



On the viscosity of natural hyper-saline solutions and its importance: The Dead Sea brines



Noam Weisbrod^{a,*}, Yoseph Yechieli^{a,b}, Semion Shandalov^a, Nadav Lensky^b

^aDepartment of Environmental Hydrology and Microbiology, Zuckerman Institute for Water Research, Blaustein Institutes for Desert Research, Ben-Gurion, University of the Negev, Midreshet Ben-Gurion, Israel

^bGeological Survey of Israel, Jerusalem, Israel

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SUMMARY

The relationship between the density, temperature and viscosity of hypersaline solutions, both natural and synthetic, is explored. An empirical equation of the density–viscosity relationship as a function of temperature was developed for the Dead Sea brine and its dilutions. The viscosity levels of the Dead Sea brine (density of $1.24 \cdot 10^3 \text{ kg/m}^3$; viscosity of 3.6 mPa s at 20 °C) and of the more extremely saline natural brine (density of $1.37 \cdot 10^3 \text{ kg/m}^3$) were found to be ~ 3 and ~ 10 times greater than that of fresh water, respectively. The combined effect of the above changes in viscosity and density on the hydraulic conductivity is reduction by a factor of 3–7. The chemical composition significantly affects the viscosity of brines with similar densities, whereby solutions with a higher Mg/Na ratio have higher viscosity. This explains the extremely high viscosity of the Dead Sea and related Mg-rich brines in comparison with the much lower values of NaCl and KCl brines with similar density. Possible impacts of the results include reduced settling velocity of grains in hypersaline viscous brines and changing hydraulic dynamics at the freshwater–saltwater and the vicinity of sinkholes.

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1. Introduction

Density and viscosity are very important fluid properties for understanding and quantifying flow and transport processes in aquatic systems. Typically, increasing the salt concentration in a solution causes increases in the density and viscosity. However, different salts affect viscosity in different ways (Isono, 1984). As of now, only a limited number of studies have explored these properties and relationships in natural solutions. Most studies have focused on synthetic solutions, usually of single component salt, such as NaCl or KCl (e.g., Kestin et al., 1981; Palliser and McKibbin, 1998). In the case of natural hypersaline brines, which are typically multi-component solutions, the correlation between the total dissolved salts (TDS) and viscosity is more complicated and rarely explored. The viscosity of aquatic solutions is strongly dependent on temperature, less dependent on salinity, and almost negligibly dependent on pressure (e.g., Adams and Bachu, 2002; Qiblawey and Abu-Jdayil, 2010). Most studies where solution

viscosity is considered are in geothermal fluids, petroleum systems (e.g., Ward and Martin, 1981). In most natural aquatic environments, the salinity is relatively low, and therefore, changes in viscosity are minor and typically considered to be constant. However, in hypersaline environments, this simplification is not justified since viscosity and density vary significantly and are thus expected to be important factors controlling groundwater flow. In shallow subsurface water bodies, the role of pressure changes on viscosity are typically insignificant and can thus be neglected. However, the salt concentration and composition may play a major role in the viscosity of the solution. The accurate quantification of the viscosity and density of a solution is important for quantifying flow and transport processes as they dictate the relationship between the permeability and hydraulic conductivity of porous media for a given solution, as can be seen in Eq. (1):

$$K = k\rho g/\mu \quad (1)$$

where K is the hydraulic conductivity (m/s), k is the permeability (m^2), ρ is the density (kg/m^3), μ is the dynamic viscosity of the fluid (mPa s) and g is the acceleration due to gravity ($9.8 \text{ m}^2/\text{s}$).

In hypersaline lakes, the high viscosity and density result in the reduced settling velocity of suspended particles (Lensky et al., 2013). The slower settling may result in the increased turbidity and efficiency of sediment transport. In addition, viscosity controls

* Corresponding author at: Department of Environmental Hydrology & Microbiology, Zuckerman Institute for Water Research, Blaustein Institutes for Desert Research, Ben-Gurion University of the Negev, Midreshet Ben-Gurion, 84990, Israel. Tel.: +972 8 659 6903; fax: +972 8 6595901.

E-mail address: weisbrod@bgu.ac.il (N. Weisbrod).

the double-diffusive salt-fingering flux through thermo-haline layering in lakes and oceans (Stern, 1969; Howard and Veronis, 1992; Kunze, 2003). Therefore, quantifying transport processes in hypersaline environments requires measured values of viscosity in the typical range of concentration, composition and temperature.

Hypersaline water bodies are found in arid environments around the globe, ranging from continental terminal lakes to salinas, closed lagoons and sabkhas (Yecheili and Wood, 2002). These include, among many others, the Great Salt Lake in the United States, Lake Magadi in Kenya and Lake Eyre in Australia. One of the most saline large water bodies on Earth is the Dead Sea (DS; salinity of $\sim 340 \text{ kg/m}^3$), including the saline groundwater in its vicinity (Gavrieli et al., 2001). The rapid drop of the DS water level in the last 40 years (recently at an average of $\sim 1 \text{ m/yr}$) is accompanied by halite precipitation (0.1 m/yr) and a continuous change in the residual brine composition (Gavrieli, 1997; Lensky et al., 2005). The fresh-saline groundwater interface of the DS is declining due to the rapid sea level decline, and consequently, salt layers dissolve and sinkholes form (Yecheili et al., 2006), as was also studied in laboratory experiments (Weisbrod et al., 2012). These sinkholes may contain even more concentrated solutions than the DS brine due to further evaporation and the halite precipitated out of the residual brine (DSB, Zilberman-Kron, 2008).

Fluid viscosity reduces with increasing temperature, and the exponential relationship closely fits the measurements (Reynolds, 1886):

$$\mu = a * \exp(-b * T) \quad (2)$$

where T is temperature in Kelvin, and the coefficients a and b depend on the fluid composition and salt concentration. The coefficients a and b are not determined yet for the DSB and its dilutions, whereas the density dependence on temperature and salinity is well-defined (Anati, 1997; Gertman et al., 2010).

The aim of this study was to determine the viscosity and density of natural and synthetic brines, as a function of their composition and salt content. We provide the above exponential coefficients (Eq. (2)) for the hypersaline natural solutions of the DSB and its diluted members. More concentrated brines derived from the DSB, as can be found in sinkholes along the DS shore, are depleted in water and NaCl by the processes of evaporation and salt precipitation, and the residual brines' compositions differ from the DSB. The effect of the chemical composition (ion ratio) on viscosity, density and their ratio is discussed. Synthetic brines were also measured for comparison. The importance of quantifying the fluid viscosity is presented concisely through a series of examples of natural processes in high-salinity environments.

2. Materials and methods

2.1. Description of solutions

Three natural brines were used: DSB, sinkhole brine (SIHB; from the DS shore) and Great Salt Lake (GSL) brine (Utah, USA). The DSB was taken from the lake, 20 m offshore from the Ein Gedi coast. The

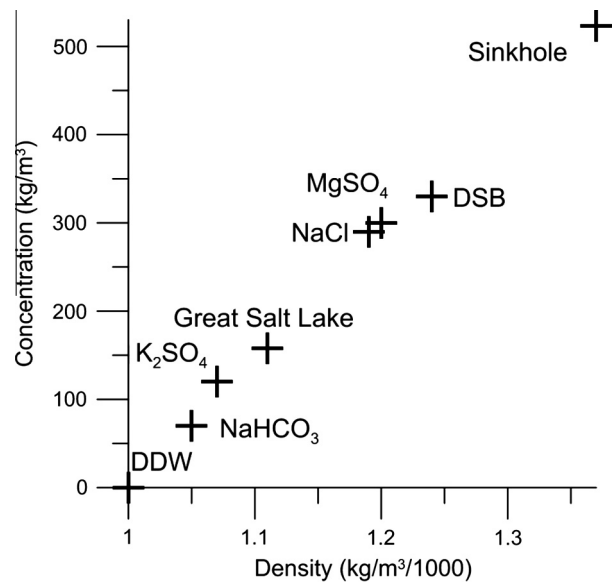


Fig. 1. The densities and total salt concentrations of the natural and artificial brines used in this study.

SIHB was taken from a 10-m-wide, shallow sinkhole, on shore 200 m away from the northern DS coast. The brine within the sinkhole originates from a DSB that had evaporated and precipitated halite and, thus, is depleted in NaCl. The GSL brine was taken from the lake, near Salt Lake City, Utah, USA. All samples were placed in plastic bottles and analyzed for their viscosity, density, total dissolved solutes and chemical composition (Table 1, Fig. 1). For the DSB, SIHB and GSL, major cations (Na, K, Ca, Mg) and SO_4 concentrations were analyzed by inductively coupled plasma-atomic emission spectroscopy (ICP-AES, P-E optima 3300) with precision of 2%. Br was analyzed by inductively coupled plasma-mass spectrometry (ICP-MS, Elan DRC II, Perkin Elmer) with precision of 5%. Cl was measured by titration with 0.01 N AgNO_3 solution with precision of 3%. The charge balance was less than 2.5%.

In addition, the following synthetic solutions were used: NaCl, KCl, MgSO_4 , K_2SO_4 and NaHCO_3 (density of 119, 115, 120, 107 and 105 kg/m^3 , respectively). These solutions were prepared from DI water and analytical salts. They were over saturated with the relevant salts for each solution and left for 48 h (in 20°C) for salt precipitation before used. Detailed chemical analysis was not obtained for the synthetic solutions. The natural solutions and the synthetic electrolyte solutions were diluted to various degrees, as detailed in the Results section.

2.2. The measurement technique and empirical equation

The densities were measured using a density meter (DMA-35N, Anton Paar, Virginia), and the viscosities were measured with a rheometer (AR2000, TA Instruments, New Castle, DE, USA). The

Table 1
The chemical composition of natural brines from GSL, DSB and SIHB (g/L) at 20°C .

	Cl kg/m^3	Na kg/m^3	Ca kg/m^3	Mg kg/m^3	SO_4 kg/m^3	K kg/m^3	Br kg/m^3	Density 10^{-3} kg/m^3	TDS kg/m^3
GSL	107	68	0.39	3.54	12.9	0.91	0.022	111	193
DSB	222	38.6	20.2	36.6	0.5	7.1	5.54	124	331
SIHB	363	1.63	45.4	98.8	<0.5	0.53	13.4	137	519

GSL – Great Salt Lake.
DSB – Dead Sea Brine.
SIHB – Sinkhole Brine.

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