwater inflows appear to have been increased over time, as the level of the Dead Sea has fallen. The average discharge of these small springs estimated to be 3l/s which is equivalent to about 3.78 *$10^6$$m^3$ /y. However, it must be noticed that the given estimates are based on approximated numbers of different springs discharge values, which are in turn influenced by the fluctuation rate of the groundwater level. Thus, the accuracy of these groundwater estimates is questionable; however, they do exist as an inflow component.

The static interface between the salt water and fresh water is given according Ghyben-Herzberg equation in (Verrjuit, Arnold 1968) as follows:

$$z = \frac{\rho_f}{\rho_s - \rho_f} h$$

Where; h the thickness of the fresh zone above sea level, z the thickness of the fresh water below sea level, ρ_f the density of freshwater (1 g/cm^3), ρ_s the density of saltwater (1.24 g/cm^3).

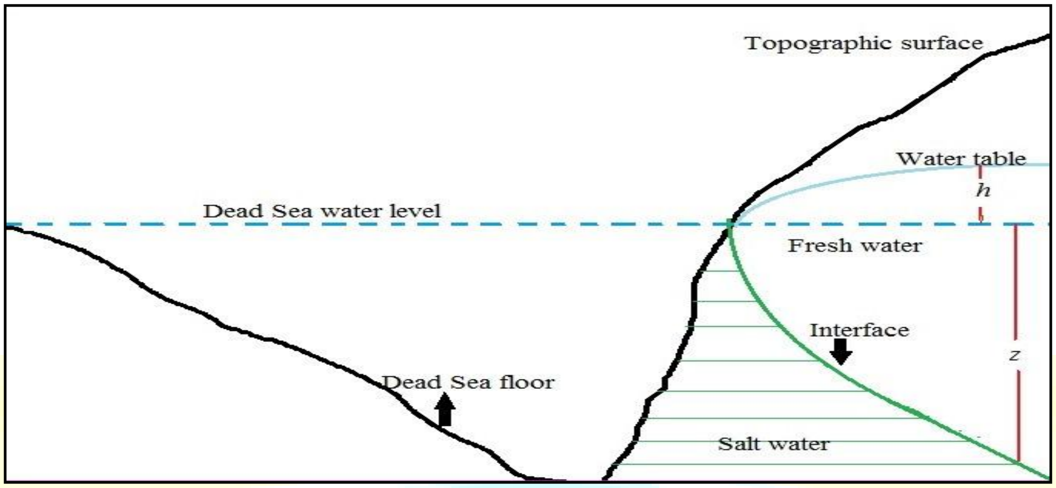

Fig. (8): The saline-fresh water interface at the Dead Sea area.

Solving for *z* in Ghyben-Herzberg equation for the Dead Sea case by assuming the thickness of fresh water *h* above the sea level equal one meter, then;

$Z = 4.166$.

Therefore, for every one meter of fresh water above the Dead Sea water level in an unconfined aquifer, there will be 4.166 meters of fresh water in the aquifer below the Dead Sea level.

Abstractions Rates from Potash Industries

Abstraction rates from the two potash factories have been estimated from the current and available production figures for the Arab Potash company (APC). APC currently produces1.75 million tones in average, whereas, its capacity is more than 2.2 million tones. On the other hand, the Israeli Dead Sea Works capacity exceeds 3.6 million tones (BGS, World Mineral Report 1993-2013). Brine abstraction rates are 118 cubic meters per ton of production based on the APC average figure and the brine return flows back to the Dead Sea is approximately 40% of the abstracted volume. Thus the total average saline water abstraction rate is calculated to be 256 * 10^6 m^3 /y by the year 2013 Table (9).

Table (9): Potash Production and the Proposed Saline Abstraction– Brine Return.

Year	APC Ton	DSW Ton*	Total potash	Saline water	Brine water	Net

			product Ton**	10^6 m^3	10^6 m^3	abstraction 10^6 m^3
1993	1476891	1309000	2785891	328.7	131.5	197
1994	1516650	1259300	2775950	327.6	131.0	197
1995	1764371	1326000	3090371	364.7	145.9	219
1996	1800000	1500000	3300000	389.4	155.8	234
1997	1447409	1488000	2935409	346.4	138.6	208
1998	1516562	1668000	3184562	375.8	150.3	225
1999	1706289	1701600	3407889	402.1	160.9	241
2000	1935989	1748400	3684389	434.8	173.9	261
2001	1962535	1774200	3736735	440.9	176.4	265
2002	1956023	1918200	3874223	457.2	182.9	274
2003	1961051	1958400	3919451	462.5	185.0	277
2004	1940648	2138400	4079048	481.3	192.5	289
2005	1829653	2224200	4053853	478.4	191.3	287
2006	1699414	2187000	3886414	458.6	183.4	275
2007	1796569	2146000	3942569	465.2	186.1	279
2008	2004634	2134000	4138634	488.4	195.3	293
2009	1199940	2446200	3646140	430.2	172.1	258
2010	2141319	2041342	4182661	493.6	197.4	296
2011	2258600	1789721	4048321	477.7	191.1	287
2012	1823894	2115468	3939362	464.8	185.9	279
2013	1046500	2155414	3201914	377.8	151.1	227
Average	1751664	1858516	3610180	426.0	170.4	256

*The Arab Potash Company Annual Report.

**The BGS World Mineral Production 1993-2013 and USGS world Mineral Commedity reports 1990s and 2000s.

Water Balance Formula

The Dead Sea water balance formula includes the following parameters:

Dead Sea Water Balance = Σ Input flow – (Σ Output flow + λ_s) …………..….. (3)

Equation (3) at equilibrium means that the input flow is equal outlet plus the precipitated evaporites then it can be written as follows;

Σ Input flow = Σ Output flow + λ_s ……………………..………………….. (4)

Σ Input flow = Direct Precipitation + Runoff + Ground water inflow + Sewage and agricultural return water + Dams live Storage* ……………………………………….. (4.1)

*The existed water in the dam reservoir which be released to the Dead Sea in the winter season

Σ Output flow = Evaporation + Industrial Abstraction …………………... (4.2)

λ_s = Volume of precipitated salts by evaporation …………………………. (4.3)

The calculated values of the annual inflow waters feeding the Dead Sea which achieve the input parameters of equation (3) are given in Table (10).

Table (10): Total Water Inflows to the Dead Sea.

Input Flow	$10^6\ m^3/y$
Direct Rainfall on the Dead Sea surface	64.95
Direct inflow of new bursted springs	3.78
Yarmouk River	282.5*
Runoff in Wadis Feeding the Dead Sea	145.8
Baseflow in East sides springs	127*
Baseflow in West sides En Fescha spring	70**
Effluens and agriculture return water	20*
Total	714.03

*MWI open files, ** TAHAL 2011.

The total annual output is equal to the sum of the evaporation and the Potash industry abstraction plus the storage of constructed dams on the side wadis which realezed annualy to flow into the Dead Sea in the winter season; equal:

$1083.57 * 10^6 m^3 + 256* 10^6 m^3 + 96.8* 10^6 m^3 = 1436.37 * 10^6 m^3$.

The volume of deposited salts by the evaporated Dead Sea saline water is:

λ_{2015} = Area * Salt thickness (Table 2)

$\lambda_{2015} = 612.7 km^2 * 0.28 m$

$\lambda_{2015} = 171.56 * 10^6 m^3$

The calculated values in Table (2) for the different parameters will be substitued in equation (3); Consequently, the water balance of the Dead Sea in 2015 is given as follows:

Dead Sea Water Balance = Total Inflow – Total outpot - λ_s

Dead Sea Water Balance = 714.03 – 1436.37 – 171.56 = $-893.9 * 10^6 m^3$.

Conclusions

1. The Dead Sea water balance calculations should emphasize on the importance of the component value of ʎs.
2. Calculating the rainfall and the related runoff values by means of the strip element method gives a considerable difference in the results, which produce figures that are more precise comparing with regular shaped elements.
3. The static compensation level of the Dead Sea fall at a depth of -546.91m needs 166 years to reach under similar conditions of calculated long term average.
4. The minimum discharge capacity of the RDSC to stabilize the current water level situation is about one billion cubic meters per year as far as the calculated annual deficit of the water balance is approximately $893* 10^6 m^3$.

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