Oceanologia, 68 (4)/2026, 68405
Polish Academy of Sciences
Institute of Oceanology
Open access article under the CC BY license
https://doi.org/10.5697/TPLX2348

Density-formulation-based estimates of TEOS-10 Absolute Salinity and Salinity Anomaly in Southern Caspian Sea waters

Fatemeh Elmi*, Milad Ghods Qazvini

Abstract
The applicability of TEOS-10 to marginal and enclosed seas with chemically non-standard waters has not been extensively evaluated. In this study, available experimental density data for Caspian Sea water were used to develop a refined regional density–salinity–temperature formulation. Because direct density measurements were unavailable for the present samples, their densities were calculated using the refined formulation. These density estimates, together with new conductivity-based salinity observations from the southern Caspian Sea, were used to invert the TEOS-10 equation of state and estimate Absolute Salinity (S_A), Reference Salinity (S_R), and Salinity Anomaly (δS_A). The resulting S_A values ranged from 14.70 to 15.24 g kg^{-1}, whereas S_R derived from Practical Salinity (S_P) was lower, yielding positive δS_A values of 2.35–2.93 g kg^{-1}. The anomaly was effectively invariant over 5–20°C but varied among stations, indicating that conductivity-derived S_P alone does not fully represent the density-equivalent salinity of southern Caspian Sea water. The positive anomalies are consistent with the non-oceanic ionic composition of the Caspian Sea, although their magnitude may partly reflect uncertainty in the regional density formulation, particularly its extrapolation beyond the salinity range of the historical density dataset. These results show that TEOS-10 can be used to identify composition-related differences between enclosed-basin waters and Reference Composition seawater.

Keywords
Caspian Sea; Density equation; Absolute salinity; Salinity anomaly; TEOS-10; Practical salinity

Department of Marine Chemistry, Faculty of Marine & Environmental Sciences, University of Mazandaran, Babolsar, Iran
***Correspondence**: f.elmi@umz.ac.ir (F. Elmi)

Received: 3 May 2026; **revised:** 22 September 2026; **accepted**: 26 October 2026

1. Introduction

The thermodynamic description of natural waters depends on the relationship between salinity, temperature and density. Since the adoption of the Practical Salinity Scale 1978 (PSS-78) and the International Equation of State of Seawater 1980 (EOS-80), Practical Salinity (S_P) has been widely used as an operational salinity variable derived from conductivity measurements (UNESCO, 1981; UNESCO, ICES and IAPSO, 1981). This approach is robust for waters close to the composition of standard seawater, but it does not explicitly account for regional variations in dissolved constituents. As a result, conductivity-based salinity may be insufficient for evaluating density and thermodynamic properties in chemically non-standard basins, particularly in enclosed or marginal water bodies.

TEOS-10 introduced Absolute Salinity (S_A) as the salinity variable required for thermodynamic calculations, together with Reference Salinity (S_R) and Salinity Anomaly (δS_A) as a way to quantify departures from Reference Composition seawater (IOC, SCOR and IAPSO, 2010; McDougall and Barker, 2011). In the open ocean, the difference between S_A and S_R is commonly small. In marginal or enclosed seas, however, compositional anomalies can be large enough to affect density, stratification estimates and other derived thermodynamic properties (Feistel et al., 2010a; Pawlowicz, 2010).

Although TEOS-10 has become the international standard for describing the thermodynamic properties of seawater, its application to waters with non-standard chemical composition remains an active area of research. Early studies in the Baltic Sea demonstrated that deviations from Reference Composition seawater produce measurable changes in density and other thermodynamic properties, making composition-dependent corrections necessary for accurate TEOS-10 applications (Feistel et al., 2010a). Subsequent laboratory and field investigations showed that these compositional effects can be quantified

© 2026 The Author(s). This is the Open Access article distributed under the terms of the Creative Commons Attribution Licence.

from direct density measurements, allowing empirical relationships between Practical Salinity and Absolute Salinity to be established for regionally distinct waters such as the Baltic Sea (Feistel et al., 2010b). The applicability of TEOS-10 was later extended to inland and chemically non-standard waters by introducing composition-dependent salinity definitions appropriate for natural aquatic systems (Pawlowicz and Feistel, 2012). Subsequent investigations also highlighted potential uncertainties associated with density-based thermodynamic calculations (Budéus, 2018) and demonstrated that salinity–density anomalies are not restricted to enclosed basins but may also occur in open-ocean environments (Weinreben and Feistel, 2019). More recently, studies in the Chinese shelf and semi-enclosed seas showed that regional geochemical processes and terrestrial inputs can significantly modify Absolute Salinity and its anomaly, emphasizing that the applicability of TEOS-10 should be evaluated on a basin-specific basis rather than assumed from standard seawater relationships (Ji et al., 2021, 2024). Despite the distinctive hydrochemical characteristics of the Caspian Sea, no study has yet systematically evaluated density-equivalent Absolute Salinity and Salinity Anomaly within the TEOS-10 framework for this basin.

The Caspian Sea is an important example of such a system. Although it is often discussed in oceanographic terms because of its size and stratified water column, it is an enclosed basin with a chemical composition that differs markedly from standard seawater. Previous work has shown that Caspian Sea water contains relatively high contributions from divalent ions such as Ca^{2+}, Mg^{2+} and SO_4^{2-}, and that its density differs from that expected for diluted oceanic seawater at comparable S_P (Millero and Chetirkin, 1980; Millero et al., 2008; Tuzhilkin et al., 2005). These characteristics make the Caspian Sea a useful natural case for testing how TEOS-10 concepts perform outside the open-ocean Reference Composition.

A practical obstacle is that high-quality density and composition data for the Caspian Sea remain limited. Millero et al. (2008) provided an empirical equation of state based on laboratory density measurements of Caspian Sea water, but its residual behavior has not been reassessed for the specific purpose of TEOS-10 density inversion. This issue is important because any systematic density bias propagates directly into the derived S_A and hence into the estimated δS_A.

The aim of the present study is therefore to reassess the available Caspian Sea density formulation and to use the refined relationship to estimate S_A, S_R and δS_A for southern Caspian Sea samples. The emphasis is not on a simple conversion from S_P to S_A but on evaluating whether the resulting salinity anomaly provides physically meaningful information about the non-standard composition of Caspian Sea water. By combining new conductivity-based observations with a reassessed experimental density dataset, this study provides a regional TEOS-10-based evaluation of density-equivalent salinity behavior in the southern Caspian Sea.

2. Methods

2.1 Water sampling

Water samples were collected on August 20, 2017, from both the surface and a depth of 10 m at four different sites located approximately 5 km off the southern coast of the Caspian Sea, as listed in Table 1, using a 1 L Hydro-Bios plastic water sampler. Samples were filtered through 0.45 μm sterile syringe filters (FilterBio®), transferred into sealed 50 mL plastic Falcon tubes, and transported on ice to the laboratory for further analysis. The locations of the sampling sites are shown in Figure 1.

Table 1. Geographic coordinates of the sampling sites in the southern Caspian Sea.

Sample	Assigned number	Latitude (ϕ)	Longitude (λ)
Amirabad	1	36°52′50″N	53°17′21″E
Babolsar	2	36°45′12″N	52°40′01″E
Nowshahr	3	36°40′28″N	51°32′23″E
Ramsar	4	36°57′21″N	50°42′23″E

2.2 Measurement of electrical conductivity

The electrical conductivity of the filtered samples was measured at 15°C using an AZ Instrument model 86505 benchtop multimeter (Taiwan). The conductivity accuracy is ±1% of full scale ±1 digit, with a resolution of 0.05% of full scale, while the temperature accuracy is ±0.5°C with a resolution of 0.1°C. The measured conductivity values were converted to Practical Salinity (S_P) following PSS-78 (UNESCO, 1981; UNESCO, ICES and IAPSO, 1981), using the notation adopted in TEOS-10. Density values required for the TEOS-10 inversion were not measured directly for the present samples; instead, they were calculated using the reassessed Caspian Sea-specific density formulation based on the published experimental density dataset of Millero et al. (2008).

2.3 Reassessment of the Caspian Sea equation of state

Millero et al. (2008) provided an empirical density formulation for Caspian Sea water as a function of S_P and temperature (Eqs. (1)–(5)).

$$(\rho - \rho^0)\ \mathrm{kg/m^3} = \mathrm{A} + \mathrm{B}S_P + \mathrm{C}S_P^2 \tag{1}$$

$$\begin{aligned}\rho^0 = {} & 999.83952 + 16.952577(\mathrm{T} - 273.15) - \\ & 7.9905127\mathrm{E}-03(\mathrm{T}-273.15)^2 - \\ & 4.6241757\mathrm{E}-05(\mathrm{T}-273.15)^3 + \\ & 1.0584601\mathrm{E}-07(T-273.15)^4 - \\ & (2.8103006\mathrm{E}-10(\mathrm{T}-273.15)^5) \div \\ & [1 + 0.016887236(T-273.15)]\end{aligned} \tag{2}$$

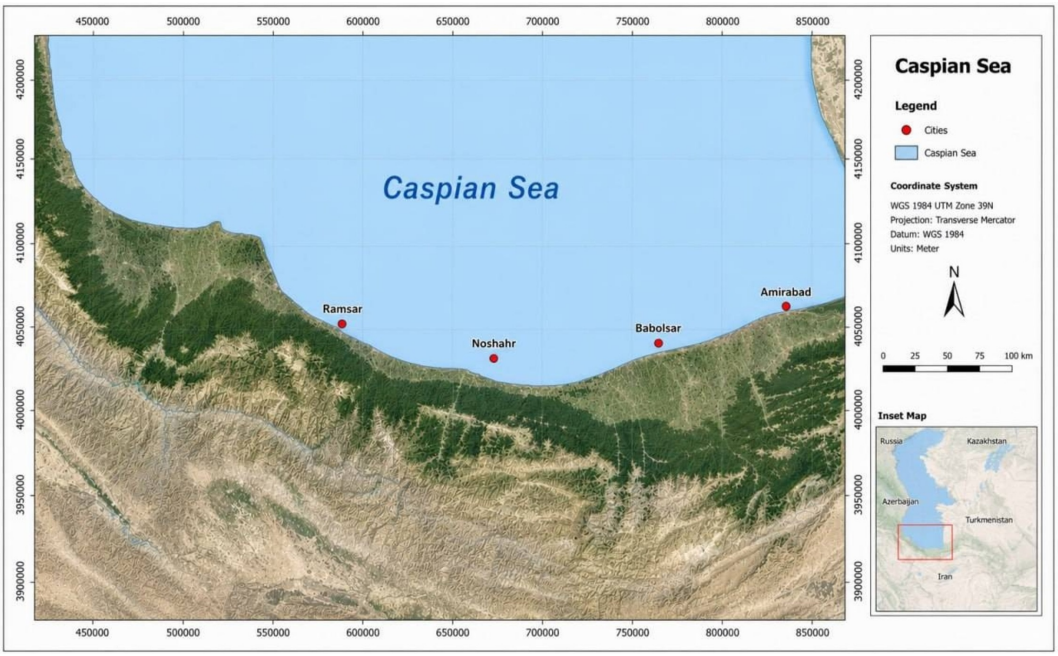


Figure 1. Geographic map showing the sampling locations along the southern coast of the Caspian Sea.

$$A = 0.0350 - 1.73E-03(T - 273.15) + 5.2E-05(T - 273.15)^2 - 4.947E-07(T - 273.15)^3 \quad (3)$$

$$B = 0.9877 - 3.66E-03(T - 273.15) + 4.903E-05(T - 273.15)^2 - 2.276E-07(T - 273.15)^3 \quad (4)$$

$$C = -1.25E-04 \quad (5)$$

These equations incorporate coefficients A, B and C to represent the dependence of density on S_P and temperature. In the present study, the published experimental density data of Millero et al. (2008) were re-examined before being used as the basis for TEOS-10 density inversion.

The densities calculated using the published formulation were compared with the published experimental density values reported by Millero et al. (2008) to assess whether systematic differences were present before the data were used for S_A estimation.

For the derivation of the refined formulation, data from samples 3–9 and measurements at temperatures up to approximately 40°C were retained. Samples 1 and 2 were excluded because they showed the largest deviations from the behavior of the remaining dataset, while measurements above approximately 40°C were excluded to limit potential compositional changes associated with elevated-temperature conditions. The retained data were fitted in MATLAB using a polynomial relationship between density, S_P, and temperature. Density was expressed in kg m^{-3}, temperature in °C, and S_P was treated as dimensionless. The retained dataset covers S_P values of approximately 7.81–11.38 and temperatures of approximately 5–40°C. Fit performance was assessed from the residuals between fitted and published experimental densities. Because the same dataset was used for fitting and residual assessment, this represents an in-sample goodness-of-fit assessment rather than independent validation. The resulting refined polynomial is presented in Section 3.2 as Eq. (8).

The present samples have S_P values of 11.88–12.81, above the upper S_P limit of the fitted dataset. Application of the refined formulation to these samples therefore involves extrapolation with respect to S_P, whereas the investigated temperature range of 5–20°C remains within the fitted temperature range. Because direct density measurements are not available for the present samples in this higher S_P range, the additional uncertainty associated specifically with this extrapolation cannot be independently quantified from the fit residuals alone. The refined formulation is therefore used as a practical regional density representation rather than as a universal equation of state for the entire Caspian Sea.

2.4 Absolute Salinity and Salinity Anomaly calculations

S_A was calculated from the refined density values using the TEOS-10 function gsw_SA_from_rho_t_exact (IOC, SCOR and IAPSO, 2010; McDougall and Barker, 2011), with density, temperature and pressure as inputs. This inversion gives the S_A that a Reference Composition seawater sample

would require to reproduce the same density at the specified temperature and pressure. In this study, S_A is therefore interpreted as a density-equivalent thermodynamic salinity rather than as a direct chemical mass determination. S_R was calculated from S_P using the TEOS-10 scaling relation:

$$S_R = S_P \times \frac{35.16504}{35} \tag{6}$$

Salinity Anomaly was then computed as:

$$\delta S_A = S_A - S_R \tag{7}$$

For each sample, S_A was evaluated over 5–20°C to examine its variation across the investigated temperature range.

3. Results

3.1 Practical Salinity of southern Caspian Sea samples

The electrical conductivity measurements and resulting S_P values are summarized in Table 2. The S_P values of the southern Caspian Sea samples range from 11.88 to 12.81. The small differences between the surface and 10 m samples indicate limited upper-water-column variability at the time and locations sampled.

Table 2. EC and S_P of southern Caspian Seawater samples.

Sample	Depth (m)	EC at 15°C (mS/cm)	S_P
Amirabad (A-1)	1	16.22	12.01
Amirabad (A-10)	10	16.06	11.88
Babolsar (B-1)	1	16.39	12.14
Babolsar (B-10)	10	16.52	12.24
Noshahr (N-1	1	16.33	12.01
Noshahr (N-10)	10	16.56	12.81
Ramsar (R-1)	1	16.39	12.14
Ramsar (R-10)	10	16.52	12.25

3.2 Density residuals and refined density representation

The comparison between the measured densities reported by Millero et al. (2008) and the densities calculated from the available formulation is summarized in Table 3. The calculated-minus-measured density differences range from 0.12 to 0.52 kg m^{-3} and remain positive throughout the dataset. This one-sided residual pattern indicates that the differences are not distributed randomly around zero. The refined polynomial fit (Eq. (8)) shows closer agreement with the reported density data, yielding a standard error of 0.02162, an RMS error of 0.03466, and $R^2 = 0.9998$. These fit metrics show how closely Eq. (8) fits the historical dataset used to derive it. They should therefore be viewed as measures of in-sample fit, not as independent validation or as estimates of measurement uncertainty.

$$\begin{aligned}\rho = {} & 1002.33 + (0.4926 \times S_P) - \\ & (0.1087 \times t) + (0.02471 \times S_P^2) + \\ & (0.0285 \times S_P \times t) - (0.006773 \times t^2) - \\ & (0.001525 \times S_P^2 \times t) - \\ & (5.508 \times 10^{-5} \times S_P \times t^2) + \\ & (3.872 \times 10^{-5} \times t^3)\end{aligned} \tag{8}$$

Using Equation (8), densities for the southern Caspian Sea samples were calculated over the temperature range of 5–20°C. As noted in Section 2.3, these calculations involve extrapolation with respect to S_P, because the S_P values of the present samples exceed the upper limit of the fitted dataset. The corresponding S_A values are presented in Table 4. Residuals between densities calculated from the refined polynomial and the published experimental densities of Millero et al. (2008) are shown in Figure 2.

The TEOS-10 inversion yielded S_A values of 14.70–15.24 g kg^{-1} for the southern Caspian Sea samples over the investigated temperature range. In all samples, S_R calculated from S_P was lower than the corresponding S_A. The temperature-averaged δS_A values were consistently positive and ranged from 2.35 to 2.93 g kg^{-1} (Table 5). The variation in δS_A over 5–20°C was very small, with within-sample standard deviations of 0.0075–0.0203 g kg^{-1}. Accordingly, δS_A was considered effectively invariant with temperature over the investigated interval, and these small numerical differences were not interpreted as a temperature-dependent change in water composition. Differences among samples were nevertheless evident. For example, the Nowshahr 10 m sample had the highest S_P but the lowest mean δS_A, indicating that the magnitude of the anomaly is not determined by S_P alone. Because S_P is derived from electrical conductivity, dissolved constituents that contribute to density but have little or no influence on conductivity may not be fully represented by S_P. In waters with non-standard composition, such as the Caspian Sea, this can contribute to a difference between conductivity-derived S_P and density-equivalent S_A. The positive δS_A values observed here are therefore interpreted primarily as a density-equivalent indication of compositional differences rather than as a temperature effect.

To assess the influence of the residual error of the refined density formulation on the derived S_A, a first-order sensitivity analysis was performed using Eq. (9):

$$\Delta S_A \approx \left| \frac{\partial S_A}{\partial \rho} \right| \Delta\rho \tag{9}$$

where $\left|\frac{\partial S_A}{\partial \rho}\right|$ represents the sensitivity of S_A to density and $\Delta\rho$ is taken as RMS residual of the refined density fit. From the density S_A relationship represented by the data in Table 4, $\frac{\partial S_A}{\partial \rho}$ was approximately 1.30 (g kg^{-1})/(kg m^{-3}).

Table 3. Comparison of measured densities reported by Millero et al. (2008) with densities calculated in this study using EOS of Caspian Seawater.

Sample	Practical Salinity (S_P)	Temperature (K)	Measured Density (kg m^{-3})	Calculated Density from Eq. (1)	Difference (kg m^{-3})
1	11.274	278.2	1010.76	1011.23	0.47
1	11.274	288.2	1009.70	1010.04	0.34
1	11.274	298.2	1007.32	1007.754	0.43
1	11.274	298.2	1007.50	1007.754	0.25
1	11.274	313.1	1002.40	1002.753	0.35
1	11.274	323.2	998.03	998.4567	0.43
1	11.274	333.1	993.20	993.6226	0.42
1	11.274	338.2	990.55	990.9077	0.36
2	11.304	279.1	1011.00	1011.205	0.21
2	11.304	283.2	1010.62	1010.819	0.20
2	11.304	293.2	1008.90	1009.047	0.15
2	11.304	298.2	1007.66	1007.782	0.12
2	11.304	313.2	1002.60	1002.741	0.14
2	11.304	323.2	998.26	998.4835	0.22
2	11.304	333.2	993.30	993.5976	0.30
2	11.304	343.2	987.83	988.1306	0.30
3	11.262	278.2	1010.90	1011.219	0.32
3	11.262	288.1	1009.70	1010.047	0.35
3	11.262	298.1	1007.51	1007.771	0.26
3	11.262	313.2	1002.40	1002.703	0.30
3	11.262	323.2	998.16	998.4459	0.29
3	11.262	328.2	995.80	996.0782	0.28
3	11.262	343.2	987.70	988.0932	0.39
4	7.8124	278.2	1007.60	1007.879	0.28
4	7.8124	278.2	1007.62	1007.879	0.26
4	7.8124	288.1	1006.50	1006.802	0.30
4	7.8124	288.2	1006.53	1006.785	0.25
4	7.8124	298.1	1004.30	1004.594	0.29
4	7.8124	303.2	1002.87	1003.109	0.24
4	7.8124	313.2	999.41	999.5888	0.18
4	7.8124	323.2	995.11	995.3536	0.24
4	7.8124	328.2	992.70	992.9927	0.29
4	7.8124	343.1	984.81	985.076	0.27
5	11.326	278.2	1011.01	1011.281	0.27
5	11.326	288.1	1009.80	1010.107	0.31
5	11.326	298.1	1007.49	1007.83	0.34
5	11.326	313.1	1002.50	1002.8	0.30
5	11.326	323.2	998.19	998.5033	0.31
5	11.326	328.2	995.81	996.1354	0.33
5	11.326	333.2	993.29	993.6172	0.33
5	11.326	343.2	987.90	988.1502	0.25
6	11.3821	278.16	1011.00	1011.337	0.34
6	11.3821	288.15	1009.91	1010.151	0.24
6	11.3821	298.15	1007.60	1007.868	0.27
6	11.3821	313.16	1002.50	1002.827	0.33
6	11.3821	323.15	998.19	998.5764	0.39
6	11.3821	328.15	995.80	996.21	0.41
6	11.3821	333.15	993.26	993.6932	0.43
6	11.3821	343.16	987.70	988.2231	0.52
7	11.0466	278.15	1010.69	1011.013	0.32
7	11.0466	278.16	1010.70	1011.012	0.31
7	11.0466	288.13	1009.60	1009.839	0.24
7	11.0466	298.13	1007.30	1007.564	0.26
7	11.0466	298.15	1007.25	1007.559	0.31
7	11.0466	313.16	1002.20	1002.524	0.32
7	11.0466	323.15	997.95	998.2758	0.33
7	11.0466	333.13	993.10	993.4041	0.30
7	11.0466	343.15	987.60	987.93	0.33
8	11.3036	278.05	1011.00	1011.267	0.27
8	11.3036	288.15	1009.80	1010.077	0.28
8	11.3036	298.15	1007.50	1007.795	0.30

Table 3. *Continued.*

Sample	Practical Salinity (S_P)	Temperature (K)	Measured Density (kg m^{-3})	Calculated Density from Eq. (1)	Difference (kg m^{-3})
8	11.3036	308.15	1004.30	1004.63	0.33
8	11.3036	323.14	998.15	998.5107	0.36
8	11.3036	333.15	993.30	993.6231	0.32
8	11.3036	343.14	987.92	988.1647	0.24
9	11.2961	278.16	1011.00	1011.254	0.25
9	11.2961	288.16	1009.80	1010.068	0.27
9	11.2961	298.13	1007.50	1007.794	0.29
9	11.2961	313.15	1002.50	1002.753	0.25
9	11.2961	323.15	998.21	998.4994	0.29
9	11.2961	333.14	993.30	993.6216	0.32
9	11.2961	343.15	987.80	988.1523	0.35

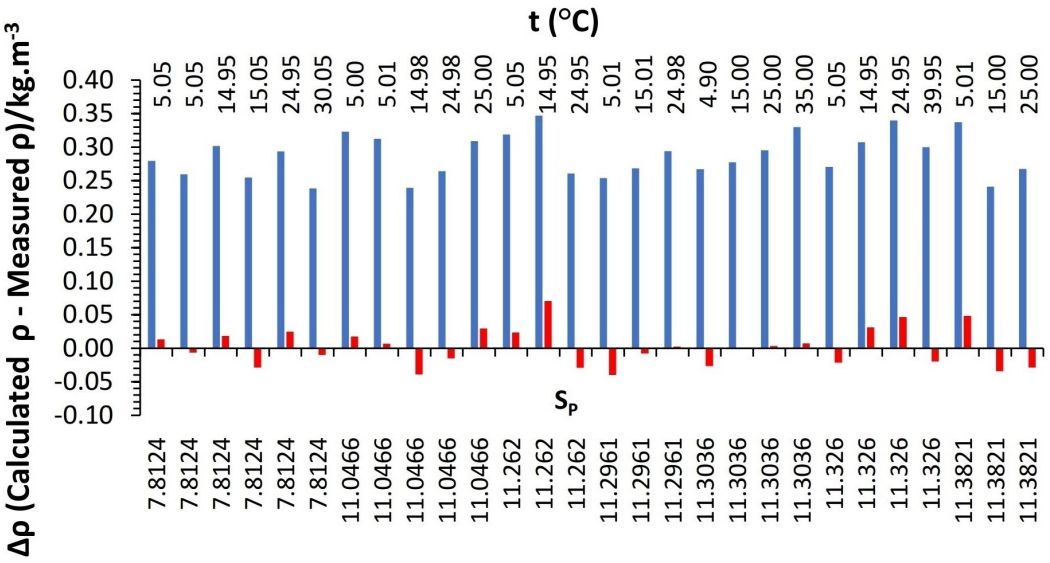


Figure 2. Residual comparison between measured densities reported by Millero et al. (2008) and densities calculated using the original formulation (Eq. (1)) and the refined polynomial representation (Eq. (8)) over the available salinity-temperature range.

Using the RMS residual of 0.03466 kg m^{-3}, $\Delta S_A \approx 1.30 \times 0.03466 = 0.045$ g kg^{-1}. This value represents a first-order estimate of the sensitivity of S_A to the residual error of the density formulation, rather than a complete propagated uncertainty budget. Additional uncertainty may arise from spatial and temporal variations in the chemical composition of Caspian Sea water. This contribution could not be quantified independently because contemporary direct density measurements were not available.

4. Discussion

4.1 Significance of the refined density representation

The consistently positive residuals between calculated and published experimental densities indicate that the available density formulation required reassessment before being used for the TEOS-10 inversion. The improved agreement obtained with the refined polynomial representation is important because density values are subsequently used as input for estimating S_A. Any systematic density bias would propagate into the derived S_A and therefore into δS_A. The residual pattern may reflect the combined effects of published coefficient values, the fitting procedure, rounding or transcription effects, or limitations associated with the original dilution-based dataset. Therefore, the refined formulation should be interpreted as a practical regional representation derived from the available historical density data, rather than as a universal equation of state for the entire Caspian Sea. Because the present samples extend beyond the upper S_P limit of the historical density dataset, application of Eq. (8) involves extrapolation and introduces additional uncertainty that is not fully represented by the fit residuals.

4.2 Interpretation of positive Salinity Anomalies

The positive δS_A values indicate that, at the same S_P, southern Caspian Sea water has a higher density-equivalent salinity than Reference Composition seawater. This result

Table 4. Densities of southern Caspian Sea samples calculated from Eq. (8) at different temperatures and the corresponding density-equivalent S_A.

Sample	t (°C)	Calculated density (g kg^{-1})	S_A
A-1	5	1011.70	14.87
A-1	7.5	1011.51	14.88
A-1	10	1011.24	14.89
A-1	12.5	1010.89	14.88
A-1	15	1010.47	14.88
A-1	17.5	1009.98	14.88
A-1	20	1009.42	14.86
A-10	5	1011.56	14.70
A-10	7.5	1011.38	14.71
A-10	10	1011.11	14.72
A-10	12.5	1010.77	14.73
A-10	15	1010.35	14.73
A-10	17.5	1009.86	14.72
A-10	20	1009.30	14.70
B-1	5	1011.84	15.05
B-1	7.5	1011.65	15.06
B-1	10	1011.38	15.07
B-1	12.5	1011.03	15.07
B-1	15	1010.60	15.05
B-1	17.5	1010.10	15.04
B-1	20	1009.54	15.02
B-10	5	1011.94	15.18
B-10	7.5	1011.75	15.19
B-10	10	1011.48	15.20
B-10	12.5	1011.12	15.18
B-10	15	1010.70	15.18
B-10	17.5	1010.20	15.17
B-10	20	1009.63	15.14
N-1	5	1011.79	14.99
N-1	7.5	1011.60	15.00
N-1	10	1011.33	15.00
N-1	12.5	1010.98	15.00
N-1	15	1010.56	15.00
N-1	17.5	1010.06	14.98
N-1	20	1009.50	14.97
N-10	5	1011.98	15.23
N-10	7.5	1011.79	15.24
N-10	10	1011.51	15.24
N-10	12.5	1011.16	15.24
N-10	15	1010.73	15.21
N-10	17.5	1010.23	15.21
N-10	20	1009.66	15.18
R-1	5	1011.84	15.05
R-1	7.5	1011.65	15.06
R-1	10	1011.38	15.07
R-1	12.5	1011.03	15.07
R-1	15	1010.60	15.05
R-1	17.5	1010.10	15.04
R-1	20	1009.54	15.02
R-10	5	1011.95	15.19
R-10	7.5	1011.76	15.20
R-10	10	1011.49	15.21
R-10	12.5	1011.13	15.20
R-10	15	1010.70	15.18
R-10	17.5	1010.21	15.18
R-10	20	1009.64	15.15

is consistent with the known non-oceanic ionic composition of the Caspian Sea, particularly its relatively high contributions of calcium, magnesium and sulfate compared with NaCl dominated seawater (Millero and Chetirkin, 1980; Millero et al., 2008). This distinction is important because S_P is derived from electrical conductivity and S_R is calculated from S_P, whereas density-derived S_A reflects the density-equivalent effect of dissolved constituents within the TEOS-10 framework (IOC, SCOR and IAPSO, 2010; McDougall and Barker, 2011). Dissolved constituents that affect density but contribute little or no conductivity signal may therefore not be fully represented by S_P. In waters with non-standard composition, this can contribute to a difference between conductivity-derived S_P and density-equivalent S_A. Therefore, δS_A provides a diagnostic measure of the departure of Caspian Sea water from Reference Composition seawater and should primarily be interpreted in terms of compositional differences rather than temperature effects.

Table 5. Mean S_A, S_R, and δS_A calculated for southern Caspian Sea samples over the 5–20°C interval.

Sample	S_P	S_R (g kg^{-1})	Mean S_A (g kg^{-1})	Mean δS_A (g kg^{-1})	S_D δS_A (g kg^{-1})
A-1	12.01	12.07	14.88	2.81	0.008
A-10	11.88	11.94	14.71	2.78	0.011
B-1	12.14	12.20	15.05	2.85	0.016
B-10	12.24	12.30	15.18	2.88	0.017
N-1	12.01	12.07	14.99	2.93	0.012
N-10	12.81	12.87	15.22	2.35	0.020
R-1	12.14	12.20	15.05	2.85	0.016
R-10	12.25	12.31	15.19	2.88	0.017

4.3 Temperature invariance and station-to-station variability

The very small variation in δS_A over 5–20°C is negligible relative to the magnitude of the anomaly and, within the precision of the present analysis, δS_A can be considered effectively invariant with temperature over this interval. The small numerical differences were therefore not interpreted as temperature-driven changes in salinity or water composition. This distinction is important because electrical conductivity is strongly temperature dependent, whereas S_A and δS_A represent composition-related quantities.

However, the observed station-to-station variability shows that a single basin-wide correction based only on S_P would be premature. This is particularly important for the Caspian Sea, where river input, evaporation, mixing, and regional differences in ionic composition can modify the relationship between conductivity, density, and thermodynamic salinity. The Noshahr 10 m sample, which has the highest S_P but the lowest mean δS_A, further illustrates that conductivity-derived S_P alone does not fully characterize the density-equivalent salinity of Caspian Sea water.

4.4 Implications for regional TEOS-10 applications

The magnitude of δS_A obtained in this study has important implications for applying TEOS-10 to the Caspian Sea. In open-ocean waters, the correction from S_R to S_A is gener-

ally small, and global TEOS-10 algorithms are often adequate for most thermodynamic calculations. In contrast, the positive anomalies calculated for the southern Caspian Sea are large enough to affect density-equivalent salinity and may influence estimates of stratification and derived thermodynamic properties. Therefore, the use of S_R alone would underestimate the density-equivalent thermodynamic salinity of these waters.

The results suggest that TEOS-10 can be used not only as a salinity conversion tool but also as a diagnostic framework for evaluating composition-driven departures from standard seawater behavior in enclosed basins. However, because Eq. (8) is extrapolated beyond the upper S_P limit of the historical density dataset for the present samples, the associated uncertainty is not fully represented by the fit residuals. The resulting S_A and δS_A values should therefore be interpreted as extrapolated density-equivalent estimates rather than direct measurements. Future studies combining high-precision density measurements with complete major-ion composition would further refine δS_A estimates and improve assessment of their spatial, seasonal, and long-term variability in the Caspian Sea.

5. Conclusions

This study reassessed the density–salinity–temperature relationship available for Caspian Sea water and applied the TEOS-10 framework to estimate S_A, S_R, and δS_A for southern Caspian Sea samples. The refined polynomial representation provided a closer fit to the published experimental density data and was used as the density input for the TEOS-10 inversion. The resulting salinity anomalies were consistently large and positive, indicating that S_R derived from S_P does not adequately represent the density-equivalent salinity of southern Caspian Sea water. The very small variation in δS_A over 5–20°C indicates that the anomaly is effectively invariant with temperature within the precision of the present analysis. At the same time, the observed station-to-station variability indicates that the anomaly cannot be represented reliably by S_P alone. Although the magnitude of the estimated anomaly depends on the adopted regional density formulation and is subject to additional uncertainty from extrapolation beyond the historical S_P range, the systematic behavior of the derived anomalies suggests that TEOS-10 provides a useful diagnostic framework for identifying composition-related departures from Reference Composition seawater in the Caspian Sea. Future studies combining direct high-precision density measurements, conductivity observations, and comprehensive major-ion analyses will help test and refine these estimates and better constrain their spatial and temporal variability.

Acknowledgements

This work was supported by the Department of Marine Chemistry, Faculty of Marine & Environmental Sciences, University of Mazandaran, Babolsar, Iran.

Conflict of interest

None declared.

References

Budéus, G., 2018. *Potential bias in TEOS10 density of sea water samples*. Deep Sea Res. Pt. I, 134, 41–47. https://doi.org/10.1016/j.dsr.2018.02.005

Feistel, R., Marion, G.M., Pawlowicz, R., Wright, D.G., 2010a. *Thermophysical property anomalies of Baltic seawater*. Ocean Sci. 6 (4), 949–981. https://doi.org/10.5194/os-6-949-2010

Feistel, R., Weinreben, S., Wolf, H., Seitz, S., Spitzer, P., Adel, B., Nausch, G., Schneider, B., Wright, D.G., 2010b. *Density and Absolute Salinity of the Baltic Sea 2006–2009*. Ocean Sci. 6 (1), 3–24. https://doi.org/10.5194/os-6-3-2010

IOC, SCOR, IAPSO, 2010. *The International Thermodynamic Equation of Seawater – 2010: Calculation and Use of Thermodynamic Properties*. Intergovernmental Oceanographic Commission, Manuals and Guides No. 56, UNESCO, Paris.

Ji, F., Pawlowicz, R., Xiong, X., 2021. *Estimating the Absolute Salinity of Chinese offshore waters using nutrients and inorganic carbon data*. Ocean Sci. 17 (4), 909–918. https://doi.org/10.5194/os-17-909-2021

Ji, F., Yang, J., Ding, F., Zheng, B., Ning, P., 2024. *The salinity anomalies due to nutrients and inorganic carbon in the Bohai Sea*. Front. Mar. Sci. 11, 1418860. https://doi.org/10.3389/fmars.2024.1418860

McDougall, T.J., Barker, P.M., 2011. *Getting Started with TEOS-10 and the Gibbs Seawater (GSW) Oceanographic Toolbox*. SCOR/IAPSO WG127.

Millero, F.J., Chetirkin, P.V., 1980. *The density of Caspian Sea waters*. Deep Sea Res. Pt. A, 27 (3–4), 265–271. https://doi.org/10.1016/0198-0149(80)90017-5

Millero, F.J., Mirzaliyev, A., Safarov, J., Huang, F., Chanson, M., Shahverdiyev, A., Hassel, E., 2008. *The equation of state for Caspian Sea waters*. Aquat. Geochem. 14 (4), 289–299. https://doi.org/10.1007/s10498-008-9037-0

Pawlowicz, R., 2010. *A model for predicting changes in the electrical conductivity, practical salinity, and absolute salinity of seawater due to variations in relative chemical composition*. Ocean Sci. 6 (1), 361–378. https://doi.org/10.5194/os-6-361-2010

Pawlowicz, R., Feistel, R., 2012. *Limnological applications of the Thermodynamic Equation of Seawater 2010 (TEOS-10)*. Limnol. Oceanogr. Methods, 10, 853–867. https://doi.org/10.4319/lom.2012.10.853

Tuzhilkin, V., Katunin, D., Nalbandov, Y., 2005. *Natural chemistry of Caspian Sea waters*. [In:] Kostianoy, A.G., Kosarev, A.N. (Eds.), *The Caspian Sea Environment*. Springer, Berlin, 83–108. https://doi.org/10.1007/698_5_005

UNESCO, 1981. *Background Papers and Supporting Data on the Practical Salinity Scale 1978*. UNESCO Technical Papers in Marine Science No. 37, UNESCO, Paris.

UNESCO, ICES, IAPSO, 1981. *Background Papers and Supporting Data on the International Equation of State of Seawater 1980*. UNESCO Technical Papers in Marine Science No. 38, UNESCO, Paris.

Weinreben, S., Feistel, R., 2019. *Anomalous salinity-density relations of seawater in the eastern central Atlantic*. Deep Sea Res. Pt. I, 154, 103160. https://doi.org/10.1016/j.dsr.2019.103160