Changes in the Dead Sea Level and their Impacts on the Surrounding Groundwater Bodies

Änderungen des Spiegelniveaus des Toten Meeres und damit verbundene Auswirkungen auf die umgebenden Grundwasserkörper

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Keywords: Dead Sea, Fresh-/Saltwater Interface, Sea Level Change, Hydrograph

Summary: In this paper the reaction of the salt-/freshwater interface due to the changes in the Dead Sea level are elaborated at in details by using the inflows into the Dead Sea, the outflows due to evaporation losses and artificial discharges, and the hydrographic registrations of the Dead Sea level.

The analyses show that the interface seaward migration resulted in a groundwater discharge of around 423 Mio m^3 per meter drop in the level of the Dead Sea in the period 1994–1998 and of around 525 Mio m^3/m in the period 1930–1937. The additional amount of groundwater joining the Dead Sea due to the interface seaward migration was 51 Mio m^3 per one square kilometer of shrinkage in the area of the Dead Sea in the period 1930–1937 and 91 Mio m^3/km^2 in the period 1994–1998.

The riparian states of the Dead Sea are nowadays loosing 370 Mio m^3/a of freshwater to the Dead Sea through the interface readjustment mechanisms as a result of their over exploitation of waters which formerly fed the Dead Sea.

Schlagwörter: Totes Meer, Süß-/Salzwasser-Grenze, Meeresspiegeländerung, Wasserspiegel, Hydrograph

Zusammenfassung: In dieser Arbeit wird der Einfluss des veränderten Meeresspiegelniveaus des Toten Meeres auf die Lage der Süß-/Salzwasser-Grenze studiert. Dabei werden die Zuflüsse zum Toten Meer, die Verluste durch Evaporation und Wasserentnahme sowie die hydrographischen Aufzeichnungen des Wasserspiegelniveaus ausgewertet.

Es zeigt sich, dass die Verlagerung der Süß-/Salzwasser-Grenze in Richtung Totes Meer zwischen 1994 und 1998 bzw. zwischen 1930 und 1937 zu einem Grundwassereintritt in das Tote Meer von 423 Mio m^3 bzw. 525 Mio m^3 pro Meter gefallenem Wasserspiegel geführt hat. Zusätzlich traten durch die Verlagerung der Süß-/Salzwasser-Grenze aufgrund der Verkleinerung der Wasseroberfläche pro verlorenem Quadratkilometer zwischen 1930 und 1937 51 Mio m^3 und zwischen 1994 und 1998 91 Mio m^3 Grundwasser in das Tote Meer ein.

Durch diese Verlagerungsmechanismen, die auf übermäßige Wasserentnahme aus den Zuflüssen des Toten Meeres zurückgeführt werden, verlieren die Anrainer gegenwärtig pro Jahr 370 Mio m^3 Süßwasser an das Tote Meer.

1 Introduction

The level of the Dead Sea (DS) has been continuously dropping since the late fifties, from about 392 m below sea level (bsl) in 1958 to about 411 m below sea level in 1998. The reason for this drop is the extensive exploitation of water resources which formerly used to flow into the DS [1–3]. The water balance of the DS has since the late 1950s been disturbed, and evaporation losses have been partly compensated by reducing the stored amounts of groundwater.

The deprivation of the DS of the larger part of water inflows resulted only in a moderate drop in the DS level. The possible explanation for this fact is that the DS water body is not only what is seen as a lake at the surface and its downward extension, but also its extension in the underground of its surroundings. Declines in the DS level produce declines in the corresponding groundwater levels of the surrounding areas and result in a seaward migration of the salt-/freshwater interface. In this article, the interaction between the DS level and the groundwater bodies via the corresponding interfaces will be elaborated at and quantified.

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2 Water Balance of the Dead Sea

In a previous study [3] the water balance of the DS for the time period which proceeded the recent development was prepared. That water balance represented the natural system of the DS water, where its level only showed seasonal fluctuations and where evaporation losses were fully compensated by the inflows.

The other part of the balance dealt with the present day water balance of the DS considering all the effects of water projects within its catchment area on that balance. In Tables 1 and 2 these DS water balances are given. This balance means that the actual average addition to the water level of the DS equals: 1980 Mio m^3/a over 984 km^2 result in 2013 mm/a or about 2000 mm/a which are lost by evaporation.

Present day water losses from the Dead Sea: Formerly only evaporation losses balanced the incoming amount of

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Table 1: Summary of water amounts which used to flow into the Dead Sea prior to the water resources development within its catchment area.

Die dem Toten Meer zufließenden Wassermengen vor der Entwicklung der Gewässer in seinem Einzugsgebiet.

Source	Amount, Mio m^3/a
I. Surface water	
– Lake Tiberias (outflows)	542
– East side Wadis	607
– West side Wadis	58
– Dead Sea Eastern catchment	219
– Dead Sea Western catchment	163
– Wadi Araba basin	
Eastern side	31
Western side	50
Subtotal Surface Water	**1670**
II. Groundwater	
– Eastern side	90
– Western side	100
– Northern and Southern basins	30
Subtotal Groundwater	**220**
III. Precipitation	
Subtotal ppt over the Dead Sea	90
TOTAL	**1980**

Table 2: Present days water balance.

Wasserbilanz des Toten Meeres zum gegenwärtigen Zeitpunkt.

Source	Amount, Mio m^3/a
The average outflow from Lake Tiberias	40
The average surface runoff of the Western Jordan River catchments	10
Average discharge of the Yarmouk River	50
Eastern side of the Jordan River	42
Eastern side of the Dead Sea (surface)	147
Eastern side of the Dead Sea (ground)	90
Western side of the Dead Sea (surface)	13
Western side of the Dead Sea (ground)	50
Western Wadi Araba	10
Eastern Wadi Araba	10
Irrigation return flows, subsurface flows, and saltwater diversions into the Jordan River	85
Precipitation over the Dead Sea ($750 km^2$)	70
Total Inflows	**617**

water to the DS. But since the establishment of the DS works on both sides of the sea, water has been extracted and exposed to evaporation in salt pans to extract the different valuable salts. This process is presently consuming an average of 290 Mio m^3/a (pumping minus return flows). The net amount of water reaching the DS at present equals therefore (617–290) Mio m^3/a = 327 Mio m^3/a, whereas the evaporation from the DS at present ($667 km^2$) amounts to 1334 Mio m^3/a.

3 Changes in the Level of the Dead Sea and their Impacts on the Surrounding Groundwater Bodies

Any rise or drop in sea level has diverse effects on the groundwater bodies, which are in hydraulic connection with the seawater [4–6]. In the following elaboration these effects will be specified in kind and quantified in terms of impact for the case of the DS.

3.1 The Dead Sea System

The DS is the ultimate base level for all the surface and groundwater resources of the surrounding areas (Fig. 1). It is an exit-less water body loosing water only by evaporation from its surface.

Surface water: Many surface water flows end up in the DS, such as the Jordan River, Zerqa, Mujib, Karak, Hasa, Araba, Harod, Quilt, Malih, Mishash, Arugot, etc., as shown in Figure 1. The inflows of these sources cause a rise in the level of the DS, especially in the rainy season.

Groundwater: Along the entire shore of the DS, the groundwater of the surrounding areas discharges directly or via surface courses into the DS [7–10]. The groundwater levels (in a distance of some 10 km from the DS shores) lie at a few hundred meters above sea level compared to 411 m below sea level for the DS. The groundwater gradients are directed radially to the DS. Under the conditions of constant DS level (with the exception of the seasonal fluctuations) the surface and groundwater inflows feeding the DS are lost by evaporation.

3.2 Lowering the Dead Sea Level

Since about 4 decades the DS level has been dropping due to the development and consumption of the larger part of the surface and groundwater sources which formerly used to feed the DS. The continuous lowering of the DS level resulted in the following effects:

- Increasing the head differences between the DS and the groundwater levels in the surrounding areas. This effect resulted in draining larger amounts of groundwater into the DS.
- Interface configuration and equilibrium state: Generally, a dynamic equilibrium is reached at between a saline surface water body and a fresh groundwater body receiving recharge.

The configuration and depth of the fresh-/saltwater interface depends on a variety of factors such as the densities of the two water bodies, the permeability and porosity of the aquifers, the throughput capacity of the aquifers, amounts of discharged groundwater to the surface water body and others. The most important of these factors is the density difference between the freshwater and the saltwater. In the case of oceanic water, this difference is around 0.025 g/cm^3 but in the case of the DS, it is around 0.23 g/cm^3. Accordingly, the depth of the interface must be different. Ghyben-Herzberg [4] equation gives the configuration of the salt-/freshwater interface as illustrated in Figure 2.

3.3 Rising Dead Sea Level

Any rise in the DS level will certainly have the apposite effects of lowering the DS level. Even the rise in the winter season has the following effects:

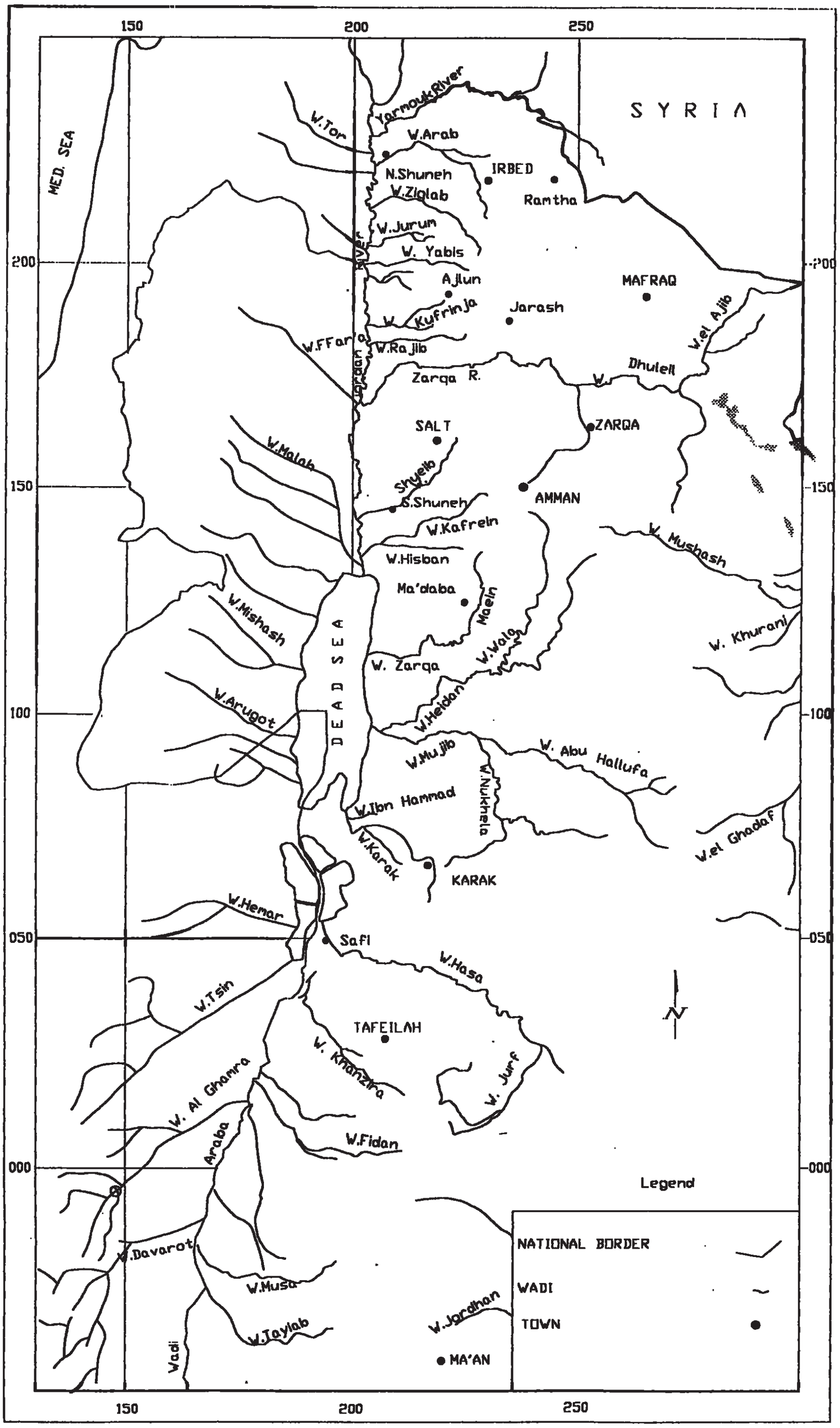


Fig. 1: Dead Sea catchment area.
Einzugsgebiet des Toten Meeres.

– Refilling the drained coastal aquifers along the shorelines of the DS to correspond with the new level of the DS (a type of bank storage).
– Additional pressure on the saltwater side of the interface, which may cause a landward migration of the interface, if this additional pressure (higher level of the DS) persists (Fig. 3).

3.4 Hydrographic Analyses

Figure 4 illustrates the changes of the DS level from 1930 to 1998 according to the Arab Potash Company and Israeli measurements [11]. In general, the hydrograph shows different distinct sections:
– On a one-year scale, seasonal fluctuations are observed (summer, winter).

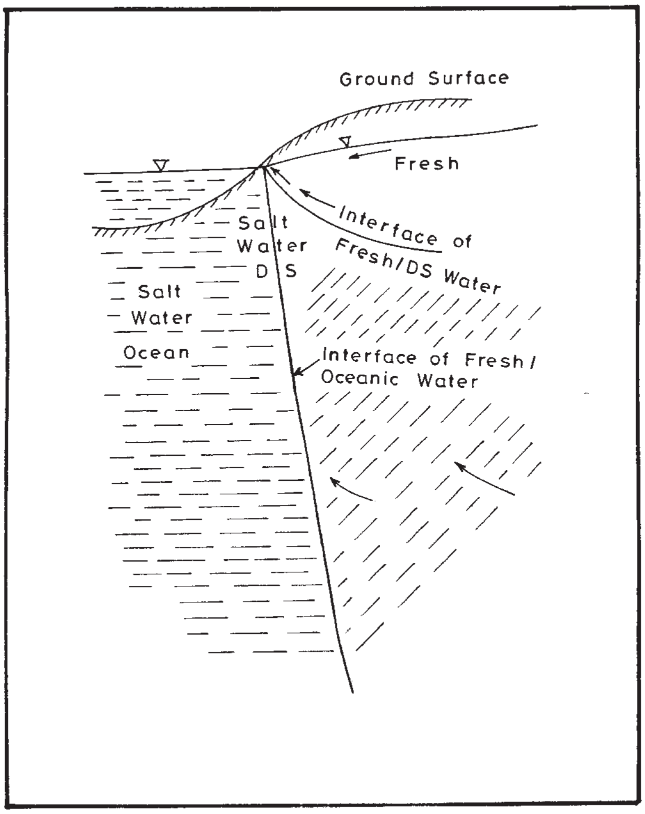


Fig. 2: Comparison of interface configurations freshwater/oceanic water and freshwater/Dead Sea water.

Vergleich der Lage der Süß-/Salzwasser-Grenze im System Süßwasser/Ozeanwasser und im System Süßwasser/Wasser des Toten Meeres.

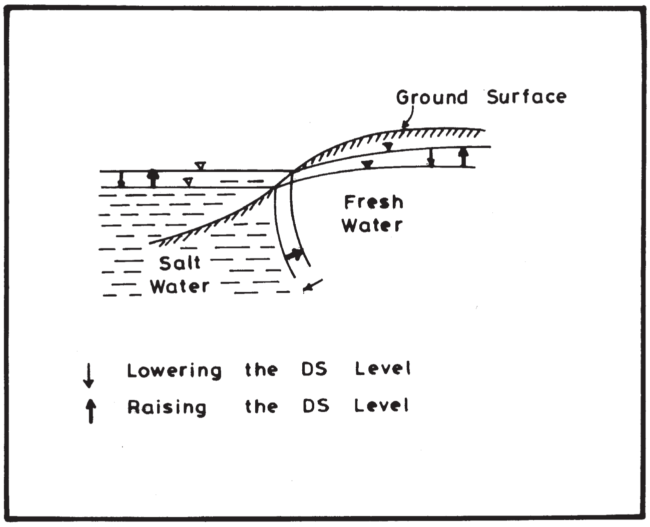


Fig. 3: Raising, lowering of the Dead Sea level and its effects on the fresh groundwater body and salt-/freshwater interface.

Änderung des Meeresspiegelniveaus des Toten Meeres und die Auswirkungen auf den Grundwasserkörper und die Süß-/Salzwasser-Grenze.

– Periods of constant level, 1948–1957, 1937–1943, and 1963–1971.
– Periods of drop in level, 1930–1937, 1958–1962, 1972–1990, and 1994–1998.
– Periods of rise in level 1943–1946 and 1991–1993.

The shape of the yearly rise and drop in DS level differs from one year to another and from one period (named above) to another. The rise and drop in level the within one year is a result of:
– amount of winter inflows,
– amount of summer inflows,
– source of summer inflows.

To illustrate that, the slopes of level declines against time during the summer periods are considered for different years.
– These slopes show a wide range in periods of monotonous declines in the DS level 1930–1937, 1958–1962, 1972–1990, and 1994–1998 (30...52°).
– Slopes are steepest in the periods indirectly after the high rises in the DS level 1947–1949 and 1992–1994 (65°).

To understand the reasons for these differences, the system of water inflows and losses during the dry seasons has to be analyzed (Fig. 5). Klein [12] concluded by using morphological evidence that the 12 m drop in the Dead Sea level from 1929 to 1979 had not been continuous, but corresponded to three periods of drought over its catchment area of 40650 km^2.

3.4.1 Inflows during the Dry Season

The inflows to the DS consist of:
– surface water inflows (variable),
– groundwater inflows (almost constant),
– inflows due to interface migration in a seaward direction (only in periods of dropping sea level).

Surface water inflows: The surface water inflows mainly come from the Jordan River. With the exception of the thermal water discharges all the other surface water sources are exploited and utilized. In the predevelopment stage, the total surface inflows averaged (30 years) 1670 Mio m^3/a (Table 1), 69% of which were discharged through the Jordan River. In recent years, the surface water discharge into the DS declined to an average of 407 Mio m^3/a, (Table 2), 58% of which were discharged through the Jordan River. The dry season discharges of the Jordan River (April to October) are listed in Table 3.

Groundwater inflows: The groundwater inflows into the DS in the predevelopment stage averaged (30 years) 220 Mio m^3/a. In recent years, the groundwater discharges decreased to an average of 140 Mio m^3/a, evenly distributed over the year. During the dry season they average 70 Mio m^3/a.

The total surface and groundwater inflows into the Jordan River are calculated and listed in Table 3.

Inflows due to interface migration in a seaward direction: These inflows are mobilized by the non-seasonal drop in the DS level and depend in their amounts on the amount of drop in DS level and the inflows and outflows into and from the DS during the dry season.

3.4.2 Outflows during the Dry Season

The DS is exit-less. Losses of its water are a result of evaporation or extraction for the uses by the Potash Works on both sides; east and west.

Evaporation losses: The Arab Potash Company in Jordan keeps records of evaporation losses from the DS water for a variety of DS water densities [13]. The dry season evaporation losses are calculated for the dry months from 1980 to 1997. The average evaporation rate equals 202 mm per month.

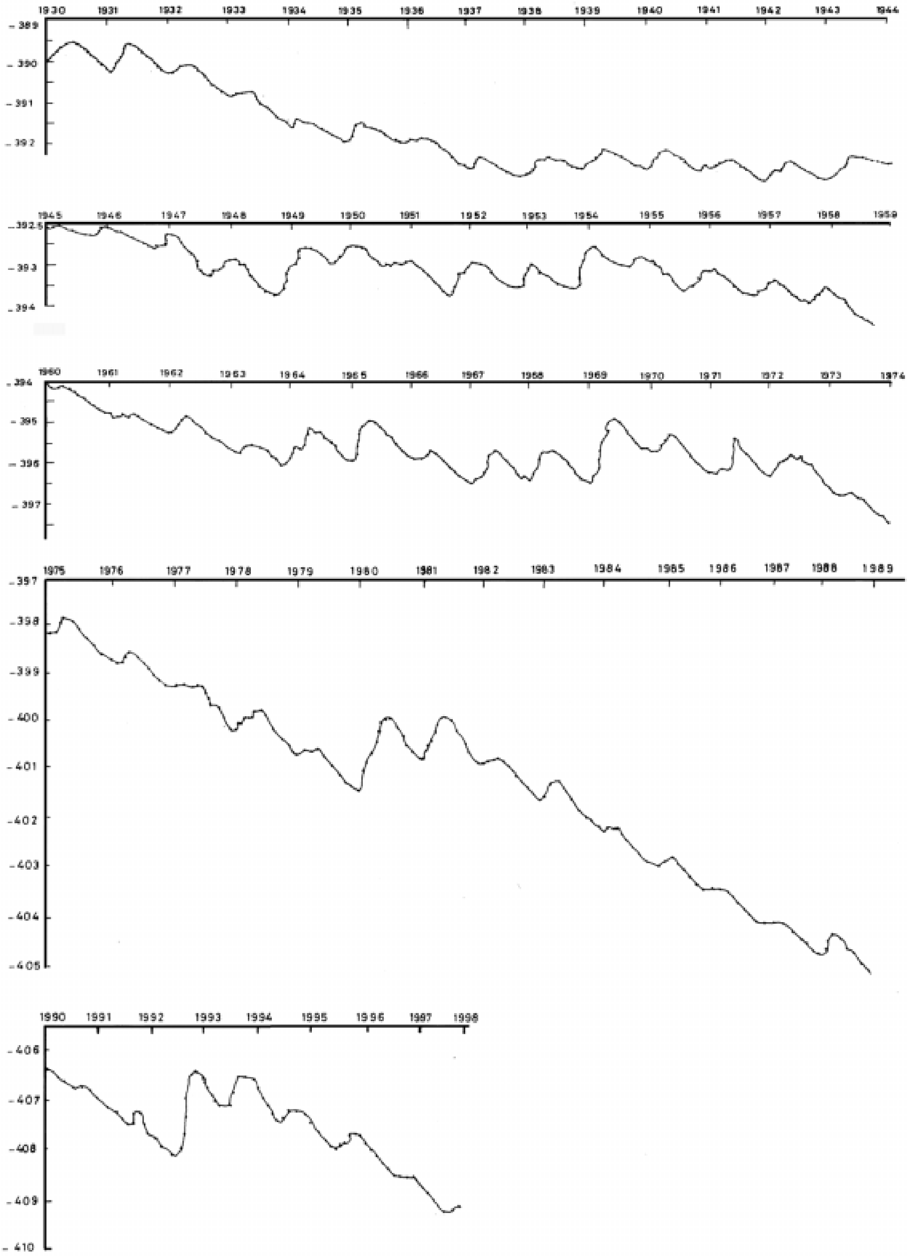


Fig. 4: Dead Sea level in the period 1929–1997.

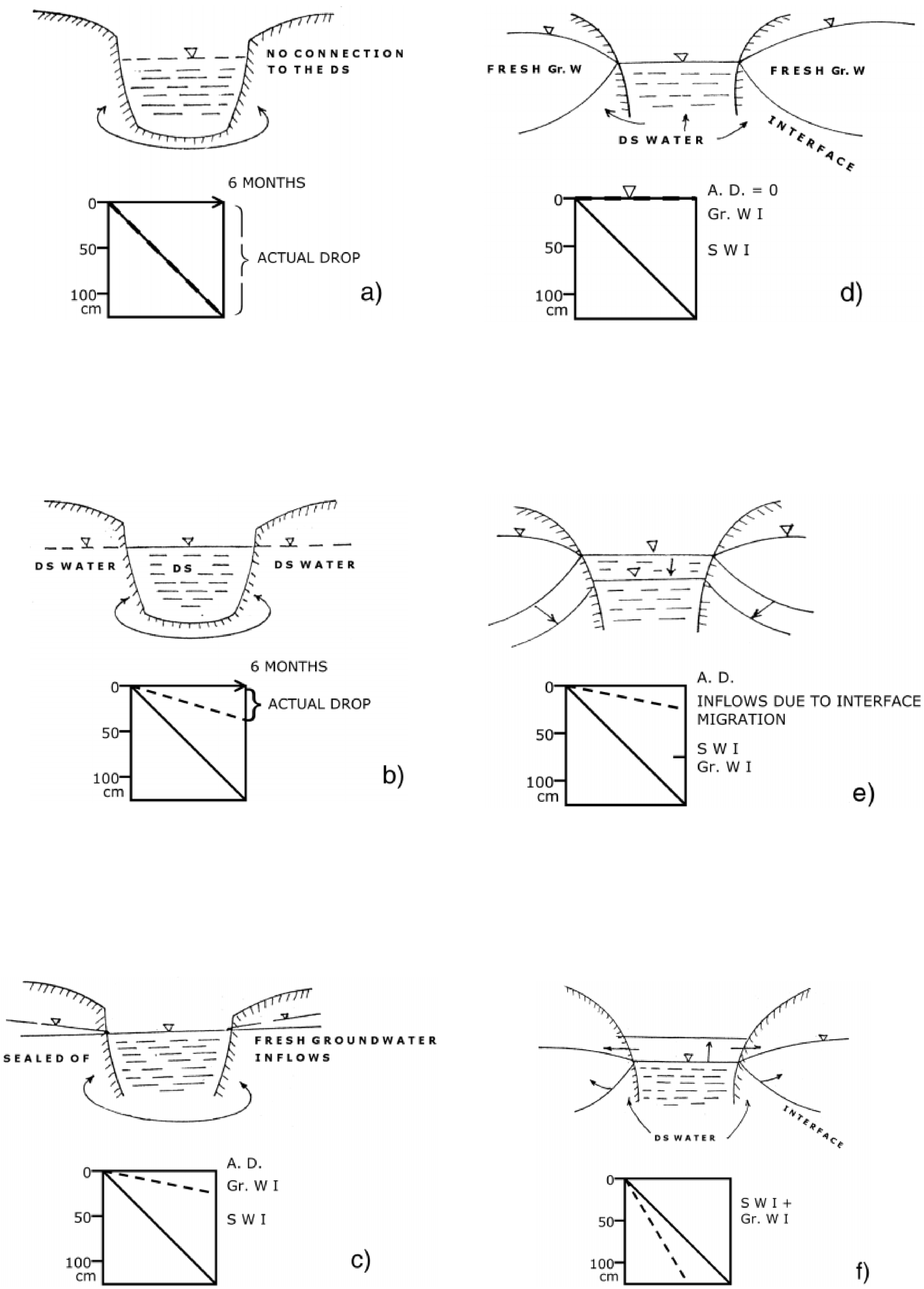
Wasserspiegel des Toten Meeres im Zeitraum 1929–1997.

Dead Sea works: The DS works both in Jordan and Israel extract around 450 Mio m^3/a from the DS water body and return back around 160 Mio m^3/a. An average of 290 Mio m^3/a is actually consumed. In the dry season, the net extractions average 195 Mio m^3.

4 The Hydrographs

If the hydrographs of 1989/90 and that of 1991/92 are considered the following differences can be found:

1. The 1991/92 summer slope of the DS level is steeper than that of 1989/90 (1991/92: 65°, 1989/90: 46°).
2. In the year 1988/89 the DS water level dropped compared to the previous year 1987/88 by around 90 cm.
3. In the year 1991/92 the DS level rose compared to the previous year 1990/91 by 195 cm.
4. The surface water inflows during the dry seasons of 1990 and 1992 were 153 and 392 Mio m^3 (Table 3).
5. The potash extractions in both years were almost the same, since there were no changes in the potash activities, and no new lines were introduced.
6. Evaporation losses in both years were considered equal (water density 1.23 g/cm^3). Although the surface layer of the DS in the rain-rich year 1991/92 was diluted and therefore evaporation losses in this year should have been slightly higher, the lower spring temperature of that year must have compensated the lower salinity effect.
7. In the case where no inflows join the DS in the dry season the drop in its level must parallel the evaporation line of the dry season.
8. Any deviation (flattening) in the slope of the actual drop of the DS level from the dry season evaporation line is due to inflows in the dry season.


NO CONNECTION
TO THE DS
6 MONTHS
0
50
100
cm
ACTUAL DROP
a)
FRESH Gr. W
FRESH Gr. W
DS WATER
INTERFACE
A. D. = 0
Gr. W I
S W I
0
50
100
cm
d)
DS WATER
DS
DS WATER
6 MONTHS
0
50
100
cm
ACTUAL DROP
b)
A. D.
INFLOWS DUE TO INTERFACE
MIGRATION
S W I
Gr. W I
0
50
100
cm
e)
SEALED OF
FRESH GROUNDWATER
INFLOWS
A. D.
Gr. W I
S W I
0
50
100
cm
c)
DS WATER
INTERFACE
S W I +
Gr. W I
0
50
100
cm
f)

The hydrograph of the DS 1930 to 1995 was analyzed according to the above mentioned elaborations. Table 4 shows the detailed analyses of the hydrograph for the years 1981–1995, for which the Arab Potash works detailed measurements were available. The table gives the details about winter highest rises in the DS level relative to the previous summer lowest level, the deviation of the actual DS level drop from that expected due to summer evaporation, the net water incomes into the DS during each dry season, the net water incomes from surface and groundwater sources and the contributions due to the interface seaward or landward movements (Potash consumptions were taken into consideration according to their

Fig. 5: Possible declines in the level of the Dead Sea during the dry season as a function of influencing factors.

Möglichkeiten der Senkung des Wasserspiegelniveaus des Toten Meeres während der Trockenzeit in Abhängigkeit von verschiedenen Einflussfaktoren.

a) Sealed up DS bottom and sides. No inflows of water. Losses take place only as a result of evaporation.

   Grund und Wände des Beckens undurchlässig. Keine Wasserzuflüsse. Wasserverluste nur durch Evaporation.

b) The DS water extends beneath its surrounding areas. No renewable groundwater. No inflows of any type.

   Wasser des Toten Meeres dringt in die angrenzenden Bereiche ein. Kein erneuerbares Grundwasser. Keinerlei Zuflüsse.

c) Surface and groundwater inflows cannot compensate evaporation losses. No interface. Only shallow groundwater flows into the DS.

   Zuflüsse von Oberflächenwasser und Grundwasser können die Evaporationsverluste nicht vollständig kompensieren. Keine Süß-/Salzwasser-Grenze. Nur oberflächennahes Grundwasser fließt dem Toten Meer zu.

d) DS equilibrium (constant level). Total inflows equal evaporation losses. No interface migrations.

   Gleichgewicht – konstanter Meeresspiegel. Evaporationsverluste werden durch die Summe der Zuflüsse ausgeglichen. Keine Verlagerung der Süß-/Salzwasser-Grenze.

e) Dropping DS level. Surface and groundwater inflows cannot compensate evaporation losses. The result is a seaward migration of the interface which allows additional flows of deep groundwater into the DS. The actual drop in DS level is less than it should be if no migration of interface takes place.

   Sinkender Meeresspiegel. Zuflüsse von Oberflächenwasser und Grundwasser können die Evaporationsverluste nicht kompensieren. Es resultiert eine Verlagerung der Süß-/Salzwasser-Grenze in Richtung Totes Meer, die einen zusätzlichen Zufluss von Tiefengrundwasser zum Toten Meer mit sich bringt. Es wird ein geringeres Absinken des Meeresspiegelniveaus beobachtet, als ohne diese Verlagerung der Süß-/Salzwasser-Grenze zu erwarten wäre.

f) Rising DS level. Surface and groundwater inflows exceed evaporation losses. This results in a higher level of the DS. Bank infiltration takes place; water flows from the DS into its shore deposits. Interface landward migration to reach at a new hydrodynamic equilibrium.

   Steigender Meeresspiegel. Zuflüsse von Oberflächenwasser und Grundwasser überkompensieren die Evaporationsverluste, so dass das Meeresspiegelniveau steigt. Es findet Uferfiltration statt, Wasser fließt aus dem Toten Meer in küstennahe Grundwasserspeicher. Die Süß-/Salzwasser-Grenze verlagert sich landeinwärts, ein neues hydrodynamisches Gleichgewicht stellt sich ein.

Table 3: Discharges into the Dead Sea in the summer period.

Zufluss zum Toten Meer im Sommerhalbjahr.

Hydrologic year	Jordan River summer discharges Mio m^3	Ground and surface inflows into the Dead Sea Mio m^3
1931/32	378	581
1932/33	195	300
1933/34	270	415
1934/35	297	457
1935/36	617	952
1936/37	415	638
1937/38	496	763
1938/39	522	803
1939/40	469	721
1940/41	455	700
1941/42	509	783
1942/43	570	877
1943/44	669	1030
1944/45	439	675
1945/46	521	802
1946/47	428	658
1947/48	295	454
1948/49	459	543
1949/50	348	706
1950/51	125	192
1951/52	378	582
1952/53	362	557
1953/54	486	748
1954/55	181	278
1955/56	345	531
1956/57	301	463
1957/58	225	346
1958/59	190	292
1959/60	111	170
1960/61	192	295
1961/62	151	232
1962/63	166	255
1963/64	166	255
1964/65	124	191
1965/66	88	135
1966/67	205	315
1967/68	133	205
1968/69	201	309
1969/70	149	229
1970/71	144	221
1971/72	129	198
1972/73	113	168
1973/74	152	234
1974/75	123	189
1975/76	126	194
1976/77	129	198
1977/78	121	186
1978/79	114	175
1979/80	148	228
1980/81	161	247
1981/82	196	301
1982/83	260	400
1983/84	180	267
1984/85	145	223
1985/86	117	180
1986/87	170	262
1987/88	155	239
1988/89	120	185
1989/90	100	153
1990/91	95	146
1991/92	255	392
1992/93	155	239
1993/94	123	189
1994/95	170	262

Table 4: Inflows into the Dead Sea (1981–1995).

Zufluss zum Toten Meer (1981–1995).

Hydrologic year	Rise in the Dead Sea in the rain season cm	Deviation of actual drop in the dry season from the line of evaporation angle degrees (Fig. 4)	Net water incomes to the Dead Sea during the dry season* Mio m³	Net incomes of surface on the groundwater** Mio m³	Contribution to the Dead Sea due to interface movement*** Mio m³
1981/82	20	12.5	500	246	388
1982/83	42	11	498	222	267
1983/84	0.0	14	409	341	283
1984/85	23	11.5	290	236	210
1985/86	–10	14	288	190	285
1986/87	–10	21	500	153	457
1987/88	40	10	500	223	492
1988/89	0.0	21.5	812	203	850
1989/90	0.0	16	562	157	626
1990/91	23	10	285	131	357
1991/92	190	0	0.0	124	–139
1992/93	70	2	80	334	72
1993/94	25	8.5	191	203	157
1994/95	23	8.3	225	161	205

* Surface water + groundwater incomes ± interface contributions ± storage differences – (summer evaporation losses and Potash consumption).
** Net summer incomes of surface water and groundwater without any contributions due to interface migration.
*** Surface water and groundwater incomes ± change in storage – (summer evaporation losses and Potash consumption).

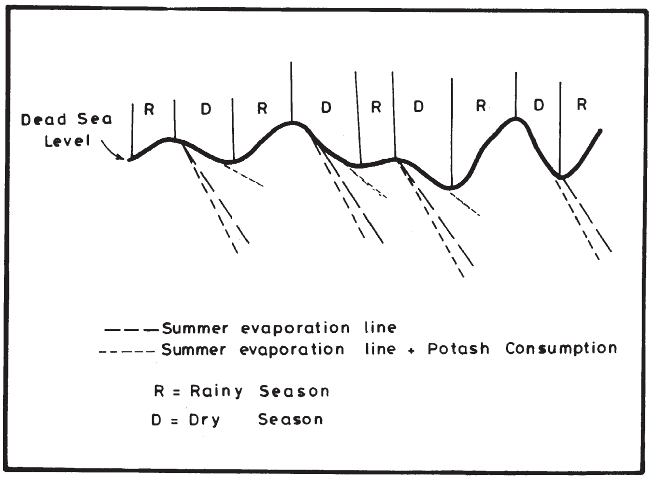


Fig. 6: Different types of declines in the level of the Dead Sea during the dry season.

Das Meeresspiegelniveau des Toten Meeres im Jahresgang – Unterschiede in der Neigung während der Trockenzeit.

actual average pumpings and return flows.). The deviations are generally explained in Figure 6.

In Table 5, the results of the hydrograph analyses for the DS level 1931 to 1995 are listed to show the contributions of the interface migration (sea- or landward) to or from the DS water. It exactly shows that in periods of ± constant sea levels no contribution from the DS to the interface or the contrary takes place. It also shows that in the rain-rich years 1945/46, 1979/80, and 1991/92 the DS contributed to push the interface landward, whereas in periods of dropping DS level hundreds of millions of cubic meters of water joined the DS to compensate its dropping level and its decreasing pressure on the interface.

Although the summer surface inflow amounts in 1992 were higher than those of 1990, the slope of the DS level decline in 1992 was higher than that of 1990, and it resembled that of the evaporation line. This can only be explained by out-

Table 5: Contributions to and from the Dead Sea to the groundwater body due to interface readjustment as a result of rising or dropping Dead Sea level.

Zufluss aus dem Grundwasserkörper in das Tote Meer bzw. Spende des Toten Meeres an den Grundwasserkörper (negative Werte) aufgrund der Verschiebung der Süß-/Salzwasser-Grenze infolge des gefallenen oder gestiegenen Meerespiegelniveaus.

Hydrologic year	Contribution to the Dead Sea due to interface movement Mio m³	Hydrologic year	Contribution to the Dead Sea due to interface movement Mio m³
1931/32	263	1962/63	406
1932/33	65	1963/64	0.0
1933/34	159	1964/65	0.0
1934/35	214	1965/66	0.0
1935/36	372	1966/67	0.0
1936/37	162	1967/68	0.0
1937/38	0.0	1968/69	0.0
1938/39	0.0	1969/70	0.0
1939/40	0.0	1970/71	0.0
1940/41	0.0	1971/72	0.0
1941/42	0.0	1972/73	154
1942/43	0.0	1973/74	85
1943/44	0.0	1974/75	51
1944/45	0.0	1975/76	65
1945/46	–50	1976/77	141
1946/47	0.0	1977/78	236
1947/48	0.0	1978/79	160
1948/49	0.0	1979/80	–67
1949/50	0.0	1980/81	67
1950/51	0.0	1981/82	388
1951/52	0.0	1982/83	267
1952/53	0.0	1983/84	283
1953/54	0.0	1984/85	210
1954/55	0.0	1985/86	285
1955/56	0.0	1986/87	457
1956/57	0.0	1987/88	492
1957/58	263	1988/89	850
1958/59	160	1989/90	626
1959/60	188	1990/91	356
1960/61	369	1991/92	–139
1961/62	345	1992/93	72
		1993/94	157
		1994/95	205

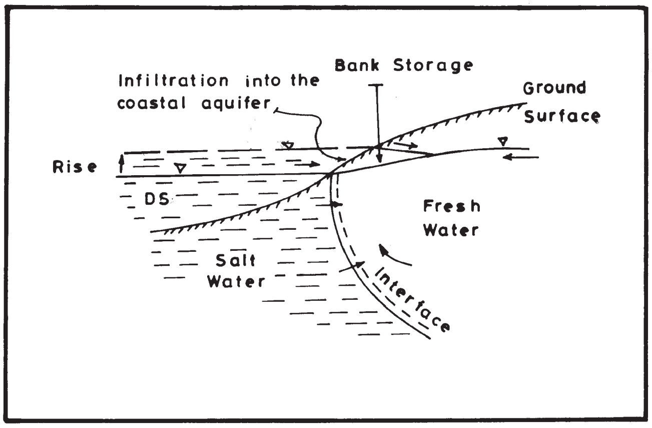


Fig. 7: Rises in the level of the Dead Sea and their effects on the coastal groundwater body and the fresh-/saltwater interface.

Anstieg des Wasserspiegels des Toten Meeres und damit verbundene Auswirkungen auf den küstennahen Grundwasserkörper und die Süß-/Salzwasser-Grenze.

flows from the DS water body during the dry season. The only explanation in this case is the infiltration of the DS water into the coastal aquifer due to the high rise in the DS level during the rainy season of 1991/1992 (Fig. 7).

The additional load due to the rise in the DS level in 1991/92 must also have produced an increasing pressure on the saltwater side of the interface and pushed that interface landward. Accordingly, water from the DS must have entered the aquifer to compensate for the interface migration in a landward direction (Fig. 3). The coastal infiltration and the infiltration to compensate for the interface migration are estimated at: (392 + 195) Mio m^3 = 585 Mio m^3 (392 Mio m^3 are inflows in the dry season and 195 Mio m^3 are potash net extraction).

The year 1991/92 is an extreme year concerning infiltration from the DS water into DS surrounding aquifers to readjust the interface and account for the rise in the DS level. Contrary to 1992, in the summer of 1990 the inflows into the DS were 193 Mio m^3 and the potash net extraction was 195 Mio m^3. Therefore, the actual drop in DS level must coincide with the summer evaporation line. But it does not, and additional water must have joined the DS by the seaward movement of the interface. From the hydrograph of 1989/90, this amount must have equaled 626 Mio m^3. The deviation in between the actual DS level at the end of the dry season from the evaporation line slope was calculated as 94 cm · 666 km^2 = 626 Mio m^3 of water. This is of course a very extreme year concerning outflows from the aquifer due to interface adjustment. Applying the same procedure to the different periods of drops in the level of the DS gives the amounts contributed by the groundwater to the waters of the DS as a result of interface readjustment (Table 6).

The additionally discharged amounts from the groundwater bodies into the DS to readjust the interface hydrodynamic equilibrium is listed in Table 6. It ranges from 493 Mio m^3 per meter drop in DS level in recent years (1994–1998) to 525 Mio m^3/a in the period 1930–1937. These amounts decline almost monotonously, in accordance with the shrinkage of the DS surfac area from 950 km^2 in 1930 to 650 km^2 in 1998.

The additional groundwater outflows into the Dead Sea per square kilometer shrinkage of the DS area is also listed in Table 6. It starts with 51 Mio m^3/km^2 in the period 1930–1937 with a DS water level ranging from 390 to 392.4 m bsl to 91 Mio m^3/km^2 in the period 1994–1998 with a DS level ranging from 407.5 to 410.5 m bsl.

The sudden change between the two periods (1957–1964 and 1972–1979) is a result of the disappearance (falling dry) of the southern basin of the DS, which is generally surrounded and underlain by salts or salty marls with very low drainable porosity and hence negligible contributions to the DS as a result of interface readjustment.

The riparian states of the DS are nowadays loosing an average of 420 to 450 Mio m^3 of their fresh groundwater resources to the DS by each lowering of the DS level by 1 m. The present day annual drop in the level of the DS ranges from 70 to 100 cm with an average of 85 cm which means that Jordan, Israel, and Palestine are loosing every year an average amount of 370 Mio m^3 of fresh groundwater to compensate for the declining DS level and the corresponding fresh-/saltwater interface readjustment.

5 The Porosity of Rocks in the Interface Area

At the eastern side of the DS in a depth ranging from 350 to 1400 m below DS level the impermeable basement complex

Table 6: Changes in the Dead Sea level and the corresponding outflows due to interface readjustment, and related parameters.

Änderungen der Spiegelhöhe des Toten Meeres und die durch die Verschiebung der Süß-/Salzwasser-Grenze bedingten Grundwasserabflüsse sowie weitere damit zusammenhängende Parameter.

Period	(a) Groundwater outflows due to interface readjustment Mio m^3	(b) Drop in DS level m	(c) Amount per meter drop in Dead Sea level (a/b) Mio m^3/m	(d) Amount per square kilometer Dead Sea area shrinkage Mio m^3/km^2	(e) Year average outflows Mio m^3
1930–1937	1073	2.4	525	51	179
1957–1964	1573	3.3	492	42.7	371
1972–1979	1706	3.8	449	80	293
1982–1990	3622	8	452	86 only northern basin	402
1994–1998	1277	3	423	91	255

consisting of granite rocks is encountered [14, 15]. The salt-/freshwater interface terminates at impermeable layers. In the case of the DS, at least on the eastern side, the depth to the impermeable layer below DS level averages around 700 m, hence the length of the interface line averages 1125 m.

The additional land area falling dry due to the shrinkage of the DS from 1930 to 1998 is (950–650) km^2 = 300 km^2. The average length of the shoreline (800 km^2 area) is 150 km. The average width of the new land (new shores) equals (300 km^2 : 150 km) = 2 km. The average groundwater outflows due to interface readjustment amount to around 450 Mio m^3 per one meter drop in level. The total drop in level from 1930 to 1998 is (390 to 411 m bsl) 21 meters.

The average topographic slope of the new land is 21 : 2000 = 1%, which is a negligible slope for the calculation of the average thickness distance of the interface migration. The drainage (outflow of groundwater) per square meter of new land equals (9450 : 300) m^3 = 31.5 m^3. The total discharge due to interface readjustment in the last 3 decades equals (21 · 450) Mio m^3 = 9450 Mio m^3.

From the average length of the interface from the surface of the DS to the impermeable basement of 1125 m, the average porosity of the interface area can be calculated to equal 31.5 : 1125 = 2.8%. This porosity coincides well with that reported by Schneider et al. [16] of less than 5%. Schneider et al. concluded that the original porosity of 25...30% was reduced to 15...24% by homoaxial overgrowth of quartz grains followed by calcite and dolomite cementation which reduced the porosity to less than 5%.

6 Conclusions

Hydrograph analyses of the available water level records for the DS since 1930 have shown four different distinct sections i.e seasonal fluctuations, periods of constant level, periods of drop in level, and periods of rise in level. The fluctuations in the level of the DS differ annually and periodically. This is attributed to the amount of winter inflows, evaporation losses, the amount and source of summer inflows/groundwater inflows seaward due to interface migration as a result of changes in the DS itself. The actual drop or rise in DS level relative to the previous summer lowest level is a function of: the slope of the actual DS level, net water income during dry season, the net water incomes from surface and groundwater sources, and the contribution due to interface readjustment. The DS level hydrographs have indicated that the deviation between the actual DS level declines and the evaporation line is realted to the in- or outward movement of the interface and the associated groundwater flows in both directions.

The quantitative analyses have shown that the interface seaward migration resulted in a groundwater discharge of around 423 Mio m^3 per meter drop in the level of the Dead Sea in the period 1994–1998 and of around 525 Mio m^3 per meter in the period 1930–1937. Furthermore, the additional amount of groundwater joining the Dead Sea due to the interface seaward migration was 51 Mio m^3 per one square kilometer of shrinkage in the area of the Dead Sea in the period 1930–1937 and 91 Mio m^3/km^2 in the period 1994–1998.

The groundwater outflows due to interface movement were reanalysed to calculate the physical characteristics of the aquifer within the area of the interface. The porosity was found to average around 2.8%.

The riparian states of the Dead Sea are nowadays loosing 370 Mio m^3/a of freshwater to the Dead Sea through the interface readjustment mechanisms as a result of their over exploitation of waters which formerly fed the Dead Sea.

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