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Final Report

**Equations of state for the Dead Sea and Aral Sea:
Searching for common approaches.**

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1. Abstract

The Dead Sea and Aral Sea water samples were acquired in dedicated expeditions and analyzed for ions concentration in IO RAS (Russia) and for density changes in IOLR (Israel). Water from both seas showed long term changes in concentrations of major ions. The Dead Sea ionic composition, dominated by magnesium chloride has a long term increase in the relative concentration of Magnesium ions and a long term decrease in the relative concentration of Sodium. The Aral Sea ionic composition which is dominated by sodium chloride has a decrease in the concentration of Calcium. In this report, we present new equations of state connecting change in water density with changes in water temperature and the density anomaly from 1000 kg/m³ at constant temperature 32°C, which is proposed as an indicator of salinity.

2. Introduction

The present hydrological regimes of the Aral Sea and the Dead Sea are strongly affected by drastic anthropogenic runoff reduction, intensified after 1960 (Table 1). Due to a large value of area/depth ratio (about 1600 km²/m for the Aral Sea and 3 km²/m for the Dead Sea) the Aral Sea desiccation is much faster relative to the Dead Sea. Nevertheless the degradations of the ecological situation in the vicinity of both seas are characterized as a disaster (Gavrieli et al., 2005; Zavialov et al., 2003)

Table 1. Changes in geomorphological parameters of the Dead Sea and Aral Sea (derived from Neev and Emery, 1967; Anati, 1997; Gertman and Hecht, 2002; Oren, 2003, Zavialov, 2005 and recent unpublished observations).

1960	Aral Sea	Dead Sea
Area [km ²]	66 x 10 ³	0.95 x 10 ³
Volume [km ³]	1100	155
Depth (mean/max) [m]	16/67	145/326
Salinity range [g/l]	10-12	290-326
2005	Aral Sea	Dead Sea
Area [km ²]	18 x 10 ³	0.62 x 10 ³
Volume [km ³]	120	133
Depth (deepest point) [m]	42	298
Salinity range [g/l]	80-120	340-355
Percentage of remaining area relative to 1960	27	65

The Dead Sea is a relatively large and deep terminal lake situated in the lowest section of the Jordan Rift Valley between Israel and Jordan. Since the early 1960's, the countries controlling the fresh watershed of the Dead Sea (i.e. Israel, Syria and Jordan) began to use these waters intensively (e.g. Salameh and Khawaj, 1984). As a result, the inflow of fresh waters into the Dead Sea has diminished significantly and the evaporation from the lake exceeded rain and runoff into it. Moreover, Israel and Jordan are using the Dead Sea waters for the production of minerals, which also contributes to the depletion of these waters. Until 1978 the morphology of the Dead Sea consisted of a large and deep northern basin and a smaller and much shallower southern basin connected via the Lynch straits (e.g. Neev and Emery, 1967). Following the recession of the water level, the entire Southern Basin would have dried up. However, the

erection of dikes transformed the area of the Southern Basin into evaporation ponds for the production of minerals. The water to those ponds is pumped in from the Northern Basin.

Since 1980, the surface level of the Dead Sea has been lowered at an average rate of about 60 cm per year and for the period from 1998-2000 the lowering rate has reached about 1 m per year (Fig. 1). Two layers thermohaline structure of the Dead Sea with relative light, less saline upper layer remained impenetrable by the winter mixing for hundreds of years (Oren, 2003). As a result of the runoff reduction, the upper layer salinity of the Dead Sea increased and the gravitational stability of the water body diminished. Eventually, during the winter of 1978-1979, the lake waters overturned, bringing to an end the long-term stable hydrological regime (Steinhorn and Gat, 1983; Anati, 1997). Since that winter the lake entered a new phase in which its hydrological regime is switched between two stable states. During the first state (termed holomictic hydrological regime by Hutchinson, 1957) the Dead Sea water body is well mixed from surface to bottom during the winter period, and is hydrostatically stable during the summer due to high temperature of the upper layer. During the second state (meromictic hydrological regime) the Dead Sea water body exhibit stable stratification throughout the year, i.e. no overturning during the winter. The meromictic regime appears only after extremely rainy winters when hydrostatic stability increases and limits winter convection owing to low salinity of the upper layer. Since 1979 the meromictic hydrological regime was reestablished twice. The first meromictic period (1980-82) lasted for three years. It was succeeded by a nine years holomictic period (1983-91). The second meromictic period (Fig. 1) lasted for four years from 1992 to 1995 (Anati, 1997, Gertman and Hecht, 2002).

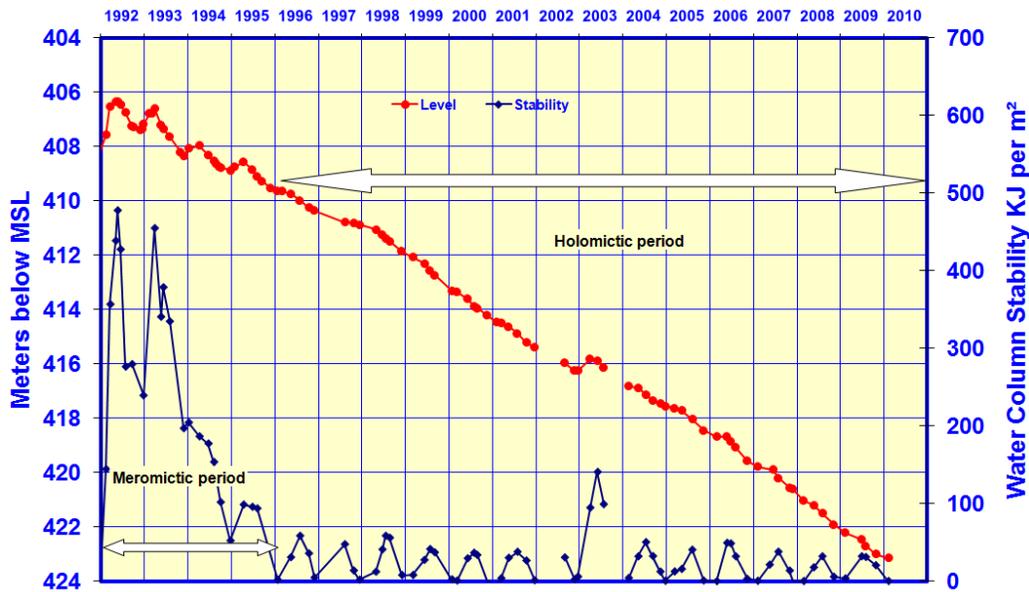


Figure 1. Changes in the surface level of the Dead Sea and in the total stability of the Dead Sea Water Column since 1992.

Since the early 1980s the Dead Sea is halite supersaturated (Oren, 2003). Massive amounts of halite have precipitated from the water column as halite crystals causing changes in the chemical composition of the Dead Sea water (Gavrieli, 1997). An additional factor, which contributes to significant changes in the water physical and chemical properties, is the water

exchange with the evaporation ponds used for industrial purposes (Gavrieli and Oren, 2004). Part of the water is returned to the northern basin as very hot, saline and extremely dense (1350 kg/m^3 , Lensky et al., 2005) end brine via an outlet in the most southern part of the Dead Sea. Recently it was found that the end brines propagate by slope convection, forming a warm and more saline bottom layer covering the whole deep region. During each holomictic winter this layer is mixed with the main water body contributing to long term changes of the chemical composition of the water in the entire basin.

Until the early 1970s, the Aral Sea was the World's fourth largest inland water reservoir, and it supported major ecosystem and biodiversity functions in Central Asia. In the 1950s, its dominant freshwater supply rivers, Amu Darya and Syr Darya, flowing through the Kara Kum and Kyzyl Kum deserts, were diverted for irrigation. This caused a catastrophic shallowing and salinization of the sea (see table 1). As a result, the natural water body was divided into two separate parts: a relatively big (about $150 \times 100 \text{ km}$) but very shallow (about 3 m) eastern basin and a relatively small ($150 \times 40 \text{ km}$) but deep (up to 42 m) western basin. According to 2006 observations, sea surface salinity in the western and eastern basins was about 97 g/l and 120g/l, respectively. The western and eastern parts remain connected through a narrow (about 3 km) and shallow (1-3 m) channel. The water exchange via the channel is highly intermittent in time. A massive advection of more saline eastern water to the western basin can switch its hydrological regime from holomictic to meromictic. The increase of gravitational stability due to strong salinity gradient between upper and bottom layers lead to anoxia and appearance of hydrogen sulfide in the bottom layer. Limited advection of saline water from the eastern basin leads to relaxation of the pycnocline and development of winter convection. Therefore the hydrogen sulfide in the Aral Sea is not permanent, but typical to meromictic conditions (Zavialov, 2005).

Halite precipitation in the Aral Sea was also found by Russian oceanographers during the last three years (Zavialov, 2005). This discovery provides solid basis for asserting that the Aral Sea water ionic composition and physical properties are also nonstationary at interannual time scale.

The most important changes of water physical properties are the changes in the relationship among water density, salinity and temperature. This relationship is represented typically in the form of an empirical equation of state (EOS) which is a very important part of any mathematical model for the sea. For the water basins connected to the World Ocean, the chemical composition of water has small deviations from a standard chemical composition of sea water. The UNESCO EOS (1981) was derived by fitting curves for density (measured in the laboratory) as a function of temperature, pressure and salinity and has an accuracy of 10^{-5} g/cm^3 . The EOS applies to salinity less than 45 g/kg and can neither be used for the Dead Sea nor for the Aral Sea, which have large salinities and changing chemical compositions.

The last Dead Sea water EOS was developed using water sampled in 1977 (Steinhorn, 1981 and Anati, 1997). The thermal expansion coefficient ($\partial\rho/\partial T = \alpha = -0.4309 \text{ kgm}^{-3}/^\circ\text{C}$) was determined by repeated density measurements (scanning) at various temperatures. The saline expansion coefficient ($\partial\rho/\partial S = \beta = 0.936 \text{ kgm}^{-3}/\text{‰}$) was also determined by repeated density measurements of water samples with known salinity. To increase the range of salinities the samples were diluted in the Dead Sea Works Laboratory with an accuracy of about 1-2%. Salinity of undiluted samples was almost constant (275 - 277 g/kg) within the accuracy of measurement. The linear equation of state was written in the following form:

$$\sigma_T = \sigma_0 + \alpha \cdot T + \beta \cdot S \text{ [kgm}^{-3}\text{]} \quad (1)$$

were σ_T is density anomaly from 1000 kg/m³ at temperature T [°C]. To calculate σ_T or S or T, when two others parameters are known, one has to know a reference point accurately connecting all three parameters. The last publication of such point was done by Anati (1997):

$$\sigma_{20}(S=277\text{g/kg}) = 235.0 \text{ kg/m}^3, \quad (2)$$

From here σ_0 can be calculated: $\sigma_0 = \sigma_T - \alpha T - \beta S = 235 + 0.4309 \cdot 20 - 0.936 \cdot 277 = -15.654 \text{ g/kg}$
and having a measured σ_T one can calculate salinity in g/kg:

$$S = (\sigma_T - \sigma_0 + T \cdot 0.4309) / 0.936. \quad (3)$$

3. Sampling Dead Sea water

6 sampling cruises were carried out during the project (see Appendix, Table A-1). All samples were taken on the EG-320 station (Fig. 2) where the water depth at the end of 2009 was about 295-298 m.

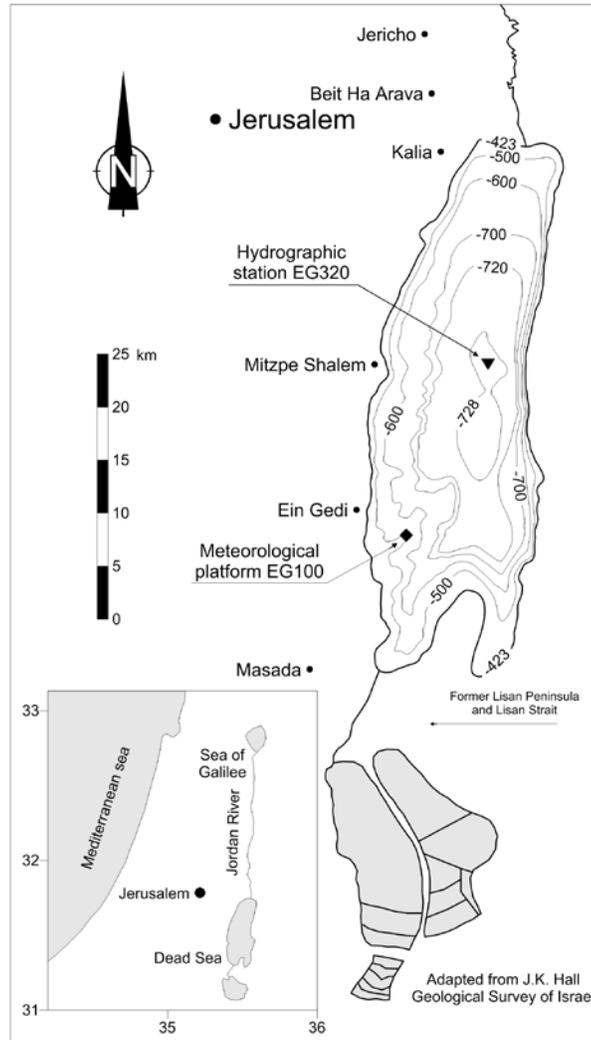


Figure 2. Location of the Dead Sea sampling station – EG320.

Sampling was done by Niskin bottles from 10 standard levels (1, 10, 20, 30, 50, 75, 100, 150, 200 and 250 meters) and from 3 additional levels at 2, 12 and 22 meters above the bottom. Water temperature was measured by SIS reversing thermometers (<http://www.sis-germany.com/rtm.htm>) and also by Sea-Bird temperature profiler (http://www.seabird.com/products/spec_sheets/19plusdata.htm). Pressure measurements from the profiler are converted to depth by dividing the pressure in decibars by the reference Dead Sea water density 1.24 g/cm^3 . Hermetically sealed water samples were delivered to the IOLR laboratory in a thermo isolated box with inner temperature of about 32°C to prevent salt precipitation due to cooling. Water density was measured with “Anton Paar” densimeter DMA

5000 (<http://www.anton-paar.com/>) at temperature $32 \pm 0.001^\circ\text{C}$. Traditionally, the density anomaly of Dead Sea water from 1000kg/m^3 at 25°C was used as an indicator of water salinity (Anati, 1997). It was called “quasi salinity” and denoted as σ_{25} or SIGMA-25 (Gertman and Hecht, 2002). In this section we used the Anati EOS to derive quasi salinity (σ_{25}) from σ_{32} by noting: $\sigma_{25} = \sigma_{32} + 0.4309 \cdot (32 - 25)$.

During the winter cruises (December 2007 and February 2009) the Dead Sea water body was well mixed from surface to bottom (Fig. 3). During summer and autumn periods (July 2007, May, August 2008, November 2008), the Dead Sea deep water is sealed by a stable pycnocline in the layer between 20m to 30m depth. This pycnocline is attributed to a strong thermocline which counteracts the influence of very high quasi-salinity values in the upper mixed layer (Fig. 4).

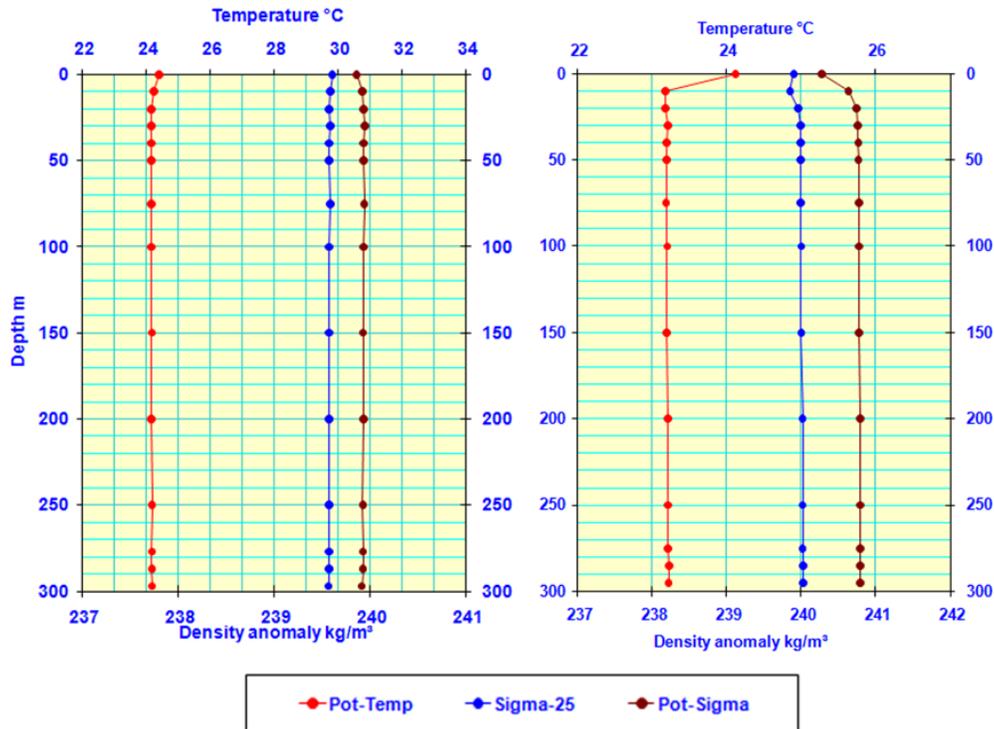


Figure 3. Homogeneous Dead Sea water body in December 2007 (left) and February 2009 (right). Small hydrostatic stability in the surface layer is typical for day time and is usually eroded during the night cooling.

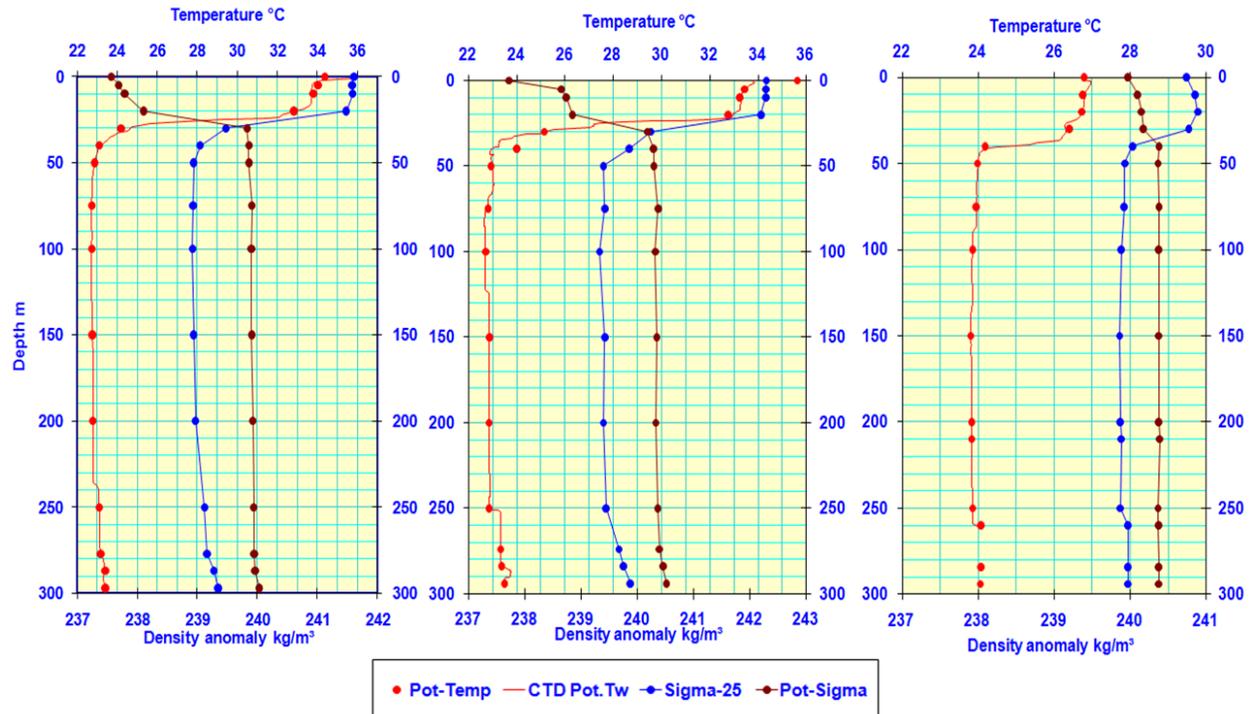


Figure 4. Vertical profiles of potential temperature, quasi salinity and potential density anomaly (Pot-Sigma) on the EG320 station during summer-autumn period (July 2007- left, August 2008- center, November 2008 – right).

In the summer vertical profiles, one can also see an increase of potential temperature and quasi-salinity near to bottom. Measurements on North-South sections revealed that this is caused by advection of warm and saline end-brine waters coming from the southern part of the Dead Sea. Step like structures near the bottom of temperature profiles suggest double diffusion as a mechanism of vertical mixing. However, judging from the profiles, the end brine do not penetrate depths higher than 250 m. We can conclude that water properties on the 100 m level have formed as a result of winter mixing of the entire Dead Sea water body and do not change rapidly by summer turbulent diffusion process. Therefore samples from 100m depth were selected for chemical composition analyses, and density scanning within extended temperature and salinity ranges.

During the sampling period, quasi-salinity of the Dead Sea water continued to increase at a rate of about 0.2 kg/m^3 per year (Fig. 5). Water temperature on the depth 100 m does not show a stable interannual tendency but has seasonal fluctuations from 22.5 to 24.2°C .

Since 1996 and throughout the sampling period, the Dead Sea water below the upper mixed layer was constantly saturated with halite (NaCl) and possibly other ions. We can make this conclusion based on visual observations of salt crystals accumulated on equipment and cable located below 30 m.

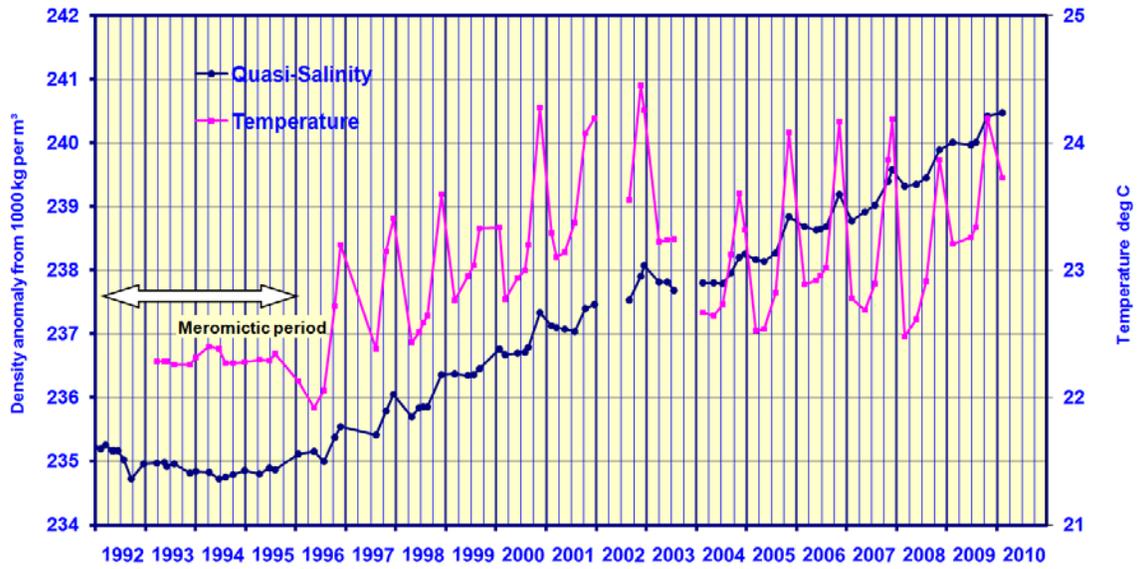


Figure 5. Interannual changes in quasi-salinity and temperature in the Dead Sea deep water (averaged for the water column below 100 m).

4. Concentration of the major ions in the Dead Sea water

Determination of major ions concentration in water samples were carried out in the chemistry laboratory of P.P. Shirshov Institute of Oceanology of Russian Academy of Science (IO RAS). The chemical analysis was done according to Russian standards for drinking water:

- GOCT 52407-2005 (international analogs: ISO 6059-1984; ISO 7980-1986; ISO 11885-1996).
- GOCT 52181-2003 (international analog ISO 10304-1:1992).

The Dead Sea water samples were delivered to IO RAS scientists undiluted (sealed hermetically after sampling by Niskin bottles) and also as diluted water. The undiluted samples always had salt crystals when they arrived in IO RAS. This happened because the samples were saturated with some ions, and during transportation experienced temperature lower than their in situ temperatures. The salt crystals in IO RAS were dissolved by distilled water with known volume proportion. Samples from the last cruise were delivered to IO RAS after dilution at IOLR's laboratory to prevent salt crystals formation. The dilution was carried out by deionized water with known mass dilution ratio. Before the dilution, samples were stored in a thermostat with temperature of about 32°C. Salt crystals absence was confirmed visually.

It should be pointed out that undiluted samples as well as diluted samples could not be analyzed directly, according to the above mentioned standard methods. The concentrations of major elements in Dead Sea samples were several orders of magnitude higher than the upper limit of concentration for drinking water. Therefore all samples underwent further significant dilution with distilled water to get concentrations which are measurable by the methods. Results of analyses are shown in Appendix, Table A-2. The range of the total dissolved salts (TDS) values in the table is significantly larger than salinity values calculated by Anati's equation (265.4-290.4 versus 284.1-285.2 g/kg). A possible reason of this inconsistency could be a low accuracy in the ratio of the dilution which was done prior to the determination of ions concentration. Comparison of published TDS values with corresponding salinity values calculated by Anati's equation (3) (Appendix, Table A-3, Steinhorn, 1981; Gavriely, 1997; Oren, 2003) shows a good consistency. We have expected to get results of about the same accuracy. Apparently the above mentioned methods of chemical analyses are not suitable to achieve the necessary accuracy with the hyper saline Dead Sea water.

Nevertheless, in spite of the fact that absolute concentrations appears to be too inaccurate for derivation of EOS, it should be pointed that relative concentrations of major ions derived from them appears to be quite consistent (Table 2).

Ranges of relative concentrations for each ion are quite reasonable. This supports the hypothesis of low accuracy in the dilution ratio which led to significant discrepancy in TDS estimations. Errors in the dilution ratio do not influence the percentage of ionic concentrations and this data can be used for estimation of changes of ionic relative composition in comparison with data published earlier (Fig 6).

Table 2. Percentage concentration of major ions in the Dead Sea water measured in IO RAS.

Date	Samp. No.	Mg ⁺⁺	Na ⁺	Ca ⁺⁺	K ⁺	Cl ⁻	SO ₄ ⁻⁻	HCO ₃ ⁻⁻
29-Jul-07	1-A	14.3	9.2	5.0	2.4	69.0	0.1	0.1
29-Jul-07	1-B	14.4	9.1	5.1	2.3	68.9	0.1	0.1
03-Dec-07	2	14.7	8.8	5.7	2.3	68.3	0.1	0.1
10-Nov-08	3	21.8	12.0	4.0	3.8	58.2	0.1	0.1
12-Feb-09	6-A	18.3	6.4	6.8	5.2	61.8	0.8	0.8
12-Feb-09	6-B	15.7	5.5	5.9	4.9	66.9	0.8	0.3
12-Feb-09	6-C	15.1	4.8	6.3	4.7	68.3	0.5	0.3
Average2008		15.7	7.8	5.6	3.6	66.8	0.3	0.2

Average2008 is the average percentage (minimal and maximal values of percentage were excluded from averaging).

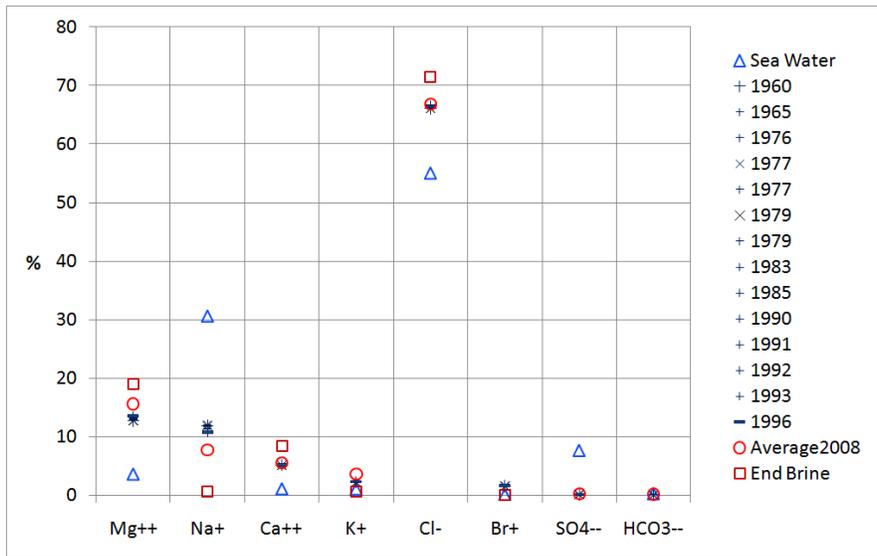


Figure 6. Percentage of ionic concentrations in the Dead Sea water. Data derived from publication (Table A-4: Steinhorn, 1981; Gavriely, 1997 and Oren, 2003) is combined with new data (Average2008). Composition of End Brine water and standard sea water are used to provide reference points.

In general one can conclude that the relative ionic concentrations are shifted from the ocean water typical values to the End Brine typical values. Consistent monotonic changes can be found in time series of magnesium Mg⁺⁺ and sodium Na⁺ (Figs. 7). Percentage of other ions remains stable within the accuracy of analyses.

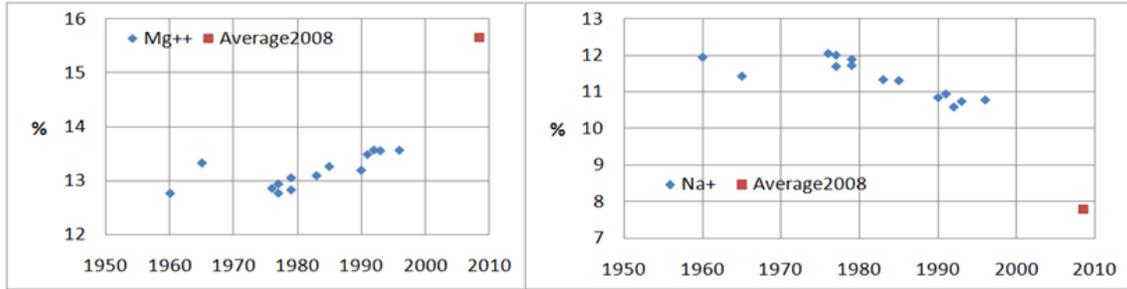


Figure 7. Long term changes in relative ionic concentrations of magnesium and sodium in Dead Sea water.

Unfortunately, we cannot make any conclusion regarding the reference point without absolute values of salinity. The average value of quasi-salinity (σ_{25}) for the project period is about 239.5 kg/m^3 and it is 6.7 kg/m^3 higher than the accepted reference point, but average TDS value (275 g/kg) derived from IO RAS data is less than the salinity of the reference point (277 g/kg). Therefore we do not have reliable data to re-estimate the reference point suggested by Anati, 1997.

5. Equation of state for the Dead Sea water

The Dead Sea water thermal expansion coefficient ($\partial\rho/\partial T = \alpha = 0.4309 \text{ kgm}^{-3}/^{\circ}\text{C}$) which has been used since 1981 (Steinhorn, 1981; Anati, 1997) was derived from Dead Sea water densities which were measured in a relative narrow range of temperature 23-35°C. The range is quite suitable to cover natural seasonal fluctuation of water temperature observed during holomictic periods (Anati, 1997, Gertman and Hecht, 2002). However during meromictic periods, the winter water temperature in the upper layer can drop to about 12-14°C (as was observed during February 1993).

In this project, 6 undiluted samples and 36 diluted samples (obtained from the undiluted samples by dilution with deionized water) were scanned with density measurements by DMA5000 in the range of 12 to 32°C (with interval of 5°C) in order to cover possible ranges for holomictic and meromictic periods. Some samples were scanned with 1°C interval in the range 20-32°C in order to get more accurate data for the current holomictic period. In some cases, subsamples were scanned twice to prove good repeatability of measurements. A total of 69 scans were accepted for statistical analysis (Fig. 8 and Appendix, Table A-4).

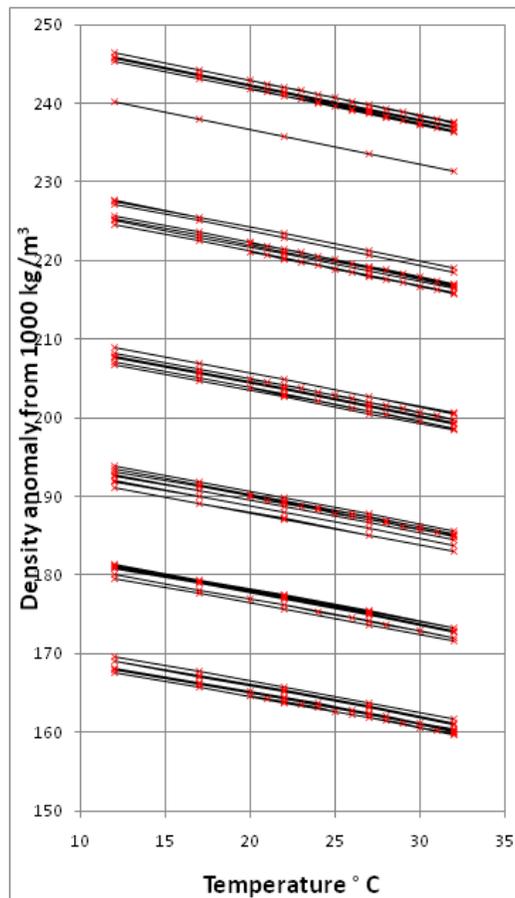


Figure 8. Dead Sea water density dependence on temperature for undiluted and diluted samples.

We first tested the suitability of linear regression (assuming $\sigma_T = B_0 + B_1 * T$) for approximation of the Dead Sea water thermal expansion as was done by Steinhorn (1981) and Anati (1997). This attempt was unsuccessful for the full ranges of temperatures and quasi-salinities because:

- Significant nonlinearity in the σ_T changes with water temperature. Root mean square (RMS) of residuals from linear regression for each single scan in the interval 12-32°C are too large: 0.01-0.08 kg/m³ (compared to RMS values from nonlinear regression in Appendix, Table A-5).
- Thermal expansion coefficient exhibits strong dependence on the quasi-salinity of the samples (Fig. 9). On this chart σ_{32} (and further in the text) is used as quasi-salinity instead of σ_{25} . The σ_{32} was measured on the start of each scan and seems to be more robust than σ_{25} .

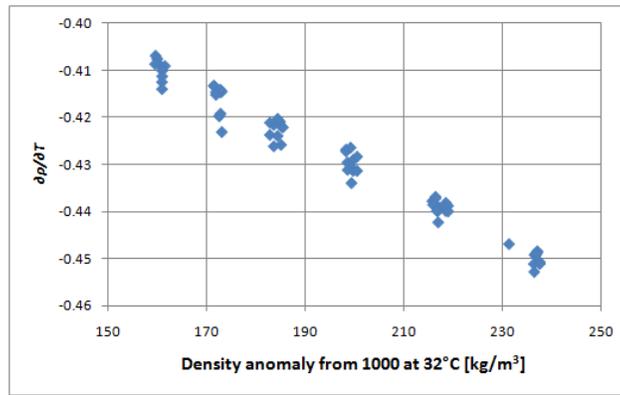


Figure 9. Decrease of thermal expansion coefficient of the Dead Sea water with increase of the water quasi-salinity.

In the next step we checked the possibility of deriving thermal expansion coefficient for narrow ranges of water temperature and quasi-salinities which are typical for the current holomictic Dead Sea state. We found that a simple linear regression ($\sigma_T = B_0 + B_1 * T$) can be quite accurate for such intervals: $T \approx 22-32$ °C and $\sigma_{32} \approx 235-245$ kg/m³ (Table 5 and Fig. 10).

The suggested new thermal expansion coefficient of the Dead Sea water which is valid for typical temperature and salinity intervals during 2007-2009 (Fig. 10) is the median value from Table 5:

$$\partial\rho/\partial T = -0.450 \pm 0.001 \text{ kg m}^{-3}/\text{°C} \quad (4)$$

A nonlinear Dead Sea water equation of state $\sigma_T = f(T, \sigma_{32})$ was derived using the density measurements of all subsamples (Appendix, Table A-5) in a wide range of temperatures. The quality of each scan was estimated before formulating the equation of state for the entire temperature and quasi-salinity ranges (Fig. 8). This was done by checking the RMS of residuals from quadratic regression in the temperature interval $T \approx 12-32$ °C (Appendix, Table A-5). RMS values are much better than those received by linear regression. Only four scans had RMS larger than 0.01 kg/m³ (Fig. 11) and therefore rejected from the following processing.

Table 5. Thermal expansion coefficient of Dead Sea water derived from linear regression using undiluted samples scanned in the narrow (22-32°C) temperature interval.

Sample	Sampling Date	RMS of residuals	Number of points	$\partial\rho/\partial T$	σ_{32}
1	29-Jul-07	0.0070	11	-0.4509	237.526
4	3-Dec-07	0.0111	6	-0.4511	236.401
5	3-Dec-07	0.0156	3	-0.4528	236.463
6	21-May-08	0.0062	11	-0.4492	236.518
8	4-Aug-08	0.0118	3	-0.4511	237.553
9	4-Aug-08	0.0113	3	-0.4507	237.553
10	10-Nov-08	0.0066	3	-0.4489	236.861
11	10-Nov-08	0.0090	3	-0.4491	236.861
12	12-Feb-09	0.0069	3	-0.4484	237.076
13	12-Feb-09	0.0084	3	-0.4487	237.076

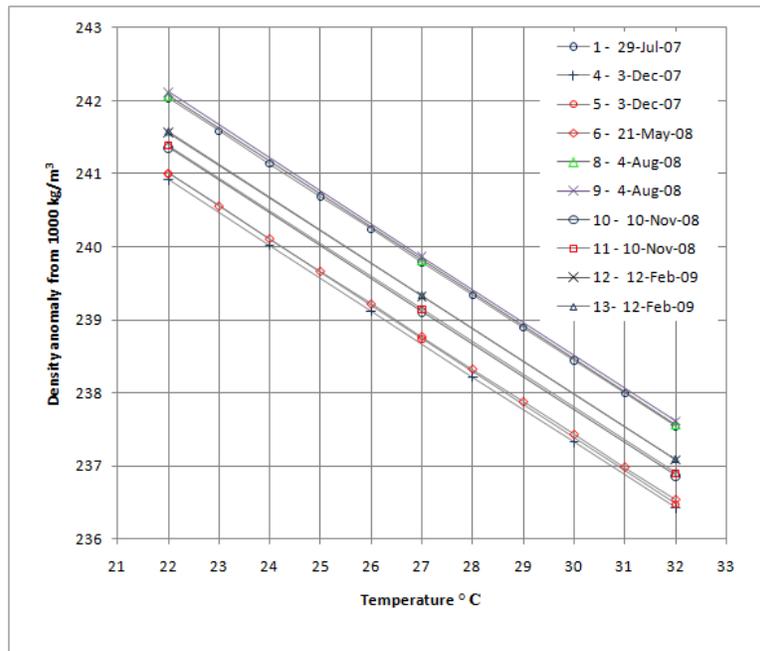


Figure 10. Changes in Dead Sea water density from undiluted samples in a temperature interval typical for the holomictic period 2007-2009.

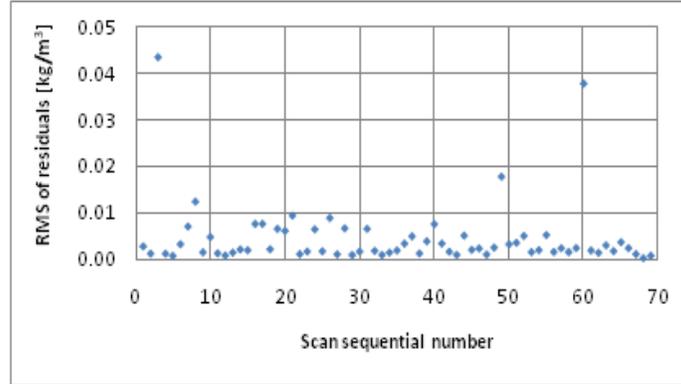


Figure 11. RMS of residuals from quadratic regression of the Dead Sea water scans.

To cover the relatively wide ranges of temperatures and quasi-salinities (Fig. 8) the following equation is suggested:

$$\sigma_T = A_0 + A_1 * T + A_2 * T * T + A_3 * \sigma_{32} + A_4 * \sigma_{32} * \sigma_{32} + A_5 * T * \sigma_{32} \quad (5)$$

This equation includes second order terms both for temperature and quasi-salinity. Parameters of equation of state in form (5) were estimated by three iterations of least square fitting followed by rejection of measurements with extremely large residuals (Table 6).

Table 6. Iterative improvement of parameters of the least square fitting of equation (5) for the density scanning of the Dead Sea water samples (Fig. 8).

NN	Number of points	RMS of residuals	Max residual	Min residual	Accepted residuals range	Number rejected points
1	353	0.0361	0.2589	-0.0835	< 0.2	5
2	348	0.0247	0.0942	-0.0778	Abs. Val < 0.06	16
3	332	0.0188	0.0650	-0.0502	All	-

Coefficients $A_0 - A_5$ derived in the third iteration (Table 7) are accepted for the final equation of state. 76% of the residuals do not exceed the accuracy of density measurements (0.02 kg/m^3).

Table 8. Coefficients of nonlinear state equation in form (5) (Fig.7).

Coefficient	A_0	A_1	A_2	A_3	A_4	A_5
Value	9.2837	-0.24267	-1.17871E-3	1.01708	5.70817E-6	-6.18976E-4
Standard Error	0.074	0.017	0.0026E-3	0.0071	1.745E-6	0.0633E-4

6. Equation of state for the Aral Sea water

During last 20 years IO RAS carried out systematic oceanographic investigation in the Aral Sea (Oberhansli and Zavialov, 2009). During the project two dedicated expeditions were carried out: November 2007 and June 2008.



Figure 12. Aral Sea in 2008 (satellite image by NASA's Earth Observatory: <http://earthobservatory.nasa.gov>).

Water was sampled in the eastern and western parts of the sea (Fig. 12). Determination of major ions concentration in water samples were carried out in the chemistry laboratory of P.P. Shirshov Institute of Oceanology of Russian Academy of Science (IO RAS). Tabl. 9 contains historical data since 2002 (Zavialov et al, 2008).

In general the Aral Sea ionic composition is dominated by sodium chloride (as it is in the normal sea water, Fig. 13). This is the main difference with ionic composition of the Dead Sea, which is dominated by magnesium chloride. A major long term change in ionic composition of the Aral Sea is the decrease of Calcium. One can see also that ionic composition of the eastern Aral water is different from the western Aral water. Taking into account that desiccation of the eastern Aral is very fast and properties of its water are different from the western Aral water, we did not use eastern Aral water sample for derivation of EOS.

Table 9. Absolute and relative (%) concentration of major ions in western and eastern Aral during 2002-2008.

N	Units	Date/region	Cl-	SO4--	HCO3--	Na+	K+	Ca++	Mg++	TDS
1	g/kg	05.07.02	27.16	20.16	0.49	18.96	0.18	0.80	4.38	72.13
	%	West	37.65	27.95	0.68	26.29	0.24	1.11	6.07	
2	g/kg	25.10.03	38.01	22.10	0.46	8.63	1.00	0.70	13.22	84.12
	%	West	45.18	26.27	0.54	10.26	1.19	0.83	15.72	
3	g/kg	08.04.04	33.18	22.94	0.44	21.14	1.13	0.60	5.40	84.83
	%	West	39.11	27.04	0.52	24.92	1.34	0.71	6.37	
4	g/kg	10.08.04	34.79	23.82	0.37	22.31	1.21	0.58	5.41	88.50
	%	West	39.31	26.92	0.41	25.21	1.37	0.66	6.12	
5	g/kg	30.09.05	37.58	25.06	0.15	24.10	1.21	0.54	5.76	94.39
	%	West	39.81	26.55	0.16	25.53	1.28	0.57	6.10	
6	g/kg	10.10.05	44.67	36.66	0.18	30.95	1.18	0.42	7.52	121.58
	%	East	36.74	30.15	0.15	25.46	0.97	0.34	6.19	
7	g/kg	25.09.06	38.92	26.00	0.56	23.92	1.18	0.57	6.54	97.70
	%	West	39.84	26.61	0.58	24.48	1.21	0.58	6.70	
8	g/kg	01.06.08	44.36	23.15	0.58	25.35	1.55	0.55	6.87	102.40
	%	West	43.32	22.60	0.57	24.75	1.51	0.54	6.71	
9	g/kg	08.06.08	78.98	67.78	0.95	57.32	2.50	0.25	12.33	220.09
	%	East	35.88	30.79	0.43	26.04	1.14	0.11	5.60	

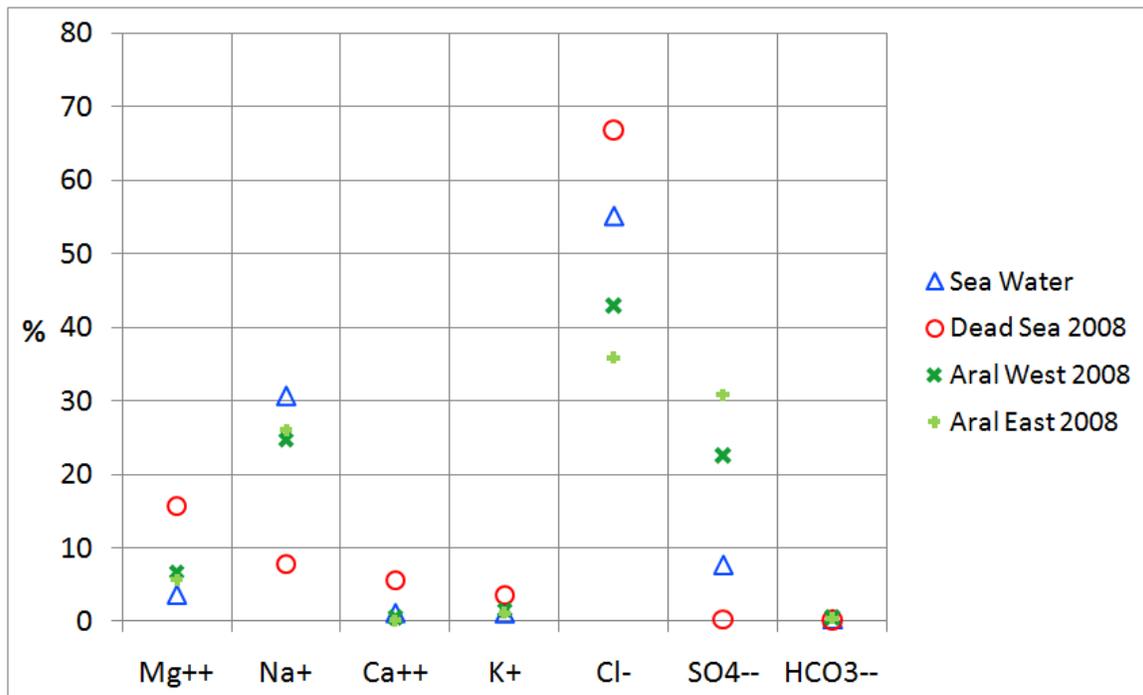


Figure 13. Relative contents of major ions in the Dead Sea water, Aral Sea water and normal sea water.

Four west Aral water samples were delivered to IOLR for density scans. Salinity of the samples was measured in situ by a specially calibrated CTD. To extend the range of salinity, the samples were diluted with dionized water and the salinity of the diluted samples was calculated by using a known mass dilution proportion (Appendix, Table A-6). All samples were scanned with density measurements by DMA5000 in the range of 2 to 32°C (with intervals of 1°C, 2°C or 5°C). In some cases, subsamples were scanned twice to prove good repeatability of measurements. A total of 60 scans were accepted for statistical analysis (Fig. 14 and Appendix, Table A-7).

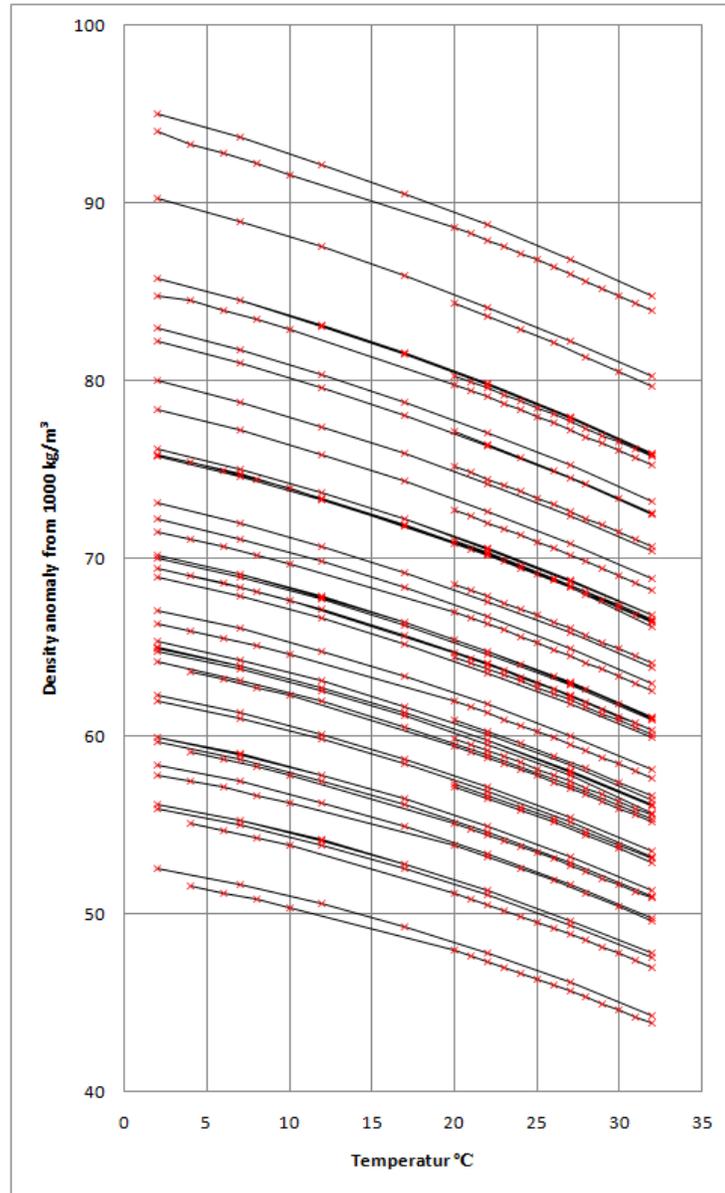


Figure 14. Aral Sea water density dependence on temperature for undiluted and diluted samples.

11 scans were rejected because their RMS of residuals from quadratic regression was greater than 0.015 kg/m^3 (Fig. 15)

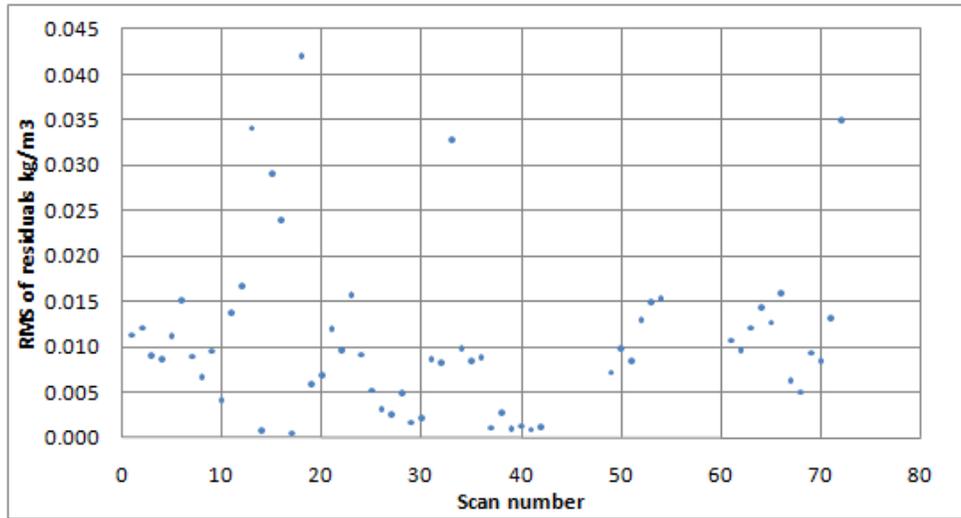


Figure 15. RMS of residuals from quadratic regression of the Aral Sea water scans.

The form of the west Aral water EOS is assumed to have the same form as (5). Two iterations of least square fitting were enough to reach acceptable RMS of residuals (Table 10).

Table 10. Iterative improvement of parameters of the least square fitting of equation (5) for the density scanning of the west Aral Sea water samples (Fig. 14).

NN	Number of points	RMS of residuals	Max residual	Min residual	Accepted residuals range	Number rejected points
1	445	0.0319	0.092	-0.236	< 0.06	20
2	425	0.0216	0.058	-0.068	All	

Coefficients $A_0 - A_5$ derived in the third iteration (Table 11) are accepted for the final equation of state. 67% of the residuals did not exceed the accuracy of density measurements (0.02 kg/m^3).

Table 11. Coefficients of nonlinear state equation in form (5) accepted for the west Aral Sea water (Fig.14).

Coefficient	A_0	A_1	A_2	A_3	A_4	A_5
Value	6.4212	-0.09498	-3.29E-3	1.05326	-3.1E-5	-1.61E-3
Standard Error	0.042	0.001	1.41E-5	1.242E-3	9.27E-6	1.26E-5

As in the Dead Sea, this Aral Sea EOS is based on quasi-salinity (σ_{32}) instead of salinity (g/kg) which is usually accepted. The Table A-6 contains salinity of samples which are based on measurement of a CTD specially calibrated by Russian oceanographers for the Aral Sea water. Unlike the case of the Dead Sea, these salinities are quite consistent with quasi-salinities measured independently by DMA 5000 (Fig. 16).

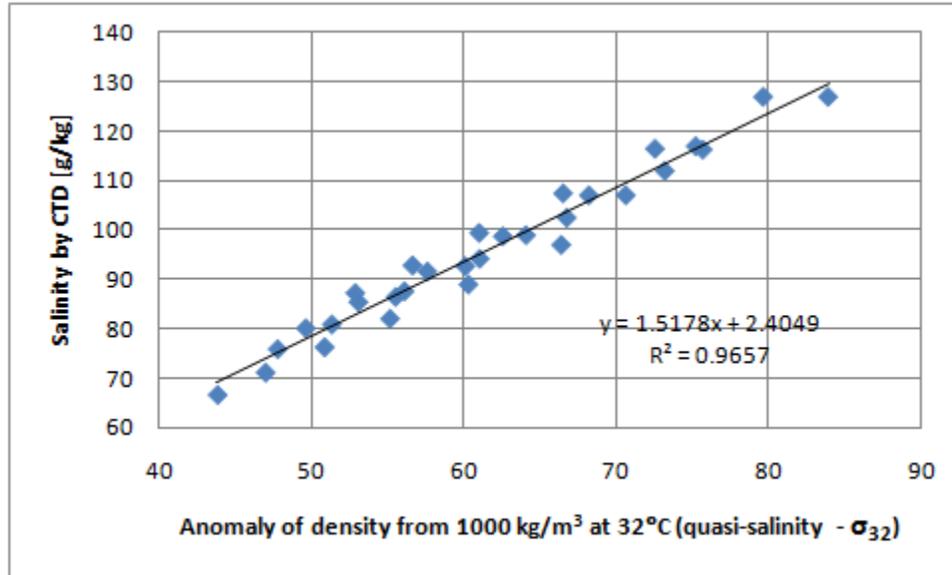


Figure 16. Salinity of Aral water measured by specially calibrated CTD versus quasi-salinity measured by DMA5000.

Therefore we have also derived EOS of western Aral Sea where quasi-salinity is replaced by the usual salinity:

$$\sigma_T = A_0 + A_1 * T + A_2 * T * T + A_3 * S + A_4 * S * S + A_5 * T * S \quad (6)$$

Table 12. Coefficients of nonlinear state equation in form (6) accepted for the west Aral Sea water.

Coefficient	A ₀	A ₁	A ₂	A ₃	A ₄	A ₅
Value	16.1762	-9.672E-2	-3.17E-3	0.49947	8.41E-4	-1.17E-3
Standard Error	3.21	7.53E-2	1.21E-3	6.26E-3	3.16E-4	6.50E-4

The RMS of residuals for this regression is quite large 1.94 (max=3.90; min=-4.03) g/kg. The distribution of residuals has not extreme outliers therefore we did not implement iterative technique improvement of approximation. The possible error of density estimation by this equation is about the error of first term (A₀) in the equation which is about 3.2 kg/m³.

7. Conclusions

- P.P. Shirshov Institute oceanography of Russian Academy of Science (IO RAS) and Israel Oceanographic and Limnological Research (IOLR) coordinated successfully field works, water sampling and experiments directed towards the investigation of chemical and physical properties of Aral Sea and Dead Sea.
- During 2007-2008 several dedicated expeditions were carried out in the Aral Sea (by Russian oceanographers) and in the Dead Sea (by Israeli and Russian oceanographers).
- Thermohaline structures of both seas were investigated and appropriate water samples were delivered to laboratories of both institutions.
- Determination of major ions concentration in sea water samples were carried out in IO RAS. Dead Sea water analyses by IO RAS did not achieve satisfactory accuracy of absolute concentration of major ions in the hyper saline Dead Sea water. Only relative concentrations are consistent with early published results. Further investigation of methods for hyper saline water analyses is required.
- The instability of chemical composition of water in both seas were confirmed and estimated. The Dead Sea ionic composition, dominated by magnesium chloride has a long term tendency of increase in Magnesium relative concentration and decrease in Sodium relative concentration. The Aral Sea ionic composition which is dominated by sodium chloride has a tendency of decrease in Calcium concentration.
- Density scanning of water samples and analysis were carried out in IOLR.

Based on water sampled during 2007-2009 from the Dead Sea, the following properties were derived:

- New Dead Sea thermal expansion coefficient $\partial\rho/\partial T = -0.450 \pm 0.001 \text{ kg m}^{-3}/^{\circ}\text{C}$, which is acceptable for a limited ranges of temperature ($T \approx 22\text{-}32^{\circ}\text{C}$) and quasi-salinity ($\sigma_{32} \approx 235\text{-}245 \text{ kg/m}^3$);
- New Dead Sea equation of state which is acceptable in a wide range of temperatures ($T \approx 12\text{-}32^{\circ}\text{C}$) and quasi-salinities ($\sigma_{32} \approx 150\text{-}250 \text{ kg/m}^3$):

$$\sigma_T = 9.2837 - 0.24267 * T - 1.17871E-3 * T * T + 1.01708 * \sigma_{32} + 5.70817E-6 * \sigma_{32} * \sigma_{32} - 6.18976E-4 * T * \sigma_{32}$$

Based on water sampled during 2007-2008 from the Aral Sea, the following properties were derived:

- New Aral Sea equation of state which is acceptable in a wide range of temperatures ($T \approx 2\text{-}32^{\circ}\text{C}$) and quasi-salinities ($\sigma_{32} \approx 40\text{-}90 \text{ kg/m}^3$):

$$\sigma_T = 6.4212 - 0.09498 * T - 3.29E-3 * T * T + 1.05326 * \sigma_{32} - 3.1E-5 * \sigma_{32} * \sigma_{32} - 1.61E-3 * T * \sigma_{32}$$
- New Aral Sea equation of state of limited accuracy which is acceptable in a wide range of temperatures ($T \approx 2\text{-}32^{\circ}\text{C}$) and salinities ($S \approx 65\text{-}130 \text{ kg/m}^3$):

$$\sigma_T = 16.1762 - 9.672E-2 * T - 3.17E-3 * T * T + 0.49947 * S + 8.41E-4 * S * S - 1.17E-3 * T * S$$

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9. References

- Anati, D. A., 1997. The hydrography of a hypersaline lake. In: “The Dead Sea: the lake and its setting”, edited by Tina M. Niemi, Zvi Ben-Avraham, Joel R. Gat. Oxford University Press, Oxford, 89-103
- Gavrieli, I., 1997. Halite deposition from the Dead Sea: 1960-1993. In “The Dead Sea: the lake and its setting”, edited by Tina M. Niemi, Zvi Ben-Avraham, Joel R. Gat. Oxford University Press, Oxford, 161-170
- Gavrieli, I., and A. Oren. 2004. The Dead Sea as a dying lake. In J. C. J. Nihoul, P. O. Zavialov and P. P. Micklin [eds.], *Dying and Dead Seas, Climatic Versus Anthropogenic Causes*. NATO ASI SERIES. Kluwer Academic Publishers, 287-305.
- Gavrieli, I., A., Bein and A., Oren. 2005. The expected impact of the “Peace Conduit” project (the Red Sea - Dead Sea pipeline) on the Dead Sea. *Mitigation and Adaptation Strategies for Global Change* 10, 3-22
- Gertman, I. and A. Hecht, 2002. The Dead Sea hydrography from 1992 to 2000. *J. Mar. Syst.* 35: 169-181.
- Hutchinson, G.E., 1957. *A treatise on limnology*. Willey, New York, 1015 pp.
- Lensky, N. G., Y. Dvorkin, V. Lyakhovskiy, I Gertman, and I. Gavrieli, 2005, Water, salt, and energy balances of the Dead Sea, *Water Resources Research*, 41, W12418, doi:10.1029/2005WR004084.
- Neev, D. and K.O. Emery, 1967. *The Dead Sea. Depositional processes and environments of evaporites*. Geological Survey Israel. Bull. 41, 147 pp.
- Nihoul J.C.J., P.O. Zavialov, P.P.Micklin (Eds.), 2005. *Dying and Dead Seas: Climatic versus Anthropogenic Causes*. Kluwer Academic Publ., Dodrecht, Germany, 384 pp.
- Oberhansli, H., and P. Zavialov, 2009. Aral Sea hydrological, chemical, and biological dynamics today, compared with trends of the past 50 years. *J. Marine Systems*, 76, 251-253, doi:10.1016/j.jmarsys.2008.08.001
- Oren A., 2003. Physical and Chemical Limnology of the Dead Sea. Chapter 3. In: “Fungal Life in the Dead Sea”. (eds. Nevo, E, A. Oren and S. P. Wasser). A.R.G. Ganter Verlag K.G. 325 p.

Salameh, E and M. Khawaj, 1984. The Mediterranean – Dead Sea canal and its environmental impacts. Univ. of Jordan, Aman, Water Research and Study Center, Newsletter No. 2, 36 pp.

Steinhorn I., 1981. A hydrographical and physical study of the Dead Sea during the destruction of its long-term meromictic stratification. Thesis for the Degree of Ph. D. Weizman Institute of Science, Rehovot, Israel. 323 pp.

Steinhorn I. and J. R. Gat, 1983. The Dead Sea, Scientific American, 249 (No. 4):102-109.

UNESCO, 1981 Background papers and supporting data on the International Equation of State of Seawater 1980. Unesco Technical Papers in Marine Science. No. 38, 192 pp.

Zavialov, P. O., A. G. Kostianoy, S. V. Emelianov, et al., 2003. Hydrographic survey in the dying Aral Sea. Geophysical Research Letters, 30, 13, 1659-1662, doi: 10.1029/2003GL017427.

Zavialov, P. O., 2005. Physical Oceanography of the Dying Aral Sea. Springer-Verlag – Praxis, Chichester, UK, 199 pp.

Zavialov, P.O., A.A. Ni, D.P. Ishniyazov, T.V. Kudyshkin, A.K. Kurbaniyazov, and D. Mukhamedzhanova, 2008. Ongoing changes in salt composition and dissolved gases in the Aral Sea. Aquatic Geochemistry, doi: 10.1007/s10498-008-9057-9.

10. Appendix

Table A-1. Dead Sea water sampling.

Date of cruise	Cruise number	Sample name	Station	Depth of sample	Analyzed for ion composition
29/JUL/2007	1	1-A	EG320	1	Yes
29/JUL/2007	1	1-B	EG320	100	Yes
03/Dec/2007	2	2	EG320	100	Yes
21/MAY/2008	3	3	EG320	100	Yes
04/AUG/2008	4	4	EG320	100	
10/NOV/2008	5	5	EG320	100	
12/FEB/2009	6	6-A	EG320	100	Yes
12/FEB/2009	6	6-B	EG320	100	Yes
12/FEB/2009	6	6-C	EG320	100	Yes

Table A-2. Concentration of major ions (g/kg) in the Dead Sea water measured in IO RAS (note that the accuracy of the results is not satisfactory, see text. Section 4).

Date	Samp. No	Mg ⁺⁺	Na ⁺	Ca ⁺⁺	K ⁺	Cl ⁻	SO ₄ ⁻⁻	HCO ₃ ⁻⁻	TDS	σ_{25}	Sal. by Anati
29-Jul-07	1-A	41.4	26.7	14.6	6.9	200.3	0.3	0.2	290.4	238.92	285.2
29-Jul-07	1-B	38.4	24.2	13.6	6.1	183.4	0.2	0.2	266.2	238.92	284.1
03-Dec-07	2	41.4	24.8	16.0	6.4	191.5	0.2	0.2	280.4	239.38	284.0
10-Nov-08	3	58.9	32.3	10.8	10.2	156.8	0.3	0.2	269.4	239.30	284.5
12-Feb-09	6-A	50.3	17.6	18.6	14.3	170.3	2.2	2.3	275.6	240.00	284.7
12-Feb-09	6-B	43.7	15.3	16.3	13.7	186.1	2.2	0.8	278.0	240.00	284.7
12-Feb-09	6-C	40.1	12.7	16.8	12.5	181.2	1.3	0.8	265.4	240.00	284.7

TDS is the sum of concentrations of the measured ions.

σ_{25} is water density anomaly from 1000 kg/m³ measured by DMA5000 at temperature 25°C.

Sal. by Anati is water salinity calculated from σ_{25} according to the equation by Anati (3)

Table A-3, Concentration of major ions (g/kg) in the Dead Sea water published in: Steinhorn,1981; Gavriely, 1997 and Oren, 2003

	Mg ⁺⁺	Na ⁺	Ca ⁺⁺	K ⁺	Cl ⁻	Br ⁺	SO ₄ ⁻⁻	HCO ₃ ⁻⁻	TDS	σ_{25}	Sal. by Anati
Sea Water	1.29	10.77	0.41	0.4	19.35	0.07	2.71	0.12	35.1	23	
1960	34.5	32.3	14.0	6.2	178.4	4.3	0.3	0.2	270.2	229	272.9
1965	36.1	31.0	13.7	6.4	179.5	4.2			270.9	230	274.0
1976	35.1	32.9	13.6	6.2	180.8	4.1			272.7	232	276.1
1977	35.3	33.2	14.2	6.2	182.6	4.4	0.4	0.2	276.4	231	274.6
1977	35.6	32.2	14.1	6.3	182.2	4.3	0.4	0.2	275.4	232	276.1

1979	35.6	33.0	14.2	6.4	183.4	4.3	0.4	0.2	277.5	232	276.1
1979	36.1	32.5	13.7	6.4	183.2	4.3	0.4	0.2	276.8	232	276.1
1983	35.8	31.0	14.4	6.2	181.3	4.3	0.4		273.4	232	276.1
1985	36.5	31.1	14.2	6.4	182.0	4.2	0.4	0.2	275.0	234	278.2
1990	36.1	29.7	13.8	6.4	182.7	4.5	0.4	0.2	273.8	235	279.3
1991	37.1	30.1	13.8	6.4	182.7	4.4	0.4	0.2	275.0	235	279.3
1992	37.8	29.5	14.3	6.3	185.5	4.5	0.4	0.2	278.4	234	278.2
1993	37.2	29.5	14.0	6.3	182.3	4.5	0.3	0.2	274.5	234	278.2
1996	37.3	29.7	14.3	6.3	182.4	4.5	0.4		275.0	232	276.1
End Brine	67.0	2.1	29.6	2.1	252.6				353.4	350	

Table A-4. Percentage of major ions derived from published data (Table A-3).

	Mg++	Na+	Ca++	K+	Cl-	Br+	SO4--	HCO3--
Sea Water	3.7	30.7	1.2	1.1	55.1	0.2	7.7	0.3
1960	12.8	12.0	5.2	2.3	66.0	1.6	0.1	0.1
1965	13.3	11.4	5.0	2.4	66.3	1.6		
1976	12.9	12.1	5.0	2.3	66.3	1.5		
1977	12.8	12.0	5.1	2.2	66.1	1.6	0.1	0.1
1977	12.9	11.7	5.1	2.3	66.2	1.6	0.1	0.1
1979	12.8	11.9	5.1	2.3	66.1	1.5	0.1	0.1
1979	13.1	11.7	5.0	2.3	66.2	1.6	0.1	0.1
1983	13.1	11.3	5.3	2.3	66.3	1.6	0.1	
1985	13.3	11.3	5.2	2.3	66.2	1.5	0.1	0.1
1990	13.2	10.9	5.1	2.3	66.7	1.6	0.1	0.1
1991	13.5	11.0	5.0	2.3	66.4	1.6	0.1	0.1
1992	13.6	10.6	5.1	2.3	66.6	1.6	0.1	0.1
1993	13.6	10.7	5.1	2.3	66.4	1.7	0.1	0.1
1996	13.6	10.8	5.2	2.3	66.3	1.7	0.1	
End Brine	19.0	0.6	8.4	0.6	71.5	0.0		

Table A-5. Approximation of 69 density scans of Dead Sea water diluted and undiluted samples by the equation $\sigma_T = A_0 + A_1 * T + A_2 * T^2$.

NN	σ_{32}	Min T	Max T	N_Point	RMS	A0	A1	A2
1	159.703	12	32	5	0.003	171.663	-0.3225	-0.001598
2	159.789	20	32	13	0.001	171.741	-0.3246	-0.001525
3	160.01	12	32	5	0.044	171.814	-0.2714	-0.003018
4	160.147	12	32	5	0.001	172.151	-0.3265	-0.001520
5	160.147	12	32	5	0.001	172.163	-0.3274	-0.001487
6	160.363	20	32	7	0.003	172.251	-0.3167	-0.001708
7	161.095	12	32	5	0.007	173.063	-0.3177	-0.001753
8	161.095	12	32	5	0.012	173.009	-0.3157	-0.001814
9	161.122	12	32	5	0.001	173.102	-0.3220	-0.001634
10	161.122	12	32	5	0.005	173.158	-0.3218	-0.001658

11	161.697	12	32	5	0.001	173.723	-0.3273	-0.001516
12	171.61	12	32	5	0.001	183.876	-0.3395	-0.001369
13	171.61	12	32	5	0.001	183.878	-0.3394	-0.001369
14	171.999	20	32	7	0.002	184.191	-0.3315	-0.001543
15	172.011	12	32	5	0.002	184.292	-0.3379	-0.001432
16	172.713	12	32	5	0.008	184.998	-0.3315	-0.001634
17	172.713	12	32	5	0.008	184.998	-0.3315	-0.001634
18	172.903	12	32	5	0.002	185.190	-0.3399	-0.001377
19	172.903	12	32	5	0.006	185.241	-0.3454	-0.001297
20	172.952	12	32	5	0.006	185.248	-0.3330	-0.001599
21	173.216	12	32	5	0.009	185.486	-0.3252	-0.001815
22	173.216	12	32	5	0.001	185.526	-0.3405	-0.001372
23	182.937	12	32	5	0.002	195.493	-0.3504	-0.001311
24	182.937	12	32	5	0.006	195.487	-0.3480	-0.001395
25	183.737	12	32	5	0.002	196.322	-0.3522	-0.001283
26	183.737	12	32	5	0.009	196.305	-0.3409	-0.001578
27	184.503	12	32	5	0.001	197.089	-0.3541	-0.001226
28	184.503	12	32	5	0.007	197.030	-0.3460	-0.001440
29	184.887	20	32	13	0.001	197.475	-0.3531	-0.001259
30	184.973	12	32	5	0.002	197.594	-0.3558	-0.001207
31	185.213	12	32	5	0.006	197.787	-0.3449	-0.001497
32	185.219	20	32	7	0.002	197.742	-0.3466	-0.001396
33	185.587	12	32	5	0.001	198.221	-0.3549	-0.001246
34	198.37	12	32	5	0.001	211.302	-0.3710	-0.001037
35	198.37	12	32	5	0.002	211.304	-0.3700	-0.001063
36	198.637	20	32	7	0.003	211.481	-0.3597	-0.001300
37	198.674	12	32	5	0.005	211.597	-0.3640	-0.001242
38	199.265	12	32	5	0.001	212.186	-0.3706	-0.001036
39	199.265	12	32	5	0.004	212.188	-0.3653	-0.001206
40	199.445	12	32	5	0.007	212.387	-0.3613	-0.001344
41	199.81	12	32	5	0.003	212.776	-0.3671	-0.001189
42	199.835	20	32	13	0.001	212.811	-0.3710	-0.001076
43	200.596	12	32	5	0.001	213.570	-0.3720	-0.001046
44	200.596	12	32	5	0.005	213.486	-0.3646	-0.001237
45	215.811	20	32	13	0.002	229.144	-0.3853	-0.000976
46	215.997	12	32	5	0.002	229.347	-0.3860	-0.000974
47	216.498	12	32	5	0.001	229.858	-0.3887	-0.000900
48	216.498	12	32	5	0.002	229.873	-0.3892	-0.000886
49	216.64	12	32	5	0.018	229.955	-0.3671	-0.001521
50	216.764	12	32	5	0.003	230.133	-0.3854	-0.001011
51	216.988	20	32	7	0.003	230.295	-0.3803	-0.001107
52	217.021	12	32	5	0.005	230.388	-0.3820	-0.001115

53	217.027	20	32	13	0.001	230.419	-0.3883	-0.000940
54	218.564	12	32	5	0.002	231.975	-0.3913	-0.000869
55	218.564	12	32	5	0.005	231.911	-0.3889	-0.000937
56	219.019	12	32	5	0.001	232.439	-0.3910	-0.000886
57	219.019	12	32	5	0.002	232.397	-0.3894	-0.000932
58	231.352	12	32	5	0.001	245.073	-0.4025	-0.000823
59	236.401	20	32	7	0.002	250.176	-0.4001	-0.000946
60	236.438	12	32	5	0.038	250.226	-0.3579	-0.002256
61	236.463	12	32	5	0.002	250.300	-0.4027	-0.000928
62	236.518	20	32	13	0.001	250.379	-0.4101	-0.000721
63	236.861	12	32	5	0.003	250.711	-0.4096	-0.000726
64	236.861	12	32	5	0.002	250.739	-0.4089	-0.000746
65	237.076	12	32	5	0.004	250.904	-0.4085	-0.000742
66	237.076	12	32	5	0.002	250.915	-0.4085	-0.000746
67	237.526	20	32	13	0.001	251.402	-0.4086	-0.000783
68	237.553	12	32	5	0.000	251.412	-0.4069	-0.000818
69	237.553	12	32	5	0.001	251.451	-0.4065	-0.000820

Table A-6. Dilluted and undiluted samples of west Aral water used for density scanning

Date	Name	Depth [m]	Salinity	Dillution	Salinity	Sigma-32
			CTD [g/kg]		Calc [g/kg]	
15-Apr-06	3-Ar	8	97	0	97.00	66.41
15-Apr-06	3-Ar	8		1	88.95	60.32
15-Apr-06	3-Ar	8		2	82.02	55.17
15-Apr-06	3-Ar	8		3	76.25	50.86
15-Apr-06	3-Ar	8		4	71.09	46.99
15-Apr-06	3-Ar	8		5	66.55	43.84
15-Nov-07	21-Ar	30	127	0	127.00	83.95
15-Nov-07	21-Ar	30		1	116.30	75.71
15-Nov-07	21-Ar	30		2	107.06	70.66
15-Nov-07	21-Ar	30		3	98.97	64.10
15-Nov-07	21-Ar	30		4	92.65	60.10
15-Nov-07	21-Ar	30		5	86.44	55.54
15-Nov-07	4-Ar	8	117	0	117.00	75.25
15-Nov-07	4-Ar	8		1	107.05	68.23
15-Nov-07	4-Ar	8		2	98.74	62.57
15-Nov-07	4-Ar	8		3	91.60	57.62

Date	Name	Depth [m]	Salinity	Dillution	Salinity	Sigma-32
			CTD [g/kg]		Calc [g/kg]	
15-Nov-07	4-Ar	8		4	85.40	53.08
15-Nov-07	4-Ar	8		5	80.08	49.63
15-Nov-07	5-Ar	37	127	0	127.00	79.68
15-Nov-07	5-Ar	37		1	116.47	72.58
15-Nov-07	5-Ar	37		2	107.44	66.54
15-Nov-07	5-Ar	37		3	99.43	61.02
15-Nov-07	5-Ar	37		4	92.83	56.64
15-Nov-07	5-Ar	37		5	87.24	52.88
03-Jun-08	A0805-Ar	35	112	0	112.00	73.22
03-Jun-08	A0805-Ar	35		1	102.49	66.77
03-Jun-08	A0805-Ar	35		2	94.18	61.05
03-Jun-08	A0805-Ar	35		3	87.58	56.11
03-Jun-08	A0805-Ar	35		4	80.86	51.34
03-Jun-08	A0805-Ar	35		5	75.84	47.77

Table A-7. Approximation of 60 density scans of west Aral Sea water diluted and undiluted samples by the equation $\sigma_T = A_0 + A_1 * T + A_2 * T^2$.

NN	Scan	σ_{32}	Min T	Max T	N_Point	RMS	A0	A1	A2
1	1	66.41	4	32	17	0.011	76.302	-0.2113	-0.003057
2	2	60.32	4	32	17	0.012	69.909	-0.1994	-0.003143
3	3	55.17	4	32	17	0.009	64.382	-0.1799	-0.003387
4	4	50.86	4	32	17	0.009	59.857	-0.1698	-0.003484
5	5	46.99	4	32	17	0.011	55.785	-0.1612	-0.003553
6	6	43.84	4	32	17	0.015	52.101	-0.1296	-0.004027
7	7	66.48	2	32	7	0.009	76.292	-0.2027	-0.003256
8	8	60.34	2	32	7	0.007	69.858	-0.1852	-0.003508
9	9	55.32	2	32	7	0.010	64.529	-0.1742	-0.003556
10	10	51.00	2	32	7	0.004	60.029	-0.1690	-0.003533
11	11	47.51	2	32	7	0.014	56.249	-0.1527	-0.003770
12	12	44.29	2	32	7	0.017	52.825	-0.1455	-0.003804
13	13	75.25	2	32	18	0.034	85.315	-0.2088	-0.003334
14	14	68.23	20	32	13	0.001	78.290	-0.2219	-0.002889
15	15	62.57	2	32	18	0.029	71.811	-0.1710	-0.003669
16	16	57.62	2	32	18	0.024	66.625	-0.1610	-0.003756
17	17	53.08	20	32	7	0.000	62.331	-0.1856	-0.003235
18	18	49.63	2	32	12	0.042	58.057	-0.1341	-0.004020

19	19	75.85	2	32	7	0.006	86.194	-0.2229	-0.003134
20	20	68.84	2	32	7	0.007	78.802	-0.2074	-0.003250
21	21	62.99	2	32	7	0.012	72.618	-0.1954	-0.003305
22	22	58.09	2	32	7	0.010	67.471	-0.1814	-0.003495
23	23	53.55	2	32	7	0.016	62.642	-0.1709	-0.003551
24	24	49.77	2	32	7	0.009	58.701	-0.1582	-0.003779
25	25	79.68	20	32	7	0.005	90.147	-0.2304	-0.003012
26	26	72.58	20	32	7	0.003	82.753	-0.2207	-0.003039
27	27	66.54	20	32	7	0.003	76.414	-0.2083	-0.003134
28	28	61.02	20	32	7	0.005	70.565	-0.1907	-0.003354
29	29	56.64	20	32	7	0.002	66.199	-0.2036	-0.002973
30	30	52.88	20	32	7	0.002	62.073	-0.1796	-0.003366
31	31	80.23	2	32	7	0.009	90.763	-0.2357	-0.002928
32	32	72.49	2	32	7	0.008	82.640	-0.2149	-0.003204
33	33	66.18	2	32	7	0.033	76.158	-0.1910	-0.003740
34	34	60.92	2	32	7	0.010	70.448	-0.1893	-0.003399
35	35	56.41	2	32	7	0.009	65.704	-0.1758	-0.003589
36	36	53.22	2	32	7	0.009	62.344	-0.1681	-0.003657
37	37	83.96	20	32	13	0.001	94.793	-0.2558	-0.002589
38	38	75.71	20	32	13	0.003	86.161	-0.2383	-0.002749
39	39	70.65	20	32	13	0.001	80.883	-0.2308	-0.002777
40	40	64.10	20	32	13	0.001	73.949	-0.2118	-0.003001
41	41	60.10	20	32	13	0.001	69.770	-0.2049	-0.003036
42	42	55.54	20	32	13	0.001	64.967	-0.1948	-0.003120
43	49	73.22	2	32	7	0.007	83.404	-0.2177	-0.003146
44	50	66.77	2	32	7	0.010	76.598	-0.2049	-0.003202
45	51	61.05	2	32	7	0.008	70.577	-0.1874	-0.003450
46	52	56.11	2	32	7	0.013	65.353	-0.1780	-0.003476
47	53	51.34	2	32	7	0.015	60.297	-0.1652	-0.003600
48	54	47.77	2	32	7	0.015	56.530	-0.1558	-0.003696
49	61	73.23	2	32	7	0.011	83.396	-0.2189	-0.003093
50	62	66.78	2	32	7	0.010	76.603	-0.2037	-0.003230
51	63	61.07	2	32	7	0.012	70.579	-0.1908	-0.003337
52	64	56.10	2	32	7	0.014	65.326	-0.1775	-0.003474
53	65	51.33	2	32	7	0.013	60.293	-0.1631	-0.003665
54	66	47.75	2	32	7	0.016	56.501	-0.1553	-0.003705
55	67	84.74	2	32	7	0.006	95.526	-0.2425	-0.002953
56	68	75.90	2	32	7	0.005	86.252	-0.2241	-0.003102
57	69	70.39	2	32	7	0.009	80.433	-0.2138	-0.003137
58	70	63.83	2	32	7	0.008	73.535	-0.1964	-0.003342
59	71	59.89	2	32	7	0.013	69.347	-0.1876	-0.003385
60	72	55.68	2	32	7	0.035	65.091	-0.1635	-0.004042

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